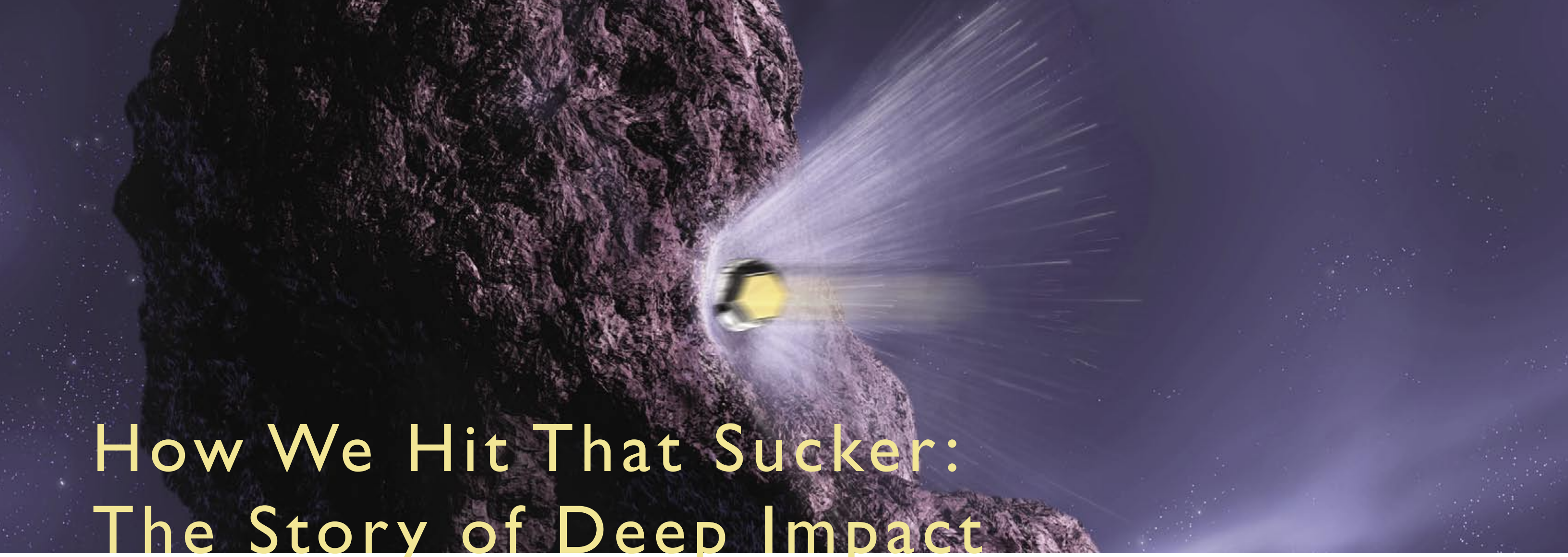


How We Hit That Sucker: The Story of Deep Impact

by William M. Owen Jr.

"It's a big bullet with a small bullet hitting a comet. So Dr. Owen, how did *they hit that sucker?" – Le Val Lund*

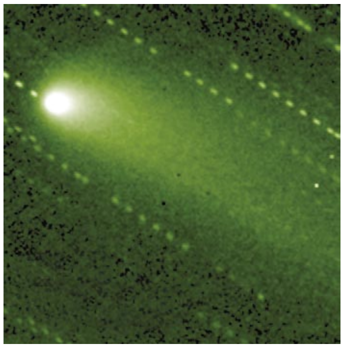
"You want to do WHAT??!!"

In a fit of irrational exuberance on the Fourth of July 2005, our project manager Rick Grammier yelled out, "We hit that sucker!"

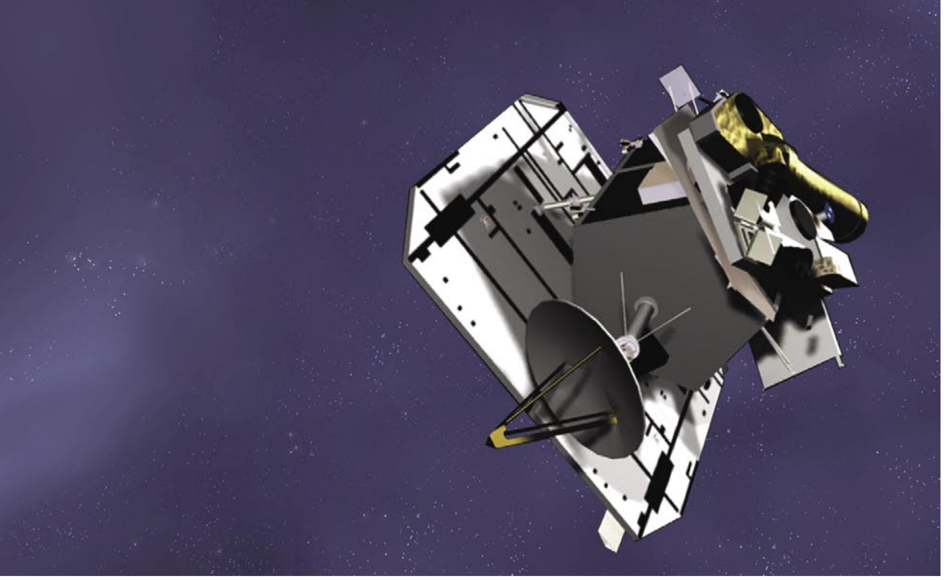
How do we make a hit like that? To paraphrase the bridgekeeper in *Monty Python and the Holy Grail*, we just had to answer these questions three: First, what was our quest, or where did we want to go? That falls under the general heading of mission design. Second, where in space were we, and where was our target? That's orbit determination, which is where I fit into the scheme. And what could we do about getting to our target? That's maneuver analysis.

Before we get into how Deep Impact did it, we need a little bit of background. As always at the start of a mission, we begin with the science objectives. In our case, the requirements were, "We want to hit a comet." At JPL, the reaction was, "You want to do WHAT??!!" The principal investigator, Michael A'Hearn at the University of Maryland, planned this mission to improve our knowledge of key properties of a comet's nucleus by means of a massive impact at high velocity. In other words, he wanted to make a crater in order to directly assess the interior properties of a comet and figure out what it is made of. Every time a comet sails past the sun, it loses a little bit of material, which is what makes its tail. But if we could dig a hole deep enough, we would excavate to a pristine level that hasn't been perturbed the way the surface has. The underlying material preserves the primordial ingredients from which the planets of our solar system condensed some 4.5 billion years ago.

Our target was Comet 9P, otherwise known as Tempel 1. The P means periodic and the nine means it's the ninth periodic comet discovered. Comet 1P is Halley, which was the first discovered to be periodic. Tempel 1 was the first of four periodic comets discovered by astronomer Ernst Wilhelm Leberecht Tempel during a scan of the sky on April 3, 1867. All periodic comets, and there are 182 known, have orbital periods of less than 200 years. Tempel 1 has an orbital period of less than six years, and although gravitational influence from Jupiter threw off its orbit and led to its "disappearance" between 1879 and 1967, since 1978 it has been viewed from Earth, like clockwork, every 5.5 years. It's not bright enough to be seen by the naked eye—Tempel 1 has an apparent magnitude,



Comet Tempel 1 on August 21, 2000. The color is false: the areas that appear green are actually the darkest, and the bright cloud is sunlight reflected off of dust grains in the comet's tail. This picture, which captures about 175,000 kilometers of sky at the distance of the comet, is a composite of 19 separate images taken as the comet moves across the sky, so background stars appear as dotted lines. North is at the top and east is to the left. The images were taken by J. Pittichová and K. Meech at the University of Hawaii's 2.2-meter telescope on Mauna Kea.



or brightness, of 11, and the magnitude of the dimmest stars we can see without a telescope is six. But it's predictable and easy to get to.

When you look at a comet, you see mostly the fuzzy head, or coma. Not all comets have tails, and periodic comets are generally faint and don't have much of a tail. Tempel 1's coma is thousands of kilometers across and a bit asymmetric, which might suggest difficulties in finding a good impact site. To make this mission even more challenging, we needed to hit the nucleus, or the hard core of the comet, inside the coma. And, as David Levy once said, "Comets are like cats. They have tails, and they do precisely what they want."

We were aiming for a cometary nucleus whose dimensions were estimated to be 14 × 4 kilometers. Which is pretty crazy, because if we miss the target by 500 meters, it could all be over.

This was not the first time a spacecraft had launched something on a collision course with a planetary object. Galileo carried a probe to Jupiter in 1995. Cassini dropped the Huygens probe onto Saturn's moon, Titan, in early 2005. But Jupiter is the largest planet in the solar system, and Titan is bigger than Mercury. We were aiming for a cometary nucleus whose dimensions were estimated by the Hubble and Spitzer space telescopes to be 14 × 4 kilometers. Which is pretty crazy, because if we missed the target by 500 meters it could all have been over. And our spacecraft reached its position just one day before impact, while in other missions the spacecraft arrived weeks or months ahead of time. But I'm getting ahead of myself.

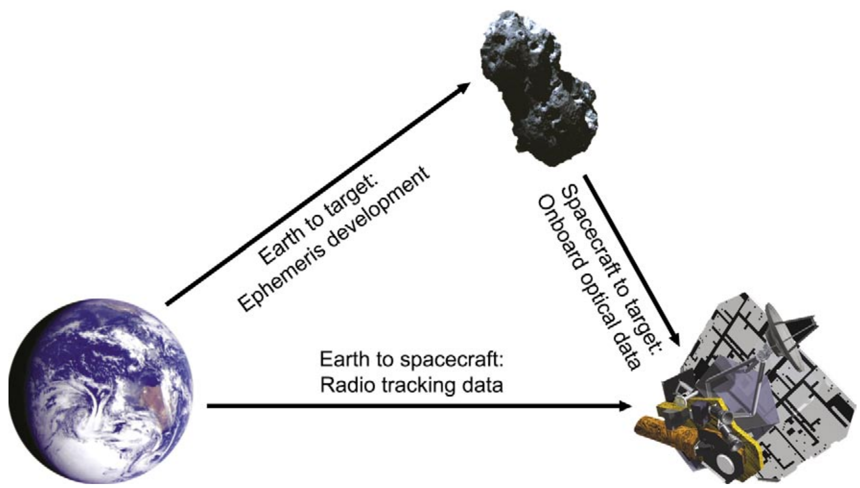
Designing a Mission

A space mission begins with trajectory design, which includes orbit determination and maneuver analysis. Trajectory design answers the question, "How do we get there?" The comet's nucleus is just a few kilometers across, so our flight path has to be known to something better than a couple of kilometers if we want to have a prayer of hitting it. So we've got accuracy requirements, and in order to achieve them we've got to have enough data coming in. That drives all the schedules for radio data, for onboard camera capability to gather optical data, for maneuver capability (including errors!), and all the other operations necessary for a successful mission. And it's all got to fit in the schedule and the budget, and, we hope, not work our people too darn hard.

To integrate a trajectory, or in other words determine where in the solar system our spacecraft is, all we need to do is a plain old numerical integration of the Newtonian formula $F = ma$ (force equals mass times acceleration)—just figure out the gravitational accelerations of each solar system object, right? Well, Newton doesn't work here anymore. We rely on general relativity to accurately calculate the gravitational forces. These not only affect the spacecraft, they deflect all electromagnetic radiation in space, including the radio signals we use to command and communicate with the spacecraft. Don't let anybody ever tell you that Einstein was wrong or general relativity has not been proved. At JPL we demonstrate it daily.

But gravity is not the only thing that affects the spacecraft. Maneuvers do, obviously. As does the solar wind, which is the stream of charged particles emitted in all directions from the sun. Also solar pressure, just the light from the sun, affects the motion of spacecraft; this was discovered by surprise by Echo, a 1960s NASA project that deployed an inflatable passive communications satellite in the form of an aluminum-covered Mylar balloon. Outgassing and other mass losses to the spacecraft are also critical to calculating its path.

The navigation triangle, each side of which is measured in a different manner and must be constantly updated in order to reach the target. Side one: Earth to the spacecraft. Side two: Earth to the target, comet Tempel 1. Side three: The spacecraft to the target.



The Navigation Triangle

A simplified trajectory can be thought of as a navigation triangle, which in our case will consist of Earth, the spacecraft, and the comet, our "target du jour." The triangle has three sides, each measured in a different manner. For the distance from Earth to the spacecraft, side one, we use radio tracking data, of which there are three different types. The first type of data is range, or how far away the spacecraft is from Earth. The spacecraft receives a signal and turns it back around, and, using the speed of light and the travel time of the signal, we calculate the distance it traveled. The second is Doppler, which is the change in frequency of the signal due to the effects of the spacecraft's movement. We know what the frequency of the signal is going up, and then we measure it coming down, and the difference between the two frequencies—the Doppler shift—tells us how fast the spacecraft is receding (or approaching) along our line of sight. And the last one is called ΔDOR, or the delta difference of one-way range. It is essentially very-long-baseline interferometry. Two widely separated antennas look at the spacecraft and determine the difference in the distance that each measures. Then they turn away from the spacecraft in unison and look at a well-known object nearby, like a quasar. They do this over and over, going back and forth, back and forth, providing the information to cancel out all sorts of systematic errors and biases that are difficult to calibrate out, and ultimately yielding the precise angular position of the spacecraft. When it works it works really well, but sometimes it's hard to pull off because it takes two tracking stations working in sync with each other on two different continents.

Of course these things have their subtleties. Errors in range can arise from phase delays as the signal travels through Earth's ionosphere and troposphere. We can calibrate these out a little bit. As for Doppler, the difficulty with it is that the antennas are on Earth, and Earth rotates, so the antennas are moving as the Earth spins. This means that the antenna has its own velocity, which gets impressed upon the signal, resulting in a little sine wave on top of the signal. But, luckily, that sine wave gives you the position of the spacecraft in the sky. The sine wave phase tells you the right ascension, which, like longitude on Earth, gives the east-west position, only measured in increments of hours from zero to 24. And the wave's amplitude yields the declination, which is the same as latitude on Earth, from –90˚ S to +90˚ N. So we take Doppler measurements, which are radial velocity measurements, and wind up being able to infer position. Who'd a thunk it?

Navigation triangle, side two, is from Earth to the target, and this is the province of our ephemeris group—the scientists in charge of determining the future positions of solar-system objects. These are the JPL people whose names you might read in the paper, like Don Yeomans, Paul Chodas, and Steve Chesley, because they save us from killer asteroids. They get the orbit of whatever it is that our spaceship is going to fly by, whether it's a comet or a planet or an asteroid or a satellite. In the case of Deep Impact we needed the orbit for our comet, Tempel 1, which was determined initially by optical astrometry from ground observatories and improved when new observations came in.

Finally, the position of the spacecraft relative to the target, side three, is determined through optical navigation, using photos taken from cameras aboard the spacecraft. That's where I come in. These cameras take pictures of whatever they are facing, with stars in the background. Thanks to the European Space Agency's Hipparcos mission, which between 1989 and 1993 pinpointed the positions of more than 100,000 stars, and a lot of other work being done in stellar astronomy, we have good star catalogs now, and we know quite well where these stars are. We didn't used to, and in those times we contracted with Lick Observatory, up in San Jose, to take big photographic plates of the night sky. Then I would go up to Lick and survey the plates, picking out stars with a joystick and a little button that said "push" to record their positions on the plate. After a while, the "push" became engrained on my thumb. Luckily, those days are over.

So our onboard cameras take a photo of whatever target we are seeking against a background of stars, and from there it's fairly simple to figure out the direction the cameras were facing when they took the pictures. We can't get information on the distance of the spacecraft from the target with this method, but we can infer the right ascension and the declination of the target from the relative positions of stars photographed in a sequence.

Having measured the three sides of the navigation triangle, we put all three different data types together to get the position of the spacecraft—and, of course, they don't match. So we have to move on to higher math, with calculations that include about 100 parameters. We take each new solution as the starting condition and calculate again, and again, and again, until the difference between one solution and the next is sufficiently small. The final answer is subjective, because we are dealing with three disparate data sets—ground-based astrometry, radiometric, and spacecraft optical—and the relative weights assigned to the three data sets determines the answer. It becomes a question of knowing how to weight the data, so we try different things and see what holds together.

The result is another trajectory file, just like the one that went in but with different numbers, based on the spacecraft's initial position and velocity, the orbits of planets and satellites, solar pressure, maneuvers, and anything else that can affect the trajectory of the spacecraft. We're left with a whopping covariance matrix, several hundred elements on a side, showing how well we think we know the solution. For Deep Impact, we actually had good reason not to believe our solution. For starters, we knew that ground-based observations of the center of the comet's light were biased. Results from small, mostly amateur observatories were different from those of the large professional observatories, because the brightest part of the coma is offset sunward from the nucleus. We fully expected to see the same effect in the optical navigation images. So we knew there were systematic errors, but we couldn't model them, and we didn't know how big they were. But we also knew that the systematic errors would fade away as we got closer to our target and could observe it more closely.

This digitized sky survey, now accessible via the Internet, shows the type of photo astronomers once used to determine the positions of stars. These star positions would aid in navigation through space.

http://archive/stsci.edu

The *B* Plane

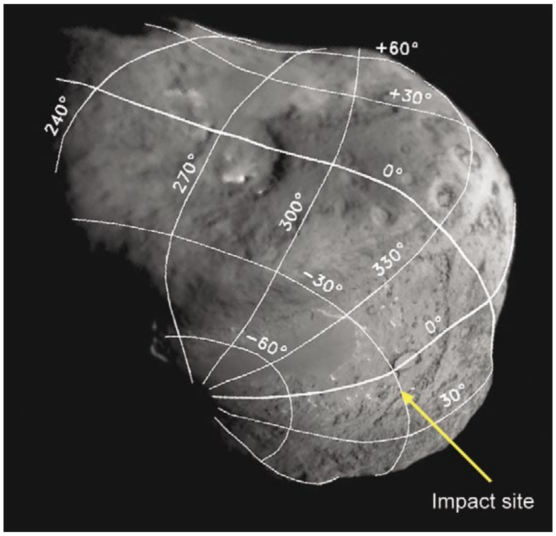
No space science coming out of JPL is complete without mentioning the *B* plane. If you ever took a course in particle physics, you might remember that *B* is the "miss distance," between something traveling by and the thing it was supposed to hit. The same *B* is considered here. We pretend that our comet is massless, which means that it has no gravitational pull on the spacecraft, which then travels in a straight line. Then we draw a plane perpendicular to the flight path and going through the target. The *B* vector goes from the center of the target to the point where the spacecraft goes splat! Right through the *B* plane.

That is just an idealization, to illustrate the operation conceptually. What we really do is transform the position and the velocity of the spacecraft relative to the comet, at some agreed-upon time, into Keplerian orbital elements, which are the parameters needed to uniquely specify an orbit. This world is made of circles and ellipses, and in this case we want to consider a hyperbola because the spacecraft is flying past the comet at a speed faster than escape velocity—it is not going back. And a hyperbola, if you can remember back to analytic geometry, has two asymptotes, one incoming and one outgoing. The *B* plane is perpendicular to the incoming asymptote, and the *B* vector is the miss distance of the incoming asymptote.

Now we know, from the optical determination team, the point on the *B* plane to which our spacecraft is headed. And we know the target in the *B* plane that we *want* it to hit, and these two don't match. So we need to move, or maneuver, the spacecraft, and we have a whole new set of equations for maneuver analysis. To a first approximation, space is big. It takes a long time to get from point A to point B. When a spacecraft fires its thrusters, it's like somebody with a

Comet Tempel 1 was overlain with a coordinate grid in order to map surface features like craters, one of which served to define the comet's prime meridian. The impact site was chosen because it would be sunlit and visible from the spacecraft.

NASA/U. of Maryland/Cornell/Peter Thomas & Tony Farnham



giant croquet mallet went POW! And the velocity is instantaneously changed. The change looks like an impulse, an abrupt change in the momentum of the spacecraft produced by the forward thrust: Force times time equals mass times change in velocity, or ΔV (delta vee) in the business.

We start by changing the velocity in one direction, let's say by adding one meter per second in the *x* direction. Where does the spacecraft go in the *B* plane, and when is its new closest approach to the target? Now we add one meter per second in the *y* direction, and then we do it a third time, a meter per second in the *z* direction. For each of the three changes in velocity, there is a numerical partial derivative for where the spacecraft will go. In fact, we already know where it's going because the orbit determination solution of the navigation triangle has told us, and we know where we want it to go. These pieces of information form three equations with three unknowns, which, when solved simultaneously, yield the three components of the ΔV that will remove the error, or match the spacecraft's trajectory to the target.

Except, unfortunately, the thrust is not *really* an impulse, so we have to do a numerical integration even for the brief moment the thrusters are on. And, of course, the problem is not linear, so the 3 × 3 set of linear equations will give you close to the right answer, but not quite, and the calculations have to be repeated until the right solution is found.

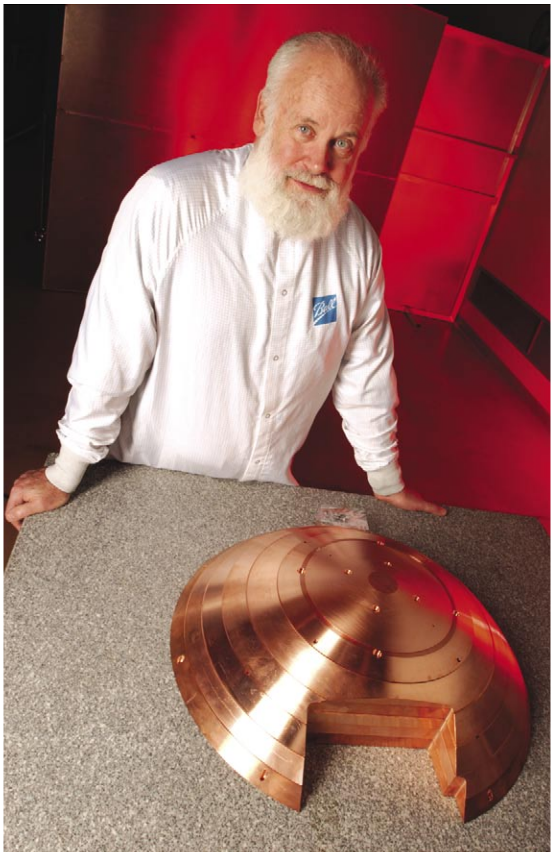
That concludes Navigation 101, which is all background and not the information you were hoping to get out of this article, so let's move on to Deep Impact.

Seeing white, red, and blue

The fact that we wanted pictures of the impact from beginning to end meant that we needed two spacecraft—one to hit the comet and the other to hang back and take pictures of it. Remember how the Tribbles of the *Star Trek* universe were born pregnant? Well, Deep Impact was launched pregnant. There was one flight system, to use the nomenclature, but it was really two spacecraft joined at the hip, or somewhere else.

The mother ship is called the "flyby" and it is a basic spacecraft, with propulsion systems, telemetry systems, data storage systems, instrumentation, and an autonomous navigation system. It also carries a couple of telescopes, which are useful for optical navigation. One is the Medium-Resolution Imager (MRI), and it has about the same resolution as Voyager's camera. The other is the High-Resolution Imager (HRI), with a resolution that is close to that of the Hubble's. A big antenna beams signals back to Earth. And there's also a solar array, which not only provides power, but doubles as a shield. Each of the two panels is 2.7 × 1.5 meters, with a honeycombed core and exterior made of graphite fiber, and weighs less than 11 kilograms. When it passed the comet postimpact, the spacecraft would be shielded by these solar panels. You can see on this page what the mother ship looked like in the clean room.

The mother ship, nicknamed the "flyby," hovers near the impactor spacecraft, which houses the copper disk shown on the next page. The two were joined on April 7, 2004, at Ball Aerospace and Technologies Corp. in Boulder, CO, and shipped to Cape Canaveral, FL, for the January launch.



Michael A'Hearn, principal investigator for Deep Impact, poses near the 300-kilogram copper disk that will smash into comet Tempel 1.

Then there was the impactor, which was 300 kilograms of copper. Why copper? Because comets have no copper, so that if instruments monitoring the ejecta saw spectral lines indicating copper, then we would know it was from the impactor, not from the comet. The impactor was not just a dumb hunk of copper—it would have its own telemetry, its own propulsion system, and a sophisticated autonomous navigation system that would help it home in on the target. It would also carry a duplicate of the mother ship's MRI, which we called the Impactor Target Sensor, to figure out where Tempel 1 was and to see how the comet was moving.

I've heard the project described as a bullet launching a bullet to hit a bullet. It's hard enough to hit a comet, and we wanted to hit it in a place where it was lit so that the mother ship could take pictures of the resulting crater. No problem—things hardly ever go wrong, right?

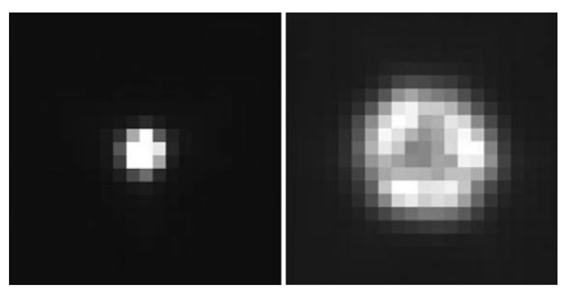
The key challenge fell to the solar-system dynamics group, to give us the best orbit they could that would bring the impactor to the bright side of the comet. But the brightness of a comet, and the location of the nucleus inside the gas- and dust-bearing coma, isn't necessarily that well predicted, so we needed to be prepared for any uncertainties that could lead us off target. We ran simulation after simulation and study after study on the impactor's autonomous navigation system. How well would it perform if the comet turned out to be dustier than we expect? Or if the nucleus had a weird shape and most of it was in shadow when we observed it? We tried to answer these "what-ifs" under extreme conditions, knowing that if the system worked well in these simulations it would do very well under more benign conditions. If our trajectory worked in the worst possible case, we started feeling a little bit good.

We launched January 12, 2005, with a specific energy of 10.9 km^2/s^2, the optimal energy needed to send the spacecraft on a path that would intersect the comet's orbit six months later. Tempel 1 follows a slowly changing elliptical orbit that would bring it closest to the sun (its perihelion) and to its peak of activity on July 5. This was also, luckily, when the comet would be easiest to reach as it crossed the plane of Earth's orbit.

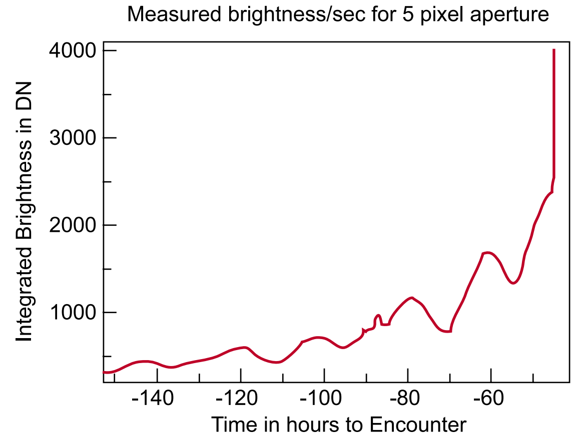
We planned for impact on July 4, 2005, a date set by celestial mechanics rather than the folks back in 1776. But of course we took advantage of it. Project management bought red, white, and blue polo shirts. The boxes arrived a week before the Fourth of July, and instead of what we expected, we got red shirts, white shirts, and blue shirts. Well, life gives you lemons, so the best lemonade we could make out of that one was to give the colored shirts to the team members who might be on TV. So the impactor crew got red shirts and the mother ship crew got blue shirts. And the white shirts, which don't look too good on TV, went to those of us who worked behind the scenes.

Bad News, Good News

Back to the mission. The mother ship was traveling one million kilometers per day toward the comet, and two days after launch it sent its first star-alignment pictures. The first photos from the impactor's camera followed a week later. We wanted to make sure these cameras were working, but more importantly we wanted to check the alignment of each camera with respect to the spacecraft.



The first photos sent by cameras aboard the mother ship bore good and bad news. At left, a typical star image taken by the Medium-Resolution Imager (MRI). On the right, the High-Resolution Imager (HRI) was too out of focus to be useful during the mission. Loss of the HRI required a retooling of the entire navigation strategy.



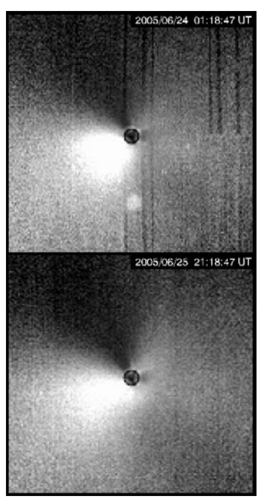
As the spacecraft neared the comet, it measured the brightness of both the nucleus and the coma. This graph shows the brightness of the nucleus growing steadily toward encounter time, with a sharp increase just before encounter. The sharp blip just left of E-80 hours is a cometary outburst, and the large-scale peaks show the rotation period of the elongated nucleus is 41.85 hours.

The first picture from the MRI looked like a typical star image. But the first picture from the mother ship's HRI was *way* out of focus. This camera had five times the magnification of the MRI and was the one we hoped to use both for navigation and to take high-resolution images of the comet. Because of the weight, the camera was launched without a focus motor, so the only way to have changed the focus would have been to heat the camera by exposing it to enough sunlight to burn off accumulated moisture and change the focal plane. Well, the heat shrank the camera, and this did change the resolution, but not by much.

But we were prepared, because among the contingency studies before launch was, "What if the HRI fails?" So we switched to Plan B and the MRI. This meant losing a factor of five in resolution, requiring a retooling of the whole maneuver strategy. If a pixel on the HRI was 20 kilometers, it would be 100 kilometers on the MRI, and our knowledge of the location of the comet's nucleus would be similarly compromised. The information we would have gotten five days out we now would get only one day out. There was consequently much more uncertainty in the trajectory of the spacecraft relative to the comet that dictated each maneuver.

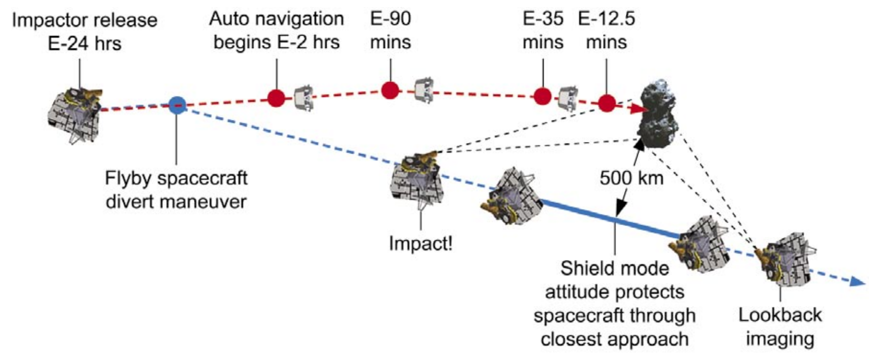
The optical navigation team needed to set a route to the nucleus, but the nucleus is surrounded by the coma, this bright cloud of diffuse material whose brightness is offset toward the sun by an unknown amount. The nucleus, being a solid object, has a brightness that varies as $1/R^2$, with R being the distance from it to the observer. But the coma is not solid, it is optically thin—you can see through it—so its brightness varies as $1/R$ instead. So we were observing two different behaviors of light, and when complications like the changing geometry of light in space were added, it became very difficult to tease out light from the nucleus versus light from the coma. But we did a pretty good job at it. On this page, you can see the light from the nucleus getting gradually brighter and brighter until it takes off just before encounter. In the last week we got a pretty good light curve.

Every time we processed an image, we applied six different techniques. The one that turned out to work the best involved measuring the brightness of each pixel in a 3 × 3 box of pixels. We then fit a Gaussian distribution curve centered on the brightest measured pixel, and the center of the best-fit curve was taken to be the location of the nucleus. In the last week of the mission, the differences between the brightness of each pixel and the average brightness showed that we had found the target to within two tenths of a pixel. So we pretty well nailed that sucker.



NASA/U. of Maryland/Tony Farnham

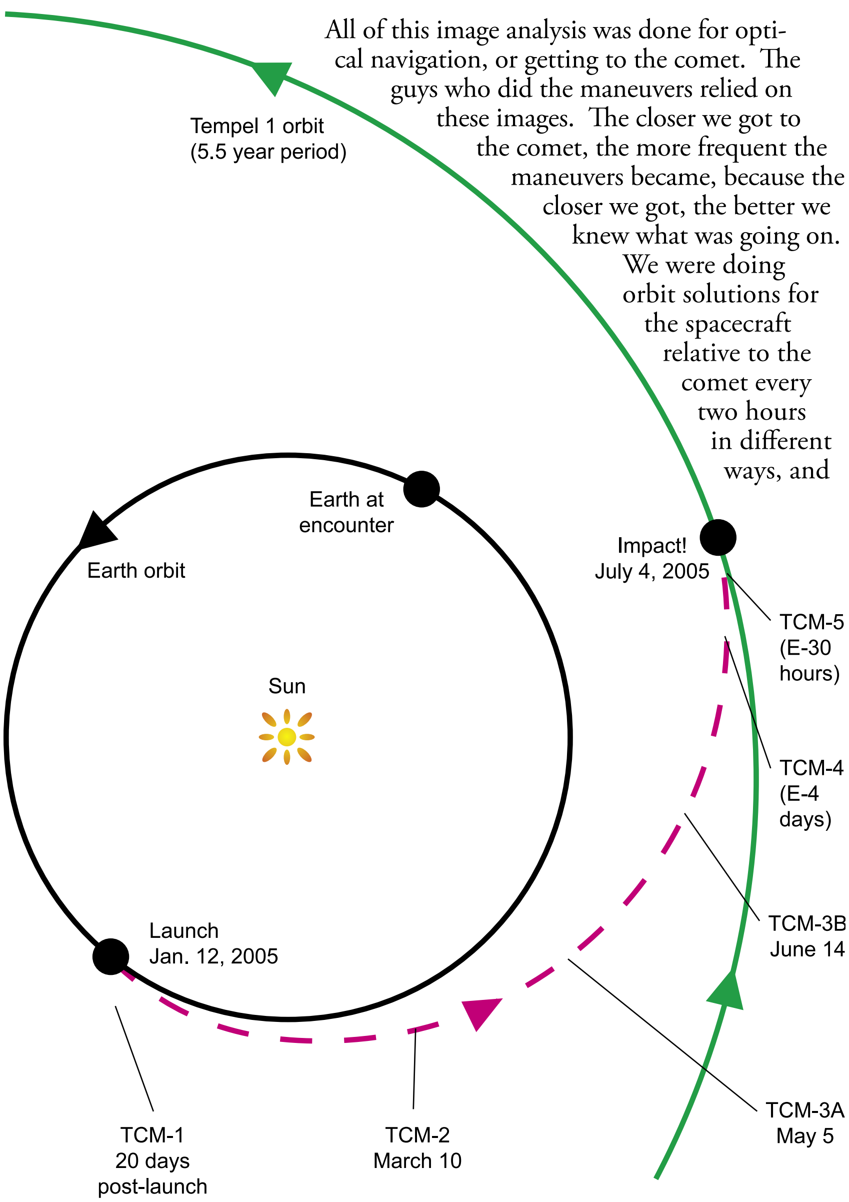
Several unexpected outbursts were detected as Deep Impact neared its target. These two, in images taken 44 hours apart, probably originated from the same location on the nucleus. The field of view is about 1,800 kilometers in the top image and 1,500 kilometers in the bottom one.



Encounter day began with the mother ship releasing the impactor at E-24 hours. The mother ship then moved a little to the side and slowed down to avoid potential collision. It continued to take photos until it reached its closest approach to the comet, 500 kilometers away, whereupon it went into "shield mode," turning its solar panels toward the debris flying from the impact. It then turned back to take postimpact photos. The Mauna Kea observatories were in darkness to best record the impact.

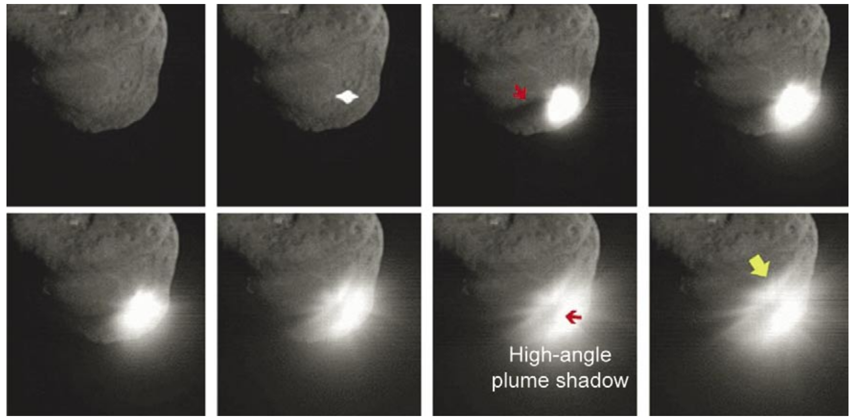
Impact!

All of this image analysis was done for optical navigation, or getting to the comet. The guys who did the maneuvers relied on these images. The closer we got to the comet, the more frequent the maneuvers became, because the closer we got, the better we knew what was going on. We were doing orbit solutions for the spacecraft relative to the comet every two hours in different ways, and using a lot of different assumptions to determine the trajectory change maneuvers (TCMs) that would bring the mother ship into position just before it released the impactor. The good thing is they all kind of, more or less, sort of agreed. The TCM 11 days before impact had brought us on a trajectory that was 34 kilometers off course in the horizontal direction. TCM-5, the final maneuver, was six hours before the release of the impactor, and it was our last chance to change the incoming trajectory. The optical data that had come in during the intervening 10 days helped immensely, and no matter what we tried, our solutions always landed within a box two kilometers wide by four kilometers high, centered on the four-kilometer-wide nucleus. We were confident that we were within two kilometers or so of our designated impact site.



Orbits of Earth, Tempel 1, and the spacecraft during the five-and-a-half month mission. Trajectory Change Maneuvers (TCMs) brought the spacecraft into impact trajectory, and the first came 20 days after launch. They increased in frequency until the last one, at Encounter-minus-30 hours, just six hours before release of the impactor. Deep Impact was planned for July 4, 2005, which coincided with the closest approach of Tempel 1 to the sun.

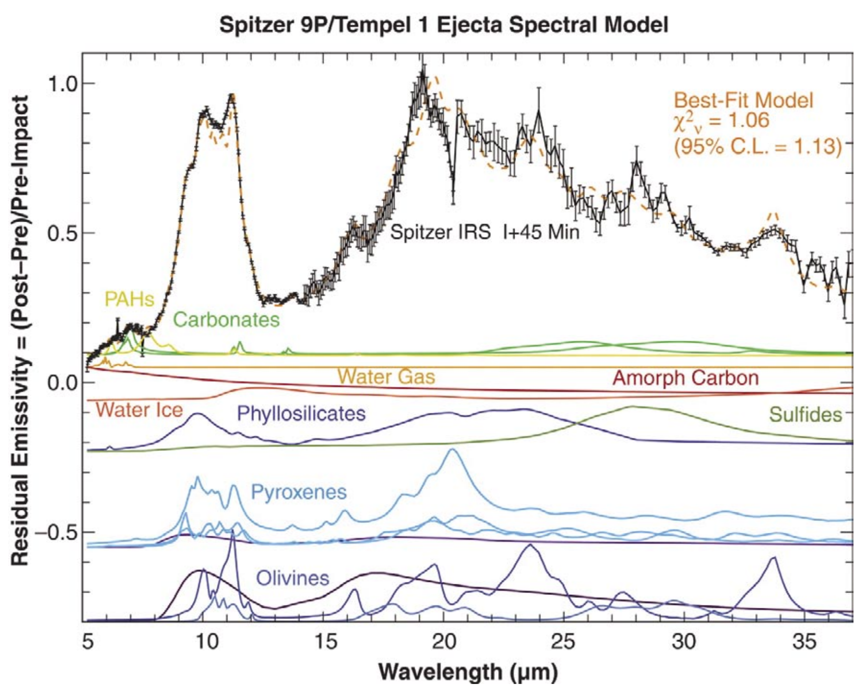
This sequence of images depicts the development of the ejecta plume when Deep Impact's impactor collided with comet Tempel 1 at 1:52 a.m. eastern time, July 4. Brightness peaked three to four seconds after impact. The red arrows point to shadows cast by the opaque ejecta, and the yellow arrow in the last image indicates the "zone of avoidance," where relatively little ejecta flew because of the oblique angle of impact. The eight images, taken by the mother ship, were spaced 0.84 seconds apart.

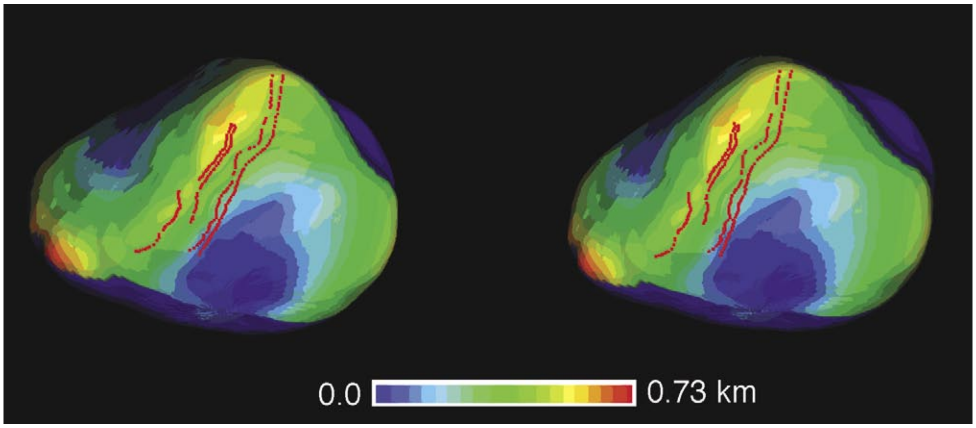


Finally, five and a half months after launch (it was a quick mission!), we reached Encounter-minus-one: one day before encounter with Tempel 1. The impactor was to be released 24 hours out. Now, when engineers say 24 hours out, they mean 24 hours, 00 minutes, 00 seconds. Point 00. At this point the whole flight system was on an impact trajectory, so that if we released the impactor and the mother ship stayed the course, it too would get smashed. So there was a postrelease maneuver planned—a little thrust in one direction to slow it down, a little slide to the left, and the mother ship takes a zigzag path. It didn't take much of a change in speed to accomplish this: the mother ship's speed relative to the comet slowed by only 100 meters per second, to about 10.2 kilometers per second. In this way, we could take nice pictures of the impactor flying toward the comet. The mother ship continued taking pictures until 800 seconds after impact, when the comet got really close, about 500 kilometers away. This was close enough to the coma that we were worried about flying particles, so to protect its instruments, the mother ship went into shield mode, where it turned its solar panels toward the comet. Once it was safely past the coma, the mother ship turned again to take look-back pictures.

Meanwhile, the impactor and comet were flying at each other at a relative speed of 10.3 kilometers per second (that's 26,000 miles per hour!). Now, one of the things we were told was not to get too excited—just because the telemetry from the impactor stopped, that didn't necessarily mean it hit the comet. It could have had some other

Silicates dominate the post-impact emissivity spectrum for the Tempel 1 ejecta. The dust composition, shown in black with the orange dashed line as the best fit, was determined by subtracting the post-impact spectrum from the pre-impact spectrum and dividing the result by the pre-impact spectrum. The colored lines show the individual consituents, and were generated from optical constants of each.





Stereo view of the shape model of Tempel 1's nucleus, keyed for gravitational heights, with red lines tracing linear outcrops. When viewed at the proper distance, the image should appear three-dimensional.

problem instead. So we were told to wait for the scientists to say "Yeah, it hit." But then we started getting pictures back of a glow from the comet, so we all got excited anyway. I happened to be on the stairs going from the navigation area down to the science area, so I missed it. When I got down there everybody was cheering and jumping up and down and hugging each other. The glow from the impact lasted for several hours, and nearly every telescope in the world was trained on Tempel 1 for the event.

Even with the unfocused HRI, we got back 97 percent of the pictures that we wanted. The MRI covered about 25 percent of the nucleus. And the high-resolution images weren't garbage: they were deconvolved later and yielded coverage of 30 percent of the nucleus at a resolution of less than 10 meters per pixel. These images show the comet's surface materials vary quite a lot, and that geologic processes refined the comet during its 4.5-billion-year history. Unfortunately, the debris from the impact cloud obscured the crater, but a proposed second mission to Tempel 1 could take pictures of it.

Sky and Telescope couldn't resist the inevitable pun, "A smashing success." Deep Impact released 19 gigajoules of kinetic energy, which sounds like a lot, but it did not change the course of the comet. It did give us some of the science we wanted—the comet's local gravitational field and the average density of its nucleus, 600 kilograms per cubic meter, were estimated from the ejecta. Spectra from the debris cloud, which reached about 500 meters above the comet's surface, showed water, methanol, methane, methyl cyanide, carbon monoxide, carbon dioxide, and formaldehyde.

The mother ship's trajectory will now bring it back to Earth, where a gravity assist will send it off to another comet. As for the impactor, well, as one of our spacecraft operators put in the log, "On eBay: One impactor, used only once. Some assembly required." □

Bill Owen is a principal member of the technical staff at the Jet Propulsion Laboratory, and he was the principal engineer of the Optical Navigation Group for Deep Impact. He also served a short stint as principal navigator for Deep Impact, in July 2005. He got his bachelor's in astronomy at Caltech in 1976, and after spending a year as a church organist he joined the JPL staff. He worked there until 1986, when he took a leave of absence to get his doctorate in astronomy at the University of Florida. His JPL good-bye picnic was cancelled when an armed robber hid out at the lab and all employees were evacuated. He returned to JPL nonetheless, and was working there again when he finished his PhD in 1990. Among his recent activities, Owen was on the search for the incommunicado Mars Global Surveyor (see Random Walk, p. 7).

This article was adapted by Elisabeth Nadin from Owen's Seminar Day talk last May.

PICTURE CREDITS: 10–11, 16 — NASA/U. of Maryland; 10 — Karen Meech, U. of Hawaii; 12 — Doug Cummings; 14, 15 — Ball Aerospace; 17 —Raymond Frauenholz, JPL