DEEP SPACE 1: Robotic Exploration in the New Millennium

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Abstract

Deep Space 1 (DS1), launched on October 24, 1998, was the first mission of NASA's New Millennium program. DS1 was chartered to flight validate twelve high-risk, advanced technologies important for future space and Earth science programs. Advanced technologies tested during its primary mission included solar electric propulsion, high-power solar concentrator arrays, three on-board autonomy technologies, two low-mass science instrument packages, and several telecommunications and microelectronics devices. During the primary mission, which was completed in September 1999, the technology payload for the mission was exercised extensively to assess performance so subsequent missions will not have to incur the cost and risk of being the first users of these new capabilities. DS1 was the first deep space mission to use solar electric propulsion as its main source of propulsion. In addition, DS1 was the first mission to demonstrate the ability to perform autonomous on-board navigation for a deep space probe. Although DS1 was driven by the requirements of the technology validation, it also presented an important opportunity to conduct solar system science, though as a secondary objective to its main technology validation mission goals. As such, the spacecraft flew by asteroid Braille in July of 1999; later encounters during its recently approved extended mission with comets Wilson-Harrington and Borrelly are planned in the year 2001. This paper will describe the technology and mission aspects of Deep Space 1.

Introduction

NASA's plans for its space and Earth science programs call for many scientifically compelling, exciting missions. To make such programs affordable in the

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new millennium, it is anticipated that small spacecraft, launched on low-cost launch vehicles 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.

The New Millennium program (NMP) is designed to accelerate the realization of ambitious missions by developing and validating high-risk, high-benefit technologies. NMP conducts deep space and Earth orbiting missions focused on validating 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. This is 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 of the technologies during the flight.

Deep Space 1 (DS1) was the first project of NMP. Its payload consisted of the following 12 technologies:

- Solar electric propulsion (SEP)
- Solar concentrator arrays
- Autonomous navigation
- Miniature camera and imaging spectrometer
- Small deep space transponder
- Miniature integrated ion & electron spectrometer
- Beacon monitor operations
- Autonomous remote agent
- Low power electronics
- Power actuation and switching module
- Multifunctional structure
- K_a-band solid state power amplifier

All the above technologies completed their required testing by July 1999, and the mission exceeded NASA's formal criteria for mission success. Further background on the project, including the technologies, mission and spacecraft design, are presented elsewhere.[1,2]

Technology Results

Because of space limitation, only 4 of DS1's 12 advanced technologies will be provided in this paper. A more thorough description of the rest of the technologies and the mission itself are discussed elsewhere.[2]

Solar Electric Propulsion

Solar electric propulsion (SEP) offers significant mass savings for future deep space and Earth-orbiting spacecraft that require substantial velocity changes and was provided by the NSTAR (NASA SEP Technology Application Readiness) program for the mission. The SEP system on DS1 uses an ion propulsion system (IPS) that has 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.

By October 20, 1999, the IPS had operated for 3500 hours, using 22 kg of Xenon, which increased the speed of the spacecraft by 1.3 km/sec. This included several dedicated tests, though the majority of the time was devoted to placing the spacecraft on a trajectory to reach asteroid Braille and comets Wilson-Harrington and Borrelly. 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 pre-launch prediction throughout the range.

Solar Concentrator 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). 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 pre-launch 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 multi-bandgap cells.

Autonomous Navigation (AutoNav)

One portion of the core of the autonomous systems validated on DS1, AutoNav, 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 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 ephemeredes of the DS1 target bodies, distant "beacon" asteroids, and all planets except Pluto; and a catalog of the positions of 250,000 stars.

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. 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.

AutoNav also performs target relative tracking at encounters by providing accurate pointing information to the attitude control system, and it initiates the encounter sequences based on its estimate of the time to closest approach.

Integrated Camera and Imaging Spectrometer

The Miniature Integrated Camera Spectrometer (MICAS) was conceived and developed by a team from JPL, United States Geological Survey, the University of Arizona, Boston University, Rockwell, and SSG. In one 12-kg package, this instrument 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 collected science data during the primary mission at the asteroid and will be used at other encounters during the extended mission.

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. Further tests are planned for late in 1999.

MICAS images and IR spectra revealed scattered light. Stray light analyses 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 did not significantly interfere with encounter science.

Mission

DS1's launch occurred on October 24, 1998 on the first Delta II 7326-9.5 (from The Boeing Company), the smallest vehicle in the Delta stable. This launch vehicle was selected largely on the basis of prompt availability and low cost. 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.

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 initial thrusting, the spacecraft was turned to thrust along the optimal vector for reaching the encounter targets for the mission.

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. 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.

On July 29, 1999, the spacecraft flew-by asteroid Braille at a distance of 27 km and a speed of 15.5 km/s. The asteroid encounter was not a required part of the mission, but allowed additional technology testing and the return of bonus science data. The spacecraft's infrared sensor on MICAS returned four sets of spectrum data that will help scientists determine the asteroid's composition. In addition to two black-and-white images taken 20 seconds apart at approximately 15 minutes after the encounter, two black-and-white images about 70 minutes prior to closest approach, were returned. Close-up images of Braille were not obtained because it appeared far dimmer (by a factor of 5 to 10) than anticipated due to its albedo, surface morphology and topography. In addition, the Active Pixel Sensor (APS) channel in MICAS presented an anomalously low signal to an already dim input flux due to non-linearity in the electronics output from the APS that was insufficient to cross the AutoNav threshold for "detection". The cause of the anomaly is well understood by the team and it is expected that improved science results will be obtained at the next encounters. All science data planned for acquisition with the miniature integrated ion and electron spectrometer were returned. In addition, sensors onboard to monitor field and particle effects of the IPS were reprogrammed to collect science data at Braille, and all desired measurements were completed.

The spacecraft's xenon ion engine was restarted following the asteroid encounter on July 30, 1999 and will continue thrusting almost continuously in preparation for flybys of two comets during an extended mission which started on September 27, 1999, the conclusion of Deep Space 1's primary mission of technology validation. With the technology testing complete, the extended mission will be devoted to comet science. With AutoNav controlling the IPS, the spacecraft will travel to Comet 107P/Wilson-Harrington and Comet 19P/Borrelly. In January 2001, DS1 is planned to reach Comet Wilson-Harrington. It is considered to be a dormant comet or a comet/asteroid transition object, with an estimated radius of 2 km. In September

2001, DS1 is planned to 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 × 2 km with an active surface area of 7% - 10%. Science data at the comets 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.

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 space flight 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. 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 technologies, now will encounter lower risk and cost by building upon the successful results of the mission.

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