A new generation of low-cost space missions relies on subtle orbital dynamics rather than brute force to loop and dart through the inner solar system

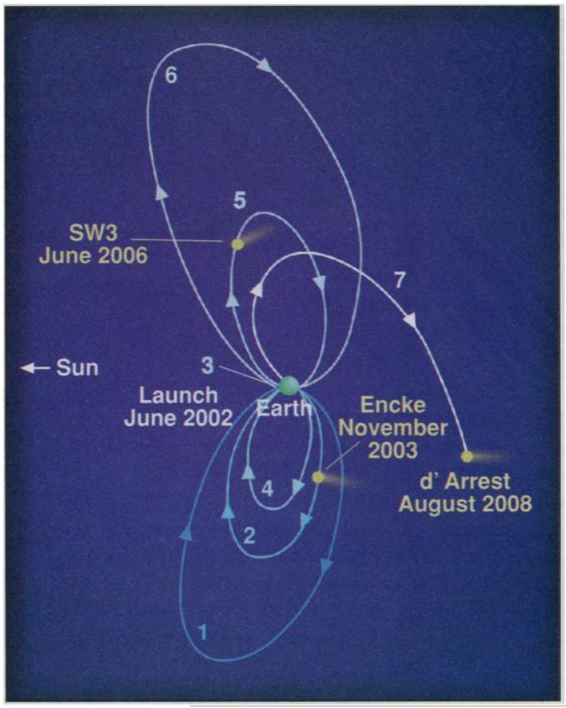
The Art of the Orbit

The agendas of a flotilla of small spacecraft set to explore the inner solar system over the next decade are nothing if not ambitious. One has already reached an asteroid and will eventually orbit and maybe even land on it. One will photograph the nuclei of three different comets over 5 years. And two will take samples of extraterrestrial material—gas and dust from a comet and a whiff of the solar wind—and carry it back to Earth. It's a display of technological audacity unmatched since the 1970s, the time of the Apollo missions, the Viking landings on Mars, and the unmanned Soviet sample return missions to the moon. But one thing has changed since those Cold War days of spare-no-expense space exploration. Ask Chen-Wan Yen of the Jet Propulsion Laboratory (JPL) in Pasadena, California, the mission designer for the Stardust comet-sampling mission, what her primary criterion was in plotting a trajectory to get Stardust out to its comet and back home again, and her response is one word: "cheap."

Extreme economy is what makes Stardust and other "Discovery-class" missions viable at all under the constraints of the NASA philosophy of "faster, cheaper, better," and the need for it has forced a renaissance in the art of spacecraft navigation and trajectory design. These missions all must cost less than $300 million in today's dollars—less than a tenth the estimated price, for instance, of Cassini, the last of NASA's behemoth planetary missions, which is currently en route to Saturn—and they must use inexpensive Delta rockets to get into orbit. This, in turn, puts a tight limit on the weight of the probes, including both their scientific payload and the fuel they carry to get where they're going and even back home again.

As a result, mission designers have been learning to do with the nuances of gravity and sheer ingenuity what previous generations at NASA did with huge amounts of fuel and brute force. In place of hundreds or even thousands of kilograms of fuel, they make do with tens. "From the point of view of spacecraft design, these missions are relatively easy," says JPL mission designer Jim Miller. "You build them from existing parts and launch them on Delta rockets. But the inverse is true when it comes to navigation. There the problems become really complex. So the navigation area has been breaking new frontiers in the last few years."

Even after 40 years of space flight, trajectory design and navigation is still "more of an art than a science," says Bob Farquhar, mission director for the Near Earth Asteroid Rendezvous (NEAR) mission and a longtime NASA veteran who is now at the Applied Physics Laboratory at Johns Hopkins University. The canvas on which he and his colleagues work is what is known in mathematics as the *N*-body problem—the notoriously intractable mathematics describing the gravitational attraction between bodies in space. To the mission designer, the *N*-bodies can be any combination of the space probe with Earth, the sun, and other bodies in the solar system. Although Newton's laws of gravity and motion, which govern the orbits, are simple enough for two bodies, add in just one more body and their behavior becomes classically chaotic. Change the initial conditions even infinitesimally, and trajectories can change unpredictably and dramatically, making them essentially impossible to calculate except in the simplest cases.



A whirl of comets. The CONTOUR mission will rely on multiple Earth flybys to rendezvous with three comets.

SOURCE: CONTOUR

For this reason, trajectory designers have traditionally worked with two bodies at a time. For two bodies, the equations can be solved exactly, which results in trajectories known as conics, because they are all various arcs that exist on the surface of a cone. Mission designers start with Earth and the spacecraft and find conics that send the craft toward its target, then shift their focus to the target body and the spacecraft to find intersecting conics that bring the probe into orbit. They then optimize the choice of conics and connecting paths to find the best trajectory.

The pivotal variable in this endeavor is what mission designers refer to as "delta v" or change in velocity, which is a working synonym for the amount of fuel a spacecraft must carry to shift between conics and make necessary velocity changes once it leaves a parking orbit around Earth. The "standard trick" to minimize delta v, says planetary scientist Donald Brownlee of the University of Washington, Seattle, Stardust's principal investigator, is to swing past Earth or some other body to get a "gravity assist" that can accelerate, slow, or redirect a space probe, depending on the direction the spacecraft approaches relative to the planet's orbit. Cassini, for instance, is counting on gravity assists from two flybys of Venus and then one each of Earth and Jupiter to speed the more than 5000-kilogram spacecraft to Saturn.

Help from the home planet

Many of the new missions take such gravitational gymnastics to new heights by relying on what are known as "Earth-return" trajectories—repeated passes by Earth, each of which boosts the spacecraft's velocity a notch or flings it off on a new course. They are following an example set by Farquhar in 1983, when he took the International Sun Earth Explorer-3 (ISEE-3), which had been sitting between Earth and the sun for 4 years studying the solar wind, and, with a minimal expenditure of fuel, looped it around the moon five times to set it on course to rendezvous with the comet Giacobini-Zinner. The probe, promptly renamed the International

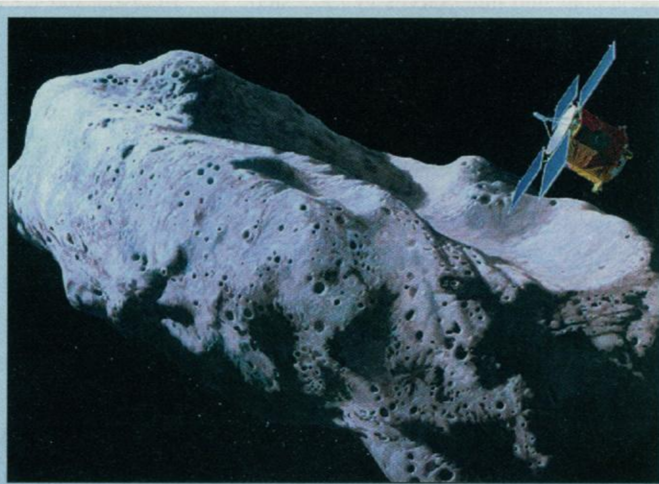
NEAR's Risky Embrace With Eros

Last month, the Near Earth Asteroid Rendezvous space probe, known as NEAR, ignored all messages from its mission controllers for a crucial 27 hours and went speeding past its target. The interruption did not scuttle the mission, but it did deprive space aficionados, at least for the coming year, of witnessing one of the more elegant demonstrations of the art of spacecraft navigation and mission design: easing a car-sized probe into orbit around an oddly shaped asteroid about 1 billionth the mass of the Earth.

Measuring 40 kilometers at its longest, the asteroid Eros has a gravitational pull so weak, says NEAR mission designer Jim Miller of NASA's Jet Propulsion Laboratory in Pasadena, California, that a Volkswagen sitting on its surface would weigh less than a kilogram. Eros also has an irregular shape and a 5-hour rotational period. This means its gravitational field is irregular and could change quickly and dangerously as the probe orbits and the asteroid spins. "It can actually eject the spacecraft from orbit or suck it in and make it crash," says Miller.

Had NEAR made its planned rendezvous in January, Miller and his colleagues would have had to put the probe into orbit knowing no more about the asteroid's shape and mass than could be gleaned from telescope images and radar data gathered from Earth. But NEAR's unplanned flyby allowed it to snap pictures that will make the task considerably easier next time around. As Miller explains it, mission controllers will start with a series of burns to drop the craft's flyby speed to 36 kilometers an hour and put it in an orbit 400 kilometers out. From there, they will begin an iterative process, dropping the orbit in steps—first to 200 kilometers, then 100, then 35—as they get increasingly higher resolution information on the gravity field of Eros by combining data from the probe's orbit and from photographs. "It gets to be a fairly complicated problem," says Miller. "I hope we can do it."

Bob Farquhar, mission director of NEAR, says eventually he'd like to get NEAR down to 100 meters from the asteroid and maybe "even land on the thing," despite NEAR's lack of landing legs. Miller says they may be better served with a series of slow, very low altitude flybys. Why not land? "We probably lose the spacecraft," says Miller. –G.T.



NEARing Eros. After entering orbit around the oblong asteroid, the NEAR spacecraft may drop close to its surface.

Cometary Explorer (ICE), passed through the tail of Giacobini-Zinner in September 1985, a good 6 months before two dedicated missions—Giotto and Sakigake—caught up with Halley's Comet with considerably more publicity. According to Farquhar, the surcharge for the comet rendezvous was a mere $2 million over ISEE-3's original cost of $26 million.

NEAR, Farquhar's current mission, used a similar gravitational slingshot to reach the asteroid Eros. The probe was launched in February 1996 into deep space, eventually traveling more than twice the distance of Earth from the sun before falling back toward Earth. While in deep space, however, says Farquhar, a small delta v maneuver redirected the craft, so that when NEAR returned to Earth 2 years after launch, the flyby gave it a large swing—11 degrees out of the plane of Earth's orbit—to Eros. Without this roundabout path, says Farquhar, "we wouldn't have had enough oomph out of the launch vehicle to do Eros."

Farquhar and his colleagues had expected to begin slowing NEAR for its Eros rendezvous on 19 December, when the probe was 250,000 kilometers from the asteroid and closing in at nearly 1 kilometer per second. But NEAR shut down its rocket prematurely; by the time the mission controllers got a message to it 27 hours later, it was already committed to flying by. On 3 January they successfully got NEAR into a trajectory that will float it back to Eros on 14 February 2000. ("Valentine's Day and Eros," says Farquhar. "It makes sense.") Once it arrives, controllers will begin the delicate task of easing the probe into a close orbit around the asteroid and perhaps even landing it (see sidebar).

Stardust uses a similar Earth-return gravity assist to get out to the comet Wild-2, but on a path that will bring its precious cargo back home again, as well. In the early 1980s, says Brownlee, researchers considered a sample-return mission to Halley. But Halley orbits the sun in the opposite direction to Earth. Any probe sent to meet it would race past at roughly 70 kilometers a second, so fast that any samples it might collect would be atomized. "You could capture the atoms," says Brownlee, "but they would lose memory of what form they were in before you captured them."

To recover the dust in something like its original form, comet-chasers had to find a way to cushion the impact, and they had to choose a slower moving comet as a target. Peter Tsou of JPL solved the first problem when he suggested that particles could be captured with an aerogel—a tenuous silicon "foam" consisting mostly of empty space. Targeting Wild-2 solved the second problem because it orbits the sun in the same direction as Earth and is easily accessible, with an orbit that sits between those of Jupiter and Mars.

Stardust will reach Wild-2 with the help of an Earth gravity assist that will accelerate it to a speed roughly matching that of the comet. The gravity assist will also give it an elongated orbit that will cross paths with the comet in 2004 and bring the probe back to Earth again in 2006. Particles of gas and dust collected in the aerogel will be stored in a small atmospheric reentry capsule, which the spacecraft will jettison with a spring 4 hours before hitting Earth's atmosphere. The main spacecraft will be diverted back out into space, while the capsule will float down by parachute and, if everything goes as planned, land on a dry lake bed in Utah.

The "pièce de résistance" and the "quintessential utilization" of Earth-return trajectories, as Farquhar puts it with characteristic modesty, is the CONTOUR mission. CONTOUR is scheduled to launch on 26 June 2002—"That's my wife's birthday," he says—and will rendezvous with and photograph the nuclei of three comets in 5 years: Encke, Schwassmann-Wachmann–3 (SW-3), which is of particular interest be-

CREDIT: NEAR/JHU APL

cause it split into three pieces in 1995, and then d'Arrest. In between comets, "the thing to do is get back to Earth," says Farquhar. "Then you can find lots of ways to retarget" to the next comet without needing to carry fuel to do it with thrusters.

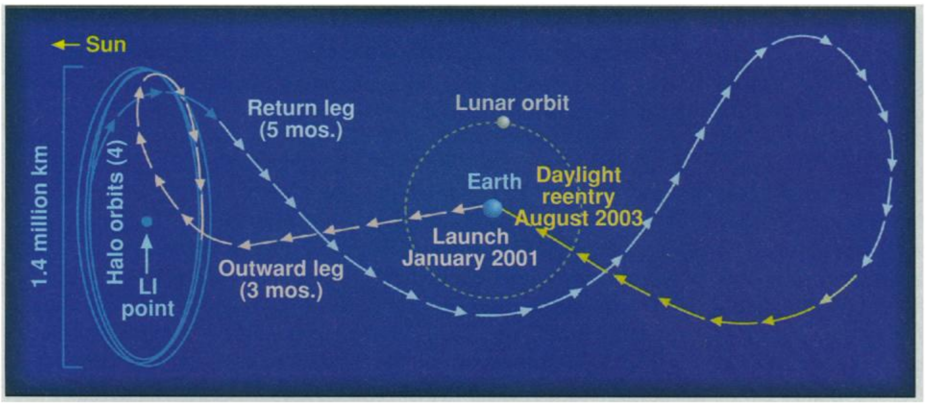
CONTOUR will be launched on an Earth-return trajectory that will bring it by Encke and back toward Earth. Then three Earth gravity assists will redirect it to SW-3 and back to Earth, and two more will get it to d'Arrest. The total mission will use just 85 kilograms of fuel, leaving plenty for contingencies—and perhaps for encounters with two more comets, one of which would be Encke on its trip back in 2023. To rendezvous with all five comets would require a total of 15 Earth gravity assists, says Farquhar, a "record likely to stand for some time."

Three-body perfection

Of all the Discovery missions, the Genesis probe has the least newsworthy goal but uses the most elegant mathematics. Its fellow Discovery missions, in spite of their sophisticated use of gravity assists, still follow courses stitched together from solutions to two-body problems. Genesis is among the first NASA missions to have a trajectory based on solutions to the three-body problem, an approach that could set the pattern for a host of other missions planned for the next decade.

The Genesis spacecraft, to be launched in January 2001, will spend 2 years collecting particles of solar wind from a point 1/100 of the way from Earth to the sun, known as L1 or the first Lagrangian point, where centripetal force and the gravitational pulls of Earth and sun all cancel out. It's one of five such points in the Earth-sun system where a space probe could in principle sit forever as though balanced on the gravitational version of the head of a pin. Another one, L2, is on the far side of Earth from the sun, 1.6 million kilometers out.

Both L1 and L2 are ideal venues from which to look out toward the universe, and L1 is a good vantage on Earth and the sun, as well. But they have drawbacks: At L1, a spacecraft's signal would be overwhelmed by the radiation from the sun behind it. At L2, Earth's shadow blocks the solar radiation a probe needs to power its instruments. The solution, pioneered by Farquhar and Stanford's John Breakwell in the 1960s, is to put spacecraft into "halo orbits" around the Lagrangian points. A spacecraft in a halo orbit around L1 describes huge, lazy loops perpendicular to the Earth-sun axis, endlessly falling toward the balance point.



From halo to halo. The Genesis spacecraft will collect solar wind from a "halo orbit" around a gravitational balance point between Earth and sun, then drift to a second halo orbit on the opposite side of Earth, and finally return home.

In 1978, Farquhar's ISEE-3 became the first spacecraft to sit in a halo orbit, which it did for 4 years. It was almost 2 decades before NASA got around to sending more missions to a halo orbit—SOHO and ACE, which went up in 1996 and 1997, respectively, both studying the sun. Reaching a halo orbit, unlike orbiting a single object, is intrinsically a three-body problem, because the sun and Earth tug equally on a spacecraft there. Until Genesis, however, these halo missions were planned by a technique of trial and error. Mission designers would first identify a likely halo orbit, then try to find conics to get out to it. They would pick a likely set of initial conditions and solve the equations to see if their spacecraft would go where they wanted, then pick another set, and so on until they had a course that required a minimum of corrections.

Since the 1980s, however, Purdue University astronautical engineer Kathleen Howell has been developing software to design trajectories that employs the mathematics of dynamical systems, which is known colloquially as chaos theory and is the study of systems that change unpredictably with time. Building on the work of University of Barcelona mathematicians led by Carlos Simó, Howell and JPL mission designer Martin Lo have been able to plot trajectories using the subtle gravitational interactions of all three bodies involved: Earth, sun, and spacecraft. The technique, as Howell explains it, is to solve for families of solutions that have slightly different initial conditions, resulting in a set of trajectories that define a multidimensional surface—a manifold, in the lingo of topologists—describing the local gravitational field.

By looking at these manifolds, Howell, Lo and their collaborators realized that the gravitational field of three bodies is replete with what Lo calls "dynamical channels": paths along which a spacecraft would, in effect, fall slowly from one orbit to another—even from one side of Earth to the other—with no expenditure of fuel. They are "the paths the vehicle takes with the thrusters off," says Howell. "All of those won't go where we want, but if we know how [they] intersect in space, we can go to a certain point with one solution and use our thrusters to change our velocity to switch on to a solution that will take us where we want."

The result for Genesis is a trajectory that comes as close to perfect as mission designers have come. After the Delta rocket puts Genesis in a parking orbit around Earth, the spacecraft will execute a small burn to tap it into a path that will float it toward the sun and, with another slight nudge 3 months later, onto a halo orbit around L1. After four orbits of 6 months each, it will be tapped onto a "heteroclinic" connection, on which the spacecraft will fall from the halo orbit around L1 all the way behind Earth onto a halo orbit around L2.

The reason, explains David Folta, head of mission design at NASA's Goddard Space Flight Center in Greenbelt, Maryland, is that Genesis is meant to bring its cargo of solar wind back home in 2003 by entering the atmosphere over Utah, floating down by parachute, and being snatched by helicopter before it hits the ground. Trajectories coming in from L1 intersect Earth on the night side, making the helicopter snatch problematic. L2, however, should deliver the spacecraft into a return course that gets it back in daylight.

"If everything goes as planned," says Folta, "we probably get away with the whole mission for a few tens of kilograms of fuel. Very cheap. Maybe even less." It's this kind of extraordinary efficiency, says Folta, that has NASA already starting to use the same methods for future spacecraft designed to fly in halo orbits, among them the Next Generation Space Telescope, the Earth-observing satellite Triana, and the Microwave Anisotropy Probe, which will map the cosmic background radiation. "This is really going to change the way we view mission design," he says.

–Gary Taubes

SOURCE: GENESIS/JPL