COMMUNICATIONS IN SPACE

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Abstract

This paper provides an overview of the imaging results of the JPL/NASA unmanned exploration missions to all of the planets of the solar system (except Pluto) as well as the telecommunications capability which was developed to enable/support those missions.

The telecommunications link improvements will be described to show increases in data rate capability resulting from the addition of ground antenna aperture, transmitter power, coding techniques, lower noise receivers, etc. This paper will also describe (briefly) the current and future flight missions.

The presentation will be supported by a significant number of pictures taken during the planetary encounters as well as pictures of the Deep Space Network Antennas.

Introduction

The Jet Propulsion Laboratory of the California Institute of Technology, under contract to the United States National Aeronautics and Space Administration, conducts space flight projects for scientific research. The laboratory also has developed and currently operates a deep space tracking network and data acquisition facility supporting the scientific exploration of space.

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Historical Perspective of Telecommunications

Space communications technology, as we use the term, started with military rockets. The concept of measuring performance parameters on board a vehicle and radioing the encoded data to a ground receiving station proved a successful technique. Consequently, this technique was expanded and refined to enable the development of the flight and ground equipment for the early earth orbiting satellites. The first US satellite with this technology was the Explorer 1 which was designed and built by JPL and used a modified US Army sponsored ballistic missile to place the satellite in orbit. The flight data from that first on board flight instrument were returned to the ground receiving stations via the communications link. That flight instrument detected what is now known as the Van Allen Belt of charged particles that orbit the earth. The receiving stations formed the basis of the world wide Deep Space Network (DSN). Satellite technology has contributed to the development of the deep space planetary exploration spacecraft that are in flight today.

Discussion

The overall evolution of the unmanned space program, which began with earth orbiters, was followed by flights to the moon, and eventually lead to the exploration of all of the planets (except Pluto), has been well documented in the world press, scientific journals and academia. The development of the DSN and its use to support those planetary missions is rarely recognized.

Today's world wide DSN consists of three tracking complexes located near Madrid, Spain; Canberra, Australia; and Goldstone, California, near Los Angeles, in the United States. Each of these complexes contain one 70 meter antenna, one 26 meter antenna, and two 34 meter antennas. These antennas are remotely operated from a centrally located signal processing center at each complex. The complexes are connected to a network control center at JPL in Pasadena, California. There is also a launch support facility located at Cape Canaveral, Florida. The DSN has grown significantly from its original facilities and capabilities, to become a world leader in the development of large, fully steerable microwave antennas, low noise receiving systems, digital signal processing capabilities, and deep space radio navigation.

The primary difference between the DSN and other communication systems is the extreme distances and accuracies required by planetary missions. The DSN is required to support communications over billions of kilometers with signal levels on the order of 10 to the minus 16 watts and to determine the velocity of the spacecraft to a millimeter of a second and its position within a few meters.

The early years of the planetary program (1960 to 1975) were characterized by flights to the various inner planets by the Mariner series of spacecraft. These spacecraft were three-axis stabilized and used solar energy to provide the required power. The instrument complements included various experiments such as ultraviolet spectrometers, infrared interferometer spectrometers, magnetometers, as well as an imaging system (TV). Ten missions were flown, seven were successful. The Mariner flights, the planets they visited, and the years they were launched are listed in Table 1 below.

Table 1.

Mission	Planet(s)	Launch Year
Mariner 1*, 2	Venus	1962
Mariner 3*, 4	Mars	1964
Mariner 5	Venus	1967
Mariner 6, 7	Mars	1969
Mariner 8*, 9	Mars	1971
Mariner 10	Venus/Mercury	1973

*Failures experienced during launch phase.

The Mariner 9 Mars flight in 1971 was the first planetary orbiting mission. This long term observation of Mars from orbit refined the basis for the follow on Viking flights in 1976 which placed the main spacecraft in orbit and instrumented landers on the surface. The Viking mission was built on the findings of Mariner 9 and significantly added to our knowledge of Mars. The orbiter photographed, in greater detail, the volcanoes as well as the great rift valley discovered by Mariner 9. The landers sampled the martian soil for signs of life with negative results. However, the overall data gathered by the two orbiters and landers have provided the definitive source for the current scientific study of Mars today.

The Venus/Mercury mission in 1973 was the first mission to utilize the gravitational assist of one planet to add energy to the spacecraft in order to propel it on to the next. This technique, demonstrated by the 1973 mission, enabled the flight of the Voyager spacecraft to travel to the outer planets in the late 1970s and the 1980s. The Voyager mission will be described later.

The DSN provided tracking, command and telemetry support for all of these missions. The results of these flights to the inner planets are summarized below.

Mercury - Very moon-like - Characterized by an extremely cratered surface with large flat circular basins. Large scarps approximately 3 km high by up to 500 km in length.

Venus - Surface temperature - 477 degrees C; Atmosphere - Carbon Dioxide and Nitrogen; Upper atmosphere - Sulphuric Acid; Surface - Many volcanoes, Impact craters, continent sized highlands.

Mars - Few but massive volcanoes; evidence of surface water in the past; many impact craters; atmosphere very thin but enough to support massive, planet covering, dust storms; polar ice caps (water as well as carbon dioxide); long (over 4500 km) "grand canyon".

In the early 1960s, the data rates from a Mars flyby were 8 1/3 bits per second and took almost 8 hours to return one picture. By 1974 the DSN was capable of receiving up to 117,600 bps from Venus and Mercury. By 1979 it was capable of receiving 115,200 bps from Jupiter.

The remainder of this paper will emphasize the communication rates the DSN supported from the extreme distances of the Voyager Mission. These high data rates were and still are primarily required for the imaging systems. Although a lot of valuable scientific exploration can be carried out without imaging, its added value is considered important enough to continue to invest in the capability to obtain images.

The Voyager mission, when originally conceived, was referred to as the "Grand Tour". The mission was to take advantage of the infrequent alignment of the planets that would allow a spacecraft to go to Jupiter, get a gravity assist to send it on to Saturn, another gravity assist to send it to Uranus, and finally another to send it to Neptune. The mission would have to include a capability on the spacecraft to gather and transmit a significant amount of data to justify its flights. While technically possible, the funding was not available to support such a mission. Consequently, it was descoped to a Jupiter/Saturn mission with a smaller spacecraft and much less powerful transmitters.

All considered, even a Jupiter/Saturn mission was considered very costly. With descoping the missions, NASA and JPL, from the very beginning, were still considering extending the Voyager missions to the "Grand Tour" concept in order to benefit from the planetary alignments. A large part of the responsibility to accomplish this fell on the DSN.

The two Voyager spacecraft were launched in mid 1977 and arrived in mid 1979.

Jupiter

The Jupiter encounter was supported by the 64 meter antennas at 115,200 bps. In anticipation of the follow on requirements, an advanced development concept of electronically connecting two antennas together in an array to increase the received signal strength was tested. The concept proved a successful technique to the extent that continued work was authorized for its use on the upcoming Saturn encounters. There were 33,000 clear pictures received at the rate of one 5-million-bit image per every 48 seconds.

Saturn

The spacecraft flew on to Saturn arriving on November 12, 1980 and August 25, 1981. This encounter was supported by arraying a 64 meter antenna with a 34 meter antenna. This allowed the mission to use a 44,800 bps data rate rather than the 29,000 bps rate that would have been used with only the 64 meter antenna. The Network received 30,000 high quality television images of Saturn, its rings, and its satellites.

Uranus

The Voyager 1 spacecraft was allowed to continue into interstellar space and the Voyager 2 spacecraft was directed on to Uranus with an arrival date of February 1986. The next challenge was to support this Uranus encounter with a data rate that would support a meaningful imaging experiment. The 64 and 34 meter antennas arrayed were far short of what was needed for the 3.0 billion km distance. To increase the elements of the array, another 34 meter antenna at Goldstone and Australia had to be built.

The spacecraft's closest approach to Uranus would occur over Australia, so the greatest improvements would be made there. An agreement was negotiated with the Australian Government for the use of a 64 meter radio telescope located at Parkes, Australia about 290 km North of Canberra.

A microwave link was installed between the facilities allowing real-time transmission of the digitized intermediate frequency signal from Parkes to Canberra. The three Canberra antennas (64m and two 34m) were then arrayed together and afterward arrayed with the Parkes signal to allow a 21 Kilobit data stream. This allowed for the high quality imaging experiment desired.

Changes were also made on the Voyager spacecraft. Since the spacecraft was computerized (with six onboard computers) it was possible to reprogram some of the control functions. Two of the computers were reprogrammed to implement a data reduction technique that allowed a 60 percent reduction in the number of bits needed to produce an image. This, along with the increased data rates provided by the DSN, allowed a picture to be transmitted every 4 minutes allowing the capture of 2516 images of Uranus, its rings and satellites.

Another spacecraft modification that was necessary is of interest. Since the light intensity was less than 1/10 of that at Jupiter, a longer exposure was necessary. To prevent picture smearing as the spacecraft flew by the planet and its moons at a very high speed, it was necessary to turn the cameras at the same rate the spacecraft was moving. This technique was very successful and provided outstanding images of the Uranian moons.

The Uranus encounter occurred in January 1986 and was very successful.

Neptune

The Voyager 2 spacecraft was then directed to Neptune with an arrival date of August, 1989. Another monumental challenge given to the DSN was to obtain the same quality pictures of Neptune that were obtained at Uranus only with less than half the light intensity of Uranus.

Arranging for the reuse of the Parkes antenna was relatively straight forward, but far more was required. It was necessary to modify the 64 meter antennas to increase the diameter to 70 meters. This increased aperture resulted in a 50 percent increase in gain. Arrangements were made with the National Science Foundation to use the National Radio Astronomy Observatory's very large array (VLA) at Socorro, New Mexico. The VLA consists of twenty-seven 25 meter antennas that can be moved in position along three Y-shaped radial railroad tracks. This facility is normally used for radio astronomy. A number of modifications had to be made to use the VLA. New X band receivers, low noise amplifiers, and a correlator to combine the signals from the 27 antennas were added. A satellite communications link was established between the VLA and Goldstone. New combiners were developed for Goldstone that enabled reception of the signals from the three arrayed Goldstone antennas to be combined with the signal received from the VLA. It was also necessary to add the needed equipment and training to convert the VLA from a research type facility to a highly reliable operational facility for the several months of significant Voyager support. The VLA provided a capability of more than 2 1/2 times that of a DSN 70 meter antenna. This added aperture for the array enabled the required signal power to be received thus achieving the desired picture quality.

The encounter with Neptune in August, 1989 was very gratifying to the navigation and science teams. In order to fly by Neptune and Triton, Voyager 2 was targeted to pass only 4900 km above the cloud tops. This close approach to the planet allowed Voyager's trajectory to be bent sharply as it passed over the planet to assure an acceptably close flyby of Triton. The navigation team was congratulated for achieving an aim point miss of less than 40 km from a distance of over 4.4 billion kilometers.

The science team anticipated finding portions of rings (called ring arcs) about Neptune, but were surprised to observe complete, though tenuous, rings. The team was also surprised by the high velocity wind storms that were observed in the atmosphere.

The encounter with Neptune concluded the tour of the outer planets for Voyager 2. The continuing flights of the two Voyager spacecraft into interstellar space will be monitored by the DSN well into the next century. It is anticipated that the onboard consumables, such as power and attitude control gas, will maintain the Voyagers beyond the current range of the DSN tracking capability.

The Voyager flights obtained sufficient data to essentially rewrite the encyclopedia of the outer planets. Some of the high level results are listed below.

Jupiter - Significant details of the planet's atmospheric dynamics; discovery of a tenuous ring; Observation of volcanism on Io, Close up view of the four Galilean satellites; Discovery of new moons.

Saturn - Significant details of the diverse structure of the rings and ring/moonlet interaction; Observation of the atmosphere of Titan; Intriguing observations of the varying surface features of the larger moons; Discovery of new moons.

Uranus - Skewed magnetic field relative to rotation axis; Unusual surface features on the larger moons; Significant numbers of rings.

Neptune - High speed winds; Cyclonic storms in the atmosphere; Tenuous rings; Weak magnetic field; Volcanism on Triton; Nitrogen frost on Triton.

Current Missions

The planetary missions that are currently being supported include Magellan in orbit at Venus and Galileo en route to Jupiter. By the time this paper is presented, the Magellan Spacecraft will have entered the Venus atmosphere and been lost. Magellan was launched in May, 1989 and was placed in an elliptical, nearly polar orbit around Venus in August 1990. The primary objective of the mission was to map at least 70% of the planet's surface. This flight placed unusual demands on the DSN to rapidly acquire telemetry signals under very high doppler rates and for handling the large quantities of data that are characteristic of imaging type missions. The DSN has supported a 268 kilobit data rate for two hours out of every three since the mapping sequence began in 1990. Magellan exceeded its primary objective and returned data to produce a map of 99% of the surface. At the conclusion of the mapping sequence, the spacecraft was configured to lower its elliptical orbit in order to test aerobraking as a means of trajectory or orbit adjustment. The aerobraking technique allows the atmosphere of a planet to slow the spacecraft enough to modify the flight path without a significant expenditure of on board propellant. The successful application of this technique may have significant positive impact on future missions in terms of weight tradeoffs between propellant and instruments.

The Galileo spacecraft includes an orbiter and an atmospheric entry probe to investigate the Jovian System. The spacecraft was launched by the space shuttle, and following three gravity assist flybys of Venus (1) and Earth (2), is well on its way to Jupiter to arrive in 1995. The probe will be released to enter the atmosphere and relay its findings to the orbiter. The orbiter will then begin its detailed investigations of the larger of Jupiter's moons. Challenges are presented to the DSN from this mission because of the long cruise, increased distance, and lower power at encounter.

Future Missions

Cassini - The Cassini mission will explore the Saturnian system, which contains a host of volatile-rich bodies and indications of the processes that have modified them. The mission will be composed of a Saturn orbiter spacecraft, built by JPL for NASA, and a detachable Titan entry probe supplied by the European Space Agency (ESA). The Cassini spacecraft will deliver the probe to Titan and on each orbit of Saturn, will make a close flyby of Titan to allow intensive study of this most unusual moon. One of the most intriguing aspects of Titan is the possibility that its surface may contain lakes of liquid hydrocarbons that result from photochemical processes in the upper atmosphere. Additional studies will be conducted of Titan to determine the composition and structure of the atmosphere as well as the surface features. The orbiter will make extensive studies of Saturn's moons to enhance the knowledge gained during the earlier Voyager flyby of the Saturnian system.

To prepare for the Cassini Mission and to replace the aging 34 meter standard antennas, a new series of 34 meter Beam Waveguide Antennas are currently being implemented into the DSN. In addition, a new digital receiver and higher frequency microwave reception equipment are being planned.

Mars Global Surveyor - This mission, scheduled for launch in 1996, is intended to be the first of a series of low cost orbiters and landers to be launched every 26 months through the year 2005. These spacecraft will continue the investigations of Mars on a planet-wide scale. The instruments will build on the heritage of the Mars Observer mission which was lost just prior to entering orbit in 1993.

Pluto Fast Flyby - Advanced planning and mission design studies are being conducted to determine the feasibility of sending a pair of small spacecraft to Pluto. The objective is to investigate the last unexplored planet and its moon, Charon, while they are close enough in their highly elliptical orbit of the sun to have a measurable atmosphere.

Reflection

The thirty two years of planetary exploration has yielded an enormous amount of data and knowledge of the planets of our solar system. The overall goal of the United States' civilian space program throughout the three decades plus of NASA's existence, has been the understanding of the birth and evolution of our planetary system. In pursuit of that goal, a strategy of planetary reconnaissance (accomplished by fast flybys), exploration (achieved by orbiters and entry probes), and intensive study (implemented by landers) has been followed. The results to date have surprised and amazed the scientific community as well as the general public. It is hoped that the discoveries of the past will encourage significantly more challenging missions of exploration and intensive study of the planets. When those missions are flown, the DSN will continue to bring the data to the waiting science teams.

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