EXPERIENCES IN RIDING A TECHNOLOGY ROLLER COASTER TO DEEP SPACE

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Abstract

Deep Space 1 (DS1) was the first mission of NASA's New Millennium program and was chartered to flight test twelve high-risk, enabling technologies important for future space and Earth science programs on both a fast schedule and a low budget. Concept studies for the project were initiated in July of 1995 and the spacecraft was launched in October 1998. DS1's prime mission was successfully completed in September of 1999. Advanced technologies flight-tested during the mission included ion propulsion, high-power solar concentrator arrays, three on-board autonomy technologies, two low-mass science instrument packages, and several telecommunications and microelectronics devices. Among its firsts, DS1 was the first deep space mission to use ion propulsion to actually go somewhere (asteroid Braille in July of 1999) and the first mission to use a totally autonomous on-board navigation system. Approved by NASA for an extended mission in September of 1999, the spacecraft is on track to flyby Comet 19P/Borrely in September of 2001.

The authors were members of the project management team, and experienced all the "ups and downs" of riding a technology roller coaster to deep space. In this paper we will describe the key space technologies and mission aspects of DS1. We will also describe the lessons learned for the development and operations phases of the project.

Introduction

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. 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) is the first project of NMP. Its payload consists of the following 12 technologies:

- Solar electric propulsion (SEP)
- Solar concentrator arrays
- Autonomous navigation
- Miniature integrated camera spectrometer (MICAS)
- 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. Further background on the project, including the technologies, mission and spacecraft design, are presented elsewhere (Ref. 1).

Technology Results

Because of space limitation, only 3 of DS1's 12 advanced technologies will be discussed in this paper. A more thorough description of the technologies and the mission itself are discussed elsewhere (Ref. 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 ion propulsion system (IPS) on DS1 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.

By September 25, 2000, the IPS had operated more than 5800 hours, using 32 kg of xenon, and increased the speed of the spacecraft by 1.9 km/sec. During the technology validation phase of the mission, 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

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). 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 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. 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

One portion of the core of the autonomous system 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. 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.

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 $C_3 = 2.99\ \text{km}^2/\text{s}^2$.

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. 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.

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 was also used to conduct IPS or SCARLET experiments.

On July 29, 1999, the spacecraft flew-by asteroid Braille at a distance of 27 km and a speed of 15.5 km/s (Ref. 3). 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 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 now well understood by the team.

The spacecraft's xenon ion engine was restarted following the asteroid encounter in preparation for a flyby of Comet 19P/Borrelly during an extended mission that 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 is devoted to comet science. During the extended mission on November 11, 1999, the spacecraft's commercial star tracker failed. This critical loss prevented the spacecraft from achieving 3-axis attitude control or knowledge. Following 4 months of new software development and testing, new software was uploaded to DS1's main computer. The reprogrammed computer has since been using the science camera as an attitude sensor in place of the failed star tracker. The ambitious rescue was fully successful, and the extended mission is back on track (Ref. 3).

In September 2001, DS1 is planned to encounter Comet 19P/Borrelly at 16.5 km/s, within days of the comet's perihelion. Comet 19P/Borrelly 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. Though the fly-by plan is still under development, the 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. This is a high risk and ambitious encounter given the extended age of the spacecraft, the very small budget available for operations, and the absence of the star tracker; but if it is successful the flyby will be another bonus accomplishment of the project.

Lessons Learned

As stated previously, the authors were members of the project management team, and experienced all the "ups and downs" of the project. At its peak the project employed over 200 dedicated people, all of whom had to be efficiently employed to ensure everything got done when it had to be done. To the credit of the team, in this day and age of long delays for the typical complex aerospace project, DS1 not only exceeded its mission success criteria, but had only a 3-½ month delay in launch (which did not affect the achievement of its technical objectives). This was achieved in the face of numerous setbacks and problems with getting high-risk, high-payoff technologies (with large performance unknowns at the beginning of the project) ready to launch only 39 months after the first concept study for the mission. In addition, the spacecraft had to survive the rigors of launch and the radiation and temperature environment of deep space. Throughout the development of the spacecraft and its mission operations phase, the project team had to deal with the paradox of developing and operating "high-risk technologies" on a short fused schedule at relatively low cost on a mission that the customer wanted with little to no chance of failure. The key lessons learned on DS1 are as follows:

Project Management:

DS1 had only a short 2-month pre-project phase, which was not enough to develop a robust plan. A project needs to spend sufficient time during its formulation phase to develop its project plan, culminating in a review to ensure the mission concept is sound, the requirements are agreed to, and there are sufficient resources to do the job. During the formulation phase, the project needs to define the phasing of funding, the need dates for the launch vehicle, requirements and success criteria, technical and programmatic margins, etc., and not proceed with further commitments until the entire project is sufficiently understood and agreements are in place with NASA Headquarters.

Upper management needs to ensure the continuity of the project management team. It is best to have the same core people on the project from the beginning through the end of the mission.

Maintain an open door environment – with the emphasis that it is okay to surface bad news.

Organization and Team Dynamics:

The project team is the most important factor in mission success. An unambiguous organization, adequate resources and the right environment are essential to allow the team to succeed. It's critical to have adequate resources to allow the team to do their job.

Co-locate the key members of the team as early as possible.

The project had many team lunches and after-work parties together; we also had numerous "all-hands" meetings to help develop the teamwork necessary in all successful projects. We worked hard to develop a "badgeless" environment for all our different partners. Needless to say, project managers can never do enough to build a good team-working environment.

Reviews:

Peer reviews add the most value to ensure the technical design and programmatic plan are correct. Set up a peer review plan early and get institutional management support.

Advanced Technologies:

Develop a technology plan during the formulation phase that addresses risk mitigation and technology readiness. Include technical readiness gates to assess development progress and develop a clear action plan if gates are not met.

Timely Decisions:

Early in the development phase of DS1, a key decision was required to demanifest or descope two of the advanced technologies on the spacecraft (called the 3D Stack and the Remote Agent technologies). The information to make that decision was available to the project manger, but for political and other reasons the decision was delayed. Six months later, it was absolutely required to make the decision in order for the project to survive. At this time the decision was finally made and, ultimately, this delay was a factor in the 3-1/2 month launch delay. The lesson learned is that delaying decisions, regardless of the reason, can cripple a FBC project needlessly.

Effective Partnerships:

To make DS1 happen we had to work hard to build effective partnerships with various organizations, both to keep costs down and to ensure a successful mission. These partnerships included items such as the main spacecraft bus, the launch vehicle, most of the technologies and their associated sponsors and lead engineers, spare hardware from other projects, and the use of facilities at various agencies. The partners included other projects at JPL and other NASA centers, commercial organizations, and other government agencies, both in the US and in Europe. On a fast-paced project like DS1 this makes schedule management extremely difficult, because your partners don't always have the same skills, concerns, objectives or goals as you do. The project manager should remember that the number of partners on a project is inversely related to the ability to control the "rudder" of the project. This means that project managers have to work extra hard to build "effective" coalitions to keep the project team working smoothly together.

Assembly Test and Launch Operations (ATLO):

Include adequate margin in the development schedules, particularly for new technology developments. Develop an ATLO plan that is resilient to late deliveries.

Develop a thorough test program with a good closed loop problem assessment and resolution process. Strive to ensure no "open paper" at launch. Ensure there are sufficient test equipment, test beds and test articles of hardware to maintain the schedule and overcome the down stream inevitable development and operations disasters.

Operations:

Resources (both personnel and schedule) need to be made available to allow spacecraft and payload team participation in operations planning early. Time must be allocated to allow development personnel to complete integration and test activities and to prepare for mission operations.

We learned during our first attempt to start the IPS (it didn't work until 2 weeks after our first try), that it is best to develop contingency procedures and update them during development and operations as new information makes them obsolete.

We learned to rely upon our operations testbed, and that if an activity is important and uncertain enough to test in the testbed, then require all subsystem engineers with major involvement in it to review the test results. We also learned that the testbed configuration should be as flight-like as possible and differences must be understood completely by the operations team.

Perseverance:

Many critics said that DS1 could not be done, especially in the early years. It was too much to develop, launch and operate revolutionary technologies in such a short period of time on a shoestring budget. The key members of the project's staff and the majority of the project team, nevertheless, stayed with the project from the beginning to the end and persevered in spite of many severe setbacks and at great personal sacrifice. To us, the perseverance of the team to get the job done, regardless of the obstacles (both from a technical and bureaucratic nature), was the key to our success.

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. Finally, from a management standpoint we hope that future projects will benefit from the lessons of managing DS1 so that they will not face the problems DS1 encountered or will be able to weather them more smoothly.

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