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STRATEGIC DEFENSE INITIATIVE

The Applied Physics Laboratory first became involved with the Strategic Defense Initiative Organization (SDIO) in April 1984. Seven programs were initiated, five of which have resulted in launches; another is nearing a launch date. The teamwork between SDIO and APL, along with many other subcontractors, began with the Delta 180 program, the first in a series known as the Delta programs. The Delta series set new standards for accomplishing orbital missions in extremely short periods. Although the seven programs are somewhat diverse, the constant theme throughout was to understand and develop sensors that SDIO could use in a deployed architecture and that could be used from ascent through the midcourse phase of a booster trajectory.

DELTA 180

The Delta 180 Program was spawned by a rare conjunction of circumstances: a major national need; the new, forward-looking Strategic Defense Initiative Organization (SDIO); available funding; adaptable hardware; and, most important, an innovative and imaginative group of people in government, in industry, and at APL who became the Delta 180 team. This team became a driving force in the follow-on Delta 181, Delta 183, and Midcourse Space Experiment (MSX) programs.

In its early days and with only a limited technical staff in place, SDIO urgently needed the assistance of other governmental and not-for-profit organizations with experience in space and weapons systems. David Finkelman, on loan from the Army Missile Command, had worked with APL before. He met with members of APL's Fleet Systems and Space Departments and the Director's Office on 17 April 1984. Samuel Koslov was charged to see if low-level technical support could be provided in areas such as guidance, control, structures, thermodynamics, and electronics. Toward the end of the year, SDIO also sought APL's views on some quick-response space missions. This got our attention! As a result of the request, the Space Department accepted from Fleet Systems the lead role within the Laboratory, with Dr. Koslov continuing to act for the Director. At that time, Vincent L. Pisacane, Head of the Space Department, appointed John Dassoulas Program Manager and Michael D. Griffin Systems Engineer. On 20 November 1984, as part of the tasking for a work statement, APL was asked to define a near-term flight experiment to support the concept of a boost-phase intercept, that is, of destroying an Intercontinental Ballistic Missile (ICBM) during powered flight.

The Laboratory had long been concerned with the design and operation of land- and sea-based test ranges. Carl O. Bostrom, Director of the Laboratory, saw this type of experiment as an initial step, leading to his concept of a space test platform. Drs. Pisacane, Koslov, and Griffin and Mr. Dassoulas met to discuss this new opportunity; with the Director's approval, APL agreed to undertake a six-week study to define a near-term space intercept for SDIO. The only guidelines were that the mission comply with the 1972 Anti-Ballistic Missile Treaty, that it "look down, shoot down," and that it be accomplished within two years; if expanded to thirty months, SDIO would lose interest.

Preliminary Planning

A design team was assembled and began to derive mission requirements. Before beginning, we were asked by General Abrahamson, "What can you do in a year?" This turned our thinking around completely, and we laid out some ground rules that might allow the mission to be done within a year. The following assumptions were made: (1) it would not be a shuttle launch (payload integration and safety requirements for a manned space flight would take too long to satisfy); (2) only existing technology would be used; and (3) only minimal documentation could be tolerated. We generated a master schedule and were well on the track to telling SDIO what they could have in a year and how it could be done.

We had been considering several interceptor guidance technologies, including laser radar (ladar), passive infrared, passive ultraviolet, and millimeter wave radar. Because we were expert in the Aegis and Standard Missile 2 systems, a semiactive homing system using target illumination by missile ships was one of the first concepts considered. We were seeking something that could lead directly to a first-generation Strategic Defense Initiative/Kinetic Energy Weapon platform. We were talking about hit-to-kill, based on the results of the Army's Homing Overlay Experiment, which had intercepted an incoming ballistic missile with a ground-launched interceptor using infrared homing, but with guidance upgrades to deal with an accelerating target.

With a firm one-year schedule, the team considered only conventional radar, which we felt was proven. On the basis of tactical experience, we knew that hit-to-kill was not a high probability with this technology, but that any state-of-the-art guidance system should be able to place an interceptor within 100 ft of a target vehicle. The actual demonstration of a modified proportional guidance system was, in itself, an important experimental objective. We calculated how much loose steel (ball bearings) the spacecraft would have to carry to saturate a reasonable area (a few hundred square feet) with lethal pellets, which would at least be about the size of a typical blast fragmentation warhead carried on a surface-to-air or air-to-air missile. We then consulted with Michael W. Roth, in the Fleet Systems Department, who indicated that considerable analysis of Standard Missile's capability against space targets had determined that this idea was not completely ridiculous. By the end of that crucial day late in January 1985, we had derived a "kluged up" interceptor composed of a tactical missile radar seeker with a warhead, an unspecified control system, and rocket motors for propulsion. Obviously, the aerodynamic guidance systems in the available missiles would not be useful. We had not yet identified an interceptor vehicle for a particular target. Our early baseline was Standard Missile, but we had agreed to investigate Phoenix, the Advanced Medium Range Air-to-Air Missile (AMRAAM) (which was in development), and others to determine the best candidate.

We began considering launch vehicles for both the target and the interceptor and had previously agreed "no shuttle," but we had not yet discussed this matter with SDIO. The results of inquiries regarding the availability of Atlas and Titan vehicles were not promising, and the Scout payload capability was too low; only Delta remained. McDonnell Douglas Astronautics Corporation indicated that two, possibly three, vehicles were available because NASA had off-loaded payloads from Delta to add to the shuttle manifest, which the Delta Office at Goddard Space Flight Center confirmed. We then assumed that we would launch on a Delta vehicle.

During the first week in February 1985, Koslov, Pisacane, Dassoulas, and Griffin met with SDIO officials to brief them on the basic approach. Colonel (now Major General) Malcolm R. O'Neill was pleased with the concept and carried it to General James Abrahamson. A peer review of our concept (and others) was to be held on 20 February 1985 at Lockheed's Washington Headquarters.

Compliance with the Anti-Ballistic Missile Treaty

Before the meeting, Colonel O'Neill arranged for Koslov, Dassoulas, and Griffin to discuss Anti-Ballistic Missile Treaty compliance with members from the legal and political staffs of the Department of Defense and State Department. Until the meetings, we had been loosely planning to shoot at some separately launched target such as Scout, Minuteman, or Poseidon, but we soon learned that compliance with the Treaty meant we would have to launch the target vehicle suborbitally, from either Kwajalein Atoll or White Sands Missile Range. Neither site had the means to orbit anything. Not using those sites imposed severe restrictions on target identity (no ICBM or components thereof, no object on an ICBM-like trajectory or velocity). We discussed a possible launch from Kwajalein but promptly abandoned that idea after learning that the launch facilities had been disassembled after completion of the Homing Overlay Experiment Program and could not be restored within reasonable time or at reasonable cost.

For a short while, we were in the dilemma of trying to find a viable mission within Treaty constraints. Griffin noted that the Delta second stage (D2) was a restartable NASA stage, not an ICBM, thus satisfying Treaty compliance. After orbit insertion and interceptor deployment, we could restart the D2 along a non-ICBM trajectory and let the interceptor go after it. This idea was well received because of its high probability of approval by the Department of Defense and the State Department. During the approval cycle, some cooperation by the target was requested to help ensure success of both the approval process and the intercept. The response was manifest in the form of a corner reflector that provided target enhancement.

The Final Resolution

By the meeting on 20 February, Lt. Col. Michael J. Rendine, Special Assistant for Space Experiments, SDIO, was on board. The meeting was chaired by Colonel O'Neill and was attended by most of the major aerospace contractors and representatives of the Air Force Space Division. Most of the presentations were Treaty-noncompliant, expensive, and not responsive to the schedule's urgency. The APL concept, however, as presented by Griffin, met all the criteria. By the end of the day, Colonel O'Neill indicated that he had seen nothing to dissuade him from pursuing the APL mission concept, and he would present it to General Abrahamson.

High-level meetings of members from SDIO and NASA Headquarters resulted in the dedication of the Delta vehicles to the SDIO mission. We still had not identified the seeker or the propulsion hardware by the end of February 1985. Dassoulas thought McDonnell Douglas might have some spare second-stage engines, one of which might be about the right size. In a conversation with Kenneth Englar (McDonnell Douglas Delta Chief Engineer), a quick mission assessment to size the propulsion system was accomplished; they had the hardware. From then on, McDonnell Douglas was on the team as much more than just the launch vehicle contractor.

We were also converging on the Phoenix missile as having the seeker of choice. Its active radar seeker in homing mode was essentially a sealed system adaptable to space use. In March 1985, Phoenix was identified as clearly the best available seeker.

Our briefing to General Abrahamson was set for 1 April 1985. Guidance and control simulations were under way to analyze the end game. The Fleet Systems Department had undertaken this task because of its experience with intercept guidance analysis. An early conclusion was that the encounter had to be approximately head-on because the interceptor did not have a significant acceleration advantage over the target. (A guideline for the suitability of basic proportional navigation for intercepting a maneuvering target is that the interceptor must have at least a 3:1 lateral acceleration advantage.) The resultant orbital geometry became a cross-orbital plane intercept, where the target and interceptor were placed perpendicular to the orbital plane before intercept initiation (Fig. 1).

By the last week of March 1985, we had a conceptual design that most of us believed would hold up, and after several dry runs, we briefed General Abrahamson on 1 April 1985. Follow-up questions and speculations resulted in starting the encounter from a longer initial range than planned (220 km instead of 20 km) and also resulted in inserting a coast period into the end game to prevent the final speed from exceeding the relative velocity that the Phoenix Doppler radar could handle. Otherwise, our approach remained unchanged.

On 12 April 1985, we received word from Lt. Col. Rendine that General Abrahamson had given a go-ahead for the mission, with a nominal fourteen-month schedule from receiving authority to proceed. Program kickoff occurred on 15–16 May 1985 at APL and rapidly accelerated to a full-bore program. The preliminary design review was held in June 1985.

More infrared data were urgently needed on rocket plumes and bodies and on backgrounds in space. Also, the nagging question remained as to whether ultraviolet sensors could yield information useful to SDIO, but almost no data were available. The primary original purpose of the Delta 180 Program was to understand the problems of tracking and guidance for a space intercept. The possibility of using ladars was intriguing, but building a complex, multipurpose spacecraft on so short a schedule was an overwhelming concern. The decision was made to go ahead with a Science Module to be attached to the D2 stage , but with the absolute rule that nothing involved with the Science Module, no function (or malfunction), could interfere with the primary intercept mission. The go-ahead was given to try to assemble off-the-shelf sensors, including a ladar and an ultraviolet/visible system and two infrared systems that could function completely independently, receiving only a single signal from the D2 guidance system to start the Science Module timing sequence. The Laboratory had agreed to act as technical advisor for the overall experiment and now took on the added responsibility of designing a spacecraft essentially without propulsion and guidance (which were supplied by the D2 stage). In June 1986, the Science Module was shipped to Cape Canaveral for the start of launch preparations (Fig. 2). Vector Sum (the program code name) launched Delta 180 on 5 September 1986, sixteen months after the program's start. About 10,000 seconds later, a direct hit occurred at a closing velocity of 2.9 km/s (Fig. 3).

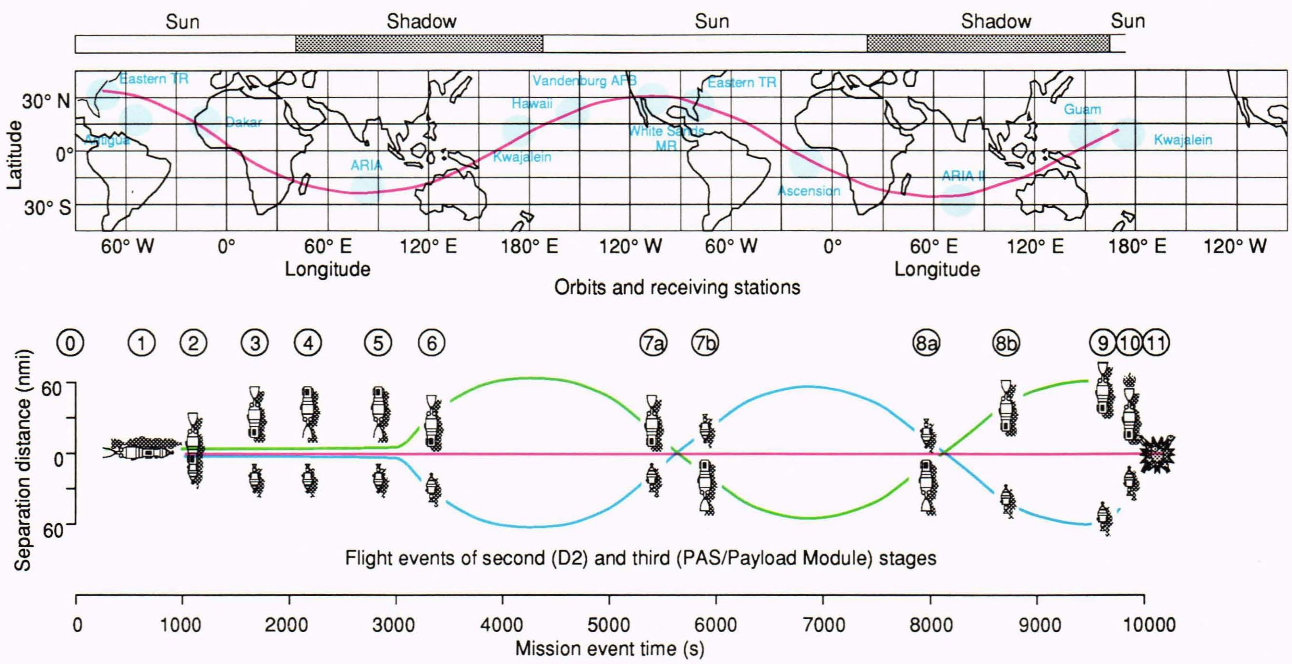


Figure 1. The Delta 180 Program flight events. (0) The Delta 180 experiment is launched from the Eastern Test Range, Cape Canaveral, Fla., on 5 September 1986. (1) After burnout of the first stage, the combined second (D2) and third (Payload Adapter System, PAS) stages are placed in a 220-km circular orbit by the D2 rocket engine. (2) The combined D2/PAS structure is rotated to fly cross-plane to the flight orbit. (3) The D2 is separated from the PAS by means of springs but continues in the same orbit. Insruments on the D2 view the separation. (4) The D2 is turned through 180°. Its instruments view the Earth limb and Earth. (5) The D2 rocket engine thrust provides a slightly altered orbit. The D2 insruments view its own rocket exhaust plume. (6) The D2 PAS are turned to face each other again, nose-to-nose. The D2 laser tracks the separation distance between the D2 and the PAS. (7a) Just before Cold Pass 1, the D2 is maneuvered so that its instruments acquire an Aries 1 rocket launch from White Sands Missile Range, N. Mex., at a distance of 480 km. (7b) The D2 and PAS are turned again to face each other nose-to-nose. (8a,b) Near Cold Pass 2, the D2 and PAS are turned again so that the D2 instruments continue to face the PAS. (9) At maximum separation (220 km), the D2 and PAS rocket engines are ignited to provide thrust for the two spacecraft to accelerate toward each other. The D2 instruments obtain ultraviolet, visible, and infrared signatures of the PAS. (10) After a coasting phase, the D2 and PAS rocket engines are ignited again at a separation distance of 60 km. The PAS guidance system provides terminal homing. (11) Collision takes place in space between the two accelerating bodies 9871.6 s after launch and 36.7 s after step 9.

What Was Left Unsaid

Many key events occurred after the program began but are not elaborated in this article; however, they do deserve mention: the addition of Draper Laboratory to our guidance analysis team; the regularly held reviews; the development of the instrument complement and the Science Module; the advanced Mission 2 (which became Delta 181), mission design discussions concerning in-plane versus cross-plane scenarios; the warhead modification that removed the fragmentation jacket to reduce the junk in space; orbit debris and safety panel; the Delta 178 failure and subsequent modifications to the Delta 180 launch vehicle; extensive flight operations involving all major ranges; the precise photometric coverage of the intercept (both airborne and from the ground at Kwajalein Missile Range); and the late addition of an Aries rocket launch at White Sands to provide additional opportunities for scientific measurements (or observations). At the very last was the tedious process of clearing a launch time with the Air Force and others, including consideration of foreign government assets in space that might be placed in jeopardy by our mission.

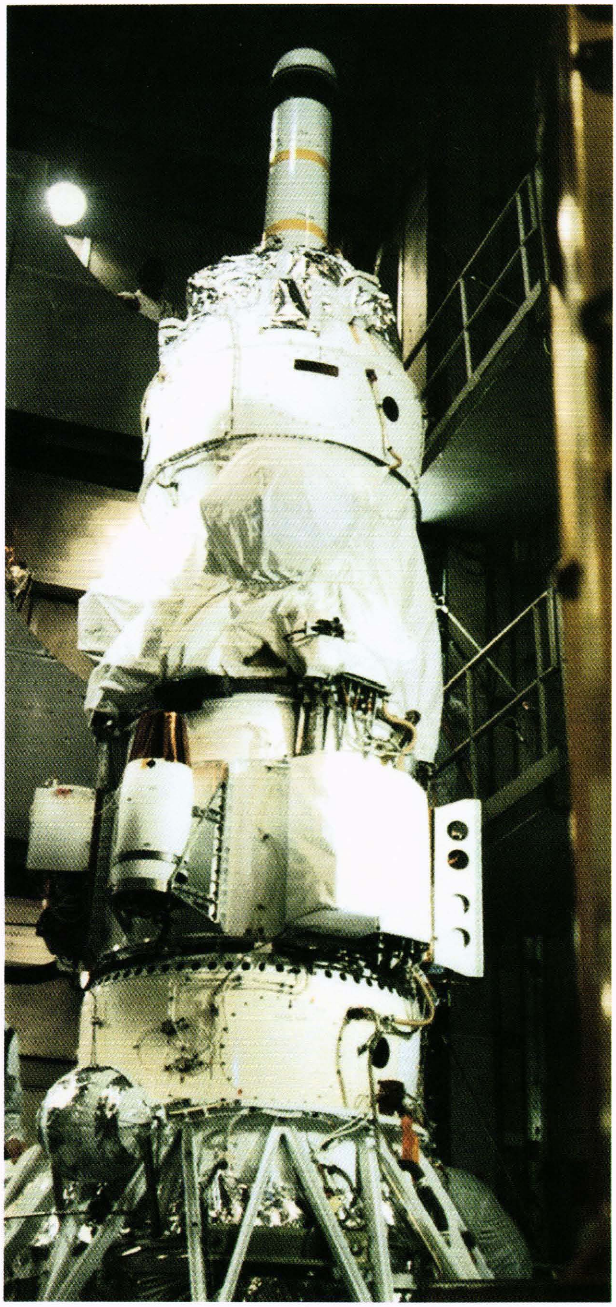


Figure 2. The Sensor Module (the target) and the third stage (the interceptor) on the Delta 180 launch vehicle at Cape Canaveral, Fla.

Several key individuals at APL undertook major responsibilities for tasks vital to the achieved performance of the Delta 180 mission. Thomas B. Coughlin managed the Science Module design, development, instrument acquisition, and integration. Thomas L. Roche directed the integration of experiments and subsystems and was test conductor. Larry J. Crawford, who undertook the task of intercept verification and aircraft instrumentation, flew to the Cape from Kwajalein with the video films confirming the intercept. Richard W. Eakle organized and led the team that managed night operations, establishing vital communications links and coordinating the activities of all the involved ranges. He also was responsible for the timely issue of the three-day report of mission performance. James F. Smola guided the effort to acquire and launch from White Sands Missile Range an Aries rocket with an instrumented reentry vehicle designed to produce data for a future mission. This was accomplished in less than one year, and the launch was flawless. It produced plume data and exercised the infrared instruments on the Science Module. (The ultraviolet systems were turned off for fear of overloading the sensors.)

James C. Hagan analyzed the orbit debris and developed the operations plan for launch-window clearance and evaluation. This work has become the benchmark against which future missions will be compared. Charles Brown directed the modification program in which the warhead igniter and fuze were redesigned. Later the fragmentation jacket was removed because of debris considerations. Brown and his team from the Naval Weapons Center, China Lake, and the Naval Surface Warfare Center delivered a redesigned, and fully tested, blast-only warhead to the mission. Glen H. Fountain assumed responsibility for designing a new ultraviolet/visible imager/spectrometer sensor, which produced data of incalculable value to SDIO, and was a truly superb instrument. Koslov took on the role of Program Scientist for the first year to oversee the initial development of the Science Module. Ching–I. Meng later followed as Program Scientist for Delta 180/181, predicting instrument performance and the implications thereof. Meng defined UV and visible observational systems and guided assessment of the data. He led the postflight analysis effort with both oral and written reports, yielding a surprising amount of data. Bruce B. Holland, Assistant Program Manager, undertook the administrative and fiscal aspects of Delta 180 while assuming the growing technical and managerial responsibilities for Delta 181, which was maturing as a parallel effort. J. Courtney Ray's creativity and systems-oriented approach to space mission design and

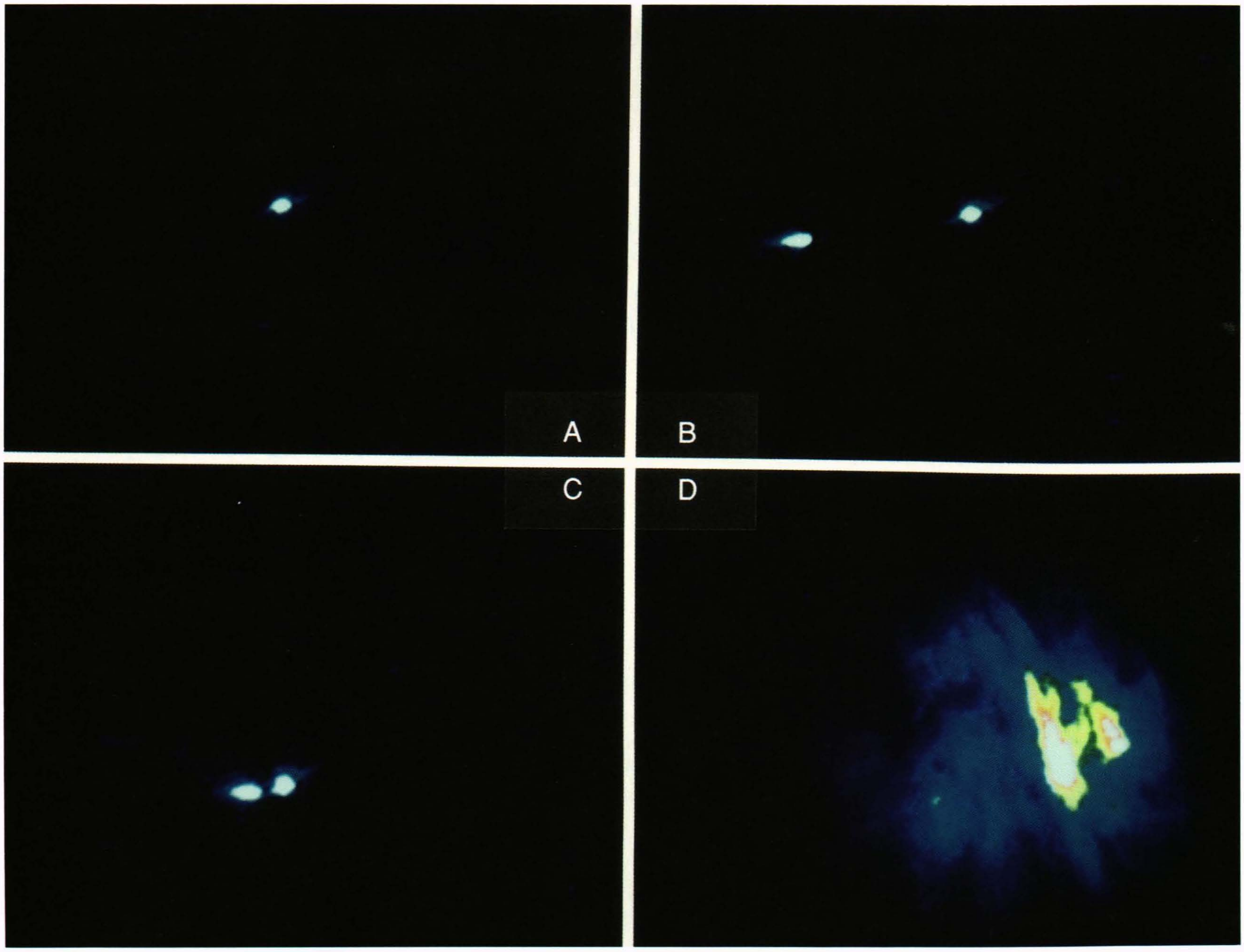


Figure 3. The intercept (computer-enhanced) as viewed in the visible spectrum from an observing aircraft. **A**. The Sensor Module. **B.** The interceptor approaches. **C.** Close approach. **D.** Direct hit.

spacecraft systems engineering made him an absolutely essential member of the Delta 180/181 team.

Details of this rewarding and technically significant mission are discussed elsewhere.[1] The primary mission of Delta 180, code named Vector Sum, was to understand the problems of tracking, guidance, and control for a space intercept of an accelerating target and to demonstrate this understanding by actual flight test. What became equally important was the urgent need for multispectral data on rocket plumes, postboost vehicles, and the background against which they would be viewed. At this time very little sensor data had been collected on ICBM threats, and no thrusted intercept against a thrusting target had ever been attempted in space.

The Laboratory undertook the role of technical advisor for the overall experiment and had the additional responsibility of designing the sensing spacecraft that was part of the target vehicle. The D2 stage, to which we remained attached, provided propulsion and attitude control.

Much has been written about Delta 180 since the spectacular intercept of 5 September 1986. A complete list of Delta 180 accomplishments and benefits to SDI would be formidable indeed. Touching only on the high points, certain products can be summarized.

Regarding the interceptor, the Delta 180 team accomplished the major tasks of design, fabrication, test, and flight of a new liquid-fueled third stage for the Delta vehicle. This became the propulsion system for the interceptor. Major modifications to the AIM 54C Phoenix missile for spaceflight included a new radome, gyros, software, fuze, and warhead. The Phoenix was integrated with the new third stage to complete the interceptor.

The sensor module contained all the usual elements of a spacecraft, that is, the power, telemetry, and command; it also included the first space-based laser radar, a modified AGM-45 Maverick infrared seeker, an ultraviolet/visible imager/spectrometer sensor, and an additional infrared telescope. The sensor module was designed, fabricated, and integrated by APL. Close collaboration with McDonnell Douglas Aerospace resulted in the successful integration of the sensor module with the D2, which was modified to extend its life for multiple orbits, including four engine starts and the ability to respond to ground commands from the Delta Program Operational Control Center.

A number of incidental accomplishments turned out to be of major proportions: creation of more than a million lines of new software to support guidance and control;

orbital safety and real-time satellite operations by the worldwide network; and integration of 170 range assets, including ten test ranges, thirty-eight radars, thirty-one satellite links, and four aircraft into the largest network ever used in a space operation. These assets are preserved as the Space Test Range. Another first was the use of gimbal cameras in aircraft for metric measurements. These cameras were directed by Kwajalein Missile Range radars via satellite link and the aircraft inertial navigation system.

With the exception of the actual intercept, all maneuvers and events were carried out open loop, including the synchronized launch of an Aries rocket from White Sands Missile Range within one-tenth of a second of the desired time for imaging by the orbiting sensor module. Significant upgrades to the National Test Ranges to conduct the real-time control from the Eastern Test Range included the capability to receive, record, and evaluate quick-look telemetry using eighty percent of the available bandwidth of the S-band downlink. Technical contributions to the aerospace community resulting from the Delta 180 success include the first thrusted intercept in space, the acquisition of revolutionary new data on rocket plumes in the space environment, the first flight of a laser radar in space, and significant improvements in hypervelocity debris models and orbital safety computer predictions. Ultraviolet sensing of rocket plumes, because of the success of the APL instrumentation and analysis on Delta 180, has now become an important tool in space booster and space object identification.

The experiment was conducted under highly streamlined program management and reporting procedures that resulted in schedule and cost compression to fourteen months and $150 million, respectively. A program of this complexity normally would take three to five years at a cost of $300 to $500 million. The program was carried out while the U.S. space program was under virtual siege because of several failures, including the loss of *Challenger* in January 1986 and the failure of Delta 178 in May 1986. Despite its being a high-risk venture and the extraordinary complexity of the orbital mission, Delta 180 delivered to the nation its first major space success after a string of disappointments.

DELTA 181

Background

Delta 181 went through a remarkable evolutionary process before its final emergence. As early as August 1985 (more than a year before the Delta 180 launch), mission planning was under way. First thoughts involved a more ambitious intercept than could be accomplished by the Delta 180. Mission 2, using Delta 181 and 182 boosters, was conceptualized but never implemented because it would have stressed the 1972 Anti-Ballistic Missile Treaty. The SDIO scrupulously adhered to the Treaty, and as much attention was devoted to Treaty compliance as to technical reviews.

By September 1985, another concept was proposed, incorporating a full-spectrum complement of sensors, and Delta 181 became a comprehensive phenomenology mission. A probe (an independent vehicle) was included on the spacecraft in addition to a large complement of test objects for calibrating the sensors and whose physical characteristics would be observed by the sensors. The U.S. Army became a major program participant by providing the test objects and dispensing the apparatus. The U.S. Air Force undertook the probe development. The instrument complement was selected and the conceptual design of the spacecraft initiated. On 20 January 1986, General Abrahamson was briefed on the mission and gave the go-ahead. Funding was provided, and detailed design and mission planning got under way. In parallel with this effort was the Delta 180 fabrication, systems integration, and testing. The successful conduct of the Delta 180 experiment resulted in deletion of the probe from Delta 181 and incorporation of a plume generator and a gas-release experiment. Additional studies on a variety of mission enhancements were not implemented but resulted in some schedule relief and a new ship-to-the-Cape date of 30 November 1987. Delta 181 had became solely a phenomenology and test-object sensing platform.

Mission Description

Using instruments integrated in the Sensor Module, the Delta 181 Mission conducted a number of experiments that were crucial to development of the Strategic Defense Initiative. The experiments were designed to fulfill the principal objectives of the mission: observation and characterization of various test objects, rocket exhausts, and vehicle outgases. Secondary mission objectives were observation and characterization of various space, Earth, and Earth-limb backgrounds and the quantification of spacecraft glow phenomena.

The Delta 181 mission itself represented one of the most complex and ambitious unmanned experiments ever conducted. The McDonnell Douglas Delta rocket boosted the various instruments, computers, test objects, and observation rockets into a low Earth orbit. The test objects were ejected from the satellite for observation and tracking against the natural backgrounds expected to be seen by an attacking ballistic missile in midcourse flight.

After deployment of the test objects, several rockets were launched to provide exoatmospheric plume signatures for the instruments to observe. A subsatellite released test gases to simulate vehicle outgases in space. The Delta platform executed more than 200 maneuvers expected to be needed for a low-orbit battle station. The maneuver offered the passive instruments opportunities to sample rapidly changing backgrounds, to view test objects against such backgrounds, and possibly to determine the extent of contamination presented by the spacecraft glow phenomenon.

To attain these objectives, the mission used an array of state-of-the-art observation instruments covering wavelengths from the far ultraviolet through the visible and out to the long-long wavelength infrared range. The passive and active instruments, along with support functions (power, telemetry, recorder, flight processor), were mounted on the exterior of a 12-ft extension of the D2 that was a component of the spacecraft in orbit (Fig. 4). The spacecraft's flight processor, working with sensor measurements, maneuvered the 6000-lb spacecraft as it made observations. Closed-loop tracking, acquisition, and reacquisition of multiple objects were required during the mission, and the data are being used for future system development.

The seven-instrument complement for the SDIO space platform experiment consisted of two infrared imagers, an infrared spectrometer, an ultraviolet and visible instrument, two laser instruments, and a microwave radar. The Lockheed-built infrared imager generated a multicolor image in short and medium wavelengths; the Aerojet infrared instrument provided imagery in the long wavelengths. Spectral information in the infrared range was derived from the two variable-wheel spectrometers of Space Systems Engineering's instrument. The APL-developed instrument consisted of six sensors: an ultraviolet imager and a visible imager to complement the infrared imagers and four linear-reticon spectrographs whose ranges overlapped to observe the visible and ultraviolet ranges.

Delta 181's active instruments included the pulsed ladar built by GTE Government Systems Corporation, a coherent Doppler ladar built by Martin Marietta Orlando Aerospace, and a continuous wave Doppler radar built by Teledyne Ryan Engineering. The instruments were integrated into the Sensor Module during the summer of 1987 and underwent environmental testing at NASA's Goddard Space Flight Center in November 1987. The Sensor Module was delivered to Cape Canaveral in early December for integration with other flight elements. Launch was on 8 February 1988.

Mission operations were conducted in two phases: (1) data acquisition during test-object and phenomenology observations; and (2) data retrieval, planned for two weeks but carried out for two months because of extended battery life. Delta 181 reentered on 2 April 1988 over the Atlantic Ocean equatorial region.[2] Mission results have been published in five documents. The raw data now reside in the Army's Space Defense Command Thrusted Vector Central Data Facility in Huntsville, Alabama.

Remarks by President Ronald Reagan to the Institute for Foreign Policy Analysis Conference marking the fifth anniversary of his speech outlining the Strategic Defense Initiative (SDI), as reported in the *Washington Times,* Tuesday, 15 March 1988, stated that "Space tests of Delta 180 and 181 have demonstrated their ability to track fast moving targets in space and distinguish dummy warheads from the real thing. American Scientists and engineers are not constructing a bargaining chip but building a future free from nuclear terror."

THE JANUS PROGRAM

In August 1986, a memorandum of understanding (MOU) documented the Janus Program agreement between SDIO and the Strategic Systems Project (SSP) to launch SDIO payloads with Trident missiles to satisfy SDIO objectives and to demonstrate a Navy submarine orbital launch capability. Four missions were described in the MOU with the first orbital mission (Janus Mission II) to follow two experiments using ballistic trajectories. Two suborbital missions were conducted. The first mission was launched in August 1987, the second mission in February 1989.

By February 1989, the Navy had completed its review, identified the technical issues to be resolved during the development phase, and concluded that the proposed concepts for Mission II were technically feasible and safe without substantially affecting missile reliability. In May 1989, SDIO terminated engineering development of the mission and of the spacecraft design because of funding constraints.

For the suborbital mission, APL was responsible for the experiment designs, implementation of the missions, and assisting Captain Geist of the U.S. Navy, the SDIO Pro-

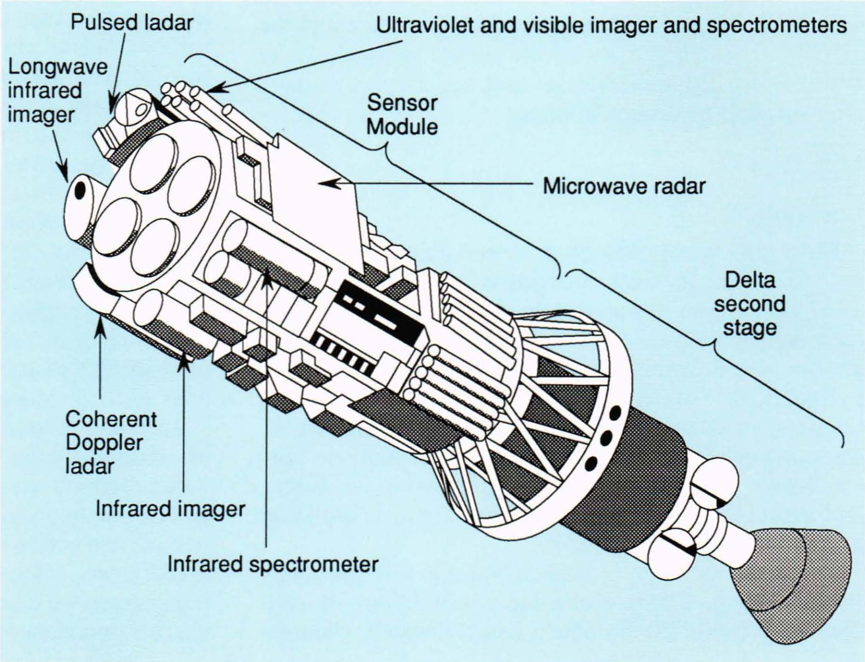


Figure 4. The Delta 181 Sensor Module and second stage, showing the arrangement of the scientific instruments.

gram Manager, with management of the program. Payloads were supplied by Hughes Aircraft and Sandia Laboratory for integration onto a C4 missile. Space Systems Engineering provided an infrared instrument to Sandia via a subcontract with APL.

For the suborbital missions, SDIO-supplied payloads were integrated onto a C4 missile and launched from a submarine off the coast of Florida. One objective was to obtain long-wavelength infrared images of objects in space. The infrared sensor package used to make these measurements was provided by Hughes Aircraft. A cutaway view of this payload is shown in Figure 5. The other objective of these missions was to measure the environment in the vicinity of space objects by using numerous optical instruments supplied by Sandia National Labs.

The planned objective of Janus Mission II was to demonstrate the capability of a Submarine-Launched Ballistic Missile (SLBM) to inject an SDIO payload into orbit (Fig. 6). The experiment involved integration of a unique experimental payload with the operational Fleet Ballistic Missile (FBM) weapon system. Given the ground rules to conduct the experiment aboard an operational submarine without compromise to FBM weapon system safety or reliability and without design modification to the FBM weapon system, several significant programmatic and technical challenges were presented to both SDIO and SSP. Overall, these challenges were resolved to the extent that no "show stoppers" were identified before full-scale development.

DELTA 183 (DELTA STAR)

The Delta 183 program was initiated in early February 1988 with a highly accelerated schedule aiming for a late May 1988 launch date. The spacecraft was based on using heritage and spares from the Delta 180 and 181 programs (Fig. 7). McDonnell Douglas Corporation, Huntington Beach, California, was to design part of the spacecraft. The Applied Physics Laboratory was to design and integrate a suite of sensors (the Sensor Module) and to provide technical advice to the SDIO sponsor.

Sensor Module and Instruments

The 49-in.-high Sensor Module had an outside diameter of about 86 in., including instruments, and weighed

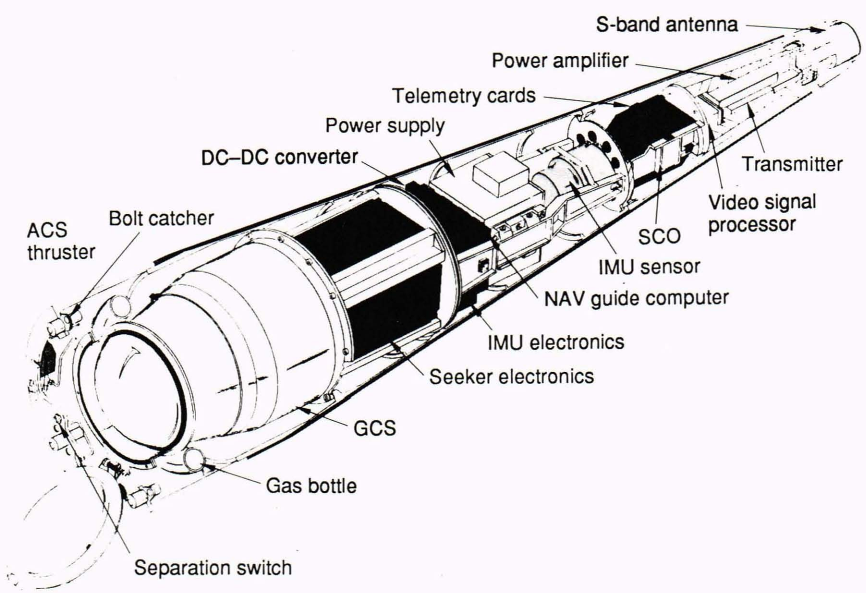


Figure 5. Payload A, cutaway view. ACS = Attitude Control System; GCS = Guidance Control System; SCO = Subcarrier Oscillator; IMU = inertial measurement units.

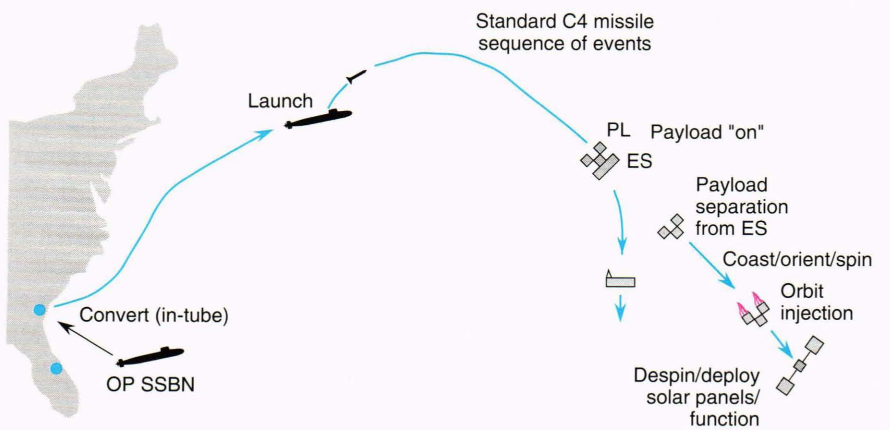


Figure 6. Janus Mission II operational deployment sequence. OP SSBN = operational nuclear missile submarine; ES = equipment section; PL = payload.

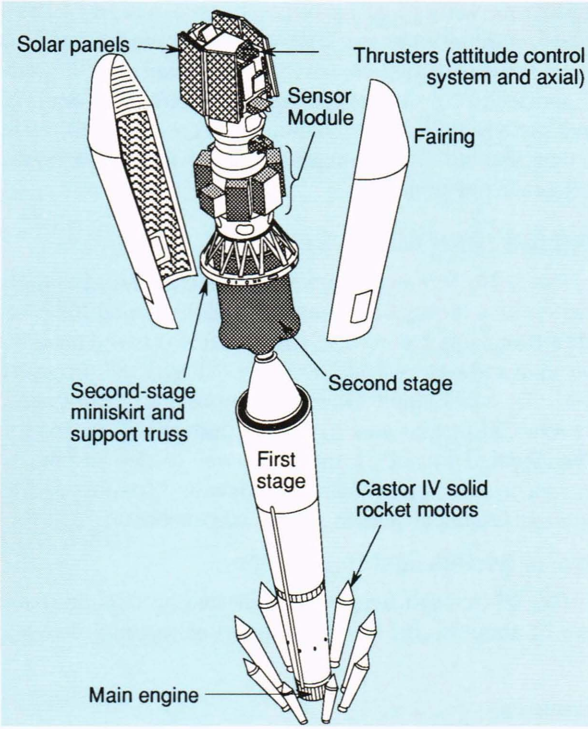


Figure 7. The Delta 183 (Delta Star) spacecraft and launch vehicle.

about 1538 lb. Among the instruments were seven video imagers, a ladar, an infrared imager, and a materials experiment. The experiments were mounted around the exterior of the module.

The ultraviolet and visible instruments included four imagers and four photometers. Two were high-sensitivity intensified video cameras responsive to ultraviolet light. Two other cameras imaged in visible light with different fields of view. These instruments were built by APL. One of the ultraviolet video cameras was built by the Air Force Academy; the other, for imaging selected targets in four ultraviolet bands, was built by the Jet Propulsion Laboratory.

A third optics-based experiment was the midwave infrared video camera, developed by General Electric's Astro-Space Division. Designed for the space shuttle and modified for the Delta Star mission, it acquired infrared information on plumes and the space environment and acquired and tracked targets. This tracking ability was used to keep the target within the fields of view. The longwave infrared camera was developed by Hughes Aircraft. Together, these instruments provided greater understanding of plume emissions and the environmental backgrounds against which they may be observed.

The Sensor Module consists of ten modular platforms, five containing sensors and five containing support systems. The sensors were scheduled for delivery to APL in mid-July 1988. The support systems developed by APL were ready for integration in late June 1988.

The launch date was subsequently changed to January 1989. The Sensor Module integration was completed during August 1988 and shipped to Goddard Space Flight Center in late August 1988 for launch environment acoustics and thermal vacuum testing. After these two major tests were accomplished, the Sensor Module was shipped to McDonnell Douglas, Huntington Beach, California, for integrated testing with the remainder of the spacecraft. The integrated tests involved mechanical fit check, software, and transient power turn-ons. Because of the coordinating efforts by teams on opposite sides of the country over a period of seven months, these tests went without any significant incident.

The Sensor Module was delivered back to APL in late October 1988 and was shipped to Cape Canaveral Air Force Station in early December 1988, ten months after program initiation. The mission had been redesigned several times. Each time the schedule was extended, we found time to enhance the instrument suite. A line drawing illustrating the functionality of the orbitally configured spacecraft is shown in Figure 8.

During December 1988, the Sensor Module was mated with the remainder of the spacecraft and all testing was completed in order to support the January launch date. Our program, however, got involved in a launch queue with several other programs. In mid-January 1989, the spacecraft was hoisted onto the Delta 183 launch vehicle. On the adjacent Delta launch complex was a spacecraft/launch vehicle to be launched before the Delta 183 mission. The launch crew was sent home during the third week of January 1989 with expectations of a return in mid-February to complete the job. On 15 March 1989, the attempted launch of Delta 183 was scrubbed minutes before launch because of an anomaly within the Sensor Module.

Commands are stored on board the Sensor Module in a unit called the Command Decoder Unit (CDU). During countdown, three of the commands intended to be stored in the CDU were not accepted properly. The problem surfaced three hours before launch, but troubleshooting the problem took up until five minutes before the launch. It was at this time that the intended launch was scrubbed. The problem was found to be a computer chip failure within the CDU. The unit was sent to the supplier, where the chip was replaced and the unit subjected to both functional and environmental tests.

On 24 March 1989, the Delta Star spacecraft was again ready for launch. A near-perfect countdown followed by a completely nominal launch put the Delta 183 spacecraft into orbit. After an initial "getting smart" period all sensors worked well. The mission, which was originally estimated to last three months, ended with hydrazine fuel depletion after nine months, in December 1989.

During the nine months in orbit, 126 experiments were completed. These experiments included observing understanding Earth and space backgrounds, observing missile plumes, observing space resident objects, and many other studies that cannot be discussed in the open literature.

Five dedicated rockets were associated with Delta 183. Of these, one of the more significant produced and measured an artificial polar mesospheric cloud structure. In addition, a ground-based CO_2 laser transmitted through the atmosphere to the orbiting Delta 183. The spacecraft was operated from the Consolidated Space Test Center at Onizuka Air Force Station in California.

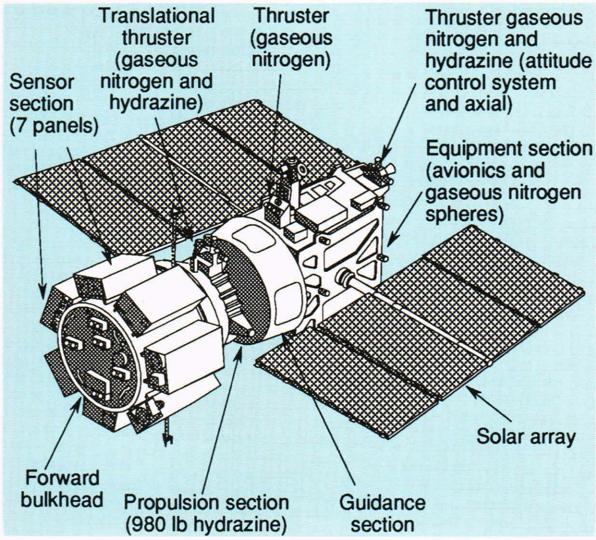


Figure 8. Design features of the Delta Star.

A Sensor Module team was located at the station. The Delta 183 Data Center was located at APL. The data were coordinated, disseminated, and finally sent to storage at the Mid-Course Data Center in Huntsville, Alabama.

The Delta 183 program illustrated what can be done with creative sponsor management and a team atmosphere. Throughout this program, with so many organizations involved, the living Interface Control Documents were held sacred. Each agency had a single individual responsible for continuous maintenance of this document. Schedule constraints made it necessary for the normal design review cycle to be converged to a single peer review called the ODR (Only Design Review). Although many programs obviously cannot be done this way, for experimental missions amazing results can be accomplished in a short time.

BRILLIANT PEBBLES PROGRAM

The Strategic Defense Initiative Organization (SDIO) has been conducting research since the mid-1980s to develop defensive systems intended primarily to provide low to moderate protection against a large-scale ballistic missile attack on the United States. As an outgrowth of the recent Persian Gulf War, the President directed in his State of the Union address, ". . . that the SDI Program be refocused on providing protection from limited ballistic missile strikes, whatever their source." The new SDI mission is referred to as a Global Protection Against Limited Strikes (GPALS).

The GPALS mission is to provide protection against limited strikes rather than deterrence of a massive attack. The single space-based weapon element of the GPALS architecture is the Brilliant Pebbles interceptor. Each Pebble is an autonomous interceptor that can act entirely on its own, once appropriately authorized. It basically looks out and sees the ballistic missiles when they rise from their silos or from mobile launchers. At the appropriate time, the Pebble drops its life jacket and proceeds to maneuver into the oncoming path of the threat ballistic missile or during the mid-course phase of a reentry vehicle transiting space. The Pebble weapons would work in concert with other orbiting sensors and ground-based missiles to provide the necessary defenses against accidental launches and other small-scale missile launches.

The Strategic Defense Initiative Organization plans to decide on engineering and manufacturing development (EMD) of Brilliant Pebbles in mid-1996. The concept is currently under development and a pre–EMD phase is being executed by industry. The Pebbles Program is managed by Colonel P. Worrell, Director of the Global Defense Segment, under whom APL is performing Brilliant Pebbles Test and Evaluation (TE) tasks. The TE element is conducting suborbital flights, including actual target intercepts from Wallops Island and Usaka test ranges, to evaluate the Pebbles concept and the Pebbles system performance.

In the summer of 1989, SDI requested support from the Space Department in establishing a program and an industrial team to evaluate the Pebbles concept through a series of suborbital flight tests. The Space Department provides mission planning support, field operations support, launch vehicle coordination, development of target and interceptor instrumentation, data management coordination, and functions as overall technical and security advisors to the Brilliant Pebbles Program. In 1990 the Aeronautics and Strategic Systems Departments began to support the Space Department in performing these tasks, and in 1991 they were awarded separate contracts. Their support continues to be coordinated, however, by the Space Department. The Strategic Systems Department also does independent analyses of flight test data and reports the results directly to SDIO.

During the suborbital flight tests, the trajectory of the interceptor will be determined using the Global Positioning System (GPS), and the interceptor performance will be determined by analyzing interceptor data telemetered to ground stations. Some flights will use an APL-designed system. This system is a combined lightweight (550–650 g) GPS translator and telemetry transmitter (GTT). The GTT block diagram is shown in Figure 9 and a picture of the engineering model is shown in Figure 10. In this configuration, the GTT system will be mounted on the cylindrical fuel tank of the Brilliant Pebbles interceptor. The design satisfies the TE instrumentation requirements of high-accuracy three-dimensional trajectory determination and interceptor-vehicle encrypted telemetry data recovery.

The target vehicle to be intercepted during the suborbital flight tests will be instrumented by APL to provide additional data to assist in evaluating the interceptor performance and to provide data to permit an independent assessment. Figure 11 shows the layout of the planned instrumentation systems to be installed on the target vehicle. The target trajectory will be determined by using the Ballistic Missile Translator (BMT) GPS data. The APL-designed lidar (light plus radar) detectors shown in Figure 12 will be mounted on the target nose. This system is intended to provide independent verification that the target was illuminated by interceptor lidar homing sensor during the test. The final system (Fig. 11) is a miss-distance measurement system. This system will be sup-

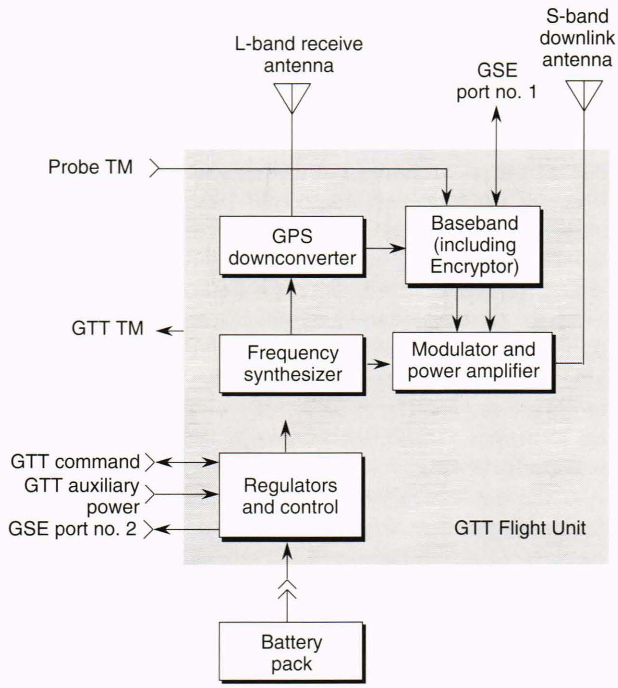


Figure 9. Global Positioning System (GPS) Translator and Telemetry (GTT) Transmitter block diagram. GSE = ground support equipment; TM = telemetry.

Figure 10. Global Positioning System Translator and Telemetry (GTT) Transmitter electronic assembly.

plied by Cartwright Electronics, Inc., through a subcontract with APL. This equipment is a range-gated, Doppler radar system that relies on a unique application of Synthetic Aperture Radar (SAR) principles to generate coherent images and provides measurements of target/interceptor miss distance, time of closest approach, and relative

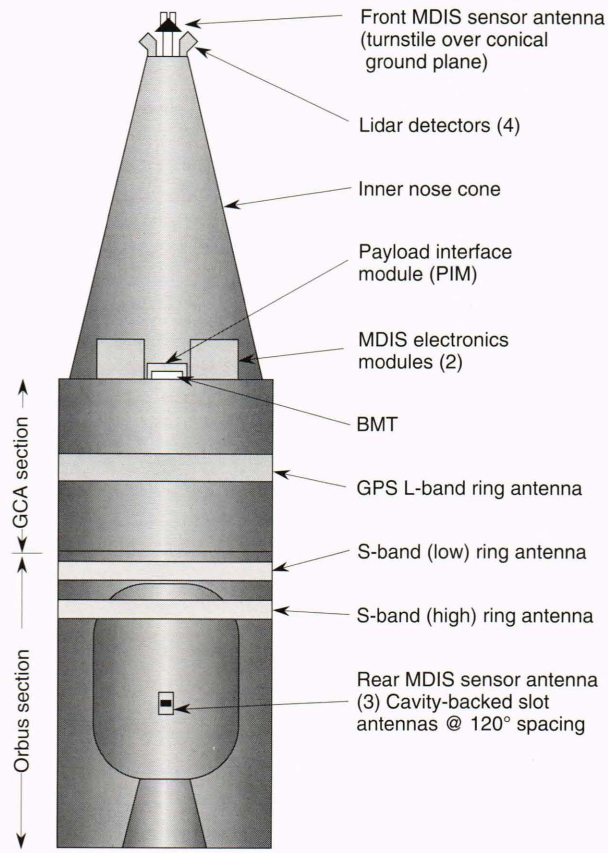


Figure 11. Terminal target vehicle (TTV). BMT = Ballistic Missile Translator; GPS = Global Positioning System; MDIS = Miss-Distance Indicator System; BMT = Ballistic Missile Translator.

closing speed on each major scattering point associated with the interceptor vehicle.

VEHICLE INTERACTIONS PROGRAM

The past ten years have revealed anomalies in optical radiometric and spectral measurements in a number of Department of Defense and NASA space experiments. Although some anomalies are attributable to improper sensor calibration, ample evidence suggests that the computer codes used to predict optical signatures do not account for all the relevant physical effects that contribute to the optical signature of a vehicle in space. As early as 1985, APL proposed a research program to study this problem. As the problem became more apparent, APL proposed a comprehensive program of basic, laboratory, and applied research supplemented by flight experiments to characterize the interactions of a vehicle in space with the ambient space environment under conditions relevant to strategic defense. The program would also assess the implications of these vehicle interactions on the strategic defense mission. This program, called the Vehicle Interactions Program, was finally approved by SDIO and formally initiated in October 1989.

Figure 13 illustrates the problem. On the left is the conventional view of a vehicle in space. Space is seen as a vacuum in which the optical signature of a vehicle is composed solely of its own thermal (or gray body)

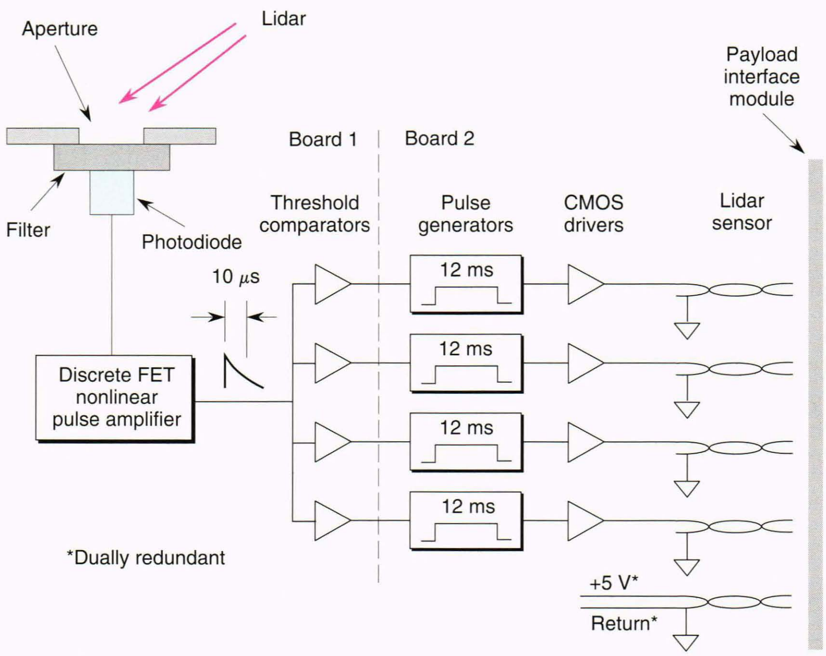


Figure 12. Lidar detector block diagram. FET = Field Effects Translator; CMDS = complementary metal oxide semiconductor.

radiation and reflected energy from the Sun and the Earth. The current optical signature codes adequately model these conventional effects. On the right is an extended view of a vehicle in space that accounts for additional phenomena, which are attributable to the interactions of the vehicle and its local environment with the ambient space environment, giving rise to the term vehicle interactions effects. Because these effects are not well understood, they are not currently included in optical signature codes. The vehicle's local environment, in addition to the vehicle itself, consists of a dusty gaseous cloud surrounding the vehicle. This cloud is composed primarily of outgassed water vapor and small dust particles that were either carried up with the vehicle when it was launched, are a by-product of vehicle activity (such as rocket motor firings for station keeping), or were generated by gradual erosion of the vehicle's exterior surfaces from interactions with the space environment.

The ambient space environment consists primarily of neutral and charged atomic and molecular particle species of oxygen and nitrogen moving at a high relative velocity with respect to the vehicle. Considering ICBM's, satellites, and space-based interceptors, relative velocities in the range of 3 to 13 km/s are possible. Also, at the high latitudes of interest in a strategic defense scenario, the Earth's magnetic field lines extend almost vertically, allowing fluxes of high-energy–charged particles of solar and magnetospheric origin to be channeled to low altitudes. This condition is responsible for many polar geophysical phenomena, including the aurora borealis (or northern lights). Interactions of the natural space environment with the local vehicle environment can produce emissions at optical wavelengths from the ultraviolet through the infrared and, to a less significant extent, plasma waves. The processes that lead to these emissions are summarized in Figure 14.

The magnitude of effects of interactions for many of the gas–gas and gas–surface processes depends on velocity (collisional energy), altitude (ambient gas density), and vehicle configuration (surface material properties). For example, the excitation cross sections for some of the gas–gas interactions have pronounced thresholds in the range of 2 to 6 km/s relative velocity. It is therefore important to test for these effects under conditions of altitude, velocity, vehicle configuration, and latitude that are representative of a realistic strategic defense scenario. A familiar example of a gas–surface interactions effect is the so-called shuttle glow first observed by astronauts on the early shuttle flights.

The problem is further complicated by the fact that vehicle interactions effects can be associated with both an observing sensor in space and the target vehicle it is trying to observe. This situation gives rise to the look-out and look-in scenarios (Figs. 15 and 16). In reality, these two scenarios can occur simultaneously, making it difficult to separate near-field interactions effects from far-field interactions effects.

The Vehicle Interactions Program is addressing this problem with a combination of activities: basic research and modeling, laboratory research, data analysis, applied research, and flight test experiments. The program has sought participation from a variety of resources: universities, industry, and government laboratories, wherever the best expertise can be found. The largest investment of the program will be in obtaining a definitive database for understanding vehicle interactions phenomenology by means of several dedicated flight experiments. The experiments will be designed to measure simultaneously both the vehicle local and ambient space environments and the optical emissions from the resultant vehicle interactions. The database must be done so as to demonstrate convincingly the existence of these effects and

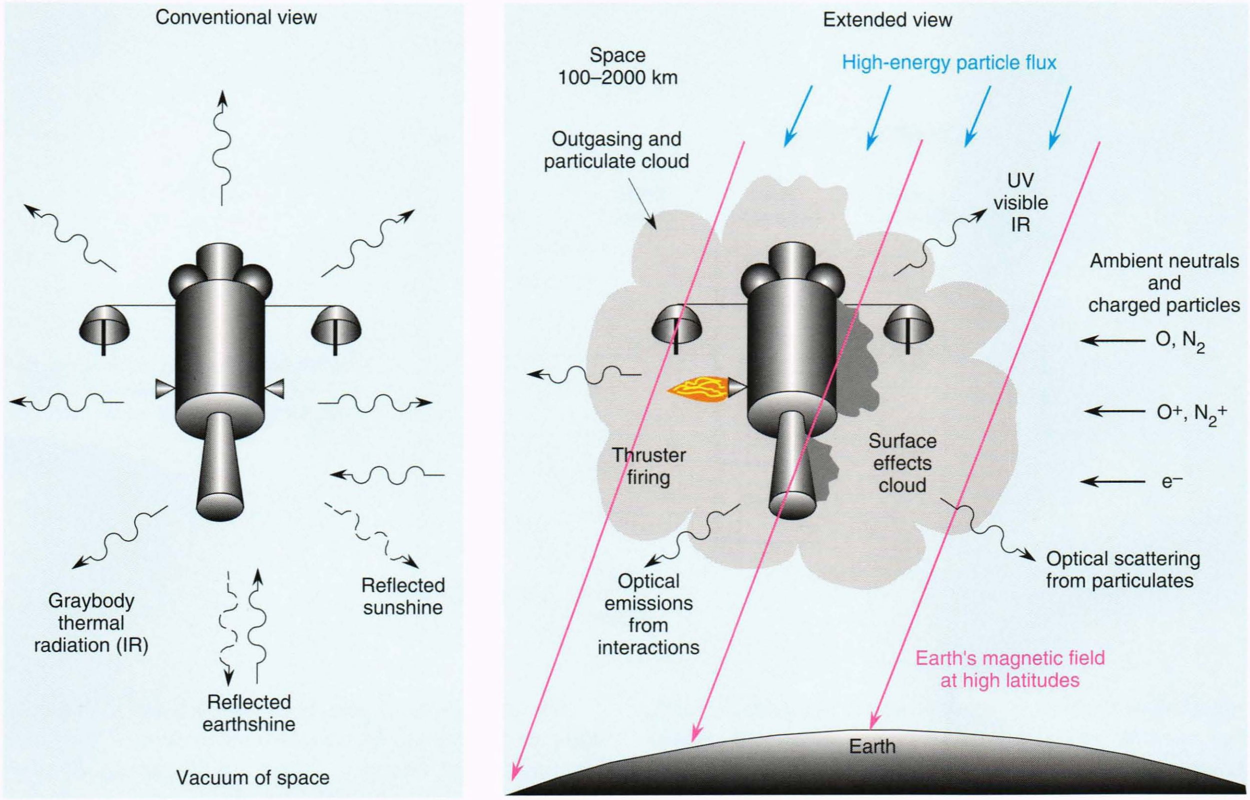
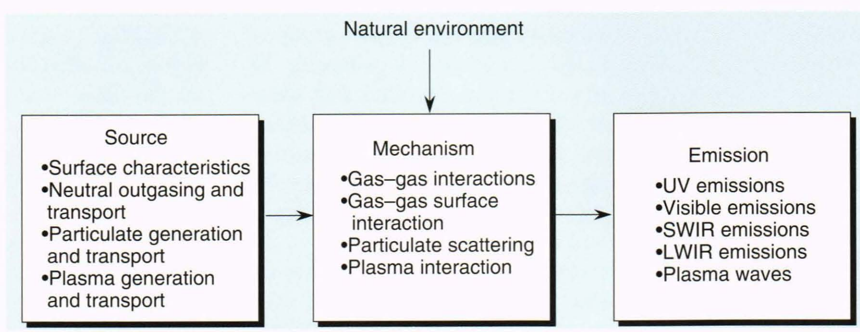


Figure 13. Vehicle interactions phenomenology.

Figure 14. Vehicle interaction processes. SWIR = short-wave infrared; LWIR = long-wave infrared.



quantitatively characterize them so that the models developed in the ground research effort can be extended and validated. The mission scenario for such an experiment, called the Vehicle Interactions Characterization Experiment (VICE), is shown in Figure 17. The experiment concept involves an ICBM-type ballistic trajectory, a mother (observer) vehicle, a daughter (target) vehicle, inflight sensor calibration, reference sphere releases, a controlled water vapor release, and possibly a controlled particulate release. Low-cost piggybank experiments on ballistic flights of opportunity are also being pursued to collect pertinent data. Such an experiment was recently flown and yielded unique data on outgas rates and particulates surrounding a small space vehicle in a ballistic trajectory.

MIDCOURSE SPACE EXPERIMENT

The Midcourse Space Experiment (MSX) program, conducted by APL for the SDIO Sensor Technology Directorate (SDIO/TN), will be primarily a data collection experiment, concentrating on the phenomenology of target detection and tracking. A wide array of targets will be viewed by sensors carried on board the orbiting spacecraft, including those launched from the ground and others deployed from the satellite itself. The MSX will thereby provide the first system demonstration in space of technology that could identify and track incoming ballistic missiles during their midcourse flight phase. Contamination data and background data on celestial and Earth limb phenomena will also be collected. With a

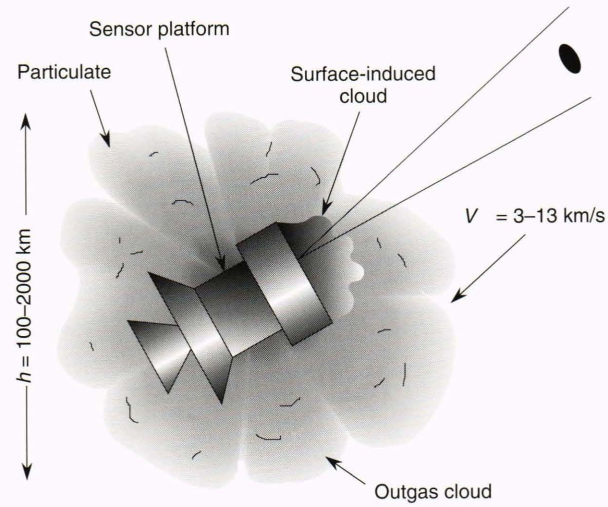


Figure 15. Look-out scenario.

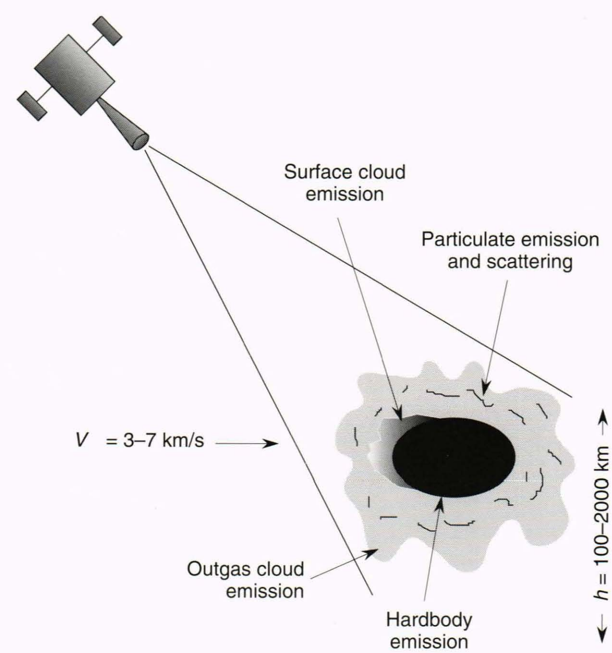


Figure 16. Look-in scenario.

mission lifetime of several years, MSX will provide the long-duration collection of complete data sets needed for ground data processing demonstrations by the Brilliant Eyes (BE) and the Ground Surveillance and Tracking System (GSTS).

Figure 18 is an artist's concept of the MSX spacecraft in orbital configuration, and Figure 19 is an overview of the mission concept. The onboard sensors will gather data on various objects in space (satellites, sounding rockets, and ICBM's) and on space backgrounds (aurora, Earth limb, and celestial spheres).

Onboard instrumentation includes the following: a Space Infrared Imaging Telescope (Spirit III) provided by the Space Dynamics Laboratory/Utah State University (SDL/USU); an Ultraviolet and Visible Imagers and Spectrographic Imagers (UVISI) instrument and Contamination Experiment provided by APL; and a Space-Based Visible (SBV) instrument and Reference Objects provided by Massachusetts Institute of Technology Lincoln Laboratory (MIT/LL). An Onboard Signal and Data Processor (OSDP) experiment, developed by SDIO/TN and provided by Hughes Aircraft, will also be flown as a demonstration of real-time onboard processing and orbital radiation effects.

The MSX spacecraft will be launched from Vandenberg Air Force Base in California, into a 99.2-degree inclination, 888 km near Sun-synchronous 3 AM (descending mode)–3 PM circular, polar orbit. The orbit was chosen to provide the desired background during the midcourse flight of an ICBM. Launch is expected in 1993, using a Delta II launch vehicle.

The Spirit III sensor will be cooled by frozen hydrogen and will remain functional only as long as cryogen is left in its dewar to cool the infrared detector. To preserve the cryogen, the spacecraft design and equipment layout minimizes the heat load on the dewar and sensor aperture by isolating the heat from other onboard systems and by providing shielding from the Sun, Earth, and moon. During the mission, the spacecraft is oriented with the instrument aperture pointed away from the moon, Sun, and Earth. Also, whenever possible, the Sun and Earth are kept on the shielded sides of the dewar. A program goal is that sufficient cryogen be available to maintain Spirit operational for approximately twenty-one months of the four-year MSX mission.

The UVISI instrument derives from a succession of ultraviolet and visible instruments flown on orbital missions by APL. These include the Auroral Ionospheric Mapper (AIM) that flew on the Hilat (High-Latitude–Ionospheric Research) spacecraft in 1983 and the Auroral Ionospheric Remote Sensor (AIRS) that followed on the Polar Beacon Experiment and Auroral Research (Polar BEAR) satellite in 1986. These two instruments operated at ultraviolet wavelengths and provided the first observations of the auroral oval in the daytime, confirming its continuity through 360 degrees.

The Delta 180, 181, and 183 missions (1986–89) have all carried ultraviolet and visible instruments built at APL. The one UI instrument on Delta 180 made the first exoatmospheric observations of plume phenomena in 1986. Two years later, the U2 instrument on Delta 181 observed various midcourse test objects, characterized plumes, and made detailed observations of the Earth limb at several local times. The U3 and V1 instruments on Delta 183 have recently made a number of strategically significant observations, and their operations have been coordinated with those of other major SDI programs.

The UVISI instrument consists of a suite of five spectrographic imagers and four other imagers and associated electronics. Three sensors provide complete spectral and imaging capabilities from the far ultraviolet (100 nm) to the near infrared (900 nm). The UVISI can operate in a number of modes so as to perform optimum observations of diverse phenomena. It employs a robust design that is based on redundancy and distribution of function. For example, each of the nine sensor units has an independent power supply and electronics that allow it to operate when other units fail. The single-point failure of one unit

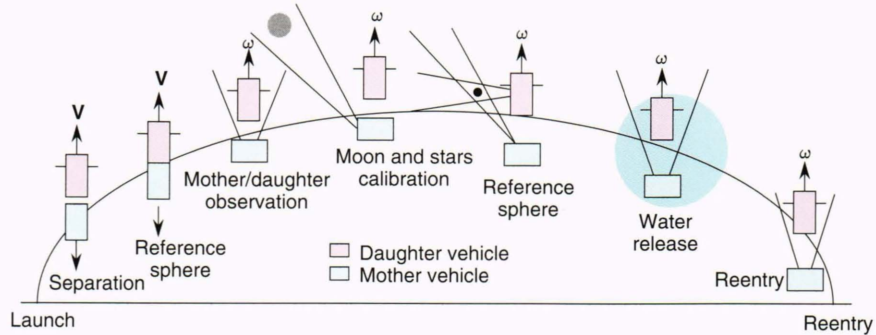


Figure 17. Vehicle Interactions Characterization Experiment (VICE) mission scenario.

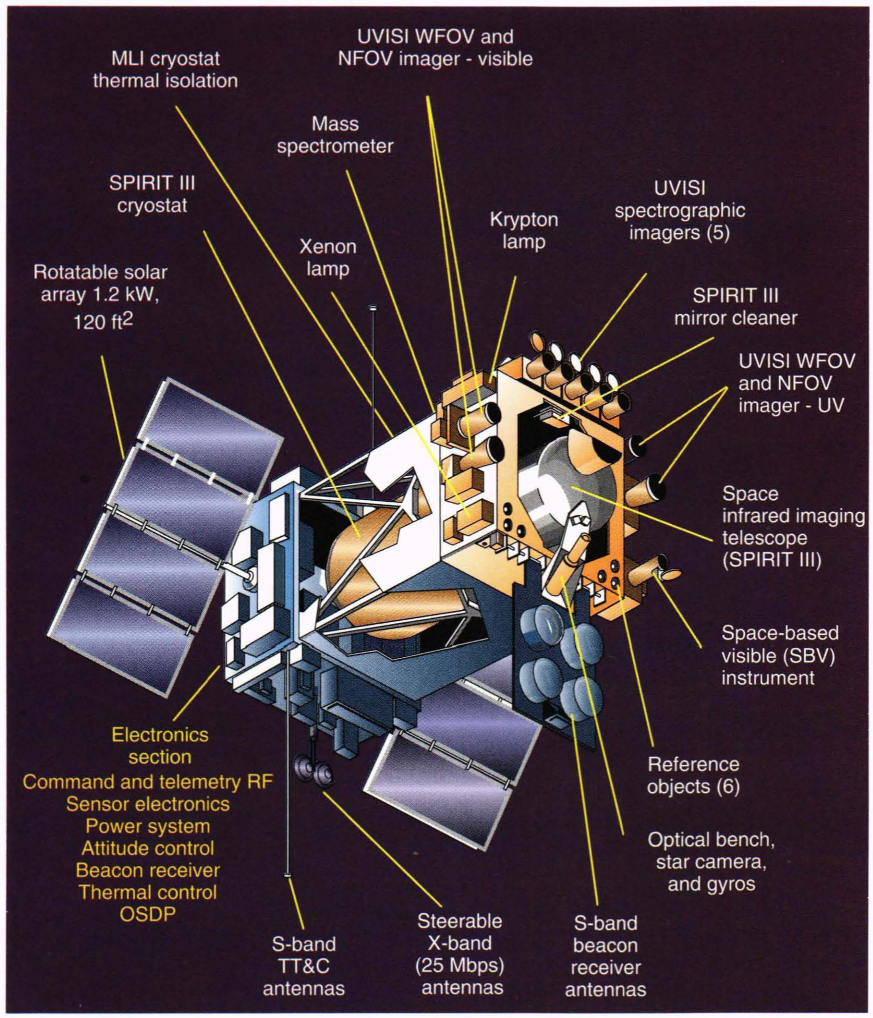


Figure 18. Midcourse Space Experiment (MSX) and instrumentation. MLI = multilayer insulation; UVISI = ultraviolet and visible imagers and spectrographic imagers; WFOV = wide field of view; NFOV = narrow field of vied; OSDP = onboard signal and data processor; TT&C = telemetry.

by itself will thus only partially degrade the performance of the instrument as a whole.

The Space-Based Visible (SBV) instrument, provided by MIT/LL under the sponsorship of the SSD and SDIO, is designed to demonstrate an above-the-horizon surveillance capability from a space platform using a visible wavelength optical sensor. Specifically, the primary experiment objectives are as follows:

1. To demonstrate advanced visible-band sensor technologies in space, such as a CCD focal plane, a signal processor, and off-axis rejection optics.
2. To collect and use visible-band target and background phenomenology data to address critical midcourse surveillance issues, that is, detection of targets in background clutter and signature extraction for possible discrimination.

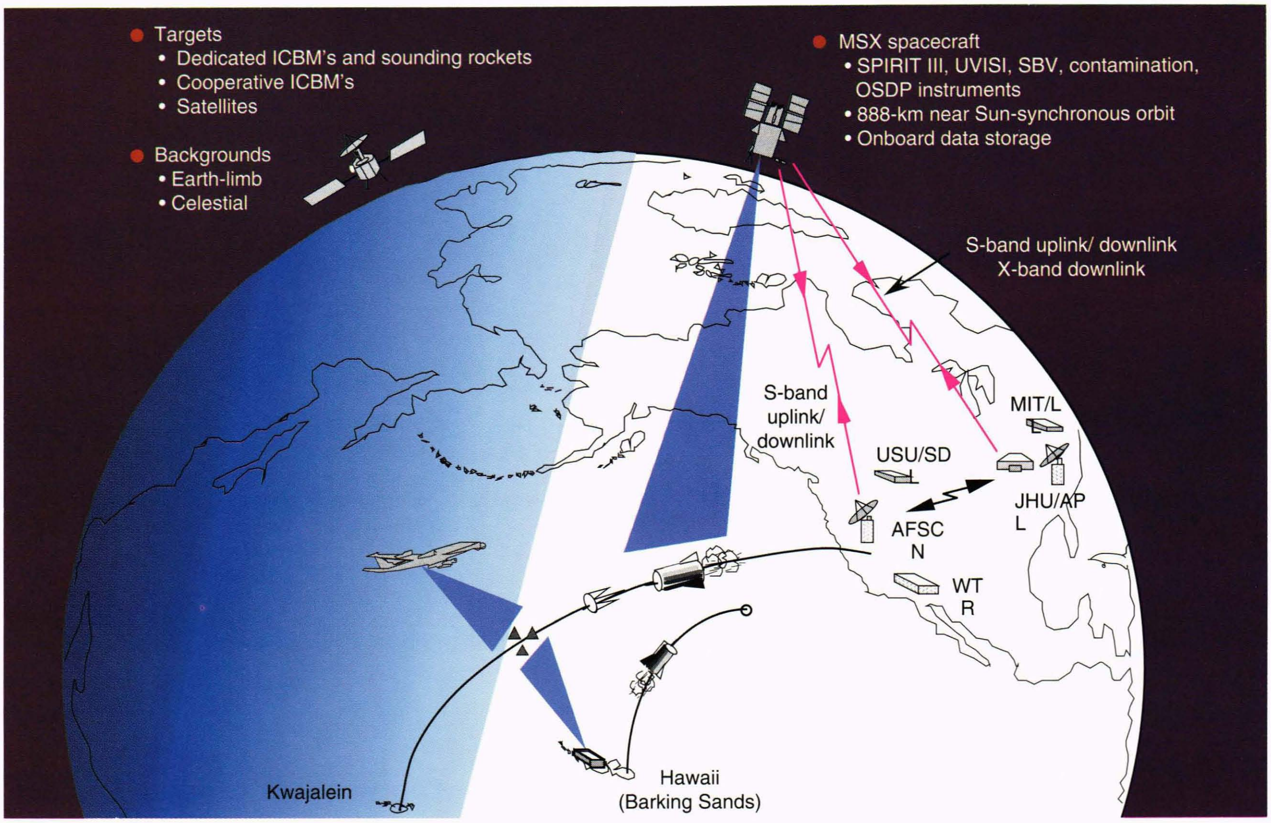


Figure 19. Midcourse Space Experiment (MSX) program, mission concept. MIT/LL = Massachusetts Institute of Technology/Lincoln Laboratory; ICBM = Intercontinental Ballistic Missile; UVISI = ultraviolet and visible imagers and spectrographic imagers; WTR = Western Test Range; SBV = space-based visible; AFSCN = Air Force Space Command Network; USU/SDL = Utah State University/Space Dynamics Laboratories; OSDP = on-board signal and data processor.

3. To collect ICBM flight data for input to ground-based functional demonstrations that employ scan-to-scan correlation and sensor-to-sensor correlation.

4. To perform experimental demonstrations of the space surveillance capability from space.

The telescope and analog processing assemblies are located forward of the spacecraft, the first for a clear field of view and the latter to maintain low noise in the focal plane processing. The remaining units are located in the electronics section.

The telescope assembly is the sensor head for the SBV instrument and consists of a telescope, a CCD focal plane, a contamination prevention door, and a small set of focal plane electronics. The telescope is a 6-in.-aperture off-axis reimager that is designed to be compatible with a four-element array of the Lincoln Laboratory CCDI7 frame transfer CCD imagers. The cooling unit required for the focal plane is a thermoelectric cooler that can maintain the focal plane temperature at -40°C. The focal plane electronics include a video multiplexer, preamplifier, clock drivers, and filters. The payload also includes one reflective and three emissive reference objects, or spheres, provided by MIT/LL. These objects are for instrument calibration purposes and are used to evaluate flight sensor performance and band-to-band precision. The spheres have a diameter of about 2.5 cm and an ejection velocity of 10 m/s.

Optical sensor performance is degraded when particles and gas molecules are deposited on mirrors and windows. The major source of this contamination is the spacecraft itself. This self-contamination results from spacecraft materials outgassing in a vacuum and from particles floating free from the spacecraft. To minimize this self-contamination, only low outgassing materials are used in building the spacecraft, and the spacecraft is kept as clean as possible by performing assembly and test in a 100,000-class clean room provided with class-10,000 air. To measure the effectiveness of an extremely rigid contamination control plan, sensors will monitor the spacecraft environment during the mission to identify and quantify the types of contamination it contains.

CONCLUSIONS

The efforts provided by the Applied Physics Laboratory in support of the SDIO have constituted a major element in the assessment of sensor technology. In particular, the consideration and development of the ultraviolet sensors technology throughout the Delta programs have provided unforeseen benefits to SDIO. Through these programs, space-borne observations of rocket plumes have provided SDIO significant data for use in the development of deployed sensor architecture.

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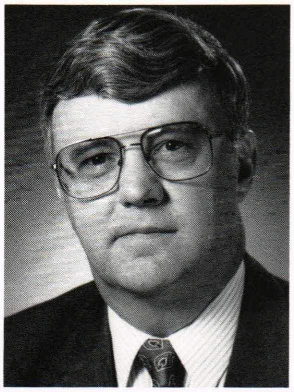

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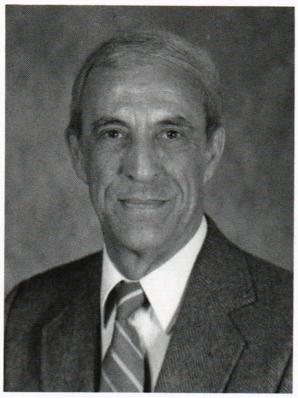

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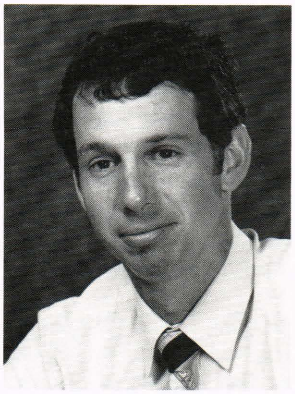

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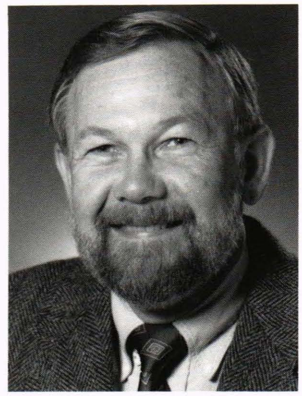

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