NAVIGATORS OF THE SPACEWAYS

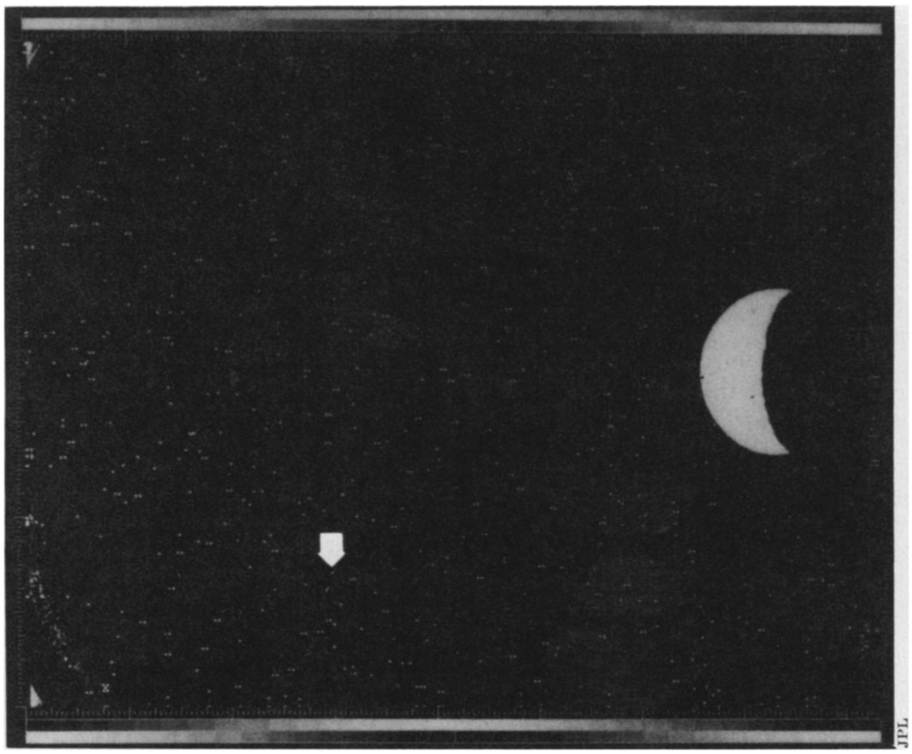
Among the least-known heroes of the Space Age, their hair-fine guidance is the key to unmanned exploration of the solar system

by Jonathan Eberhart

Celestial mechanics—what a lovely name for a science. The two words clash a bit, but how much nicer than, say, gravitational interactions analysis. The stately elegance and predictability with which objects in space affect one another in their orbits has enabled advances ranging from the discovery of whole planets—Clyde Tombaugh found Pluto "blind" by its influence on Neptune's orbit—to intricate space flights that borrow energy from one target world to reach another.

The perpetrators of these latter feats, the guiding hands whose remarkable but unsung efforts send robot probes on unbelievably precise paths with the mere occassional flick of a rocket nozzle, are the navigators of the spaceways, backed by hundreds of state-of-the-art engineers who strive to provide hardware capable of matching the precision encouraged by celestial mechanics.

Their accomplishments have already passed the "awesome" stage; metaphors such as "sinking a two-cushion shot on a 10,000-mile pool table" are not uncommon. But future unmanned missions to the outer planets, where less is known and chances for error are greater, already have the navigators hard at work on more accurate ways to get from A to B—when B may be an imaginary 10-mile hole a billion miles away and the only way to reach an even smaller C. One proposed flyby, for example, would send a probe to the nucleus of Halley's Comet while the "mother" craft went zipping past the comet's head at a distance as small as 60 miles. Another idea calls for settling into an orbit around Jupiter, then flitting from one of its moons to another at average intervals of 26 days (some as little as a week) for three years.


JPL

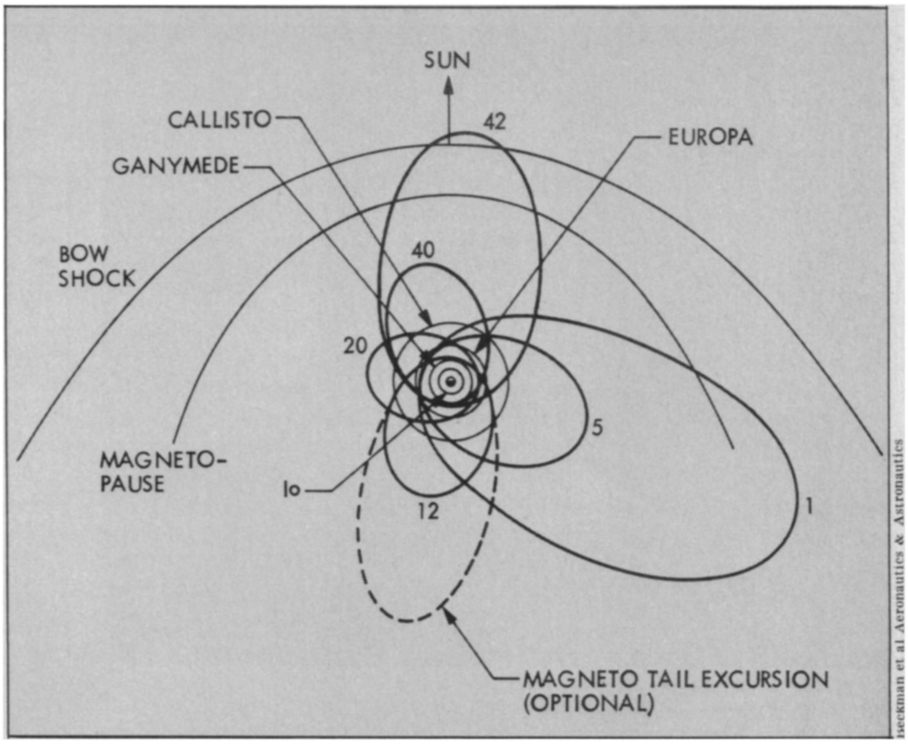
Mariner 10 photographed Mercury's limb and a reference star in "opnav" test.

Such exotica are being considered for the 1980's, still but dreams in their author's eyes. But it is already clear that the new age of space navigation has begun.

Though assigning birthdates to "ages" often requires subtlety to the point of uselessness, a reasonable candidate for the beginning of the new navigation might be Jan. 21, 1974. On that date, flight controllers at the Jet Propulsion Laboratory commanded the Mariner 10 spacecraft to turn 46 degrees on its roll axis, just under 35 degrees on its pitch axis and fire its engine for a brief 3.8 seconds, thereby setting up the most ambitious flight plan in the history of unmanned space exploration—a triumph of celestial mechanics.

Carefully calculated months before, the maneuver was the first attempt at making use of two new navigational techniques: the gravity-assisted swing-around, or "slingshot," and orbital multiples, referred to as "resonance." The slingshot idea—in this case using the gravity of Venus to speed and redirect the spacecraft toward Mercury, thus saving time and energy (and thereby fuel, weight and dollars)—had been around for years; Mariner 10 was to be the proof of the pudding. The possibility of resonance, however, was not realized for the mission until 1970, when Italian astrophysicist Giuseppe Colombo pointed out that if Mariner were aimed to pass Mercury just so, the probe would end up in a sun-circling path that would intercept the planet's orbit exactly every two Mercurian years, so that Mercury would be there waiting for a second, and even a third, look (SN: 9/28/74, p. 197). Painstakingly checked and rechecked, the signal went out from JPL. It worked.

The slingshot was tried a second time only three months later when Pioneer 11, on its way to Jupiter, was redirected imperceptibly so that the giant planet would then send it off to Saturn. Not even seriously considered until the



Multiple "slingshots" around Jovian moons would aid science, drain navigators.

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spacecraft had already been launched, the feat required navigators to aim for an imaginary 600-by-1,200-mile ellipse near Jupiter while the probe was still almost 160 million miles away. Their achievement (already confirmed, although the spacecraft will not arrive until 1979) was about equivalent to hitting the northern half of New York's Central Park from the Moon with a bullet. And after passing the planet, a secondary slingshot will carry the probe past Saturn's moon Titan.

One of the factors that made the Jupiter slingshot possible was the visit a year before of Pioneer 10. Thanks to the precision of tracking and navigation techniques, a spacecraft becomes a sensor in itself, with analysis of tiny perturbations in its path providing a valuable tool for measuring subtle variations in a planet's gravitational field. It was just this sort of backtracking that led to the discovery of the "mascons," or mass concentrations, beneath the surface of the moon and which helped Pioneer's navigators understand the Jovian ephemeris well enough to set up their tricky maneuver.

In large part due to their obvious economies—extra planets for free—gravity-assisted missions may become the way to go in unmanned planetary flights of the next 20 years. A variety of two-planet flybys are possible, and the National Aeronautics and Space Administration is even considering a mid-1980's triple play that would take in Jupiter, Uranus and Neptune. A

Comment: On credit overdue

Although I've been vaguely interested in the subject for years, I think what really turned me on to miracles being wrought routinely by the people who navigate unmanned spacecraft was a conversation I had last fall with Tom Duxbury at the Jet Propulsion Laboratory in Pasadena. Mariner 10 was coming around for a second look at Mercury, and the poor navigators were having to maneuver the thing virtually by hand. While shepherding the most critical trajectory ever attempted for an unmanned flight, they found themselves forced also to contend with (a) a star tracker that kept losing sight of its target, thereby activating (b) a nerve-rackingly erratic gyroscope, which kept frittering away (c) Mariner's dangerously depleted supply of gas—all while managing a mission that included the first gravity-assisted flyby, the first two-planet encounter and the first multiple encounter of the same planet.

Like any high-technology effort, the space program is liberally peppered with geniuses, innovators and hard-to-define types whose major contribution is often the flexibility that comes from believing that one's chosen brand of science or engineering is at least 50 percent art. The field of spacecraft navigation is no exception. Yet in all the publicity that has attended many recent unmanned space spectaculars, notably visits to other planets in the solar system, the navigators has remained unheralded.

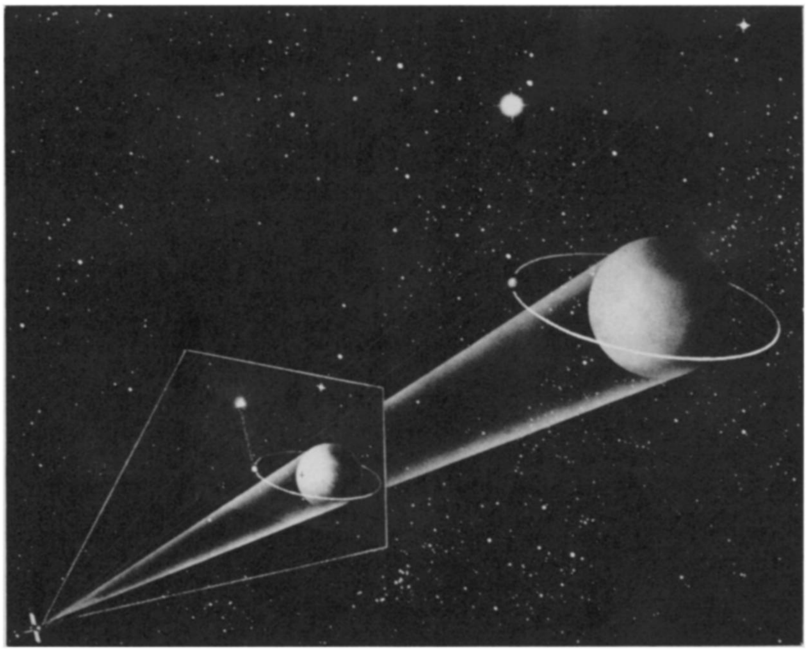
It is not unreasonable, strange to say, to maintain that there is really no such thing as a "space navigator." In the accompanying article I have used the term to encompass a variety of professionals who are collectively responsible for charting, instrumenting, tracking, guiding and controlling an otherwise helpless probe on a precise path through the trackless wastes beyond our earth. They include specialists in electronics, computer programming, celestial mechanics, propulsion systems, optics, mathematics and a host of other disciplines—but bound together by a common task: sending a tiny robot where it is supposed to go.

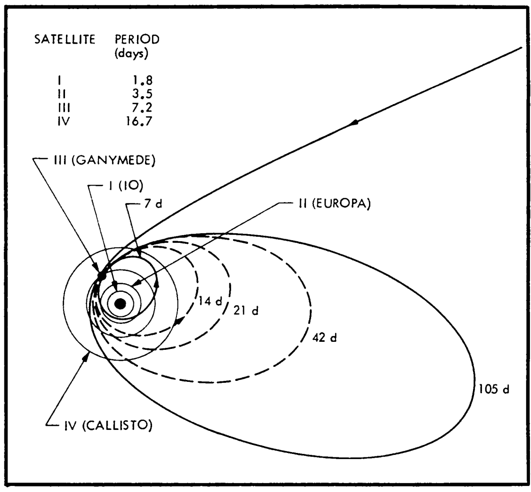
My original plan had been to write a historical account of the evolution of the field, replete with the names of those who contributed to the passing of critical milestones. Since the first artificial satellites were placed in their orbits—*any* orbits, just get them up there—there has been a comradely contest between technique and technology. First, design a guidance system precise enough to reach a predicted earth orbit. Then, with the equipment in hand and earth orbits a reality, expand the theory to get to the moon. Next, refine the hardware again for the planets, and retune the equations to allow for the countless tiny errors that will become critical over the millions of miles between worlds. Thus inspired, program planners conceive unprecedentedly exacting missions, which require more sophisticated navigation schemes, which in turn require more esoteric computers, sensors and other instrumentation. And so it goes.

It didn't take much research into the past, however, to reveal that a new future for space navigation is just beginning. Confronted with finite limitations on my time and the magazine's space, the future won out over the past.

Although the article as written is rather heavy on sources at JPL, the collective expertise of the space navigators spans the United States and beyond. I hope that those pioneers whose names, and indeed whose whole period of early endeavor, have been omitted will nonetheless take this brief survey as a compliment.

—*J.E.*





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Using a spacecraft to measure angles between its target planet and a reference point such as a moon or star is the basis of optical navigation (left), as well as an aid to future techniques such as resonance-hopping (above) that may require quick reactions from the probe.

slightly different approach has been suggested by German physicist Harry Ruppe, whose idea for a near-solar mission would require navigators to send a probe on a pinpoint-accurate path that would use Venus' gravity to set up a sun-circling orbit. After a single trip around the sun, the spacecraft would come by Venus a second time, Mariner 10 style, but the second encounter would be just different enough to bend the probe so that the repeat solar visit would be about 33 percent closer than the first.

The most exotic idea of all is a navigator's nightmare—except that they'll probably be more than ready when the time comes. A spacecraft in orbit around Jupiter would fly close to one of its 13 moons, which would redirect the probe just enough so that after a few orbits another moon would come near enough to redirect it a second time, and so on. One version of this proposal, says Charles Kohlhase of JPL, would make use of 42 such flybys in 36 months. "The 'nav' guys," says another JPL researcher, "could stand alternate shifts with their psychiatrists."

Such a mission would involve a host of navigational spectaculars, some of which have not even been tried yet. "Pumping," for example, is navigationese for flying ahead of or behind a target body in order to gain or lose just the right amount of energy to reach the next stop. Another technique, called "cranking," is a way of flying repeatedly past the same moon so that the moon's gravity will alter the inclination, or tilt, of the spacecraft's orbit, thus letting it see all latitudes of the moon's host planet. "Resonance hopping" is a sort of cross between pumping and Mariner 10's simple resonant orbit with Mercury, in which a spacecraft's initially large orbit is shrunk by repeated flybys to successively smaller multiples of its host planet's orbital period; in other words, a fuel-saving way of taking closer and closer looks at the same target.

The notion of rolling the navigators to work on their psychiatrists' couches comes from the fact that, for all the sophistication of the art, no such maneuver is ever quite perfect. The navigators must be there every step of the way to do the fine tuning. But this poses a problem. Flying the correct course past a big, nearby planet such as Venus is one thing; doing the same trick among tiny, close-together moons or distant, "poorly calibrated" planets such as Neptune is another. One promising aid, already the object of considerable attention, is on-board navigation, which simply means letting the spacecraft do some of the work on its own.

Spacecraft tracking—you can't tell where you're going if you don't know where you are—has so far been done with virtually a single tool: ground-based radio, monitoring the signal from the probe's transmitter. Tracking and guiding a spacecraft from the earth has been adequate for the relatively straightforward missions flown so far, even the two-planet, gravity-assisted, multiple encounter of Mariner 10. But more elaborate—and even simply more distant—goals for the future have the navigators engrossed in two new areas: optical navigation and its further extension, on-board or autonomous navigation.

Distance measurments are easy. It is possible to measure, by radio, how far a spacecraft is from earth to within as little as five meters. The hard part is to pinpoint the probe's exact direction. A tiny angular error of .1 second of arc—one thirty-six-thousandth of a degree—in an earth-based measurment can produce a 750-kilometer error in the position of a spacecraft out by Saturn. But what if the spacecraft can measure its *own* position, relative to the nearby target planet? Over such a short distance, small angular errors would become much less significant. This is the idea behind optical navigation.

The idea, says Charles Acton of JPL, is about 10 years old. Basically, a spacecraft takes a picture that includes the illuminated edge of the target planet and another reference point, usually a star (because it will appear as a precisely locatable point-source from anywhere in the solar system). The picture is transmitted to earth, where the navigators use it to calculate the location that would give the spacecraft that viewpoint. Two or more such photos can reveal the probe's trajectory.

The technique was first tested (not for actual guidance—just to see if the calculations could be made) with the Mariner 6 and 7 Mars probes in 1969. The reference star, however, was located not in a photo of the planet but in the spacecraft's optical star tracker (a standard device for unmanned probes, but which is subject to error in determining the viewing angle between it and the camera aimed at the planet). It was not until two years later, on the Mars-bound flight of Mariner 9, that optical navigation really proved that it had a future.

As the spacecraft approached the planet, a series of photos were taken showing the Martian moon Deimos (whose small size gives it a highly curved limb, or profile, making it easier to locate the center of the disk for measuring the angle) and variously no stars, one star or about five stars. Con-

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ventional radio tracking was able to keep errors down to about 70 kilometers for the approach, so optical navigation was not needed, but had it been needed, a combination of radio (to measure the spacecraft's speed) and optical tracking (for position) could have steered the probe on in with an accuracy of only 10 kilometers—and using only a single star per photo.

The same idea was tried a third time with Mercury and Mariner 10. This time, with no moons to sight on, navigators had to use the planet itself. One of the questions in optical navigation is how well the center of a planet (to which navigation angles are figured) can be estimated from a portion of its curved limb. The other difficulty is exposing the photo enough to show stars, but not enough to overexpose the planet, thus making its exact edge harder to locate. To the untrained eye, Mercury's limb looks dramatically sharp in the photos, but it took computer analysis to satisfy the navigators that indeed, the test had been passed. With optical navigation, says Tom Duxbury, who is refining the technique at JPL, Pioneer 10 could have been 7.5 times more accurate in its already precise approach to Jupiter.

The first real use of "opnav" will take place in the summer of 1976, as the two Viking spacecraft approach Mars, followed a few years later by the Mariner Jupiter-Saturn slingshot. Meanwhile, however, several other exotic techniques are being considered.

During the Mariner 9 Mars flight, a large team of experimenters tried, with moderate success, to determine the spacecraft's position with long-base interferometry using radio signals from distant quasars. Though technical problems limited the accuracy of the results, the group has predicted that within five years the method could trim position errors to as little as 10 kilometers at a distance of 93 million miles. A similar proposal has suggested the use of pulsars as natural navigation beacons, by comparing the phase differences of signals received at the spacecraft and at earth. (Pulsars, in fact, were once suggested by some to be possible components in an actual intergalactic navigation system. "This," says George Downs of JPL, "was known as the LGM Hypothesis, where LGM = Little Green Men.") But for all the pumpings and crankings, pulsars and quasars, there are missions on the drawing boards that will tax the best of them.

How, for example, do you fly those short hops among the Jovian moons, or graze an asteroid, or land on Neptune, even with optical navigation, if you have to steer so close that there is not time to relay pictures to earth, process them and send instructions back to your spacecraft? That probe-drop at Halley's nucleus, for example, says Kohlhase, could require a reaction time as short as eight minutes, and a round-trip signal from Neptune could take eight and one-half hours. The answer? Simple. You don't send them at all.

Let the spacecraft do the work. Send along a computer smart enough to measure its own angles, calculate its own position and give its own instructions. It won't happen tomorrow—you'll need one with a large memory, lots of flexibility and the ability to be crammed into perhaps a 20-pound package that can live on maybe 10 watts of power. But there are already preliminary version in the works, such as "Sum-C," a baby genius now being nursed along by engineers at NASA's Marshall Space Flight Center in Alabama.

For really close flying, however, such as looking for a landing site, it will take more than just looking at limbs and measuring angles. One possible tool for the navigators and self-navigating spacecraft of tomorrow is being developed at Martin Marietta Aerospace in Denver, where Roger Schappell is working on a camera-like device that can select smooth places to land by their relatively low contrast. The device can even carry a description of some preselected site (such as from an earlier orbiting probe) in its memory and help the spacecraft hunt it down.

An important concern in navigation plans for the future, in fact, is the precision with which a spacecraft will be able to "see" where it is. Some researchers feel that magnetic and electric fields can cause enough distortion in conventional television vidicon tubes to make them dangerously unreliable in such a critical task as the pinpoint location of a star—especially if the spacecraft is working "on its own." The leading contender for bypassing the problem is a tiny, still-experimental chip called a charge-coupled device. It has an array of elements, analogous to the elements of the picture on a TV tube, but each element is individually connected to the computer or other system that is "reading" the image falling on the chip. Thus, although a given CCD chip may not have as many picture elements as a vidicon tube, it is free of the distortions between adjacent elements that make it hard to be sure just which element is really showing the true position of a point-source such as a star.

The problems of the space navigator are almost limitless, ranging from tiny velocity changes caused by the physical pressure of sunlight to uncertainty about the precise locations of his own tracking stations on earth. Yet the missions get fancier—and the spacecraft get through. ☐