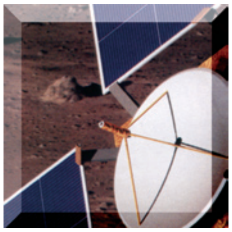

Making NEAR Work: Cooperative Modeling and Simulation with an Advanced Guidance and Control System

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The Near Earth Asteroid Rendezvous spacecraft performed a 1-year orbital mission around asteroid 433 Eros until 12 February 2001. The mission consisted of daily science data collection events and occasional orbit correction maneuvers, and culminated with a controlled descent and soft landing on the asteroid's surface. These events all required meticulously planned, simulated, and executed spacecraft pointing scenarios. An advanced guidance and control system and a high-fidelity visual planning tool were critical for these operations as was the close interaction among the imaging scientists, the guidance and control engineers, and the navigation team. These teams used detailed truth models of both the spacecraft and asteroid environments. Of particular interest was the controlled descent to Eros' surface, which consisted of pointing and thrusting events simultaneous with image collection. The unexpected survival of the spacecraft on landing permitted the collection of telemetry data pertaining to the final resting attitude.

INTRODUCTION

The Near Earth Asteroid Rendezvous (NEAR) mission was the first launch of the NASA Discovery Program.[1] Built by APL, the spacecraft launched on 17 February 1996 and commenced a 3-year journey (plus a 1-year aborted burn recovery period) to asteroid 433 Eros, which it orbited for nearly a year (14 February 2000 to 12 February 2001) to collect scientific data. Since NEAR had no gimbaled subsystems, the entire spacecraft had to be maneuvered to accomplish the various around-the-clock pointing events. Daily science events involved pointing the sensor suite toward designated asteroid surface areas or toward star fields for instrument calibration. Several times per week, NEAR was maneuvered to point its high-gain antenna toward Earth for a period averaging about 8 h per contact. During the yearlong orbital phase around Eros, the spacecraft also performed 25 orbit maneuvers that necessitated specific inertial pointing attitudes. When not performing one of these three events, NEAR was maneuvered to point its fixed solar panels a specified angle and direction off the Sun to perform system momentum changes using opportunistic solar radiation pressure.

Because the guidance and control (G&C) system was involved with spacecraft pointing and control at all times (except in the lowest-level safing modes), a considerable amount of modeling and simulation of the G&C system was required to support the various pointing events. Handling of Earth contact and passive solar momentum dumping events soon became routine and was accomplished with onboard algorithms[2] with little human interface. Design of the science events, however, required considerable simulation time and manpower, not only for the G&C team, but also for other teams at facilities remote to APL. Each team (G&C at APL, navigation at the Jet Propulsion Laboratory [JPL] of the California Institute of Technology, imaging at Cornell University, and mission design at APL) used a high-fidelity model of the spacecraft and/or asteroid tailored to its specific area of emphasis, and required coordination with the others via an iterative process.

This article gives a brief description of the spacecraft and overall G&C system and then describes in detail the simulations and iterative simulation processes used by the teams that were necessary to create and implement NEAR's science collection events. A major event at the end of the mission was the controlled descent and soft landing on the surface of Eros,[3] where the spacecraft survived and continued operating until powered down 2 weeks later. The descent was monitored in real time by using the onboard NEAR Laser Rangefinder (NLR) as a surrogate altimeter and comparing the time history of collected ranges against predicted ones. We discuss the method of prediction and the final results. Finally, we discuss the impact and probable resting attitude of the spacecraft on the surface of Eros based on available post-impact telemetry and anecdotal information.

OVERVIEW

The Spacecraft

The NEAR spacecraft was conceptually simple with a minimum of moving parts. All sensors and solar panels were rigidly fixed to the spacecraft, i.e., there were no gimbals for moving either G&C sensors or science sensors. Since the solar panels were fixed, the G&C system oriented the $+z$ side of the spacecraft sunward, normal to the solar panels, at all times to maintain charge on the relatively small battery. During nonscience events, the spacecraft spent most of the time with the z axis pointed directly at the Sun for power, slightly off the Sun for momentum dumping, or directly at Earth for communications purposes. While in orbit, NEAR maintained an orbit normal of 30° or less from the Sun at all times; therefore, when pointed directly at nadir, science instruments (aligned along the spacecraft x axis) caused a 30° Sun angle or less on the solar panels. At times these instruments pointed away from nadir to image other asteroid features and produced a larger solar panel Sun angle.

The Guidance and Control System

Spacecraft attitude determination, guidance, and attitude control were the responsibility of the G&C system.[4] The mission required attitude knowledge to be accurate to 50 μrad and attitude control to be within 1.7 mrad for all three axes, although star calibrations suggest attitude control was at least an order of magnitude better than the requirement. Four reaction wheels controlled attitude at all times except during thrusting maneuvers. Since spacecraft torque from only a single thruster would overwhelm the reaction wheels, the wheels were not useful during orbit maneuvers. Instead, the suite of thrusters was programmed to provide attitude control by individually modulating on/off as needed at a 25-Hz rate.

The onboard guidance algorithms were made relatively complex and advanced to ease the burden of pointing the spacecraft. Guidance algorithms computed the desired attitude and rate based on a small set of parameters. The guidance portion of the G&C system used current spacecraft position and velocity, an object position and velocity, and a roll orientation to compute the instantaneous seven-element desired attitude state at the 25-Hz rate. Algorithms and code were reused, with slight modifications, from the Midcourse Space Experiment (MSX), which was required to track moving objects as well as observe ground or atmosphere locations fixed to the rotating Earth. Early in NEAR's development process, analysts recognized these algorithms as being ideal for smoothly pointing at a moving asteroid or a fixed feature on a rotating asteroid, given the orbital motion of the spacecraft.

NEAR could point any vector in the spacecraft body coordinate system in any inertially fixed or moving direction defined in one of four coordinate systems: (1) J2000 inertial, (2) asteroid centered inertial, (3) asteroid body fixed (ABF), and (4) off-nadir angles. Additionally, each of the four methods optionally invoked a scan pattern that overlaid a cyclical time-dependent motion relative to the baseline attitude profile. These motions took the form of linear, raster, sawtooth, or great-arc scan patterns. Examples included the motion of an object across an imager's focal plane and motion through various asteroid surface locations to build up organized mosaics. The workhorse of the science collection events was an algorithm called the spacecraft body fixed (SBF) scan pattern.

Modeling and Simulation

Figure 1 shows the interactions among the various support teams for simulating two types of events—science data gathering events that occurred multiple times nearly every day for the entire year and thrusting maneuver events that were comparatively infrequent (approximately twice per month). Given the unpredictable nature of the mission, the science teams could implement very little automation. In anticipation of the tremendous workload, pointing design was divided between two science subteams. The Multi-Spectral Imager/Near Infrared Spectrometer (MSI/NIS) instrument team at Cornell controlled pointing for all

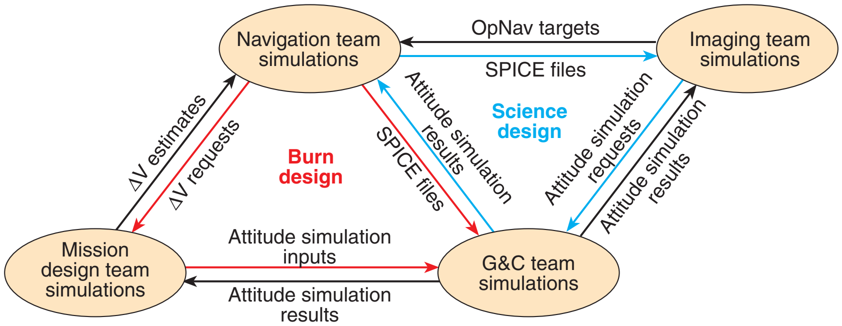

Figure 1. Design process interactions. An OpNav file contains an optical navigation image. A SPICE (spacecraft, planet, instrument, "C-matrix" events) file is a standardized means of transmitting planetary, spacecraft, and other ancillary information.

high orbits and for the special events that included the low-phase flyover, low-altitude flyovers, and landing. The X-Ray/Gamma-Ray Specrometer instrument team, also located partly at Cornell, controlled pointing for all low-orbit mapping cycles. The much less frequent thrusting event simulations demanded nearly as much attention and manpower because of the necessary attention to detail, the high risk associated with failure, and the continuous effort to improve the gyro, accelerometer, and thruster models.

As shown in Fig. 1, the science simulation process included primarily the science teams at Cornell and the navigation and G&C teams from JPL and APL, respectively, that played critical support roles. The thrusting simulation process involved the navigation team, the G&C team, and an additional team at APL dedicated to mission design. Imaging simulations were not involved in thrusting events.

Navigation Team Modeling and Simulation

A description of the navigation team's modeling and simulation efforts is discussed in depth in several sources.[5,6,7] Their responsibility was to provide after-the-fact navigated orbits based on radiometric and optical (landmark) tracking, provide predicted orbits up to 2 weeks in the future, and design the final descent trajectory. As such, the team had to model the complete environment of the spacecraft, including radiation pressure, thruster forces, asteroid shape and density, and Eros' gravity field. The navigation team created and used a shape model, augmented by NLR measurements, that was derived independently from the Cornell imaging team's model, which used only image data.

G&C Modeling and Simulation (Nearsim)

Nearsim was a 30 to 35 times faster-than-real-time simulation involving a mixture of Ada and C that evolved into a high-fidelity model of the spacecraft dynamics. It was the primary method of modeling and verifying that the G&C system would perform the attitude and thrusting maneuvers requested by the science and navigation communities. The genesis of Nearsim involved the flight software development group that needed a method to test G&C algorithms. They had to verify that the guidance system would produce the correct commanded attitude state and that the control system would guide the spacecraft to that state. It quickly became apparent that, with a little enhancement, the method could be upgraded to a complete dynamic model.

The appeal of Nearsim was that it ran the actual G&C flight code that was written in Ada, minus any real-time and run-time controls; thus, it was not dependent on the error-prone process of interpreting and recoding the algorithms into a second language. The Tartan Ada compiler for the 1750a processor generated the actual flight code. The truth model and highest-level controlling routines in Nearsim were written entirely in C and invoked the Ada code as subroutine calls. The truth model simulated a complete spacecraft environment for encompassing the Ada code and consisted of models of the star camera, Sun sensors, gyros, accelerometers, reaction wheels, thrusters, solar pressure, solar panel vibrations, fuel inertias, fuel slosh, etc. Inputs to Nearsim were via text files; no attempt was made to simulate realistic serial digital command streams. Output from Nearsim consisted of a file of time-dependent attitude states, thruster firings, wheel speeds, spacecraft modes, fuel levels, system momentum, and other derived variables. In particular, attitude states were analyzed for pointing performance and were then forwarded to scientists at Cornell for imager footprint analysis by a program called Orbit.

Imaging Modeling and Simulation (Orbit)

The NEAR imaging team at Cornell developed the Orbit program as a tool to assist with the creation of imaging and spectrometer command sequences (personal communication, developer Brian Carcich, Cornell University). Orbit was a C-based program that ran on Unix platforms using the Motif graphical user interface. The advantage of building the tool rather than buying a commercial off-the-shelf visualization program was simply that within the limited resources available, the program could be continually updated and modified throughout the mission to suit the changing needs of the sequence design process. Total control and flexibility were formidable allies against the ultimately unpredictable nature of NEAR's mission.

The primary function of Orbit was to project instrument footprints onto a shape model of Eros. Trajectory information, spacecraft orientation, and asteroid orientation were accepted from predicted files or from after-the-fact telemetry from the spacecraft. Orbit was capable of displaying the correct orientation of Eros and the footprints at each time step through a sequence, i.e., the user could step through a sequence of images and watch the displayed orientation of Eros update to the corresponding time of each image. This program provided a means of integrating instrument commands with spacecraft pointing by allowing the user to visualize the outcome of specific command sequences. The user could evaluate frame-to-frame overlap and changes in viewing conditions on the surface with time.

The Eros shape model used by Orbit was generated by another software package developed at Cornell called Points.[8] Using MSI images along with corresponding spacecraft position and pointing information, Points employed a stereogrammetric algorithm to determine control points (locations of features on the asteroid's surface). The set of individual control points was then transformed into a global shape model that was of sufficient detail to allow for efficient science planning. Refinement of the model was a continual process throughout the mission as new regions of the asteroid became illuminated for the first time, and as already imaged regions were acquired at better resolution.

Orbit was most heavily used for building actual command sequences for science observations. In this mode, Orbit used predicted trajectory information provided by the navigation team for the spacecraft and planetary bodies. It also used pointing and instrument command parameters in a format identical to the spacecraft's command data structures. Orbit most often applied a simplified model of the spacecraft pointing; however, for observations that either stressed the guidance system or required more sensitive modeling, the G&C team performed simulations using Nearsim and generated high-fidelity inputs for Orbit.

As already noted, Orbit could be driven by information extracted from actual spacecraft telemetry. By saving footprint information generated in this manner from observations performed throughout the mission, Orbit and associated programs generated coverage history maps, i.e., maps indicating how the quality and quantity of coverage varied across the surface of the shape model. Sequence planners used these maps to develop strategies to optimize future coverage of Eros.

EROS SCIENCE OBSERVATION DESIGN AND SIMULATION

The NEAR orbital mission represented the first time in history that a spacecraft had been put into orbit about a low-gravity, fast-spinning, irregularly shaped object. The yearlong mission presented a remarkable array of opportunities to acquire unique high-resolution imaging and spectral data of an asteroid surface. Equally tremendous was the array of challenges confronting sequence planners in their attempt to ensure the acquisition of high-quality science data. The imager, spectrometers, and NLR each imposed specific requirements on the spacecraft viewing and solar illumination angles. A complex and changing array of spacecraft, navigation, and operational requirements imposed further constraints on the science sequence design process during the different phases of the mission. The versatility of the NEAR G&C system, combined with the ability to simulate every aspect of this complex problem, was fundamental in handling these constraints and ultimately enabled every goal to be achieved.

Solving the Geometrical Challenges

The process of simulation and evaluation began years prior to the Eros encounter when long-range mission planning trajectories were made available by the JPL navigation team. The science teams analyzed these trajectory profiles using the simulation software described previously and evaluated coverage possibilities offered by the variety of orbital options, analyzed the potential degrading effects of pointing error, and tested the effectiveness of sequence update procedures. In an iterative fashion with the navigation and mission design teams, the mission plan and operating procedures were refined to enhance the science opportunities.

The final NEAR mission plan provided complete mapping of Eros' surface during two-thirds of the asteroid's 1.72-year orbit about the Sun. With its spin pole tilted 60° from its orbit normal, illumination on Eros slowly progressed from north to south over the course of the mission year. Solar panel requirements constrained the spacecraft orbital plane to never deviate more than 30° from the plane normal to the Sun. As Eros proceeded about the Sun, NEAR's orbital plane was gradually shifted to continually satisfy this constraint. As shown schematically in Fig. 2, equatorial orbits were required at the start and end of the mission, and polar orbits were required during the middle of the mission. The overall plan included opportunities to view Eros' southern and northern hemispheres when lit both from high orbits (100–200-km radius) and lower orbits (50- and 35-km radius). Special events included a zero-phase flyover (both Sun and spacecraft at "high noon" above imaged region) of the illuminated northern hemisphere, several extremely low-altitude flyovers near the end of the mission, and the slow descent to landing.

Understanding the geometry of each phase was the first step in determining what could be accomplished scientifically. The viewing opportunities depended on many factors including orbital radius, spin rate of Eros, solar illumination, and orbital inclination. The orbital

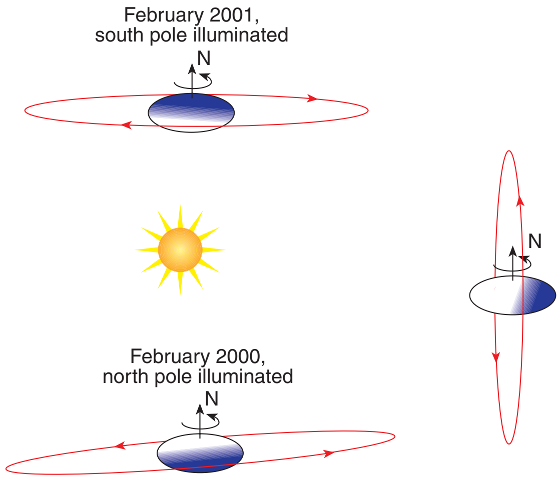

Figure 2. Schematic view of spacecraft orbits about Eros at selected positions in the asteroid's orbit about the Sun.

radius roughly determined the size of the instrument footprint as it projected on the surface. At high altitudes, the imager footprint subtended a large portion of the asteroid, whereas at low altitudes it only subtended a tiny fraction. The spin of Eros continuously brought new longitudes into view, repeating the same longitude every 4.5 to 6.0 h depending on the orbital radius and direction. The latitude of the subsolar point determined the overall illumination of Eros; however, illumination was also affected greatly by the irregular shape of Eros and its spin. On spherical bodies, the terminator (line between lit and shadowed surface) traces a great circle about the planet, but on Eros' elongated and deeply faceted body, the terminator wandered wildly across ±50° of latitude during each rotation. Finally, the orbital inclination determined the extent of latitudinal viewing available to the instruments.

Each observational phase could be grossly characterized by understanding the relationship between the subsolar latitude and the inclination of the orbit. An example is the 200-km north phase, a 4-week period that began soon after orbit insertion. This 206 × 203 km orbit had a period of 10.1 days and was inclined 34° to the equator. The Sun was shining on the mid-north latitudes. The schematic orbital view in Fig. 3 shows that the northern hemisphere was continuously sunlit through each full spin of Eros, while the southern hemisphere was in perpetual darkness. Spacecraft latitude cycled slowly from 34°N to 34°S and back over the course of each 10-day orbit, bringing the spacecraft view to the lit and dark sides, respectively. The Orbit plots in Fig. 3 contrast the two viewing opportunities (the blue axis is the north spin pole, and the red and green axes lie in Eros' equator). The right panels show two snapshots of Eros as viewed from the peak northern orbital latitude; the left panels show views from the south.

A second example, shown in Fig. 4, is from a 50-km orbital phase when the Sun was near the equator and the orbit was nearly polar. Over the course of each orbit (about 1.25 days) the spacecraft flew once over each pole and provided good high-resolution viewing of the north polar region, which was still illuminated at this time of the mission. The two left views show an image track laid down through a 4-h sequence during a north pole crossing (image frame spacing is 10 min). The imaging strips spiral around the planet because of asteroid spin. The color scale represents emission angle

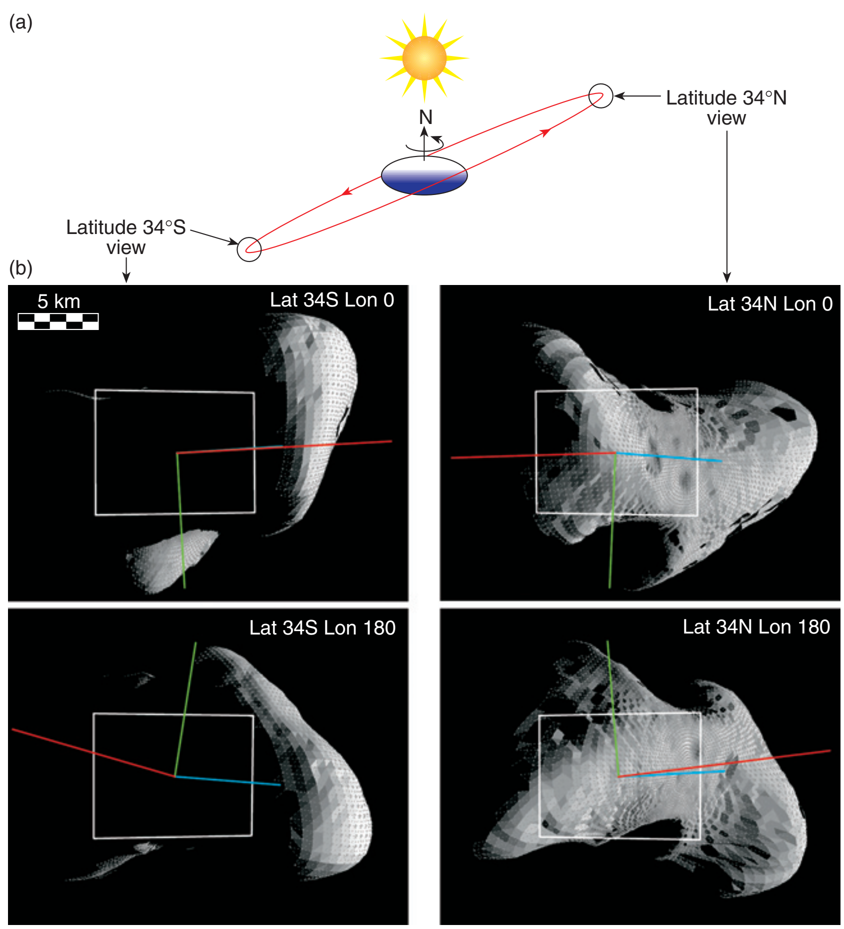

Figure 3. (a) Schematic of a 200-km-altitude orbit inclined 34° to equator (spin period = 5.27 h, orbital period = 10.1 days). (b) Orbit plots: two snapshots of Eros viewed from the peak northern (right) and southern (left) orbital latitude.

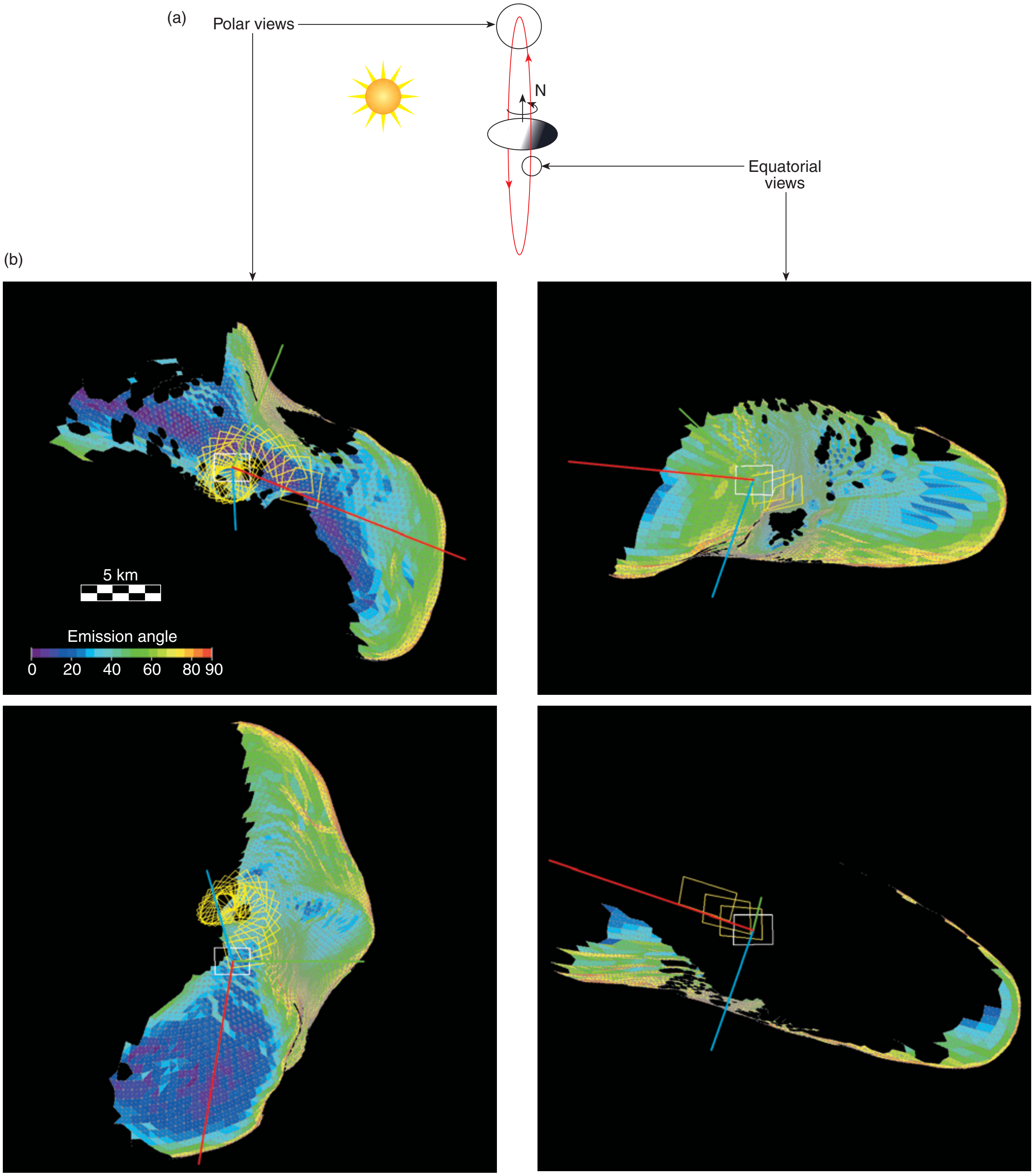

Figure 4. (a) Schematic of a 50-km-altitude polar orbit (spin period = 5.27 h, orbital period = 1.25 days). (b) Views of Eros at polar (left) and equatorial (right) crossings. Upper and lower plots are from the spacecraft perspective at the start and end, respectively, of each sequence.

(blue regions indicate a view that is more perpendicular to the surface). The two right views are from an Eros equatorial crossing; in a matter of only 30 min, much of the lit hemisphere was consumed by darkness. In general, high-resolution color imaging of the equatorial regions required critical timing to catch the brief periods when patches of surface were illuminated properly; however, the bulk of the mapping sequences in the low polar orbits proceeded without concern that some images or spectra would be dark. Pointing was optimized to give the best cumulative lit coverage over each daily 16-h mapping period.

Naturally, the high orbits were good opportunities to acquire global views of Eros because the fields of view

(FOVs) subtended a large portion of the asteroid. At a 200-km range, it was possible to capture the entire globe of Eros with a mosaic of 9 to 16 frames (depending on the view). At a 100-km range, global mosaics were nearly impossible. In the lower orbits (50- and 35-km radius), the pointing strategy was limited to staring passively at a fixed or slightly varying off-nadir position while taking spectra and images at the proper rates as the territory passed beneath the FOV. This resulted in long spiraling strips of images or spectra that built up regional coverage on a time scale of days and weeks.

Mission orbital restrictions prevented the spacecraft groundtrack from deviating more than 30° from the terminator throughout the mission, thereby forcing high incidence (low Sun) to occur simultaneously with low emission (vertical viewing). This can be seen in Fig. 4 where the lowest emission views (blue areas) occur mostly near the terminator. The result was good shadowing that highlighted surface morphology and facilitated shape determination and landmark identification. Ideal viewing conditions for the spectrometers, however, required simultaneous low emission angles and low incidence angles, i.e., vertical viewing with the Sun at high noon. These conditions were geometrically impossible to achieve; nevertheless, whenever possible, the mission design team was able to improve viewing by deliberately tilting the orbital plane toward the Sun as far as panel restrictions allowed.

Pointing Options at Eros

The NEAR G&C system afforded seemingly infinite flexibility in the pointing of instrument sequences; however, for orbital operations designers relied primarily on the use of off-nadir and ABF targeting, and on the SBF scanning algorithm. Off-nadir was used heavily throughout all phases of the mission, pointing the boresight to an off-nadir position and then holding that position indefinitely. This polar coordinate system is defined by an elevation value (angle from nadir) and azimuth value (direction from nadir). The advantage of this targeting mode was that zero azimuth was always in the direction of the Sun, regardless of the spacecraft position in orbit or asteroid spin state. Constant off-nadir values of 4° to 6° elevation and −30° to +30° azimuth maximized lit viewing time regardless of downtrack errors.

The SBF scanning algorithm deviated pointing from the target by using rotations about the SBF axes, driving scan pattern motion in directions parallel to instrument FOV edges, and making it possible to build up square mosaic patterns with predictable frame-to-frame overlap. This system was also disengaged from asteroid rotation, thereby making the mosaics easy to slide in the timeline. An important use of SBF was building cooperative MSI/NIS observation mosaics, especially in the high orbits for global imaging. The mosaic slewing proceeded continuously along each column (normal to the NIS mirror scanning direction), so that strips of images could be acquired while simultaneously stacking multiple NIS scans (Fig. 5). This scanning technique was also used to create "flyover" movies whereby the scanning motion steered the pointing along limbs, or to regions of interest, giving the illusion of flying over the surface of Eros.

The alternative to off-nadir pointing was to target an ABF position. This forced the boresight to track a selected point on or within the asteroid as it spun below, providing the opportunity to follow regions of interest on the surface. A feature could be tracked for hours as it passed through a wide range of spacecraft viewing and solar incidence angles. Superimposed over this track was an optionally applied SBF or ABF scan pattern. The former was used to create a small coherent mosaic about the surface feature; most optical navigation mosaics were designed with this scheme. The latter could drive scanning along the spinning axes of Eros for which there were numerous applications.

Last Minute Pointing Corrections

Prior to orbit insertion, the NEAR G&C system had proven to be extremely accurate by routinely pointing the imager within 1 pixel of any object. Thus, any orbital phase pointing error was purely derived from orbit prediction error resulting from a combination of burn execution errors and imperfect knowledge of the gravity field. It was anticipated that gravity knowledge error would be an issue after dropping to each new low orbit; however, it ultimately was a factor only during the first few weeks following orbit insertion.

The long-range predicted mission trajectory used for planning (before orbit insertion) assumed an asteroid mass that carried with it fairly significant uncertainties. After arrival and determination of the mass to first order, it was known that the mission plan might have to be revised immediately and signifcantly.

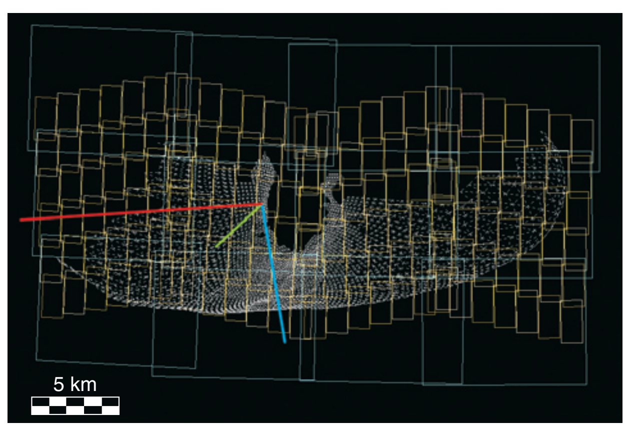

Figure 5. Cooperative MSI/NIS observation design.

The JPL navigation team agreed that when revising the long-range orbital predictions, they would hold the dates of maneuvers and orbit radii constant, and would accommodate any change in mass by letting the orbital periods vary. This would benefit planning in that mosaic shapes would not have to be resized because of the change in angle subtended by the asteroid that accompanied a change in orbital radius. The observations could simply be moved in time by sliding the predesigned mosaics until they fit properly on the revised timeline at the correct latitudes of viewing and within the previously fixed Deep Space Network tracks. This strategy most directly benefited the highly critical 200-km north orbital phase described earlier, which came shortly after orbit insertion.

Throughout the remainder of the mission, the main source of orbit prediction error came from uncertainty in burn execution. Though it was never possible to predict the magnitude of the errors, on average they were less than about 3% of the magnitude of the burn. To visualize the degrading effects of orbit error, it was useful to model the components of the errors in the downtrack, radial, and crosstrack directions. The solar incidence, emission, and viewing angles to any surface area could be drastically affected by only moderate downtrack errors, which were synonymous with a rotation of Eros (see Fig. 4). Radial errors caused the asteroid surface to subtend a larger or smaller angular size relative to the footprint but never created a problem. Crosstrack errors, however, resulted in lateral offsets of the FOVs that at times were significant.

The extent that trajectory error affected any sequence was a function of how long the error would propagate as well as the availability of a pointing correction. In the normal sequence building process, pointing and timing parameters were developed based on the best available predicted trajectories and were frozen 1.5 weeks prior to upload of the sequence. At the time of sequence upload (and sometimes during execution of the sequence) a more accurate trajectory would become available and would be uploaded to the spacecraft. For off-nadir targeted observations, the orbit update would correct crosstrack error (lateral displacement of the frame) by recentering the observations relative to asteroid nadir. However, it could not correct for the effects of downtrack error.

In contrast, an orbit update would force any ABF-targeted observation to point to the most accurate revised location of the target, correcting both crosstrack and downtrack error. In the low orbits, where the asteroid subtended a very large angle relative to the FOV, with a moderate downtrack error, this correction could also result in a significant angular shift in pointing direction and with it the potential for solar panel violations. As a precaution, for several weeks following each drop to low orbit, the use of ABF was restricted to prevent such violations while the burn errors were characterized and worked into the revised predicted trajectories. The exceptions were several high-risk events, where Mission Ops allowed the loading of revised trajectories and shifted sequenced times merely hours before the scheduled event.

Throughout the mission, characterization and simulation of the effects of these potential errors was key to planning observations that had a high probability of success. The Orbit visualization tool allowed scientists to simulate the maximum possible downtrack errors by playing with the rotational state of the asteroid. Crosstrack errors could generally be assessed by eye. Burn errors were never predictable, but sequences were planned for the full range of possible errors, from none to worst case. Designs were made for the case of large uncorrectable errors by building observations that would safely return a nonoptimized data subset. Additionally, designs were made for complicated observations that required nearly perfect burn performance. These had a higher science payoff and carried the risk that they might not work. Albeit, greater than 99% of all observations attempted were successful.

DESCENT SIMULATION AND RESULTS

The descent design, described in detail by Ref. 7, incorporated five thruster braking events called end-of-mission maneuvers (EMM-1 through EMM-5). EMM-1 moved the spacecraft from a circular 36-km near-equatorial orbit to a 36×7 km elliptical orbit with 135° inclination and with perigee over the mid-southern latitudes near the nominal impact point. EMM-2 occurred near perigee at approximately a 5-km altitude, took the spacecraft out of orbit, and put it on its final, nearly vertical trajectory.

Of particular interest to the G&C team was the remainder of the vertical descent after termination of EMM-2 when continuous surface imaging was initiated. Beginning at that time, NEAR was maneuvered such that the high-gain antenna kept in continuous contact with Earth, while simultaneously the NLR and imagers pointed generally in the nadir direction (see Fig. 6a for descent orientation). The remaining EMMs (3–5) were designed to keep the instruments pointed near nadir and to minimize the vertical and lateral impact velocities. The spacecraft was rolled slightly for each particular burn such that the instruments pointed less than 10° off the vertical trajectory plane. This attitude design allowed for a continuous transmission of images, NLR ranges, and attitude frames to Earth during the descent.

The capability of putting the NLR range data into the real-time telemetry stream provided the opportunity to monitor the progress of the descent by considering the NLR as a surrogate altimeter and comparing the real-time range observations with a set of predicted

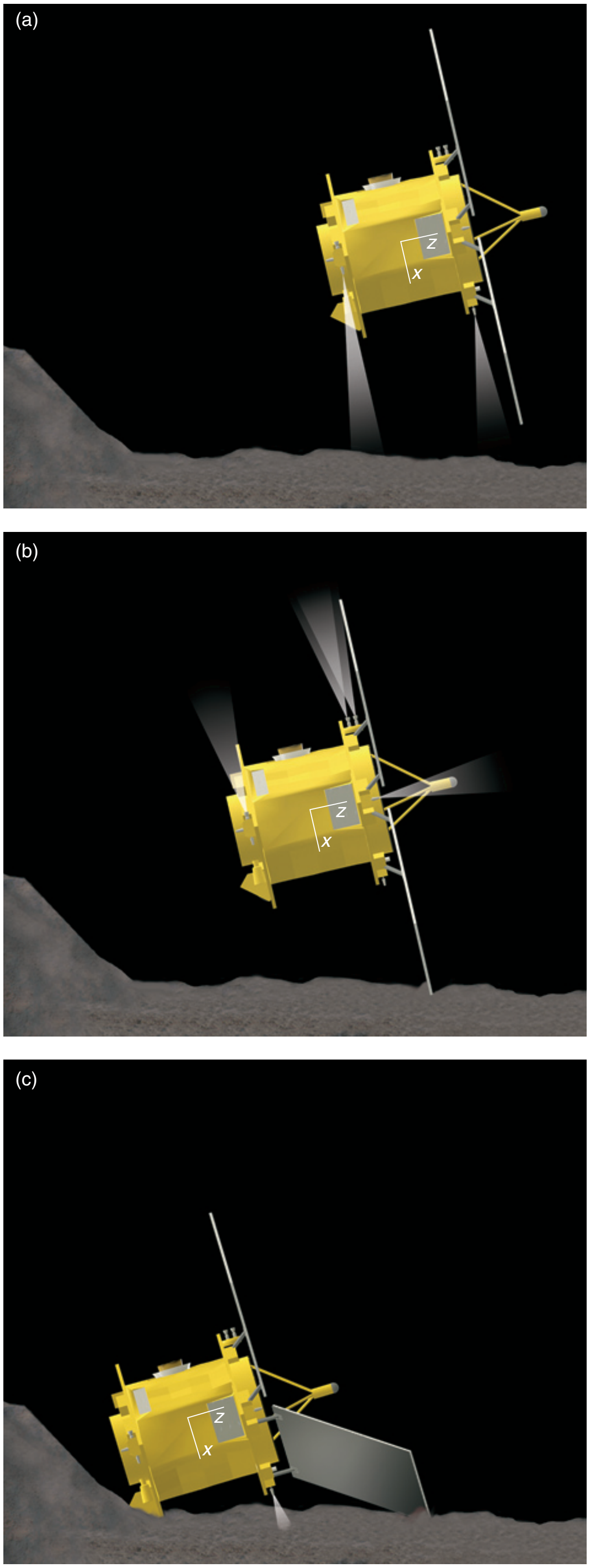

Figure 6. Sequence of events from impact to final resting attitude. (a) −*x* thrusters slow descent of NEAR, with slight aft component. (b) Impact creates a sensed overburn condition, causing −*z* and large +*x* thrusters to force spacecraft into the surface and aft. (c) Attitude correction firings attempt to raise nose toward Earth, but NEAR is wedged or panels permanently planted in surface.

range observations. The predicted ranges were generated by a concerted and iterative effort using products from all three simulation teams. First, the navigation team incorporated the thrusting profile provided by the G&C and mission design teams and delivered their final predicted trajectory for the descent (many months of effort had been spent to reach this point). Next, the G&C team used Nearsim with the EMM 3–5 orientations and slew rates to generate the final detailed attitude profile and supplied it to Cornell for use in the Orbit program. Using the planned trajectory, the Nearsim products, and the preplanned sequence of image times, the imaging team used the Orbit program to project footprints of the imager's FOV onto the 3D model of the asteroid. A by-product of this effort was the set of predicted ranges (from the spacecraft to the center of each footprint) that was created by using a pierce-point algorithm. These ranges were plotted versus elapsed time from the start of EMM-2 and were displayed on a publicly accessible Web page.

Software automatically extracted the actual NLR ranges from the real-time telemetry frames that were deposited every 55 s in NEAR's Science Data Center. These ranges were overlaid in real time on the predicted plot on the Web page; thus, anyone accessing the page could monitor the progress of the descent to the surface. Operationally, mission personnel used the plot to predict the time of impact, the time of expected last image, and the time of expected loss of signal. Figure 7a shows the final predicted/actual range results; Fig. 7b shows the residuals. The simulations and models used in creating the expected range calculations were an accurate gravity model from the JPL team, the precise shape model from the Cornell team, accurate thrust predictions for a fuel system running on empty, and an accurate spacecraft attitude pointing prediction.

IMPACT AND ATTITUDE STABILIZATION

Initial concerns

The capability of the spacecraft to survive the surface impact was never a requirement; however, it became obvious during planning of the descent that a few simple measures could be implemented to increase the minuscule chances of survival. The G&C team and navigation team collaborated on iterative simulations to converge on a final plan. The foremost factor was to minimize the impact velocity; as the design matured, the navigation team was able to estimate that the impact velocity would be in the interval range (1.0–2.8 m/s),[7] but no one knew of or had conducted any mechanical analysis to estimate what a survivable impact velocity might be.

Another concern addressed was the possibility that the spacecraft might have excessive lateral velocity at

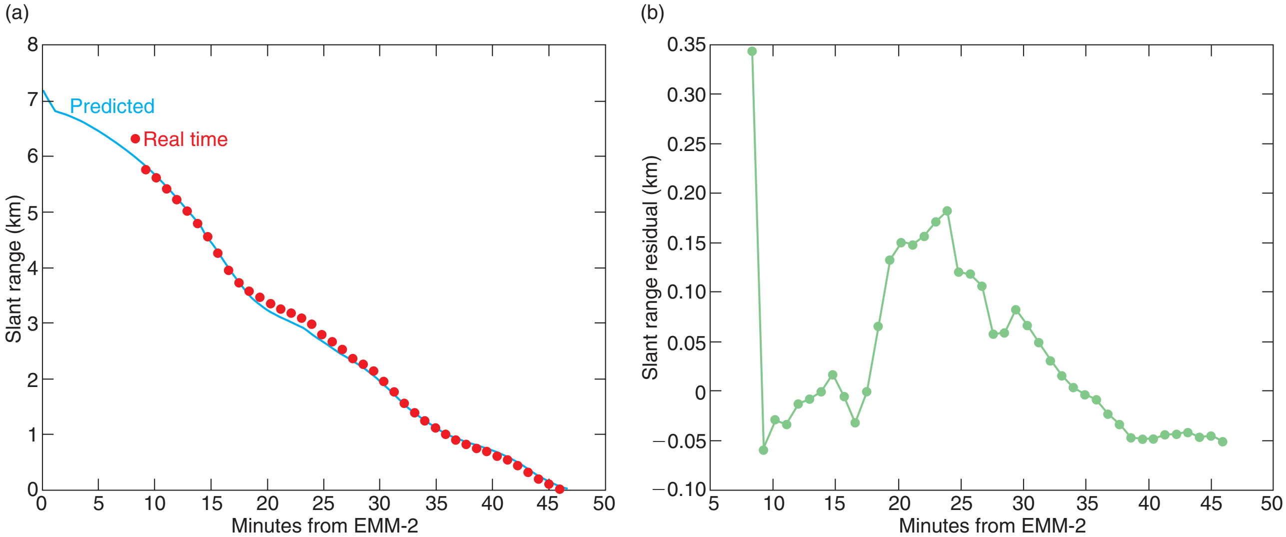

Figure 7. (a) Predicted range to surface and actual laser ranging data during descent. (b) Difference between predicted and actual laser ranging data during descent.

the point of impact and start tumbling end-over-end an unknown number of times, perhaps coming to rest upside down. Simulations showed that in the low-gravity environment, a lateral velocity exceeding 1.0 m/s in any direction might provide enough momentum to overwhelm the attitude thrusters and tumble the spacecraft at least once. With this in mind, the navigation team designed EMMs 3–5 to minimize the ground drift rate at the nominal time of impact (a natural westward component of drift existed because of the asteroid's west-to-east rotation). The histogram of the final Monte Carlo simulation results showed that lateral speed would range between 0.02 and 0.76 m/s and would be centered at 0.4 m/s.[7]

Finally, there was speculation that NEAR could actually bounce off the surface to a height conducive to further image collection. The response of the spacecraft to the impact depended on the elasticity of the mechanical frame, the hardness of the surface, and the time of impact—all of which were unknown. If the spacecraft impacted during EMM-5 while the thrusters were firing, it was conjectured that the vehicle might bounce dozens of meters above the surface. If it impacted during a benign thrusting period, it was thought that the ground and NEAR might absorb most or all of the kinetic energy and result in little or no bounce. The idea of a high bounce was not really a concern, but was treated as an opportunity to acquire additional images of the surface; therefore, image collection and thruster attitude control remained enabled for 14 min after nominal impact time. Speculation of what would happen during the 14 min of thruster activity after impact ranged from the idea of total nominal attitude control while above the surface (the "high bounce" assumption) to continuous attitude thrashing and "crabbing" about on the surface until fuel was depleted.

Reconstructed Impact Scenario

Based on time of loss of the high gain telemetry signal and observed change in Doppler signal, NEAR impacted the surface approximately 185 s into the planned 309-s-long EMM-5. This implies that the thrusters on the bottom were firing continually upward, slowing the descent rate at the instant of impact (this was one of the *a priori* factors of the high bounce hypothesis). After loss of the high gain telemetry, the only telemetry recovered during the following 2 weeks of extended life was a small slice of high-rate gyro/accelerometer/thruster data from the few minutes following impact but before thruster shutdown, and a few quaternion attitude solutions each day derived from gyro and solar data. From these data and other anecdotal information, the best-guess sequence of events from the instant of impact to the time of final resting attitude has been formulated as follows (and see Fig. 6).

The navigation team estimated an impact velocity of about 1.7 m/s by propagating the trajectory downward using trended NLR altimetry data (which terminated at an altitude of 17 m), the predicted thrusting profile, and the JPL gravity model. Likewise, the science team estimated a lateral velocity at point of impact of about 0.2 m/s in a groundtrack direction going away from Earth. Image analysts derived this value by trending feature centroids from the last four images received from NEAR. Unknown thruster pulses after the final image added a small uncertainty to this value.

The sudden stop of the fall of the spacecraft caused the top-side thrusters to ignite in an attempt to maintain downward velocity for the remaining 124 s of the planned 309-s burn. Since EMM-5 was configured as a closed-loop burn, thrusting control was based on measured accelerometer data. In this mode, a burn that exceeded the desired ΔV target value, as measured by the accelerometers, caused opposing thrusters to fire in an attempt to restore the accumulated ΔV to the target value. Because of the early surface impact, this feature was apparently triggered during EMM-5; the accelerometers had sensed a sudden stop, and thrusters fired to restore the motion. The downward thrusting pushed the spacecraft into the surface, either wedging or "embedding" it, possibly in an immovable position. Telemetry showed that the attitude transient from impact had been benign, changing only enough to lose high-gain antenna telemetry that was spread out over a relative wide frequency range. The Deep Space Network system maintained carrier lock in a small (10-Hz) frequency range, apparently on a spacecraft sidelobe, that allowed uninterrupted Doppler data collection.

After thrusting to attempt a downward velocity for 124 s (until the end of the EMM-5 burn window), preset commands disabled the downward-forcing thrusters, and, most likely, upward-forcing thrusters were fired in an attempt to correct attitude. The fragment of high-rate telemetry data received after impact suggested that these firings were at a fairly high duty cycle, but there was no appreciable attitude motion (supporting the embedded theory). Later telemetry fragments from the surface containing tank pressures and thruster pulse counts suggest that fuel was depleted roughly 15 m after impact.

Final Resting Attitude

Over the 16 days following impact, 34 usable telemetry frames containing G&C attitude information were collected. Attitude data generated onboard from gyro measurements and Sun angles allowed analysts to construct the final resting attitude. The Star Tracker telemetered a saturated background state at all times, suggesting that, even though it was pointed generally toward deep space, there was a large bright object (e.g., a hill or boulder) just to the rear of the spacecraft. This corroborates an independent hypothesis[9] based on final images that the spacecraft landed near the edge of the bottom of a 4.5-m crater, implying that the star camera would have been pointed at or near the brightly lit wall of the crater.

The JPL navigation team released a preliminary estimate of the landing site a few days after the impact. From that, the G&C team identified the corresponding plate in the 22098-plate shape model, determined the local normal to the plate and, by knowing the rotation attitude of the asteroid, calculated NEAR's attitude relative to the plate, the Earth, and the Sun. Figure 8 shows the best-guess final attitude derived from telemetry. The back end of the spacecraft is declined only 17° from horizontal. This implies that the back end is sitting on a raised prominence, the solar panels are embedded in the surface, and/or they are bent forward around their attach hinges, thereby lowering the front end. The star camera points up and 25° to the rear. Since the star camera was saturated for all monitored telemetry frames after impact, the implication is that the local relief must be very high beyond the rear of the spacecraft. During each rotation of the asteroid after NEAR came to rest, the Earth and Sun swept out 34° and 12° cones, respectively, in the spacecraft body coordinate system. These cones were inherently predictable during the 2-week extended surface mission and eased the burden of spacecraft operations. Figure 9 is an artist's rendition of the most probable resting attitude.

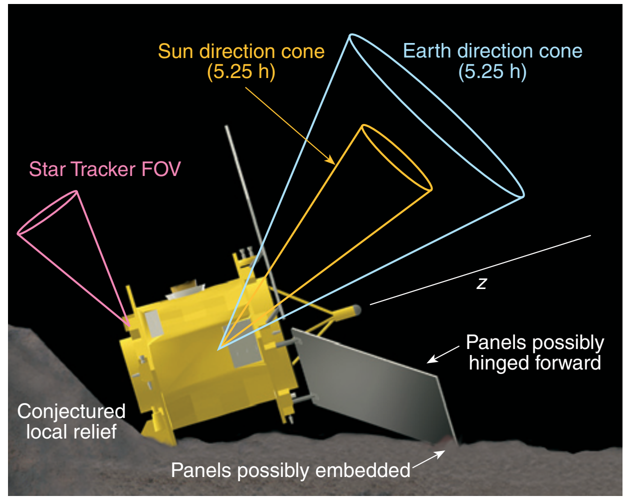

Figure 8. Best-guess resting attitude.

CONCLUSIONS

The NEAR spacecraft used advanced G&C algorithms that benefited from the coordination of many sophisticated simulations, models, and interactions among planning teams in Ithaca, New York, Pasadena,

Figure 9. Artist's rendition of the most probable resting attitude.

California, and Laurel, Maryland. These algorithms enabled pointing capabilities that accomplished the tasks of collecting imaging mosaics (≈180,000 images), tracking inertially moving objects (features on the rotating asteroid), and executing a soft survivable landing on the surface.

Cornell's Orbit simulation program was the workhorse for creating imager sequences that mapped the entire surface of Eros. This visualization program, which overlaid instrument footprints on a computer model of the asteroid, was essential for planning the geometrically challenging pointing requirements.

Software simulations by JPL's navigation team completely modeled the spacecraft's challenging external environment to successfully navigate, plan, and predict spacecraft positions and velocities over the course of the orbital phase and through the landing event.

The planning of the soft landing event involved extensive simulation by the navigation and G&C teams. Only through these accurate and iterative simulations could the landing speed have been designed small enough (≈1.7 m/s) such that the vehicle miraculously survived to operate an additional 2 weeks on the surface of Eros.

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ACKNOWLEDGMENT: The research in this article was performed jointly by JPL, APL, the Cornell University Center for Radiophysics and Space Research, and the Northwestern University Department of Geological Sciences under contract with NASA.

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