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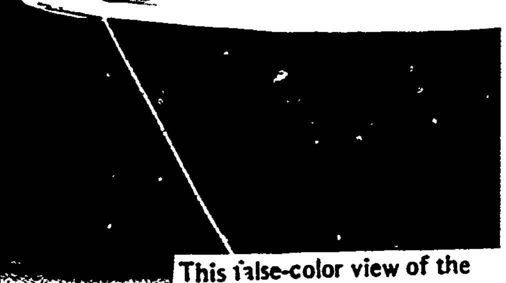
ABSTRACT

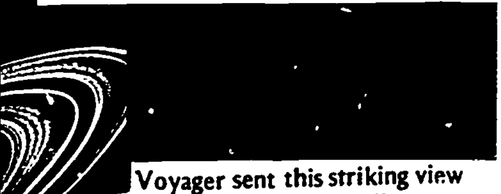
This booklet discusses image processing from spacecraft in deep space. The camera system on board the spacecraft, the Deep Space Network (DSN), and the image processing system are described. A table listing photographs taken by unmanned spacecraft from 1959-1977 is provided. (YP)



This false-color view of the Uranian ring system shows all nine known rings. Six 15-second narrow-angle images were taken: two each through green, clear, and violet filters. The images were averaged, then combined through computer enhancement. The final image shows that the brightest or epsilon ring at the top is neutral in color, with the fainter eight other rings showing color differences between them. Scientists will use this color information to try to understand the nature and origin of the ring material.

Huge whirling storms and sawtoothed turbulent flows spread out in Jupiter's atmosphere as pictured by Voyager 2 from 6 million kilometers.

The surface of Uranus is almost void of contrasting features. Here, however, a distinct cloud (lower left) is shown as a bright streak near the planet's limb. To gain this resolution, however, the image had to be so highly enhanced that faint blemishes on the camera lens appeared as donut-shaped features (as seen on the top and to the right of the image).



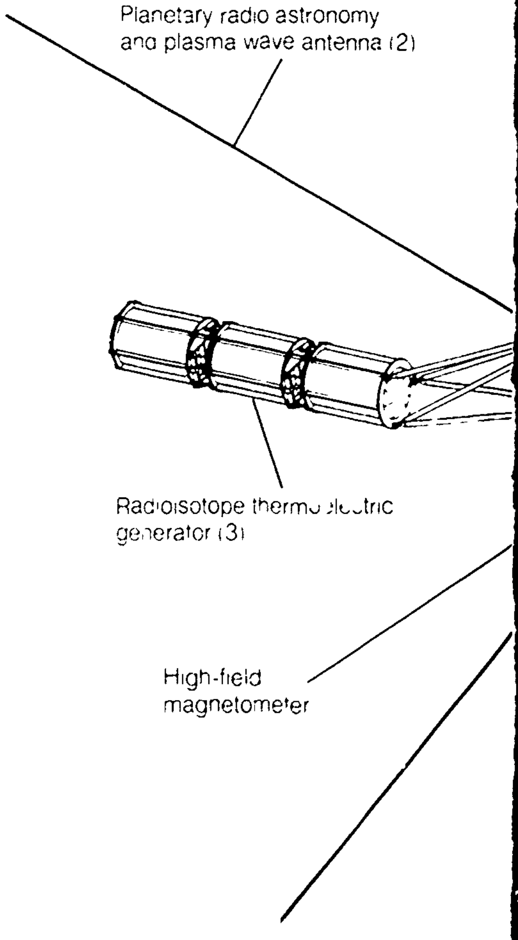
Voyager sent this striking view of Saturn's rings 8.9 million kilometers away from the planet, showing possible variations in the chemical composition from one part of the system to another. Besides the previously know blue color of the C-Ring and the Cassini Division, the picture shows additional color differences between the inner B-Ring and outer region (where the "spokes" form) and between these and the A-Ring.

Since the first cave dweller ventured out to gaze up at the night sky, people have sought to know more about the mysterious images and lights seen there. Being limited by what could be seen with the unaided eye, that early stargazer relied on intellect and imagination to depict the universe, etching images in stone by hand, measuring and charting the paths of the wanderers, and becoming as familiar with the sky as the limited technology would allow.

Although stargazers frequently took the wrong paths in attempting to explain what they saw, many of them developed new tools to overcome their limitations. Galileo crafted a fine telescope for observing the heavens. His hand-drawn pictures of the satellites of Jupiter, the "cup handles" of Saturn, and the phases of Venus when combined with the possible reasons for those facts, shook the very foundations of the European society in the Middle Ages. Bigger and more powerful telescopes combined with even newer tools such as spectroscopes and cameras have answered most of the questions of those ancient stargazers. But in doing so, they have unfolded even newer mysteries.

Beginning in the 1960s, our view of the heavens reached beyond the obscuring atmosphere of Earth as unmanned spacecraft carried cameras and other data sensors to probe the satellites and planets of the Solar System. Images those spacecraft sent back to Earth provided startling clarity to details that are only fuzzy markings on the planets' surfaces when seen from Earth-based telescopes. Only two of the presently known planets, Neptune and Pluto, remain unexplored by our cameras. In August 1989, *Voyager 2* will snap several thousand closeup frames of the planet Neptune and its largest satellite, Triton. By the end of the 20th century, only Pluto will not have been visited by one of our spacecraft.

The knowledge humans have today of outer space would astound Galileo. Spacecraft have sent back pictures of a cratered and moon-like surface on the planet Mercury and revealed circulation patterns in the atmosphere of Venus. From Mars, they have sent back images of craters, giant canyons, and volcanoes on the planet's surface. Jupiter's atmospheric circulation has been revealed, active volcanoes on the Jovian moon Io have been shown erupting, and previously unknown moons and a ring circling the planet discovered. New moons were found orbiting Saturn and the Saturnian rings were resolved in such detail that over 1 000 concentric ring features became apparent. At Uranus, *Voyager* sent back details of a planet that is



covered by a featureless, bluish-green fog The planet is encircled by rings darker than charcoal and shaped by shepherding satellites, accompanied by five large satellites, and immersed in a magnetic field

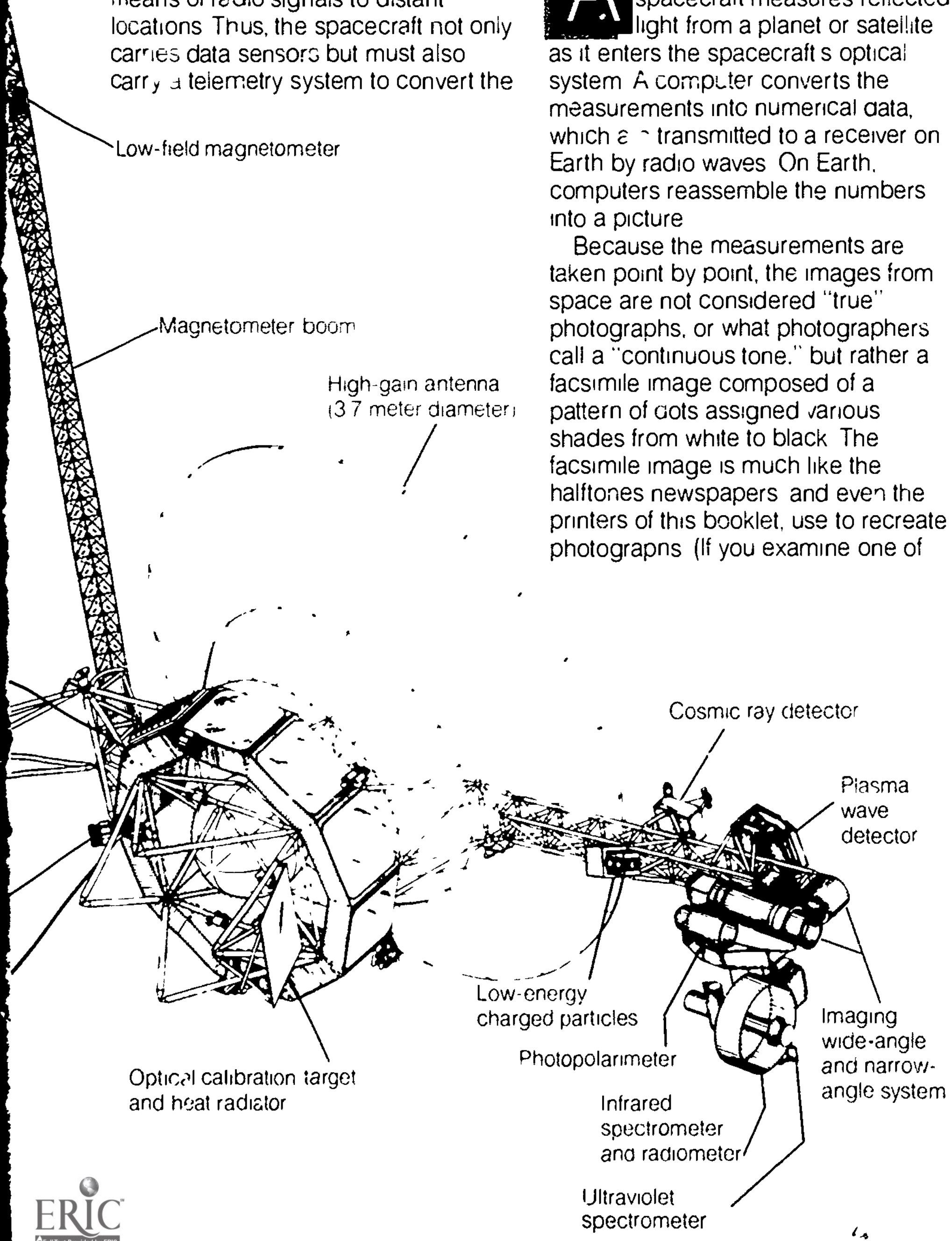
Those discoveries and thousands of others like them, were made possible through the technology of telemetry, the technique of transmitting data by means of radio signals to distant locations Thus, the spacecraft not only carries data sensors but must also carry a telemetry system to convert the data from the various sensors into radio pulses These pulses are received by a huge dish antenna here on Earth The signals are relayed to data centers where scientists and engineers can convert the radio pulses back into the data the sensors originally measured

A camera system on board the spacecraft measures reflected light from a planet or satellite as it enters the spacecraft s optical system A computer converts the measurements into numerical data, which are transmitted to a receiver on Earth by radio waves On Earth, computers reassemble the numbers into a picture

Because the measurements are taken point by point, the images from space are not considered "true" photographs, or what photographers call a "continuous tone," but rather a facsimile image composed of a pattern of dots assigned various shades from white to black The facsimile image is much like the halftones newspapers and even the printers of this booklet, use to recreate photographs (If you examine one of the pictures in this booklet with a magnifying glass, you will see that it is composed of many small, variously shaded dots)

Even more closely related to the way images are received from space is the way a television set works For a picture to appear on a television set, a modulated beam of light rapidly illuminates long rows of tiny dots, filling in one line then the next until a picture forms These dots are called picture elements, or pixels for short, and the screen surface where they are located is called a raster Raster scanning refers to the way the beam of light hits the individual pixels at various intensities to recreate the original picture Of course, scanning happens very fast, so it is hardly perceptible to the human eye Images from space are drawn in much the same manner on a television-like screen (a cathode-ray tube)

Although cameras on a spacecraft probing the Solar System have much in common with those in television studios, they also have their share of differences For one, the space-bound cameras take much longer to form and transmit an image While this may seem like a disadvantage, it is not The images produced by the slow-scanning cameras are of a much

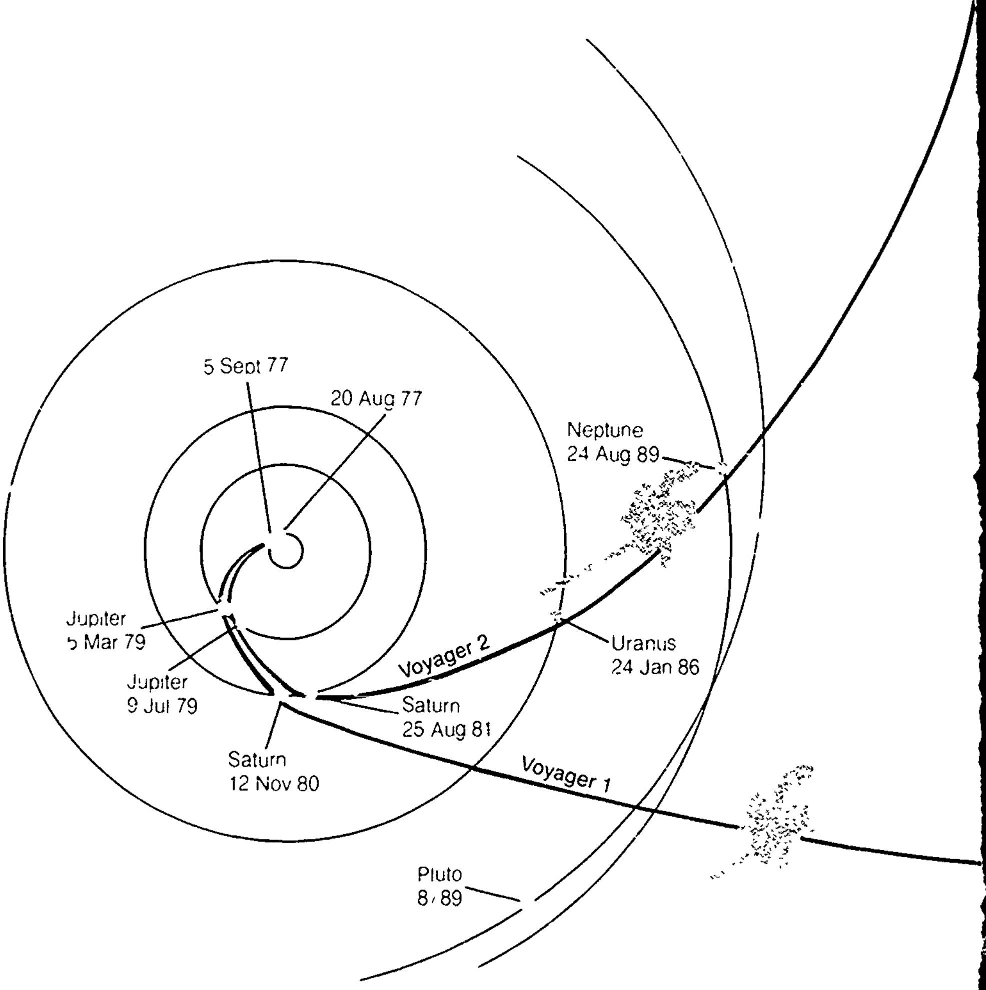


The Voyager spacecraft weighs 773 kilograms Of this, 105 kilograms are scientific instruments The large dish antenna measures 3 66 meters in diameter A gold-plated copper record of Earth greetings, sights, and sounds is attached to the craft inside a gold-plated aluminum canister, which has instruction symbols on its face On the boom at the left are the nuclear power generators and above this boom is the 13-meter magnetometer boom The boom to the right contains the optical and particle sensors, including the camera Two 10-meter whip antennas, which study planetary radio astronomy and plasma waves, extend from the spacecraft's body below the magnetometer boom higher quality and contain more than twice the amount of information present in a television picture

The most enduring image gatherer in space has been the *Voyager 2* spacecraft *Voyager* carries a dual television camera system, which can be commanded to view an object with either a wide-angle or telephoto lens The system is mounted on a science platform that can be tilted in any direction for precise aiming Reflected light from the object enters the lenses and falls on the surface of a selenium-sulfur vidicon television tube, 11 millimeters square A shutter in the camera controls the amount of light reaching the tube and can vary exposure times from 0 005 second for very bright objects to 15 seconds or longer when searching for faint objects such as unknown moons

The vidicon tube temporarily holds the image on its surface until it can be scanned for brightness levels The surface of the tube is divided into 800 parallel lines, each containing 800 pixels, giving a total of 640 000 As each pixel is scanned for brightness, it is assigned a number from 0 to 255

The range (0 to 255) was chosen because it coincides with the most common counting unit in computer systems, a unit called a byte In computers, information is stored in bits and bytes The bit is the most fundamental counting or storage unit, while a byte is the most useful one A bit contains one of two possible values, and can best be thought of as a tiny on-off switch on an electrical circuit A byte, on the other hand, contains the total value represented by 8 bits The value can be interpreted in many ways, such as a numerical value, an alphabet character or symbol, or a pixel shaded between black and white In a byte, the position of each bit represents a counting power of 2 (By convention, bit patterns are read from right to left)

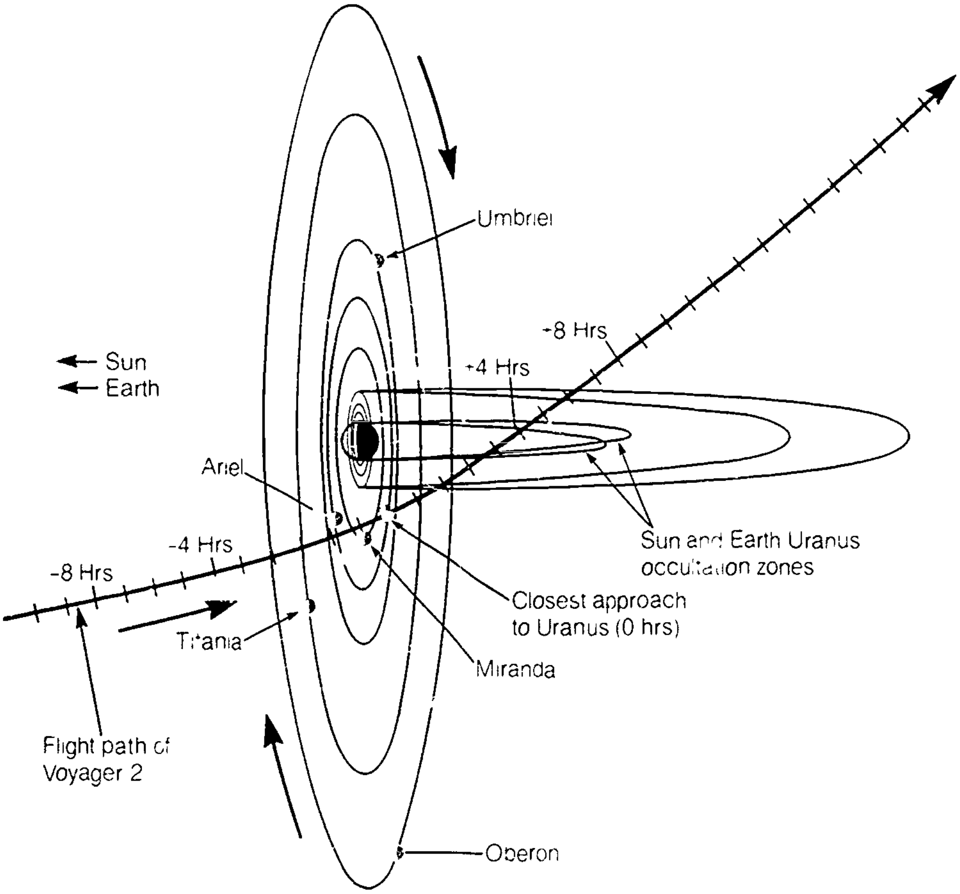


The Voyager *missions began from Cape Canaveral, Florida Two probes launched 16 days apart were to explore the outer planets, returning images and data Both explored Jupiter and Saturn and their moons, but* Voyager 1 *veered up out of the ecliptic plane to return data on fields and particles it encounters, while* Voyager 2 *flew on to encounter Uranus It sent back striking images of that planetary system which is barely visible from Earth* Voyager 2 *is now on its way to Neptune and will arrive in late 1989*

Binary Table

Bit of Data	8	7	6	5	4	3	2	1	
Sequence Value	128	64	32	16	8	4	2	1	
Binary Value	0	0	1	0	1	1	0	1	
Byte Value	0	+ 0	+ 32	+ 0	+ 8	+ 4	+ 0	+ 1	= 45

Sequence Value	128	64	32	16	8	4	2	1
Brightness Values	Binary Values							
0 (black)	0	0	0	0	0	0	0	0
9 (dark gray)	0	0	0	0	1	0	0	1
62 (gray)	0	0	1	1	1	1	1	0
183 (pale gray)	1	0	1	1	0	1	1	1
255 (white)	1	1	1	1	1	1	1	1



Previous planetary encounters for the Voyager *spacecraft were almost leisurely excursions At Saturn, for example, the spacecraft encountered one planetary feature at a time, exploring it before focusing on the next, until it had photographed all it could However, at Uranus the planetary system is tilted almost 90° to the planetary plane For this reason* Voyager *has been compared to a dart tossed at a bull's eye, passing the center, the outer rings, and virtually everything at the same time That meant cameras had to scan many areas very quickly to catch even brief glimpses of features*

Thus, the first bit (the rightmost bit) of the eight-bit sequence represents 2 to the zero power (2^0), the second bit refers to 2 to the 1 power (2^1), and so on For each bit in a byte that has a one in it, you add the value of that power of two (the sequence value) until all eight bits are counted For example, if the byte has the bit value of 00101101, then it represents the number 45 The binary table at left shows how translation of bits and bytes to numbers is done

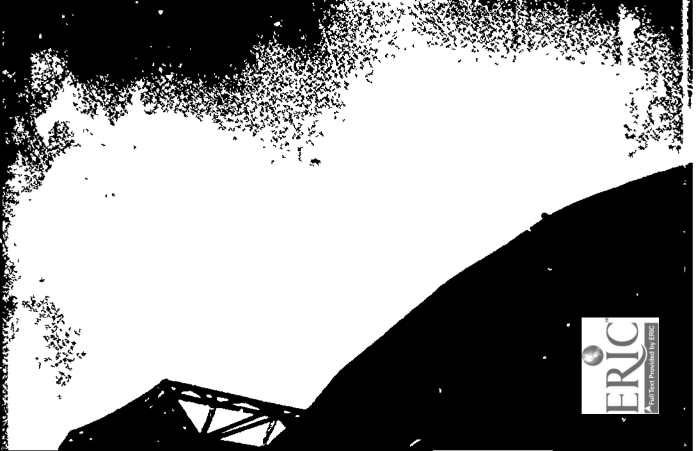
If all the bits in an eight-bit sequence are ones, then it will correspond to the value 255 That is the maximum value that a byte can count to Thus, if a byte is used to represent shades of gray in an image, then by convention the lowest value, zero, corresponds to pure black, while the highest value, 255, corresponds to pure white All other values are intermediate shades of gray

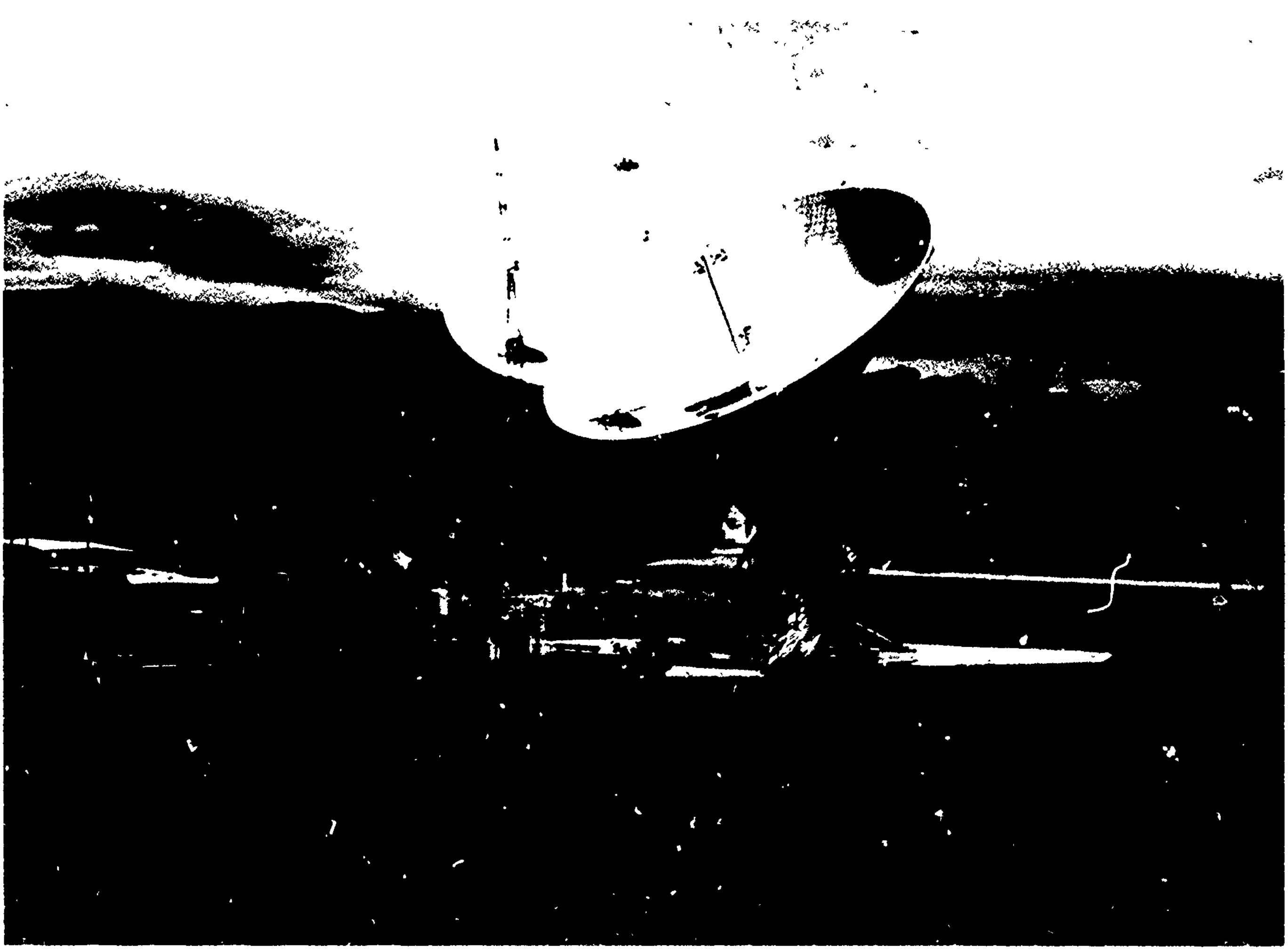
When the values for all the pixels have been assigned, they are either sent directly to a receiver on Earth or stored on magnetic tape to be sent later Data are typically stored on tape on board the spacecraft when the signals are going to be temporarily blocked, such as when *Voyager* passes behind a planet or a satellite For each image, and its total of 640,000 pixels, 5,120 000 bits of data must be transmitted (640,000 × 8) When *Voyager* flew close to Jupiter, data were transmitted back to Earth at a rate of more than 100 000 bits per second This meant that once data began reaching the antennas on Earth's surface, information for complete images was received in about 1 minute for each transmission

As the distance of the spacecraft from Earth increases, the quality of the radioed data stream decreases and the rate of transmission of data has to be slowed correspondingly Thus, at the distance of Uranus, the data has to be transmitted some six to eight times slower than could be done at Jupiter That means that only one picture can be transmitted in the time six pictures were taken at Jupiter However, for the Uranus encounter, scientists and engineers devised a scheme to get around that limitation The scheme was called data compression

To do that, they reprogrammed the spacecraft en route Instead of having *Voyager* transmit the full 8 bits for each pixel, its computers were instructed to send back only the differences between brightness levels of successive pixels That reduced the data bits needed for an image by about 60 percent Slowing the transmission rate meant that noise did not interfere with the image reception, and by compressing the data, a full array of striking images was received The computers at NASA's Jet Propulsion Laboratory restored the correct brightness to each pixel, producing both black-and-white and full-color images

The radio signals that a spacecraft such as *Voyager* sends to Earth are received by a system of large dish antennas called the Deep Space Network (DSN) The DSN is designed to provide command, control, tracking, and data acquisition for deep space missions Configured around the globe at locations approximately 120° apart, DSN provides 24-hour line-of-sight coverage





NASA's Deep Space Network consists of huge dish antennas like these positioned at three receiving stations around the globe The stations in Goldstone, CA, Madrid, Spain, and Canberra, Australia, track the spacecraft as it speeds through deep space The farther the spacecraft travels away from Earth, the weaker its signal becomes To compensate for this weaker signal, the antennas are electronically "arrayed so that two or more antennas focus on receiving the same signal Arraying not only increases the apparent strength of the signal, but also gives valuable information about the spacecraft's speed and distance

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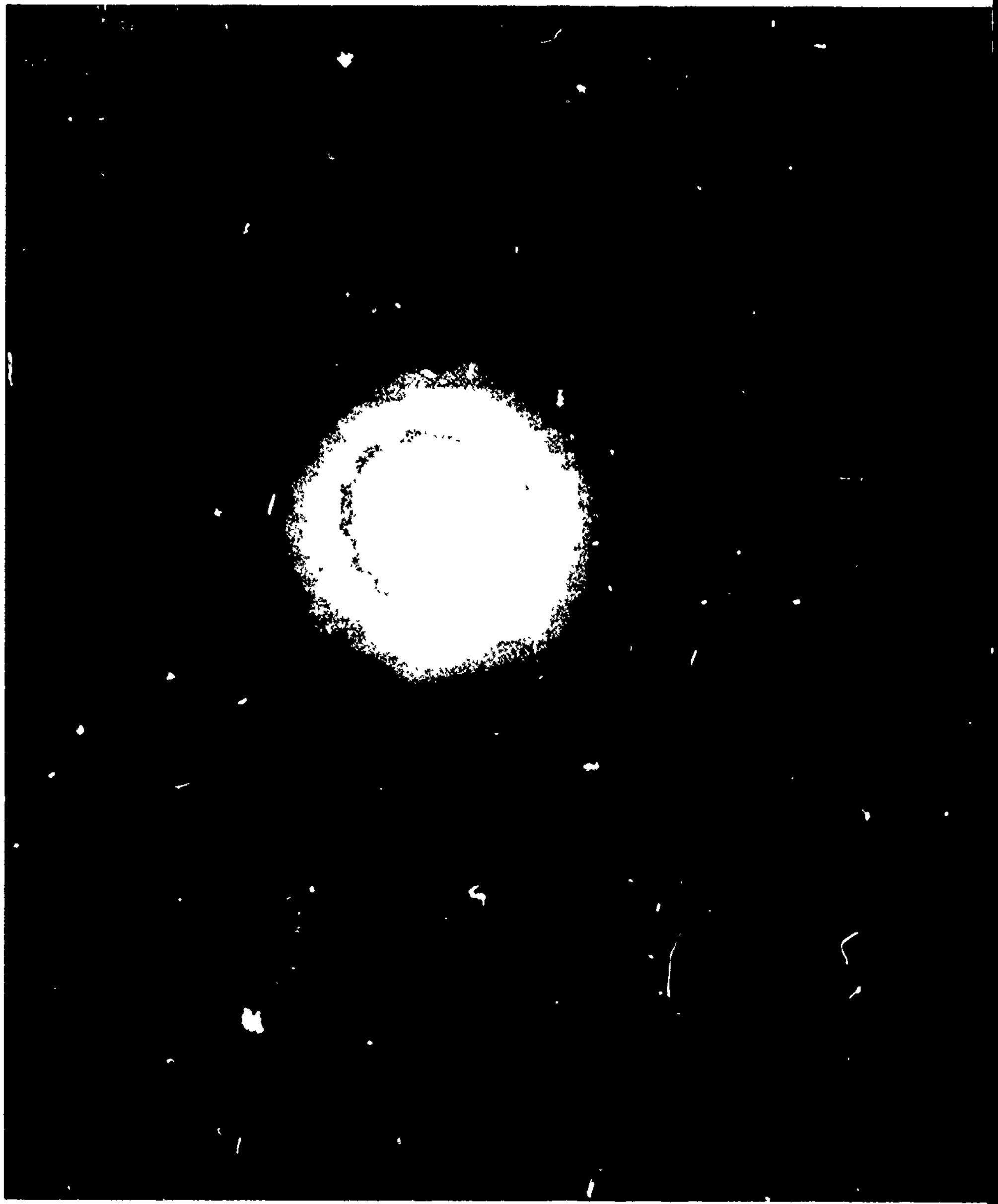
Stations are located at Goldstone, California, and near Madrid, Spain, and Canberra, Australia The DSN, managed by NASA's Jet Propulsion Laboratory in Pasadena, California, consists of three 64-meter (210-ft) diameter dish-shaped antennas, six 34-meter (111-ft) diameter antennas, and three 26-meter (85-ft) antennas As antennas at one station lose contact, due to Earth's rotation, antennas at the next station rotate into view and take over the job of receiving spacecraft data While one station is tracking a deep space mission, such as *Voyager*, the other two are busy tracking spacecraft elsewhere in the sky

During *Voyager*'s contact with Saturn, the DSN recovered more than 99 percent of the 17,000 images transmitted That accomplishment required the use of a technique known as "antenna arraying" Arraying for the Saturn encounter was accomplished by electronically adding signals received by two antennas at each site Because of the great distance Uranus is from the Earth, the signal received from *Voyager 2* was only one-fourth as strong as the signal received from Saturn A new arraying technique, which combined signals from four antennas, was used during the Uranus encounter to allow up to 21,600 bits of data to be received each second

Arraying's biggest payoff came in Australia, whose government provided its Parkes Radio Astronomy Observatory 64-meter antenna to be linked with the DSN's three-antenna complex near Canberra The most critical events of the encounter, including *Voyager*'s closest approaches to Uranus and its satellites, were designed to occur when the spacecraft would be transmitting to the complex in Australia The data were successfully relayed to JPL through that array

The DSN was able to track *Voyager*'s position at Saturn with an accuracy of nearly 150 kilometers (about 90 miles) during its closest approach This accuracy was achieved by using the network's radiometric system, the spacecraft's cameras, and a technique called Very Long Baseline Interferometry, or VLBI VLBI determines the direction of the spacecraft by precisely measuring the slight difference between the time of arrival of the signal at two or more ground antennas The same technique was used at Uranus to aim the spacecraft so accurately that the deflection of its trajectory caused by the planet's gravity would send it on to Neptune

When the DSN antennas receive the information from the spacecraft, computers at the Jet Propulsion Laboratory store it for future use and reassemble it into images To recreate a picture from data that has been sent across the vacuum of space, computers read the data bit by bit, calculating the values for each pixel and converting the value into a small square of light The squares are displayed on a television screen that duplicates the vidicon screen on the spacecraft The resulting image is a black-and-white facsimile of the object being measured



This image of the coma of Comet Halley was sent to Earth from the Pioneer Venus *spacecraft and was compiled from more than 20,000 separate vertical ultraviolet scans The coma, or cloud of gases surrounding the nucleus, is 20 million kilometers in diameter Concentric areas show decreasing brightness from the comet's center outward Data were collected and beamed to Earth on February 2 5, 1986*

In January 1986, Voyager 2 made its closest encounter with the planet Uranus It returned never-before-seen close-up views of a planet barely visible from the Earth's surface

Color images can be made by taking three black-and-white frames in succession and blending ("registering") them on one another in the three color-planes of a television screen In order for that to work, however, each of the three frames has to be taken by the camera on board the spacecraft through different filters On *Voyager*, one frame is taken through a blue filter one through a green, and one through an orange

Filters have varying effects on the amount of light being measured For example, light that passes through a blue filter will favor the blue values in the image making them appear brighter or transparent, whereas red or orange values will appear much darker than normal On Earth the three images are given the appropriate colors of the filters through which they were measured and then blended together to give a color image

An important feat the interplanetary spacecraft must accomplish is focusing on its target while traveling at extremely high speeds *Voyager* sped past Uranus at more than 40,000 miles an hour To get an unblurred image, the cameras on board had to steadily track their target while the camera shutters were open The technique to do this, called image-motion compensation, involves rotating the entire spacecraft under the control of the stabilizing gyroscopes The strategy was used successfully both at Saturn's satellite Rhea and at Uranus Both times, cameras tracked their targets without interruption

Once the image is reconstructed by computers on Earth, it sometimes happens that objects appear nondescript or that subtle shades in planetary details such as cloudtops cannot be discerned by visual examination alone This can be overcome, however, by adding a final contrast enhancement to the production The process of contrast enhancement is like adjusting the contrast and brightness controls on a television set Because the shades of the image are broken down into picture elements, the computer can increase or decrease brightness values of individual pixels, thereby exaggerating their differences and sharpening even the tiniest details

For example suppose a portion of an image returned from space reveals an area of subtle gray tones Data from the computer indicates the range in brightness values is between 98 and 120, and all are fairly evenly distributed To the unaided eye, the portion appears as blurred gray patch because the shades are too nearly similar to be discerned To eliminate this visual handicap the brightness values can be assigned new numbers The shades can be spread farther apart, say five shades apart rather than the one currently being looked at Because the data are already stored on computers, it is a fairly easy task to isolate the twenty-three values and assign them new ones 98 could be assigned 20, 99 assigned 25, and so on The resulting image is "enhanced" to the unaided eye, while the information is the same accurate data transmitted from the vicinity of the object in space

The past 25 years of space travel and exploration have generated an unprecedented quantity of data from planetary systems Images taken in space and telemetered back to Earth have greatly aided scientists in formulating better and more accurate theories about the nature and origin of our Solar System Data gathered at close range, and from above the distorting effects of Earth's atmosphere, produce images far more detailed than pictures taken by even the largest Earth-bound telescopes

In our search to understand the world as well as the universe in which we live, we have in one generation reached farther than in any other generation before us We have overcome the limitations of looking from the surface of our planet and have traveled to others Whatever yearning drew those first stargazers from the security of their caves to look up at the night sky and wonder still draws men and women to the stars

Brief History of Pictures By Unmanned Spacecraft

Name	Year	Mission
[illegible]	[illegible]	[illegible] in a flyby; entered heliocentric orbit
[illegible]	[illegible]	[illegible] Sea of Clouds; impacted
[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]
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[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]
		Mercury: pictures of moon-like surface with long, narrow valleys and cliffs; flyby; three Mercury encounters at 6-month intervals

Name	Year	Mission
[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]
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[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible] Neptune encounter scheduled for 1989

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