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RESULTS FROM THE DEEP SPACE 1 TECHNOLOGY VALIDATION MISSION

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Launched on October 24, 1998, Deep Space 1 (DS1) is the first mission of NASA's New Millennium program, chartered to validate in space high-risk, new technologies important for future space and Earth science programs. The advanced technology payload that was tested on DS1 comprises solar electric propulsion, solar concentrator arrays, autonomous on-board navigation and other autonomous systems, several telecommunications and microelectronics devices, and two low-mass integrated science instrument packages. The technologies were rigorously exercised so that subsequent flight projects would not have to incur the cost and risk of being the first users of these new capabilities. The performances of the technologies are described as are the general execution of the mission and plans for future operations, including a possible extended mission that would be devoted to science.

INTRODUCTION

NASA's plans for its space and Earth science programs call for many scientifically compelling, exciting missions. To make such programs affordable, it is anticipated that small spacecraft, launched on low-cost launch vehicles and with highly focused objectives, will be used for many of the missions. To prevent the loss of capability that may be expected in making spacecraft smaller and developing and operating missions less expensively, the introduction of new technologies is essential.

With many spacecraft carrying out its programs of scientific exploration, NASA could accept a higher risk per mission; the loss of any one spacecraft would represent a relatively small loss to the program. Nevertheless, the use of new technologies in space science missions forces the first users to incur higher costs and risks. The concomitant diversion of project resources from the scientific objectives of the missions can be avoided by certification of the technologies in a separate effort.

Overview of New Millennium

The New Millennium program (NMP) is designed to accelerate the realization of ambitious missions by developing and validating some of the high-risk, high-benefit technologies they need. NMP conducts deep space and Earth orbiting missions focused on the validation of these technologies. The spacecraft flown by NMP are not intended to be fully representative of the spacecraft to be used in future missions, but the advanced technologies they incorporate are. As each NMP mission is undertaken, the risk of using the technologies that form its payload should be substantially reduced because of the knowledge gained in the incorporation of the new capability into the spacecraft, ground segment, and mission design as well as, of course, the quantification of the performance during the flight.

Although the objective of NMP technology missions is to enable future science missions, NMP missions themselves are not driven by science requirements. They are dedicated to technology, with the principal requirements coming from the needs of the advanced technologies they are testing. The science return from NMP missions is in the subsequent science missions that become feasible.

By their very nature, NMP projects are high risk. The key technologies that form the basis for each mission are the ones which require validation to reduce the risk of future missions. Indeed, if an advanced technology does not pose a high risk, testing by NMP is not required. In many cases, these unproven technologies will not have functionally equivalent back-ups on their test flights. Nevertheless, the failure of a new technology on an NMP mission, even if it leads to the loss of the spacecraft, does not necessarily mean the mission is a failure. If the nature of the problem with the technology can be diagnosed, the goal of preventing future missions from accommodating the risk can be realized. Showing that a technology is not appropriate for use on subsequent science missions would be a very valuable result of an NMP flight. The acquisition of this information would achieve the goal of reducing the cost and risk to candidate future users of the technology. Of course, it is likely that such a determination would lead to modifications of the implementation of the technology, thus restoring its potential value to future space science missions.

Overview of DS1

Deep Space 1 (DS1) is the first project of NMP. Its payload consists of 12 technologies. The criteria for "complete mission success," agreed to by NASA Headquarters and JPL, are:

1) Demonstrate the in-space flight operations and quantify the performance of the following 5 advanced technologies:

- Solar electric propulsion (SEP)
- Solar concentrator arrays
- Autonomous navigation
- Miniature camera and imaging spectrometer
- Small deep space transponder

and any 3 of the following 6 advanced technologies:

- K_a-band solid state power amplifier
- Beacon monitor operations
- Autonomous remote agent
- Low power electronics
- Power actuation and switching module
- Multifunctional structure

2) Acquire the data necessary to quantify the performance of these advanced technologies by September 30, 1999. Analyze these data and disseminate the results to interested organizations/parties by March 1, 2000.

3) Utilize the on-board ion propulsion system (IPS) to propel the DS1 spacecraft on a trajectory that will encounter an asteroid in fiscal year 1999.

4) Assess the interaction of the IPS operations with the spacecraft and its potential impact on charged particle, radio waves and plasma, and other science investigations on future SEP-propelled deep space missions.

The first criterion clearly indicates that the goal of the mission is to determine how well the technologies work. Indeed, the wording reflects the recognition of the high risk of the technologies by allowing for the possibility that some might not be operable.

A twelfth technology, a miniature integrated ion and electron spectrometer, was not included in the success criteria, because it was so late in being delivered that even six weeks before launch it was uncertain whether the device would be ready. (This is another facet of the risk in planning to fly with advanced technologies.) Nevertheless, it was delivered and has performed very well.

All the technologies except autonomous navigation received 100% or more of their required testing by the end of June 1999. An asteroid encounter planned for July 29, 1999 tests 5% of the autonomous navigation system.

In addition to its technical objectives, DS1 was intended to probe the limits of rapid development for deep-space missions. The initial study of DS1 was undertaken only 39 months before launch, an unprecedentedly short time for a NASA deep-space mission in the modern era. At the time the preliminary concept study was initiated, the only definition of the project was that it should validate solar electric propulsion and other unidentified technologies in deep space and that launch should occur sometime in 1998. The level-1 requirements and goals[1] were formulated 26 months prior to launch.

Further background on the project, including the selection of technologies and the mission and spacecraft design, and additional information on NMP are presented elsewhere.[1,2]

TECHNOLOGY RESULTS

Overviews of DS1's advanced technologies and the results from flight testing follow. The mission in which the technologies were used is discussed in the next section.

Solar electric propulsion

Solar electric propulsion (SEP) offers significant mass savings for future deep-space and Earth-orbiting spacecraft that require substantial velocity changes. The objective of the NSTAR (NASA SEP Technology Application Readiness) program, to validate low-power ion propulsion, was a good match to NMP's goals. NSTAR involved a collaboration among JPL, NASA's Glenn Research Center, Hughes Electron Dynamics, Spectrum Astro, Moog, and Physical Science, Inc.

The ion propulsion system (IPS) on DS1[3] uses a hollow cathode to produce electrons to collisionally ionize xenon. The Xe^+ is electrostatically accelerated through a potential of up to 1280 V and emitted from the 30-cm thruster through a pair of molybdenum grids. A separate electron beam is emitted to produce a neutral plasma beam. The power processing unit (PPU) of the IPS can accept as much as 2.5 kW, corresponding to a peak thruster operating power of 2.3 kW and a thrust of 92 mN. Throttling is achieved by balancing thruster electrical parameters and Xe feed system parameters at lower power levels; and at the lowest PPU input power, 525 W, the thrust is 19 mN. The specific impulse ranges from 3200 s with about 2 kW delivered to the PPU to 1900 s at the minimum throttle level.

Because the purpose of flying the IPS was to validate it for future space science missions, a comprehensive diagnostic system is also on the spacecraft.[4] This aided in quantifying the interactions of the IPS with the spacecraft, including advanced-technology science instruments, and validating models of those interactions. The diagnostic instrument suite includes a retarding potential analyzer, two Langmuir probes, search-coil and fluxgate magnetometers, a plasma wave sensor, and two pairs of quartz-crystal microbalances and calorimeters. One of these pairs has a direct view of the ion thruster exit, while the other is shadowed by spacecraft structure. Measurements included the rate and extent of contamination around the spacecraft from the Xe^+ plume and the sputtered Mo from the grid, electric and magnetic fields, and the density and energy of electrons and ions in the vicinity of the spacecraft. As a bonus, the sensors will be used to complement science measurements of DS1's ion and electron spectrometer (see below) during the small body encounters.

By June 30, 1999, the IPS had operated for nearly 1800 hours. This included several dedicated tests, but the majority of the time was devoted to placing the spacecraft on a trajectory to reach asteroid 1992 KD (in accordance with the third mission success criterion).

The IPS operated over a broad range of its 112 throttle levels, from input powers of 580 W (throttle level 6) to 2140 W (throttle level 90). The corresponding specific impulses were 1975 s and 3180 s. Measured thrust (determined through radio navigation) was within 2% of the prelaunch prediction throughout the range.

Comparison with the extensive ground-test program showed that operation in space is more benign and contamination is lower. The vast body of data from the diagnostics sensors on the effects of the IPS allows the development of guidelines for future designers on how to make fields and particles measurements on future IPS-propelled spacecraft without interference from the propulsion system.

In the first attempt to thrust with the IPS (on November 10, 1998), it operated for about 4.5 minutes and then switched to a standby mode. It is believed that the unplanned termination of the thrusting was the result of a contaminant causing a short between the two grids. Attempts to restart the thruster on that day were unsuccessful. Thermal cycling during the subsequent two weeks changed the spacing between the grids, thus stressing the contaminant, and when the IPS was commanded on again it operated as desired. Similar phenomena have been observed with other ion thrusters in space.

In the 1799.4 hours of thrusting (for deterministic thrust, trajectory correction maneuvers, and dedicated tests), the total Xe consumption was 11.4 kg, providing 699.6 m/s. After the first day of unsuccessful attempts to resume thrusting, all 34 IPS starts in the mission were successful.

All spacecraft systems operated normally during IPS thrusting. Telecommunications during IPS thrusting, even with the radio signal passing through the plasma, were unaffected. Sensors 0.7 m from the thruster with a direct line of sight to the exit grid recorded about 10 nm of surface contamination. Nearby sensors, without a direct line of sight, accumulated an order of magnitude less.

Solar concentrator array

Because of the IPS, DS1 required a high-power solar array. The Ballistic Missile Defense Organization (BMDO), working with NASA's Glenn Research Center, AEC-Able Engineering, and Entech, developed the Solar Concentrator Array with Refractive Linear Element Technology (SCARLET II).[5] BMDO wanted a flight test for SCARLET, and because it could provide the necessary high power, including it on DS1 was mutually beneficial.

SCARLET uses cylindrical silicone Fresnel lenses to concentrate sunlight onto $GaInP_2$/GaAs/Ge cells arranged in strips. Including the optical efficiency of the lenses, a total effective magnification greater than 7 is achieved. With relatively small panel area actually covered by solar cells, the total cost of cells is lowered, and thicker cover glass becomes practical, thus reducing the susceptibility to radiation. The dual junction cells display significant quantum efficiencies from 400 nm to 850 nm, and achieved an average efficiency in flight of about 22.5%.

The pair of arrays produced 2.5 kW at 1 AU, within 1% of the prelaunch prediction. Each array comprises four panels that were folded for launch, and a single-axis gimbal controls pointing in the more sensitive longitudinal axis. The two wings include a total of 720 lenses, each focusing light onto 5 cells. DS1 is the first spacecraft to rely exclusively on refractive concentrator arrays; it also is among the first to use only multibandgap cells.

The array is one of the three new technologies that had to work correctly immediately after launch in order for the mission to proceed; stored battery energy was sufficient only for a few hours. A substantial part of the validation of the array was the mechanical deployment and subsequent pointing. The deployment was so accurate that, following dedicated tests, no pointing adjustments were deemed necessary, and the array provided stable operation throughout the mission.

<u>Autonomous navigation</u>

Because mission operations is a significant part of its science budget, NASA explicitly included autonomy in its guidelines to NMP. A reduction in requirements for Deep Space Network (DSN) tracking of spacecraft will come from the placement of a complete navigation capability on board the spacecraft. (Other autonomy technology experiments are discussed below.) In addition, autonomous navigation allows a smaller navigation team during flight.

One portion of the core of the autonomous system validated on DS1, AutoNav[6], began functioning immediately upon activation of the spacecraft after separation from the launch vehicle, which occurred in Earth's shadow. The attitude control system (ACS) used a commercial star tracker to determine its attitude. Then the real-time part of AutoNav correctly provided ACS with the position of the Sun so that ACS could turn the spacecraft to the attitude needed to illuminate the solar arrays upon exiting the shadow.

Data stored on board for use by AutoNav include a baseline trajectory, generated and optimized on the ground; the ephemerides of the DS1 target bodies, distant "beacon" asteroids, and all planets except Pluto; and a catalog of the positions of 250,000 stars (all contained in the Tycho catalog).

Throughout the mission, about once per week, AutoNav was invoked by the operating sequence to allow it to acquire optical navigation images. It issues commands to ACS and the integrated camera and imaging spectrometer (see below) to acquire visible-channel images, each with one beacon asteroid and known background stars. On-board image processing allows accurate extraction of the apparent position of each asteroid with respect to the stars, thus allowing the spacecraft location to be estimated. The heliocentric orbit is computed with a sequence of these position determinations combined with estimated solar pressure, calculated gravitational perturbations, and on-board knowledge of the thrust history of the IPS and incidental accelerations from unbalanced turns by the hydrazine-based reaction control system (RCS). The trajectory then is propagated to the next encounter target, and course changes are generated by the maneuver design element. In general, those course corrections are implemented through changes in the IPS thrust direction and duration, but in certain cases described below, the maneuvers are accomplished with dedicated IPS or RCS maneuvers.

After AutoNav parameters were tuned in flight, typical autonomous cruise heliocentric orbit determinations differed from radiometric solutions (developed to provide a reference against which to test AutoNav) by < 1000 km and < 0.4 m/s. With simple ground-based removal of some images (based on an algorithm that would be straightforward to implement in the flight software), accuracies improved to < 400 km and < 0.2 m/s.

For encounters, navigation is target-relative, and 1σ delivery accuracy is ~ 3 km. AutoNav also performs target tracking at encounters to provide accurate pointing information to ACS, and it initiates the encounter sequences based on its estimate of the time to closest approach.

During periods of IPS thrusting, AutoNav controls the IPS. It selects the throttle level based on models of SCARLET power generation and spacecraft power consumption; pressurizes, starts, and stops the IPS; and commands ACS to achieve the attitude needed for thrusting. AutoNav also commands updates to the throttle level and spacecraft attitude every 12 hours.

During periods of ballistic coast, AutoNav is given time windows, in each of which it can execute a trajectory correction maneuver (TCM), which it designs autonomously if it has established that a TCM is necessary. In most cases, the TCMs are conducted with the IPS. To save time during the final 2 days before an encounter (and for the purposes of dedicated AutoNav testing), the hydrazine RCS is used. With either propulsion system, if thrust is required in an attitude that is prohibited by ACS, the TCM is autonomously decomposed into two allowed maneuvers.

Integrated camera and imaging spectrometer

If NASA is to conduct missions with smaller spacecraft, it is essential to have correspondingly smaller science instruments. One of the advanced technologies DS1 tested is the Miniature Integrated Camera Spectrometer (MICAS), conceived and developed by a team from the United States Geological Survey, the University of Arizona, Boston University, Rockwell, SSG, and JPL. In one 12-kg package, this derivative of the original concept for a Pluto Integrated Camera Spectrometer[7] includes two panchromatic visible imaging channels, an ultraviolet imaging spectrometer, and an infrared imaging spectrometer plus all the thermal and electronic control. All sensors share a single 10-cm-diameter telescope. With a structure and mirror of highly stable SiC, no moving parts are required; the detectors are electronically shuttered. Spacecraft pointing directs individual detectors to the desired targets.

The instrument includes two visible detectors, both operating between 0.5 µm and 1 µm: a 1024×1024 CCD with 13-µrad pixels and a 256×256 18-µrad/pixel CMOS active pixel sensor, which includes the timing and control electronics on the chip with the detector. The imaging spectrometers operate in push-broom mode. The infrared spectrometer covers the range from 1.2 µm to 2.4 µm with spectral resolution of 12 nm and 54-µrad pixels.

MICAS serves three functions on DS1. First, as with all the advanced technologies, tests of its performance establish its applicability to future space science missions. Second, AutoNav uses the visible channels for optical navigation. Third, as a bonus, it will collect science data during the primary mission at the asteroid and at other encounters if an extended mission is conducted.

The ultraviolet channel, designed to operate between 80 nm and 185 nm, did not function properly and never returned interpretable data. Several tests were conducted to diagnose the problem, and indications are that the malfunction is in the signal chain after the detection of the photons.

MICAS images and IR spectra revealed scattered light. Stray light analysis and dedicated tests established the multiple paths responsible. The scattered light is the result of spacecraft surfaces directing off-axis light to reflective components inside MICAS, particularly the multilayer insulation surrounding the IR detector. The problem is easily avoided for future missions with different mounting of the instrument and alteration of the internal baffling. Modifications to AutoNav significantly increased its immunity to the light, and the flux is sufficiently low that it is not expected to interfere with encounter science.

Integrated ion and electron spectrometer

Just as MICAS integrates several different measurement capabilities into one low-mass package, the Plasma Experiment for Planetary Exploration (PEPE)[8] combines multiple instruments into one compact package. At 5.6 kg and 9.6 W, PEPE is less than 25% of the mass and consumes less than 50% of the power of a comparably performing (but more expensive) instrument on Cassini. Designed and built by Southwest Research Institute and Los Alamos National Laboratory, PEPE determines the three-dimensional plasma distribution over its 2.8π sr field of view.

PEPE measures the energy spectrum of

electrons and ions simultaneously from 8 eV to 33 keV per unit charge with at least 5% resolution. Rather than using moving parts, it electrostatically sweeps its field of view. PEPE measures ion mass with a resolution of 5% in the range of 1 to 500 amu per unit charge.

PEPE plays three roles on DS1. It has validated the design for a suite of plasma physics instruments in one small package; it has assisted in determining the effects of the IPS on the local plasma environment, including interactions with the solar wind and photoelectrons[4]; and it makes scientifically interesting measurements during the cruise and the encounters.

PEPE made measurements of the solar wind with the IPS on and off, and a very important result is that the data suggest that SEP can be used on future science missions without interfering with the scientific payload. PEPE data showed Xe^+ returning to the spacecraft from the 1 ampere exhaust plume of the IPS and allowed limits to be placed on electrical charging of the spacecraft. In January 1999, a favorable alignment of the DS1 and Cassini spacecraft allowed 36 hours of collaborative solar wind measurements, with the two spacecraft separated by nearly 0.5 AU.

Telecommunications technologies

DS1 validated a small deep-space transponder (SDST), built by Motorola, and a K_a-band solid state power amplifier developed by Lockheed Martin.[9,10] Combining the receiver, command detector, telemetry modulator, exciters, beacon tone generator (see below), and control functions into one 3-kg package, the SDST allows X-band uplink and X-band and K_a-band downlink. To achieve the SDST's functionality without a new technology development would require over twice the mass and 4 or 5 individual subassemblies. The SDST, along with SCARLET and AutoNav, had to function correctly from the beginning of the mission. Based on extensive routine use and dedicated experiments, its performance was in excellent agreement with preflight tests.

The SDST's K_a-band signal is amplified by the 0.7-kg power amplifier to 2.3 W with an overall efficiency of 13%. In addition to characterizing the operation of the hardware device, DS1 provided K_a-band signals for DSN use in verifying systems for acquiring, demodulating, decoding, and processing telemetry as well as in producing 2-way Doppler and ranging data. The DSN also applied the K_a-band signals to the validation and improvement of system designs in preparation for upgrading to operational use of K_a-band. As the Earth-spacecraft range increased, certain tests were repeated to assure that the transition through threshold in a selected K_a-band data rate would be observed. All communication and radiometric tests proved to be in good agreement with models or with X-band results for the tests that were enhanced by simultaneous X-band operation.

Beacon monitor operations

The SDST generates the tones needed for beacon monitor operations[11], conceived to reduce the large demand that would be expected on the DSN if many missions were in flight simultaneously, as envisioned by NASA. In beacon monitor operations, an on-board data summarization system determines the overall spacecraft health. The system then transmits one of four tones to indicate to the operations team the urgency of the spacecraft's need for DSN coverage. Without data modulation, these tones are detected easily with small, low-cost systems, reserving the large, more expensive DSN stations for command radiation and data reception when a beacon indicates that such services are needed. The four tones correspond to *i*) the spacecraft not needing any assistance because all is well; *ii*) informing the ground that the spacecraft has encountered an unusual but not threatening event, so a DSN track should be scheduled when convenient; *iii*) alerting the ground that intervention is needed to prevent the loss of important data or to assist in resolving a threat to the mission, so DSN coverage should occur soon; and *iv*) requiring immediate assistance because the spacecraft has encountered a mission-threatening emergency it was unable to solve. In each case, when tracking is initiated, the data summarization system provides a synopsis of the pertinent spacecraft data.

This artificial intelligence technology uses adaptive alarm limits, which allow tighter monitoring than traditional limits. Furthermore, the spacecraft parameters that are monitored and their limits depend upon the spacecraft activity. The system adaptively filters data so instead of using fixed limits, it can compute variable limits on the fly; it can apply this not only to single data parameters but also to functions of multiple data parameters. These alarm limit functions are "trained" using a neural network on the ground with actual DS1 engineering data to create functions that can perform more precise anomaly detection and detect important trends sooner than with conventional limits. Although this ground software is quite complex, only the resulting functions are uploaded to the spacecraft.

Experiments conducted during DS1 addressed both the data summarization and the tone generation and detection (in both X-band and K_a-band), which agreed well with preflight models. Beacon monitor operations may be relied upon during an extended mission if it occurs.

Autonomous remote agent

For the third autonomy technology DS1 tested, an artificial intelligence system was placed on board to plan and execute spacecraft activities.[12] The team that developed this system was drawn principally from JPL and NASA's Ames Research Center. Rather than standard remote control, this technology uses an agent of the ground team on board the spacecraft. This remote agent was tested in a restricted case on DS1, in preparation for more ambitious experiments on subsequent flights. The remote agent includes an on-board mission manager that carries the mission plan, expressed as high-level goals. A planning and scheduling engine uses the goals, comprehensive knowledge of the spacecraft state, and constraints on spacecraft operations to generate a set of time-based or event-based activities, known as tokens, that are delivered to the executive. The executive expands the tokens to a sequence of commands that are issued directly to the appropriate destinations on the spacecraft. The executive monitors the response to these commands and reissues or modifies them if the response is not what was anticipated. A mode identification and reconfiguration engine aids in assessing the spacecraft state and in recovering from faults without requiring help from the ground except in extraordinary cases.

In the experiments on DS1, the remote agent operated selected subsystems based on plans formulated on board. Injection of four (simulated) faults tested remote agent's ability to resolve or work around different classes of problems, and in each case it devised the correct response. A bug in the executive interrupted the first experiment, and the successful diagnosis of the problem was one important benefit of the testing; it also illustrated the value of trying out a new technology on a dedicated test mission. The bug proved to be easily correctable for future uses of the technology. Analysis showed that it was safe to continue experiments on DS1 without fixing it, so a second experiment was devised, and it captured the remaining remote agent test objectives.

Microelectronics and structures

Electronics mass, volume, and power consumption are important drivers for overall spacecraft design. DS1 included tests of two microelectronics technologies and a mechanical/electronic experiment intended to contribute to the achievement of NASA's vision of spacecraft in the future. To reduce the power consumption of electronics, one experiment used devices with very low voltage and low capacitance.[13] This low-power electronics experiment contained four ring oscillators and some discrete transistors to test 0.9-volt logic and 0.25-μm gate lengths (achieved with 248-nm lithography) based on silicon-on-insulator technology. Provided by the Massachusetts Institute of Technology Lincoln Laboratory, the functioning of the devices in flight was in good agreement with prelaunch tests. DS1 also tested two power actuation and switching modules, the result of a joint development among Lockheed Martin, Boeing, and JPL.[14] Each device contained four power switches, controlled by a mixed-signal ASIC, providing voltage and current sensing and current limiting. High-density packaging technology quadruples the packing density over the current state of the art. Designed to be capable of switching up to 40 V and 3 A, the experiment switched an internal test load on DS1. Regular tests showed that the performances of both PASMs were consistent with prelaunch tests.

A multifunctional structure[15] was provided to DS1 by the United States Air Force Phillips Laboratory and Lockheed Martin Astronautics as a test panel that was attached to the spacecraft bus. This new packaging technology integrates electronic housings and thermal control into load-bearing elements, thus offering great reductions in the mass of spacecraft cabling and traditional chassis. The DS1 experiment returned data on the performance of the electronic connection systems for embedded test devices and on the thermal gradients in the panel. The connectors displayed no evidence of degradation, and the thermal gradients were consistent with preflight predictions.

MISSION

Two objectives provided the impetus for a short mission. The principal requirement of DS1 was to return results promptly to the future users of the technologies. Except for tests of lifetime, most technologies could be evaluated on short (but intense) missions as well as long ones. In addition, in general shorter missions are less expensive that longer ones. As a result, it was decided that the primary mission would be about one year. This allowed sufficient time to exercise all the technologies under a wide range of conditions while keeping costs low and not forcing eager potential users to wait unreasonably long before being confident about the new systems. It also allowed sufficient time to accomplish the objective of thrusting with the IPS long enough to place DS1 on a ballistic trajectory to an asteroid (the third criterion for success).

DS1 was planned for launch in July 1998, based on the earliest expected spacecraft readiness in a schedule that was extremely aggressive (particularly given the large number of unproven technologies incorporated into the mission). The mission design, including solar system encounter targets, was based on that plan.[16]

In the spring of 1998, it became clear that launching DS1 in its planned launch period presented an unacceptable risk to mission success, so the launch period was shifted to October - November 1998. DS1 was given the slot vacated by the Far Ultraviolet Spectroscopic Explorer when its launch was moved to 1999. Still, an unusually dense schedule of launches and other activities at the Eastern Test Range made scheduling DS1's launch difficult. Once the launch period was selected, a new mission was designed with the requirements that it necessitate changes in neither the spacecraft nor ground systems and still be compatible with the secondary payload (see below). The original mission plan was sufficiently robust that its architecture did not need to be changed, but the encounter targets and thrusting and coasting times did change.

DS1's launch occurred at 12:08:00.502 UTC on October 24, 1998. It was launched on the first Delta II 7326-9.5 (from The Boeing Company), the smallest vehicle in the Delta stable, and was the first launch of NASA's Med-Lite program. This launch vehicle was selected largely on the basis of prompt availability and low cost, but its capability exceeded what was needed for DS1, with relatively low mass and low injection energy (in part attributable to the high performance of the IPS). Including 81.5 kg of Xe and 31.1 kg of hydrazine, DS1 was 486.3 kg at launch, and the Delta provided a $C_3 = 2.99\ km^2/s^2$; the launch vehicle could have delivered approximately 600 kg to DS1's escape trajectory. The excess launch vehicle performance allowed the manifesting of another spacecraft on this launch. SEDSAT-1, built by the Students for the Exploration and Development of Space at the University of Alabama in Huntsville, in collaboration with NASA's Marshall Space Flight Center and Johnson Space Center, was mounted on the second stage, which accomplished insertion into Earth orbit. After the second stage's second burn, to raise the orbit of the third stage and DS1, the stage separated and carried SEDSAT-1 to its intended orbit, where it was separated. The third stage completed DS1's injection to heliocentric orbit.

Following launch, several days were spent conducting an initial evaluation of the spacecraft, verifying its health and preparing it for early mission operations. Dedicated technology experiments began within one week of launch. Of course, some technologies were used as part of regular spacecraft operations, in particular the solar array, transponder, and AutoNav, but those and all other technologies also were subjected to in-depth characterization tests.

Radiometric determination of the actual trajectory was combined with results of the first SCARLET and IPS tests to generate and optimize an updated low-thrust trajectory that was transmitted to the spacecraft. After verification of its functional capability, AutoNav was tuned in flight, particularly to account for discrepancies between the predicted and the actual MICAS images. As the mission progressed, more reliance was placed on AutoNav, with conventional radio navigation used to validate its performance.

Initial IPS thrusting was conducted with the thrust vector along the Earth-spacecraft line to maximize communications rates and the Doppler signature, in order to quantify the actual thrust at selected throttle levels. After 10 days of thrusting, the spacecraft was turned to thrust along the optimal vector (subject to a variety of pointing constraints) for reaching the encounter targets for the primary and extended mission.

To meet the demanding schedule prior to launch, some software development was completed after launch. The launch load did not include all functions needed to conduct tests with the low-power electronics, power actuation and switching modules, multifunctional structure, beacon monitor operations, and remote agent. These technologies were selected for exclusion from the earlier software because they were not needed for the basic operation of the mission. In February 1999, a completely new software load of 4.1 megabytes was installed. This new software enabled the testing of four of the previously excluded technologies (remote agent was not in this load), upgraded AutoNav (principally to accommodate scattered light in the MICAS images), corrected bugs identified after launch, and improved spacecraft operability.

To accommodate the remote agent experiments in May, the flight software was patched; in addition, the remote agent software was uploaded. In June, following the remote agent experiment, the entire flight software was replaced again. This last load contained new operational enhancements and upgrades to a number of systems, but primarily it included further AutoNav upgrades for enhanced image processing (such as image differencing to gain greater suppression of scattered light and more powerful corrections for MICAS' large geometric distortions) and the functions needed to execute encounters. All three changes to the flight software, which included substantial development and testing, large uplink volumes, and rebooting of the nonredundant main spacecraft computer, were completed without incident.

The mission operations system made extensive use of standard tools and mission services JPL provides to support a wide range of missions. DS1 employed JPL's multimission ground data system to provide the uplink and downlink data transport capabilities as well as much of the telemetry processing and display system. Project-developed applications augmented the system to be consistent with the autonomous capabilities of the spacecraft.

DS1 mission operations were significantly different from that of typical deep space missions at JPL. This was primarily attributable to the technology-validation focus of the DS1 mission. Unlike typical deep space missions, with its very active technology testing campaign, DS1 did not have a quiet cruise. Because of the experimental nature of the spacecraft and the technologies, early sequence development was confined to implementing and validating command activity blocks that could be modified readily and executed on board by real-time commanding to achieve a desired technology experiment. In the first three months of flight, about 1800 real-time commands were executed by the spacecraft.

The judicious use of multimission tools and services and standards such as CCSDS (Consultative Committee for Space Data Standards) kept the cost of the ground system and mission operations to a minimum. The small operations team averaged about 50 full-time equivalents, including system and subsystem analysts, flight controllers, technology support teams, testbed engineers, and project management and staff.

During the routine IPS thrust periods, one DSN pass each week allowed high-rate commanding and return of spacecraft engineering and technology validation data through the high gain antenna. This weekly track was immediately preceded by AutoNav's collection of optical navigation images, and both activities were conducted with the IPS off. The IPS thrusted for the remaining 90% of the week. One or two shorter passes were scheduled between the longer ones. Conducted only with one of the low gain antennas, to allow communication in the preferred thrust attitude, the shorter passes were used to verify that the IPS was thrusting. On occasion this coverage also was used to conduct IPS or SCARLET experiments.

The strategy for selecting IPS thrust and coast times was based on compromises between optimizing the trajectory and conducting the technology experiments and other mission activities incompatible with the attitudes or other spacecraft states required for thrusting.[16] As illustrated in Figure 1, the deterministic thrusting for the primary mission was accomplished in two major periods. The brief hiatus in the first major thrust arc was inserted to allow several days for activation and initial testing of PEPE in the absence of the IPS plasma, and SDST and K_a-band experiments incompatible with the IPS thrust attitude. When the second thrust segment ended on April 27, 1999 (under direction of AutoNav), the spacecraft was on a ballistic trajectory that would encounter asteroid 1992 KD, thus

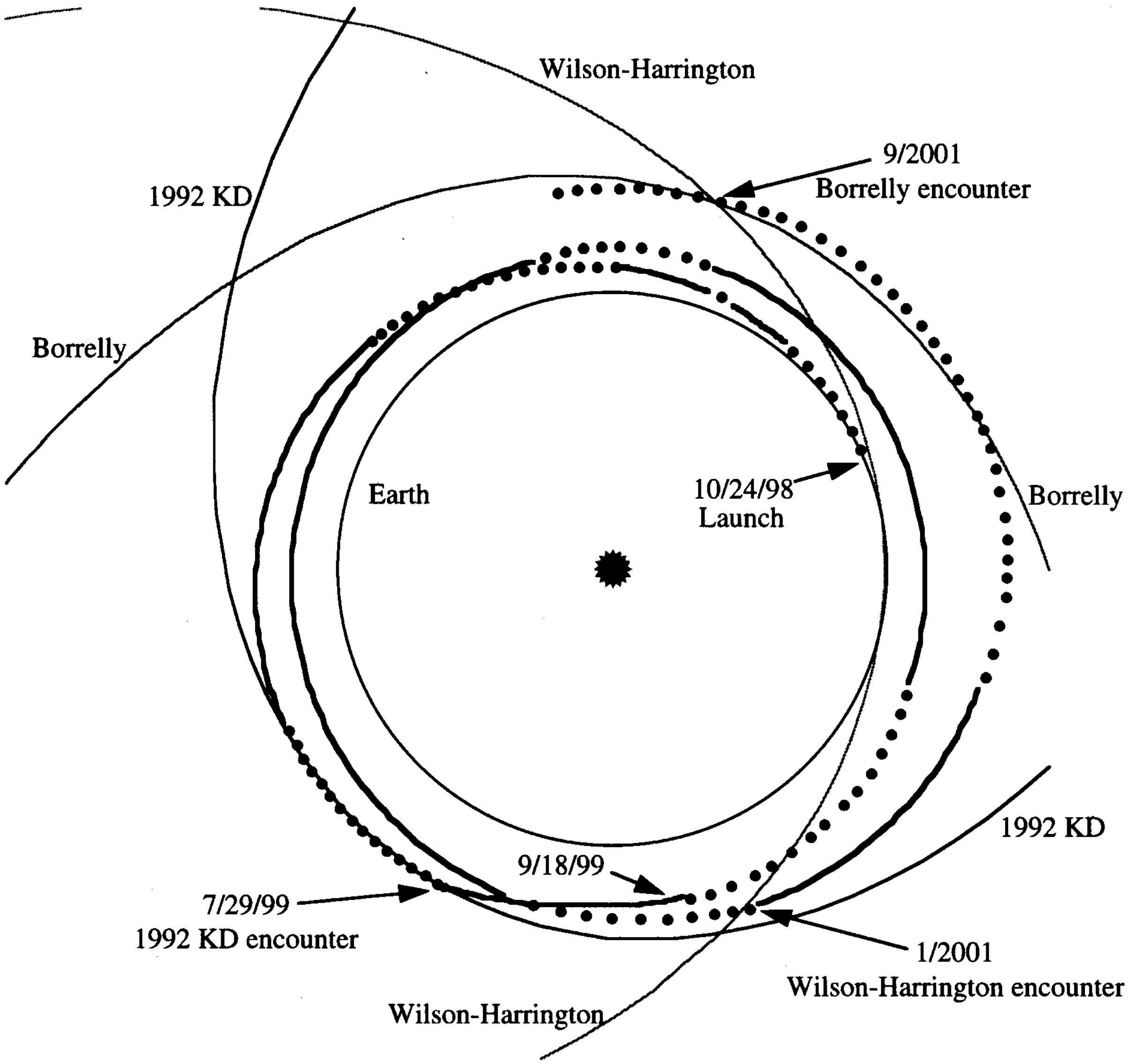

Figure 1. DS1 trajectory for the primary mission (through September 18, 1999) and proposed extended mission. The dotted portion is for ballistic coast; the solid portion indicates the IPS thrust is on.

accomplishing the third mission success criterion. The thrust plan was developed to maintain the option for an extended mission (see below).

On July 29, 1999, the spacecraft will encounter (9969) 1992 KD at 15.5 km/s. The size and shape are poorly known, but this asteroid is believed to be elongate with a mean radius of roughly 1 km. During the final 20 days of the spacecraft's approach to the body, AutoNav will require optical navigation images and trajectory correction maneuvers at increasing frequencies to control the targeting of the final encounter. The maneuvers prior to 2 days before closest approach will be executed with the IPS, and in the final 2 days the RCS will be used to save time.

Because 1992 KD is so faint, it will not be detected by AutoNav (using MICAS images) until about 1 day before closest approach; until the asteroid is detected on board, AutoNav will continue to use 1992 KD's *a priori* ephemeris. A flyby 15 km from the center of the body is planned. With an expected navigational delivery accuracy of about 3 km (1σ), this assures a safe but very exciting encounter. The last opportunity for a trajectory correction maneuver will be 3 hours before closest approach.

During the final approach, AutoNav's MICAS images will be interspersed with MICAS images and spectra collected for science purposes. The late navigation images will contain information AutoNav needs to provide rapid updates to its estimate of the position of 1992 KD, critical for keeping the asteroid in MICAS' field of view. The 4 command sequences, sequentially governing activities during the final 5 minutes before closest approach, will be activated by AutoNav based on its estimates of the time to closest approach. Because MICAS is body-fixed, the termination of imaging is dictated by when the angular acceleration of the line of sight to the asteroid exceeds ACS' capability to keep 1992 KD in the MICAS field of view. Measurements by PEPE and diagnostics sensors for the IPS will continue through closest approach.

The asteroid encounter will allow an opportunity to gather data on the size, shape, geomorphology, albedo, and the mineralogy and compositional heterogeneity of the surface material. It may be possible to measure, or at least constrain, the asteroid's magnetization, interaction with the solar wind (including sputtering), and outgassing.

The spacecraft will point its high gain antenna at Earth about 1 hour after closest approach to begin returning technology validation and science data. Although the data return will require several days, the IPS may resume thrusting as soon as several hours after closest approach. It turns out that with the antenna Earth-pointed, the IPS is within 30° of the optimal attitude for thrusting for the extended mission. For purposes of the extended mission, it is better to thrust in that attitude than to coast.

The end of the primary mission is on September 18, 1999. No new technology experiments are planned after the asteroid encounter. Following the completion of the return of data, some minor engineering activities will be conducted to prepare for the resumption of long-term thrusting, and then the regular cycle of IPS thrusting, interrupted only for weekly acquisition of optical navigation images and DSN communications, will resume.

EXTENDED MISSION

If the spacecraft remains healthy and the resources for an extended mission are available, the DS1 project could conduct a scientifically exciting mission. With the technology testing complete, the extended mission would be devoted to comet science. With AutoNav controlling the IPS, the spacecraft would travel to Comet 107P/Wilson-Harrington and Comet 19P/Borrelly.

As illustrated in Figure 1, most of the extended mission would be devoted to IPS thrusting. By the end of the extended mission, the spacecraft would have expended essentially all of its Xe, providing a total of about 4.5 km/s.

Because of the reduced mission operations staff and the increasing geocentric range during the extended mission, beacon monitor operations likely would be used to augment the team's ability to monitor the spacecraft's health. Demand-access operations have not been implemented by the DSN however, so that aspect of beacon monitor operations cannot be implemented.

In January 2001, DS1 would reach Comet Wilson-Harrington. This comet was lost after its discovery in 1949. In 1992, asteroid (4015) 1979 VA was recognized to be the same body. It is possible therefore that this comet was seen just as its activity was terminating. It is considered to be a dormant comet or a comet/asteroid transition object, with an estimated radius of 2 km.

With DS1's relative speed of 15.8 km/s, the encounter would be similar to the 1992 KD encounter, but it would occur when the comet is near solar conjunction. Although the operations team would have reduced control authority at that time, AutoNav would control the trajectory and timing of sequence activations. Of course, there would be sufficient time to incorporate the results of the final testing of AutoNav at 1992 KD.

In September 2001, DS1 would encounter Comet Borrelly at 17.0 km/s, within days of the comet's perihelion; this is one of the brightest and most active short-period comets. The nucleus is believed to be a prolate spheroid of about 4 km $\times$ 2 km with an active surface area of 7% - 10%. Science data at the comet that could be collected include the structure and composition of the coma and tail (including gas, plasma, and dust), the nature of jets and their connection to surface features, the interaction with the solar wind, and the same kind of characterization of the nucleus as at the asteroid.

The extended mission plan, although devoted to science, illustrates the benefits of the advanced technologies. If DS1 had used conventional technologies, including a bipropellant propulsion system (and excluding the fraction of the solar arrays needed for operation of the IPS), a transponder similar to that on the Mars Climate Orbiter and Mars Polar Lander (launched a few months after DS1), and science instruments with similar capability but without all the innovations being tested on DS1, the spacecraft would be significantly more massive. Reaching 1992 KD, Wilson-Harrington, and Borrelly would have required an injected mass of approximately 1300 kg compared to DS1's 486.3 kg. And rather than being able to share a launch on the least expensive Delta II, the requirements of this hypothetical mission would have exceeded the capability even of a dedicated Delta II 7925, the most expensive member of that family. The smallest operational US launch vehicle that would have met the requirements is the Atlas IIA, for which a shared launch would suffice.

CONCLUSION

The successful flight of DS1 provided an extensive body of data characterizing the 12 technologies it tested in space. By operating these advanced technologies under actual spaceflight conditions, the cost and risk to subsequent users should be greatly reduced, thus allowing rapid integration of the important capabilities they offer into future space and Earth science missions. Another significant benefit of the testing of technologies on DS1 was the experience gained by engineering teams. In many cases, the technologists had not worked on flight projects, and their experiences in both development and operations should prove helpful in their work on future versions of their technologies. The incorporation of the technologies into an operational mission yielded valuable insights into implementation issues that would not be expected to arise in typical technology development or conceptual mission studies. In addition, spacecraft, ground system, mission planning, and mission operations teams discovered the implications of integrating these new technologies into their designs and, of course, learned how to take advantage of the capabilities of the technologies to create new designs. Any informed user, seeking to benefit from the capabilities of these advanced technolo gies, now will encounter lower risk and cost by building upon the successful results of the DS1 project.

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REFERENCES

1. Rayman, Marc D. and David H. Lehman, "Deep Space One: NASA's First Deep-Space Technology Validation Mission," *Acta Astronautica* **41**, p. 289 (1997).

2. Rayman, Marc D. and David H. Lehman, "NASA's First New Millennium Deep-Space Technology Validation Flight," Second IAA International Conference on Low-Cost Planetary Missions, Laurel, MD, April 16-19, 1996, IAA-L-0502.

3. Polk, J. E., R. Y. Kakuda, J. R. Anderson, J. R. Brophy, V. K. Rawlin, M. J. Patterson, J. Sovey, and J. Hamley, "Validation of the NSTAR Ion Propulsion System on the Deep Space One Mission: Overview and Initial Results," 35th AIAA/ASME/SAE/ASEE Joint Propulsion Conference, Los Angeles, CA, June 20-24, 1999, AIAA-29-2274.

4. Wang, J., D. Brinza, R. Goldstein, J. Polk, M. Henry, D. T. Young, J. J. Hanley, J. Nordholt, D. Lawrence, and M. Shappirio, "Deep Space One Investigations of Ion Propulsion Plasma Interactions: Overview and Initial Results," 35th AIAA/ASME/SAE/ASEE Joint Propulsion Conference, Los Angeles, CA, June 20-24, 1999, AIAA 99-2971.

5. Stella, Paul M., Donald G. Nieraeth, David M. Murphy, Michael I. Eskenazi, and John Stubstad,

"Validation of the SCARLET Advanced Array on DS1," *Proceedings of the 34th Intersociety Energy Conversion Engineering Conference*, Vancouver, British Columbia, August 1-5, 1999, paper 1999-01-2630.

6. Riedel, J. E., S. Bhaskaran, S. P. Synnott, S. D. Desai, W. E. Bollman, P. J. Dumont, C. A. Halsell, D. Han, B. M. Kennedy, G. W. Null, W. M. Owen Jr., R. W. Werner, and B. G. Williams, "Navigation for the New Millennium: Autonomous Navigation for Deep Space 1," 12th International Symposium on Space Flight Dynamics, Darmstadt, Germany, June 2-6, 1997, paper 88.

7. Beauchamp, P. M., R. H. Brown, C. F. Bruce, G-S. Chen, M. P. Chrisp, G. A. Fraschetti, T. N. Krabach, S. W. Petrick, D. H. Rodgers, J. Rodriguez, S. L. Soll, A. H. Vaughan, L. A. Soderblom, B. R. Sandel, and R. V. Yelle, "Pluto Integrated Camera Spectrometer (PICS) Instrument," *Acta Astronautica* **35**, Supplement 1995.

8. Bolton, S. J., D. T. Young, J. E. Nordholt, J. L. Burch, H. O. Funsten, N. Eaker, and D. J. McComas, "Plasma Experiment for Planetary Exploration (PEPE)", in *Proceeding of Space Technology and Applications International Forum*, Albuquerque, NM, 1997, AIP Proceedings 387, ISBN 1-56396-679-4.

9. Herman, M. I., S. Valas, W. Hatch, C. C. Chen, S. H. Zingales, R. P. Scaramastra, L. R. Amaro, and M. D. Rayman, "Deep Space One Telecommunication Development," 12th Annual AIAA/USU Conference on Small Satellites, September 6-10, 1998, Logan, Utah, paper SSC98-IV-1.

10. Karnacewicz, M. K., W. J. Taft, S. Valenti, T. Renna, M. Hirokawa, S. Conway, and L. Newman, "2.6 Watt K_a-Band Solid State Power Amplifier for Deep Space Communications," *1999 Digest of Papers, Government Microcircuit Applications Conference*, pp. 247-250.

11. Wyatt, Jay, Rob Sherwood, Miles Sue, and John Szijjarto, "Flight Validation of On-Demand Operations: The Deep Space One Beacon Monitor Operations Experiment," *Proceedings of the 5th International Symposium on Artificial Intelligence, Robotics and Automation in Space (iSAIRAS-99)*, Noordwijk, The Netherlands, June 1-3, 1999.

12. Nayak, P. Pandurang, Douglas E. Bernard, Gregory Dorais, Edward B. Gamble Jr., Bob Kanefsky, James Kurien, William Millar, Nicola Muscettola, Kanna Rajan, Nicolas Rouquette, Benjamin D. Smith, William Taylor, and Yu-wen Tung, "Validating the DS1 Remote Agent Experiment," *Proceedings of the 5th International Symposium on Artificial Intelligence, Robotics and Automation in Space (iSAIRAS-99)*, Noordwijk, The Netherlands, June 1-3, 1999.

13. D'Onofrio, R. P., C. L. Keast, A. M. Soares, P. W. Wyatt, "Low Power Flight Experiment: Flight Qualifying Sub-0.25-µm Fully Depleted SOI CMOS Technology," *1999 Digest of Papers, Government Microcircuit Applications Conference*, pp. 238-241.

14. Salim, Abbas, Gerhard Franz, Jim Jud, David Hogue, and Gregory Carr, "PASM, The Advanced Power Actuation and Switching Module as the Building Block for Space Micropower Systems," *1999 Digest of Papers, Government Microcircuit Applications Conference*, pp. 242-246.

15. Barnett, David M. and Suraj P. Rawal, "Multifunctional Structures Technology Experiment on Deep Space 1 Mission," *IEEE AES Systems Magazine*, January 1999, pp13-18.

16. Rayman, Marc D., Pamela A. Chadbourne, Jeffery S. Culwell, and Steven N. Williams, "Mission Design for Deep Space 1: A Low-Thrust Technology Validation Mission," Third IAA International Conference on Low-Cost Planetary Missions, Pasadena, CA, April 27 - May 1, 1998, IAA-L98-0502.