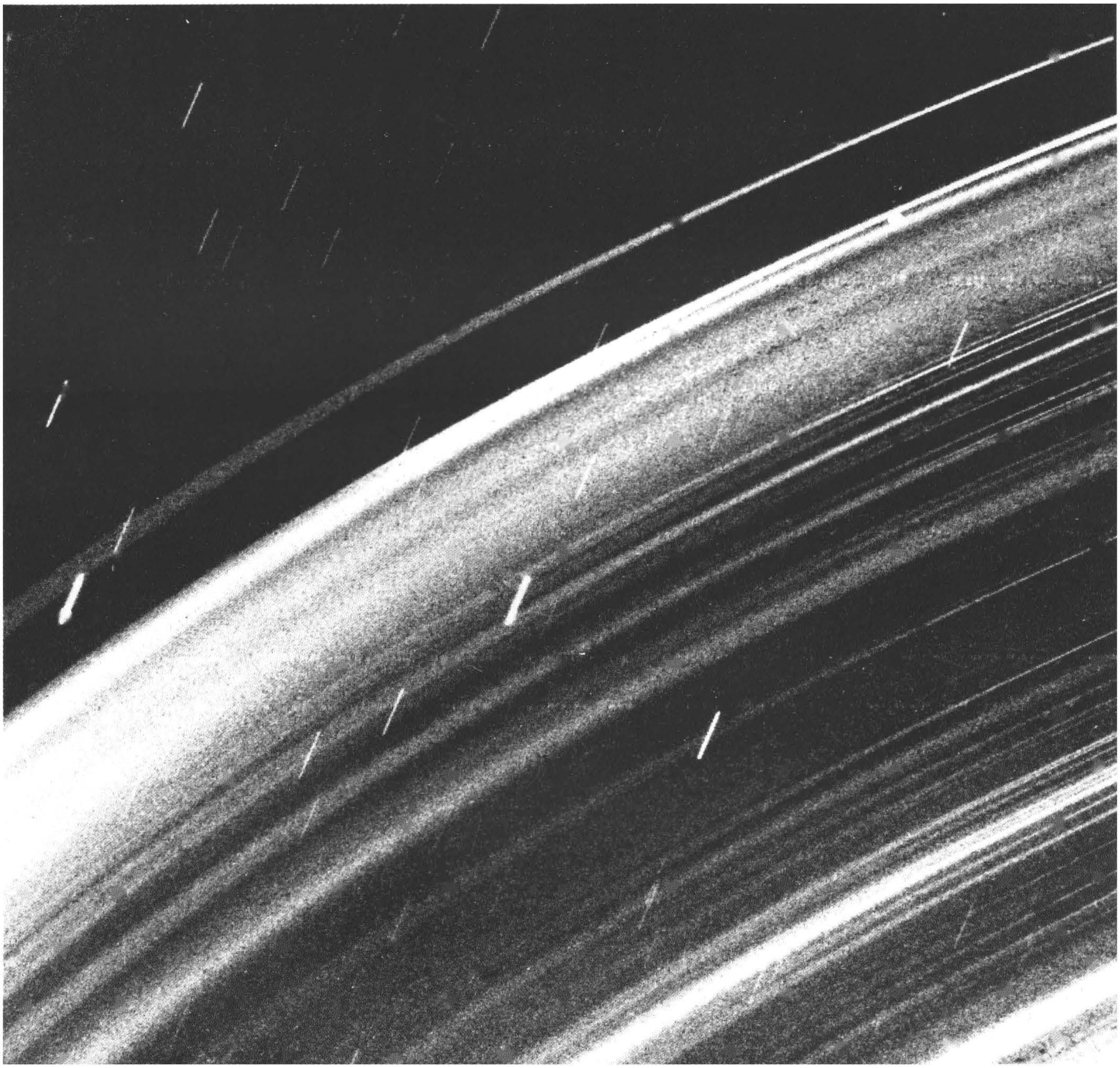
Voyager Bulletin

MISSION STATUS REPORT NO. 77 FEBRUARY 5, 1986



Small particles are distributed continuously throughout the Uranian ring system, although most ring particles are larger than 1 meter across. Voyager 2 took this image while in the shadow of Uranus, at a distance of 236,000 kilometers (147,000 miles) and a resolution of about 33 km (20 mi). This unique geometry – the highest phase angle at which Voyager imaged the rings – allows us to see lanes of fine dust particles not visible from other viewing angles. All the previously known rings are visible here; however, some of the brightest features in the image are bright dust lanes not previously seen. The combination of this unique geometry and a long, 96-second exposure allowed this spectacular observation, acquired through the clear filter of Voyager's wide-angle camera. The long exposure produced streaks due to trailed stars as well as a noticeable, non-uniform smear.

Navigation

Voyager 2 traveled an arc of nearly 5 billion kilometers to Uranus, yet engineers estimate the actual closest approach to have been within 20 kilometers of where they thought they would be.

"Uranus was a navigational challenge for several reasons," explained Bill McLaughlin, manager of Voyager's Flight Engineering Office. "First, we had no data from previous spacecraft to guide us to Uranus.

"Second, Uranus is so far away that it was difficult to measure the satellite positions from Earth and obtain accurate *a priori* orbits that could be refined by spacecraft measurements."

"And third, Uranus lies on its side, making triangulation difficult and presenting a different navigational situation than we have dealt with before," McLaughlin concluded. As the spacecraft approached the planet, there was an element of the unknown in exactly where the ship was in relation to the plane of the planet, rings and satellites. Even a small navigational error could have resulted in pictures of deep space rather than the intended target, for example. In addition, the spacecraft had to pass through a specific region just inward of Miranda to be able to use Uranus' gravity to slingshot itself on to Neptune.

"We don't know perfectly where the spacecraft is," says Don Gray, Voyager's Navigation Team Chief, "but we know within kilometers."

The Voyager flight team uses four navigational tools: optical navigation and three radio techniques – Doppler, ranging, and a version of very-long baseline interferometry (VLBI).

Navigating by the Stars

"During the approach phase, optical navigation is the most precise way to determine the spacecraft's position in relation to a planet," explained optical navigation engineer Bill Owen.

Engineers use Voyager's images of known star fields to determine the spacecraft's location. The targeting of the images is designed to include a known star in the same field of view as a planet or satellite. Lick Observatory at the University of California, Santa Cruz, provides up-to-date star positions based on astrographic plates requested by JPL's opnav engineers. This information is stored in computers and compared with optical navigation frames sent down by the spacecraft.

Software developed since the Saturn encounters allows engineers to manipulate the data for easier analysis. For example, one can zoom in on (enlarge) a small set of pixels (picture elements) out of the total 800 by 800 array. One can also stretch the original gray scale of 256 levels to make small variations about a given level easily visible for analysis.

Currently, Voyager's backdrop is the constellation Sagittarius, in the middle of the Milky Way, so there are many stars suitable for use in optical navigation. Most are dim – about eighth or ninth magnitude.

In the Uranus encounter period, from November 4, 1985 through February 25, 1986, nearly 250 optical navigation pictures will be taken, usually with 1.44-second exposures. This data is correlated with other tracking data and used to update the pointing and timing of critical science observations.

Optical navigation is also used to determine the satellite orbits. By measuring the center of the satellite and the location of known stars in successive images, engineers can infer the satellite's position and thus determine its orbit.

Navigating by Radio

"Radio data usually best determine the spacecraft's position relative to Earth. However, in the last few days before closest approach to a planet, powerful planet-relative information becomes available due to a strong gravitational signature in the data. In the case of Uranus, this occurred within five days of closest approach," explained Tony Taylor, lead orbit determination analyst.

The spacecraft's direction and velocity is determined by measuring the Doppler shift. Doppler is a shift in frequency caused by relative motion between the source and the receiver (a familiar, audible Doppler phenomenon is the change in pitch heard as a locomotive bears down upon and then sweeps past a stationary observer.) One-way Doppler measures the downlink signal from the spacecraft's ultrastable oscillator electronics, while two-way Doppler measures the change in a signal uplinked from Earth, received at the spacecraft, changed in frequency by a prespecified amount, and downlinked back to Earth.

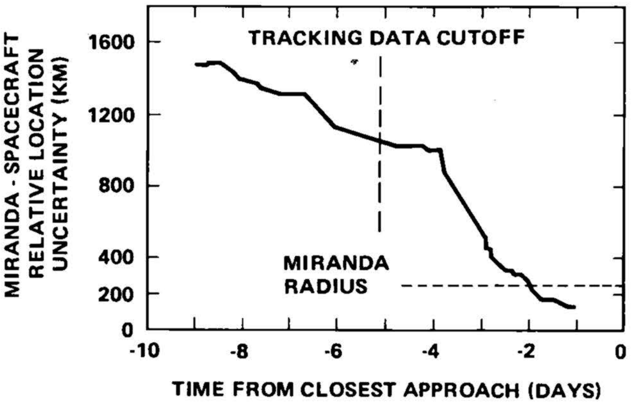
The distance, or range, from Earth to the spacecraft can be determined by measuring how long it takes for a coded signal to travel from Earth to the spacecraft and back to Earth.

Voyager also uses a version of very-long baseline interferometry called delta differential one-way ranging (ΔDOR). Two ground stations observe the spacecraft, note the difference in time of signal receipt as the Earth rotates, and then slew simultaneously to a quasar and again measure the difference in time of signal receipt. These results are then differenced (hence the "delta differential" in the name) and from this, the angle of the spacecraft with respect to a line between the two stations is calculated. Doppler and ranging together with ΔDOR give a good three dimensional knowledge of the spacecraft's position.

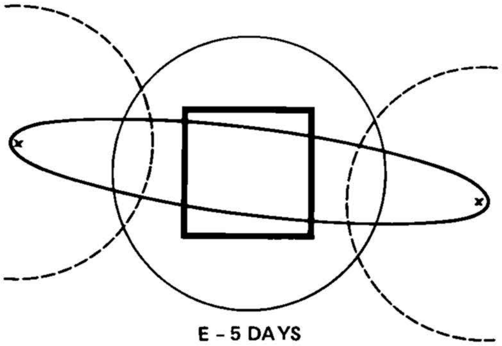
A combination of these four navigational tools is used to guide the spacecraft, to deliver it to the right place at the right time, and then, after the fact, to reconstruct the actual flight path followed.

Maneuver Design

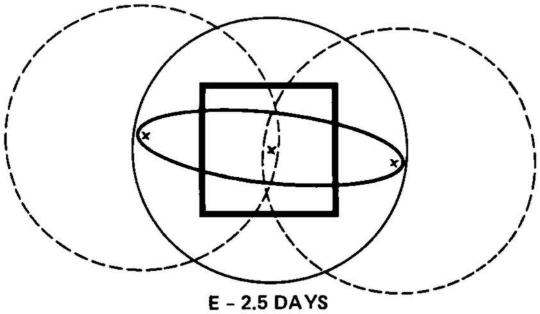
Once the spacecraft's position is estimated and a target aimpoint is selected, the Navigation Team determines what change is needed in the spacecraft's velocity to arrive at the right place at the right time. The Spacecraft Team then



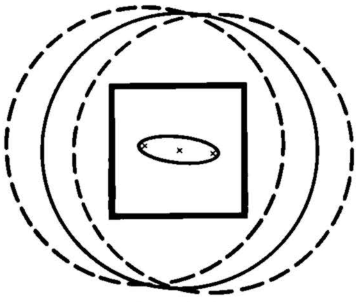
Voyager 2 had a depth perception problem as it approached the Uranian system, since the orbital plane of the Uranian moons was perpendicular to the flight path. The possibility of mispointing the science instruments was very real, and it was imperative to incorporate the latest tracking data possible, both Doppler radiometric data sensing the gravitational tug of the planet and optical navigation pictures. Plans were devised and carried through to use tracking data obtained as late as one day before closest approach and to modify the spacecraft's instructions after the instructions had begun to be carried out. The above chart shows that if the data cutoff had been five days before closest approach, the uncertainty in the pointing would have been much larger than the satellite Miranda, and the satellite might have been missed altogether. By sending late updates to the spacecraft, the uncertainty was narrowed to an acceptable level, as shown in the sequence at right. The square represents the field of view of the narrow-angle camera; the solid-line circle represents Miranda; the ellipses represent the size of the uncertainty; the X's represent the center of Miranda; and the dashed-line circles indicate where Miranda would have been at various uncertainty points. In fact, the final orbit determination was so accurate that spectacular images of Miranda were returned.



E - 5 DAYS



E - 2.5 DAYS



E - 1 DAY

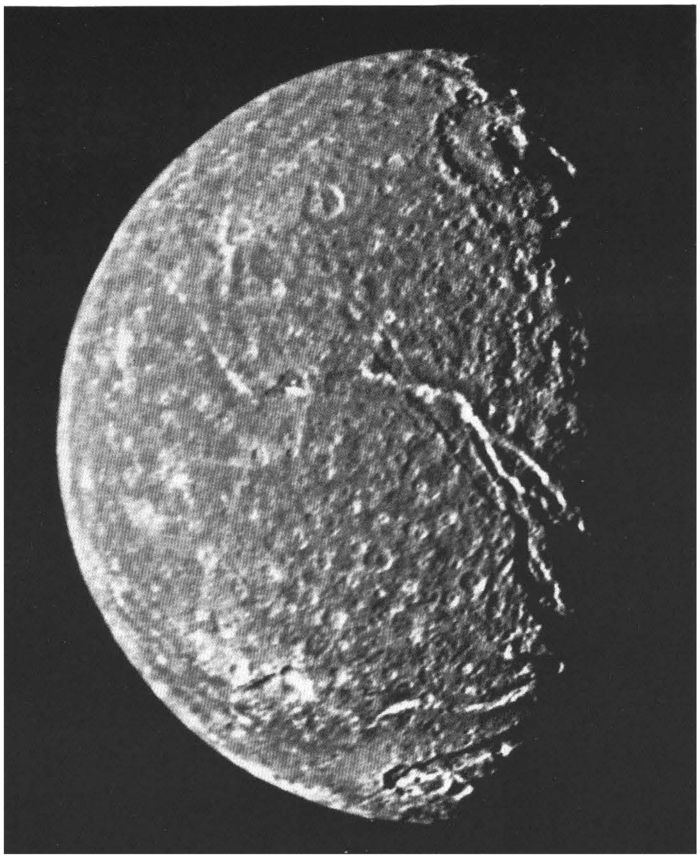
designs a trajectory correction maneuver using the spacecraft's attitude control and propulsion subsystems. Finally, the Sequence Team translates this design into instructions for the spacecraft's computers. Course corrections may be small, such as the 14.5-minute burn performed on December 23 (which used about 2.1 pounds of hydrazine propellant and accelerated the craft by 2.1 meters per second), or large, such as the 2-1/2-hour burn on February 14 which will impart an acceleration of 21.1 meters per second to the spacecraft. (The spacecraft is currently travelling at about 18 kilometers per second.)

"The February 14 trajectory correction will set up the correct timing for a good look at Neptune's big satellite Triton in August 1989," noted Gray.

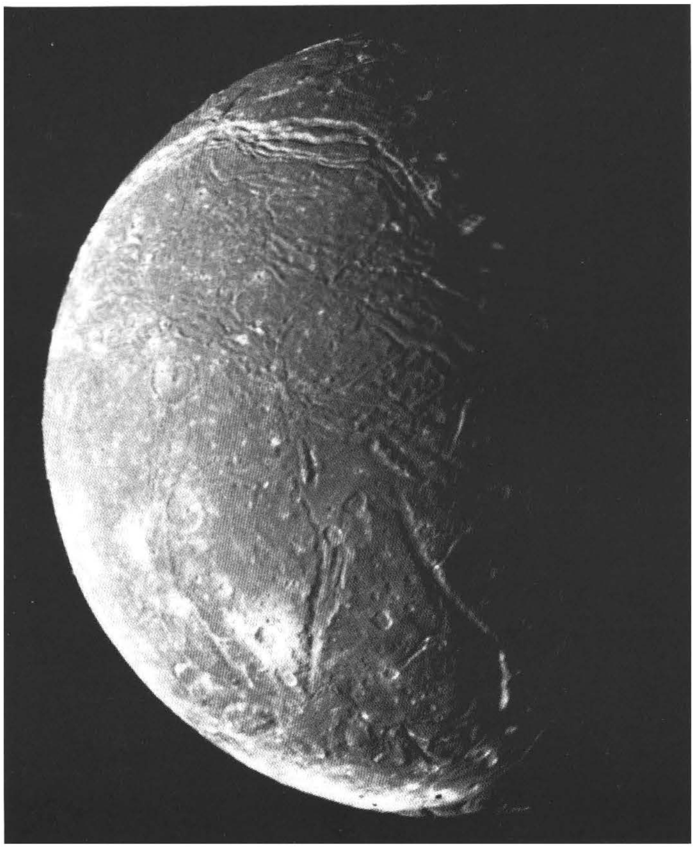
Support of Science Observations

Navigation data is also critical to the success of crucial science observations which depend not only on knowledge of the spacecraft's location, but also on proper, accurate pointing of the instruments aboard Voyager's steerable platform. During the Uranus encounter, the entire spacecraft itself was rotated at precisely determined rates to provide a camera panning motion that reduced image smear. This technique – target motion compensation – supported eight separate sets of imaging observations. For example, the best resolution of the satellite Miranda was obtained in an eight-frame mosaic taken as the spacecraft, sweeping past Miranda at 70,000 kilometers per hour, rotated to track the tiny satellite.

Also, since the exact time of arrival could not be determined early enough to make changes in the flight path, an 8-hour segment of science observations near closest approach was designed in a movable block of instructions to the spacecraft. The entire block could be shifted by up to ±12 minutes in 48-second increments, while within the block, critical radio science observations could be shifted by ±72 seconds in 1-second increments. This design allowed the timing of the observations to be shifted without expending fuel to change the time of flight. The instructions that modified the timing of the movable block were sent to the spacecraft on January 24 as an overlay to a sequence already in progress. As it turned out, the navigation data was so accurate that the movable block needed to be shifted by only -48 seconds.



Abundant impact craters of many sizes pockmark the ancient surface of Titania, the largest satellite of Uranus with a diameter of a little more than 1,600 kilometers (1,000 miles). The most prominent features are fault valleys that stretch to 1,500 km (nearly 1,000 mi) long and as much as 75 km (45 mi) wide. In valleys seen at right-center, the sunward-facing walls are very bright. While this is due partly to the lighting angle, the brightness also indicates the presence of a lighter material, possibly young frost deposits. An impact crater more than 200 km (125 mi) in diameter distinguishes the very bottom of the disk; the crater is cut by a younger fault valley more than 100 km (60 mi) wide. An even larger impact crater, perhaps 300 km (180 mi) across, is visible at top. This is the highest-resolution picture of Titania returned by Voyager 2. It is a composite of two images taken January 24, 1986, through the clear filter of Voyager's narrow-angle camera. At the time, the spacecraft was 369,000 km (229,000 mi) from the moon; the resolution is 13 km (8 mi).



Much of Ariel's surface is densely pitted with craters 5 to 10 kilometers (3 to 6 miles) across. Numerous valleys and fault scarps crisscross the highly pitted terrain. The valleys may have formed over down-dropped fault blocks (graben); apparently, extensive faulting has occurred as a result of expansion and stretching of Ariel's crust. The largest fault valleys, near the terminator at right, as well as a smooth region near the center of this image, have been partially filled with deposits that are younger and less heavily cratered than the pitted terrain. Narrow, somewhat sinuous scarps and valleys have been formed, in turn, in these young deposits. It is not yet clear whether these sinuous features have been formed by faulting or by the flow of fluids. Ariel is about 1,200 km (750 mi) in diameter; the resolution here is 2.4 km (1.5 mi). This is a mosaic of the four highest-resolution images of Ariel, taken through the clear filter of Voyager's narrow-angle camera on January 24, 1986, at a distance of about 130,000 km (80,000 mi).

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JPL 410-15-77 2/86

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