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VOYAGER 2: TRIUMPH IN SPACE

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Engineering Voyager 2's Encounter with Uranus

Difficult problems posed by vast distances, low light levels, aging equipment and mechanical breakdowns were solved by radio control from the ground as the Voyager 2 *spacecraft hurtled toward Uranus*

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On January 24 of this year the *Voyager 2* spacecraft came within 81,000 kilometers of the cloud tops of Uranus. From that unprecedented vantage point the craft was able to transmit spectacular images of the planet, its moons and its rings across the three billion kilometers that separate it from the earth. In addition to acquiring the striking visual images, the assortment of scientific instruments on the spacecraft collected copious amounts of other valuable data on the Uranian system—enough data to keep planetary scientists occupied for years to come. What made this remarkable feat ultimately possible was more than resolve and a measure of good luck. The necessary additional ingredient was extensive in-flight engineering: the monitoring, control and modification of *Voyager 2* during the course of its travel through interplanetary space.

Indeed, the very decision to send *Voyager 2* to Uranus was made three and a half years after the craft's launch into space in 1977. *Voyager 2,* like its twin *Voyager 1,* had been designed only to explore Jupiter and Saturn. By January, 1981, when the decision to add Uranus to the itinerary of *Voyager 2* was made, the two spacecraft had completed all the combined mission objectives. *Voyager 1* had encountered Jupiter and Saturn, returning a wealth of information about the two planets, including evidence of active volcanoes on Io, one of the Jovian satellites. *Voyager 2* (which was actually launched before *Voyager 1*) had arrived at its closest approach to Jupiter and was on its way to its follow-up exploration of the Saturnian system.

Yet the Voyager-project team had a compelling reason to extend the mission: the alignment of the outer planets would allow *Voyager 2* to be flung in the direction of Uranus and Neptune by the gravitational force of Saturn. (Such a gravitational "slingshot" had in fact been exploited to send the Voyagers from Jupiter to Saturn.) The last time the outer planets were similarly aligned was during the presidency of Thomas Jefferson about 180 years ago. The uniqueness of the opportunity outweighed the fact that the probability of *Voyager 2's* lasting for another five years was estimated to be between 60 and 70 percent, well below the National Aeronautics and Space Administration's usual criterion for approving such missions. And so the decision was made to go for Uranus.

As it passed Saturn *Voyager 2* was 1.5 billion kilometers from the earth and about four years old. When it arrived at Uranus, it was twice as far away and twice as old. Yet it had in fact become better: most of the spacecraft's subsystems had actually been improved en route. The project engineers had accomplished this in spite of the difficulties posed by the vast distances, the spacecraft's age, the low light levels and a dwindling power supply. The result of their efforts was the nearly flawless encounter with Uranus, with more to come: the prospect of a successful encounter with Neptune in 1989.

The Voyager probes are a far cry from the sleek spacecraft often depicted in motion pictures and television. The dominating feature of the Voyager is its large parabolic-dish antenna, 3.7 meters in diameter, through which it transmits and receives radio signals to and from the earth. Extending in roughly opposite directions from the base of the antenna dish are two trusses. One of them supports three radioisotope-thermoelectric generators and the other supports a platform on which an array of scientific instruments, including the imaging system, are fastened. Between the two trusses are other ungainly extensions: a long boom that holds a low- and a high-field magnetometer, as well as two wire antennas for plasma-wave and radio-astronomy observations.

The three generators on the spacecraft produce electricity by applying heat, which is released by the radioactive decay of plutonium oxide, to a thermoelectric material. Such a material converts heat directly into electricity. The efficiency of the generators is low (about 5 percent); their great advantage is that they can operate in the dark outer regions of the solar system, where photovoltaic cells (which convert light directly into electricity) would be ineffective.

Along with the two cameras of the imaging system, three devices are housed on the platform opposite the generators: a photopolarimeter, an instrument that measures the intensity and angle of polarization of light, and two spectrometers, which record the component wavelengths of electromagnetic radiation. One spectrometer operates in the infrared region of the spectrum and the other in the ultraviolet. The platform is capable of scanning in two directions by means of gear-driven actuators: azimuth (side to side) and elevation (up and down). Attached to the scan-platform truss is an assortment of elementary-particle detectors. All this equipment, in addition to the magnetometers and the wire antennas, enables the Voyager spacecraft to perform 10 different scientific experiments. The spacecraft's radio system, which is its vital link to the earth, is also the means by which an 11th, radio-science experiment can be carried out.

The Voyagers' most important on-board data-handling equipment is the Flight Data Subsystem (FDS), which consists of two computers (one serving as a backup for the other). These computers, among other tasks, control the state of the scientific instruments and put the data obtained from them into the correct format for transmission to the earth.

Two different sets of thrusters control the orientation and navigation of the spacecraft. The thrusters expel gases produced in a catalyzed reaction of hydrazine, a compound of hydrogen and nitrogen that is stored as a liquid in a tank. The on-board supply of hydrazine is critical since it fuels the attitude-control thrusters that keep the highly directional parabolic antenna pointed toward the earth. The Voyager spacecraft are essentially projectiles in free flight; their speed and direction are affected by gravitational interaction with solar-system bodies, by small and continuously decreasing forces that photons emitted by the sun and the spacecraft's own power source exert and by their own thrusting. Careful management of the hydrazine left the *Voyager 2* fuel tank about half full after the Uranus encounter.

The hydrazine fuel is just one of several items that are unavoidably depleted during the course of the Voyager mission. Others include the decaying radioisotope in the thermoelectric generators and, more generally, various parts that are subjected to wear and tear. The only way to minimize the loss of these resources and thereby extend the effective lifetime of the spacecraft is to use them sparingly.

The electric-power supply actually proved to be a bigger problem than the fuel supply during the Uranus encounter. When *Voyager 2* was launched, the thermoelectric generators had a power output of more than 470 watts. By the time the spacecraft reached Uranus the natural decay of the plutonium oxide had reduced the available power output to about 400 watts, which was not enough to operate all spacecraft subsystems simultaneously. As a consequence some subsystems could only be switched on after others had been switched off, and this put certain con-

VOYAGER MOCKUP, along with duplicates of the spacecraft's various subsystems, is available at the Jet Propulsion Laboratory for testing new procedures that might be tried on *Voyager 2* as it moves toward Neptune following its successful encounter with Uranus this past January. The mockup differs from the actual spacecraft in that the magnetometer boom (*see illustration on next page*) is not extended.

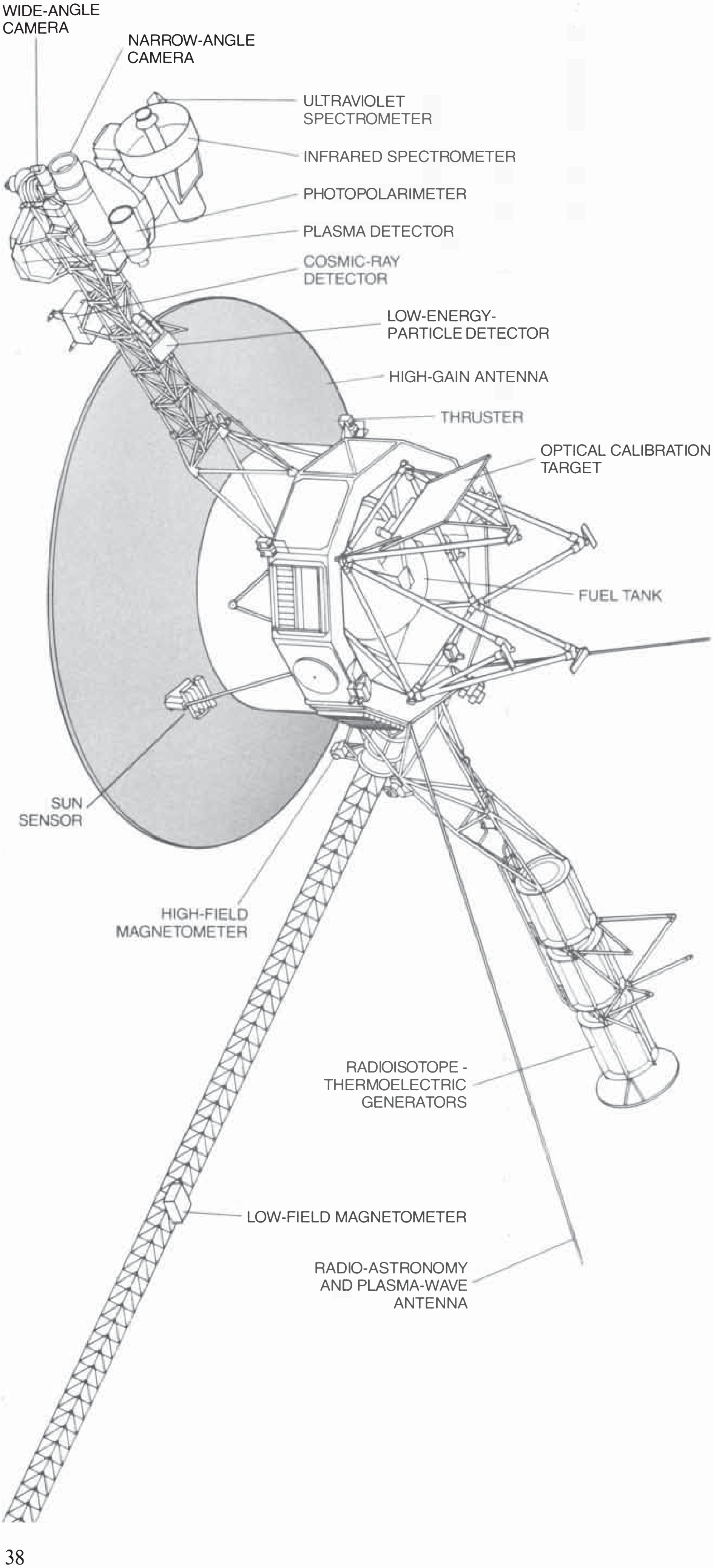
straints on the design of the mission.

As the spacecraft rounded Uranus, for example, it was eclipsed by the planet's rings and the planet itself, an event called an occultation. The hope was to gather information on the temperature and composition of the planet's atmosphere and the size of the objects that form the rings by noting how radio signals beamed to the earth from the spacecraft were affected as the signals traversed the rings and the atmosphere during *Voyager 2's* passage behind Uranus. For this experiment the project investigators planned to switch one of the spacecraft's transmitters to high power, adding 53 watts to the electric load.

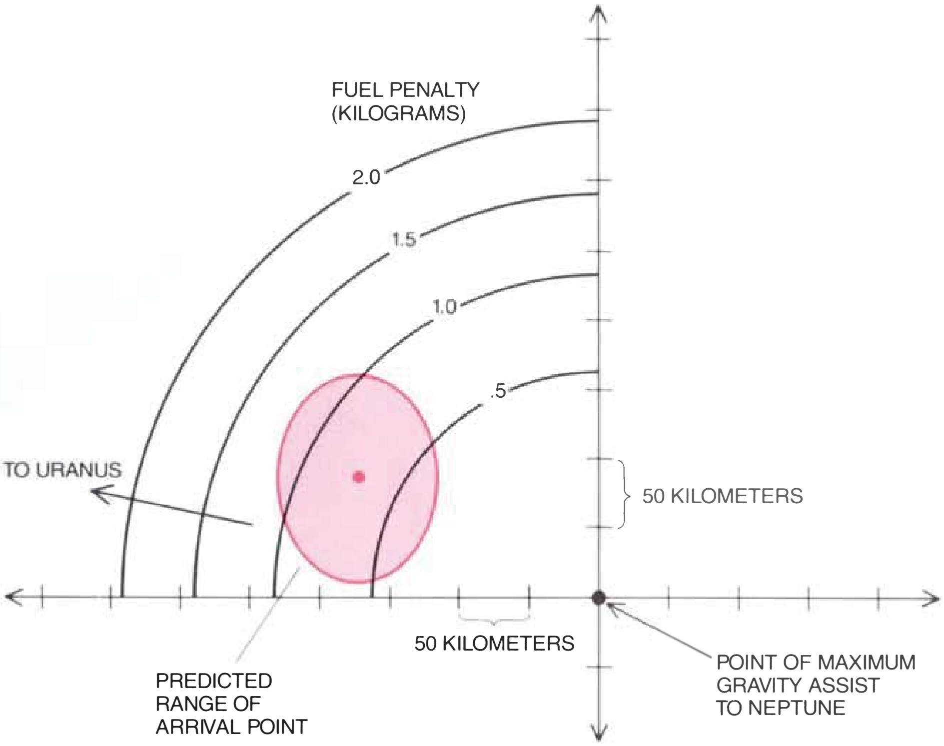
During that time the investigators also planned to make pictures of the dark side of the planet and its backlighted rings. These activities involved pointing the cameras by moving the scan platform and recording the images on tape. Both activities would be additional consumers of power. If for some reason the subsystems on the spacecraft attempted to draw more than the available power, an overload-protection system would automatically turn off several subsystems. Such an occurrence in the middle of the occultation would have interrupted the scientific observations until restoration commands could be sent to the spacecraft from the earth.

Hence a careful ballet of turning subsystems and heaters on and off had to be performed in order to ensure adequate power throughout the period of the occultation experiment. The choreography was not without risk: it required operation of the spacecraft near the 400-watt limit. To minimize the risk a series of tests in which the spacecraft was operated close to the limit of available power was run on *Voyager 2* prior to the occultation. The results suggested the procedure would indeed work.

Another important resource in short supply near Uranus was one not carried on *Voyager 2:* light. Although Uranus is twice as far from the sun as Saturn is, the level of the light at Uranus is only a fourth of what it is at Saturn. That meant a fourfold increase in exposure times for the cameras, which



ELEVEN EXPERIMENTS can be carried out by various remote-controlled scientific instruments on *Voyager 2*. The spacecraft is also outfitted with an electric-power supply, communication equipment and data-handling computers. Two sets of thrusters serve to control the orientation of the spacecraft as well as its flight trajectory.



VOYAGER 2'S FUEL CONSUMPTION is minimized by taking full advantage of the gravitational force of large solar-system bodies to deflect the craft toward its targets. The penalty (_quarter circles_) for not reaching the point where Uranus' gravity would have most assisted it on its journey to Neptune was estimated, five days before the closest approach, to be between one-half and one kilogram of fuel. The project team elected not to perform a trajectory-correction maneuver at that time since the fuel penalty was not costly (62 kilograms of fuel remained in the tank), it would have made tracking the spacecraft more difficult and the team's limited manpower resources could be better applied to other important matters. The coordinate plane is drawn so that it passes through the center of Uranus, some 100,000 kilometers in the direction indicated, and is nearly perpendicular to the direction of travel of _Voyager 2_ as it approached the planet. The fuel carried on the spacecraft is hydrazine, a compound of hydrogen and nitrogen. It is stored in liquid form but is converted into a gas before it is expelled through the thrusters.

in turn increased the likelihood of blurred pictures from unintentional jiggling of the spacecraft while the camera shutters were open.

The solution to that problem was achieved by two engineering changes designed to steady the spacecraft as an observing platform. The first change addressed the unwanted angular momentum imparted to the spacecraft every time its tape recorder was switched to the high-speed mode employed to store digitized images and other data. To cancel that momentum the logic coded in the on-board attitude-control computers was modified to briefly fire the appropriate thrusters whenever the recorder's high-speed mode was switched on or off.

The second change required a still more delicate corrective use of the attitude-control subsystem. Two celestial sensors, one pointed at the sun and the other at a reference star, provide the information on the actual orientation of the spacecraft. When the spacecraft drifts too far from the desired orientation, the appropriate pitch, yaw or roll thruster is fired briefly to nudge the vehicle back to its correct position. Drifting, such as that caused by the residual torques from the tape recorder or by external torques from the pressure of solar photons, is controlled to within .05 degree along the three rotational axes during planetary-encounter periods. This range of maximum allowable drift is called the dead band.

Clearly, image smear would be reduced if drift rates through the dead band could be reduced. The Voyager engineering team analyzed the control logic and found a way to reprogram the attitude-control computer in order to reduce the length of time the thrusters are fired once the spacecraft has reached the limit of the dead band. As a result the force of the thrusts could be reduced and shifts in the spacecraft's orientation would be gentler.

Although it is simple in principle, this procedure raised practical difficulties. Ground testing on duplicate thrusters was done to determine how far the thrust levels could be reduced and still maintain firm control of the spacecraft's orientation. A reduction by a factor of about two in the thrust appeared to be feasible. Additional ground testing confirmed that the reduced-thrust mode would not shorten the expected lifetime of the thruster assemblies.

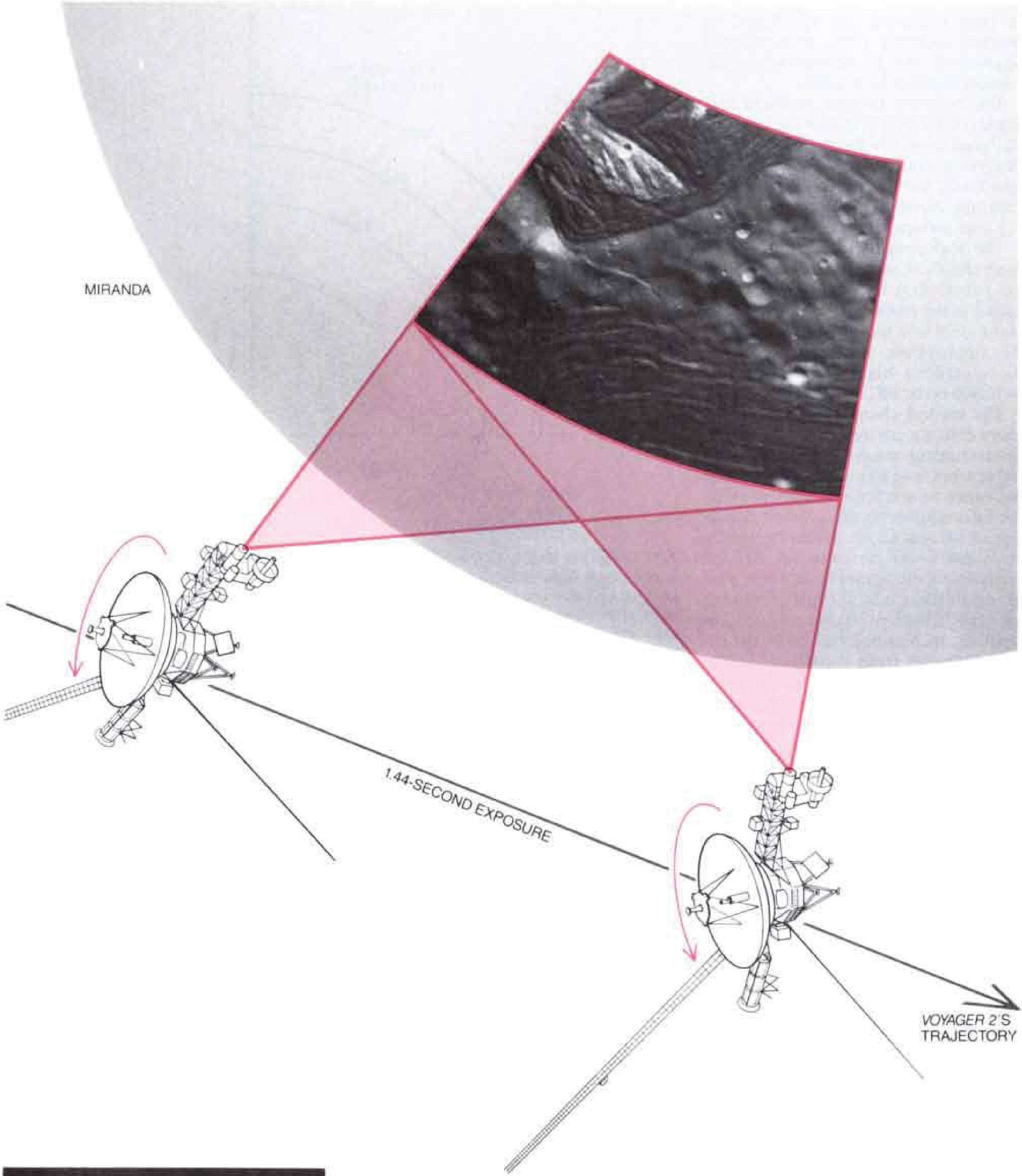
After the logic of the control algorithm was verified with a laboratory simulator, the next step was to incrementally reduce the thrust impulse on *Voyager 1,* observing the results at each step. Although *Voyager 1* has no more planetary encounters in its itinerary, its on-board scientific experiments still provide valuable data. Furthermore, it remains a valuable engineering tool in that it serves as a convenient test-bed for new procedures proposed for *Voyager 2.* Since the procedure appeared not to have resulted in any problems with *Voyager 1,* it was implemented on *Voyager 2.*

Although the two stabilizing procedures did help to make the images recorded at Uranus a lot sharper, *Voyager 2* was scheduled to approach so close to the planet's five known satellites that in their case another source of picture smear had to be considered: the relative motion of the spacecraft with respect to the satellites. Such a situation is familiar to any amateur photographer who has snapped pictures from a rapidly moving vehicle: the objects in the foreground are blurred even when background objects remain quite sharp.

The strategy in *Voyager 2*'s case was much the same as the one experienced photographers resort to: "panning" the camera. The camera is moved while the shutter is open in order to hold the object of interest in a fixed position within the camera's field of view.

That type of motion compensation was achieved in the case of *Voyager 2* by firing the attitude-control thrusters to turn the entire spacecraft at the proper rate while the images were being made. A similar motion-compensation procedure carried out solely by the scan platform, on which the cameras are fixed, would have been too jerky. The necessary three-axis turn rates were implemented by "fooling" the attitude-control subsystem: a message was sent to the spacecraft that commanded the attitude-control logic to compensate for a fictitious drift in the attitude-reference signal. An undesirable consequence of this process was that the spacecraft antenna would be pointed away from the earth. The temporary loss of radio communication was outweighed by the value of the high-resolution images acquired.

Like the light levels, the supportable bit rate, which is the amount of digitally coded information that can be reliably received in a given time, is inversely proportional to the square of the distance of the spacecraft from the



HIGH-RESOLUTION IMAGES OF MIRANDA, one of the moons of Uranus, are among the best images ever made in the course of a planetary flyby. Because of the low levels of sunlight in the vicinity of Uranus, long exposure times were necessary for the various images made during the encounter. To avoid blurred images, the computer logic that operates the firing of the attitude-control thrusters was rewritten to minimize jiggling of the camera while the shutter was open. More important in the case of Miranda was the precise firing of the thrusters to rotate the entire spacecraft smoothly in such a way as to compensate for the relative motion of the spacecraft and its target. During the exposures *Voyager 2* was traveling at 72,000 kilometers per hour as it sped by within 29,000 kilometers of Miranda. The clarity of the images eventually obtained made it possible to resolve surface features as small as half a kilometer. If the spacecraft had not been accurately guided, positioned and rotated, the resolution of the pictures would have been about 26 kilometers, comparable to that of the smaller picture of Miranda on the left, and many of the satellite's topographic characteristics would not have been visible.

earth. In contrast, the amount of data scientists want to collect tends to increase with distance. The way around the dilemma in the case of *Voyager 2* was to modify the data-processing software run on the spacecraft's computers and to enhance the capability of the receiving stations on the earth.

On *Voyager 2* data streams are coded prior to transmission so that errors can be detected and corrected on the ground. A simple example of such a coding scheme is one in which each bit, or digit, of a binary number (a 1 or a 0) is appended to a pair of repetitions of the bit. In other words, if the data bit were 1, 111 would be transmitted. Similarly, 000 would be transmitted for each 0 data bit.

The fact that a 111 is transmitted by the spacecraft does not guarantee that 111 will be received at a ground station. Because of unavoidable background noise in radio-signal reception and processing, occasionally a 1 will be recorded as a 0, or vice versa. Therefore three-digit binary numbers could be received as eight possible combinations of 1's and 0's. Yet if a "majority rules" decoding tactic is applied, with the data bit assumed to be the value of whatever digit is repeated at least once in the transmitted triplet, then the overall probability that the data bit will be erroneously interpreted is significantly less than it would be if the data bit were transmitted without encoding and decoding.

Although that is a simple example, it gives a sense of the tradeoffs involved in applying any error-detecting and error-correcting code: one can improve the reliability of data reception, but only by increasing bit overhead, or the total number of bits transmitted. For *Voyager 2,* however, any increase in the total number of bits that have to be transmitted reduces the rate at which scientific data can be returned.

In the example cited above two coding bits constitute what is called the coding block and one data bit what is called the data block; the coding block is twice the size of the data block, in effect tripling the transmission load. The actual coding schemes used on Voyager are naturally much more sophisticated than the example, and the bit overhead is fortunately not quite as large. During the Jupiter and Saturn encounters the particular coding scheme used, called Golay coding, had resulted in code blocks that were equal in size to the data blocks. At Uranus another coding scheme was employed (Reed-Solomon coding), so that the code block was only one-seventh the size of the data block. The decision to turn to Reed-Solomon coding at Uranus carried with it some risk. The onboard hardware for implementing it was nonredundant, whereas the Golay hardware had a backup.

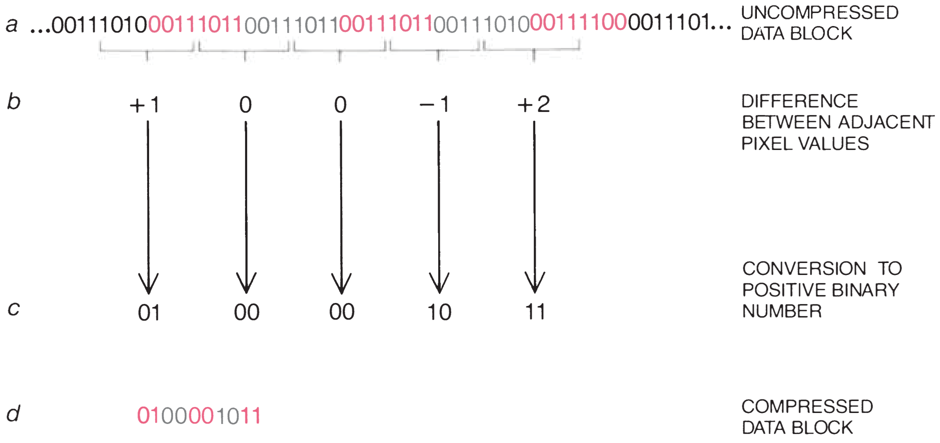


IMAGE-DATA COMPRESSION was applied during the Uranus encounter to reduce the number of bits that had to be transmitted to ground stations. Each line of an image consists of a row of 800 pixels, or picture elements. The brightness of each pixel is expressed as an eight-bit binary number. Rather than transmitting the brightness value for each pixel to the earth, as was done for the earlier Saturn and Jupiter encounters, only the difference in brightness levels between adjacent pixels was transmitted. A simplified version of the technique is illustrated. First the 800 pixels in each row are divided into 160 groups of five pixels each (*a*). The differences in brightness between the first pixel in a group and the last one in the preceding group and between adjacent pixels within the group are calculated (*b*). The differences are then converted into positive binary numbers (*c*). (In this example two-digit numbers suffice.) The final compressed data block transmitted to the earth consists of the five two-digit numbers strung together. In this example data that would have required 40 bits to express are compressed into a block of 10 bits.

It is interesting to note that the Reed-Solomon hardware had been installed on the spacecraft for another purpose. Voyager was the first space mission to rely on a radio frequency of 8.4 gigahertz (in the so-called *X* band) for data return. There was concern that this new channel might fail to perform satisfactorily, and the Reed-Solomon capability would then have been valuable as an adjunct to the less capacious *S* band (2.3 gigahertz), in which the Voyagers can also transmit data.

Another measure that reduced still further the number of bits that had to be transmitted back to the earth from Uranus was "compression" of the image data. The cameras of *Voyager 2* decompose the image in the field of view into an array of pixels, or picture elements, much as pictures in newspapers consist of tiny dots. The spacecraft transmits to the ground a binary number that corresponds to the brightness level of each pixel.

A Voyager image is composed of 800 rows of pixels, each row consisting of 800 pixels, for a total of 640,000 pixels. Each pixel can assume one of 256 different brightness levels ranging from black to white. To express such a range of brightness levels (a total of 2^8 levels) in binary code, eight bits would be necessary. Hence it takes a total of 5,120,000 bits ($800 \times 800 \times 8$) to transmit one picture (not counting the bits that are added to serve as error-detecting and -correcting bits).

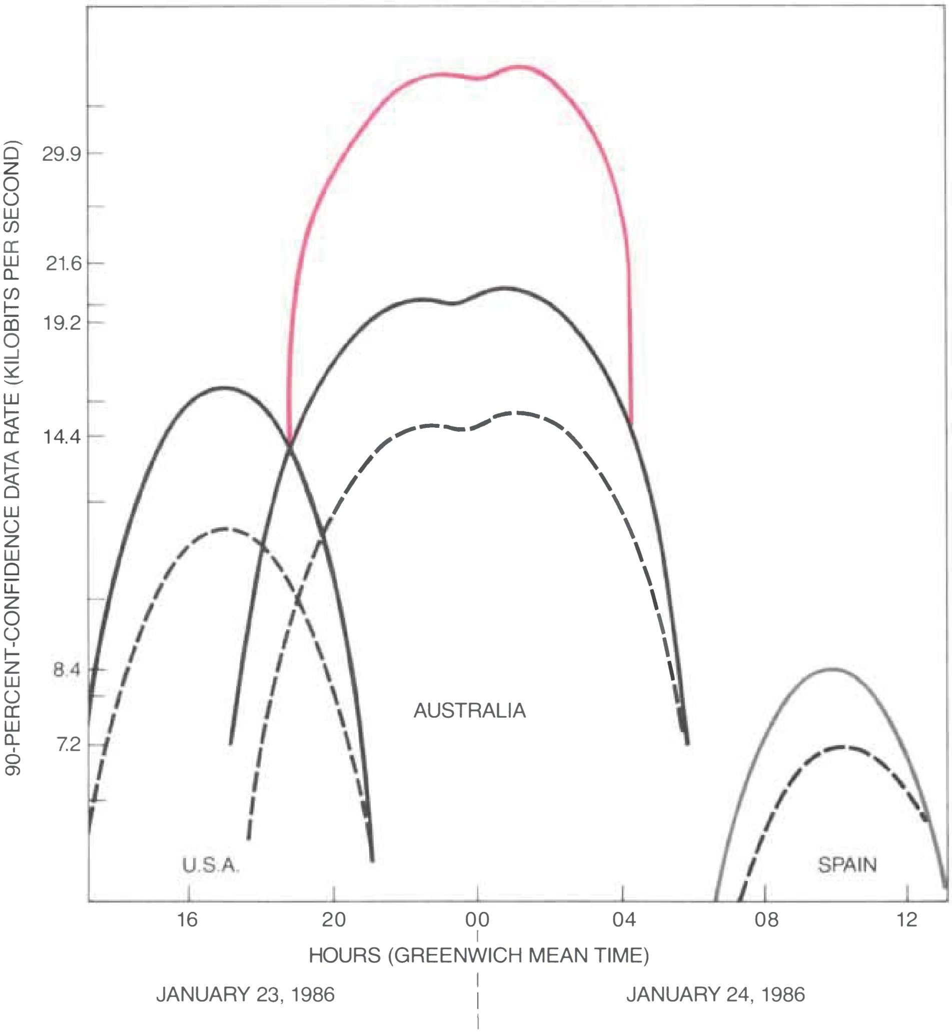
The number of bits necessary to express such an image can be more than halved by taking advantage of the fact that adjacent pixels usually have brightness levels that are close in value. This is particularly true for those pixels that do not straddle the borders delineating an object. If *Voyager 2* could be made to transmit only the change in brightness value from pixel to pixel rather than the absolute brightness value for each pixel, then on the average about three bits per pixel would suffice rather than eight. (Obviously the absolute brightness of the first pixel in each row must be transmitted as a starting point.)

This in fact was done. The backup function of the second FDS computer was sacrificed so that the device could be reprogrammed with data-compression algorithms. The image-compression approach is more vulnerable to errors, however, since each pixel-brightness value (except for the first pixel) is dependent on the value of the preceding pixel. Hence a one-bit error could affect an entire row of a compressed image rather than just a single pixel of an uncompressed image. Both compressed and uncompressed modes were therefore applied in the transmission of the almost 6,000 images obtained of the Uranian system.

Not all the measures taken to enhance the reliable return of data took place on the spacecraft. The bitcollection capability of the ground stations was improved by electronically combining the signals received by several antennas on the earth, a procedure called arraying. For example, the 64-meter antenna dish and the two 34-meter dishes of NASA's Deep Space Network tracking complex in Australia were arrayed together and then combined with the 64-meter Parkes radio telescope, which was borrowed from Australian radioastronomers. The rate at which data could be reliably received was increased from 14.4 kilobits per second for a single 64-meter antenna to a potential 29.9 kilobits per second for the array. In practice the highest data rate at Uranus was held to 21.6 kilobits per second; the rate of 29.9 kilobits per second was reserved for emergency situations.

Another activity of importance that took place on the ground had to do with the steering of the spacecraft. Large, earth-based computers have to be relied on to do trajectory calculations based on sophisticated celestial-mechanics models and statistical techniques. Nevertheless, interplanetary navigation remains a mixture of science and art. To produce sensible answers a certain amount of human judgment is required.

Input to the navigational process can be classified into two basic types: radiometric and optical. Radiometric data rely on the interaction of a spacecraft's radio system with ground-based antennas in three different ways: the Doppler shift of radio signals (the shifting of the radio frequency due to the relative motion of the transmitter and the receiver), the signal's round-trip time and the angle between the spacecraft's radio beam and a reference radio-signal source in the sky. These three measurements respectively yield information about the line-of-sight component of the spacecraft's velocity, its distance and its angular location on the celestial sphere.



COMMUNICATION CAPABILITY was augmented during the *Voyager 2* Uranus encounter by electronically combining the signals received by an array of antennas. Communication capability is measured in terms of the probability that a given data rate can be received relatively free of error. Shown here are curves representing a 90 percent probability of capturing data from *Voyager 2* as it neared the point of closest approach to Uranus. Various antenna combinations were available at the Deep Space Network complexes of the National Aeronautics and Space Administration in the U.S., Australia and Spain: a 64-meter parabolic-dish antenna alone (*broken curves*); a 64-meter antenna arrayed with one 34-meter antenna (*gray curve*), and a 64-meter antenna arrayed with two 34-meter antennas (*black curves*). By adding the 64-meter Parkes radio telescope in Australia (*colored curve*) as much as 29.9 kilobits per second could be reliably received. The best reception was achieved in Australia, because Uranus was in the southern sky then.

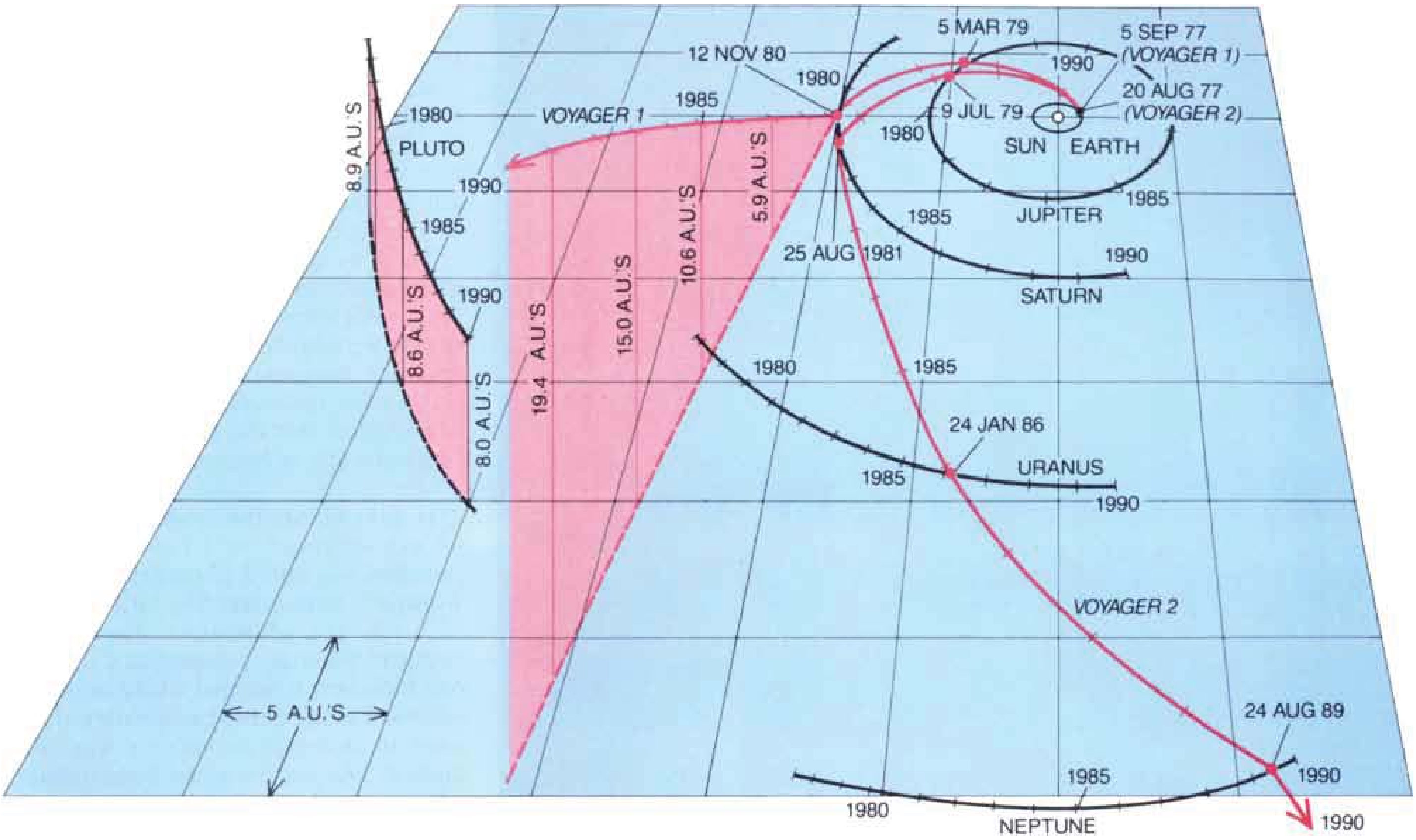
Optical data are produced by the two cameras on the Voyager spacecraft. Optical navigation, which was first tested on Mariner and Viking probes to Mars, was in fact indispensable in the Voyager mission. Unlike radiometric data, optical data enable one to determine the spacecraft's position in relation to the objects of interest—Uranus and its satellites in the case of *Voyager 2*—rather than in relation to the earth. The optical approach allows one to determine the orbits of natural satellites, which do not have radio receivers, as well as the orbit of the spacecraft. This is of considerable importance when one is trying to point instruments at a nearby satellite, particularly if its mass and orbit are not known precisely.

Both radiometric and optical data were processed to pin down *Voyager 2*'s location to within 23 kilometers from more than three billion kilometers away. Such precision actually was greater than that required for accurate pointing of the cameras during the close flyby of Miranda, one of the moons of Uranus, but it was not achieved without travail.

In December, 1985, some difficulties were encountered in fitting the navigational data to the dynamical model of the flight path. It took a relatively large change in the estimate of the mass of Uranus, amounting to an increase of .3 percent, before the difference between predictions and observations became small and the navigational process could go forward smoothly. It turned out that the orbit-determination programs had calculated the mass of Uranus incorrectly and needed to be reset "manually."

Failures are in a certain sense expected for the Voyager space probes, which have already exceeded the lifetime for which they were designed. When a component does fail, diagnosing the problem, correcting or repairing it or, in the worst case, trying to make do without it often tests the ingenuity of the project team.

The most serious problem the flight team faced occurred in 1978, during *Voyager 2*'s passage from the earth to Jupiter: its primary radio receiver failed. To be sure, the spacecraft was equipped with a backup receiver, but unfortunately this device was also



NAVIGATION of Voyager spacecraft is accomplished by continually determining the spacecraft's position and velocity, calculating whether it will reach the target point at the correct time and precisely steering it back on course by firing thrusters. Other forces that act on the spacecraft also have to be taken into account—principally gravitational forces and the force exerted by photons emitted by the sun. The position and velocity of the spacecraft are computed from two types of data: radiometric and optical. Radiometric data are obtained by analyzing the radio signals from the spacecraft. Optical data are obtained from the spacecraft's cameras. The flight path is plotted and needed trajectory-correction maneuvers are calculated from the data by earth-based computers. *Voyager 1* flew over Saturn's south pole and was gravitationally deflected above the plane of the ecliptic, which is defined by the plane of the earth's orbit. It is now about 14 astronomical units (A.U.'s) above the plane. (One A.U., the average distance from the earth to the sun, is approximately 150 million kilometers.) *Voyager 2,* still in the ecliptic plane, is targeted to fly over the north pole of Neptune on August 24, 1989. The encounter will deflect *Voyager 2* downward, below the plane of the ecliptic.

flawed. Its bandwidth (the range of frequencies over which signals can be received) was found to be reduced to less than a thousandth of its design specification. The cause of the reduced performance of the backup receiver has been attributed to the failure of a single capacitor.

In order to get commands through the backup receiver's narrow bandwidth window, the flight team has to keep careful account of any factor that could alter the frequency of received radio signals. Most obvious is the Doppler shifting of radio signals due to the rotation of the earth and the motion of the spacecraft. The earth's rotation can shift the frequency of the uplink signal (the signal transmitted to the spacecraft) by more than 30 times the bandwidth of the crippled receiver.

The most difficult frequency-related events to characterize are those that affect the temperature of the spacecraft. Changes in the temperature can shift the center of the available bandwidth of the receiver. Indeed, if the receiver temperature changes by just a quarter of a degree Celsius, the center of its bandwidth shifts by about 100 hertz. Hence any process that might generate or remove heat has to be monitored carefully. These processes include turning the spacecraft and switching power loads.

The effect of such processes on the receiver's bandwidth is constantly gauged by frequent on-board temperature measurements and by direct testing to determine what is the best frequency for communication. Although an extensive reservoir of knowledge has been gained over the years and techniques have been developed to maintain radio command over *Voyager 2,* communication with the spacecraft can still be disrupted for a period of a few days by major thermal events.

Just after its closest approach to Saturn in 1981, *Voyager 2* suffered a mechanical breakdown. The actuator that controls the azimuthal position of the scan platform became stuck. Some scientific data about Saturn were lost in the incident, but what concerned the Voyager team more was the possibility that the platform would be inoperable for the upcoming Uranus and Neptune encounters. To ascertain the likely cause of the trouble and to develop a plan to work around it, extensive testing was done on the ground and on both Voyagers.

At the Jet Propulsion Laboratory (J.P.L.) 86 mockups of the actuator were built and tested in an attempt to infer the state of the on-board actuator and to determine the factors (such as temperature, actuator rate and applied torque) influencing the probability of jamming. An actuator in a spacecraft simulator also proved valuable in obtaining statistical data.

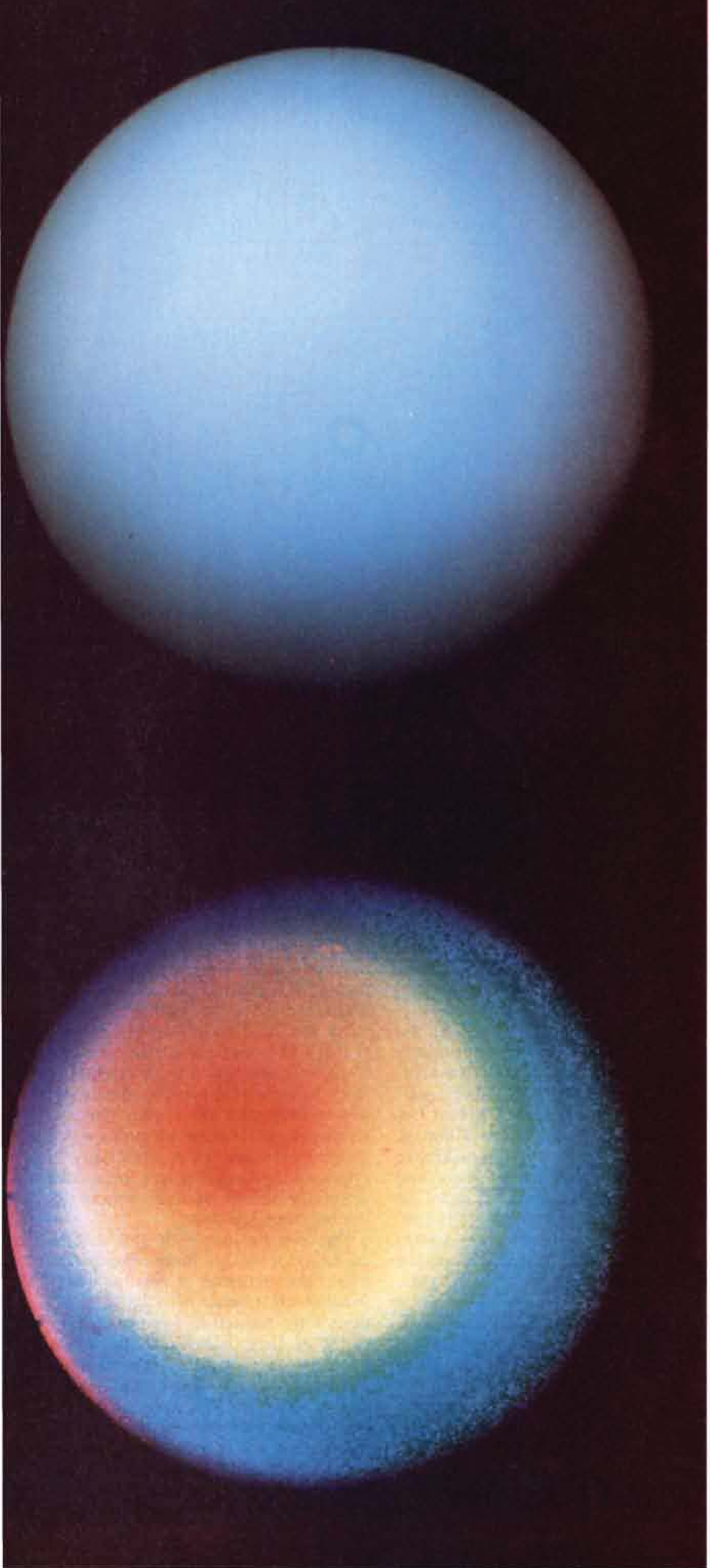
Engineering judgment and statistical analyses yielded three conclusions. First, the actuator would probably function at Uranus if platform motions were limited to low speed. (Because of their high scientific value, however, four medium-rate motions were allowable exceptions.) Second, the observations at the closest approach to Uranus should be protected by having a contingency computer program ready to transmit to *Voyager 2* if the actuator showed signs of jamming. The program would substitute less accurate and more difficult spacecraft rolls (using the attitude thrusters) for the motion of the azimuth actuator. Third, the condition of the actuator should be monitored by occasionally reducing the applied torque and observing its performance.

The Voyager team put these recommendations into effect, and when the spacecraft approached Uranus, the actuator performed flawlessly; the contingency computer program was not sent to the spacecraft. There is every expectation that the system will function normally at Neptune as well.

Six days before the spacecraft's closest approach to Uranus another problem was noted: photographs from *Voyager 2* were marred by large blocks of black and white lines. Since only compressed images displayed the curious blotches, it seemed likely that the software in the earth-based computers used to decompress images was the culprit. The software had been updated recently, and perhaps some "bugs" had been inadvertently introduced. Engineers of the Voyager team undertook the tedious task of decompressing selected lines of the images by hand, but the same perplexing black and white lines showed up. The only remaining possibility was a problem on the spacecraft itself.

The next day commands were sent to the spacecraft to transmit the contents of the FDS-computer memory that held the instructions responsible for compressing the images. After the readout was received at the J.P.L., what was in the computer's memory was compared bit by bit with what should have been there. It was discovered that a single bit of an instruction word, which should have been a 0, was a 1. There were two possible explanations for the incorrect bit: either a cosmic ray had caused the bit in the memory cell to flip from 0 to 1, in which case it could easily be reset to 0, or there had been a permanent hardware failure in the memory.

The FDS experts at the J.P.L. were immediately directed to write a program that could act as a patch, circumventing the possibly failed memory lo-



URANUS would have appeared as a pale, greenish blue sphere (*top*) to a human traveler on *Voyager 2*. The image is a composite made from images that were recorded with various color sensitivities. By enhancing the differences in brightness among the images, a false-color image (*bottom*) brings out atmospheric features that would be imperceptible to the unaided eye. The ringlike features seen in the images are artifacts caused by dust in the camera optics.

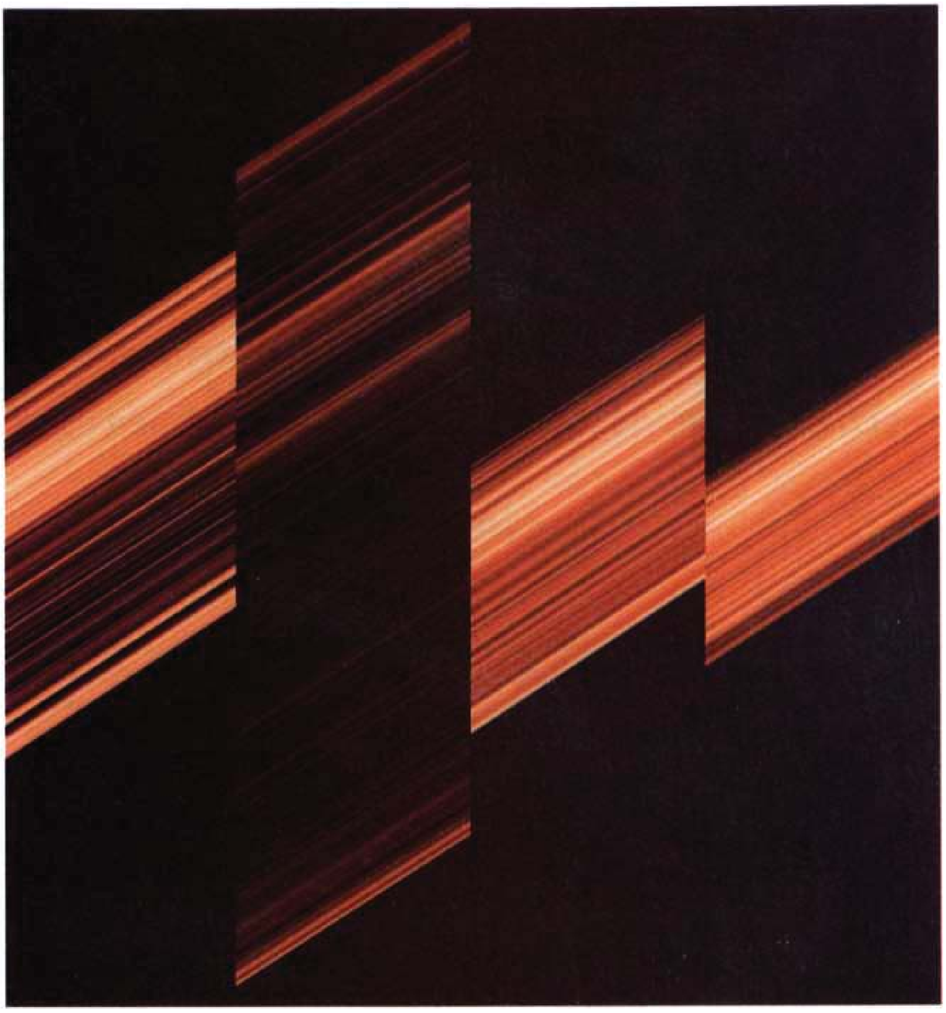
cation. The patch was programmed into the spacecraft's computer on the evening of January 20, four days before the closest approach. The next morning the transmission of fault-free compressed photographs resumed. Although the troublesome memory location had been bypassed by the patch, a command that could reset the incorrect bit was also transmitted to the spacecraft. The bit did not reset, however, and is considered to have failed permanently.

The success of the Voyager team's efforts can be measured by the mission's scientific achievements during the Uranus encounter. The improvement in spacecraft steadiness, combined with the capability afforded by data-compression and data-coding changes, facilitated the search for new objects by the imaging system and the photopolarimeter and led to the discovery of 10 new Uranian satellites and several new rings.

The accurate navigation and the motion-compensation maneuver resulted in pictures of Miranda that are among the best images ever returned by a planetary flyby mission. The execution of the power-management procedure during occultation allowed observations to proceed without a hitch, and detailed information on Uranus' atmospheric structure, including temperature and composition, was obtained. The finding that the temperatures at the poles and at the equator were nearly the same was unexpected. During the occultation one 96-second exposure of the back-lighted ring system was successful, and it revealed an intricate dust structure within the system of rings. The magnetometers on the spacecraft revealed another oddity: Uranus' magnetic field. It is tilted 60 degrees from the rotational axis. Hence as Uranus rotates with a period of 17.25 hours (a fact indicated by Voyager data), the entire magnetic field wobbles.

Barring any catastrophic failure of a vital component, a flood of valuable scientific data is also expected when *Voyager 2* encounters Neptune from June 5 through October 2, 1989—12 years after its launch. Current plans call for the spacecraft to pass over the north pole of Neptune within a few thousand kilometers of its cloud tops, making it the closest approach to any celestial body by a Voyager spacecraft. Its subsequent flight path will carry it south of the ecliptic (the orbital plane of the earth), perhaps eventually to reach the heliopause, the boundary between the sun-influenced region of space and interstellar space.

The heliopause has not been reliably detected by remote-sensing techniques; when and where it will be crossed by either of the two Voyager spacecraft is not predictable. Estimates of its distance from the sun range from 50 to 100 astronomical units. (One A.U. is the average distance from the earth to the sun, about 150 million kilometers.) If the heliopause is found at the low end of the distance estimates, the Voyagers' scientific instruments may confirm that fact in the mid-1990's, when the two spacecraft will be 50 A.U.'s from the sun.



EPSILON RING OF URANUS, outermost of the many rings that encircle the planet, has a nonuniform mass distribution and radial width. The four "slices" of the ring shown here have been reconstructed from data obtained by *Voyager 2*'s polarimeter. Reddish areas represent parts of the ring containing less material; yellow areas contain more material. The varying width of the ring is evident from the varying length of each slice, although the pair of slices at the left differ in scale from the pair at the right. The smallest features discernible are about 270 meters across. The color scheme enhances the visibility of small-scale structures; it does not show the ring's true color, which is gray.

If a fatal failure does not end the Voyagers' mission, exhaustion of one of the consumables eventually will. The rate of depletion of the most obvious consumable, the attitude-control fuel, depends heavily on interaction with other elements of the mission design. Based on the amount of fuel expended so far, there would appear to be enough hydrazine on both spacecraft to last through about the year 2030. A more serious limitation is electric power. Generator output is projected to decay to the threshold (245-watt) level in about 2013. Below this power level none of the scientific experiments can be supported. The limitation that might effectively end the two Voyagers' scientific missions is the sensitivity of the sun sensor. The amount of impinging sunlight may fall below the sensor's threshold level before the power gives out. Without a sensor to control the pointing of the antenna, the Voyagers' ability to communicate with the earth would be lost.

With continuing support from the ground, NASA's most productive scientific facility is likely to continue to provide data into the next century. The unqualified success of the Voyager project is a testament to the project team's expertise, ingenuity and determination in engineering across billions of kilometers of space.