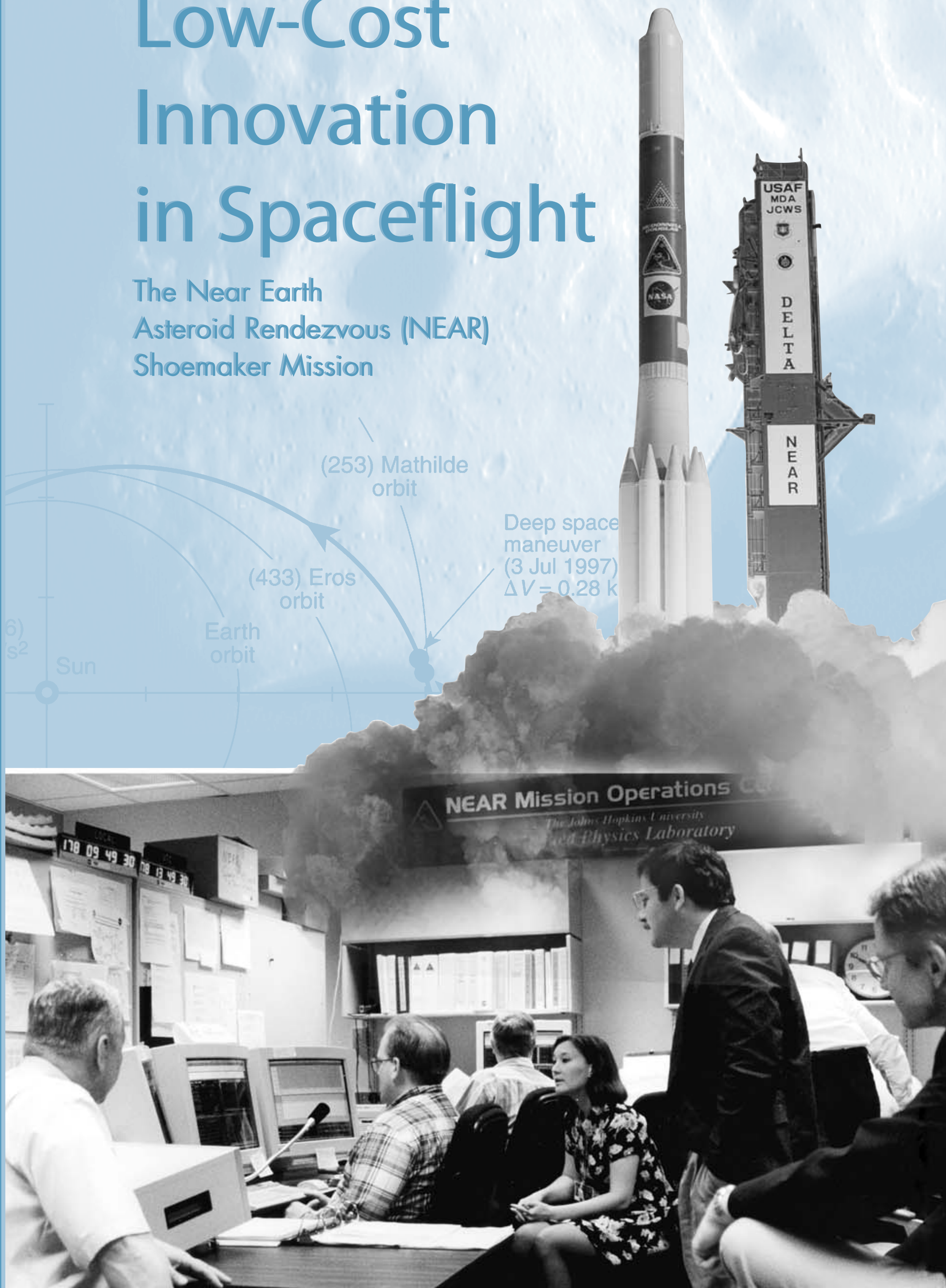
Low-Cost Innovation in Spaceflight

The Near Earth Asteroid Rendezvous (NEAR) Shoemaker Mission



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Cover (from the top): *The cover combines a closeup image of Eros, a photograph of the 1996 launch of the Near Earth Asteroid Rendezvous (NEAR) expedition, and a picture of the mission operations center taken during the second year of flight. NEAR operations manager Mark Holdridge stands behind the flight consoles.*

Asteroid and operations center photographs courtesy of Johns Hopkins University/Applied Physics Laboratory.
Launch photograph courtesy of the National Aeronautics and Space Administration. (NASA KSC-96PC-308)

Howard E. McCurdy

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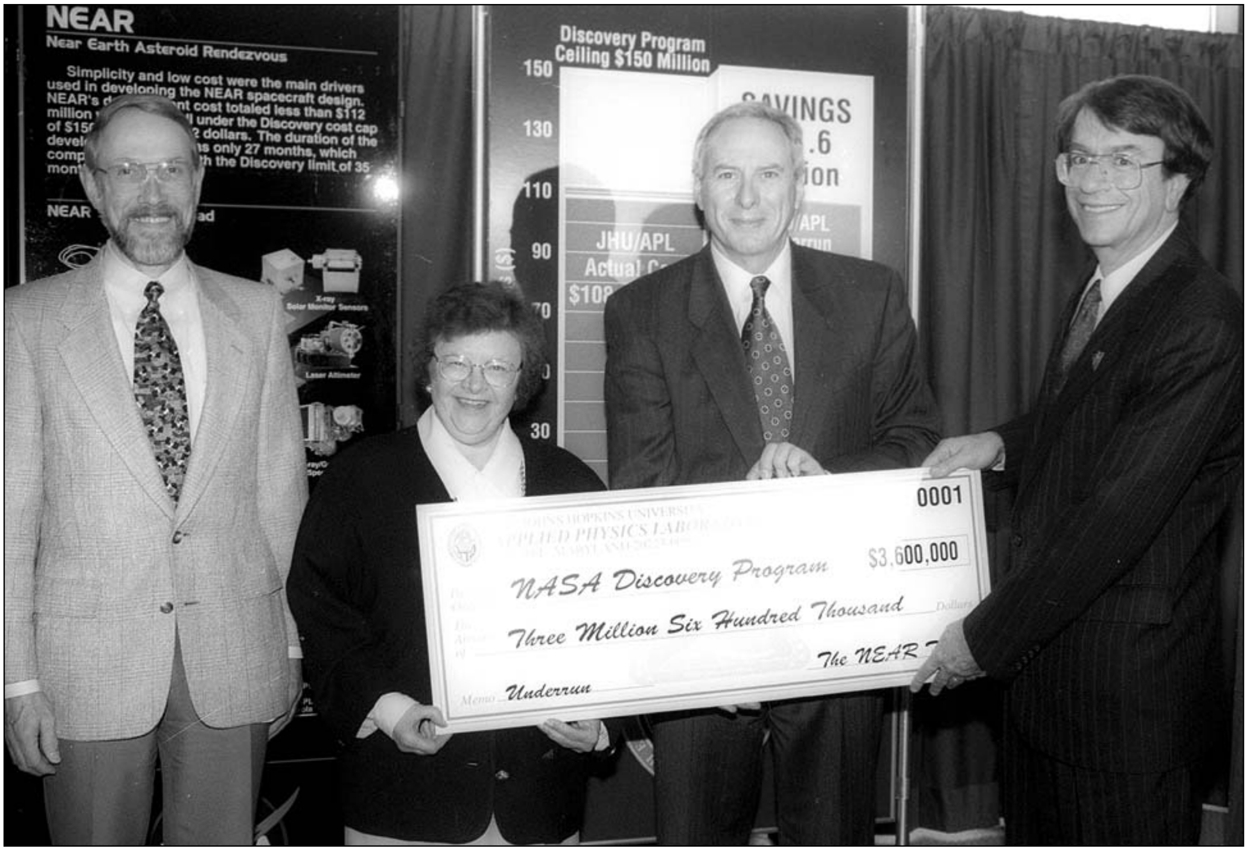
Chapter 1: Challenge

On a spring day in 1996, at their research center in the Maryland countryside, representatives from the Johns Hopkins University Applied Physics Laboratory (APL) presented Administrator Daniel S. Goldin of the National Aeronautics and Space Administration (NASA) with a check for $3.6 million.[1] Two and a half years earlier, APL officials had agreed to develop a spacecraft capable of conducting an asteroid rendezvous and to do so for slightly more than $122 million. This was a remarkably low sum for a spacecraft due to conduct a planetary-class mission. By contrast, the Mars Observer spacecraft launched in 1992 for an orbital rendezvous with the red planet had cost $479 million to develop, while the upcoming Cassini mission to Saturn required a spacecraft whose total cost was approaching $1.4 billion. In an Agency accustomed to cost overruns on major missions, the promise to build a planetary-class spacecraft for about $100 million seemed excessively optimistic.

As a test of the feasibility of their "faster, better, cheaper" initiative, NASA officials had begun funding the Near Earth Asteroid Rendezvous (NEAR) mission in late 1993. They had assigned the mission to the Applied Physics Laboratory, a not-for-profit research and development division of Johns Hopkins University located on a 365-acre campus between Baltimore, Maryland, and Washington, DC. Scientists and engineers from the laboratory's Space Department ran the mission. The Space Department at APL had come into being in 1959 to build navigation satellites for the United States Navy. Although increasingly involved in NASA work, APL scientists and engineers had never managed a major planetary mission. That responsibility commonly fell to the Jet Propulsion Laboratory (JPL), a NASA Field Center in Pasadena, California, operated by the California Institute of Technology.

Officials at the Applied Physics Laboratory spent 27 months designing, constructing, and testing their 468-kilogram (1,032-pound) NEAR spacecraft. On 17 February 1996, they launched the spacecraft from the U.S. Air Force Cape Canaveral



Stamatios Krimigis, head of the Space Department at the Johns Hopkins University Applied Physics Laboratory (right), presents to NASA Administrator Daniel Goldin and Maryland Senator Barbara Mikulski a check representing the cost savings achieved during the design and construction of the NEAR spacecraft. Gary Smith, Director of the Applied Physics Laboratory, stands on the left.

(Courtesy of Johns Hopkins University/Applied Physics Laboratory)

launch station in Florida. The development program was over, the spacecraft launched and gone. APL officials totaled the money spent on design, testing, flight systems, scientific instruments, prelaunch operations, and project management. To the delight of mission advocates, the cost of developing the NEAR spacecraft totaled $3.6 million less than the original estimate. Someone suggested that the project leaders present an oversized, ceremonial check to NASA for the money they had saved. Goldin happily accepted it that spring.

Ten months later, on 4 December 1996, another Delta 2 model 7925 rocket departed from the Canaveral launch station. It too carried a low-cost spacecraft, commissioned by NASA executives but, in this case, built by workers at JPL. This spacecraft was bound for the planet Mars. Called Mars Pathfinder, the second spacecraft carried in its arms a small, 22-pound microrover named Sojourner.

The NEAR and Pathfinder missions were the most visible and highly publicized products of NASA's early efforts to demonstrate the feasibility of low-cost spaceflight. Both missions were hugely successful. The Pathfinder robot landed on Mars in the summer of 1997. NEAR chased the asteroid Eros around the solar system for four years, finally orbiting the 21-mile-long object in February 2000. After circling Eros for one year, the renamed NEAR-Shoemaker spacecraft touched down on the asteroid's surface in February 2001, the first such landing in the history of spaceflight.

Much has been written about the management of the Pathfinder mission, including books by team leaders Brian Muirhead and Donna Shirley.[2] Reports on the NEAR spacecraft, the asteroid rendezvous, and science results are likewise extensive, including a book entitled *Asteroid Rendezvous: NEAR Shoemaker's Adventures at Eros* that features illustrations and articles by many of the principal participants.[3] Reports on the management of the NEAR mission are neither as extensive nor as accessible. This monograph tells the story of the NEAR mission from the point of view of the management challenges involved in conducting low-cost missions while daily confronting the possibility of defeat.

The history that follows is divided into four sections. The first section recounts the origins of the expedition and the struggle to get the mission funded and approved. It explains how a small group of people came to believe that an asteroid rendezvous could be conducted as a low-cost mission, a revolutionary proposition at the time. Section two concentrates on the methods employed to translate the low-cost philosophy into a robotic spacecraft that actually worked. Attention is given to the team-building techniques that allowed the people organizing the mission to simultaneously restrain cost, meet the launch schedule, and reduce risk. In section three, the management challenges involved in flying the NEAR spacecraft over the five-year flight regime are described. The difficulties were substantial, involving the guidance of a low-cost robotic spacecraft and the coordination of mission teams at three different locations. On the first rendezvous attempt with Eros, the little spacecraft missed its target, thus requiring another trip around the solar system and significant changes in organizational protocols. Finally, section four assesses the "faster, better, cheaper"[4] initiative and the NEAR mission's contribution to it.

The scientific returns from the first sustained examination of a near-Earth asteroid were impressive. Equal to them in importance were the management lessons learned. For many decades, visionaries have predicted a future of cheap and easy spaceflight by which means humans and their machines would spread into the solar system. The NEAR mission team undertook one of the pioneering efforts in that regard, producing a spacecraft that tested not only scientific theories concerning the formation of the solar system, but also management theories on the reduction of cost.

In the years that followed, enthusiasm for the "faster, better, cheaper" initiative waned. In 1999, NASA officials lost four of the five "faster, better, cheaper" missions they attempted to fly that year. In 2003, the loss of the Space Shuttle *Columbia* caused experts to question the wisdom of applying cost-saving techniques to spacecraft on which humans fly. The expenses associated with planetary missions rebounded. The "faster, better, cheaper" phrase disappeared, replaced by a commitment to "One NASA," a new initiative with no major references to low-cost innovation.[5]

The legacy of the NEAR spacecraft and the Pathfinder mission with which it once competed nonetheless remain important to the overall development of spaceflight. If humans and their machines enter space on the scale envisioned by various experts, the movement will not occur with ships that each cost billions of dollars to build. As with earlier movements into other realms, ambitious and expensive expeditions will give way to affordable technologies. The early efforts to create low-cost spacecraft contain important lessons for the people who work to make this vision come true.

Chapter 2: Origins

To send a spacecraft to an asteroid, where it could orbit and study the object, required in the minds of most experts a medium-size machine of the Mariner-Observer class. The Mariners were a series of robotic spacecraft, launched between 1962 and 1975, that flew to Venus, Mercury, and Mars. Most of the Mariner spacecraft flew by planets; one orbited its destination. Most of the Mariners were purchased and produced in pairs. Mariners 8 and 9 each had a dry mass (not including fuel) of about 2,200 pounds. Given the value of the aerospace dollar in the late 20th century, when the NEAR spacecraft was produced, each pair of Mariner twins cost an average equivalent of $600 million. That sum paid only for the spacecraft, along with the salaries of the people who designed and built it. To pay for the rockets necessary to launch the spacecraft, to navigate through the solar system, to operate the spacecraft upon arrival, and to collect and analyze the scientific data required even more money. For an entire mission, a Mariner-class spacecraft, in the currency of the late 20th century, could easily approach $1 billion to design, build, launch, and fly.

Observer-class spacecraft continued the Mariner tradition. Although conceived as a new line of spacecraft, only one Observer ever flew. Launched in 1992, Mars Observer was designed to orbit the red planet and study its climate and geology. The robotic spacecraft had a mass of 2,240 pounds at launch, not counting its fuel. Although it was originally conceived as a low-cost mission, project expenses soared until they reached more than $800 million for the spacecraft, its launch vehicle, and the operations team ready to fly the mission and conduct experiments.

The Mars Observer story strongly influenced the debate over whether to undertake an asteroid rendezvous. Stories often form the basis for institutional learning, an important element in the formation of an organization's culture. Employees use stories, presented in a narrative form, in order to make organizational lessons more memorable and transmit the cultural beliefs that remind others of the hard-learned lessons of experience. As a number of scholars and practitioners have observed, stories shape the assumptions that people hold as they go about their work. In the 1990s, no story had more influence on the people planning NASA's planetary program than the one told about Mars Observer.

The facts of the case are these. Space scientists in the early 1980s proposed a series of low-cost robotic spacecraft called Planetary Observers that would be used to explore the inner solar system. Based on the design of Earth-orbiting satellites, the Planetary Observers were to provide an inexpensive means for conducting studies of Mercury, Venus, and Mars. In 1984, the U.S. Congress authorized and funded the first project in this series, then called the Mars Geoscience Climatology Orbiter, later renamed simply Mars Observer. In the beginning, advocates promised to build the spacecraft for the relatively low cost of $252 million.[1] Project scientists and engineers designed the spacecraft so that it could map the surface of Mars, study geologic features, and provide all-season weather reports. They launched the spacecraft in 1992. Actual spending on the project totaled $813 million, measured to the point in the summer of 1993 when the spacecraft approached Mars. At that moment, the spacecraft disappeared.

Mars Observer symbolized the folly of the low-cost philosophy. From the date of its conception, the cost of the mission grew. Even so, the mission failed. People familiar with space missions generally explained the results in the following way. No spacecraft had visited Mars for 17 years, not since the arrival of the Viking mission in 1976. The Soviet Union had attempted two missions but had failed, and the last of the Viking orbiters had run out of fuel in 1980. The pent-up desire of scientists to study Mars led them to attach an ambitious array of instruments onto the Observer spacecraft: a high-resolution camera, a thermal emission spectrometer, a laser altimeter, a gamma-ray spectrometer, a pressure modulator infrared radiometer, a magnetometer/electron reflectometer, and a radio science experiment. This arrangement increased the complexity of the spacecraft, which lengthened the development cycle, which increased the spacecraft cost and mass. A heavier spacecraft necessitated a larger launcher, which amplified launch expenses. The Titan launch vehicle and associated preparations cost $293 million; this amount, added to the $479 million expense of building the spacecraft and the $41 million spent for abbreviated mission operations, totaled $813 million. Had the spacecraft completed its mission, according to one estimate, the total cost would have approached $1 billion.[2]

Speaking of the experience, NASA Administrator Daniel Goldin complained that the cycle of growing complexity and increasing cost fed on itself, producing less frequent missions with ever-expanding appropriations. It was little wonder, he observed, that the space program was losing support among the Congress, the public, and scientists growing old while waiting to fly their experiments:

> Launching fewer spacecraft means scientists want to pile every instrument they can onto whatever's going to fly. That increases the weight, which increases the cost of the spacecraft and the launcher. Fewer spacecraft also means we can't take any risk with the ones we launch, so we have to have redundancy, which increases weight and cost, and we can't risk flying new technology, so we don't end up producing cutting edge technology.[3]

The added complexity of the spacecraft pushed against the desire of government officials to constrain the steadily growing project budget. Increased complexity pushed costs up; NASA's promise to build inexpensive spacecraft pushed costs down. The resulting equilibrium between upward and downward cost pressures created a spacecraft that was a bit too complex for the amount of money allocated to reduce project risk. The risks prevailed. Investigators concluded that difficulties within the plumbing system designed to deliver rocket fuel to the flight engine caused fuel lines to rupture and the spacecraft to spin out of control. Within the context of the story, the loss of Mars Observer in 1993 provided vindication for those who doubted the wisdom of applying a low-cost philosophy to complicated deep space expeditions. The spacecraft cost more than promised, took too long (seven years) to deliver, and did not work.

In the context of the times, scientists and engineers who proposed low-cost planetary expeditions generally were met with incredulity. People would recall the history of Mars Observer and, as two of the advocates of the NEAR mission observed, "everybody knows what has happened to that."[4]

Skepticism ran so deep that some good missions could not get approved. American scientists wanted the U.S. government to send a spacecraft to intercept Halley's Comet, due to return to the inner solar system in 1986. The thought that this would require a Mariner-/Observer-class machine of indeterminable cost caused public officials to abandon the mission. The Russians, Japanese, and Europeans sent spacecraft to visit Halley's Comet, but U.S. officials decided that they could not afford to approve a spacecraft that promised low cost but delivered cost growth.[5]

To propose a low-cost comet or asteroid rendezvous with a Mariner-/Observer-class spacecraft during the mid-1980s or early 1990s invited disbelief from public officials who approved the funds. To suggest that any such spacecraft be made massive enough to actually land on a comet or asteroid invited ridicule. For all its expense and delay, Mars Orbiter could not land on Mars. The only NASA mission to accomplish that objective—the Viking project—had consumed over $3 billion in inflation-adjusted currency. Public officials simply were not prepared to raid the U.S. treasury for the tax revenues apparently necessary to send large, expensive robots to study chunks of rock or ice.

Could it be done for less? For decades, scientists had wanted to visit asteroids and collect samples from comet tails. For much of that time, they had been told that the real cost of Mariner-/Observer-type spacecraft was too high. However, the technical feasibility of such a mission was not in doubt. By 1990, NASA spacecraft had visited all of the major planets, orbited two, and landed on Mars. "The principal issue in late 1989–1990," observed the director of the space department at APL, "was the exorbitant development cost."[6]

Inventing the Discovery Program

Scientists and engineers in the Space Department at APL wanted to move into the field of solar system exploration, a realm previously monopolized by the Jet Propulsion Laboratory. JPL employees specialized in planetary landings and flybys; as of the late 1980s, they were preparing to send the Observer spacecraft to Mars and the Galileo spacecraft to Jupiter. Rather than challenge JPL in their traditional area of emphasis, APL employees turned to the realm of comets and asteroids.

Comets and asteroids are the building blocks out of which the planets probably formed; by striking more massive bodies, they altered the characteristics of larger spheres and, in the case of Earth, redirected the evolution of life. As primitive building blocks, asteroids and comets contain clues to the formation of the solar system and the transportation of substances that give rise to life. They contain metals and other resources of potential value to future civilizations on Earth and in space. If humans maintain their terrestrial civilization long enough, they will need to redirect the course of large comets and asteroids that would otherwise strike the planet with catastrophic results. For these reasons and more, a special advisory committee in 1983 had urged NASA officials to include an asteroid rendezvous in their long-range plans. Such a mission, the Solar System Exploration Committee had proposed, might be launched in the 1990s using a spacecraft similar to the one that JPL employees were aiming toward Mars—the Mars Observer.[7] Responding to the expectation that they would be asked to direct such a mission, engineers at JPL studied the technical requirements and concluded that an asteroid rendezvous mission was feasible with a spacecraft of the Observer's size.

The Jet Propulsion Laboratory sits on a 177-acre, campus-like setting adjacent to the San Gabriel Mountains, just northwest of downtown Pasadena, California. JPL was founded during the Second World War by a group of professors, students, and associates from the nearby California Institute of Technology who perceived that the U.S. Army would pay for a research laboratory devoted to the development and testing of small rockets. When the space race began, Congress transferred the operation to the newly created National Aeronautics and Space Administration. Although listed as a NASA Field Center, JPL retains an unusual status: it is operated through the California Institute of Technology, one of the nation's leading science and engineering universities.

At the other end of the country, the rival APL sits in its own university-like setting, a bucolic campus twice as large as the main Johns Hopkins University campus 25 miles north of APL. Like JPL, APL was created during the Second World War by a group of university associates seeking to assist with the war effort. JPL was created to assist the U.S. Army; APL helped the U.S. Navy. JPL workers developed jet-assisted aircraft takeoff; APL scientists developed the proximity fuse. JPL is listed as a NASA Field Center; APL is not. Both laboratories are associated with major research universities.

Armed with the results of the JPL feasibility study, mission proponents assembled a Science Working Group to advance the concept. To chair the group, they chose Joseph Veverka, a professor from the Cornell University Department of Astronomy. When he was young, Veverka's family fled his native Czechoslovakia to avoid the communist takeover. The family settled in northern Ontario, where the brilliant night skies inspired Veverka to study physics and astronomy. Veverka had been involved in nearly every solar system exploration project since NASA built Mariner 9, when he was a doctoral student at Harvard University. He was an early advocate of comet and asteroid exploration.

Veverka's group met through 1985 and identified a suitable target, a kilometer-wide body known as asteroid 3361 Orpheus. The elliptic orbit of Orpheus causes it to cross Earth's path as both bodies travel around the Sun. Orpheus is a favored target of space enthusiasts who would like to mine it for hydrogen, oxygen, and building materials. Veverka's group wanted to visit it. Group members prepared a list of essential instruments to be flown on a robotic spacecraft and recommended a 1994 launch. The working group was dominated by JPL employees, with whom Veverka had worked on the Mariner, Viking, and Voyager projects. Significantly, no representatives from APL appeared among the outside members. The working group gave the project a name: Near Earth Asteroid Rendezvous (NEAR).[8]

Veverka reappeared in the summer of 1989 at a workshop organized by NASA's Solar System Exploration Division. NASA officials had established a series of workshops to seek advice and gather support for a broad range of solar system exploration activities through 2000. The key workshop took place at the University of New Hampshire from 26 to 30 June 1989. Veverka chaired the plenary session in which a small group of scientists made a radical proposal for a new initiative in low-cost spacecraft.

Up to that point, participants had assumed that any new initiative for a low-cost planetary mission would involve an Observer-class spacecraft. By 1989, however, Mars Observer was well over budget and behind schedule. The desire for low-cost planetary spacecraft that could be prepared in short periods of time clashed with the lessons from Mars Observer. As part of the workshop, a special Small Mission Program Group was asked "to construct a rationale for a new mission line that would be low-cost and provide a mechanism whereby focused scientific questions could be addressed in a relatively short time." The initiative, Veverka recalled, "was greeted with widespread skepticism."[9]

Stamatios Krimigis did not share the overall sense of disbelief. A 21-year veteran of APL, Krimigis was the Chief Scientist in the lab's Space Department. Krimigis was born and raised in Chios, Greece, immigrating to the United States to study physics at the University of Minnesota. After earning his bachelor's degree, he enrolled at the University of Iowa, where he studied under the notable James Van Allen, famous for building the scientific instruments on the first U.S. Earth-orbiting satellite that discovered the radiation belts bearing his name. Krimigis wrote his dissertation on solar protons and received his doctorate in 1965. Like Veverka, who would become Chair of the Astronomy Department at Cornell University, Krimigis eventually would become head of the Space Department at APL. Both were highly intelligent individuals accustomed to the academic process of drawing consensus from equally gifted and often irascible colleagues.

Krimigis suggested that the Small Mission Program Group not use Mars Observer as the basis of its quest for low-cost solar system exploration. Rather, he pointed to "a long standing NASA program called Explorer that had served the needs of the space physics community and had provided relatively easy access to space."[10] Explorer-class spacecraft are among the most versatile and inexpensive that the U.S. has launched. The first U.S. satellite sent into orbit was Explorer 1, launched even before Congress had finished work on the legislation creating NASA. It consisted of a spacecraft and upper stage designed by JPL, a launch vehicle prepared by Wernher von Braun and his German rocket team, and an experiment designed by Krimigis's mentor at the University of Iowa.[11] The Explorer 1 mission was developed in an incredibly short period of time. The Von Braun-JPL-Van Allen team organized the mission in just 84 days before its 31 January 1958 launch.

Between 1958 and 1981, civilian space officials organized some 60 Explorer-class missions. Most were designed to study phenomena like the solar wind, cosmic rays, and Earth's magnetosphere. The exact number of missions is hard to identify because Explorer-class missions often bear names like Vanguard, Ariel, and Boreas, and some satellites named Explorer (such as the Cosmic Background Explorer) are too large to fit the category. Strictly speaking, Explorer-class satellites are small and uncomplicated. Explorer 1 had a mass of just 22 pounds, while later versions (like Explorer 58) totaled about 250 pounds. With the advent of the Space Shuttle in 1981, rated to carry up to 65,000 pounds, the number of small Explorers declined in favor of larger, multipurpose (and hence more expensive) platforms.

At the time of the 1989 workshop, Krimigis was working on a concept called the Advanced Composition Explorer (ACE). This spacecraft, eventually launched in 1997, was designed to fly one million miles from Earth and study the solar wind. The spacecraft would have a mass of 1,300 pounds, small for such a distant traveler. Krimigis predicted that the ACE spacecraft would be built for less than $100 million. It would be designed and assembled using a simple management model, he added, in which a single Principal Investigator oversaw the development of the spacecraft and each of the lead investigators provided their own scientific instruments.

Geoffrey Briggs, head of NASA's Solar System Exploration Division, listened intently. He approached Krimigis after the presentation and asked if APL would be willing to turn the concept of an Explorer-type spacecraft into a proposal for a specific mission. APL employees could make such a proposal, and Briggs would appoint a Science Working Group to review it, along with other proposals. Briggs established a Science Working Group and asked Robert A. Brown, who had chaired the panel from which the Krimigis proposal had emerged at the 1989 workshop, to chair the group. The oversight group met in 1989 and 1990. Its members did not recommend a specific mission, but they did propose a name for the overall concept of low-cost initiatives: they called it the Discovery Program.

In 1990, Wesley Huntress replaced Briggs as head of the Solar System Exploration Division at NASA Headquarters. Huntress had spent nearly 20 years as a research scientist at JPL, where, in spite of the general preference for large planetary missions, he had developed a commitment to the reduction of cost. Among his scientific interests, Huntress specialized in asteroids and comets. Huntress reorganized the Science Working Group, requesting that they select a mission and test the feasibility of the low-cost approach. As part of the reorganization, Huntress selected a new chair for the Science Working Group. He asked Joseph Veverka to chair the group; Veverka agreed.

Selecting a Mission

Reducing cost while improving performance is difficult, but not impossible. As the history of the electronics and computer industries suggests, this goal requires someone to design machines that are smaller and easier to operate. The replacement of vacuum tubes with transistors, for example, allowed industrialists to design radios that worked better and cost less. One elementary measure of the operational complexity of spacecraft can be derived by examining the number of moving parts. On Mars Observer, for example, the solar panels moved. So did the high-gain antenna. The overall complexity of Mars Observer resulted in a spacecraft with a mass of 2,240 pounds at launch, excluding propellant. A 2,000-pound mass was characteristic of the Mariner-/Observer-class spacecraft.

Explorer-class spacecraft might have one-eighth that mass, but they were not designed for planetary missions. If clever engineers could cut the mass of a spacecraft designed for Mariner-/Observer-type missions by 50 percent, to about 1,000 pounds, they had a fighting chance to produce a machine that could be produced for less than $150 million. For the Mars Observer mission, the spacecraft alone cost $479 million. The Veverka group set as its goal the production of a spacecraft whose total development cost did not exceed $150 million. As the Discovery Program emerged, additional constraints appeared. The total cost of operating the spacecraft, once launched, could not exceed $35 million, and the spacecraft had to be small enough to fit on a rocket no larger than a Delta II, which, in the 1990s, cost about $55 million per launch.[12]

At the Maryland laboratory, Stamatios Krimigis assembled his staff and appointed a small group to study the NEAR concept. The group contained old-timers and youngsters, people from both inside and outside the Lab. Krimigis appointed himself as the lead scientist. He selected Robert Gold to study the instrument package. Gold, a physicist with 10 years of experience in the field of remote sensing, had joined APL in 1977 and had served as the lead investigator for two of the instruments on the ACE spacecraft. Krimigis asked Edward Reynolds to serve as systems engineer. A relative newcomer, Reynolds had joined the Lab in 1985, performing systems integration work on complex nuclear electric propulsion and strategic defense radar programs. Andrew Cheng, a young physicist who had completed his doctorate just three years earlier, agreed to serve as the chief scientist. Cheng had served on a number of NASA advisory committees but was not a member of the APL staff at that time. To study the mission design, Krimigis recruited Robert Farquhar, a brilliant aeronautical engineer with 30 years of experience in the field. Farquhar had spent most of his career at NASA and was in the process of moving to APL. As the study manager, Krimigis selected Thomas Coughlin, a soft-spoken mechanical engineer. Coughlin had joined APL in 1982 and participated in several low-cost, fast-track Strategic Defense Initiative programs, including the renowned Delta 181 project on which he had served as the program manager.

To make the mission worthwhile, the group insisted that the spacecraft carry at least two instruments, a multispectral imager and a gamma-ray spectrometer. A multispectral imager is a sophisticated camera, while a gamma ray-spectrometer senses the composition of objects under study. "We hoped we could eventually accommodate more instruments," said Andrew Chang, "but in the beginning we committed only to those two."[13]

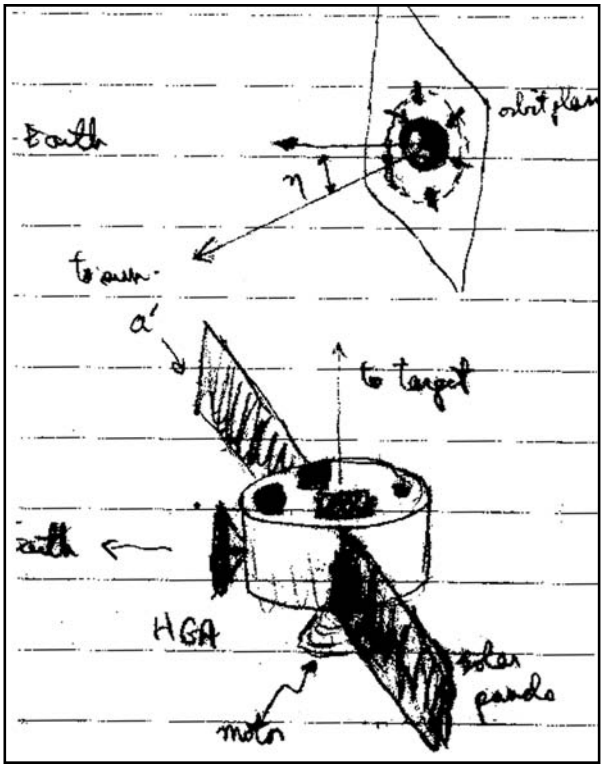
The instruments were relatively light—just 60 kilograms in the group's original proposal. The major challenge confronting the team concerned the design of the main spacecraft. The machine had to be sophisticated enough to deliver the instruments on what would be a multiyear voyage without busting the $150-million development goal.

On the other side of the country, in California, a similar group studied the problem on behalf of JPL. Unlike the people at APL, the JPL team worked at a facility with no extensive tradition of low-cost exploration. The cost of JPL planetary projects typically approached or exceeded $1 billion; the upcoming Cassini mission to Saturn would top $3.3 billion. The two teams appeared before the Veverka working group in May 1991. They met in Pasadena, California, home ground for JPL. The two teams, observed Krimigis, "had reached startlingly different conclusions."[14]

"It is improbable," JPL team members explained, that a near-Earth object rendezvous could be carried out for less than $150 million, even with a simple, no-new-technology machine.[15] To escape this improbability, the JPL team made an intriguing suggestion. By building and flying three spacecraft, team members observed, the cost of the funds assigned to the first spacecraft could be set at $150 million. The funds assigned to the second and third spacecraft would be slightly less: $149 million and $137 million, respectively. Total cost, the team explained, would be $436 million.[16]

This was an ingenious approach, a means to produce a Mariner-/Observer-class spacecraft that, on the cost accounting sheets, looked like something less. The JPL team sought to take advantage of the cost benefits inherent in a production line while reaping the accounting benefits produced by assigning project expenses to three separate but interdependent missions. The incremental expense of producing a second and third spacecraft relative to the first is typically small, an advantage the JPL team sought to exploit. On the Viking project to Mars some 15 years earlier, the incremental cost of not producing a third lander amounted to only $20 million out of a total spacecraft development budget of $357 million. The JPL team could conduct one flight for $150 million, but that approach was premised on the need to retrieve lost ground during the two flights that followed.

The JPL estimate of $436 million paid for the spacecraft only. Three rockets at probably about $50 million each would be needed to launch the three spacecraft. Operations and data analysis for



Officials from the Applied Physics Laboratory prepared this sketch in early 1991 to demonstrate how a simple spacecraft might carry out an asteroid rendezvous at a very low cost.

(Courtesy of Johns Hopkins University/Applied Physics Laboratory)

three missions could easily reach $50 million or more. Although the JPL team gave no total mission estimate, one can surmise that the overall cost would top $600 million. Such an amount approached the $813-million sum that JPL officials were spending at that time on Mars Observer, which would be launched the following year.

Members of the APL team rose to explain their approach. Tom Coughlin directed the presentation. The group's proposal, to say the least, was quite different. "The great pleasure in life is doing what people say you cannot do,"[17] team member Robert Farquhar later observed. In January, the APL team had prepared a sketch outlining a concept for a remarkably simple spacecraft. The drawing showed a cylindrical spacecraft shaped like a large tuna can. A high-gain antenna was fixed to the side of the cylinder, pointing toward Earth. Instruments were fixed to what appeared as to be the top of the spacecraft, pointing toward the target asteroid. A rocket motor was fixed to the other end; solar panels were fixed to the side. Said Cheng:

> Based on the positions of the Earth, the Sun, and the target asteroid (Anteros, at that time), we convinced ourselves that NEAR could be configured with a fixed high gain antenna, fixed solar panels, fixed instruments with a common boresight orthogonal to the antenna axis, and a rocket engine thrusting opposite to the instrument boresight. With this simple spacecraft, we could accomplish all the science objectives of the mission.[18]

The APL team agreed that they could build such a spacecraft with a dry mass of no more than 430 kilograms (946 pounds). Their actual calculations totaled 363 kilograms, plus a 67-kilogram reserve. On top of that, they added a 200-kilogram allowance for fuel. The group's ability to accomplish the mission with such a spacecraft depended upon a complex relationship among the spacecraft mass, the lifting power of a Delta 2 launch vehicle, various launch window opportunities, clever flight trajectories, and the energy required for the changes in velocity necessary to maneuver the spacecraft to its destination. The group was reasonably certain that their design could "accommodate all the tar-

Table 2-1

Mass Summary

Instruments	60 kg
Propulsion	57 kg
Power	60 kg
RF	29 kg
Attitude	25 kg
C & DH	29 kg
Thermal	12 kg
Harness	18 kg
Structure	73 kg
Dry Mass	363 kg
	18.5% Contingency (430 kg)
Fuel	200 kg
TOTAL MASS	563 kg

Source: *Johns Hopkins University APL, "Near Earth Asteroid Rendezvous" (report to Discovery Science Working Group, NASA Solar System Exploration Division, May 1991).*

geted missions . . . based on Delta II performance, launch window considerations, and mission requirements such as the maximum velocity changes that the spacecraft engines could perform."[19]

An accompanying chart laid out the spacecraft development schedule. If the project were approved soon, in 1991, detailed design and fabrication could be completed in four years. The spacecraft would be ready for launch in May 1997. The schedule, one APL study group member admitted, was "extremely aggressive."[20] Finally, the APL group agreed that they could design and construct the spacecraft for less than the $150 million target price set by the Veverka group. In fact, they offered to build the spacecraft for $40 million less—a mere $110 million.[21]

Andrew Cheng remembered a general reaction of "not so much skepticism as amusement."[22] A group of people with little experience in conducting planetary missions was offering to build a simple spacecraft and fly it millions of miles to an object of limited size. Moreover, members of the group said that they could build and test the spacecraft in less than four years and for less than $150 million. "The reviews were mixed," said one of the people attending the meeting. Many expressed disbelief that such a mission could be done.[23] Although officials in the APL Space Department had a good record of delivering low-cost projects on time, space projects within NASA as a whole were experiencing substantial cost overruns—an average of 77 percent over original estimates, according to a study completed a few years later.[24] The people reviewing the two proposals did not want to approve a low-cost project and then watch its cost grow once work began.

Joseph Veverka, the Cornell astronomer heading the reviewing board, was intrigued by the APL proposal. He had ties to JPL but favored the low-cost approach. Cheng recognized that "if we could succeed in this approach, we had a winning concept."[25]

The leadership at JPL viewed the potential for competition from APL with great concern. JPL executives considered themselves to be part of the world's leading institution for planetary exploration. APL was not, yet its leaders wanted to compete for voyages to comets, asteroids, and (they would later admit) planets like Pluto and Mercury.[26] JPL executives had competed with NASA's Ames Research Center in northern California and prevailed; they did not welcome new competition from APL.

Edward Stone, the new Director of the Jet Propulsion Laboratory, told his people to rework their concept. One month later, they responded. With a small "team of believers," the JPL team reported, "a $150 [million] discovery project is achievable at JPL." They were ready to start work on an asteroid rendezvous mission immediately. "We have the experience, capability and desire to manage this Discovery project," the report said.[27]

The study team's new position was less significant than the name of the person making the presentation. JPL executives assigned A. J. "Tony" Spear to present the new findings. Spear wanted to challenge the traditional JPL culture, then absorbed with the Cassini mission to Saturn, by moving the Center toward smaller and less expensive missions. At the time, he and other dissidents were pressing for a series of very low-cost spacecraft that would establish a network of environmental monitoring stations across the planet Mars. The concept was called the Mars Environmental Survey (MESUR). Its advocates envisioned a network of 16 spacecraft, the equivalent of meteorological posts, placed at various locations. To land such a large number of spacecraft on such difficult terrain required revolutionary technologies and severe cost constraints.

On 17 June 1991, Spear issued his presentation to the Veverka group on behalf of a JPL asteroid mission. Veverka reported to Wesley Huntress, who, like Veverka, had spent much of his career working with people at JPL. The asteroid mission was based on the proposal of a 1985 Science Working Group that had been dominated by JPL employees. JPL had more experience in flying planetary missions, but APL had a better track record with low-cost missions.

Regaining the Lead

The Veverka group issued its report the following fall, in October 1991. The group members endorsed the concept of a Discovery Program designed to encourage low-cost exploration of the solar system. According to the guidelines, each mission in the Discovery Program would cost no more than $150 million, perhaps less, for spacecraft design and development. For the first mission in the program, Veverka's group recommended an asteroid rendezvous. Although the group members left the selection decision to NASA, their recommended guidelines contained the essential elements of the APL plan.

"The first mission of the Discovery Program should be a rendezvous with a Near-Earth asteroid," the group began. The most suitable destination was asteroid 1943 Anteros, the target for which the APL team had been planning. The Veverka group recommended that the spacecraft carry three instruments, including an imaging device, and be small enough to launch on a low-cost Delta 7925 rocket. The latter imposed a severe constraint. To assess whether a spacecraft can complete its mission, planners calculate all of the changes in velocity (called ΔV) necessary for the vehicle to leave its low-Earth parking orbit, move through space, rendezvous with its destination, and complete its mission. Generally speaking, a higher ΔV requires a larger, more complex (and hence more expensive) mission. The constraints imposed by the Veverka group limited the mission to velocity changes totaling no more than 5.5 kilometers per second (12,296 miles per hour).

Including the boost necessary to move the spacecraft out of low-Earth orbit, mission planners could expect to make more than 50 velocity changes to reach and study a near-Earth asteroid. Most proposals for asteroid rendezvous missions called for total velocity changes in excess of 6 kilometers per second. Reducing that sum required a small spacecraft and a clever trajectory, exactly the approach that the APL team said they could carry out.[28] The APL team calculated that they could reach Anteros with a total ΔV not exceeding 5.35 kilometers per second.[29]

Simultaneously, in a show of support for the concept, members of the Senate subcommittee that handled NASA's budget directed the Agency to prepare a plan "to stimulate and develop small planetary or other space science projects." The subcommittee was headed by Senator Barbara Mikulski, who represented the state of Maryland. Mikulski was a strong supporter of the work of the Maryland-based laboratory. The committee report in which this language appeared urged NASA officials to emphasize projects "which could be accomplished by the academic or research communities," a way of saying that institutions like APL should be given a chance to play.[30]

On 1 April 1992, NASA acquired a new Administrator, Daniel S. Goldin. As an industry executive, Goldin had been an advocate of small, low-cost spacecraft. The White House assistants who selected him wanted someone who could reverse NASA's partiality for large, expensive missions. Goldin had participated in the Brilliant Pebbles initiative, a plan to mass-produce inexpensive orbital sensors that could detect a missile attack with bullet-proof precision. Once Goldin arrived at NASA, he found that the realities of fiscal retrenchment supported his position. The Agency simply could not afford expensive new initiatives. Goldin set out, in his own words, to "re-invent NASA":

> Let's see how many [spacecraft] we can build that weigh hundreds, not thousands, of pounds; that use cutting-edge technology, not 10-year-old technology that plays it safe; that cost tens and hundreds of millions, not billions; and take months and years, not decades, to build and arrive at their destination.[31]

Shortly after arriving at his new job, Goldin discovered the fledgling Discovery Program. He was very impressed. He called it "the world's best kept secret" and became one of its prime advocates.[32] Pushing from the top, he challenged NASA employees to cut mission costs. Build smaller spacecraft, he urged Agency employees. Make cost control as important as scientific discovery. Take chances, he said. "A project that's 20 for 20 isn't successful," he observed. "It's proof that we're playing it too safe."[33]

Shortly after Goldin assumed leadership of the civil space agency, officials in NASA's Office of Space Science and Applications unveiled their "Small Planetary Mission Plan." As expected, it embraced the low-cost approach that people in the Solar System Exploration Division had been studying for nearly three years, since the 1989 summer meeting in New Hampshire. "Two years ago, small planetary missions were just beginning to be discussed by the scientific community. Today they are the centerpiece of NASA's new programs for the 1990s." The report announced the Agency's intent to promote a new program called Discovery that would produce a series of small, cost-effective spacecraft "modeled on NASA's existing Explorer and Earth Probe programs," just as the APL team had proposed.[34]

To the shock of the APL team, however, the report did not recommend an asteroid rendezvous mission as the first Discovery project. Rather, the first flight award went to Tony Spear and the JPL team promoting MESUR. Spear's group promised to launch the first spacecraft in the MESUR series by the end of 1996, thus providing an earlier test of the low-cost concept than would be possible under the APL proposal for a 1997 launch to the asteroid Anteros. While government officials never approved the whole MESUR concept, they did authorize the first spacecraft. It was called Mars Pathfinder. Tony Spear served as the project manager for the Pathfinder mission as the spacecraft was designed and built.

What about the NEAR mission? It was a "second concept under study," according to the authors of the small planetary mission plan.[35] Under the terms suggested by Veverka's Science Working Group, the NEAR spacecraft would be launched in May 1997 as the Pathfinder spacecraft approached Mars. Within a few months, that launch date had slipped to 1998. The later launch date necessitated a new target—the asteroid known as 4660 Nereus.[36] Compared to Anteros, Nereus was a less interesting target. It was comparatively puny, just 1 kilometer in diameter. Members of the NEAR team worried about the change. "Although Nereus satisfied all the requirements for a Discovery-class mission," three of them wrote, "some scientists were concerned that its small size could restrict the quantity and diversity of the science return." Put another way, the three observed, the results would be "somewhat boring."[37] As the Pathfinder expedition gained momentum, the asteroid rendezvous project slipped away.

A few people had different ideas, and none were more outspoken in promoting their alternatives than Robert Farquhar. A mischievous, distinguished-looking gentleman, Farquhar had a reputation as an expert in celestial navigation and as something of an eccentric. "The man is a genius with celestial pinball," said one of his colleagues, "and he'd be the first to admit it."[38]

As a civil service employee at NASA's Goddard Space Flight Center in Maryland, Farquhar had participated in the International Sun-Earth Explorer-3 (ISEE-3) mission as its overall flight director. This otherwise inconspicuous satellite made spacecraft history when Farquhar invented a trajectory that allowed it to beat the Europeans, Russians, and Japanese to the first encounter with a comet. Following Farquhar's plan, flight controllers nudged the ISEE-3 spacecraft out of the L-1 libration point where it was conducting its mission and allowed it to fall toward the Moon. Arthur C. Clarke, the famous science fiction writer, called the resulting maneuver "one of the most remarkable feats of astrodynamics ever attempted." Following a path that looked like the curled ribbon on a child's birthday present, the spacecraft received a gravitational boost each time it flew by the Moon. "This maneuver was repeated no less than five times; on the last flyby, the probe skimmed only a hundred kilometers above the moon, and the slightest navigational error could have been disastrous,"[39] wrote Clarke. The lunar maneuvers, consisting of incredible twists and whirls, took 18 months to complete and eventually pointed the ISEE-3 spacecraft in the right direction to complete a nearly two-year journey to the comet Giacobini-Zinner.[40]

Farquhar's ultimate boss at the Maryland installation, Goddard Center Director Noel Hinners, characterized him as "a very bright, very innovative guy." Said Hinners: "I would like to have five more of him around here—not 100, we couldn't handle that."[41] Farquhar is something of a maverick, an outsider prone to irritating people less innovative than he. "He's an idea man," observed fellow research scientist Donald Yeomans. "He'll have 100 ideas, 99 of which may not be reasonable. But that last one is a beaut. And he does this routinely."[42]

The launch window for any asteroid rendezvous was dictated by the position of the target asteroid relative to Earth and the energy constraints imposed on a low-cost mission. In a 1991 paper, Farquhar had identified asteroid Anteros as the best of the rendezvous candidates, based on launch opportunities (in 1997), flight time (415 days), and velocity change requirements (5.35 kilometers per second), a conclusion endorsed by the Veverka group. In the same paper, Farquhar noted that a spacecraft launched in 2003 with the assist of an Earth swingby could reach the asteroid Eros by 2005 while flying by Encke's comet on the way. Eros was especially interesting, Farquhar noted, because it was the largest near-Earth asteroid.[43] Nereus is a mere kilometer wide, while Eros has a mean diameter 20 times that large.

Farquhar reexamined his calculations. A spacecraft could reach Eros at the end of what he called a "small-body grand tour" of two comets and two asteroids.[44] This approach allowed an earlier launch date in 2000, but the spacecraft would not reach Eros until 2012. Farquhar performed the calculations again and again. Eros, he noticed, was positioned in such a way that a launch in early 1996, when coupled with an Earth flyby, could place a spacecraft at the asteroid in about three years. It was a long flight, but the energy requirements worked. It could be accomplished with velocity changes that totaled just 5.53 kilometers per second, substantially less than those required by other Eros opportunities. Significantly, the February 1996 launch window allowed the APL team to beat the Pathfinder group to the launch pad by 10 months. The Pathfinder spacecraft would arrive at Mars long before NEAR reached Eros, but Farquhar also had a solution for that problem. By adjusting the NEAR flight path, the APL mission team could achieve an asteroid flyby on 27 June 1997, one week before Pathfinder reached Mars. The arrival date at Eros was unchanged, but the June flyby would give scientists a first quick look at a large, 61-kilometer-wide, carbon-rich asteroid.

With this mission plan, the NEAR project could be first again. Farquhar took the plan to Stamatios Krimigis, head of the APL Space Department since early 1991, who called it an "exciting opportunity."[45] Together, they transmitted the proposal to NASA officials in Washington, DC.

To make the mission work, Congress had to appropriate funds to start the project immediately, in 1993, as part of the appropriations bill for the fiscal year ending in 1994. In the winter of 1993, NASA executives asked Congress for funds to start both the NEAR and the Pathfinder projects. In the House of Representatives, where voting is apportioned by population, lawmakers appropriated funds for the California-based Pathfinder mission but refused to start funding the Maryland-based asteroid rendezvous.

In the Senate, where each state receives equal representation, Maryland is as big as California. Though diminutive in stature, Barbara Mikulski was a large presence on the Senate Appropriations Committee. With a small amount of help from APL executives, Mikulski placed $62 million in NASA's appropriation bill for the purpose of starting the Near Earth Asteroid Rendezvous project. In the conference committee negotiations that followed, Mikulski prevailed.

On the grounds of the Maryland laboratory on 5 December 1993, Senator Barbara Mikulski, Stamatios Krimigis, Wesley Huntress, and APL Director Gary Smith announced that APL would begin work on a Near Earth Asteroid Rendezvous. It would be the first launch in NASA's new Discovery Program of "faster, better, cheaper" spacecraft, the first mission to rendezvous with an asteroid, the first U.S. planetary-type mission conducted by a non-NASA space center, and "a significant economic milestone for Maryland."[46] The mission would be launched in February 1996 on a Delta 2 rocket and would arrive at Eros, a subsequent NASA announcement explained, in late December 1998.

When the celebration died down, the newly assembled members of the NEAR spacecraft team confronted a sobering reality. They had to deliver a flight-ready, fully workable spacecraft to the Florida launch site by December 1995, just 24 months away. "This was an unprecedented timetable for developing a planetary mission," said team leader Thomas Coughlin—a severe test of the concept that a planetary expedition could be put together cheaper, better, and faster, too.[47]

Chapter 3: Spacecraft

The Applied Physics Laboratory team won approval to begin work on the Near Earth Asteroid Rendezvous mission in late 1993. Gaining approval for the project had been difficult; creating the spacecraft would be harder. Members of the team had to design, build, and test a robotic spacecraft that actually worked—and do so within the cost and schedule constraints they had set for themselves. The mid-February 1996 launch window sat just 26 months away, an impossibly short period of time for the preparation of a planetary-type expedition. The $214.5 million that NASA officials planned to spend on the entire mission (spacecraft, launch vehicle, and flight operations) was considerably less than teams normally devoted to ventures of this sort. As the first launch in NASA's new Discovery program, the mission would be subjected to extensive scrutiny by both supporters and skeptics of the low-cost approach. In outer space, the conceptual philosophy underlying this "faster, better, cheaper" project would be tested against the unyielding reality of physics.

As a point of contrast, the mission team working on the Mars Observer spacecraft, launched in 1992, had spent seven years preparing their spacecraft after their official funding start. The Mars Observer team had devoted $479 million to spacecraft development. Even counting the months since the May 1991 presentation to the Discovery Science Working Group, the NEAR team had given themselves significantly less time. Additionally, the NEAR team had promised to finish the first phase of the project—construction of the spacecraft—for a paltry $122 million, a considerable commitment to the low-cost philosophy. (See table 3-1.)

Nor were they building an ordinary spaceship. The NEAR spacecraft would fly much further than Mars Observer, all the way into the asteroid belt between Jupiter and Mars. No spacecraft had ever flown that far from the Sun with nothing to generate electric power but solar arrays. (Missions beyond Mars typically carry radioisotope thermoelectric generators, enlarging project expense.)

Table 3-1

Planned Cost of NEAR Mission
(in millions of real-year dollars)

Mission Elements	Cost
Spacecraft	122.1
Mission operations after launch	46.2
Headquarters support	2.7
Launch vehicle	43.5
Total mission cost (planned)	**214.5**

Source: *Applied Physics Laboratory, "NEAR Mission Plan vs. Actuals ($M)," undated, folder 8722, NASA Headquarters Historical Reference Collection, Washington, DC.*

When it arrived at its destination, the spacecraft had to enter an orbit around an object possessing little mass. The spacecraft team would need to fly the tiny spacecraft around the asteroid in orbits of ever-decreasing altitude, skimming over the surface without crashing into it.

During the 1990s, NASA officials commissioned a substantial number of planetary and solar system missions. Based on the funds devoted to the development of the spacecraft, NEAR sat near the bottom of that list. (See table 3-2.) Among major solar system initiatives, including other "faster, better, cheaper" missions, only Mars Climate Orbiter sat lower on the scale of money devoted to spacecraft development, and it had failed.

Table 3-2

Selected Spacecraft Development Costs *(in millions of real-year dollars)*

Spacecraft (Launch Date)	Cost (Actual)
Cassini (1997)	1,422
Mars Observer (1992)	479
Pathfinder (1996)	200
Mars Global Surveyor (1996)	131
Stardust (1999)	127
Near Earth Asteroid Rendezvous (1996)	113
Mars Climate Orbiter (1998)	80 (est.)

Source: *NASA, "Fiscal Year Budget Estimates" (annual issues as indicated). Issues from FY 1987 through FY 1994: Planetary Exploration section; issues FY 1997 through FY 2002: Special Issues section, Major NASA Development Programs, Program Cost Estimates. Reports can be found in the NASA Headquarters library.*

Had the NEAR team taken on too much, promising to build and test a spacecraft too rapidly with too little money? Team leaders were confident they had not. They did not believe that they had taken on a task that would prove too fast or too cheap. They planned to draw upon more than 30 years of experience in managing low-cost projects. "We have a hard time convincing people that it's nothing new to us," said one APL project manager.[1]

Across the continent in California, the Mars Pathfinder group faced a substantially different challenge from the one confronting the NEAR team. The NEAR team had extensive experience with low-cost spacecraft but little familiarity with planetary-type missions. The Pathfinder group worked at an installation with an extensive tradition of planetary exploration but practically no commitment to inexpensive spacecraft. Development costs for JPL planetary spacecraft commonly ran toward $1 billion. Many JPL colleagues viewed the work of Tony Spear and his small Pathfinder team with disbelief. The notion that a small team of JPL engineers and scientists could develop a spacecraft in less than three years for under $200 million and land it on the surface of another planet was contrary to the history and culture of that Center. Most people thought it could not be done.

A different attitude prevailed at APL. Whereas excessive pessimism persisted at JPL in California, what might be characterized as excessive optimism bubbled forth in Maryland. The Applied Physics Lab had a long tradition of building inexpensive spacecraft in short periods of time. The Space Department at APL had come into existence for the purpose of building inexpensive navigation satellites for the U.S. Navy. When the first ballistic missile submarines were built in the 1950s, their inertial guidance navigation systems tended to drift. To locate their position at sea accurately (a necessary requirement for accurately firing a ballistic missile), submarine captains had to surface their ships and take celestial readings, actions that, in the words of one analyst, rendered "the whole concept of a hidden missile platform useless."[2] Navigation satellites provided a welcome solution to this dilemma. By receiving radio signals from satellites in known positions, submarine captains could fix their ships' positions in a stealthlike fashion, helping to create a credible deterrent to nuclear war. The Applied Physics Laboratory developed what became known as the Transit navigation satellite system.

The U.S. Navy insisted that Transit satellites be so small that military officers could launch them on Scout launch vehicles. Scout rockets were tiny rockets, hardly more than guided missiles, capable of pushing objects weighing little more than 400 pounds into space. Although they were mobile and easy to launch, their use created a severe constraint on the people designing the satellites. APL engineers responded by producing satellites that weighed but 119.5 pounds yet had an overall operational reliability rate of 99.9 percent.

Buoyed by their success with the Transit satellite system, APL employees offered to prepare and test a low-cost interceptor for the Strategic Defense Initiative (SDI), popularly known during the 1980s as "Star Wars." In a room full of defense contractors discussing half-billion-dollar systems and five-year preparation times, APL representatives proposed a test that would require little more than $150 million and a year of work. According to one of the people at the 1985 meeting where the concept was originally proposed, the APL representatives were warned that "you're going to embarrass the United States and the President."[3] The successful 1986 test of the APL Delta 180 interceptor became the foundation for the belief among top administration officials that space systems did not need to be expensive to work.

The prime responsibility for developing the NEAR spacecraft fell to Thomas B. Coughlin. He was one of the most experienced project managers at APL, and his participation in several fast-track SDI projects had prepared him for the technical challenges of producing the NEAR spacecraft in just two years. Coughlin had a clear vision of the management philosophy necessary to produce a low-cost, short-schedule spacecraft, but in his typical fashion, he would let other people claim credit for the new approach.

Coughlin selected Robert Farquhar as overall manager for mission design, a position from which Farquhar would oversee the flight protocols for the Mathilde flyby and the Eros rendezvous. With the help of Stamatios Krimigis, Coughlin recruited Andrew F. Cheng as the project scientist, Robert Gold as the payload manager (in charge of instruments), and Andrew G. Santo as the spacecraft system engineer. In all, about 30 people participated as members of the core group responsible for designing the spacecraft and preparing for flight.

Aerospace engineers commonly advance the philosophy that cost, schedule, and reliability are factors to be traded against each other. A low-cost, fast-schedule project, according to this perspective, should incur additional risk. To reduce risk, managers of fast-track projects typically ask for more money. Traditionally, spacecraft managers take what is characterized as a "pick two" approach toward cost, schedule, and reliability. They ask their sponsors to pick two and pay for the gains with the third.

The philosophy underlying the "faster, better, cheaper" approach challenged this outlook. The NEAR and Pathfinder teams sought to produce spacecraft that were simultaneously cheap and reliable and to produce them rapidly. The NEAR team sought to achieve this goal through simple design, high-tech instrumentation, reduced launch costs, calculated risk-taking, and team-based management techniques.

Designing for Simplicity

The immediate problem confronting the team was spacecraft design. Participants on the NEAR project had to design a spacecraft that was robust enough to accomplish its mission and spartan enough to meet its cost goals. The two-year development schedule significantly limited the time available for systems integration and testing. On a normal spacecraft, individual components like the propulsion or telecommunication subsystems usually work fairly well—so long as they are tested standing alone. When linked together, however, they have a tendency to fail. Engineers use systems integration and testing to overcome these interactive flaws. The NEAR spacecraft schedule did not leave much time for systems integration and testing. To reduce the possibility of interactive flaws, team members needed a relatively simple spacecraft.

In pursuit of mechanical simplicity, the NEAR team designed a spacecraft with few moving parts. The body of the spacecraft consisted of an eight-sided box that formed an octagon 9 feet (280 centimeters) tall. On one end of the box, the team hard-mounted a 1.5-meter high-gain antenna, the primary means for communicating with Earth, and four solar arrays, each 6 feet long by 4 feet wide. The solar arrays folded down for launch, then extended into a fixed position once in space. Following their deployment after launch, the solar arrays did not move.

On the opposite end of the spacecraft, team members hard-mounted four scientific instruments. A fifth instrument—the magnetometer—sat at the opposite end, above the high-gain antenna. The propulsion subsystem consisted of 11 small thrusters, 1 large bipropellant engine, and accompanying fuel tanks. The propellant subsystem consumed nearly all of the volume inside the spacecraft and essentially dictated its size. The main engine protruded in a visually awkward fashion through one of the panels on the octagonal spacecraft's side.

Fixing the high-gain antenna and solar arrays to the body of the spacecraft vastly simplified its design. On other planetary explorers, these mechanisms swiveled so as to allow antennas to point at Earth and panels to point toward the Sun. During most of its multiyear journey through the solar system, the NEAR spacecraft was designed to travel with its solar arrays aligned toward the Sun. In that configuration, it communicated with Earth through a fanbeam antenna, an ingeniously powerful device that resembled a large domino. When the spacecraft needed more rapid communication, it turned and pointed its dish-shaped high-gain antenna toward Earth. For those periods of the mission, the solar panels diverted from the Sun at an angle not exceeding 40 degrees. To compensate for the lesser light falling on the arrays during those periods, the mission team changed the material out of which the arrays were constructed and increased their size by an appropriate amount.

The instruments mounted to the opposite end did not point forward, along the spacecraft's usual path, but were fixed to look out from the side, like passengers sitting in an airliner. As if to confuse the uninitiated, spacecraft designers called the end of the machine moving forward along the flightpath the aft deck.[4] The spacecraft could be thought of as backing up through the solar system, except for the fact that space has no up or down.

The two-year development schedule was the "foremost design driver" for the spacecraft and its mechanisms, team members noted.[5] Components had to be designed and manufactured in a remarkably short period of time. Team leaders planned to begin assembling the whole spacecraft just 18 months after funding began. Mechanical testing of the whole spacecraft was set for the 22nd month. (The team planned to conduct additional tests at Kennedy Space Center before launch.) To prevent unexpected interactions once the spacecraft was assembled, designers minimized the sharing of common hardware. "This design," three of the team members reported, "allows parallel subsystem development, test, and integration so that the compressed spacecraft development and integration schedule can be met."[6] The propulsion subsystem was so independent that two of the engineers working on the project characterized it "more as a separate spacecraft than a subsystem."[7]

The simplified design reduced cost, cut time, and helped prevent unexpected integration problems as the launch date approached. It also created a spacecraft that was a bit hard to handle. The large velocity adjustment thruster stuck out of the side of the spacecraft, perpendicular to the line of sight back to Earth and the Sun. Misalignment of the thruster during flight maneuvers caused the spacecraft to torque. To counteract any torque, the spacecraft would have to burn precious fuel. "Precise tracing and control of the center of gravity became mission critical," lead engineers confessed.[8]

The NEAR team spent $79 million designing, constructing, and testing its spacecraft, excluding scientific instruments. In California, the Pathfinder team produced a lander for just $135 million. (See table 3-3.) These were small sums by exploration standards. Most impressive was the short development time. An analysis of NASA space programs suggested that planetary missions required an average of eight years of preparation; a subsequent review of spacecraft difficulties identified insufficient development time as a primary cause of mission failure.[9] The NEAR spacecraft team produced a simple spacecraft—from initial funding to launch—in just 27 months. Whether the spacecraft could fly and complete its mission remained an open question.

Robert Farquhar (right), Mission Director for the NEAR project, points to the large velocity adjustment thruster on the NEAR spacecraft. Project officials simplified the propulsion system so as to minimize the difficulties of integrating it into the spacecraft.

(Courtesy of Johns Hopkins University/Applied Physics Laboratory)

Table 3-3

Actual Mission Costs: NEAR and Mars Pathfinder

(in millions of real-year dollars)

Mission Elements	NEAR	Pathfinder
Spacecraft		
Flight systems	79.1	135.3
Science and instruments	15.4	13.7
Project management	2.4	7.1
Integration and prelaunch operations	9.8	10.0
Other	6.8	4.6
Subtotal	**113.5**	**170.7**
Microrover	—	25.0
Mission operations after launch	60.8	14.6
Headquarters support	2.7	4.8
Launch vehicle	43.5	50.3
Total	**220.5**	**265.4**

Sources:

Applied Physics Laboratory, "Near Earth Asteroid Rendezvous (NEAR), Phase C/D—Development Phase," undated, folder 17070, NASA Headquarters Historical Reference Collection, Washington, DC;

Applied Physics Laboratory, "NEAR Mission Plan vs. Actuals ($M)," undated, folder 10707, NASA Headquarters Historical Reference Collection, Washington, DC;

NASA, "Mars Pathfinder: Project Cost and Funding Summary," undated, folder 16263, NASA Headquarters Historical Reference Collection, Washington, DC.

Saving Through Miniaturization

The NEAR spacecraft team saved money by reducing the size of spacecraft components, particularly the instruments placed on board. So did the Pathfinder team. Much of the philosophy underlying the "faster, better, cheaper" initiative relied upon the revolution in solid state electronics. Throughout the latter part of the 20th century, industrialists used technological advances achieved through miniaturization to simultaneously improve the cost, production schedule, and reliability of computers, calculators, cameras, telephones, radios, and other electronic equipment. To NASA Administrator Daniel Goldin, microtechnologies were the sword that would "slice through the Gordian knot of big, expensive spacecraft that take forever to finish."[10]

The camera or imaging system on the NEAR spacecraft provides a good example of how such innovation can occur. Compared to the cameras on the Viking spacecraft that landed on Mars some 20 years earlier, the NEAR imaging system was a tiny affair. The Viking cameras were bulky, a consequence of the then-new technological challenge of taking pictures on an extraterrestrial world and transmitting them back to Earth. The Viking cameras (two on each lander) were 22 inches tall and 10 inches wide at their bases. They took pictures a single pixel at a time. A nodding mirror in combination with a set of lenses concentrated one dot of light on an array of diodes capable of detecting different focal lengths and colors, then repeated the process for the next dot. The array measured the light beam, whereupon the mechanism amplified the signal, converted it into digital format, and stored it for transmission back to Earth. Each camera took pictures by scanning a vertical line 512 pixels tall, pixel by pixel, then rotating and starting another line. A color panorama took about 30 minutes to prepare. Scientists anxious to locate life on Mars joked that any creature scampering across the landscape would appear as a small disturbance on a single column of dots.

Viking project managers hoped to build the camera for $6.2 million while developing this new technology. Technical problems caused them to spend $27.3 million by the time their spacecraft flew. That is the equivalent of approximately $100 million in the purchasing value of the dollar in the 1990s, more than the NEAR team planned to spend on their entire spacecraft. The imaging system on the NEAR spacecraft, by contrast, cost $1.8 million. The camera consisted of a telescope head 17 inches long that focused light on a charge-coupled device (CCD). The CCD, which scientists characterize as a piece of electronic film, sat in a protective housing that occupied a space barely 5 inches tall.

At its full field of view, the CCD captured an image 537 pixels wide by 244 pixels high. By the mid-1990s, this was not a new technology. Edward Hawkins, who led the APL team building the device, based much of its design on the wide-field imaging system prepared for the flight of the Midcourse Space Experiment (MSX) spacecraft. Hawkins was a relative newcomer at the Applied Physics Laboratory, having joined the staff just seven years earlier, and as the NEAR project began, he was still working on his doctorate in physics at Johns Hopkins University. He had helped develop the MSX imaging system, which APL had completed for the Ballistic Missile Defense Organization. The MSX spacecraft used a multispectral imager for the purpose of distinguishing potential ballistic missiles from the natural space background. It was launched in April 1996, shortly after NEAR, but work had begun in 1988, giving the MSX imager team far more time to perfect technical details. Said Hawkins:

> Fundamental to the success of NEAR was the development of instruments based on proven flight designs. By adapting existing designs and concentrating on and improving the important features, we reduced the development cost and risk.[11]

Hawkins anticipated the possibility that the focal plane detector (FPD), which contained the CCD and the timing control mechanism, might interact with the imaging system's data-processing unit (DPU) in unexpected ways. If that happened, fixing the problem would use up time needed to test and calibrate the flight instrument, which could delay the assembly and testing of the whole NEAR spacecraft. To prevent that possibility, Hawkins and his instrument team used an interface between the FPD and DPU that was very similar to the one used on the Midcourse Space Experiment spacecraft. "The use of existing, reliable ground support equipment to test the flight hardware was probably the single most important factor that enabled the instrument team to meet the tight schedule of the NEAR program," Hawkins reported.[12]

The NEAR multispectral imager was built in-house at APL. The laboratory, reported Space Department head Stamatios Krimigis, "has a long history of designing and building innovative instruments."[13]

The Pathfinder team used the same CCD technology to construct a camera in the form of a small cylinder about 4 inches in diameter. Their imaging system was constructed at the University of Arizona Lunar and Planetary Laboratory under the direction of astronomer Peter Smith. The Pathfinder team spent $7.4 million on their camera. Smith spent much of the money improving the filters and calibration of the camera, which allowed the Pathfinder operations team to produce crisp pictures with accurate colors and three-dimensional images.

In all, the NEAR spacecraft team spent $15 million on scientific instruments. (The Pathfinder team spent $14 million.) The most expensive instrument on the NEAR spacecraft was the x-ray/gamma-ray spectrometer, the primary means for determining the surface composition of Eros. The gamma-ray detector consisted of a 12-inch-long cylinder, while the x-ray detector took the form of three tube-shaped devices, sitting side by side, each about 7 inches in length. (See table 3-4.)

The scientific instruments on the NEAR spacecraft were small and, by traditional spacecraft standards, relatively inexpensive. From a distance, they were hardly visible. In essence, the spacecraft was a rocket engine (with accompanying fuel tanks and

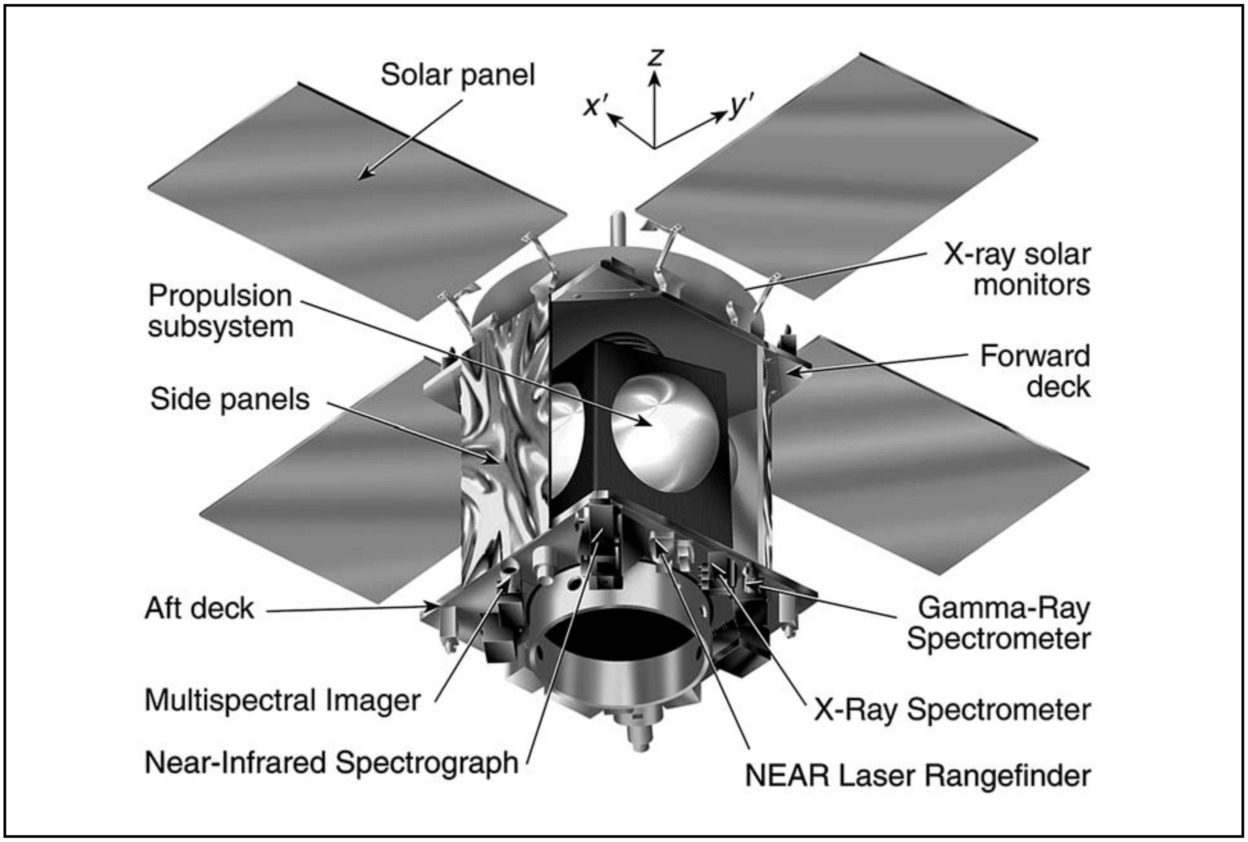
Table 3-4

Cost of NEAR Scientific Instruments

(in millions of real-year dollars)

Instruments	**Cost (Estimated)**
Gamma-ray spectrometer	4.8
Spectrograph	3.3
Imager	1.8
Magnetometer	1.0
Instrument data-processing units	4.5
Total instrument development	**15.4**

Source: *Applied Physics Laboratory, "Near Earth Asteroid Rendezvous (NEAR), Phase C/D—Development Phase," undated, folder 17070, NASA Headquarters Historical Reference Collection, Washington, DC.*



Technicians mounted scientific instruments on the section of the spacecraft that would point away from Earth and the Sun. Solar panels and the high-gain antenna were fixed to the opposite end.

(Courtesy of Johns Hopkins University/Applied Physics Laboratory)

solar arrays) that carried scientific appendages attached to its outer frame. The ability to miniaturize scientific instruments based on existing microelectronic technologies was a major factor allowing the NEAR team to achieve its cost and schedule goals.

Reducing Launch Costs

For many years, exploration advocates have touted the benefits of cheaper access to space. Imagine launch vehicles that could carry payloads into low-Earth orbit (LEO) for a cost of less than $500 per pound, they said. This would allow the transport of spacecraft, telescopes, and satellites 10 to 15 times the mass of current equipment. According to the advocates, such access would revolutionize the use of space for scientific, military, and commercial purposes.

In spite of such hopes and promises, the cost of orbital access remained stuck through the 1990s in a range that varied from about $4,500 to $7,000 per pound. (That provided access to LEO; flying to the other planets and asteroids cost considerably more.) To achieve really cheap access to space, mission managers were left with only one method of reducing launch costs: they had to reduce spacecraft size and mass, thereby flying on smaller and less expensive launch vehicles.

As a condition for approving the NEAR project, NASA officials confined the APL team to a launch on a Delta 2 rocket, model 7925. They imposed the same requirement on the Mars Pathfinder team. These restrictions produced important effects. A small launcher reduced the overall mission budget by keeping launch costs low, and the limited lifting capacity of the Delta 2-7925 provided team leaders with an additional incentive for keeping the spacecraft small. The NEAR team spent nearly $25,000 per pound to dispatch its spacecraft and the accompanying propellant—a large sum, but not unusually high for machinery sent on solar system expeditions. Overall launch costs, however, barely broke $43 million, since the mass of the fully fueled spacecraft as it sat on the launch pad totaled only 1,775 pounds (805 kilograms), including 717 pounds (325 kilograms) of fuel.

The requirement for a small launch vehicle forced the NEAR team to miniaturize the spacecraft, itself a means of cost control. Spacecraft mass was always a concern, said the NEAR spacecraft engineers. They worried about spacecraft mass until "the official weighing operation a few days before launch."[14] Makers of Mars Observer, by contrast, faced no such constraint. Scheduled to launch on a much larger Titan III, they allowed the size of their spacecraft to grow—and the cost of the mission increased commensurately. Confining missions to small launchers created a physical enforcement mechanism over cost and mass that teams developing "faster, better, cheaper" spacecraft could not avoid.

Controlling Risk

In promoting the "faster, better, cheaper" initiative, Dan Goldin told his spacecraft managers to take more risks. "Be bold," he said, "push the limits of technology."[15] By that, he meant that managers should utilize new technologies as a means of improving the performance of spacecraft. He did not mean that managers should trade away performance in their effort to reduce the cost and time required to prepare spacecraft for flight.

"Essentially, all of APL's space missions are one-of-a-kind," observed two senior managers from the APL Space Department. "So the challenge is to get it right the first time." In each case, spacecraft managers utilize technology to improve performance and then confront the risks inherent in the technology. "'Better, faster, cheaper' does not mean a trade-off among the three, but rather innovation and good technical judgment so that resources are applied to those factors that eliminate the most risk in each."[16]

The NEAR spacecraft team took risks. They used solar panels to power the spacecraft in spite of the fact that no spacecraft using solar panels had even flown that far from the Sun. They decided to install a highly sophisticated mechanism for sensing movement in the spacecraft, called hemispherical resonator gyroscopes, which utilize a standing wave pattern on a piece of quartz rather than the traditional spinning wheel. No spacecraft had ever flown with such a gyroscope.[17] In spite of these risks, the NEAR team was much less worried about the reliability of their spacecraft than the Pathfinder group, which took extensive risks as well. In the minds of NEAR team members, they had been through this before. Nonetheless, they did take many precautions as a means of counteracting the potential for difficulties arising from the technologies they used.

Team members reworked the spacecraft design. When early design studies revealed that traditional silicon solar cells would not produce sufficient electric power, the NEAR team switched to gallium arsenide. Team members built in redundancy. The spacecraft carried three separate attitude control mechanisms—a star camera, a "fully redundant" inertial guidance unit, and "redundant digital Sun sensors."[18] The inertial guidance unit contained "two power supplies, two processors, four gyros, and four accelerometers."[19] The spacecraft carried three methods of communicating with Earth: a high-gain antenna, two low-gain antennas (both fore and aft), and a fanbeam antenna with two microstrip patch arrays especially important "in the recovery of the spacecraft during emergency situations."[20]

Where the design team participants could not impart redundancy, they built in margin. Killing risk with margin is a key strategy for engineering reliability into complex systems. Margin enlarges the tolerance for miscalculations, prepares spacecraft for new environments, and protects against unanticipated errors.

The NEAR team built margins into spacecraft components. Doing so was especially important for the propulsion system that had to carry the spacecraft to Eros. As a standard precaution, the design team engineered the fuel tanks to withstand twice their maximum expected operating pressure; the fuel lines were designed to operate at four times the expected maximums. (A burst fuel line doomed the Mars Observer mission.) Bob Farquhar's insistence that a spacecraft on which he had previously worked (ISEE-3) carry extra fuel allowed it to make an unplanned rendezvous with comet Giacobini-Zinner.[21] The team put extra fuel on NEAR.

Redundancy and larger margins worked to increase the cost of the spacecraft. They also made the spacecraft more complex. The people designing the spacecraft balanced increased margins and redundancy with simplification in other areas. Complexity and simplicity coexisted within the same machine. The NEAR team simplified the design of the overall spacecraft—especially as they attached components like the antennas and solar panels to the body of the machine—and they simplified the interfaces between spacecraft components. Interfaces are the points at which components join and are the most common source of complex system failure. The propulsion system was designed as a separate module "to simplify the propulsion system-to-spacecraft interfaces and greatly reduce schedule risk," said propulsion engineers.[22] Simplification of many components counterbalanced the risks taken with others.

The short and unyielding work schedule also promoted spacecraft simplicity because it acted as a barrier against mission creep. This, too, helped to reduce cost and risk. Excessively long development schedules create windows of opportunity that engineers may fill by increasing the technical complexity of a spacecraft. Although excessive tinkering may be done with the intent of reducing risk, it often has the opposite effect, as the history of the Mars Observer mission demonstrated. The NEAR team, faced with an unusually tight development schedule, had to keep the spacecraft simple. The team was obliged to use engineering methods that were more linear than interactive in nature. Linear methods, or what engineers call "clean interfaces," enhance reliability. With their February 1996 launch window approaching, the NEAR team could not engage in actions that made the spacecraft too complex.

Redundancy, margins, simplicity, and limited capability all worked to increase the reliability of the spacecraft. The nature of the mission, the short development schedule, and the low cost ceiling served to increase risk. The NEAR team worked hard to balance the factors affecting reliability, risk, cost, and the team's ability to finish the spacecraft on time. When these design factors are well balanced, as was the case with the NEAR development effort, the contest between reliability and risk is often decided by the quality of the management team. Here, as well, great cost savings occurred.

Managing for Success

None of the money that spacecraft managers consume is spent in space. All of it purchases goods and services produced on Earth, and the greatest portion of it pays the salaries of people working on the project. Spacecraft projects are labor-intensive, with far more funds devoted to salaries than to hardware. During the 1990s, the tax-financed expense of a single employee working on a NASA project averaged $95,000, including salary, benefits, and administrative overhead.[23] Any project that lasts twice as long as usual and employs three times as many people will, of necessity, cost a great deal more than one that employs a smaller number over a shorter development period.

The practice of using small, rapid development efforts was pioneered by Clarence "Kelly" Johnson, a Lockheed Corporation engineer who helped produce America's first production-line jet aircraft during World War II. Johnson set up a "skunk works" development team that was almost too small for its task and assigned a great deal of responsibility to individual team members. Team members were isolated from ongoing operations so that they could concentrate on their assignments. According to one version, the "skunk works" term arose from the relocation of the team to a site well removed from the main corporate facilities and uncomfortably close to an adjacent plastics factory that emitted a disagreeable smell.

Aerospace managers applied the small-team philosophy embodied in the "skunk works" approach to relatively small, focused projects. Scientists at APL utilized small teams when they began conducting experiments with sounding rockets after World War II; they continued the practice when the Space Department was formed in 1959. They accumulated over 30 years of experience on some 50 spacecraft while practicing small-team management. By the time the "faster, better, cheaper" concept became popular, the management practices required to execute it had become quite familiar to APL workers.

Kelly Johnson Skunk Works Rules

- **The skunk works manager must be delegated practically complete control of his program. The manager should report to a division president or higher.**
- **Strong but small project offices must be used by everyone involved.**
- **The number of people having any connection with the project must be restricted in an almost vicious manner. Use a small number of good people.**
- **A very simple drawing and drawing release system with great flexibility for making changes must be provided in order to recover from failures.**
- **There must be a minimum number of reports required, but important work must be recorded thoroughly.**
- **There must be a monthly cost review covering not only what has been spent and committed but also projected costs to the conclusion of the program. Don't surprise the customer with sudden overruns.**
- **Team members must be delegated and must assume more than normal responsibility to get good vendor bids for subcontracts on the project.**
- **Push basic inspection responsibility back to subcontractors and vendors.**
- **Team members must be delegated the authority to test their final product in flight. They can and must test it in the initial stages.**
- **The specifications applying to hardware must be agreed to in advance of contracting.**
- **Project funding must be timely so that the skunk works manager doesn't have to keep running to the bank to manage cash flow.**
- **There must be mutual trust between the customer and the skunk works team with very close cooperation and liaison on a day-to-day basis. This cuts down misunderstanding and correspondence to an absolute minimum.**
- **Access by outsiders to the project and its personnel must be strictly controlled.**
- **Because only a few good people will be used, ways must be provided to pay people based on performance and not on the number of people supervised.**

Source: *Ben R. Rich and Leo Janos,* Skunk Works *(Boston: Little, Brown, and Company, 1994), pp. 51–53.*

Shortly after the age of modern rocketry began, managers overseeing the largest undertakings adopted a different approach. Confronted with the organizational necessities of deploying intercontinental ballistic missiles and sending humans to the Moon, they invented large-scale systems management. This approach allowed very large mission teams to coordinate frequent design changes within "crash" programs proceeding simultaneously on many different fronts. Systems management was used to develop the first fleet of U.S. intercontinental ballistic missiles and to complete the Apollo Moon project. Given the complexity of both undertakings and the number of people involved, the management challenges confronting mission leaders were as taxing as the technical problems involved. Space historian Stephen Johnson has termed the invention of systems management, the technique used to solve the coordination challenge, "the secret of Apollo."[24]

Large-scale systems management consists of a series of formal techniques designed to give project leaders ever-increasing degrees of control over the design, financing, and reliability of machinery under development. Progressive design freezes fix the configuration of spacecraft and related subsystems at increasingly specific levels of detail. Formal scheduling techniques (such as the critical path method, or CPM) track the completion of individual tasks. Total program budgets and multiyear financial plans track spending. Formal program reviews provide management oversight and identify pressing difficulties. Quality and reliability units, located outside the project hierarchy, police the work of project managers while project managers police the work of contractors. At the top, formally organized systems engineering and integration units conduct studies to determine the potential for interactive failures arising from the simultaneous operation of two or more subsystems. The integration units also check the effect of small design changes on adjacent machinery.

Formal, full-scale systems management is time-consuming, labor-intensive, and expensive. It results in an elaborate network of checks and balances wherein the result of any one action is assessed for its effect on the spacecraft, the project budget, and the development schedule. Leaders of institutions like NASA utilize formal systems management to reduce the probability of unanticipated, interactive failures once the mission is under way. Designing and building large spacecraft without the advantages provided by formal systems management is very risky—the equivalent of conducting a circus trapeze act that begins its performance without a net. The smallest undetectable error can doom the final result.

"Faster, better, cheaper" projects typically forgo the more excessive demands of formal systems management, substituting instead the advantages that arise when members of a small team intensively focus on a specific objective and feel personally responsible for the collective product of their individual contributions. Even before people like Kelly Johnson introduced team-based techniques like the "skunk works" approach, experts on management recognized the advantages that small, well-organized teams possessed in creating new products and achieving high levels of product reliability. Those advantages flow from the ability of people working on small teams to communicate with each other and coordinate their individual contributions in an informal sort of way.

Leaders of both the NEAR and the Pathfinder projects relied much more on teamwork than on formal systems management to carry out their work. In essence, they substituted teamwork for formal systems management. However, they did not abandon formal systems management entirely. The NEAR team, for example, engaged in a succession of technical, cost, design, readiness, quarterly, and subsystem reviews. Like the Pathfinder team, they established peer-review groups before which team members had to defend their work. The peer-review groups drew representation from inside the Space Department, from other units within APL, and from people outside APL. Thomas Coughlin, the NEAR project manager, established the usual reliability and quality-assurance component that accompanies formal systems management but followed the APL practice of vesting this responsibility with a product-assurance engineer who sat as a member of the core team.

Coughlin departed from formal systems management by avoiding the excessive paperwork, elaborate integration studies, and many external reviews that characterize that approach. He insisted that NASA executives, the people paying for the mission, establish a single point of contact to oversee APL. When project teams are forced to report to numerous supervisors and multiple Field Centers, the small alterations in mission requirements that tend to arise create huge cost and schedule anomalies.[25] Years earlier, Richard B. Kershner, the founder of APL's Space Department, had refused to take any further NASA contracts because he was frustrated over the requirement that his project engineers "squander every Friday briefing their NASA oversight counterparts."[26] To Coughlin, the single NASA Headquarters representative with whom he worked seemed worried in the beginning. She did not know whether the APL team could do the work. Still, she protected the team, telling other NASA officials who wanted to alter program requirements and add more instruments to leave the team alone.[27]

Coughlin worked hard to protect the team from excessive bureaucracy. He kept individuals focused on the completion of the project. He banned high-ranking APL supervisors from his weekly internal review meetings. He wanted just the technical people and lead engineers to attend. The meetings lasted 1 hour. No coffee was served. Each person had 3 minutes to report.

By eliminating the formal elements of large-scale systems management, Coughlin kept the NEAR project team small. It had to be kept small. A large team, with heavy paperwork requirements, never could have met the impending spacecraft development deadlines. The February 1996 launch window had the same effect on Coughlin's project management methods that the Delta 2 rocket had on spacecraft size. Both kept their respective products small. The impending launch date prevented other people from adding new requirements that would make the project slow and expensive. "You have to shut everything out," Coughlin remarked. "That [launch window] was the biggest friend I had."[28]

The core team at its height consisted of perhaps 40 people. This was quite small by spacecraft standards. Managers of large planetary missions commonly employ thousands of people to develop their spacecraft. Even for small projects, the core development team can exceed 100 employees. Coughlin estimated that the whole number of people working to develop the project, including people in the APL fabrication shops, totaled no more than 130 APL employees, with perhaps another 170 doing work that had been contracted out. "We tried to minimize the [number of] people who touched the hardware,"[29] Coughlin explained. The decision chain was so short that people on the team could make major decisions in a day or so.

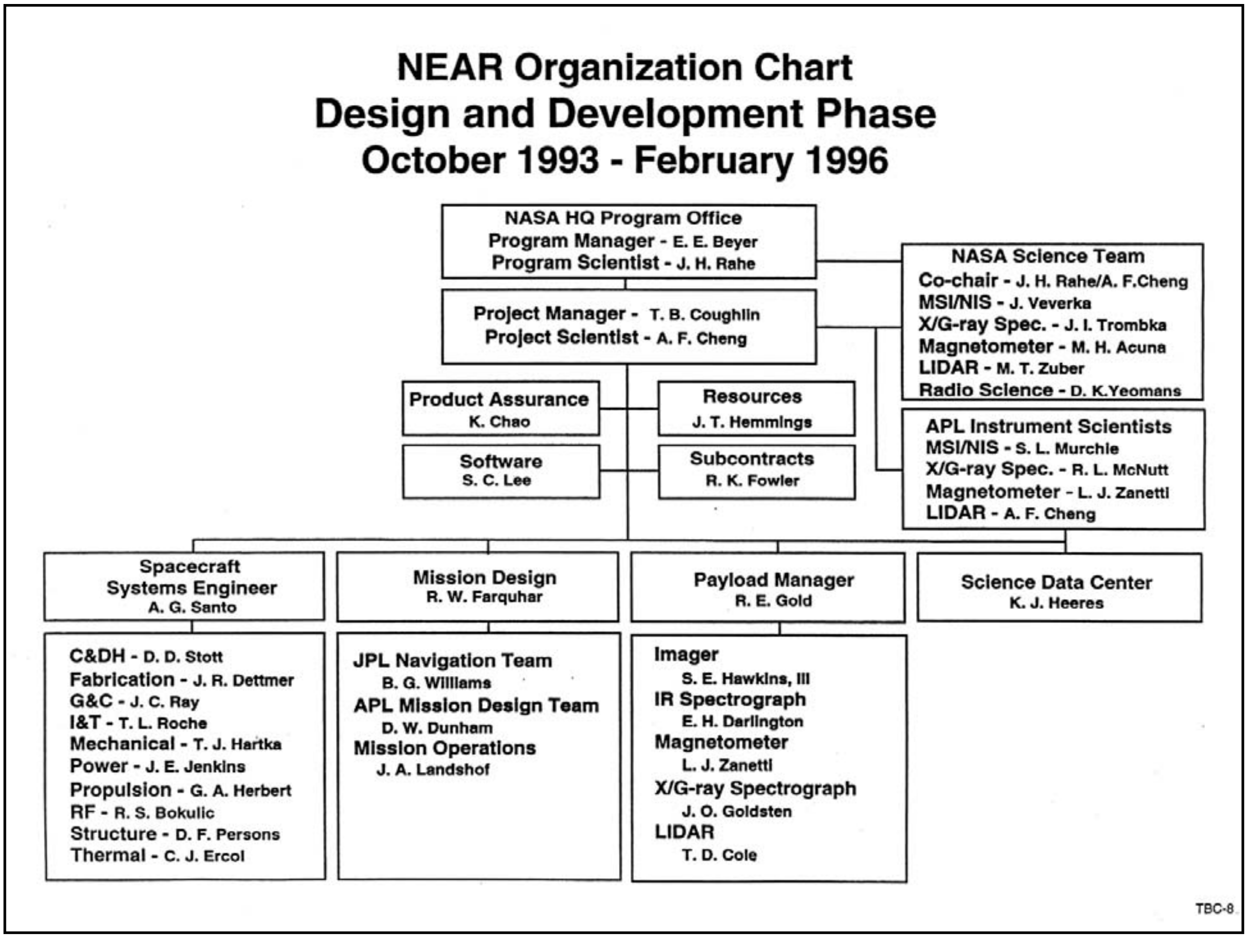
Managers of low-cost projects at the Applied Physics Lab, like those working at the Jet Propulsion Laboratory, use an organizational approach called matrix management. Workers are drawn into the project organization from other units without formally removing them from their home units and the supervisors to whom they report. The matrix refers to the way in which the project team is superimposed over the formal organization chart. APL consists of departments where project workers, technical experts, and management support personnel can be found. Within the departments, technical experts are organized into sections and groups that deal with processes like electronics and power generation. The departments are linked to a research and technology center that contains additional experts in engineering, technology, science, and analysis. APL also houses fabrication shops, where hardware is built in-house. The overall organization is further complicated by the involvement of scientists from universities or other research laboratories who oversee the creation of instruments and the involvement of contractors who produce spacecraft parts. The matrix management system consists of a small number of project leaders, reporting directly to their department heads, drawing help from a much larger network of sections, groups, branches, and shops.

Effective teamwork is essential to this approach. In the absence of the formal checks provided by full-scale systems management and the lines of authority created by a strict chain of command, project leaders must rely upon the willingness of participants to develop a personal sense of responsibility for mission success and communicate concerns openly with one another. In short, the leaders must rely upon the capacity of the members to function as a team. Like the Pathfinder group and other successful "faster, better, cheaper" projects, NEAR team leaders utilized a number of techniques that enhanced this capacity for teamwork.

NEAR leaders colocated team members at the APL campus in central Maryland. Colocation is a primary technique for promoting the high level of interpersonal communication necessary for teamwork to occur. It is especially important for the critical systems integration function. Division of the systems integration function among two or more sites, especially on a low-cost project, invites project failure. Colocation of team members is a primary safeguard against the communication difficulties that arise on complex undertakings.

Most of the work on the actual spacecraft was done in-house at APL. Hands-on experience with the spacecraft gives team members a familiarity with hardware that cannot be created through paperwork reviews. APL had a tradition of completing 70 percent of any project in-house. Because of its short development schedule, the NEAR spacecraft team retained 50 percent of its work, contracting out components such as the complicated propulsion system to firms like the Aerojet Propulsion Company.[30]

Coughlin assembled a small team of experienced personnel. (The Pathfinder group mixed experienced and inexperienced personnel.) He sought people with multidisciplinary knowledge



The organization established to design and build the low-cost spacecraft consisted of a small APL team assisted by scientists responsible for the instruments the spacecraft would carry.

(Courtesy of Johns Hopkins University/Applied Physics Laboratory)

who could understand how their contribution to the project fit into the system as a whole. Managers conducting low-cost projects often use a technique called multitasking, giving workers more than one job to perform so that they view the project from different perspectives, thus expanding individual understanding of the overall machine. Project leaders also encourage seamless management, whereby the same people move from design to fabrication to operational tasks. Coughlin appointed lead engineers for each subsystem, working out their assignments with the supervisors of the units from which these persons were drawn. Having one person responsible for each component of the spacecraft increases reliability and reduces the need for paperwork.

Coughlin insisted that project workers "design to cost" and hold to the fixed schedule. Cost and schedule goals were raised to a level equal to the scientific and technical objectives of the mission. "The single highest risk to managing a cost-capped program is 'requirements creep,'" Coughlin noted. "This is it," he said, fighting design changes and pointing to the 1996 launch window. He had no extra time to absorb design changes. "Additional time in the later stages of development means that a 'standing army' is being extended, which is very expensive and also tends to defocus the team."[31]

The exceptionally short development schedule helped Coughlin keep people on the team. On longer projects, as design and fabrication efforts drag on, workers leave. In such cases, project leaders turn to the paperwork requirements associated with formal systems management as a means of creating a written record that new workers can consult. Short development times promote teamwork because they create an incentive for people to stay. The people who stay know that they will soon see the results of their work.

Overall, Coughlin used a relatively simple project organization. He oversaw a small number of people responsible for the spacecraft, its scientific instruments, mission design, and in-flight operations. He organized six small science teams to assist with the fabrication and operation of instruments, with each team headed by an outside expert whose work was counterbalanced by instrument specialists selected from APL. Most of the fabrication work was done in-house at the Maryland campus or by the Aerojet Propulsion Company, which produced the propulsion subsystem.

Writing about the experience, Coughlin summarized the management principles that guided the work of the project team. In his typically modest way, Coughlin credited the principles to Richard B. Kershner, who founded the APL Space Department in 1959 and served as its head for nearly 20 years. John Dassoulas, an APL program manager and project engineer, codified Kershner's ideas in several publications.[32]

Kershner was a brilliant mathematician who placed more trust in the problem-solving capability of individuals than in the coordinating powers of formal management systems. Emphasizing individual skill, Kershner observed:

> In carrying out a successful development program, the importance of recognizing individual differences in staff cannot be overemphasized. It is precisely this recognition of differences that is least stressed in many books and articles on the theory of organization and management.[33]

In modern terms, Kershner was more interested in leadership than in management. A colleague noted that "he always made it fun, and could get a bunch of screw-balls to work together."[34]

Three of Kershner's seven management guidelines for low-cost missions were designed to build a tight-knit team that would stay focused on the project. Establish a small team of experienced personnel, he said. Appoint a lead engineer with full responsibility for each subsystem. Limit the schedule from concept to launch to 36 months or less. (See table 3-5.) Short development time motivated engineers to stay with the project until the spacecraft was launched and eliminated the necessity for extensive paperwork trails that would otherwise be required to inform new personnel about the work already done. Two of the guidelines dealt with the challenge of restraining project spending: the need to use cost as a design parameter and the requirement that reliability and redundancy be designed into the mission at the start of the project. Efforts to build in reliability once a project was under way, Coughlin observed, invariably caused costs to grow. One guideline dealt with the position of the persons assigned to check on reliability and safety. Unlike the practice in large programs where safety officers sit outside the project organization, APL officials preferred to appoint a product-assurance engineer as part of the development team. The final guideline addressed the method of project oversight employed by the customer or the institution commissioning the project. APL officials insisted upon a single point of oversight, even when the customer (like NASA) might be composed of a number of institutions or field centers.

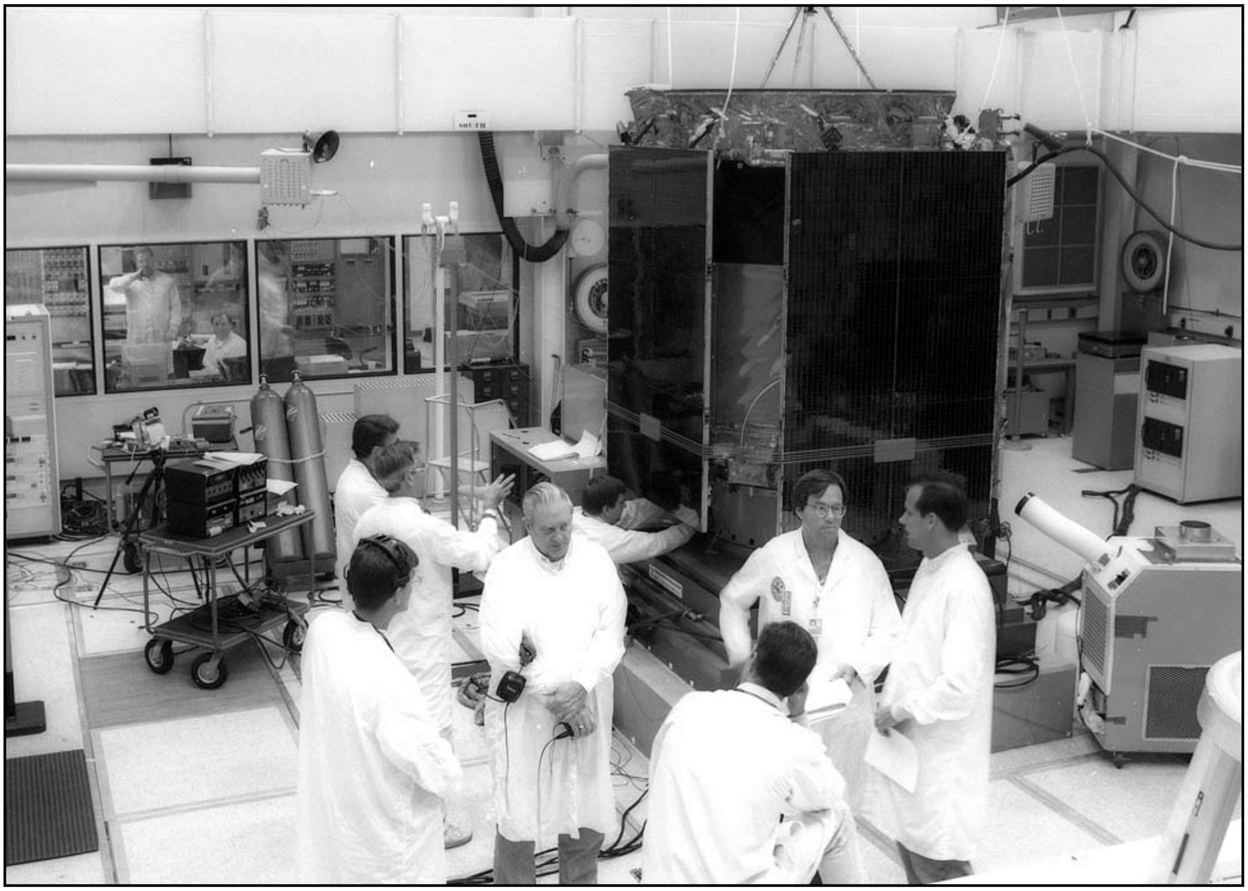
Coughlin embellished Kershner's guidelines as the NEAR project progressed. Coughlin instituted a number of design constraints, such as the require-

Table 3-5

APL Management Guidelines for Low-Cost Missions

1. Limit the schedule from start to launch to 36 months or less.
2. Establish a small, experienced technical team.
3. Design the spacecraft and instruments to cost.
4. Use the lead-engineer method for each subsystem.
5. Design in reliability and redundancy at the outset.
6. Integrate the product-assurance engineer into the program.
7. Assign a single Agency manager to interface with the development team.

Source: *Thomas B. Coughlin, Mary C. Chiu, and John Dassoulas, "Forty Years of Space Mission Management,"* Johns Hopkins APL Technical Digest *20 (October–December 1999): 507–509.*



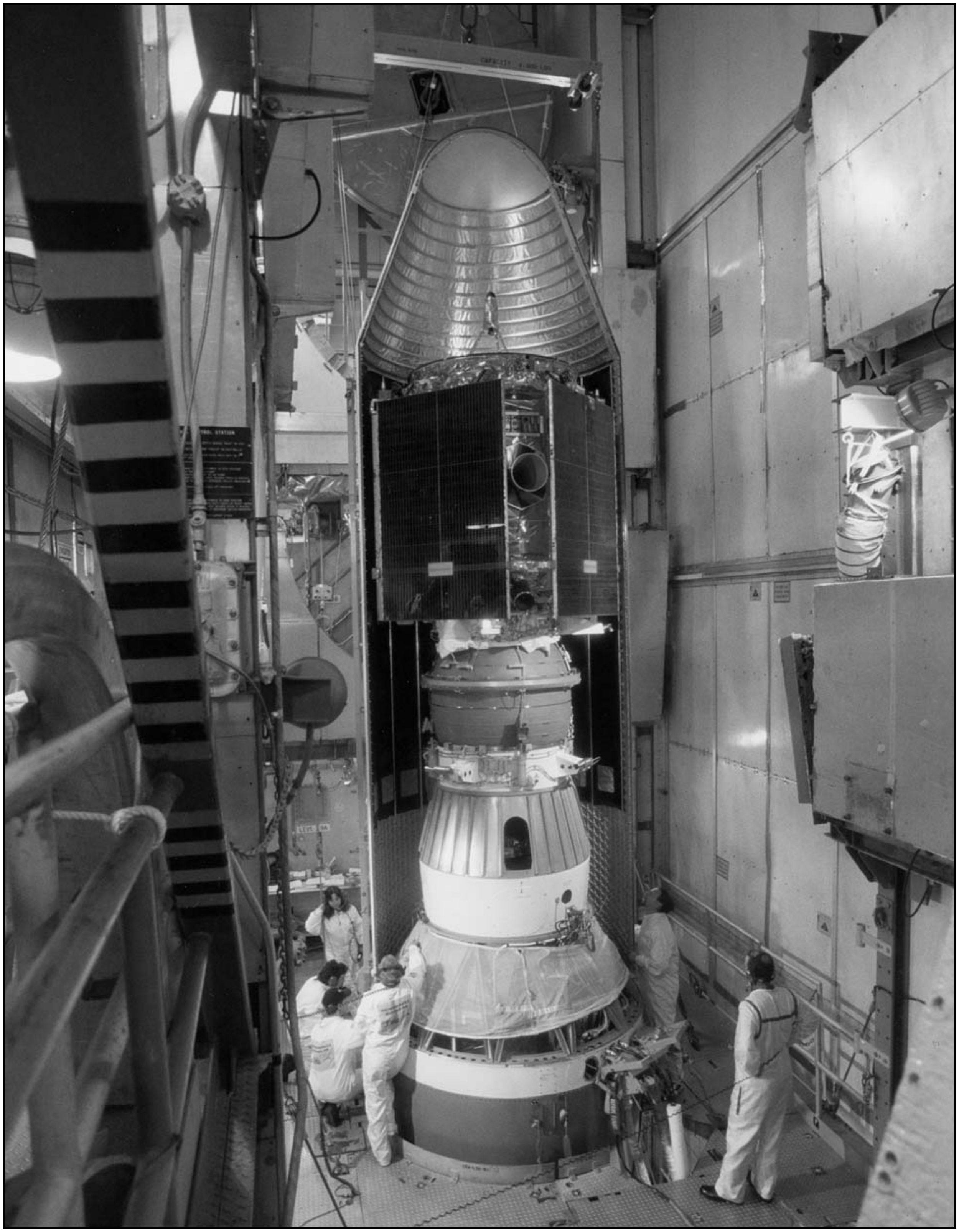
Pursuing a fast development schedule, members of the NEAR project team began full-scale testing of the assembled spacecraft in late 1995, less than 24 months after mission funding began.

(Courtesy of Johns Hopkins University/Applied Physics Laboratory)

ment that major subsystems be able to stand alone. He encouraged spacecraft engineers to attend the meetings of teams designing instruments. He kept the project team small, maintained in-house technical capability, and balanced the need for outsourcing with the necessity of completing at least half of the fabrication work at APL. He insisted that the lead engineers and the team as a whole feel personally responsible for the success of the mission and defined mission success to include cost and schedule as well as scientific goals.

Repeatedly, Coughlin and others on his team insisted that the "faster, better, cheaper" principles they used to organize the NEAR mission were not new.[35] They had been practiced within APL for decades, becoming part of the ingrained organizational culture of the nearly 40-year-old Space Department. "We've been doing that ever since we've been around," said one of the old-timers.[36]

Development of the NEAR spacecraft was relatively uneventful by comparison to other planetary-type missions like Viking and Mars Observer. The project team held its preliminary design review in April 1994, four months after funding started to flow. The team completed its critical design review the following November. Testing of individual components and assembly of the spacecraft began in June (1995), following the arrival of the propulsion subsystem from the Aerojet Company in May. Full-scale testing began in the last week of September. At the Maryland lab, technicians subjected the spacecraft, in its nearly complete flight configuration, to forces it would experience during flight. They shipped the spacecraft a few miles away to NASA's Goddard Space Flight Center, where technicians checked the capability of the machine to withstand the acoustical shock of launch and balanced it on a spin machine. They spun, shook, and vibrated the machine. They tested the propellant tanks by pres-



Technicians mounted the NEAR spacecraft on top of its Star48B third-stage rocket motor at the Florida launch center. Project leaders completed the design and development phase of the low-cost mission in just 26 months.

(Courtesy of Johns Hopkins University/Applied Physics Laboratory)

surizing them with inert gas; they froze the hinges that would open the solar arrays after launch in the subzero environment of space. They switched electronic components on and off. Equipment at Goddard was not adequate to test the ability of the NEAR spacecraft to withstand the rapid spin rate it would endure after launch (69 revolutions per minute), so technicians conducted a final spin balance operation at NASA's Payload Processing Facility at Kennedy Space Center in Florida and checked for additional anomalies that might have been caused by transporting the spacecraft south. The NEAR team shipped the spacecraft to the Florida launch site in early December 1995, 24 months after funding began.

The intensive testing program revealed flaws that the spacecraft team worked to correct. The three-person software team made 22 changes to the computer software during the integration and testing period.[37] According to Andy Santo, the team was still updating default rules in the software one week before the 17 February 1996 launch.[38]

The NEAR team designed and constructed its spacecraft over one of the shortest development schedules ever attempted for a planetary-type mission. It did so for far less money (in inflation-adjusted dollars) than ever attempted for a project of this sort. The task of preparing a low-cost spacecraft, once thought insurmountable, proved relatively easy. The more difficult challenge lay ahead. The low-cost, robotic spacecraft had to fly across the solar system to its ultimate destination—a severe test of the "faster, better, cheaper" philosophy. That challenge would prove far more difficult than the work of designing and constructing the spacecraft.

Chapter 4: Flight

The launch window for the trip to Eros began on 16 February 1996 and remained open for 16 days. The mission plan called for the rocket to place the spacecraft in a 100-nautical-mile-high parking orbit 10 minutes after launch. Thirteen minutes later, over Africa, a 4-minute blast would set the spacecraft on its path away from Earth's gravitational pull. Most of that thrust was to be provided by the Star48B third stage, spin-stabilized at a rate of about one revolution per second. Once released from the launch vehicle, the spacecraft would use an ingenious device to eliminate its spin. On the ground, technicians wrapped two carefully weighted cables around the spacecraft. After the third-stage firing, the spacecraft would activate a cable cutter, which, in combination with the spinning motion, would cause the weighted ends of the cable to move away. As the cables unwound and eventually flew away, they would absorb the spacecraft's angular momentum and reduce its spin rate to less than one revolution per minute.[1]

Additionally, the cables restrained the 1.8-meter-long solar panels that project engineers had compressed against the body of the spacecraft. As the cables unwound, the solar panels would unfold. Moving away from Earth, the spacecraft would communicate its status through NASA's ground station in Canberra, Australia. At least, that was the plan.

Launch officers canceled the 16 February launch opportunity on account of high-altitude winds and a range computer malfunction. The actual launch took place on 17 February at midafternoon under a bright Florida sky. Cheered by the performance of the Delta 2, the NEAR project team waited for the spacecraft to come into range above the Australian ground station. If the spin sequence and other launch procedures had occurred correctly, the spacecraft would signal Canberra that it was safely on its way. Conversely, a faulty spin sequence or launch vehicle separation could throw the spacecraft into a tumble that would prevent it from establishing radio contact with the ground station below.

Launch of the NEAR spacecraft occurred on 17 February 1996.

(Courtesy of the National Aeronautics and Space Administration NASA KSC-96PC-308)

Technicians at the Canberra facility, using their new block 5 receiver and its 34-meter dish, listened for the spacecraft's signal. None came. Ten minutes passed, and the NEAR team grew more anxious. Still no signal arrived. Another 10 minutes passed. Technicians working through a 1.5-meter antenna detected a signal, so they switched their search from the new block 5 receiver to an older, less sensitive one. Detailed telemetry data from the spacecraft flowed down. The spacecraft's signal was so strong that the ultrasensitive block 5 receiver refused to accept what the older model could. "The spacecraft was never in danger," Robert Farquhar joked afterward, "but people here were in danger of having heart attacks."[2]

Organizing for Operations

The incident, minor in hindsight, provided a warning of the dangers that lay ahead. The operations group planned to fly the NEAR spacecraft for three years through the solar system, gradually gaining ground on an object with very little gravitational pull. Extensive operational skill was required to approach the asteroid and begin orbital maneuvers around it.

The organizational framework for this activity was much more dispersed than the one used to produce the spacecraft. Project leaders established an operational center for the NEAR mission at the Applied Physics Laboratory in central Maryland and appointed an operations manager. Navigational work, however, was assigned to the Jet Propulsion Laboratory in Pasadena, California. A group of APL employees operated the spacecraft, but a group from JPL determined the orbit and designed trajectory correction maneuvers. Complicating this organizational arrangement further, both groups sought help from the science

The flight of the NEAR spacecraft through the inner solar system required the cooperation of three teams at different locations—the mission operations group at the Applied Physics Laboratory, a navigation group at NASA's Jet Propulsion Laboratory (shown here), and an imaging team led by Cornell University astronomer Joseph Veverka.

(Courtesy of Johns Hopkins University/Applied Physics Laboratory)

teams that had designed the spacecraft's instruments. The imaging team, under Cornell University astronomer Joseph Veverka, formulated the commands that allowed the machine to view objects in space. The radio science team, also located at JPL but not formally part of the navigation team, had to calculate the asteroid's mass. Along with the visual images, the determination of shape and mass would provide the numbers needed to keep the spacecraft in a safe orbit once it reached Eros. Additionally, these groups needed the support of NASA's Deep Space Network, through which communications with the spacecraft were made.

NASA officials planned to spend $46 million on spacecraft operations after launch.[3] The total amount worked out to be less than $12 million per year for the planned three-year flight and the year spent orbiting Eros. In keeping with the "faster, better, cheaper" philosophy, this was a relatively small sum.

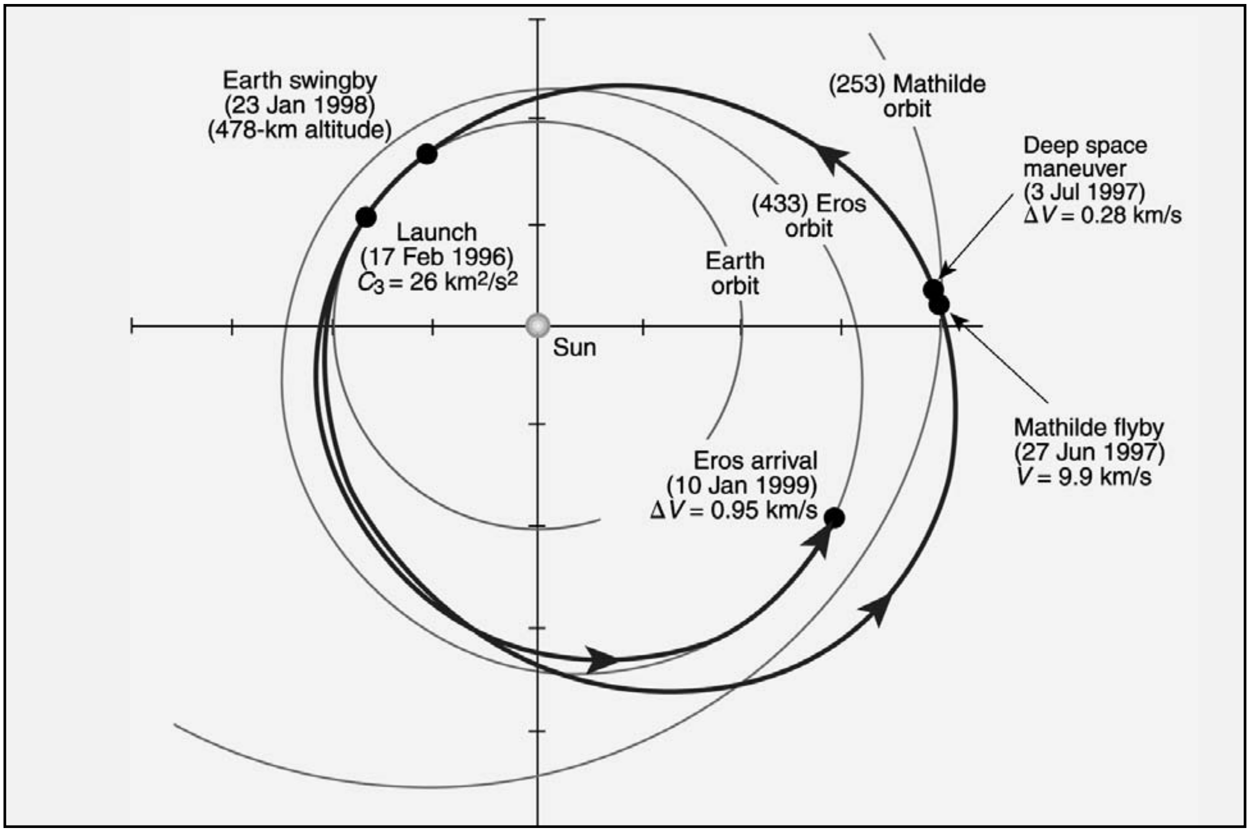
Operational difficulties can doom a mission. The flight of Mars Climate Orbiter provides a dramatic example of the manner in which poorly integrated flight responsibilities can cause a spacecraft to disappear. The lessons are instructive. The flight of Mars Climate Orbiter took place while the NEAR mission was under way. A contractor team at Lockheed Martin Astronautics in Denver, Colorado, built Mars Climate Orbiter. A management team at JPL in Pasadena, California, oversaw the project. To save money, the management team did not involve experts from the technical divisions at JPL in the design or construction of the spacecraft. Yet other workers at JPL prepared the mission plan and flew the spacecraft, while science teams, located at each team leader's institution, contributed instrument protocols. The responsibility for monitoring the status of the spacecraft during flight fell to Lockheed Martin, but navigational instructions were prepared at JPL. As an additional complication, NASA officials required that JPL officials flying Mars Climate Orbiter also manage Mars Global Surveyor, launched in 1996, and Mars Polar Lander, launched in 1999. Finally, project leaders relied upon two separate navigation teams, one for the prelaunch development phase and another for flight. The second team began its work shortly before launch and did not participate in prelaunch testing of the ground software used to fly the spacecraft. Project leaders could have appointed a systems engineer during the operations phase to help integrate these activities but did not.[4]

The investigation board examining the loss of Mars Climate Orbiter described this organizational arrangement, in a clearly understated characterization, as "geographically distributed."[5] The difficulties inherent in this loose institutional pattern were compounded by the "faster, better, cheaper" practice of minimizing formal systems engineering, as was readily apparent in the case of Mars Climate Orbiter by the absence of a systems engineer for operations. To catch small systems integration errors, the people working on other "faster, better, cheaper" projects relied upon teamwork and solid communications. Yet the techniques used to enhance teamwork on those projects, such colocating team members, soliciting peer review, and moving workers from development to operations so as to provide institutional memory, were not emphasized in this case.

The spacecraft vanished on 23 September 1999 as it prepared to orbit Mars. Subsequent analysis traced the cause to a ground software file called "small forces," which was used to construct trajectory models. The file contained thruster performance data that were stated in English units of measurement. A subsequent navigation algorithm read these data as if they were in metric units. One pound of force equals 4.45 newtons. Consequently, the navigation team underestimated trajectory effects by a factor of 4.45, causing the spacecraft to fly too deep into the Martian atmosphere and disappear.

Numerous opportunities to catch this error existed. All of them failed. In essence, the lack of appropriate program integration on a low-cost mission created a situation in which no one noticed that some people were working in metric while others were working in English units of measurement.

The NEAR project was not as "geographically distributed" as Mars Climate Orbiter. The NEAR spacecraft was designed and assembled in Laurel, Maryland, and flown from the same location. Nonetheless, NEAR flight operations were not wholly consolidated; they involved APL, JPL, the Deep Space Network, and the Veverka group at Cornell University. Whereas the people who assembled the spacecraft had extensive experience with low-cost missions, the people who flew it had very little experience with deep space missions. Nor did the NEAR operations team have much time to practice.



The 35-month transit plan called for the spacecraft to pass the asteroid Mathilde in 1997, return to Earth for an acceleration flyby in 1998, and reach Eros in early 1999.

(Courtesy of Johns Hopkins University/Applied Physics Laboratory)

Spacecraft navigation is an extraordinarily complicated process in which small errors can produce horrible results. Poor organization increases the probability that undetected errors will become serious flight difficulties.

Meeting Mathilde

The mission plan devised by Bob Farquhar called for the spacecraft to move away from Earth in an orbit of increasing radii relative to the Sun. The spacecraft would move across the orbital path of Mars and travel into the main asteroid belt. Sixteen months after launch, it would approach the asteroid Mathilde. Passing this dark, carbon-rich object, the spacecraft would fall back toward the Sun, aiming itself toward Earth. Following a journey relatively swift by comparison to the outbound voyage, the spacecraft would zip by Earth's South Pole seven months later on 23 January 1998, picking up speed.

After passing Earth, according to the mission plan, the spacecraft would chase Eros halfway around the solar system, catching it 12 months later. Eros orbits the Sun once every 1.76 Earth years, or every 21 Earth months. The planned rendezvous would occur on the outer edge of Eros's orbit, with Earth on the other side of the Sun, 35 months after the February 1996 launch.

Throughout 1996, members of the NEAR team knew they had problems with the people flying the spacecraft. During the integration and testing phase, before a spaceship is launched, the operations group develops ground support system (GSS) equipment that sends commands to the spacecraft. The spacecraft, however, still sits on Earth, usually fairly close to the equipment. People testing the spacecraft use the GSS to simulate flight before the spacecraft leaves. Simultaneously, the operations group develops the equipment and computers that will be used to communicate with the spacecraft during flight. A critical piece of equipment is the spacecraft data simulator, used during flight to check the effect of commands and procedures before they are sent to the actual machine.

On an ideal mission, all three systems—the test GSS, the flight equipment, and the spacecraft data simulator—would be the same. In practice, they tend to be distinct. As each is built and tested, observed Gary Whitworth, the lead engineer for NEAR's ground system, the spacecraft is typically "thrown over the wall" to the next entity. The equipment used to communicate with the spacecraft in one phase may bear less than ideal resemblance to the equipment used in the next. Seeking to implement the "faster, better, cheaper" philosophy, Whitworth worked to develop what he called a "common architecture" for communicating with the spacecraft before and after it left Earth.[6]

A basic measure of flight-system performance for any robotic spacecraft is the frequency with which the machine retreats to a safe mode. In the event of a serious anomaly, the NEAR spacecraft was programmed to automatically point its trailing side (called the forward end) toward the Sun and begin a 2-degree rotation around that line of sight while emitting a beacon signal from its fanbeam antenna. Eventually, the signal would sweep past the direction of Earth and be detected on the ground. Flight controllers would reply with a "stop rotation" command and begin to study the problem.[7]

Ground commands sent to the spacecraft and not recognized by the on-board computer caused the NEAR spacecraft to slip into a safe mode. (Rule 16 in the NEAR spacecraft computer did not allow the robotic machine to accept any unapproved command.) If the operations group inadequately tested a command before sending it aloft, or if the spacecraft data simulator did not adequately replicate the effect of the command, then the spacecraft might respond by flipping itself into a safe mode once the command arrived.

Watching the operations group fly the spacecraft, members of the overall project team began to worry. The operations group was not flying the spacecraft as well as team members had hoped. In turn, members of the operation group felt assaulted and unappreciated. From their point of view, the project team did not understand the difficulty of flying such a machine. Communication between the operations group and the overall team broke down, a dangerous situation in a "faster, better, cheaper" mission where teamwork is the essential mechanism for avoiding errors.

A few months into the flight, with the spacecraft traveling toward the asteroid belt, the flight operations director resigned. The project team found a replacement from outside APL. Mark Holdridge had graduated from the University of Maryland some 15 years earlier. He had worked at APL as a contractor, not on the permanent staff. He liked the no-nonsense, build-the-spacecraft-and-get-it-out-the-door culture at APL and had always wanted to join the organization as a full-time employee. For 14 years, he remained in private industry, serving in a variety of mission operations roles. In 1996, he received a call from a person on the APL staff who told him that unless the team replaced the flight operations director, "we're going to lose the mission."[8] On 7 January 1997, with the flight nearly one year under way, Holdridge arrived.

Holdridge, a stocky individual with a large, brown moustache, had not been an outstanding student at the University of Maryland, where he studied aerospace engineering; however, through practice, he had learned how to fly robotic spacecraft. His small, six-person group of generalists, he thought, "had extensive spacecraft integration and test experience but relatively little flight operations experience," the latter being especially important for a deep space mission.[9] Holdridge sought to impose more structure on the members of the operations group. They wanted him to be just another analyst. Holdridge wanted to combine the APL traditions of multitasking and cross-training with increased hierarchy, specialization, and procedures. Group members resisted these changes. Holdridge wanted to bring new members onto the group before the original six exhausted themselves. Group size was increased to 21 during orbital operations. He thought that the group's midcourse maneuvers were sloppily performed and that the group was not adequately testing the commands before sending them to the spacecraft. He insisted on regular assessments of the spacecraft and its performance, as well as that of the people working with him. He worried that the equipment was sitting out in the room where something like a plumbing leak could destroy the electronics. The simulator was set too close to the machinery for communicating with the spacecraft. Holdridge worried that a careless operator might send a simulator test command to the actual spacecraft. The loose and informal procedures—what Holdridge called a "Dodge City kind of approach"—added to the time required to control the spacecraft, and Holdridge worried that his group was growing tired and overworked.[10]

In addition to resolving difficulties within his operations group, Holdridge also had to develop good relationships with the JPL navigation group that was plotting the path of the spacecraft and calculating course maneuvers. The nature of project work changes considerably when flight begins. During the design and construction phase, the team is dominated by the project manager, mission director, chief scientist, and spacecraft engineer. During flight, the operations manager, navigation group, and science teams assume dominant roles. Many of the people who helped build the spacecraft move to other jobs. A tightly managed preflight team may unravel once flight begins.

Holdridge and his operations group began to prepare for the flyby of asteroid Mathilde set to occur in late June 1997. In laying out the mission plan, Robert Farquhar had observed that the spacecraft's path through the solar system would take it near a C-class object in the asteroid belt. A slight modification to the spacecraft's path would allow it to study the asteroid. The spacecraft would not orbit Mathilde; it would merely pass by, providing an opportunity to gather information about the composition and shape of the asteroid and practice the procedures that would grow exponentially more difficult at the Eros rendezvous.

Navigating in deep space is an art, requiring the people who chart the path to collect information from a number of sources. One source proceeds from inertia, the principle of physics that describes the tendency of an object to remain on a fixed path until acted on by some force. The NEAR spacecraft carried a sophisticated hemispherical resonator gyro mechanism to measure induced movements. These measurements were compared to the spacecraft's Doppler signal as received on Earth. (When a spacecraft accelerates relative to Earth, its signal arrives at a lower frequency.) The NEAR spacecraft also carried a star tracker and a set of five digital solar attitude detectors to provide additional information.[11]

The process of navigation requires constant checking and comparison of data from different navigation sources to locate the spacecraft and determine its position relative to the orbits of other objects. The gravitational pull of objects the spacecraft may encounter on its voyage affects its path as well. Navigating through space can be likened to sailing across the sea, where a captain has to worry about the manner in which winds and currents affect the path of the ship, except that in space, the ship is moving through three dimensions and all of the buoys, markers, islands, and landforms are moving as well.

Compounding the navigation challenge even further, the exact position of the NEAR spacecraft and the asteroid Mathilde were not precisely known as the date for the flyby approached. The calculated positions of the two objects contained small amounts of error. Roughly one Earth day before the point of closest encounter, following instructions from the imaging group, the operations group told the spacecraft to point its camera toward a position in the cosmos where the navigation group in Pasadena believed the asteroid to be and start taking pictures. In a summation of information from a collection of frames, Mathilde appeared. Visual contact with Mathilde provided the information necessary to redress the remaining navigation error. The operations group sent a command to the spacecraft adjusting the sequence clock so as to prepare the robotic machine for the activities it would perform during its close encounter with this extraterrestrial body.

On 27 June 1997, the NEAR spacecraft passed within 753 miles of asteroid Mathilde. The asteroid was impressively large. If Mathilde's center of gravity were placed above the main campus of APL in Maryland, the outer edges of this roundish object would stretch from the Potomac River north of Washington, DC, to northern Baltimore. As a point of comparison, the object that struck Earth 65 million years ago and possibly ended the reign of the dinosaurs was about 6 to 9 miles long. Mathilde is 41 miles wide. It seems to consist of a carbon-rich material, twice as dark as a piece of charcoal, reflecting only 3 to 5 percent of the Sun's light. A huge, 20-mile-wide chunk of the asteroid had blown away, leaving a crater that from one angle looked as large as the asteroid itself. "It's all crater," remarked Joe Veverka, leader of the imaging team. "There's hardly any asteroid."[12]

Holdridge was pleased with the Mathilde flyby. His operations team had performed well; the navigation group at JPL working with the NEAR radio

The NEAR spacecraft passed within 800 miles of Mathilde in June 1997, registering images of the 41-mile-wide asteroid.

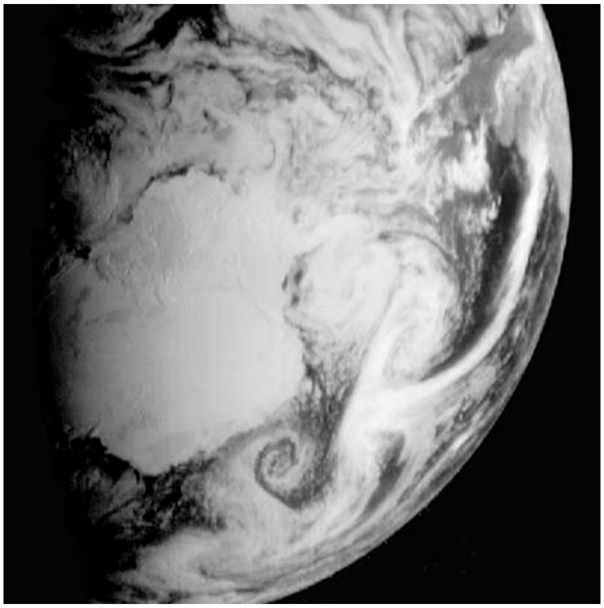
(Courtesy of Johns Hopkins University/Applied Physics Laboratory)

science team had accurately calculated the slight change in the spacecraft's trajectory produced by Mathilde's modest gravitational pull. Mathilde continued its wide orbit through the asteroid belt, and the NEAR spacecraft dropped back toward Earth for its planned 23 January 1998 swingby.

The Earth flyby was a critical and difficult maneuver. The spacecraft had been gone from Earth for nearly two years. It could have been dispatched directly from Earth to Eros, but that would have required a larger and more expensive Atlas launch vehicle. To keep mission costs low, the spacecraft needed the trajectory change imparted by the swingby to supplement the rocket power of the Delta 2 that had launched the spacecraft two years earlier.[13]

The Earth flyby required close cooperation among the operations group, the navigation team, and the scientists preparing image-taking protocols. The spacecraft passed above the Aleutian Islands and Siberia before accelerating to 29,000 miles per hour over southwest Iran. It swung over Africa and Antarctica. At its point of closest approach, the spacecraft was only 335 miles above Earth, the range within which NASA's Space Shuttle and Hubble Space Telescope fly. The swingby altered the inclination of the spacecraft's orbit, matching the Eros orbital plane. As it departed Earth for the second time, the NEAR spacecraft turned and took a series of pictures of the South Pole. In the nearly cloudless Antarctic summer, features in the snow and ice appeared as subtle shades of white and blue surrounded by the deeper blue of the southern seas.

With the Mathilde flyby and the Earth swingby complete, Holdridge grew more confident in the work of his operations group. He sensed that the overall project team was gaining confidence in his leadership as well. In the 11 months remaining before the rendezvous with Eros, group members practiced their maneuvers. They developed a complete software simulator. They executed small



Passing by Earth so as to alter its orbital inclination, the NEAR spacecraft took a picture of the Antarctic continent under its January summer Sun.

(Courtesy of Johns Hopkins University/Applied Physics Laboratory)

velocity changes. In advance of the rendezvous, they prepared a Canned Activity Sequence (CAS) into which they could quickly insert parameters. The spacecraft drew closer to Eros.

Missing the Rendezvous

As the NEAR spacecraft approached Eros, Holdridge and his operations team prepared for five propulsive maneuvers necessary to put the machine into the desired orbit around this small body. The successful Mathilde flyby and the whisker-close Earth swingby had bolstered the team's confidence. Six days after the Mathilde flyby, on 3 July 1997, the team had fired the spacecraft's main engine—the large velocity adjust thruster—for nearly 11 minutes. It was the first use of the spacecraft's main engine in space. Instruments on the spacecraft measured the amount of lateral (or sideways) movement that might accompany a main engine burn. A flight code contained in the spacecraft set a threshold on the amount of lateral acceleration allowed. If too much lateral acceleration occurred, the computer was programmed to shut the engine down. An additional command told the spacecraft how to handle such an on-board burn-abort contingency.

Unbeknownst to the operations group, the threshold was set too low. The operations group noticed an unusual startup transient during the July 1997 main engine burn. The acceleration did not cause a main engine shutdown, so the team did not feel alarmed. As the flight progressed, however, the amount of propellant in the spacecraft decreased, increasing the effect of the transient relative to spacecraft mass. In addition, one of the on-board commands necessary to execute a burn-abort contingency was missing.[14] Additional analysis of data from the July 1997 main engine burn might have revealed the anomaly. Extensive simulations might have revealed the missing command and the fact that the threshold was set too low; perhaps not. Simulations often fail to duplicate flight conditions exactly, and what is easy to see in hindsight is hard to perceive in advance.

Eighteen months after the Mathilde flyby, in late 1999, the operations group at the Applied Physics Laboratory in Maryland prepared the spacecraft for a long main engine burn. This large thruster firing would initiate the final set of maneuvers necessary to swing the spacecraft into an orbit around the target asteroid. The burn began late Sunday afternoon, 20 December (eastern time), as most people prepared for Christmas week. Doppler signals based on the spacecraft's radio transmissions received by the JPL navigation group in Pasadena through the Deep Space Network's 70-meter Goldstone antenna in the California desert confirmed the gradual velocity change expected as smaller thrusters began to prepare the spacecraft for main engine ignition. The subsequent measurements, however, did not show the velocity shift associated with a main engine burn. In fact, the Doppler signature was absolutely flat. For some reason, the main engine had shut down. Thirty-seven seconds later, all signals from the spacecraft ceased. To the people back on Earth, the spacecraft was gone.

One-third of the way around the solar system, the NEAR spacecraft was on its own. The main engine burn caused a level of lateral acceleration that exceeded the command threshold. The spacecraft automatically terminated its main engine burn and moved into a safe mode. The missing script in the burn-abort contingency program, however, caused the spacecraft to wobble and tumble. It could not hold its proper attitude, pointed toward the Sun. Working on its own, the spacecraft shot increasing amounts of hydrazine fuel through its thrusters, trying to maintain the proper position. Byproducts from the thruster firings squirted onto the optical camera. With the spacecraft out of position, its solar arrays could not collect sufficient energy, and its batteries began to wear down. To save power, the spacecraft switched off its transmitter, severing its remaining link with Earth.

Back in Maryland, the project team could only hope that the spacecraft had shut down its transmitter in order to conserve power. In that event, the spacecraft was programmed to turn the transmitter back on after 24 hours and call home.

Far from Earth, the spacecraft fought to maintain its proper attitude. It conserved its remaining electric power. After the passage of 24 hours, it turned on its transmitter and sent a weak signal through its fanbeam antenna in a rotating motion toward the center of the solar system. The signal reached Earth. The fanbeam antenna and the onboard autonomous controls saved the spacecraft, said the relieved project manager, Thomas Coughlin.[15]

So did the fuel margins that the project team had incorporated into the spacecraft design. As data from the spacecraft flowed into the flight operations center, the project team learned that the spacecraft had wasted 66 pounds of hydrazine fuel trying to stabilize its attitude relative to Earth and the Sun. Anticipating difficulties they could not know in advance, the spacecraft development team had loaded about that much additional fuel into the machine.[16] Without the margin provided by that extra fuel, any remaining chance of an Eros rendezvous would have disappeared.

The spacecraft was still speeding toward Eros. The aborted burn and ensuing maneuvers had carried the spacecraft off course, however. The spacecraft would not enter into an orbit, nor would it pass some 600 miles above Eros as planned. Instead, it would speed by at a distance of 2,378 miles.[17]

Even at that distance, the spacecraft could give mission planners their first good view of Eros, important information that would help them prepare for a second rendezvous attempt. The main work of conducting the unexpected Eros flyby fell to the JPL navigation group and the Cornell University imaging team under Joseph Veverka. The navigation group had to recalculate the spacecraft's path. As the navigators rushed through this work, the imaging team planned how to maneuver the spacecraft as it sped by a rotating asteroid so as to get the best possible pictures. They had very little time. Members of the operations group spent all night on 22 and 23 December preparing and sending commands to the spacecraft. They finished a few minutes before the sequence began.

The NEAR team nearly lost the spacecraft. "Recovery of the spacecraft was both amazing and incredibly lucky," wrote two of the participants.[18] Had the more probable result occurred, an intensive investigation of the low-cost methods used at APL would have ensued. Nine months after the flawed main engine burn on the NEAR spacecraft, workers at JPL lost Mars Climate Orbiter, another low-cost initiative. One year after the NEAR anomaly, JPL workers lost Mars Polar Lander, which crashed at its destination. Mars Polar Lander carried a pair of Deep Space 2 microprobes, designed to penetrate the Martian subsurface and search for evidence of water life. They too vanished. Had the NEAR spacecraft likewise disappeared, the loss of so many "faster, better, cheaper" projects would have precipitated an exhaustive analysis into the shortcomings of the low-cost approach. The recovery of NEAR moderated potential disappointment, certainly relative to the reaction that occurred in 1999 as other low-cost missions failed.

Near misses can provide useful information about organizational and technical shortcomings, just as investigations of full-scale catastrophes do. An Anomaly Review Board scrutinized the NEAR engine burn to understand what went wrong. Their analysis, tempered by the realization that the mission did not fail, provided insights into the project management techniques that mission participants had employed.

The very tight organizational techniques used to produce the spacecraft came apart when the spacecraft began to fly. The operations effort, constructed out of geographically dispersed groups, was neither as tight nor as failure-conscious as the development team, even though many of the same people were involved. The Anomaly Review Board criticized the operations group with regard to the startup transient on the July 1997 main engine burn: "The NEAR team failed to recognize the significance of this transient and its potential increase in importance with decreasing propellant mass."[19] A spacecraft system engineer or lead engineer for spacecraft software actively involved in mission operations might have caught the prior anomaly, but the influence of these individuals had dissipated relative to that of the people flying the spacecraft. "The comments, suggestions, and requests of the system engineer in operational matters carried no particular weight and were often ignored,"[20] members of the Anomaly Review Board wrote. The software engineer had moved to another department.

In a team-based project, these two individuals were "the principal repository of knowledge of NEAR's overall system design."[20] A more elaborate process of configuration management might have caught the underlying problem, but the leaders of the NEAR project chose to forgo elaborate configuration management techniques. Compensating practices such as the involvement of key design and development engineers in flight operations might have revealed the anomaly. Yet such practices waned once operations began.

The spacecraft had been flying for nearly three years, 50 percent longer than the time required to build the machine and deliver it to the launch site. "Risk-reduction practices that were established for critical operations prior to launch and were used during early operations had simply been abandoned," members of the Anomaly Review Board noted. What Board members characterized as a traditional "belt and suspenders" mindset among design engineers prior to launch faded as operations progressed.[22] ("Belt and suspenders" refers to the failure-avoidance habit of employing two methods to hold up one's trousers.) In short, a much looser organizational system emerged as the mission matured.

Anomaly Review Board members remembered the 1996 ceremony in which NEAR officials returned $3.6 million in a ceremonial display of cost-saving prowess. "It might have been wiser for NASA to have redirected this $3.6 million toward activities to further reduce mission risk," Board members wrote—activities such as building better simulators, testing flight software, and documenting operational procedures.[23]

In one important respect, the rendezvous burn failure strengthened the capacity of the people flying the NEAR spacecraft. The event focused their attention on the precarious nature of the mission. It taught them how to work together in a crisis. It reminded them, after three years of flight, how close the specter of disaster lurked. It also gave them another year to get ready for rendezvous.

As it sped by Eros, the spacecraft returned more than 200 images, as well as important spectral information.[24] Mission planners saw an elongated, cratered object some 20 miles long. Scientists measured the density of Eros and located its rotation pole. They found no little moons orbiting Eros—at least, none over 50 meters in size.

Armed with data on Eros and the spacecraft, the project team considered its options. The spacecraft had burned so much fuel that a large course correction and quick return seemed improbable. Team members assessed one option that allowed the spacecraft to follow the asteroid around the solar system for 14 Earth months, about three-fourths of the way through Eros's orbital year. Such a flightpath allowed a second attempt at rendezvous in February 2000, on or near Valentine's Day.

Exploring Eros

In order for a team-based management system to work, the people involved must be familiar with each other and share a common outlook toward their work. A team-based project relies upon the exceptional communication channels that exist in tight-knit groups to overcome the disadvantages imposed by the lack of formal management controls. To enhance those communication channels, physical proximity is helpful, in the sense that team members gather in one place. The people involved in flying, navigating, and commanding the NEAR spacecraft, however, were dispersed across the United States.

The 14 months added onto the NEAR flight plan by the missed rendezvous allowed the geographically dispersed operations, navigation, and science participants more preparation time. Participants used that time to improve flight software and practice their routines. That enhanced their capacity to work together as a team. "We had a good understanding of each other as a team," two participants observed.[25] Mark Holdridge, who led the mission operations team at APL, admitted that the extra time made him feel "much better prepared."[26]

The software changes were especially important. Technology improvements often strengthen the performance of persons managing risky technologies. By subjecting seemingly intractable problems to technologically guided procedures, the improvements reduce the number of distractions with which team members must deal at any one time, thus allowing them to concentrate on the issues that absolutely require human intervention. Participants in the flight of the NEAR spacecraft employed the extra time afforded by the missed rendezvous to improve supporting technology, including their flight simulator and the software used to compute the location of the spacecraft and the position of the asteroid. This work expedited the process of preparing the commands necessary to maneuver the spacecraft, reducing both tedium and the opportunity for errors.

Orbiting Eros was challenging in a number of ways. Eros's gravitational pull on the spacecraft was relatively small by comparison to other objects that space scientists had explored. Commensurately, orbital velocity was relatively slow. An object circling Earth near the surface of the globe travels at a speed of about 8,000 meters per second. The typical orbital velocity for the NEAR spacecraft in a 50-kilometer-high orbit around Eros would be about 3 meters per second (about 6.5 miles per hour). Small perturbations caused by Eros's irregular shape, combined with the unusually low orbital velocity, could cause the satellite to escape into space or crash into the surface of the asteroid. The spacecraft team had only a rough understanding of the asteroid's gravitational field as the rendezvous date approached. They planned to learn more about the gravitational field from orbital operations.[27]

As the spacecraft closed the distance to its objective, on-board cameras searched for small satellites undetected on the earlier flyby that might interfere with orbital operations. They found none. The mission plan called for the spacecraft to close on Eros slowly and pass at a relative speed of about 10 meters per second, much slower and safer than the approach 14 months earlier. As planned, the spacecraft would approach Eros from an angle slightly south of the asteroid's equatorial plane on the sunward side, providing a clear view of the asteroid's illuminated surface. The spacecraft would move slowly past Eros to a distance of approximately 325 kilometers (200 miles), at which point it would turn from its line of flight and begin orbiting the asteroid.[28]

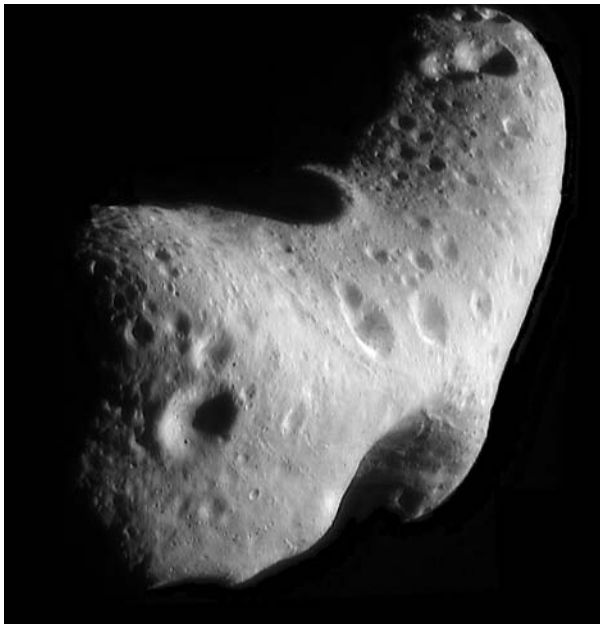
The operations group prepared for orbital insertion by instructing the spacecraft to execute a series of fine-tuning burns. On 2 February 2000, while preparing for a braking burn, the spacecraft fell into a safe mode. Concern was temporary, as the now-confident flight teams completed the necessary velocity change on the following day.[29]

The final maneuver was scheduled to take place at 10:33 in the morning, 14 February 2000, Earth-Maryland time. Preparing for the arrival of dignitaries, someone walked through the operations center and complained about the scarcity of NASA logos. As part of his effort to revitalize NASA's organizational culture, Administrator Goldin had abolished the futuristic, wormlike logo and reinstated the emblem used when NASA had sent Americans to the Moon. In an e-mail message, Gary A. Moore wrote:

> Our guys, who had already had enough of the media preparations, ran off a bunch of cheesy-looking copies on the Xerox and stuck them around at random places, tacking them up with only a single strip of tape. The morning of the burn, an indignant NASA advance man ran around the operations area doing a "search-and-destroy" operation on our mocking signs.[30]

NASA Administrator Daniel Goldin, in attendance with Senator Barbara Mikulski of Maryland, remarked that he had never seen such a controlled mission operations center. "What he did not realize," said one of the mission planners, "is that we were all in a daze after all the long hours and crises of the previous weeks." At the end of the day, after the successful rendezvous, team members went home. "Everyone was so burnt out that no one felt like going out to celebrate afterwards."[31]

Team scientists, however, were ecstatic. Eros was much more structured than anyone had imagined. The 21-mile-long rock was covered with craters and grooves. A large chunk was missing from the center, causing some to characterize the asteroid as "potato-shaped."[32] Some people saw "weird white patches."[33] "Eros has an ancient, heavily cratered surface," project scientist Andrew Cheng observed. "There are also tantalizing hints that it has



A faulty main engine burn caused the NEAR spacecraft to miss its planned January 1999 rendezvous with Eros. Flight teams spent more than one year pursuing the asteroid, eventually threading the spacecraft into an orbit around the 21-mile-long object on 14 February 2000.

(Courtesy of Johns Hopkins University/Applied Physics Laboratory)

a layered structure, as if it were made up of layers like in plywood."[34] Once again displaying his eccentricities, Mission Director Robert Farquhar arranged for the spacecraft to commence its orbit of Eros, named after the Greek god of love, on St. Valentine's Day. Celebrating the association, reporters for *Science* magazine published a photograph of a heart-shaped natural feature on the asteroid.[35]

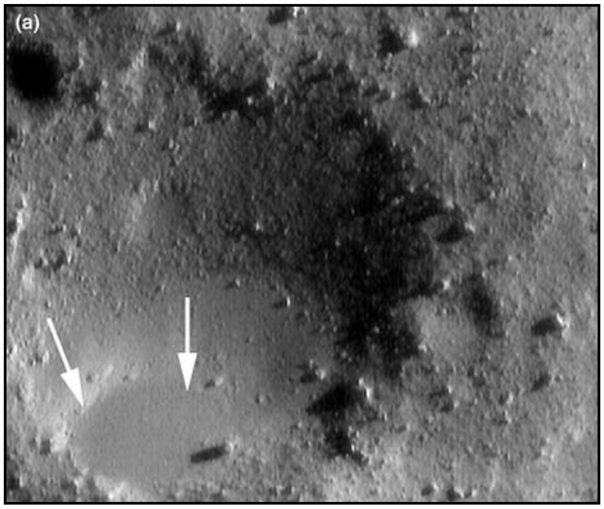
The JPL navigation group promised to give scientists a closer look. The spacecraft began its rendezvous with Eros in a relatively safe 321-by-366-kilometer orbit, one rotation every 22 Earth days. As they learned more about the asteroid's gravitational field, navigators planned to settle into a tighter orbit, some 50 kilometers or 30 miles high, with a revolution every Earth day. They even hoped to dip their orbit down to just 5 kilometers (3 miles) above the asteroid's surface, although they could not hold that altitude long due to the demanding fuel requirements of such a trajectory. The proximity of the NEAR spacecraft to Eros on these low passes was the equivalent of a commuter airline's cruising altitude over Earth's surface.

The low passes required close cooperation among the navigation, operations, and imaging groups. Members of the imaging group wanted perfect lighting conditions for the low passes; a small navigation error could produce disappointing pictures of the dark side of the asteroid or velvet black space. Participants of the three groups had been working together to fly the spacecraft around the asteroid for eight months when the low passes began. In spite of another safe-mode event, the low-altitude flyovers went well. The teams grew more confident in their capabilities and attempted a 2-kilometer flyover.

The close-in passes revealed unusual features. Looking inside craters, the spacecraft took pictures of smooth areas offset from the center that project scientists chose to characterize as "ponds." Consisting of what appeared to be fine soil, the ponds ranged in size from 7 to 100 meters wide. Similar features had never been seen on small bodies elsewhere in the solar system, such as the moons of Mars. With closer inspection, the unusual grooves detected from higher altitudes revealed themselves to be subtle depressions of up to 25 meters deep. Few small craters appeared, a fact that initially puzzled the scientists. "It is difficult to explain the scarcity of small craters on Eros," scientists wrote shortly after the images appeared.[36]

The spacecraft team flew the expeditionary machine around Eros for nearly one Earth year. The near-infrared spectrometer failed. The NEAR spacecraft began to run out of fuel. The mission was renamed NEAR-Shoemaker. The small, robotic spacecraft had been gone from Earth for five years, more than twice the length of time necessary to design and build it. Total expenses for the operational or flight phase of the extended mission had grown to $60 million, more than planned but still modest by exploration standards. NASA executives prepared to switch off funding and further communication with the spacecraft in February 2001.

Mission Director Bob Farquhar did not want the mission to end quietly. "We could let the thing quietly limp away or just turn it off," Farquhar said. "But that just wouldn't be right."[37] In fact, Farquhar contemplated a more spectacular ending, one he had envisioned earlier when the spacecraft was being designed. He wanted the spacecraft to land.[38]



Close approaches revealed strange surface features, such as the pondlike deposits (left) and the absence of small craters (right). The areas shown are about the size of a modern stadium complex on Earth—250 meters across on the left and 150 meters on the right. Controllers instructed the spacecraft to dip as close as 2 kilometers above the surface of Eros.

(Courtesy of Johns Hopkins University/Applied Physics Laboratory)

The challenges imposed by such an objective were more political than technical. No one in NASA, the sponsoring organization, had authorized a landing. No one high in the NASA or APL hierarchy wanted to commit his or her organization to an unplanned objective and then have to explain why the attempt failed. The spacecraft was not equipped with airbags or descent engines or landing legs to cushion its fall. The chances were great that the spacecraft would crash into the asteroid or tip over in such a fashion that no one would know if it had successfully touched down. NASA higher-ups told Farquhar to quit using the "landing" word to describe his proposal. "It's not a lander," said NASA's Associate Administrator for Space Science, who was warming to the idea. "This is a controlled descent."[39] The L-word continued to appear in the press, however, by reporters who recognized a good story. Farquhar was reprimanded for "taking about landing again."[40]

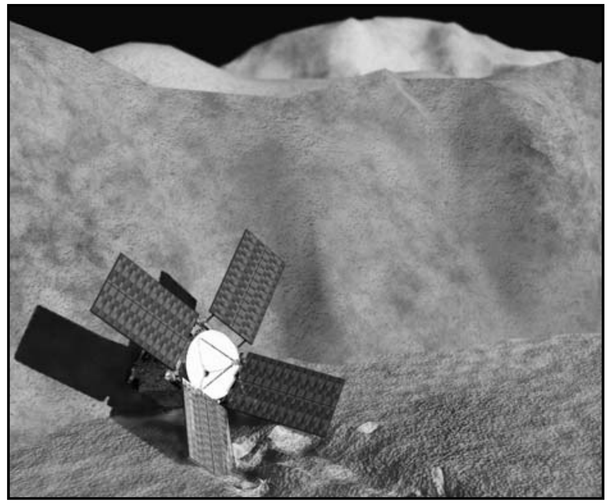
Before the near-infrared spectrometer failed, it had returned information showing the reflected sunlight from Eros to be remarkably uniform in coloration. By implication, Eros was uniform in composition. But the imaging camera had revealed incredibly diverse geologic features—boulders, fractures, ridges, ponds, and the curious absence of small craters. The gamma-ray spectrometer, designed to determine the composition of surface rocks, might have helped resolve the mysteries raised by the geologic features, but it demonstrated poor sensitivity from orbit, even on close 3-mile-high approaches. To the spacecraft team and supporting scientists, the solution seemed obvious: go closer.[41] A slow, controlled descent would allow the spacecraft to capture images from as low as a few hundred meters above the surface of Eros and transmit them back to Earth before plowing into the asteroid's surface. Features as small as 4 inches wide would be visible.

APL Space Department head Stamatios Krimigis embraced the concept and worked to convince top NASA officials, who in turn approved. NASA Administrator Goldin, chief advocate for the "faster, better, cheaper" initiative, made plans to be present at the APL operations center during the high risk-event. Mission planners scheduled the touchdown for 12 February 2001, almost one Earth year after orbital maneuvers began.

The navigation, operations, and imaging groups met extensively to lay out the sequence of events. They planned to begin the descent from a 36-kilometer (22-mile) high circular orbit. All of the team members prepared to gather at the APL operations center except for members of the navigation group, who needed to track the spacecraft from the JPL facility in California. A succession of five thruster firings would cause the spacecraft to drop toward the surface and break its fall.[42] The spacecraft would approach the landing zone on its side, with solar arrays and high-gain antenna pointed back toward Earth. From this position, the camera, positioned on the aft end of the spacecraft, would point straight down. Even if the spacecraft crashed, the camera would transmit pictures during the descent. The operations team prepared a final series of thruster firings designed to slow and soften the impending impact. Team members positioned the spacecraft so that the solar panels and aft end would hit the surface first. The navigation group would know that touchdown had occurred through Doppler tracking from Earth and the loss of the signal from the spacecraft. Said two members of the planning group, "no one expected the spacecraft to survive."[43]

However, the signal did not stop. The solar panels, in conjunction with the aft end of the spacecraft, created a perfect three-point landing. One or two of the panels possibly bent as the spacecraft backed onto the surface of the asteroid. The decision to fix the solar panels rigidly to the octagonal body of the spacecraft, initially done to save money and simplify design, allowed the spacecraft to land with the forward end elevated in such a fashion as to enhance communication with Earth. The spacecraft touched the surface with a downward impact velocity of about 1.7 meters per second (about 4 miles per hour), only twice as fast as NASA astronauts had settled their lunar landers on the surface of the Moon.[44] The NEAR spacecraft bounced slightly at touchdown, a motion revealed by a slight shift on the Doppler track. The camera, pointing down, buried itself into the surface material and was unusable. The gamma-ray spectrometer, which scientists hoped would get close enough to take a few readings, was a few feet from the surface and still transmitting—ideally situated to produce high-quality data.

Dan Goldin was so astonished by the results that he refused to announce the landing until he received additional confirmation. "This could not have worked out better," Bob Farquhar offered.[45] The JPL navigation team and the APL operation group contemplated firing the thrusters briefly in order to change the orientation of the spacecraft, creating a mobile laboratory out of what was a stationary lander, but they decided against the risky move because the quality of the transmissions coming through NASA's Deep Space Network were so fine.



Straining for closer inspection, expedition leaders allowed the small, robotic spacecraft to descend to the asteroid's surface. This illustration depicts the results of the 12 February 2001 asteroid landing, the first ever achieved on such an object.

(Courtesy of Johns Hopkins University/Applied Physics Laboratory)

As the asteroid twisted and moved further away from the Sun, the hemisphere on which the spacecraft sat moved toward its winter season. Like other objects orbiting the Sun, the asteroid experienced seasons, with temperature differentials estimated to range from the boiling point of water to the temperature of liquid nitrogen. The gamma-ray spectrometer transmitted data for 12 days. The Erostian winter approached. As night commenced on 28 February 2001, Earth-Maryland time, the NEAR-Shoemaker team put the small spacecraft to sleep and ceased communicating with the distant machine.

Chapter 5: Legacy

"This mission has been the thrill of a lifetime," said Andrew Cheng, the NEAR project scientist. Cheng had worked on the project since its origins. "It's been ten years of my life and worth every moment."[1] Cheng had joined the Applied Physics Lab in 1983, shortly after receiving his doctorate in physics from Columbia University. A cheerful and articulate scientist, he had taught physics at Rutgers University before deciding to conduct research full-time at APL.

By sending what was eventually relabeled the NEAR-Shoemaker spacecraft to Eros, Cheng hoped to look back to the point in time when the solar system and planets formed. The quest for scientific understanding provided the primary purpose for the NEAR mission, the first systematic expedition to a near-Earth asteroid. Scientists wanted to study its composition and characteristics as a means of furthering their understanding of the solar system. Yet the mission served another purpose as well. As one of the first attempts to create a new line of inexpensive spacecraft, NEAR provided a test of the low-cost approach and the management methods supporting it.

The scientific results of the NEAR mission have been described in a number of popular publications and technical papers, including *Asteroid Rendezvous*, edited by Jim Bell and Jacqueline Mitton, and the January–March 2002 issue of the *Johns Hopkins APL Technical Digest*, a quarterly publication of APL. The management and cost-cutting lessons drawn from the mission are emphasized here, along with a brief review of the scientific results.

Scientific Findings

To build asteroids and planets out of a flattened cloud of debris orbiting an infant sun, chunks of matter must come together. "That's done with collisions," Cheng explained. If bits of rock and ice collide gently, they stick together. Once enough particles arrive and the object grows sufficiently large, some of its constituent material will melt and stratify. "If we have too violent a collision, then these objects will break each other up into small pieces again, and we have to start over."[2]

The asteroid Eros is one of the most primitive objects in the solar system. "One of the most surprising results obtained by NEAR at Eros was the lack of magnetization," Cheng and his colleague Deborah Domingue observed. The absence of magnetization was discovered by the magnetic field instrument team under the leadership of Mario Acuña. If Eros ever melted, or blew away from a larger object that did, the NEAR-Shoemaker spacecraft should have detected the magnetic field that results from material melting in the presence of an ambient field. "The absence of magnetization is consistent with a thermal history in which Eros was never heated to melting."[3]

On the surface of Eros, scientists saw boulders. Parts of Eros are littered with boulders, some as large as a house. Repeated impacts by small objects should have pulverized the boulders, but there they were. Scientists inspecting close-up photographs of Eros found a clue to the reason for the prevalence of boulders. Eros possesses very few small craters. The scientists saw plenty of large impact craters, but few small ones. "Shockingly, with few exceptions, they are not there!"[4] observed Clark Chapman, a member of the NEAR imaging science team. The sort of impacts that might create small craters and pulverize large boulders are strikingly absent on Eros.

The mechanism by which this situation might have occurred, according to some scientists, provides a striking insight into the reason why some objects leave the asteroid belt and fall toward Earth. Scientists suspect that small objects, like meteorites, alter their orbits due to the unequal solar heating they receive. The warming they experience does not cancel out the cold they endure. Eventually, radiant forces cause the object to pop out of the main asteroid belt and enter a more elliptical planet-crossing orbit. According to this theory, which was developed before NEAR visited Eros, the asteroid belt should be marked by a deficiency of meteorite-sized objects. Those objects should have left the asteroid belt and fallen toward the Sun, where some should have hit the inner planets and their moons. Yet they would not hit asteroids like Eros so long as Eros stayed in the main asteroid belt. The visual evidence collected by the NEAR-Shoemaker team lent credibility to this theory.

So how did Eros escape from the asteroid belt and fall toward Earth? The solar effect works best on small objects the size of meteorites, not large asteroids. Again, the inspection of Eros provided clues. Eros appears to be a tightly packed, consolidated body. Though never massive enough to melt, it does possess material that has been pressed into tighter, rocklike forms. Several lines of evidence support this conclusion. The gravity field around Eros is consistent with that of an object of uniform density. Photographs show ridges, grooves, and pits or craters arranged in chains. Crater slopes are steeper than a more loosely assembled body could support.

One explanation is consistent with the findings. Eros could have split off from a much larger body whose mass was sufficient to consolidate the material into a more uniform density but not so large as to begin melting. Said Domingue and Cheng:

> Taken together, the gravity field measurements, linear structural features, tectonic features such as Rahe Dorsum, jointed craters, and indications of internal structural coherence all suggest that Eros is a collisional fragment from a larger parent body, or a so-called "collisional shard."[5]

Inspection of Eros suggests that it spent most its geological history in the main asteroid belt, then broke off from a larger body. That breakup, or perhaps some less-well-understood force, caused it to leave the main asteroid belt and move toward the Sun.

Having moved to the inner solar system, Eros poses a potential danger to Earth. Its path could eventually intersect that of Earth and create a celestial collision. One calculation places the odds of such an event at 5 percent.[6] This would not happen for millions of years, but it could occur. The asteroid's orbit does not currently intersect that of Earth, but eventually, Eros is destined to move even closer to the Sun and fall into it or strike a planet or some other object like the Moon. Even if Eros does not strike Earth, some other near-Earth asteroid will. It has happened before, and it will happen again. Understanding the dynamics and composition of near-Earth asteroids will be essential if humans ever need to move one.

Not all asteroids are the same. As it flew by Mathilde, the NEAR spacecraft detected an object of remarkably low density. Mathilde is loosely constructed—so much so, to use a scientific analogy, that if the asteroid were laid gently on Earth's oceans, it might float. Its low density is consistent with what scientists call a rubble pile, an asteroid that formed as the result of materials slowly gathered together. Eros is much smaller than Mathilde, but also denser. Mathilde is a C-type asteroid on which carbon compounds prevail, whereas Eros consists of metal and silicate minerals, an S-type. Both are distinguishable from M-type asteroids, where metallic iron appears.

Humans may decide to recover precious minerals by mining asteroids. This innovation might encourage orbital manipulation in an effort to move such a precious object closer to Earth. Alternatively, humans may attempt to alter the path of a near-Earth asteroid destined to collide with the home planet. As far-fetched as these schemes seem, moving asteroids is probably essential for humans intent on maintaining a long-lived, technological civilization.

What about those strange pondlike shapes? No such features are found within craters on the Moon. One group of scientists showed how long-lasting terminators between sunlit and shadowed areas could create electrostatic charges capable of lifting and redistributing very fine particles. Cheng preferred an alternative explanation. Small asteroid quakes induced by objects falling on Eros—scientists call them seismic agitations—could cause fine material on the slopes of crater bowls to shift toward the bottom and form level areas. The low gravity on Eros would render steep slopes susceptible to redistribution when the surface shook, much more so than on comparatively larger bodies such as the Moon. Under those circumstances, Cheng explained, "ponds should form easily on Eros but not on the Moon."[7] Significantly, the NEAR-Shoemaker spacecraft landed on such a pond.

Operation of the gamma-ray spectrometer and magnetometer from the surface of Eros helped to reveal the composition of the asteroid, along with a fascinating possibility. Eros appears similar in composition to the class of stony meteorites known as ordinary chondrites. Such objects, primitive building blocks left over from the construction of the solar system, have struck Earth in the past. They can be found in museum collections around the world. Measurements from Eros, along with a path that takes the asteroid close to Earth, suggest "that Eros may be the parent body of at least some of the ordinary chondrites" already on Earth, according to one project scientist. Pieces of Eros may already have struck the planet, an omen supporting the importance of further scientific investigation.[8]

Cost Implications

Along with the Pathfinder expedition to Mars, the NEAR mission to Eros was the first effort to dispatch low-cost spacecraft on planetary-type expeditions.[9] The earliest projects within the "faster, better, cheaper" initiative, including Mars Pathfinder and NEAR, performed remarkably well. The highly publicized Mars Pathfinder and its Sojourner rover explored the Ares Vallis flood plain in the summer of 1997. The following year, the low-cost Lunar Prospector detected evidence of water ice at the Moon's north pole. This mission was followed by Deep Space 1, which completed the first test of an ion propulsion engine in space and flew by the asteroid Braille. Of the first 10 missions in the "faster, better, cheaper" series, 8 (including NEAR) did exceptionally well, raising hopes for wider implementation of the low-cost approach.

The missions that followed did not produce similar results. Beginning in December 1998 and lasting through the next 13 months, NASA launched six more missions under its "faster, better, cheaper" philosophy. Four failed. Mars Climate Orbiter, Mars Polar Lander, Deep Space 2, and the Wide-Field Infrared Explorer (WIRE) all crashed or suffered uncorrectable difficulties. In January 1999, the NEAR team endured what could have been a mission-ending event during its missed Eros rendezvous. By a very slight margin, NEAR missed becoming the first of what would have been five "faster, better, cheaper" projects to fail that year.

The NEAR team recovered and went on to study Eros in detail. The other four missions were lost in full. But for a few pounds of fuel, NEAR could have joined the four. The line between triumph and catastrophe in the realm of spaceflight is very narrow. Instead of preparing a history of accomplishments, NEAR participants might have found themselves perusing a series of accident investigation reports.

The failures of 1999 empowered the people who doubted the wisdom of low-cost endeavors. Analysis of the failures suggested that NASA officials had pushed the edge of the low-cost envelope too far. The development of the Mars Pathfinder spacecraft, along with its Sojourner rover, cost $196 million. Buoyed by enthusiasm for the approach, NASA officials attempted to design and construct the next two Mars spacecraft, Mars Climate Orbiter and Mars Polar Lander, for $193 million. In essence, advocates of the low-cost approach attempted to accomplish two new Mars missions for the price of one. The enthusiasm for cost cutting affected components such as the spacecraft's landing system. Within an already thin budget, members of the Mars Pathfinder team allocated just $27 million for the development of an innovative, low-cost air bag landing system. The Polar Lander team attempted to prepare a more conventional and potentially more expensive rocket landing system for just $15 million. Pathfinder landed successfully; Mars Polar Lander crashed. NASA officials attempted to do too much with too little, an effort that produced problems of mismanagement and communication breakdowns.

The experience of 1999 repeated itself at APL three years later with the loss of another low-cost mission, the Comet Nucleus Tour (CONTOUR). Shortly after the successful NEAR flyby of the asteroid Mathilde, NASA officials approved an APL mission to fly by the comets Encke and Schwassmann-Wachmann-3 and analyze their material. The CONTOUR project was organized much like the NEAR mission before it. APL officials relied upon a small team to develop a relatively simple spacecraft with robust capabilities. In the case of CONTOUR, however, the spacecraft disappeared.

As with the NEAR spacecraft, project officials on CONTOUR relied upon an outside contractor to prepare the spacecraft's main rocket motor. The Large Velocity Adjust Thruster (LVA thruster) on NEAR was developed by the Aerojet Propulsion Company as if it were "a separate spacecraft" in order to "simplify the propulsion system-to-spacecraft interfaces and greatly reduce schedule risk."[10] A similar approach was used on CONTOUR. Two aerospace companies prepared CONTOUR's solid rocket motor, which was embedded within the spacecraft body. The APL project management team trusted the two contractors to deliver a reliable motor, well tested and ready to fly. In keeping with the "faster, better, cheaper" philosophy, team members did not enlist technical experts at APL to assist with the solid rocket motor development. Team members did not "penetrate" the contractor; they did not utilize elaborate systems engineering processes to establish contract requirements; they did not conduct an extensive test and redesign program on the rocket motor; and they did not subject technical decisions to extensive peer review.[11] The "faster, better, cheaper" initiative was predicated upon a management philosophy, known as the Deming method, that entrusts product quality to front-line workers who use statistical methods to check their own work.[12] The philosophy saves money and, when properly utilized, has been shown to increase product reliability on manufactured goods.

On the CONTOUR mission, a research and development undertaking, the approach apparently failed. When flight controllers lit the solid rocket motor to push the CONTOUR spacecraft out of its Earth-circling orbit, exhaust from the motor probably fouled the spacecraft and caused it to degrade and fail. According to the Mishap Investigation Board, the "nozzle was embedded within the spacecraft to a greater degree than is typical," a design decision not adequately analyzed during spacecraft development.[13] The investigating committee could not absolutely confirm this scenario because the CONTOUR project team did not install devices that provided telemetry on spacecraft performance during the critical engine burn. The absence of telemetry during critical mission events, another cost-saving move, was also employed on the ill-fated Mars Polar Lander and was found to be "indefensible"[14] in both cases.

With the CONTOUR mission, APL officials attempted to push the edge of the cost-saving envelope even further than they had done with NEAR. The NEAR spacecraft cost $113 million to develop—a radically low cost for a spacecraft designed to fly through the inner solar system for more than three years. APL officials attempted to develop the CONTOUR spacecraft for about $70 million. The overall cost of the CONTOUR mission, including spacecraft development, launch, and operations, was much less than the expense of NEAR—$220 million on NEAR reduced to $154 million for CONTOUR.[15]

Officials at the Jet Propulsion Laboratory, where the tradition of low-cost spaceflight had never been strong, reversed direction after the disappointing results in 1999. JPL officials garnered an $800-million commitment as protection against the possibility of failure during their next attempt to land on Mars.[16] With that sum, they developed two powerful rovers that arrived in early 2004. The $800-million budget, which covered development, launch, operations, and data analysis, contrasted sharply with the $265 million spent for Mars Pathfinder, which landed, and the $329-million total mission cost set aside for the two 1999 Mars spacecraft that failed.

For a while, advocates of the low-cost approach resisted the pressures pushing project costs upwards. During 1999, NASA officials approved four new low-cost Discovery missions: Deep Impact; the MErcury Surface, Space ENvironment, GEochemistry, and Ranging (MESSENGER) mission; Aspere-3; and the ill-fated CONTOUR. They followed with two additional Discovery-class approvals in 2001: Dawn and Kepler. As of 2003, NASA guidelines required groups proposing Discovery expeditions to confine total mission spending to less than $299 million and development time to 36 months or less.[17]

Commitment to the low-cost cause persisted in 2000, when NASA executives suspended planning of the Pluto-Kuiper Express, a mission to the outer edge of the solar system. The overall cost of the Pluto-Kuiper Belt mission, being studied by a project team at JPL, grew rapidly following the disappointing events of 1999. NASA executives issued a stop-work order on the planning effort and invited interested parties to propose alternative approaches that could fit under a $500-million cost cap.

As time passed, however, support within NASA for the low-cost approach waned. The departure in 2001 of NASA Administrator Daniel Goldin, principal advocate for the "faster, better, cheaper" initiative, significantly reduced enthusiasm for the concept. So did the loss of the Space Shuttle *Columbia* in 2003. During the mid-1990s, when enthusiasm for the concept was strongest, NASA executives had instituted a number of cost-cutting reforms in the management of the Space Shuttle program that found inspiration in the low-cost philosophy. Following the release of the Columbia Accident Investigation Board's report, which strongly criticized NASA management practices, NASA workers treated "faster, better, cheaper" as a curious but ill-fated administrative reform.

Still, the underlying conditions that had prompted the search for low-cost techniques remained. NASA's overall share of federal tax revenues remained relatively constant, forcing Agency leaders to fund new initiatives out of money taken from existing programs, and members of Congress tended to ignore space initiatives that did not demonstrate some modicum of fiscal discipline. In 2003, NASA executives told officials at APL to proceed with a mission to Pluto and the frozen objects in the Kuiper Belt. Set for launch less than three years later, the mission met many of the challenges set out by the original advocates of the low-cost approach. In 2004, APL workers launched MESSENGER, a relatively low-cost mission to Mercury approved under Discovery Program guidelines. Although NASA employees frequently denigrated the "faster, better, cheaper" phrase, new initiatives tended to contain the principal features associated with that approach.

Management Lessons

Shortly after the creation of NASA, with Americans preparing to race to the Moon, NASA executives asked workers at the California Jet Propulsion Laboratory to prepare a set of robotic spacecraft that could collect close-up pictures of the lunar surface. Through what was called Project Ranger, JPL workers designed a set of machines capable of transmitting television pictures back to Earth while speeding toward a crash landing on the lunar soil. The first six Ranger shots at the Moon failed. Subsequent investigations revealed that the project team had utilized traditional management techniques that were too weak to enlist the support of experts from other parts of JPL. The assistance of those experts was needed to make the project work.

The difficulties with Project Ranger and similar undertakings caused NASA executives to examine their management techniques closely. At the time, NASA was full of people with tremendous technical skill, but few people who understood the intricacies of managing very complex projects. Throughout the Apollo years, NASA executives worked to install large-scale systems management in the institutional habits of people conducting human and robotic expeditions. The elaborate system of institutional checks and balances characteristic of large-scale systems management guided the Apollo flights to the Moon and NASA's first large planetary expeditions, such as the Viking mission to Mars.

Low-cost projects like the NEAR mission represent an alternative approach to the challenge of spaceflight. As part of the effort to produce inexpensive spacecraft in short periods of time, low-cost projects forgo many of the elaborate procedures found in modern systems management. Yet they do not return to the weaker forms associated with the early days of Project Ranger. The low-cost approach represents an alternative to both weaker forms of project management and the more elaborate workings of full-scale systems management. It is an alternative constructed around the ability of people working in small teams to accomplish large goals.

On NEAR, scientists and engineers confronted with a limited budget and a short development schedule created a workable planetary-type spacecraft. The NEAR project team did this through a relatively simple spacecraft design, judicious risk-taking, and appropriate management techniques. To manage the project, APL officials relied upon a small project team with focused responsibilities and a capacity for resolving problems in simple ways, without resorting to the elaborate paperwork procedures associated with systems management.

The NEAR project demonstrated the importance of teamwork and communications in achieving reliability in low-cost undertakings. Low-cost projects are incredibly fragile, having forgone many of the formal protections afforded by systems management. Such projects rely extensively upon the sense of responsibility that individual players feel for their contribution to the mission, as well as their willingness to identify and resolve problems. Officials at APL utilized a wide range of techniques designed to enhance the capacity of individuals to function as a team, such as colocation of team members and extensive hands-on work with the spacecraft.

Experience with NEAR and similar projects demonstrates the limits to which the low-cost approach can be pushed. When managers of low-cost projects fail to emphasize teamwork, their projects become vulnerable to the breakdowns that foreshadow mission collapse. The spacecraft development group functioned well as a team; in the beginning, the operations group that flew the NEAR spacecraft did not. As a consequence, the operations group very nearly lost the spacecraft.

On the NEAR project, as with the Mars Climate Orbiter project launched after it, the development team handed a low-cost spacecraft to an operations team that was not prepared to fly it. The development team knew that the NEAR spacecraft would exhibit difficulties in flight, a consequence of limited funds and a quick track to launch.[18] Officials who conduct successful low-cost missions often utilize a form of seamless management in which the people possessing the institutional memory acquired during spacecraft design and fabrication work with the operations team. Sometimes the operations group is involved in spacecraft design. Dividing operations from development or loosening the teamwork techniques that have guided the project once flight operations begin invites project failure.

The NEAR project demonstrated the advantages of conducting a low-cost mission within a supportive organizational culture. Both NEAR and Mars Pathfinder were demonstration projects. They were designed to show others how low-cost planetary expeditions might be conducted. People who work on demonstration projects have a natural tendency to perform well, a consequence of "can do" attitude that tends to prevail on pioneering efforts.

A different challenge faces the people who follow. In subsequent efforts, officials are expected to institutionalize the approaches that the first projects demonstrated. Institutionalizing an approach in an organization whose members may be hostile to the overall concept is a much more difficult undertaking than exhibiting how the concept might possibly work within a group of committed individuals. What works as a demonstration for a while may prove exceptionally hard to institutionalize for many projects in a row.

In that regard, officials at APL enjoyed a large advantage, particularly in comparison to those who worked across the continent at JPL. Members of the NEAR project team worked within an institution that for decades had operated under a low-cost philosophy. Cost reduction was part of the APL tradition and culture. The NEAR team did not have to fight against an entrenched organization; they drew upon a supporting one. Eighteen months following the February 1996 launch of NEAR-Shoemaker, workers at APL dispatched their Advanced Composition Explorer (ACE), another small, low-cost spacecraft. For APL, it was business as usual, so much of a tradition that no one bothered to classify ACE as part of a new approach to spaceflight.

The flight of NEAR, as with other low-cost space missions begun in the final years of the 20th century, showed how expeditions into the solar system could be conducted rapidly and relatively inexpensively. The experience also reminded participants how thin the line between project success and failure remained. Compromises in team-based management techniques, too little money, and too little time doomed other low-cost endeavors. Management difficulties on the flight operations team nearly caused NEAR to fail. The NEAR project, like similar undertakings at that time, demonstrated that expedition costs and preparation time could be reduced considerably. It also served to illuminate the limits on the degree to which these reforms could be pursued.

Postscript

As the asteroid-rendezvous spacecraft orbited Eros in the spring of 2000, NASA officials renamed it NEAR-Shoemaker as a tribute to Dr. Eugene M. Shoemaker, a geologist who spent his life expanding human understanding of asteroids and comets. Shoemaker was a member of the Science Working Group whose 1986 report recommended the NEAR mission and created its name. In public, Eugene Shoemaker and his research partner and wife, Carolyn, along with David Levy, were best known for discovering the comet Shoemaker-Levy 9, which crashed into Jupiter in 1994, raising public awareness of the threat such bodies pose to planetary spheres. Shoemaker died in an automobile accident while conducting field research with his wife on asteroid impact craters in the Australian outback in 1997.

Chapter 1 Endnotes

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Abbreviations

ACE	Advanced Composition Explorer
APL	Applied Physics Laboratory (part of Johns Hopkins University)
CAS	Canned Activity Sequence
CCD	charge-coupled device
CONTOUR	Comet Nucleus Tour
CPM	critical path method
DPU	data-processing unit
FPD	focal plane detector
GSS	ground support system
ISEE-3	International Sun-Earth Explorer-3
JPL	Jet Propulsion Laboratory
LEO	low-Earth orbit
LVA Thruster	Large Velocity Adjust Thruster
MESSENGER	MErcury Surface, Space ENvironment, GEochemistry, and Ranging
MESUR	Mars Environmental Survey
mph	miles per hour
MSX	Midcourse Space Experiment
NASA	National Aeronautics and Space Administration
NEAR-Shoemaker	Near Earth Asteroid Rendezvous
SAMPLEX	Solar, Anomalous, and Magnetospheric Particle Explorer
SDI	Strategic Defense Initiative (also known as Star Wars)
SMEX	Small Explorer Program
U.S.	United States
WIRE	Wide-Field Infrared Explorer

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