Jet Propulsion Laboratory

Date: Beginning December 3, 1958
Type of facility: Space research center

The primary responsibility of the Jet Propulsion Laboratory (JPL) to NASA is exploration of the solar system with unpiloted, robotic spacecraft. At JPL, scientists and engineers work on some of the world's most advanced technology.

Key Figures

Frank J. Malina (1912-1981), first director of JPL
Theodore von Kármán (1881-1963), developer of the California Institute of Technology
William H. Pickering (1901-2004), JPL director, 1958-1976
Bruce C. Murray (b. 1932), principal investigator, planetary missions, JPL director, 1976-1982
Lew Allen, Jr. (b. 1925), JPL director, 1982-1990
Edward C. Stone, Jr., JPL director, 1991-2001
Charles Elachi, JPL director 2001-present

Summary of the Facility

The Jet Propulsion Laboratory had its origins in the mid-1930's at the Guggenheim Aeronautical Laboratory of the California Institute of Technology (GALCIT). Under the leadership of Theodore von Kármán, a small staff, and a group of graduate students, a number of rocket engine experiments were conducted in the Arroyo Seco, north of Pasadena, California, close to the site of the present Laboratory.

Funds and encouragement were lacking in the early stages of experimentation until Weld Arnold, a meteorology student at the California Institute of Technology, managed to scrape together one thousand dollars to purchase chemicals and equipment for the project. Later, the National Academy of Sciences provided ten thousand dollars for the development of rockets that could assist U.S. Army Air Corps planes at takeoff. The Laboratory staff expanded to include Apollo M. O. Smith, a GALCIT graduate student; Frank J. Malina, a leading aerodynamicist; Hsue Shen Tsien, a brilliant graduate student from China; John W. Parsons; Edward S. Forman; and Weld Arnold.

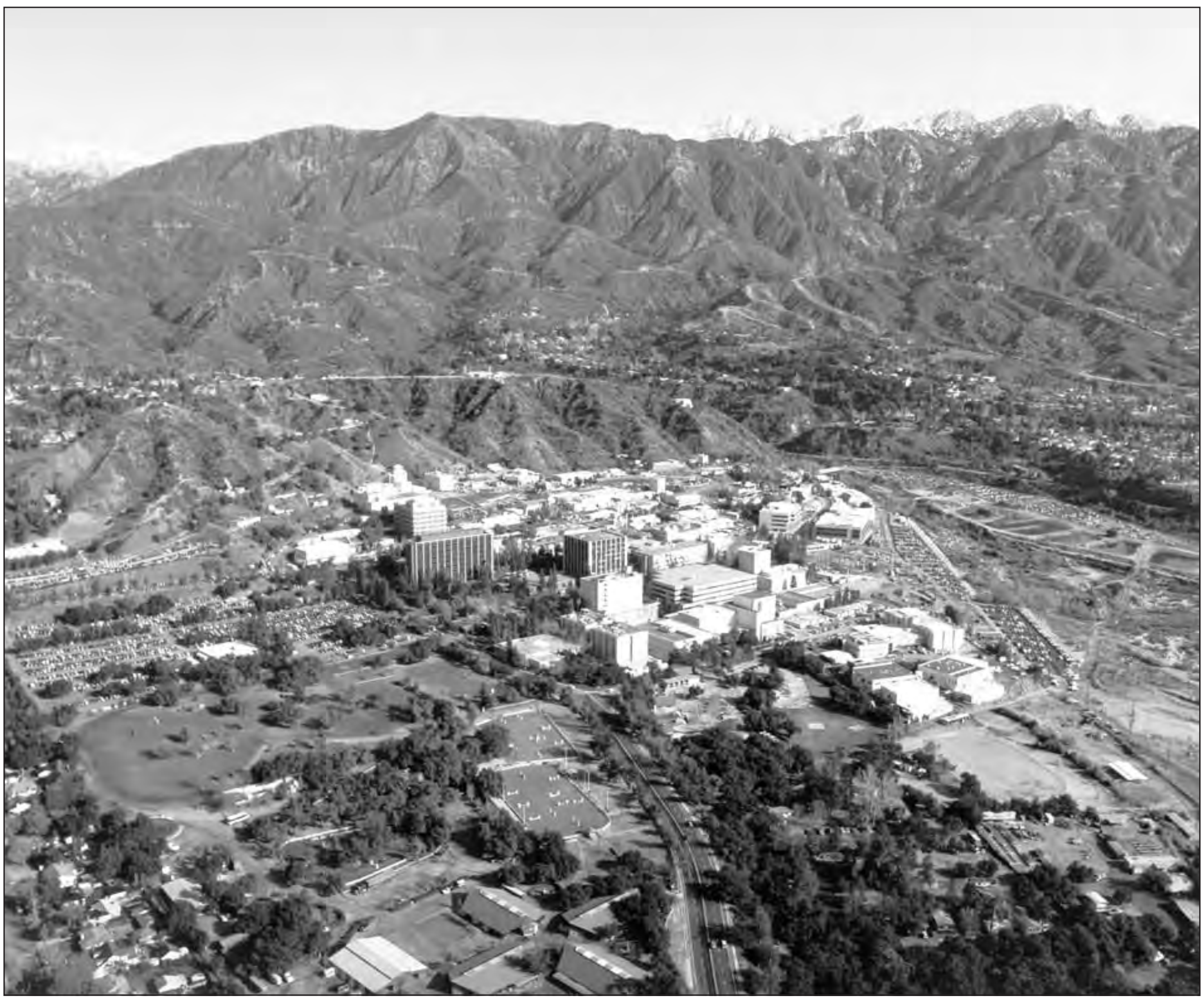
The group was studying high-speed flight and the limits of propeller-engine propulsion for aircraft. Robert A. Millikan, then head of the California Institute of Technology, was a member of a committee appointed by the Daniel and Florence Guggenheim Foundation to advise on the support being given by the foundation to Robert H. Goddard for the development of a high-altitude sounding rocket (a rocket used to collect information on the condition of Earth's atmosphere at various altitudes).

GALCIT had been experimenting with two kinds of rocket engines that could be adapted for jet-assisted takeoff (JATO); one used a solid propellant, and the other used liquid propellants. After numerous trials, a solid-propellant rocket engine was developed that produced 125 newtons of thrust and operated for twelve seconds. The Army Air Corps watched with interest when on August

12, 1941, three rockets were attached to each wing of a light monoplane. Army and Navy personnel watched the plane roar down the runway after the pilot had thrown the switch to ignite the JATO units. Calculations showed that the JATO units had shortened the time and distance required for takeoff by 50 percent.

The JATO units' disadvantages prompted more experimentation with ways of controlling the burning rate of solid propellants and greater efforts to develop a liquid-fueled rocket that might serve as a JATO unit. The work was recognized by the aircraft industry. The Consolidated Aircraft Company of San Diego, California, may have been the first American commercial organization to recognize the potential applications of rocket-assisted takeoff. The National Academy of Sciences provided funds for further research.

Early jet propulsion research was applied to the development of "superperformance" aircraft. The researchers looked for ways to shorten the time and distance required for takeoff, to increase the rate of climb temporarily, and to increase level flight speed temporarily. GALCIT was authorized



Aerial view of the Jet Propulsion Laboratory campus nestled beside the San Gabriel Mountains near La Cañada, California (north of Pasadena). (NASA) to work on both liquid- and solid-propellant rocket engines.

In early 1944, the Army asked the Laboratory to begin a research and development program on long-range guided missiles. This required basic research in physics, chemistry, metallurgy, aerodynamics, and electronics. With funds provided by the Army Ordnance Corps and the Laboratory, investigations began on new propellants, metals to withstand heat and corrosion, and remote-control devices. The staff was enlarged, new facilities were added, and the work intensified.

During World War II, a number of firsts were achieved. JPL was the first U.S. government-sponsored group devoted to the study of rockets. JPL developed the first successful jet-assisted take-off units, the first operational restricted burning solid-propellant rocket motor, and the first liquid-fuel engine to use a special, spontaneously igniting mixture. In 1942 JPL produced the first assisted takeoff of an airplane with a liquid-propellant rocket engine. The first graduate course in jet propulsion was inaugurated in 1944. In 1945 JPL designed and developed a sounding rocket that reached a record altitude of 27.9 kilometers.

JPL was also a pioneer in telemetry, the technique of transmitting instrument recordings via a radio link. Telemetry was necessary to the gathering of flight performance data from rockets and to the eventual development of guided missile systems.

Successful development of the Bumper-Wac, which reached a record altitude of 155 kilometers, in 1947; the Loki solid-propellant antiaircraft rocket in 1951; and, in 1953, the Corporal, the United States' first surface-to-surface guided missile, led to the triumphant launch of the United States' first successful Earth satellite, Explorer 1, on January 31, 1958.

Explorer 1's success was heralded as a moral achievement as well as a scientific and technological achievement. Only three months after the Soviet Union had orbited the world's first artificial satellite, Sputnik 1, the Army Ballistic Missile Agency-Jet Propulsion Laboratory (ABMA-JPL) had redeemed the United States' honor. On board the Explorer satellite was an experiment that reported a mysterious saturation of radiation counters at an altitude of 965 kilometers. James A. Van Allen, the scientist who had created the experiment, interpreted this as evidence for the existence of a dense belt of radiation (now called the Van Allen radiation belt) around Earth at that altitude. Another scientific first had been achieved.

In the mid-1950's, U.S. agencies involved in space activities included the National Advisory Committee for Aeronautics, the Atomic Energy Commission, and the Department of Defense. The consensus in Washington was that the United States needed a national space program. The military component would be under the Department of Defense, but a civil component would forge an expanded program of space exploration in concert with the military. The National Aeronautics and Space Administration (NASA) came into being on October 1, 1958, when President Dwight D. Eisenhower signed the National Aeronautics and Space Act of 1958. The act established a broad charter for civilian aeronautical and space research.

On December 3, 1958, JPL was transferred from the Army's jurisdiction to NASA's. The Laboratory would continue to be operated by the California Institute of Technology. JPL's research emphasis changed from missiles to lunar and planetary exploration. New facilities were erected, and additional scientists, engineers, and support personnel were hired.

The Laboratory pledged to support the national interest through spaceflight projects, a deep-space network, a science program emphasizing flight experiments, national security projects, and the application of advanced technology to selective fields such as energy.

Major NASA/JPL spaceflight projects have collected a wealth of information on the physical constitution of Earth's celestial neighbors and the interplanetary medium. In 1958 and 1959, Pioneer 3 and Pioneer 4 were launched. The latter was the first successful U.S. Moon probe. It collected data on particles in lunar space.

From 1964 to 1965, three Ranger spacecraft made contact with the lunar surface. High-resolution photographs of the Moon were sent to Earth by television. From 1966 to 1968, there were five successful soft landings on the Moon by Surveyor probes. The Surveyors observed details of the lunar surface and demonstrated that it was safe for astronauts.

The Mariners were planetary research vehicles. Mariner 2, the first interplanetary spacecraft, collected data from Venus. Mariner 4 traveled past Mars; it returned the first close-up photographs of the Martian surface and discovered craters there. Mariner 5 made the second flyby of Venus; it obtained data on the atmosphere of the planet. The Mariners that followed provided information about Mars. Mariner 10 was the first dual-planet, gravity-assisted mission. In 1974 and 1975, the spacecraft photographed cloud patterns and atmospheric circulation on Venus. Later, it took high-resolution photographs of Mercury's surface and achieved three new encounters with Mercury.

The Viking mission to Mars was another JPL achievement. Two Viking spacecraft were launched toward Mars, the first on August 20, 1975, and the second on September 9, 1975. Viking 1's lander reached the surface of Mars on July 20, 1976, the seventh anniversary of the Apollo crewed landing on the Moon. Viking 2 landed on September 3. During the primary mission, which lasted until mid-November, the Vikings took more than ten thousand photographs from orbit and from the surface; conducted a search for microbial life; performed organic and mineralogical studies of the Martian soil; studied physical and magnetic properties of the soil; made daily weather reports; and listened for seismic activity. The extended mission lasted about three and a half years; one lander, however, remained operational at a low level of activity until November, 1982.

Launched from Kennedy Space Center in the late summer of 1977, two Voyager spacecraft are among the most rewarding flight missions managed by JPL. Equipped with television cameras and a variety of other scientific instruments, the Voyagers performed thorough studies of Jupiter, Saturn, and Uranus. In 1988, Voyager 1 was heading out of the solar system, searching for the boundary between the solar system and interstellar space. After having passed the Jovian and Saturnian systems, Voyager 2 achieved a highly successful flyby of Uranus in January, 1986. The spacecraft's encounter with Neptune's north pole and Neptune's satellite Triton occurred in 1989. Studies of the Jupiter and Saturn systems started by the Pioneer 10/11 and Voyager 1/2 flybys were advanced by the Galileo orbiter/probe and Cassini orbiter/probe, respectively.

JPL is also involved in studies of our own planet and its environment. The Solar Mesosphere Explorer has measured concentrations of ozone and other chemicals in Earth's atmosphere, and space shuttles have carried JPL experiments and a JPL scientist into Earth orbit.

The Shuttle Imaging Radar (SIR) and shuttle multispectral infrared radiometer, geologic and resource-mapping instruments that were part of the first shuttle's scientific payload, helped prove the usefulness of the shuttle for science experiments. Another experiment, the Active Cavity Radiometer Irradiance Monitor (ACRIM), flew in Spacelab 1 and measured the Sun's energy output to help determine how variations in solar energy affect Earth's climate.

JPL's Earth-orbiting satellite Seasat demonstrated the feasibility of global monitoring of sea conditions and determined key features of an ocean dynamics monitoring system.

Another of JPL's projects was the Infrared Astronomical Satellite (IRAS), a satellite that carries a cryogenically cooled telescope designed to survey and map the entire sky at infrared wavelengths. IRAS discovered many cold astronomical objects, interstellar clouds of dust, and sites of star formation. Along with three years of Earth-based observation, IRAS's observations revealed the density of Pluto's atmosphere to be greater than previously believed. JPL and University of Arizona planetologists learned that Pluto is different from asteroids and the icy satellites of giant planets. They ob-

Close-up view of the Jet Propulsion Laboratory. (NASA)

tained precise measurements of the diameter of Pluto and of its satellite, Charon.

Ground-based scientists were active in 1986 as the famous Halley's comet passed Earth on its seventy-six-year-period trip through the solar system. Scientists were able for the first time to observe the comet at close range with spacecraft. The European Space Agency, the Soviet Union, and Japan launched flight missions to study Halley's comet. JPL and the University of Erlangen-Nuremberg in West Germany were the centers for eight observing networks.

Spacecraft and the tasks they perform have evolved side by side with computer technology. For decades, JPL has been in the vanguard of advancing microelectronics technology. Developing computers to handle more complicated tasks and solving problems with new computer architecture are among the projects in JPL's Center for Space Microelectronics Technology.

One of the center's most exciting projects, the Hypercube, a concept in computer architecture, was invented at the California Institute of Technology (CalTech) and developed at JPL with strong CalTech participation. The talents of 120 scientists, engineers, and technicians trained in solid-state physics, materials science, chemistry, electrical engineering, and computer science are invested in the project. The CalTech/JPL group has written more than forty applications programs that run on the Hypercube, and several private companies have adopted the technology.

Biomedical research was one of the first nonspace endeavors at JPL; the Laboratory used computer-enhancement techniques borrowed from planetary projects to improve x-ray images of human skulls. JPL continues to do research in areas such as atherosclerotic disease, laser medical applications, and various forms of cancer.

Context

JPL was chosen to be the nation's first space research facility because of the Laboratory's history of rocket research, which began in 1936 when Theodore von Kármán and several graduate students from the California Institute of Technology did their pioneering rocket experiments in the foothills of the San Gabriel Mountains in Southern California.

That early research led to the development of solid- and liquid-fueled rocket engines. Their first application came in 1940 with jet-assisted takeoff for aircraft. After eighteen years of work for the Army, JPL was transferred to NASA's jurisdiction. Under a NASA-California Institute of Technology contract, JPL received its first assignments to lead the nation's exploration of deep space.

For NASA, JPL has successfully completed robotic missions to the Moon and planets and opened the new frontier of the solar system. Among JPL's achievements are the Ranger and Surveyor lunar projects; the Mariner missions to Mars, Venus, and Mercury; Viking's mission to Mars; a survey of the sky at infrared wavelengths by the Infrared Astronomical Satellite (IRAS); the exploration of Jupiter and Saturn by Voyagers 1 and 2 and Uranus and Neptune by Voyager 2; Magellan, which orbited Venus and mapped its hidden surface with imaging radar; Galileo, designed to orbit Jupiter and send an instrument-laden probe into the planet's atmosphere for the first direct sampling of the planet's clouds; and Ulysses, a joint project between the European Space Agency and NASA to fly past Jupiter and then over the poles of the Sun, scanning the regions of the Sun that have never been seen before and studying interstellar space above the Sun's poles.

JPL's spacecraft are tracked and commanded by way of the Deep Space Network (DSN). In the spring of 1958, the Laboratory had been looking for a site on which to build a space vehicle tracking facility. The ideal location was determined to be at the U.S. Army's Camp Irwin, 72 kilometers north of Barstow, California, in the Mojave Desert. There, JPL engineers built a parabolic receiving dish 26 meters in diameter and 34 meters high. This dish antenna collects and focuses radio signals from space vehicles and is able to track satellites and space probes across the plane of the horizon. The data are collected and relayed to JPL's computing center in Pasadena for analysis.

More recent JPL missions of note include Mars Observer, the Magellan mission to Venus, Galileo to Jupiter and its moons, Ulysses solar-polar investigations, Mars Global Surveyor, Mars Pathfinder, Cassini to Saturn, Deep Space 1, Mars Climate Orbiter, Mars Polar Lander, and the 2003 Mars Exploration Rovers Spirit and Opportunity. NASA's Hubble Space Telescope, freed from the blindfold of Earth's atmosphere, would bring the most distant reaches of the universe many times closer for astronomers. Among the telescope's instruments was a wide-field planetary camera, designed and built by JPL and the California Institute of Technology.

In other fields, too, JPL has turned its scientific and engineering expertise to solving major problems. JPL has been committed to the United States' energy self-sufficiency program since the energy crisis of the 1970's. The Department of Energy named JPL its lead center for solar-photovoltaic development and applications. (Photovoltaic cells are solid-state solar energy devices that convert sunlight directly to electricity.)

The U.S. air carriers, and the people who operate and control them, look to space-age technology to improve conditions for the flying public. JPL has contributed to the Federal Aviation Administration's attempt to improve air safety with a computerized voice-switching and control system.

Research into new technologies is among the most fascinating work pursued at JPL. Many of the new technologies are intended to solve problems that have been with us for decades. JPL's major function, however, continues to be exploration of the solar system.

See also: Asteroid and Comet Exploration; Explorers 1-7; Infrared Astronomical Satellite; Mariner 1 and 2; Mariner 3 and 4; Mariner 5; Mariner 6 and 7; Mariner 8 and 9; Mariner 10; Pioneer Missions 1-5; Pioneer Missions 6-E; Ranger Program; Seasat; Space Centers, Spaceports, and Launch Sites; Space Shuttle: Radar Imaging Laboratories; Viking Program; Voyager Program.

Further Reading

Bilstein, Roger E. *Orders of Magnitude: A History of the NACA and NASA, 1915-1990*. 2d ed. NASA SP-4406. Washington, D.C.: Government Printing Office, 1989. This brief volume covers the U.S. history of aeronautics and space development, from the first aircraft to the space shuttle.

Burrows, William E. *This New Ocean: The Story of the First Space Age*. New York: Random House, 1998. This is a comprehensive history of the human conquest of space, covering everything from the earliest attempts at spaceflight through the voyages near the end of the twentieth century. Burrows is an experienced journalist, who has reported for *The New York Times*, *The Washington Post*, and *The Wall Street Journal*. There are many photographs and an extensive source list. Interviewees in the book include Isaac Asimov, Alexei Leonov, Sally K. Ride, and James A. Van Allen.

Davies, John K. *Astronomy from Space: The Design and Operation of Orbiting Observatories*. 2d ed. New York: John Wiley, 1997. Coverage of all space astronomy missions, with tables of launch data and orbits as well as photographs of many satellites. Organized by type of astronomy: x-ray, gamma-ray, ultraviolet, infrared and millimeter, and radio.

Hamilton, John. *The Viking Missions to Mars*. Edina, Minn.: ABDO and Daughters Publishing, 1998. Although this is a juvenile book, it does give a good overview of the Viking missions to the Red Planet.

Heppenheimer, T. A. *Countdown: A History of Space Flight*. New York: John Wiley, 1997. A detailed historical narrative of the human conquest of space. Heppenheimer traces the development of piloted flight through the military rocketry programs of the era preceding World War II. Covers both the American and the Soviet attempts to place vehicles, spacecraft, and humans into the hostile environment of space. More than a dozen pages are devoted to bibliographic references.

Klerkx, Greg. *Lost in Space: The Fall of NASA and the Dream of a New Space Age*. New York: Pantheon Books, 2004. The premise of this work is that NASA has been stuck in Earth orbit since the Apollo era, and that space exploration has suffered as a result.

Koppes, Clayton R. *JPL and the American Space Program: A History of the Jet Propulsion Laboratory*. New Haven, Conn.: Yale University Press, 1982. This volume discusses basic space and weapons research during World War II and the decades that followed. It describes the relationships between the California Institute of Technology and JPL and between JPL and NASA. More than half the volume is devoted to JPL's space projects.

Lambright, W. Henry, ed. *Space Policy in the Twenty-First Century*. Baltimore: Johns Hopkins University Press, 2003. This book addresses a number of important questions: What will replace the space shuttle? Can the International Space Station justify its cost? Will Earth be threatened by asteroid impact? When and how will humans explore Mars?

Lee, Wayne. *To Rise from Earth: An Easy to Understand Guide to Spaceflight.* New York: Checkmark Books, 1996. This is a good introduction to the science of spaceflight. Although written by an engineer with the NASA Jet Propulsion Laboratory, it is presented in easy-to-understand language. In addition to the theory of spaceflight, it gives some of the history of the human endeavor to explore space.

National Aeronautics and Space Administration, Jet Propulsion Laboratory. *The Deep Space Network.* Pasadena, Calif.: Author, 1988. This booklet explains the nature of the Deep Space Network, the largest and most sensitive scientific telecommunications and radio navigation network in the world. With illustrations and photographs, it describes the applications of the DSN in JPL's space programs.

__________. *Jet Propulsion Laboratory 1987 Annual Report.* Pasadena, Calif.: Author, 1987. Recovering from the tragedy of the *Challenger* gave impetus to a period of research in robotics, automation, machine intelligence, astrophysics, and new computer architecture. JPL researchers expanded observations of Earth's oceans and climate from space. The book contains many black-and-white photographs.

__________. *JPL Closeup.* Pasadena, Calif.: Author, 1987. This is an attractive booklet with clear, black-and-white, scientific photographs. It summarizes the findings of the planetary missions launched to date and then presents an overview of immediate and long-range plans for JPL's future endeavors. The publication touches on the Deep Space Network and the Hypercube, a concept in computer architecture invented at the California Institute of Technology.

__________. *JPL Highlights 1987.* Pasadena, Calif.: Author, 1987. Rather technical, this volume covers deep-space exploration, information systems and space technology development, defense and civil programs, and Earth-orbital applications. Contains photographs and sketches.

Ramana Murthy, Poolla V., and Arnold W. Wolfendale. *Gamma-Ray Astronomy.* 2d ed. New York: Cambridge University Press, 1993. This book, which is a fully updated new edition of the authors' earlier volume published in 1986, is invaluable in providing the background science to this important field. In assessing the current state of the art, the book also indicates the exciting basis from which new discoveries will be made. The concentration on phenomenology makes this book a fine introduction to gamma-ray astronomy. It is of use to all students and professional astronomers who are working in this developing field.

Spilker, Linda J., ed. *Passage to a Ringed World: The Cassini-Huygens Mission to Saturn and Titan.* Washington, D.C.: National Aeronautics and Space Administration, 1997. Edited by the Cassini deputy project scientist, this collection provides a preview of the Cassini-Huygens mission. Chapters include details about the spacecraft, as well as Saturn and its moon Titan. There are numerous photographs and illustrations, a glossary of terms, an acronyms and abbreviations list, and a bibliography.

Stern, S. Alan, and Jacqueline Mitton. *Pluto and Charon: Ice Worlds on the Ragged Edge of the Solar System.* New York: John Wiley, 1997. This book discusses scientists' knowledge of the Pluto-Charon system obtained from ground-based observations and images taken by the Voyager spacecraft and the Hubble Space Telescope. The book covers the advances made possible by dramatic improvements in ground-based astronomical instrumentation and the revolution in scientific perspective wrought by spacecraft visits to the planets. From its discovery in 1930 by Clyde Tombaugh to future exploration by the Pluto-Kuiper Express, this illustration-packed work thoroughly explores these two icy-cold worlds.

Wolf, Marvin J. *Space Pioneers: The Illustrated History of the Jet Propulsion Laboratory and the Race to Space*. Santa Monica, Calif.: General Publishing Group, 1999. This is an in-depth look at the Jet Propulsion Laboratory and the space missions—both piloted and robotic—to explore the depths of space. The book covers JPL from its inception through 1998. There are numerous photographs and tables.

Clarice Lolich

Russia's Mir Space Station

Date: February 20, 1986, to 2001
Type of spacecraft: Space station, piloted spacecraft

Mir, a third-generation Soviet/Russian orbital station, was home to numerous cosmonauts and international visitors between 1986 and 2000. It also provided experience for NASA astronauts before the International Space Station (ISS) was placed in orbit.

Key Figures

Sergei Pavlovich Korolev (1907-1966), widely regarded as a founder of the Soviet space program
Vladimir Pavlovich Barmin (1909-1993), pioneer of the rocket program in the USSR who led the development of launch infrastructure for Russian rocketry
Vladimir Nikolaevich Chelomei (1914-1984), Soviet rocket scientist and flight director designer who led the development of the Almaz space station
Leonid Kizim (b. 1941), Salyut 7 Expedition Five, Mir Expedition One commander
Anatoly Yakovlevich Solovyev (b. 1948), Salyut 7 Expedition Five, Mir Expedition One flight engineer
Yuri Romanenko, Mir Expedition Two commander
Alexander Laveikin, Mir Expedition Two flight engineer

Summary of the Mission

Mir's core module was launched on February 20, 1986. Mir was launched largely without any research equipment. It required outfitting during early expeditions. Mir's first crew briefly flew Soyuz T-15 to Salyut 7 to retrieve equipment for Mir. On July 16, Cosmonauts Leonid Kizim and Anatoly Solovyev departed from Mir, leaving it unoccupied for the rest of 1986.

The second crew achieved Mir's first long-duration occupation. Yuri Romanenko and Alexander Laveikin were launched aboard Soyuz TM-2 on February 6, 1987. They reactivated Mir's systems, unloaded supplies inside a previously launched Progress freighter, and established residence for eleven months, initiating research involving materials science and Earth resources imaging. Orbital construction began when the Kvant astrophysics module was launched on March 31, 1987. Difficulty with automatic rendezvous equipment developed shortly before Kvant attempted docking at Mir's aft port. Ten days later Kvant achieved a soft docking but not a secured physical mating. Cosmonauts Romanenko and Laveikin undertook an extravehicular activity (EVA), or spacewalk, to remove a foreign object obstructing the docking mechanism. Mission Control Moscow then retracted Kvant's docking mechanism and achieved a hard mating. Over subsequent months, the cosmonauts received additional Progress freighters bearing fresh consumables, performed spacewalks installing new solar arrays that expanded Mir's available electrical power, activated Kvant's x-ray telescopes, and briefly hosted other cosmonauts and a Syrian guest who arrived on Soyuz TM-3. Laveikin developed minor cardiovascular irregularities and was replaced as a resident crew member by TM-3 Cosmonaut Alexander Alexandrov. Laveikin, TM-3 Cosmonaut Alexander Viktorenko, and the Syrian guest returned home in the older Soyuz TM-2, leaving the fresh Soyuz spacecraft behind.

Soyuz TM-4's crew, Vladimir Georgievich Titov and Musa Manarov, relieved Romanenko and Alexandrov four days before Christmas. Romanenko and Alexandrov returned home in Soyuz TM-3 four days after Christmas, and Titov and Manarov started a yearlong residence. These two hosted three brief visits by cosmonauts and researchers. They were joined in late summer by Yuri Polyakov, a physician, who over two separate lengthy visits would accumulate station time equivalent to a round trip to Mars. He evaluated human physiological response when subjected to long-term weightlessness. Titov and Manarov returned home on December 21, 1988, aboard Soyuz TM-6, precisely one year after launch. Crew rotation was clearly established, with returning crews using older available Soyuz TM transports for reentry while a fresh one brought up briefly visiting crews or resident replacements. It was time to resume Mir's expansion.

Original plans predicted that Mir's orbital construction would be completed within three years, but economic and political difficulties in the faltering Soviet Union delayed the four remaining specialized research modules. While waiting for them, a new-generation Progress vehicle entered service. Progress M freighters would be equipped with separable spacecraft that would survive reentry, returning data and samples, while the freighter would undergo atmospheric destruction. Throughout 1989, crew and Soyuz rotations continued.

The Kvant 2 module was launched on November 26, 1989. Completing rendezvous, the new module approached Mir automatically, and like the first expansion module, it underwent docking delays. Unsecured solar arrays prevented the module from maintaining adequate attitude control. After that problem was solved, Kvant 2 attached itself to Mir's forward port. Later, cosmonauts used a manipulator arm to transfer it to one of four radial ports available at the core module's forward end. Kvant 2 added research facilities and incorporated a spacious air lock and large exterior hatch from which cosmonauts could begin and terminate spacewalks more easily. It also housed additional gyrodynes that increased the efficiency of Mir's attitude control system.

Kristall, the third expansion module, arrived June 10 after another aborted docking attempt several days earlier. Like Kvant 2, it initially docked at Mir's forward port, and then the cosmonauts moved Kristall to the radial port opposite Kvant 2. Several days later, Cosmonauts Solovyev and Alexander Balandin performed a contingency spacewalk securing thermal blankets that had debonded from Soyuz TM-9's descent module's hull. When that spacewalk ended, Kvant 2's outer air-lock hatch would not close. Fortunately, that air lock was double-chambered. The cosmonauts sealed the inner one while leaving the outer one exposed to a vacuum.

In 1991, despite the Soviet Union's dissolution, regular crew rotations continued. Numerous EVAs were performed by several cosmonauts, some including beam construction. Crews conducted varied research, hosted international guests, and received numerous Progress freighters. As 1991 ended, however, rumors surfaced that Russia might sell Mir. Severe funding problems beset the Russian Space Agency (RSA) as economic conditions in the country worsened.

Mir operations in 1992 and 1993 experienced financial shortfalls and program uncertainties following the Soviet Union's dissolution. Late hardware deliveries resulted in mission delays, but financial help arrived when the Bush administration initiated studies of Soyuz spacecraft and Mir's compatibility in connection with National Aeronautics and Space Administration's (NASA's) Space Station Freedom. This planted the seed of the Phase I program for the ISS—the station design the Clinton administration backed—a program that set up joint flight opportunities for cosmonauts and astronauts. Meanwhile, cosmonauts continued research and hosted international guests, which provided additional financial help and permitted continuous occupation.

Phase I operations began when STS-63 was launched on February 3, 1994, carrying Cosmonaut Vladimir Georgievich Titov among its crew. *Discovery* flew the first shuttle rendezvous to Mir, coming within 10 meters (33 feet) of Mir and blazing the path for subsequent dockings. Early that year Polyakov began an attempted endurance record. At year's end RSA announced major delays in launching Spektr, a new research module that NASA's first astronaut to live aboard Mir, Norman E. Thagard, had expected to use extensively.

Thagard was launched aboard Soyuz TM-21 on March 14, 1995, and became the first American to ride a Russian rocket. Thagard was hosted by Cosmonauts Vladimir Nikolaevich Dezhurov and Gennady Mikhailovich Strekalov but briefly overlapped with Viktorenko, Elena V. Kondakova, and Polyakov's residence early in his stay. The latter three left Mir aboard Soyuz TM-20 on March 22, ending Polyakov's record-setting endurance visit at 438 consecutive days, a standard likely to stand for quite some time.

Spektr was launched on May 20 and, after Kristall's relocation, docked at Mir's forward port on June 1, making it the first expansion module to achieve docking on its initial attempt. The next day Spektr was moved to a remaining radial port. Mir was now in proper configuration for STS-71, the first shuttle-Mir docking mission. *Atlantis* lifted off on June 27 with Cosmonauts Solovyev and Nikolai Budarin slated for residence on Mir. It docked to Kristall two days later. When the astronauts entered Mir, the total population aboard reached ten, which set a record. Thagard reunited with his training backup Bonnie J. Dunbar. After logistical transfers and official ceremonies, *Atlantis* departed on July 4 with Thagard aboard. When *Atlantis* touched down at Kennedy Space Center (KSC) three days later, Thagard had established a new NASA space endurance record.

The Mir Space Station in 1995 as viewed from the Soyuz TM transport vehicle. (NASA)

Next, NASA sent Shannon W. Lucid to Mir on STS-76, which was launched on March 22, 1996. This time *Atlantis* docked to a new docking module attached to Kristall's end, a Russian structure that STS-74 had delivered on November 15, 1995, on the second shuttle-Mir docking mission. Lucid began an even longer stay than Thagard's. The final expansion module, Priroda, which had been planned to support much of Lucid's scientific research, was launched on April 23. Three days later it docked to Mir's forward port and was subsequently positioned at the only free radial port, thereby completing Mir's orbital construction eight years after core module launch.

Lucid's stay lasted longer than expected after delays in getting *Atlantis* ready for its next docking mission. STS-79 retrieved Lucid in September. When Lucid finished her stay she had completed 188 days in space, a new NASA record. Lucid's replacement, John E. Blaha, traded places with her on the STS-79 shuttle-Mir docking mission. Blaha spent 128 days in space, was retrieved by STS-81, and was replaced by Jerry M. Linenger in January, 1997.

A lengthy series of crises occurred in 1997. During Linenger's stay, an international mission overlapped with a long-duration residence. With six people aboard, Mir's Elektron oxygen generation unit required supplementation by burning lithium perchlorate canisters. When Alexander Lazutkin changed out a canister inside Kvant, leaking chemicals ignited. Although the intense flame was attacked with fire extinguishers, it ended only when the canister's chemical supply ran out. The fire caused no significant structural damage, but thick smoke pervaded Mir. If it had not dissipated or if oxygen masks had not been available, the cosmonauts might have had to abandon Mir.

C. Michael Foale replaced Linenger. *Atlantis* was launched on May 15, 1997, carrying Foale and Cosmonaut Elena V. Kondakova among the crew. It landed at KSC on May 24 and returned Linenger after 132 days in space.

Foale encountered 1997's worst station crisis: During a manual docking test on June 25, Commander Vasili Tsibliyev did not receive necessary telemetry, nor did he have adequate control over Progress M-34 as it impacted Mir and therefore damaged radiators and solar arrays. The cosmonauts scrambled into action upon hearing pressure-loss alarms. Lazutkin and Foale sealed off Spektr's hatch and powered up their Soyuz in the event they needed to abandon Mir. Meanwhile, Mir lost attitude and power dropped precipitously. Power-hungry systems were deactivated, and it took several days to reconfigure Mir's essential systems.

Over the next several weeks, Mir's computer periodically malfunctioned, forcing cosmonauts repeatedly into a lengthy sequence of restoring power, attitude control, and life-support. Additionally, carbon dioxide scrubbers and Elektron oxygen generation units required frequent maintenance. When Spektr was abandoned, many of Foale's personal property and much of his access to research equipment were lost.

Soyuz TM-26 was launched on August 5. It brought new tools and replacement parts, and Cosmonauts Solovyev and Pavel Vinogradov to replace Tsibliyev and Lazutkin. While spacewalking inside Spektr, Vinogradov inserted electrical lines through the hatch and connected Spektr's functional solar arrays, which provided additional power. Attempts to isolate Spektr's hull breach all proved unsuccessful.

Mir's continued diminished condition caused serious Phase I review. Some believed that Mir was unfit for further flights. Despite external criticism, NASA decided to dispatch David A. Wolf to replace Foale. Three more shuttle-Mir dockings were achieved. Wolf began his stay on September 27. His visit was without the crises Linenger and Foale had survived, but frequent nuisance malfunctions continued. Wolf was replaced by Andrew S. W. Thomas on January 24, 1998. He, in turn, was picked up by STS-91, ending the Phase I program on June 8.

Cosmonauts kept Mir's habitation going until the twenty-seventh expedition departed in summer, 1999. Mir's future remained uncertain, but attempts to continue it beyond Phase I added to the ISS delays as Russia fell behind on its commitments to the new station. Finally, on November 17, 2000, news agencies announced that Russian Space Agency head Yuri Kopyev had reported the agency's decision to dump the aging space station into the Pacific Ocean early in 2001 because Mir had reached the point "where it would be normal for any system to fail."

Contributions

Russia's Mir Space Station was launched when NASA's shuttle program appeared impotent in the wake of the *Challenger* accident. Meant as an evolutionary step in Russian space station development, Mir was designed to include considerable orbital construction of separately launched modules, inflight repairs, and equipment changeouts performed by spacewalking cosmonauts.

Approaching the end of its life by the end of 2000, Mir had accumulated an impressive scientific record despite its rather significant and media-celebrated problems in later years. More than 22,000 individual scientific experiments had been run using more than 240 major pieces of apparatus. Many were launched inside expansion modules, and the rest were delivered aboard Soyuz, Progress, or space shuttles. Among Mir's final clutter was fourteen tons of science hardware. Although many research projects were short-term, twenty were long-term, and some ran during virtually Mir's entire lifetime.

Including all missions up to the twenty-seventh expedition, a total of seventy-seven spacewalks had been conducted in support of station expansion, maintenance, repairs, technology demonstrations, and scientific research. Crews encountered and responded effectively to approximately 1,500 malfunctions and accidents. For the vast majority of the fourteen years that Mir had been piloted there were only several periods during which it had been mothballed and unoccupied.

During Mir's lifetime an impressive number of cosmonauts each accumulated well over a year total time spent in space spread over several separate missions. The longest single habitation ran 438 days, accomplished by Polyakov, who also held the total time record at 681 days. He was surpassed by Sergei Avdeyev on the piloted mission of 1999. Avdeev's new record-holding stay lasted 748 days. Both of these cosmonauts had spent more than enough time in space to equal a round trip to Mars and suffered no long-term physiological or psychological maladies.

Context

Russian space station operations began in 1971 with Salyut 1. Three cosmonauts spent a record time aboard that station before returning to Earth. Although an accident resulted in their deaths during atmospheric entry, this mission marked an important step toward development of permanent space station operations. Skylab was NASA's response: a station launched virtually fully equipped, ultimately to be occupied by three separate teams staying for increasing durations in 1973 and 1974. Ten years later, NASA attained presidential authorization to build a new station called Freedom. Unfortunately, that project suffered considerable congressional interference and numerous redesigns spanning nearly a decade. Ultimately, it was reorganized into the ISS and incorporated the Russians as major partners along with the European Space Agency, the Canadian Space Agency, and the Japanese Space Agency. Between Skylab and the ISS the Russians accumulated an impressive history of space station operations with Salyuts 3, 4, and 5, which primarily bore resemblence to the initial Salyut 1. The second-generation Salyut 6 and 7 stations provided routine resupply missions using robotic Progress freighters by incorporating multiple docking ports. During the Salyut era, a large number of cosmonauts accumulated impressive amounts of time in space, sometimes as long as six months or considerably more on a single visit.

Mir represented a third-generation Russian space station. It provided additional specific research modules to the core module. Originally, Mir was designed to be completely assembled within five years, with the addition of five add-on modules, four attached radially and one axially behind the core module. Later, it would be incorporated into or superseded by Mir 2, an even larger station that might house upward of a dozen cosmonauts and be regularly visited by Russian shuttles. With the Soviet Union's dissolution, Mir suffered economic shortfalls, and both the Russian shuttle and Mir 2 programs were canceled. Mir became the only focus of Russian piloted spaceflight, and its mission was extended. Including the Russians into the ISS provided a groundbreaking preparatory stage wherein NASA astronauts could gain long-duration station experience during the Phase I program. Seven astronauts spent periods of time ranging from three to six months aboard Mir with cosmonauts. Other international visitors stayed aboard for shorter durations. Lessons learned proved to be extremely valuable for future ISS operations. Continuing Mir's operations beyond Phase I delayed fulfillment of Russian commitments to the ISS program, forcing serious delays in the early ISS orbital construction. Such considerations played a role in the final decision to deorbit Mir.

See also: Cooperation in Space: U.S. and Russian; Extravehicular Activity; International Space Station: Living and Working Accommodations; International Space Station: 1999; International Space Station: 2000; Soyuz and Progress Spacecraft; Soyuz Launch Vehicle; Space Shuttle-Mir: Joint Missions.

Further Reading

Burrough, Bryan. *Dragonfly: NASA and the Crises Aboard Mir.* New York: HarperCollins, 1998. A nonchronological account of Mir operations during NASA's Phase I involvement with the Russian space program, largely zeroing in on behind-the-scenes interactions of principal managers, astronauts, and cosmonauts. Spends considerable time discussing Mir's lengthy list of major problems encountered in 1997.

Godwin, Robert, ed. *Rocket and Space Corporation Energia.* Burlington, Ont.: Apogee Books, 2001. The story of the R-7 rocket and its many offspring, including the current Soyuz booster, is one which still remains a mystery in the West. The book contains a pictorial record encompassing the entire history of the Russian space program, from its inception at the end of World War II to the present day. Included are details of the Mir Station and its development.

Hall, Rex, and David J. Shayler. *Soyuz: A Universal Spacecraft.* Chichester, England: Springer-Praxis, 2003. The authors review the development and operations of the reliable Soyuz family of spacecraft, including lesser-known military and unmanned versions. Using authentic Soviet and Russian sources this book is the first known work in the West dedicated to revealing the full story of the Soyuz series, including a complete listing of vehicle production numbers.

Harland, David M. *The Story of Space Station Mir.* Chichester, England: Springer-Praxis, 2005. The book tells how the Soviet Union's experience with a succession of Salyut space stations led to the development of Mir, which became an international research laboratory whose technology went on to form the "core modules" of the International Space Station. The book runs through to Mir's deorbiting in March, 2001, providing the definitive account of the Mir Space Station. The book reviews the origins of the Soviet space station program, in particular the highly successful Salyuts 6 and 7, describes Mir's structure, environment, power supply and maneuvering systems, and provides a comprehensive account of how it was assembled and how it operated in orbit.

Johnson, Nicholas L. *The Soviet Year in Space, 1987.* Colorado Springs, Colo.: Teledyne Brown Engineering, 1988. Excellent, thorough review of Soviet space program activities in 1987, both piloted and, robotic, by an acknowledged expert in Soviet spaceflight history and present-day operations. A similar volume was published by this author for each of the years 1988, 1989, and 1990.

Linenger, Jerry M. *Off the Planet.* New York: McGraw-Hill, 2000. This is a personal account of Linenger's Phase I stay aboard Mir. It must be noted that his account paints a more serious situation with regard to the fire than either the official Russian or NASA account.

Provides insight into interpersonal relationships between cosmonauts and astronauts, particularly those with whom Linenger served.

Newkirk, Dennis. *Almanac of Soviet Manned Space Flight.* Houston: Gulf Publishing Company, 1990. A thorough encapsulation of Soviet spaceflight activities until the end of 1990. Mir activities during its first four years are particularly well documented. Readers will find it interesting to read future projections and compare those with what actually transpired.

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