8 On Course and Picture Perfect

Maureen Bell

Cornell University, Ithaca New York (NEAR Sequencing Team member)

Bill Owen

Jet Propulsion Laboratory, California Institute of Technology (NEAR Navigation Team member)

As one of NASA's first Discovery missions, NEAR was designed to be "better, faster, cheaper", hopefully to fulfill the program's motto. It took five years from launch to completion of the mission, which ultimately was successful on all counts. It thoroughly investigated an asteroid millions of miles away with many different scientific instruments, controlled by small groups of people distributed across the United States. Its success depended on the ultimate in teamwork: it takes more than rocket science to make a spacecraft do what you want it to do.

Navigation: How we get there from here

Primary responsibility for the navigation of any spacecraft lies with the mission's navigation team, or "NAV" for short. NEAR's NAV team was based at the Jet Propulsion Laboratory (JPL) in Pasadena. They did the math of figuring out where we were and where we wanted to go. Periodically, NAV created a computer file, called a trajectory file or ".bsp file," that contained this information and which provided all of the important spacecraft navigation data to the other teams. But NAV also relied on other teams within the mission to communicate with the spacecraft.

The Mission Operations team (MOPS) and Mission Design team (MD) at Johns Hopkins University Applied Physics Laboratory (APL) had the task of taking the trajectory files with those all-important numbers and transmitting them up to the spacecraft so NEAR Shoemaker would know where it was and what to do. The tasks included designing rocket burns, maintaining the health of the spacecraft (checking whether the solar panels still pointed toward the Sun, for example) and programming the daily return of scientific data and other information from the spacecraft.

The multispectral imager team (MSI) at Cornell University had the task of designing special commands that would use NEAR Shoemaker's camera to collect images and aid the NAV team in determining the spacecraft's position. The images, known as "opnavs" (short for "optical navigation images"), were collected periodically throughout the mission. Opnavs

Figure 8.1. The Cornell University NEAR Shoemaker spacecraft sequencing team. Clockwise from lower left: Maureen Bell, Elaina McCartney, Jonathan Joseph, Colin Peterson, Brian Carcich, and Ann Harch.

Figure 8.2. The Jet Propulsion Laboratory/Caltech NEAR spacecraft navigation team, celebrating the spacecraft's successful arrival in Eros orbit. Front row, left to right: Steve Chesley, Tseng-Chan "Mike" Wang, Jon Giorgini, John Bordi. Back row, left to right: Jim Miller, Bobby Williams, Pete Antreasian, Cliff Helfrich, Bill Owen, and Eric Carranza.

Figure 8.3. The Johns Hopkins University/Applied Physics Laboratory NEAR mission operations team, celebrating the successful completion of the mission. Front row, left to right: Lisa Segal, Carolyn Chura, Pat Hamilton. Middle row, left to right: Ron Owen Dudley, T. J. Mulich, Mark Holdridge (team leader), Nick Pinkine, Rolland Rolls, Dina Tady. Back row, left to right: Bob Dickey, Karl Whittenburg, Rick Shelton, Bob Nelson, Jon Rubinfeld, Charles Kowal, and Charles Hall.

of stars were obtained and analyzed during the Mathilde flyby and the cruise to Eros, and then opnavs of Eros itself were obtained and analyzed during the approach and orbital phases of the mission.

At its most basic level, navigating a spacecraft around the solar system is mostly about answering two questions:

1 What is the current course of the spacecraft? We need to know not just where it is at a particular moment of time, but also how fast it is going and in what direction, in order to be able to predict its future trajectory.
2 If the answer to question 1 is significantly different from the desired flight path, then we need to ask: How do we get the spacecraft back on to its correct trajectory? We need to command the spacecraft to fire its thrusters and perform "trajectory correction maneuvers," to nudge it back toward where we want it to go.

The two main tasks of spacecraft navigators like those on the NEAR NAV team are to mathematically determine the spacecraft's orbit, and to design any needed course correction maneuvers. These tasks require the application of celestial mechanics, numerical analysis, filter theory, and – yes – rocket science. We will describe first how the process usually works and then the changes from the usual pattern that had to be made for NEAR.

Orbit determination, or OD for short, is the art of using measurements such as radio tracking, pictures, or altimeter ranges, to improve upon our estimate of a spacecraft's trajectory. We have to accept that we can never claim to know the trajectory of a spacecraft exactly. Our observations are not perfect, and a multitude of similar trajectories can fit them adequately. Each time the NAV team generates the official "trajectory", it is actually just the one most likely to be correct, but there is always an element of uncertainty in both position and velocity. If we think of the optimal, desired trajectory as a thin curve between two points in space, then the best we can do to determine the actual trajectory of the spacecraft is to imagine it within something like a fuzzy tube that surrounds that curve. Furthermore, the size and shape of the fuzzy tube can vary. The tube is small in places where we have good data to constrain it, but it gets fatter as one tries to predict the trajectory farther and farther into the future.

The observations used by NEAR NAV for the normal orbit determination were radio ranging and Doppler from ground-based tracking antennas and optical navigation pictures from the on-board MSI camera. The acquisition of range and Doppler data relies on the tracking antennas of NASA's Deep Space Network (see box on following page). Optical observations are made with the spacecraft cameras.

In order to obtain range data, a DSN antenna must transmit a special set of modulated signals to the spacecraft, in essence similar to an FM radio signal. The spacecraft's on-board computer, which receives the transmission and recognizes it as a special signal from home, has software to retransmit it back to Earth immediately. Electronics at the DSN station determine the time when the return signal reaches the antenna back on Earth, and compare it to the known time that the signal was transmitted. The time difference is the time that it took the signal to get to the spacecraft and back at the speed of light, or the "round-trip light

The Deep Space Network

NASA's Deep Space Network (DSN) consists of a series of radio telescopes (antennas) near Goldstone in California, in Spain near Madrid, and near Canberra in Australia. Each DSN site has one 70-m radio dish and several smaller antennas at each location. The three sites are distributed around the Earth fairly evenly in longitude so that it is possible to receive information from a spacecraft (downlink) and send information to a spacecraft (uplink) wherever they are in the solar system without interruption as the Earth rotates. The DSN is the primary way that NASA sends and receives signals from the dozens of interplanetary space probes traveling throughout the solar system and beyond.

Figure 8.4. The Deep Space Network consists of three 70-m radio telescopes and a number of 34-m radio telescopes spaced approximately evenly around the world allowing constant communications with deep-space missions.

time," and is a direct measure of the distance from the DSN antenna to the spacecraft. The one unfortunate characteristic of range data is that the spacecraft cannot transmit science data very efficiently when it is sending back the range code. We therefore used range data rather sparingly, typically for just a few brief ranging sessions per week.

Doppler data are a measurement of the shift in the frequency of the received radio signal relative to the known frequency of the originally transmitted signal. Anyone who has ever watched a train pass by has experienced the Doppler shift of sound: the train's whistle is high-pitched as it approaches you, and then changes to lower-pitched after it goes by. The whistle itself is constantly emitting the same tone—our perception of the tone changes because the train is moving relative to us. The same kind of Doppler shift occurs with light: radio waves (which are just a form of light) from a spacecraft moving towards us are shifted to higher frequency, and those from a receding spacecraft are shifted to lower frequencies. For NEAR Shoemaker, we preferred to use a technique called "two-way Doppler" in which a signal is transmitted from the DSN at a known frequency, received and retransmitted by the spacecraft in the same way as the range data, and finally detected back on the ground. The DSN measures the incoming frequency very accurately – to a fraction of a cycle on a signal with over 7.6 billion cycles every second. Because the antenna and the spacecraft are in relative motion, there is a difference between the final received frequency and the original frequency – the Doppler shift. The size of the Doppler shift depends on the relative velocity between the spacecraft and the antenna in the direction of the line joining them. The antenna happens to be sitting on a rotating Earth, so the first part of the Doppler shift arises from the antenna's own motion. This is a valuable effect to exploit for additional information, because it depends on exactly where in the sky the spacecraft happens to be. Another part of the Doppler shift arises from the Earth's orbital motion around the Sun; this is not as interesting from a NAV standpoint, but we can compute what it is quite well. A third component comes from the spacecraft's own motion, and this is where things get interesting, especially for NEAR Shoemaker while it was in orbit around Eros. Whenever Eros's rotation brought one of the asteroid's long ends closer to NEAR Shoemaker, the spacecraft would feel a little extra gravitational tug. Similarly, when NEAR Shoemaker was over Eros's "waist," it would feel a little bit less gravity. This variable force produced a noticeable change in the spacecraft's orbit, wiggles that show up distinctly in the Doppler data. This is how we determined the various numbers that describe Eros's gravity field, as well as the size, shape, period, and orientation of NEAR Shoemaker's orbit. Doppler truly is the workhorse of the interplanetary navigator.

Obtaining and analyzing optical data to improve the trajectory are an entirely different matter. Here we use a camera on the spacecraft (the MSI) to take special pictures for navigation purposes. In all previous JPL missions, the NAV teams did their own sequencing, or at the very least gave to the sequence team a list of times and directions in which to point the camera. For NEAR it was different. It was the first time that a JPL NAV team delegated the picture planning to somebody else. The NAV team was in control of requesting all imaging time for opnavs, approval of any changes to them, and verification before each uplink that what MSI was being commanded to do was what NAV wanted. The system worked exceptionally well, for two reasons in particular: MSI had superior planning software (a program called *orbit* written by Brian Carcich at Cornell), and NAV simply did not have the time and manpower to spend on sequencing, given that they were analyzing hundreds of images every day.

For earlier spacecraft like Galileo and the Voyagers, opnav pictures would contain a satellite against a background of reference stars. We would identify the stars in each picture and, since their coordinates were well known, we would know exactly where the camera was pointing. Then the location of the satellite image in the picture told us the direction from the spacecraft to the satellite. String enough of these pictures

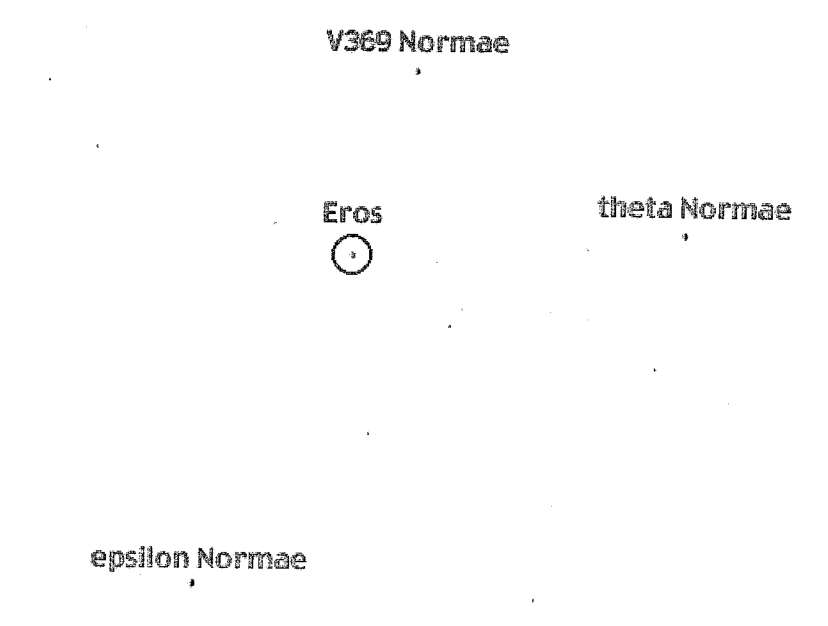

Figure 8.5. This first image of the asteroid Eros was acquired by the MSI camera on November 5, 1998, from a distance of 4 million km (2.5 million miles). Located at the center of this inverted image and circled, Eros appears against the star background as a single illuminated pixel. The exact location of the stars in the image helped to refine the trajectory so that the path to orbit insertion was exact.

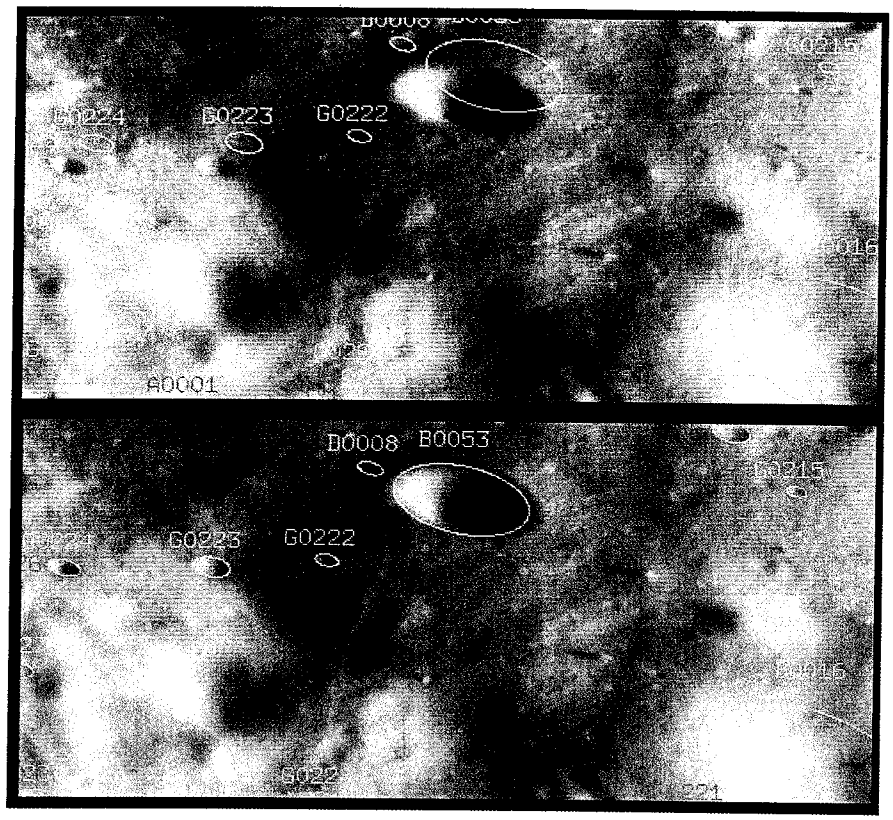

Figure 8.6. Example of a NEAR MSI optical navigation image of Eros on which craters and other landmarks were labeled and outlined in yellow based on the predicted spacecraft pointing (top), which was then refined by aligning the landmarks to their correct actual positions in the images (bottom).

together and one sees the movement of the satellite with respect to the background stars over time. In this way one can determine both the spacecraft trajectory and the satellite's orbit more accurately.

But the NAV team knew that traditional opnav techniques would not work at Eros. The asteroid is so irregular that its center cannot be located easily just by looking at a picture. What is worse, its surface is quite bright, so the camera is limited to short exposures, and only the very brightest stars have any chance of showing up. Therefore we had to develop an entirely new approach that did not rely on stars or on finding the center of Eros. Craters became the navigation landmarks for Eros instead. Not just any crater would do, though. They had to be small craters with deep sides and nice round rims so that they could be seen clearly in all sorts of lighting conditions. They also had to be easily identifiable; one misidentified crater could skew the results. Fortunately, Eros has many thousands of craters to choose from! There are over 1600 of them in the Eros navigation database, and about a hundred of the "landmarks" were used in operations over the course of the year that NEAR Shoemaker orbited Eros. Approximately 44 landmarks were used at a given time during an orbit. As the mission went on and the Sun moved progressively further south in Eros's sky, the northern side of Eros became shrouded in darkness and the southern regions, which had been in darkness, became sunlit. Our choice of landmarks had to follow the Sun. Stars were still an important tool, but only indirectly; NEAR Shoemaker's star tracker (a separate camera system dedicated to identifying the background stars) told us the orientation of the whole spacecraft, and that in turn gave us the direction in which the camera was pointing.

Measuring the landmarks was one of the few things that was literally done by hand. Each picture of the surface of Eros was displayed on a computer monitor. The computer would use the expected trajectory to calculate where the craters should be and put on top of the picture a simple overlay drawing of the outlines of the expected landmarks. First the cursor would be used to drag the crater overlays until they lined up with the actual picture. Then, using the cursor again, points were selected all around the rim of each crater. The computer would examine those points and find the center of the crater. The difference between where the crater was and where the trajectory thought it should be told NAV the deviation of NEAR Shoemaker's real path from the required trajectory. The NAV team would go through this process each day, looking at perhaps 50 pictures and measuring a dozen or so craters in each picture. During the year-long orbital phase of the mission NAV obtained, and team members Bill Owen and Mike Wang analyzed, some 134 267 crater measurements in 33 968 pictures (out of a total of about 181 393 pictures taken). It was a tedious job at times, but well worth the effort.

The orbit determination process took all these observations – not just the crater measurements, but the Doppler and range information too – and figured out which trajectory (out of the many possible trajectories) was the best match to them. JPL NAV team members Jim Miller, Pete Antreasian, and Steve Chesley were the masters of this black art.

The process of using all the available information to figure out the most probable trajectory depended in various ways on many things. These included the position and velocity of the spacecraft relative to the center of Eros; the size and direction of any needed orbit maneuvers and other thruster firings; the strength and shape of Eros's gravity field; Eros's rotation rate and the direction of its north pole, which together provide the asteroid's orientation in space; and a host of other "non-gravitational accelerations" on the spacecraft, for example from solar radiation pressure and thermal imbalances.

Each of these effects was modeled in computer software in terms of one or more "parameters," quantities that are initially unknown but whose values can be deduced from the observations. Other parameters, for instance the locations of the landmarks, did not alter the trajectory itself but did affect our observations. These were included in the OD process as well. There were several hundred parameters in total, hundreds to thousands of optical measurements, and many thousand Doppler and range data points available. In order to find the best solution, our software first answered two questions:

1 How does each observation compare with what it would have been if our knowledge of the trajectory were perfect? These differences are known as "residuals" and the object of the OD solution was to minimize them.
2 How would each residual change if each of the solution parameters were changed? This information helped us get a handle on how robust each possible solution really was, compared to the many others that were also possible.

With the answers in hand, the OD program was able to figure out the combination of parameters that did the best job of making all the residuals small. The residuals never vanished, because no measurement is perfect. Each measurement was slightly in error, and associated with each measurement was a best guess as to how big that error was likely to be. These measurement uncertainties meant that the final OD solution was likewise uncertain in some degree (hence our fuzzy tube analogy).

The OD team's best estimate of the trajectory then went to the maneuver analysts, Cliff Helfrich and Mike Wang of the JPL NAV team. Their job was to design the "orbit correction maneuvers" or thruster firings that brought NEAR Shoemaker back to its desired trajectory. This was yet another problem for the number crunchers. If we fire the thrusters in a particular direction, where does the spacecraft actually end up? Space is three-dimensional, so we asked this question for each dimension. Comparing the three answers to the OD team's estimate told us what each component of the maneuver would do. Comparing the estimate to the nominal (that is, where the spacecraft ought to be) told us what must be done. Finally, then, we had enough information to work out the maneuver.

Doing one maneuver is easy, but we often had to design four or five at a time in order to get NEAR Shoemaker where it had to be in a month or two down the road. The approach outlined above tends to be unstable, since very small maneuvers can sometimes lead to large changes in the trajectory, and the problem ceases to be "linear" – if you double the maneuver, you will not necessarily get twice the result. The maneuver design team had to proceed almost by trial and error at times, moving in very small steps until they had converged upon an appropriate answer.

NEAR Shoemaker had several problems during its long journey, most of them technical and related to on-board spacecraft systems, instruments, or software. Through it all, the new and time-tested navigation techniques described above never failed. NEAR Shoemaker stayed on course at all times during its complex dance around the solar system because of the hard work and talents of the NAV team and their colleagues on MOPS, MD, and MSI.

The flyby

In December 1998 as we approached the asteroid for orbit insertion, we were all nervous. We were working with new software, firing engines we had not used in a year and performing a maneuver that had never been attempted – entering orbit around a small body with unknown gravity factors. Several tests were run on the sequence in the hopes of minimizing our chances for disaster. The science teams, in particular the imaging team, were asked to put together "contingency" sequences in case something went wrong. David Dunham, of the mission design team at APL, is said to have run all possible contingency sequences for the operations team so that they would know what to do if there were an abort at any part of the orbit insertion sequence.

We felt that we were prepared, but we were apprehensive. The day of the insertion burn we all waited for news. And then the unthinkable happened. During the main engine firing the spacecraft stopped communicating to the DSN. We had lost NEAR Shoemaker and no one knew why. During an incredibly tense 24-hour period, the operations team worked ceaselessly trying to make contact with the spacecraft in order to regain control and find out what went wrong. We had mostly given up hope when, much to our surprise, we received a call from Karl Whittenburg from the APL MOPS team telling us that they had regained contact with the spacecraft and that we had 12 hours to put together a sequence for a flyby: the spacecraft was not going into orbit but was instead going to fly right past Eros just before Christmas.

The recovery of the spacecraft was both amazing and incredibly lucky. Because of a premature shutdown of the main engine, NEAR Shoemaker had been put into a spin, spewing thruster gas as it tumbled through space. The on-board computer had a special set of commands to follow in the event that it did not hear from Earth for a particular period of time. But because the spacecraft was tumbling and its antennas could not "lock" on the Earth, those commands were not working. NEAR Shoemaker was trying to take a star tracker image, determine where it was, and burn a thruster to put it in a configuration where it could transmit to Earth. But because the spacecraft was spinning rapidly, that process took too much time, so it would burn the wrong engine and Earth would not be in the right orientation. Finally, by chance, the recovery routine worked. The spacecraft figured out where it was, pointed toward Earth, and begged for help. Karl Whittenburg, who had not slept much in the several days of frantic activity, sent the commands to control the spacecraft and, using the contingencies that David Dunham had created, prepared it for resuming its journey. The mission was almost lost before it really began, but the hard work and earlier contingency planning of the team involved saved the day. It is also humbling to realize that plain old luck probably played an important role in averting this near-catastrophe. It is rare to get a second chance in the space exploration business.

Now the JPL NAV team had the most difficult task. They had no data to work with after the first split-second of the aborted engine firing. Once the MOPS team recovered NEAR Shoemaker, NAV still had no way of knowing exactly what had happened during the time that NEAR Shoemaker was out of contact. NAV basically had to start the process from scratch with only a day or two of tracking data to pin down the trajectory, and only a few hours to find the best solution. The range and Doppler data were the true heroes in this phase of the mission, giving NAV a decent (though not very accurate) trajectory to use for the sequencing of the flyby.

MSI decided that they needed to take mosaics of images covering everywhere the asteroid might be, to compensate for the larger-than-usual uncertainties in the trajectory. For example, if the navigation team said that the asteroid would be at a particular position plus or minus 1000 km, MSI would create a mosaic of images arranged in a square that would cover this "error ellipse." These mosaics would be repeated as quickly as possible, taking into account that the spacecraft was flying past the asteroid, the asteroid was rotating, and MSI would have to be slewing the spacecraft to get the mosaic. But MSI needed to make sure that they did not slew the spacecraft too quickly and smear the pictures. It took hours for MSI team members Scott Murchie from APL and Ann Harch and Maureen Bell from Cornell to put together all of the commands. Sometime around 8.00 p.m. on December 22 the sequence of camera commands was delivered to MOPS. They worked on it all night to prepare it for the spacecraft and sent it up, finishing just a few minutes before the sequence needed to begin executing. It worked perfectly, and the mosaics covered the asteroid almost exactly as planned. And, just as importantly, the successful firing of the main engine shortly afterwards placed us on track again for an orbit insertion with the asteroid, though one year later than expected. The images and other information about Eros were a wonderful Christmas present to the world, and provided us with crucial information about the asteroid that was used to plan the best possible orbital mission.

Cruising to the asteroid

We had one year to figure out whether we could make our lives easier the second time around. It became

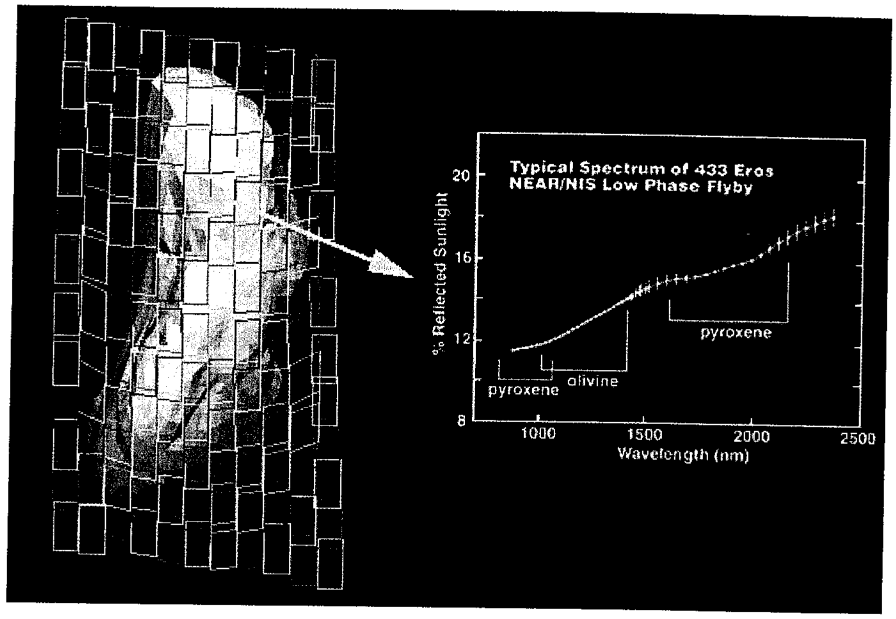

Figure 8.7. Just prior to orbit insertion on February 13 and 14, 2000, the NEAR Shoemaker spacecraft executed a series of observations using the NIS instrument with the Sun high in the Eros sky – optimal for collecting spectroscopic measurements. The predicted locations of NIS "footprints" from one such sequence of Eros measurements (left) resulted in a global spectral map; one example spectrum from the NIS data (right) shows inflections and weak absorption features diagnostic of the minerals olivine and pyroxene on the surface of the asteroid.

apparent during the flyby that MSI needed to have more sophisticated software – software that could not only compute the asteroid and spacecraft positions but also simulate the instrument commands. MOPS needed to work on a number of software problems on the ground as well as on the spacecraft. Everything needed to be fixed before January 2000 (not to mention any potential Y2K bugs) but it was decided not to send too many tests to the spacecraft during the cruise phase in order to conserve the limited available fuel.

The most important work for the imaging team involved the program that MSI used to do all of our sequence creation, *orbit*. The programmer at Cornell who had created *orbit*, Brian Carcich, spent many months adding the specific commands to move the spacecraft to create mosaics and the commands for the camera and NEAR Shoemaker's near-infrared spectrometer (NIS). One of the requirements was to be able to design something in *orbit* and create a file with the commands in the proper format so that they could be sent directly to MOPS – no edits or changes necessary. The MOPS team had all of the science teams create test sequences during the year and by December 1999, *orbit* was ready to carry the imaging sequencers through a year of weekly sequencing activities.

As we approached the asteroid again in January 2000, our software (both on the spacecraft and on the ground) was in the best possible state. We had a good understanding of each other as a team. We even had our approach sequences laid out. This time around we were not as nervous because the approach speed to Eros was only about 10 m/s, and slowing down to begin orbiting Eros did not require firing an engine, but merely performing a series of small thruster burns like the ones that we had done several times over the cruise year.

One of the unique aspects of the orbit insertion was that we were turning the spacecraft so that we could observe the "low phase point" for the NIS team. The low phase point is the spot from which sunlight reflects directly back to the spacecraft. On water this would show the glint or mirror reflection of the Sun. On small bodies like Eros, obtaining data in this kind of configuration can provide unique information about surface properties, like particle size, slopes, and degree of compaction. It was a difficult maneuver but critical for achieving the NIS science goals; NAV had determined that the best opportunity to perform this low-phase flyby was during the first part of the orbital mission. NIS sequencer Colin Peterson from Cornell worked closely with NAV and the science teams to build and deliver an excellent sequence of low-phase spectroscopic measurements.

Orbit insertion and the high orbits

NEAR Shoemaker performed the low-phase flyby and the insertion maneuver without incident. We were happy that everything went well and were ready to begin a year of science observations – and what turned out to be navigational firsts.

The high orbits (200 and 100 km from the center of mass of the asteroid) were the highest priority for the imaging team. MSI needed to map the entire asteroid

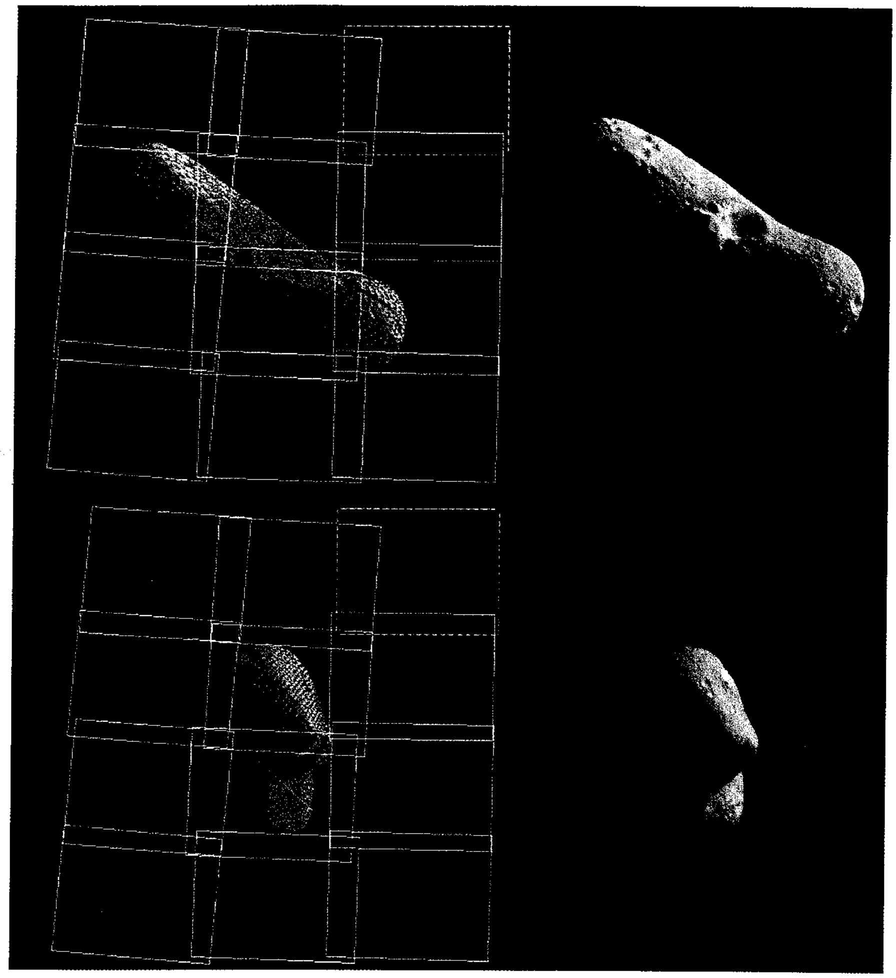

Figure 8.8. The predicted footprints and Eros orientations for two representative MSI image mosaic sequences taken during the high-orbit (> 100 km altitude) phase of the mission (left), compared to the actual mosaics acquired from these sequences (right). These were the first two mosaics of Eros taken just after the engines fired and put the spacecraft into orbit.

thoroughly from these distances through all of the available filters. We had not anticipated the amount of work that the weekly deadlines would entail and needed to continually readjust our workloads among team members.

The thruster maneuvers that changed the spacecraft distance for the high orbits were designed by Cliff Helfrich and Dan Scheeres on the JPL NAV team. They had calculated which orbits would be stable, in the sense that (a) they would not lead either to crashing on the surface or to escaping Eros's gravity and (b) small errors in the actual trajectory would not get magnified and lead to crashing or escaping. The maneuvers were usually only 1–2% less than or greater than expected. During these first few months it took the NAV team about a week's worth of data to come up with an accurate solution for the trajectory. Later in the mission, as the process was fine tuned, they could turn around a trajectory in a few days.

Additionally, MOPS had not anticipated some of the operating difficulties, including the need for extra trajectory uploads to the spacecraft for the many planned observations. It was a period of adjustment for all of the teams and stressful for many of its members. Neither the spacecraft nor the asteroid cared about human concepts like weekends and holidays.

During these high orbits the opnavs provided a framework for the navigation of the spacecraft and a sanity check for the Doppler data, which provided the bulk of the navigation information. Optical data cannot produce the gravity field parameters as effectively as Doppler data, nor can they provide the absolute size of NEAR Shoemaker's orbit; if Eros were bigger but less dense and NEAR Shoemaker had been in a larger orbit for the same period, then the pictures would not look any different. However, without optical data as a third component of the analysis, it would have been extremely difficult to get the OD to converge on the right solution using just range and Doppler data. So opnavs were typically performed three or four times a day. The opnavs would attempt to cover the entire asteroid in mosaics. Some of the most spectacular imaging turned out to be these series of opnavs during the high orbits.

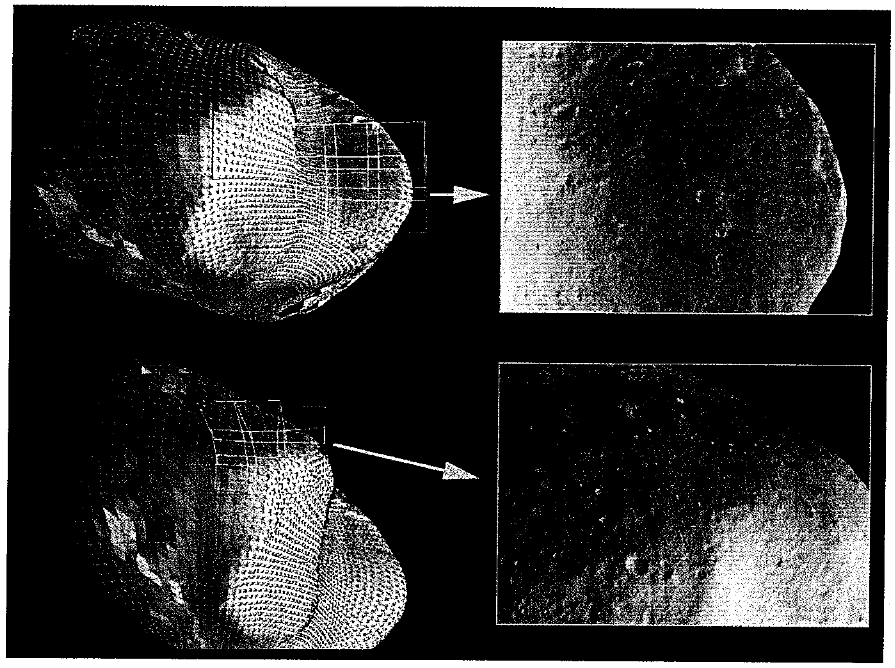

Figure 8.9. The predicted footprints and Eros orientations for two representative MSI image mosaic sequences taken during the low-orbit (50 km altitude) phase of the mission (left), compared to the actual mosaics acquired from these sequences (right). These pairs of image mosaics were taken at opposite ends of the asteroid within a 15-minute period three times per day.

Low orbits

During the low orbits the imaging team was no longer in control of the spacecraft. The X-ray/gamma-ray spectrometer (XGRS) team decided what part of the asteroid we would observe during each day. The 50-km orbit started in May 2000. We remained in a steady orbit 50 km from the center of mass of the asteroid until, in July 2000, we went into a two-week period at 35 km and then returned to 50 km before going back into another set of high orbits.

The entire low-orbit period was a time to recuperate from the grind of orbit insertion and high orbit. The XGRS team needed to view each part of the asteroid for long periods, so they usually pointed NEAR Shoemaker to a fixed position and let the asteroid rotate under them for most of the day with no fancy mosaics or movements of the spacecraft. MSI and NIS would continually shoot pictures and spectra as the asteroid rotated, which provided imaging for the XGRS team and entirely covered the asteroid at this resolution. The MOPS and MSI teams welcomed the relief of the predictable routine. But the NAV team had a different problem. The error accumulated during the five-week low-orbit operational phase meant that NAV needed to update the on-board trajectory more often to keep the instrument pointing errors to a minimum.

The 50-km orbit was retrograde; that is, NEAR Shoemaker was moving one way while Eros rotated in the opposite direction. This kind of orbit is preferred, because the gravitational "tugs" from the ends of Eros do not last as long if the spacecraft and Eros are moving in opposite directions. In the opposite scenario, a so-called "direct" orbit, the spacecraft would spend much more time over each end, and the orbit would change much more quickly. Before too long NEAR Shoemaker would have either crashed on to Eros or been thrown completely out of orbit. For this reason we had no choice but to have NEAR Shoemaker travel in a retrograde orbit. However, with the retrograde orbit and the direction of the Sun, the spacecraft was forcing itself into an "uncomfortable" position and building up momentum within its reaction-wheel pointing system whenever it pointed to the asteroid; it needed to unspin these wheels weekly through small thruster firings to release or "dump" the unwanted momentum.

Every day during the low orbits the imaging team had to point three opnavs for the NAV team. The opnavs now consisted of pairs of observations. Bill Owen identified 44 craters on the surface for MSI to target as often as possible. In order to get the best possible viewing of a crater it needed to be almost directly under the spacecraft and close to the terminator. By making observations a few minutes of time apart of a pair of craters separated by several degrees on the surface of the asteroid, the NAV team could pinpoint NEAR Shoemaker's location in three dimensions to a few meters. The navigators also used 50% of the observations taken during the fixed pointing time period. This gave NEAR Shoemaker the most accurate pointing possible and led to Bill Owen (as well as many of the science team members) knowing almost every small crater on the surface of the asteroid intimately.

The targeting of the opnavs proved to be a tedious job for MSI so Brian Carcich set out to make our lives easier once again. In his *orbit* program, he made it possible for us to place a cursor on the asteroid and simply click on a desired feature to save the x, y, and z coordinates to be put into the pointing command. He also created a process by which we could easily identify and target opportunities for imaging of any of the craters that were on the NAV team's list of favorites. It was ingenious and made our lives bearable for the week-to-week grind of targeting and turning in sequences.

During the 50-km orbit, discussion began about the possibility of a low-altitude flyover (LAF), moving the spacecraft for a short time very close to the asteroid. The NIS team had originally planned a second low-phase flyby in October but, because of the instrument's untimely demise in May, that period opened up as a good opportunity to try out the LAF idea. At the same time, planning of the final phase of the mission, when the spacecraft would run out of fuel, began. The idea of a landing on the asteroid had been kicked around for several years. No one had ever done it before so it was intriguing. All of these ideas landed on the shoulders of the NAV team. Could they put together the sequence of thruster firing events that needed to happen to have a low-altitude flyover and have the spacecraft survive?

The 35-km orbit in July provided additional tests of the maneuverability of the spacecraft, as well as the best opportunity to determine the gravity field of Eros from radio science measurements. The XGRS team found that their gamma-ray instrument was not as sensitive as they had hoped and they needed to get closer to capture the weak gamma radiation. NAV considered the opportunity to be perfect for testing their ability to maneuver the spacecraft closer to the asteroid. The 35-km orbit was a success from the point of view of the navigation team. They had come in close, orbited for a week and pulled out to 50 km without any problems. Unfortunately for the gamma-ray team, there was a solar flare that was so intense that it shut down the instrument temporarily. XGRS had lost valuable data but NAV had gained valuable experience.

Flyovers and the landing

In September of 2000, we were back in high orbit. The NAV team sent a LAF test trajectory to the science teams for their approval. They had found a way to do a low-altitude flyover that involved a number of thruster firings to bring the spacecraft close (from 100 km to 50 km to 35 km to 20 km). The last burn would sling shot the spacecraft into a highly elliptical orbit that came within 5 km of the asteroid's surface. The MSI team worked for most of September and October to create a set of commands that would maximize the viewing of the asteroid while taking into account the possible errors in the trajectory. We did not want to end up taking pictures of unlit asteroid or black space just because the trajectory was off by a degree or two.

Rick Shelton on the MOPS team and Maureen Bell on the MSI team stayed in daily contact during most of October, testing and tweaking the commands to get the best possible product. Everything went smoothly until three days before the LAF burn. Then we received a call from Karl Whittenburg in MOPS. Murphy's Law was with us and the spacecraft had gone into what is called "safe mode." NEAR Shoemaker's on-board computer was programmed to monitor the spacecraft's position and health constantly. When the computer software recognized an unacceptable situation, NEAR Shoemaker would automatically turn itself into a safe position with its antenna pointed toward Earth asking for help and instructions. It was quickly determined that the cause was minor rather than a spacecraft health problem, so the LAF burn was still on but without the optical observations for the days leading up to it. The Doppler data were vital to the NAV team for determining the pre-burn trajectory.

On October 25, 2000, NEAR Shoemaker swung in towards Eros, took its pictures and darted back out into a 200 km orbit. The data collected during the close encounter were played back three times to be sure that nothing was missed. It was a highly successful encounter. The navigation again worked perfectly. The spacecraft thrusters performed flawlessly and the images were all of the illuminated asteroid. The science team was thrilled with the diversity of geology studied for the first time at this scale on such a small solar system body. Now all the teams were ready for the final set of navigation challenges.

Another low-altitude flyby was planned for January 2001. This one would bring NEAR Shoemaker in even closer to the asteroid (within about 2 km) and it would maintain an elliptical orbit around 20 km. It was several days long and included several downlink periods and close flyby periods. It was a new level of difficulty for the NAV, MOPS, and MSI teams. This time Murphy left us alone. The thruster firings

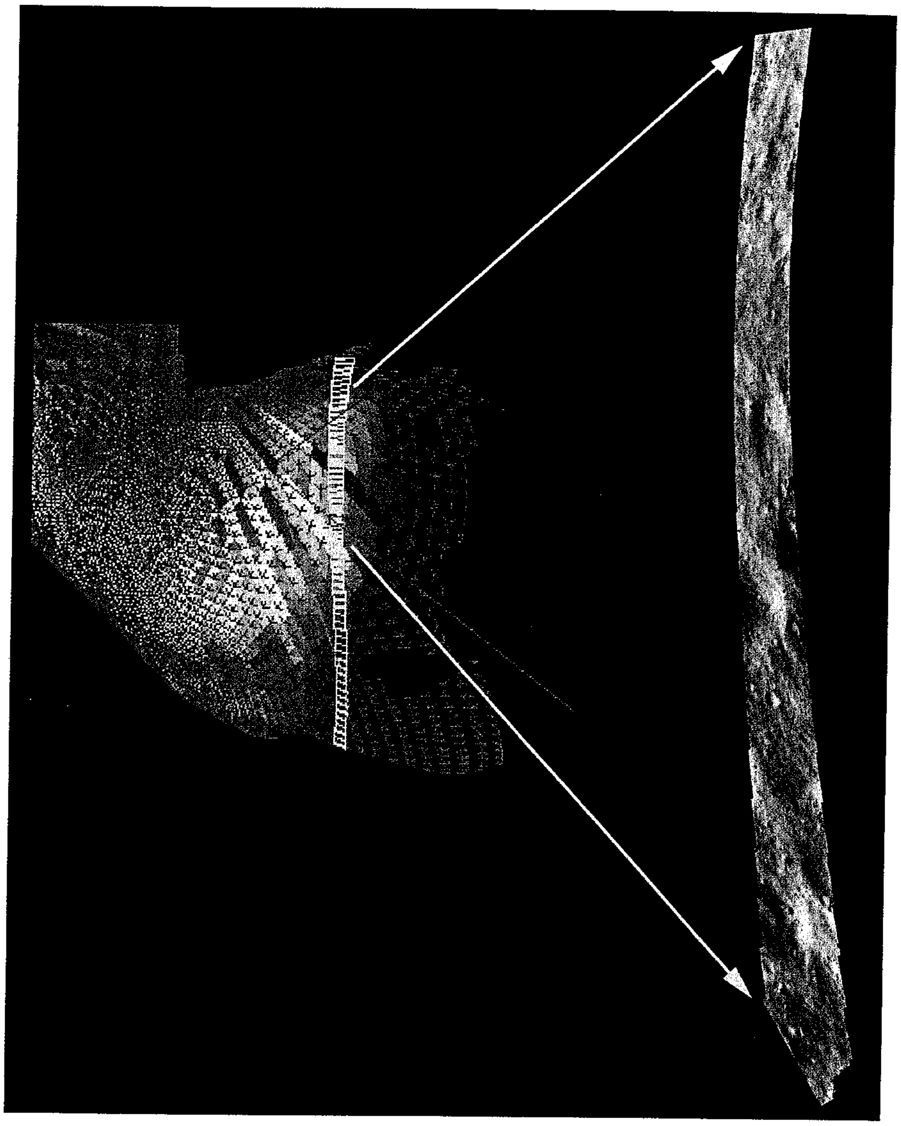

Figure 8.10. The predicted footprints of images taken as NEAR Shoemaker attempted its first low-altitude flyover on October 26, 2000 (left). The image mosaic on the right is a small portion of the images taken just after the closest approach, which was between the two craters that are shadowed in the footprint plot.

occurred without incident, and the pictures were even more spectacular.

The final challenge was landing on the asteroid. The process of determining where and how to land had started back in the summer of 2000. In November, at a meeting of the NAV, MOPS, and MSI teams, it became obvious that the descent trajectory plus the pointing constraints determined our landing site for us. In order to take pictures of the asteroid as we descended to the surface, it was necessary to maintain a very specific configuration. The spacecraft's high-gain antenna, which transmitted data to Earth, had to remain pointed to Earth constantly during the landing. The solar panels had to stay pointed at the Sun to maintain power. The cameras had to point at the surface of the asteroid. The antenna, panel, and camera are all at right angles to each other so there was only one small subset of options if we wanted to be in this configuration. The constraints led us to a landing at latitude 35° South. The position and trajectory were fixed. NAV designed a series of thruster burns to bring the spacecraft in closer. Karl Whittenburg created special commands for the spacecraft for each stage of the landing. He and Ann Harch of the MSI team worked out a set of camera commands that would take images continuously and transmit them to Earth in pairs. (NEAR Shoemaker stored all images on to a solid state data recorder and then transmitted them to Earth; there was no option for direct transmission of data.)

All the teams converged on APL on February 12, 2001, except for the NAV team who still had the job of tracking the spacecraft back at JPL. We had all worked hard for a year and felt pretty happy with the results and with the very cool way that the spacecraft was ending its life. No one expected the spacecraft to survive. The mission operations center was packed

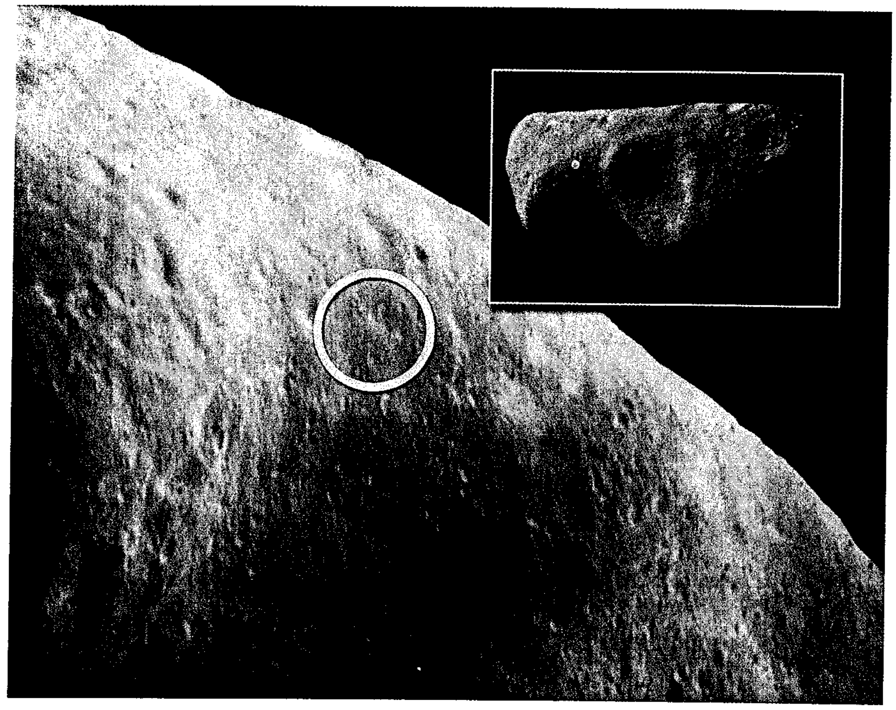

Figure 8.11. The location of the landing site for NEAR Shoemaker's "controlled descent" to the surface on February 12, 2001. The main image shows the touchdown site (yellow circle) on the edge of the saddle-shaped feature Himeros. The inset is a mosaic of eight images showing the site in the context of the eastern part of the southern hemisphere of Eros. The landing site straddles two major terrain types on Eros: older, heavily cratered southern highlands, and the younger, less heavily cratered interior of Himeros.

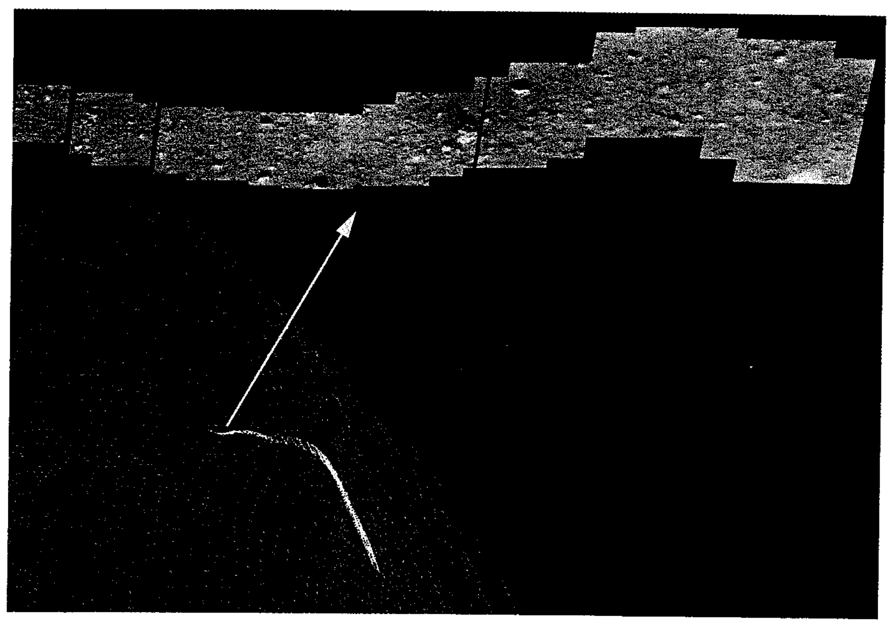

Figure 8.12. The predicted footprints of images taken as NEAR Shoemaker descended to the surface of Eros on February 12, 2001 (bottom). During the descent, NEAR Shoemaker took a strip of more than 70 images, crossing from the southern highlands into Himeros. The image mosaic of 15 of the final images taken by NEAR Shoemaker's cameras are shown at the top. The final images show details on the surface smaller than 10 cm (4 inches) across.

with the NEAR management team, the operations people, and a few press people and dignitaries. Mostly it was a room filled with anticipation; everyone was waiting to see whether NEAR Shoemaker could really do this spectacular feat.

The descent thruster firings began, the spacecraft descended, and images began to roll in. In the image-processing room at APL, we saw the pictures first and processed them, then sent them on to the mission operations center to be displayed on screen for the television cameras. We all sat together reading off the values of the height from which each image had been taken, marveling that everything was working perfectly. When the final picture came in we were startled to find out that the spacecraft had "landed" two minutes earlier than expected and was performing a burn during the landing. But even this contingency had been planned for – the onboard accelerometers detected the jolt, determined that we had supplied enough downward thrust, and then most likely reversed the thrusters. This had created a soft landing. Otherwise we might have lifted back off from the

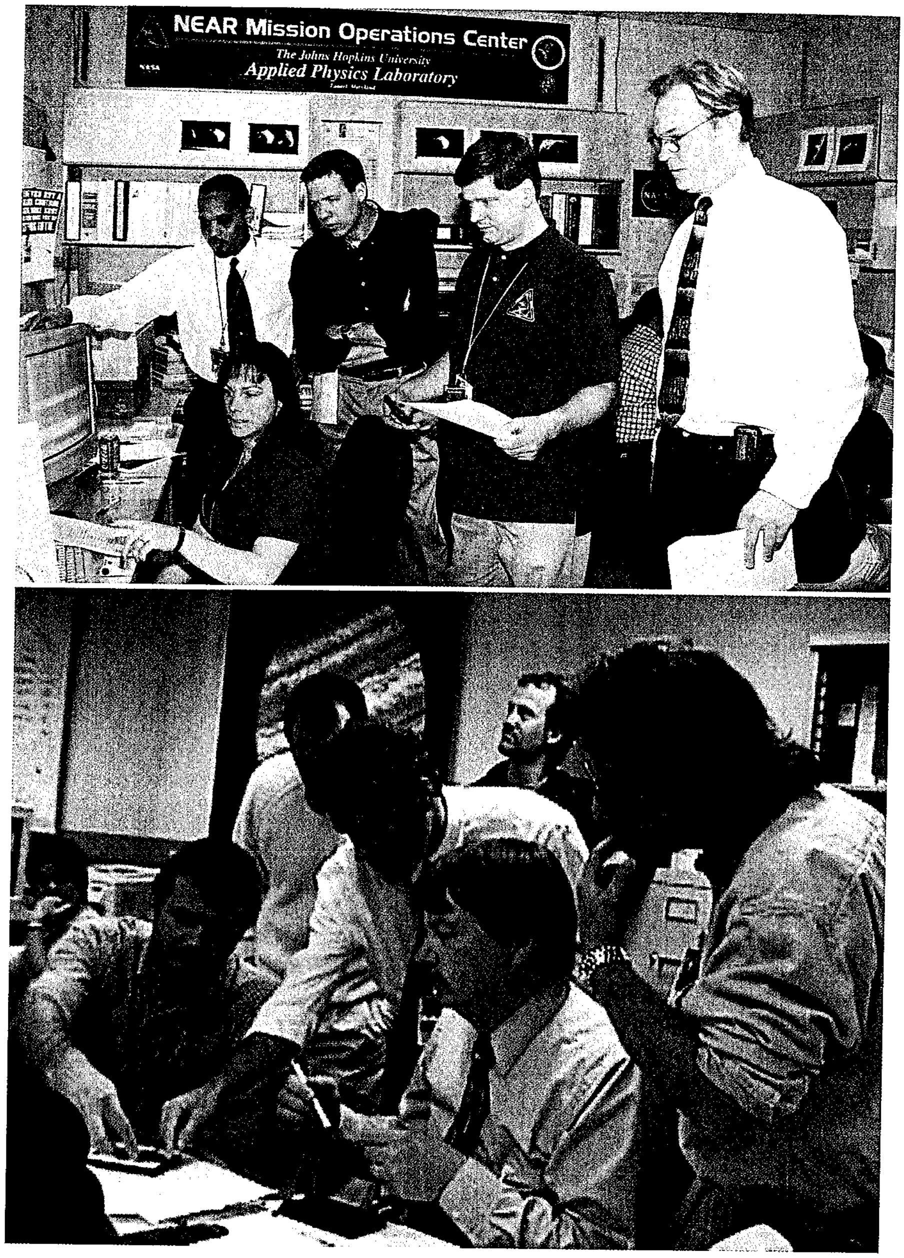

Figure 8.13. The media and science teams converged on the JHU APL Mission Operations Center (top) and the JPL navigation office (the war room, bottom) to watch NEAR Shoemaker's historic descent to the surface of Eros. Top photo: APL MOPS team members from left to right: Owen Dudley, Carolyn Chura, Robert Bokulic, Karl Whittenburg, and Robert Nelson. Bottom photo: JPL NAV team members from left to right: Margie Medina, Steve Chesley, Cliff Helfrich (head partly hidden), Mike Watkins, NAV team leader Bobby Williams (holding pen), and Pete Antreasian (foreground).

surface, or at least bounced. The spacecraft survived and maintained its antenna alignment with Earth (miraculously) and began sending back its navigation information.

Events unfolded with similar excitement at JPL. The NAV "war room" was electric, with the team still working hard. NAV team leader Bobby Williams was on the special voice line to APL; Pete Antreasian, Steve Chesley, and Eric Carranza were at computers, monitoring the real-time data; Jim Miller was watching the predicted descent curve and calling out numbers; Mike Wang and Bill Owen were running back and forth between the war room and the opnav room, where they would quickly download the latest images. There was a closed-circuit video feed from MOPS in one corner of the room. Maybe 25 other folks squeezed into the room, mostly navigators on other projects, but also a news crew. One computer monitor showed the altitude measurements superimposed upon the predicted distance from NEAR Shoemaker to the ground. The measurements fell right on top of the line, indicating that all the maneuvers had done their jobs and we were on the right course. We all realized that the events we were watching had already happened some 17½ minutes before, and that we were powerless to change things in any event, but this knowledge did nothing to dispel the tension. Then the Doppler data changed abruptly, and four of the six DSN antennas that were listening to NEAR Shoemaker lost lock. But two Goldstone antennas continued to receive a signal! Not only had we landed, but NEAR Shoemaker was still alive and well! Nobody expected that. It was a phenomenal end to a year of driving a spacecraft.

Although it would have been fun to fire the engines again and bump the spacecraft off the surface, there was not enough fuel left. So NEAR Shoemaker performed one more task. It took gamma-ray data for 12 days and transmitted these back to Earth. It was put to sleep in a safe configuration so that the team could try at some future date to do something that had never been done before – awaken a computer that has slept through a long cold night on the surface of an asteroid.

The NAV team had been planning for the NEAR mission and landing for several years. At a conference in August 1999 they had presented a paper called "Preliminary Planning for NEAR's Low-Altitude Operations at 433 Eros." In the abstract they had written, "This paper will provide preliminary plans for mission design and navigation during the last five weeks of the orbit phase, where several close passes to the surface will be incorporated to enhance the science return. The culmination of these close passes will result in the eventual impact of the spacecraft on the surface of Eros. The possibility of hovering within 1 km from Eros's surface exists and could be incorporated into a landing design." The JPL navigation team accomplished more than they dared hope for, with the help of the teams at APL and Cornell. They managed to keep the spacecraft on track so that it could take a total of almost 200000 MSI images, and similarly large amounts of data for the other science instruments. Despite many near-tragedies, it was, in the end, a picture perfect mission.