MISSION DESIGN FOR DEEP SPACE 1: A LOW-THRUST TECHNOLOGY VALIDATION MISSION

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Deep Space 1 (DS1), scheduled for launch in July 1998, is the first mission of NASA's New Millennium program, chartered to flight validate high-risk, advanced technologies important for future space and Earth science programs. DS1's payload of technologies will be rigorously exercised during the two-year mission. Several features of the project present unique or unusual opportunities and challenges in the design of the mission that are likely to be encountered in future missions. The principal mission-driving technology is solar electric propulsion (SEP); this will be the first mission to rely on SEP as the primary source of propulsion. Another technology with a strong effect on the mission design is the autonomous navigation system, which requires frequent (at least weekly) intervals of several hours during which it collects visible images of distant asteroids and stars for its use in orbit determination. The mission design accommodates the needs of these and other technologies for operational use and for acquiring sufficient validation data to assess their viability for future missions. DS1's mission profile includes encounters with asteroid 3352 McAuliffe, Mars, and comet 76P/West-Kohoutek-Ikemura.

INTRODUCTION

Overview of New Millennium

NASA's plans for its space and Earth science programs in the early years of the next century call for many exciting, scientifically compelling 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 less expensive, the introduction of new technologies is required.

With many spacecraft carrying out its programs of scientific exploration, NASA would accept a higher risk per spacecraft; 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 focused objectives of the science missions can be avoided by certification of the technologies in a separate effort.

The principal goal of the New Millennium program (NMP) is to validate selected high-risk, high-benefit technologies in order to reduce the risks and the costs future missions would experience in their use. NMP comprises dedicated deep space and Earth orbiting missions focused on the technology validation. As each mission is flown, the risk of using the technologies that formed its payload should be substantially reduced, both because of the knowledge gained in the incorporation of the new capability into the spacecraft, ground system, and mission design as well as, of course, the quantification of the performance during the mission.

By their very nature, NMP missions 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. Still, 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 needs modification before it is appropriate for use on science missions would be a useful result of an NMP flight.

Overview of DS1

Deep Space 1 (DS1) is the first mission of NMP. It is being led by JPL, with Spectrum Astro, Inc. as the partner for spacecraft development. Planned for launch in July 1998, DS1's payload consists of 12 technologies. The primary requirements of the mission are the validation of four of these:

- solar electric propulsion (SEP), implemented on

DS1 as the ion propulsion system (IPS);
- solar concentrator arrays, supplied to DS1 as solar concentrator arrays using refractive linear element technology (SCARLET);
- autonomous on-board navigation (AutoNav); and
- an integrated panchromatic visible imager and infrared and ultraviolet imaging spectrometers, implemented on DS1 as the miniature integrated camera spectrometer (MICAS).

To assist in the validation of the SEP, DS1 includes IPS diagnostic sensors (IDS), composed of instruments to quantify magnetic and electric fields, ion and electron densities, and surface contamination.

Other level 1 requirements, negotiated with the program office and NASA Headquarters, include the launch by the end of the July-August 1998 opportunity, the conclusion of the primary mission within two years of launch, and the completion of the project for $141.1 M, measured in real-year dollars. This cost includes the design and development of the spacecraft and ground segment, the launch service, and operations during the primary mission. The costs of some of the technologies provided by preexisting technology development programs are not included in this, but the cost of their integration into the spacecraft (and the mission) are.

DS1 also has level 1 goals which include the validation of eight more technologies:
- a small deep space transponder (SDST);
- a K_a-band solid state power amplifier (KAPA) and associated experiments in K_a-band telecommunications;
- an integrated ion and electron spectrometer, known as plasma experiment for planetary exploration (PEPE);
- a remote agent experiment (RAX) architecture for autonomous onboard planning and operations;
- a beacon monitor operations experiment (BMOX) for autonomous onboard health and status summarization and request for ground assistance;
- low power electronics (LPE);
- a high-packaging-density smart power switch, known as a power activation and switching module (PASM); and
- a multifunctional structure (MFS) experiment combining electronics and thermal control in a structural element.

Details on each technology (and further background on the mission) are presented elsewhere.[1]

One of the risks in the use of some of the technologies in DS1's payload is that they may interfere with the collection of scientifically useful data on future missions. Thus another goal is to return such data. Science data acquisition with MICAS and PEPE (and perhaps the IDS) at the encounters and during the cruise would accomplish this goal. Besides contributing to the validation of technology, the execution of science takes advantage of the flight of a capable spacecraft into the solar system, albeit one on a high risk mission. The level 1 goals specify that DS1 encounter one asteroid and one comet during its flight.

The mission profile, described in more detail below, includes an encounter with the type S near-Earth asteroid 3352 McAuliffe in January 1999 and comet 76P/West-Kohoutek-Ikemura in June 2000. An encounter with Mars in April 2000 provides a small gravity assist to reach the comet and presents an opportunity for bonus technology validation and science.

Although the first encounter is more than five months after the end of the launch period, most of DS1's technology validation will occur well before then. Even by conducting a "minimum mission" profile designed to deliver the spacecraft to the asteroid, a significant fraction of the technology validation activities will be completed. The IPS, powered by SCARLET and commanded by AutoNav, is essential to reaching this first encounter. The use of the visible-channel CCD in MICAS is required for the optical data used by AutoNav. The SDST is used for all telecommunications. Thus, the four required technologies and one of the goal technologies will be exercised extensively in the "routine" execution of the mission. The addition of dedicated technology validation activities during the early mission phases guarantees that most mission requirements and goals will be met within a few months of launch.

Table 1 lists the percentage of the needed data that will be returned for each technology's validation during the mission. Mission phases are explained on page 5.

	% validation by mission phase						
Technology	Launch & initial checkout (L+0 - L+40)	Cruise 1 (L+41 - L+180)	Asteroid encounter (L+181 - L+204)	Cruise 2 (L+205 - L+644)	Mars encounter (L+645 - L+668)	Comet encounter (L+669 - L+705)	Data return (L+706 - L+723)
Solar electric propulsion (IPS)	75	100		L			
Solar concentrator arrays (SCARLET)	100						L
Integrated camera/imaging spectrometer (MICAS)	50	75	85		95	100	
Integrated ion and electron spectrometer (PEPE)	50		75		90	100	
Autonomous on-board navigation (AutoNav)	25	75	90		95	100	
Remote agent architecture (RAX)		100					
Beacon monitor operations (BMOX)	25	50		100			
Small deep-space transponder (SDST)	75	100					L
Ka-band amplifier (KAPA); Ka telecommunications	50	100					L
Power activation and switching module (PASM)	50	100					L
Low power electronics (LPE)	50	100					L
Multifunctional structure (MFS)	50	100					L

Table 1. Technology validation by mission phase. These values are approximate and include a rough adjustment for the possibility that anomalies during the early part of the mission may postpone some nonessential activities. "L" indicates lifetime validation data.

TRAJECTORY DESIGN

Two important classes of challenges have been encountered in the trajectory design: one is that important parameters have high uncertainties and the other is that the tools needed to analyze low-thrust trajectories are significantly less mature than those used routinely for both preliminary design as well as high accuracy flight-quality analysis for conventional missions.

The performances of the technologies DS1 is validating (and relying upon) are uncertain. Indeed, if their functioning in flight could be predicted with confidence, they would not require validation. With the unproven IPS and SCARLET critical to the trajectory, it is clear that accurate performance predictions cannot be made. In some cases, estimates of the performance of subsystems have changed significantly during design, development, and test of these new systems. This has led to the need for trajectory redesigns, reductions of some early margins, and greater diligence to manage the resulting risk. The priorities established in the DS1 requirements and goals for NASA have been essential in making some of the design choices which accommodate the changed capabilities discovered during hardware build and test.

Other parameters that are not typically associated with traditional trajectory design, including spacecraft power consumption (which competes with the IPS) and IPS duty cycle (the fraction of the time that the spacecraft spends thrusting in the required attitude when thrusting is needed) contribute to the uncertainty in the trajectory. The major reductions in duty cycle are from the pointing of either the high-gain antenna at Earth or MICAS at asteroids and stars for optical navigation. Finally, in part because of a very tight cost cap, the solutions to many design problems on DS1 have led to increases in spacecraft mass. The instability in that value has contributed to the difficulty in the trajectory design.

As the spacecraft design (as well as estimates of the relevant models) has evolved, the trajectory optimization has required continual updating. This is one of the primary differences between designing SEP trajectories and those which employ chemical propulsion systems. The trajectory optimization and spacecraft systems characteristics are highly coupled. With SEP, in which not only the thrust but also the specific impulse of the propulsion system change with heliocentric distance, a mass optimization depends on models of the various spacecraft systems which generate or consume power. This is not the case with conventional propulsion systems where deep space maneuvers are essentially discrete events and the specific impulse does not depend on heliocentric distance.

Software tools to produce low-thrust trajectories are few and, because of the complex nature of the optimization, require more time to initialize and run than tools for missions using conventional propulsion. In addition, highly-skilled and specialized talent is needed to achieve useful and accurate products. Indeed, an important component of the validation of SEP on DS1 is the generation of the trajectories from conceptual design through flight.

As discussed earlier, the two-year DS1 trajectory begins in July or August 1998; a schematic is shown in Figure 1 for a July 20 launch. The initial requirements for the mission included only an asteroid and a comet flyby. McAuliffe and West-Kohoutek-Ikemura were selected from among a set of candidates based on high allowed "neutral" mass (defined to be all mass except Xe propellant) and good conditions at the encounters (including speeds, phase angles, and

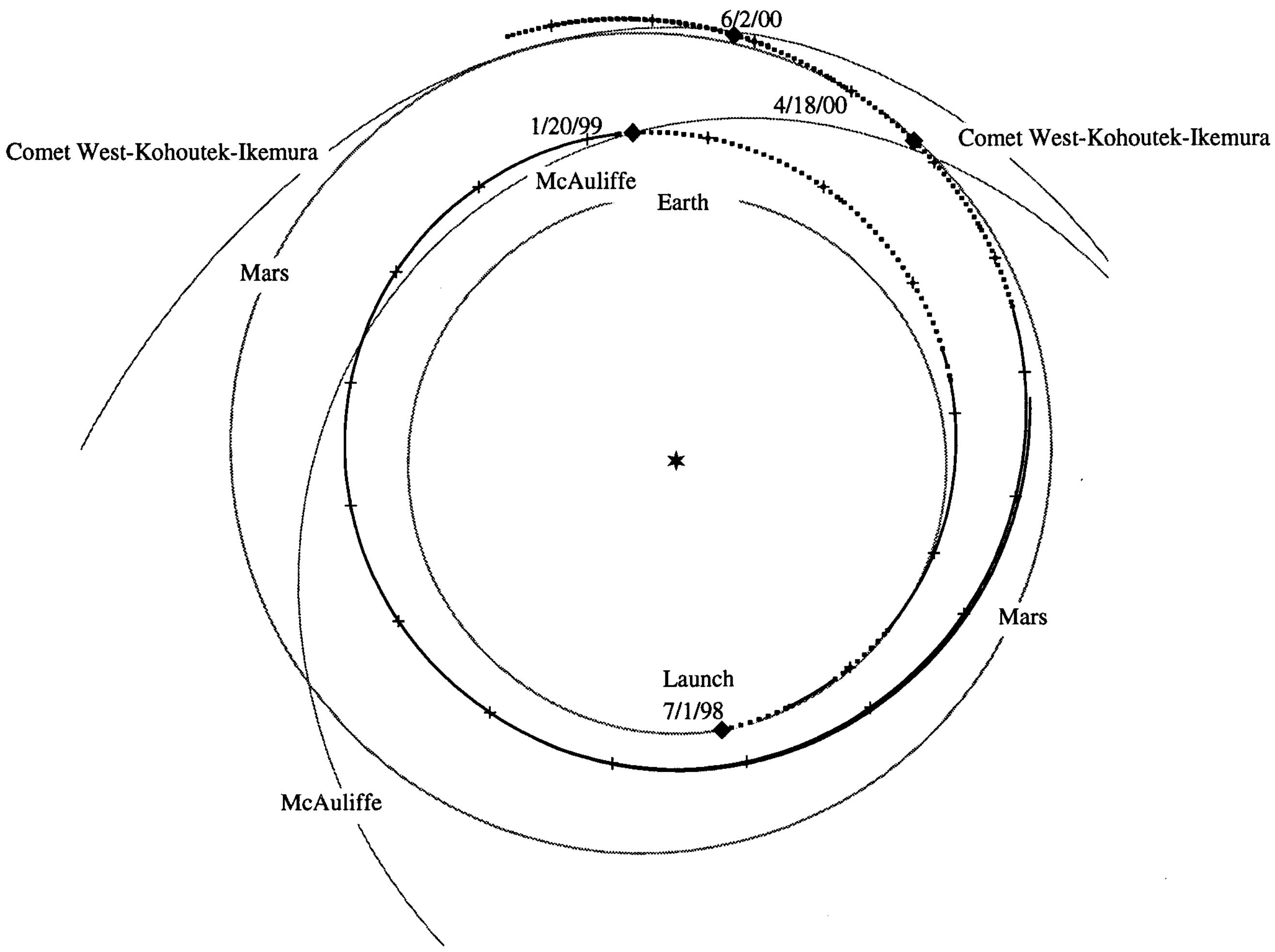

Figure 1. DS1 trajectory for a July 1 launch. The solid curve indicates the IPS thrust is on; the dotted portion is for ballistic coast. The tic marks are at 30-day intervals.

target size) for validating the technologies. Mars was added later when it was discovered that a gravity-assist provided a mass performance benefit of 5 to 10 kg as well as opportunities for enhancements of the technology validation and science.

The DS1 trajectory has been designed with the Solar Electric Propulsion Trajectory Optimization Program (SEPTOP),[2] which has been used for many years at JPL in preliminary mission design studies. This program uses a calculus of variations approach to maximize final spacecraft mass. It optimizes the thrust profile, which includes the thrust magnitude and direction as functions of time. The optimal times to thrust often lead to months-long thrust "arcs" during which the spacecraft attitude is constrained to achieve the required thrust direction. SEPTOP also finds the optimum encounter dates and launch parameters (C_3, RLA, and DLA).

The trajectory optimization is highly dependent on models of various spacecraft systems, and this coupling provides a significant challenge for mission designers. The set of software developed over the last several decades for design of interplanetary trajectories is not sufficient for this mission. Typically, higher fidelity models than are available with preliminary design software would be required to provide a sufficiently accurate representation of the trajectory to fly a mission. Because an interplanetary SEP mission has never flown, this software must be developed by DS1. The solution has been to add the appropriate models to existing software: a Computer Algorithm for Trajectory Optimization (CATO)[3]. Therefore, two trajectory tools are used to design this mission. SEPTOP is used to optimize the trajectory as described above. It is employed in performing a variety of sensitivity analyses: variations across the launch period, injection dispersions, effects of non-optimum thrust arcs and unplanned loss of thrusting due to spacecraft anomalies, as well as many others. Using SEPTOP to provide an initial estimate, a modified version of CATO "fine tunes" the trajectory. With its more accurate physical model of the solar system, CATO provides the DS1 navigation team (and AutoNav) with a more accurate representation of the trajectory.

MISSION

Mission Phases

The DS1 mission is divided into phases based on common objectives and similar activities within each phase (see Table 2). The phase definitions are similar to those of traditional missions in terms of included activities.

Mission Phase	Objectives / Activities
Launch	spacecraft initialization and achievement of safe state
Initial Checkout	activate, calibrate, validate critical technologies
Cruise 1	trajectory maintenance, technology validation
Encounter 1	asteroid approach, flyby, data return
Cruise 2	trajectory maintenance, technology validation
Encounter 2	Mars approach, flyby, data return
Encounter 3	comet approach, flyby
Data Return	return comet data

Table 2. DS1 mission phases.

Launch Phase

The launch phase is defined as the first four hours of the mission, beginning with liftoff of the Boeing Delta 7326-9.5 launch vehicle. This vehicle was chosen because of its low cost and rapid availability; however, its capability exceeds the DS1 launch energy and mass requirements, in part because of the high specific impulse of the IPS. The residual performance will be used to carry another spacecraft (SEDSAT-1) to Earth orbit. SEDSAT-1 is mounted on the second stage, which restarts after separation from the third stage. The second stage will take SEDSAT-1 to its required orbit, after which that spacecraft will separate.

The launch period for DS1 extends from lat July to mid August 1998. To reduce the cost of the launch service, DS1 uses a single specification of the launch targets (C_3 and DLA) throughout its launch period. This means that only one ascent trajectory needs to be calculated by the launch provider. The RLA is optimized for each day of the launch period simply by choosing the correct time of launch.

Initial Checkout Phase

The initial checkout (IC) phase occurs after the launch phase and lasts for 40 days (L+4 hours to L+40 days). The first two weeks of IC will be devoted to conducting initial evaluation of mission critical spacecraft technologies (IPS, SCARLET, MICAS, and AutoNav) needed for the mission's long periods of thrusting. Starting on L+15 days, AutoNav will be commanded to control an 11-day thrusting event. The thrusting will be interrupted every 2 days for optical navigation imaging. The remaining 15 days of IC are used to conduct further initializations, gather additional technology validation data, and to recover from anomalies.

The first two days of IC have very little spacecraft activity. This time will enable the flight engineering team to command the spacecraft to the checkout state and will allow outgassing before later critical events. At several times, IDS will measure the extent of spacecraft contamination. BMOX will begin data summarization during the second day of the mission.

The IPS initialization and characterization of each of the major components begins on L+2 days and concludes on L+7. The xenon feed system (XFS) is evaluated and pressurized, the ion thruster is decontaminated, and thrusting tests are conducted.

During the slow XFS data collection on L+3, SCARLET is calibrated. This process measures the array output as its two axes are independently swept through a range of Sun pointing angles.

The first thrusting event occurs on L+6. During this activity the IPS is throttled through 7 power levels while the Deep Space Network collects Doppler data, which are used to calibrate the thrust magnitude. The subsequent day has no scheduled spacecraft activity to allow the operations team to rest or to respond to IPS problems during the calibration.

MICAS and AutoNav are first evaluated on L+8. Several star fields, Jupiter, and the Earth-Moon system are imaged by sequenced commands. Next AutoNav is commanded to perform optical navigation imaging. During this event, AutoNav autonomously commands the spacecraft to target reference asteroids. At each line of sight, 4 images are collected and compressed. The compressed images are processed by AutoNav for orbit determination.

The following week of scheduled spacecraft activity is minimal. This time is available for recalibrating any of the mission critical systems. If time permits, the functionality of SDST, LPE, PASM, and MFS are evaluated.

On L+15 AutoNav is commanded to initiate IPS thrusting for 11 days, with interruptions every 2 days only for optical navigation activities. During this phase, AutoNav will use ground generated files to control the thrusting events, based on the IPS and SCARLET calibrations and the radiometrically determined spacecraft 6-state. AutoNav commands the attitude control system to turn the spacecraft and commands the IPS to pressurize and thrust. Once confidence in the AutoNav system is established (during Cruise 1), it will use onboard orbit determination and maneuver planning to update the thrusting control files.

The remaining 15 days of IC are used to finish spacecraft checkout. If problems arose during thrusting, this time will be used for analysis and recovery. The high voltages for PEPE and MICAS' ultraviolet detector will be stepped up gradually until the instruments are fully functional. To reduce risk to the instruments, this commanding will be real-time, and it will be aborted if problems arise. Further sequenced MICAS calibration activities will be performed. In addition, the SDST and KAPA functionality will be fully tested, along with K_a-band telecommunications experiments.

The final activity in IC will be to measure the effect of IPS on the spacecraft and the environment. IDS, PEPE, and MICAS data will be used to determine if SEP might interfere with, or even prohibit, the collection of scientifically useful data.

Cruise Phases

There are two cruise phases in the mission: Cruise 1 (C1), covering most of the time to reach the asteroid, and Cruise 2 (C2), spanning the period between the conclusion of the asteroid encounter and the beginning of the Mars encounter. The objectives of the two cruise phases are to achieve the planned thrusting for the trajectory maintenance, and to continue the validations of the technologies. C1 begins on L+41 and lasts about 140 days, concluding 20 days before the asteroid flyby; about 90 days will be dedicated to IPS thrusting along the required vector as updated onboard by AutoNav. C2 begins after the asteroid encounter data are returned in January 1999 and lasts about 440 days, ending 20 days before the closest approach to Mars. The IPS may be used for more than one year during C2.

Extensive validation data on the IPS continue to be collected during routine thrusting, including effects of age and varying heliocentric range (and thus power levels). In addition, dedicated IPS tests (first performed in IC) will be repeated after the thrust arcs in each cruise are completed. The first part of each test will step the IPS through selected throttle levels; the second part will collect data about the effect of the IPS on the spacecraft and its environment, using IDS, PEPE, and MICAS.

During the cruise phases, SCARLET current and voltage measurements begun in IC will continue to be taken every 2 to 4 weeks, to supply performance data over time and insolation range. During the ballistic coast of both cruises, the longer, more complex characterization of the dependence upon pointing relative to the Sun will be repeated. As with the 3 iterations of the IPS tests, the detailed solar array measurements at different times and heliocentric ranges should allow valuable analyses of life and other performance parameters.

The AutoNav modules to collect its optical data should be verified by the 15 or so events during IC. These data are stored and then used weekly by AutoNav in its orbit determination and maneuver calculations only 2 or 3 times during IC. C1 provides further opportunities to downlink and verify the orbit determination and maneuver planning files calculated onboard (orbit determination requires several solutions over time to reduce error). These first maneuver plans calculated onboard are not used to control the IPS; the first required IPS burns are accomplished to attitude and throttle specifications loaded onboard in IC. After the first 3-4 orbit determination and maneuver plans are verified by the operations team, commands will be sent to make the spacecraft use the maneuver specifications calculated onboard instead of the ground-supplied version. Thereafter, fewer onboard AutoNav files will be downlinked, and in normal operations radio navigation may be used only to verify the performance of the AutoNav software in determining the orbit, calculating the required burn parameter updates, and commanding the IPS to perform those burns for the accomplishment of the long IPS thrust arcs in C1 and C2.

MICAS is used throughout cruise to image reference asteroids for the AutoNav system. In addition, occasional repetitions of portions of the MICAS calibration in IC will be performed, using different targets.

The SDST is used for all communications and radio navigation. Downlink and uplink rates will vary with Earth range, providing validation data under over a range of conditions.

The SDST also will be used 4 to 6 times during C1 to generate subcarrier tones for BMOX. These tones will be used to test required ground hardware, software, and procedures using an experimental station at the Goldstone Deep Space Network complex. In addition, BMOX will continue to analyze and summarize spacecraft health throughout cruise.

KAPA will be used 4 to 6 times during C1 to radiate K_a-band telemetry concurrent with X-band telemetry. An attempt will be made to bracket a predicted downlink rate change to gather K_a telecommunications performance data, and other experiments may be conducted for the purpose of studying propagation.

PEPE will be used frequently during IPS thrusting in concert with IDS to provide data on the effect of IPS use on the plasma environment. In addition, PEPE will observe the solar wind during coast and will test for effects of the IPS on solar wind measurements during IPS thrusting.

Throughout both cruise phases, the LPE, PASM, and MFS experiments will continue at daily, weekly, or monthly intervals depending on other concurrent activities and data storage and downlink availability.

Finally, C1 provides an opportunity to uplink and test additional flight software for RAX. This system will receive only high-level goals from the ground; it will schedule the execution times for the activities and expand the activities into commands. The experiment includes a segment in which a MICAS fault will be simulated, thus preventing execution of the plan; the remote agent should detect the fault, recover, replan and resume intended operations within 4 hours. After the two-week technology experiment is completed, the normal spacecraft flight software will be restored.

Encounter Phases

The encounters are defined to begin 20 days before each closest approach, and last 4 or more days after each flyby. These 20 days provide ballistic coast broken only by trajectory correction maneuvers (TCMs), to assure accurate spacecraft delivery to the targets.

AutoNav is responsible for planning and commanding the TCMs on approach to the targets. These are planned to occur at 20 days, 10 days, 5 days, 2 days, 1 day, 12 hours and 6 hours, and 3 hours before the closest approach. The ground will command the TCM opportunity via an uplinked sequence. Upon receiving this command, AutoNav will establish the need for a TCM based on its the system's onboard position and velocity estimates, and execute the TCM if it is needed. The IPS will be used for the initial TCMs, and during the final two days of each approach, AutoNav will command the hydrazine thrusters to be used so that the maneuvers may be accomplished more quickly. MICAS images will provide the data to evaluate the accuracy of the flyby designed and executed by AutoNav.

The three encounters provide unique opportunities for validation of AutoNav, MICAS, and PEPE, as well as for science data acquisition at very different solar system bodies. MICAS will bring all four of its channels to bear on the bodies. PEPE (augmented by IDS) may be close enough to the targets to measure (or constrain) the associated fields and particles, and may also gather solar wind data in the upstream and downstream directions of the target bodies. The requirements for these validations are still under development by the science/instrument validation teams, and will be defined in detail later in 1998 and 1999.

CONCLUSION

As final plans are formulated for the beginning of DS1 operations, it is even now apparent that important progress in validating technologies has already been made by virtue of the work necessary to incorporate them into a space mission. This impetus has provided the technologists key insights into implementation issues that would not typically arise in technology development or conceptual mission studies. Furthermore, spacecraft, mission, and ground engineering teams have begun learning the implications of incorporating these new technologies into their designs (and, of course, taking advantage of the capabilities of the technologies in creating new designs). Thus, some of the benefits of the rapid infusion of these new technologies into spaceflight have already been realized; and any informed user, seeking to benefit from the capabilities of these advanced technologies, now would encounter lower risk and cost by building upon the results of DS1's work to date. The actual execution of the mission is expected to provide many more lessons of value for future spaceflight projects.

ACKNOWLEDGMENTS

The research described in this paper was carried out by the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

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