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 capabilities which were developed to enable support of 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 current. It operates a deep space tracking network and data acquisition facility supporting the scientific exploration of space.

The research described in this publication was carried out by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.
Historical Perspective of Telecommunications

Space communications technology, as we use it today, originated 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 anti-ground equipment for the early earth orbiting satellites. The first US satellite with this technology was the Explorer I 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 a the communications link. That flight instrument detected what is now known as Van Allen belts of charged particles that orbit the earth. The receiving station formed the basis of the world wide Deep Space Network (DSN). Satellite technology has contributed to the evolution 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 led to 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 central location 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 worldwide leader in the development of large, full-scanning steerable microwave antennas, low noise receiving systems, digital signal processing, 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-axial stabilized and used solar energy to provide the required power. The instrument complements included various experiment-such as ultraviolet spectrometers, infrared interferometer spectrometers, magnetometers, as well as an imaging system (TV). Terrestrial sessions were fixed, seven were successful. The Mariner flights, the planets they visited, and the years they were launched are listed in Table 1 below.

<table>
<thead>
<tr>
<th>Mission</th>
<th>Planet(s)</th>
<th>Launch Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mariner 1, 2</td>
<td>Venus</td>
<td>1962</td>
</tr>
<tr>
<td>Mariner 3, 4</td>
<td>Mars</td>
<td>1964</td>
</tr>
<tr>
<td>Mariner 5</td>
<td>Venus</td>
<td>1967</td>
</tr>
<tr>
<td>Mariner 6, 7</td>
<td>Mars</td>
<td>1969</td>
</tr>
<tr>
<td>Mariner 8, 9</td>
<td>Mars</td>
<td>1971</td>
</tr>
<tr>
<td>Mariner 10</td>
<td>Venus/Mercury</td>
<td>1973</td>
</tr>
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</table>

Failures experienced in launch phase Mariners 1, 3, 8.

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-anders on the surface. The Viking mission built on the findings of Mariner 9 and significant, the expanded and refined 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 the 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 concept of a gravitational assist. 'Ihis concept was to take advantage of the gravitational force of one planet to add energy to the spacecraft in order to propel it on to the next. This successful technique enabled the flight of the Voyager spacecraft to the outer planets in the late 1970s through 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 - Surf ace temp erature - 482 / -40 degrees C; Atmosphere Carbon Dioxide and Nitrogen; Upper atmosphere - Sul phuric Acids; Surf ace - Many volcanic craters, continent sized highlands.

Mars - Few but massive volcanic craters; evidence of surface water in the past.; many impact craters; atmosphere very thin but enough to support. massive, PI anct covering, dust storms; polar ice caps (water as well) as carbon dioxide).

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 communicat ion rates the DSN is capable of supporting from the extreme distances of the Voyager missions. These high data rates are primarily required for the imaging systems. Although a lot of valuable scientific exploration can be carried out without imaging, the value added to the mission is considered important enough to invest in the capability to obtain those 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 mission 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 successful to the extent that continued work was authorized to allow the technique to be used on the upcoming Saturn encounters. There were 33,000 clear pictures received at the rate of one 5.6 kilo-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 2.9,000 bps rate that would have been used with only the 64 meter antenna. The spacecraft 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, eight 34 meter antenna at GoD and one at 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 antenna to allow a 21 kilobit data stream. This allowed for the high quality imaging experiment desired.

Changes were all 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 all 1 owed a 60 percent reduction in the number of
bit 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 images of the Uranus 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 time half the light intensity of Uranus.

Arranging for the reuse of the Parkes antenna was relatively straightforward, 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 radio road tracks. This facility is normally used for radio astronomy. A number of modifications to the VLA were made to be used to detect the VLA. New X-band receivers, low noise amplifiers, and a correlator were added. A satellite communication 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 and combined it with the signal received from the VLA. It was also necessary to add the needed equipment anti training to convert the VLA from the research type facility to a highly reliable operational facility for the several months of signifcant Voyager support. The VLA provided a capability of more than 21/2 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, Voyager 2 was targeted to pass only 4900 km above the
cloudtops. This close approach to the planet also owed Voyager's trajectory to be bent sharply as it passed over the planet, to assure an acceptable close flyby of Triton. The navigation team was congratulated for achieving an aimpoint 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 until 2014. 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 encyclopedias of the outer planets. Some of the high level results are listed below.

<table>
<thead>
<tr>
<th>Planet</th>
<th>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.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jupiter</td>
<td></td>
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<tr>
<td>Saturn</td>
<td>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.</td>
</tr>
<tr>
<td>Uranus</td>
<td>Skewed magnetic field relative to rotation axis; Unusual surface features on the larger moons; Significant numbers of rings.</td>
</tr>
<tr>
<td>Neptune</td>
<td>High speed winds; Cyclonic storms in the atmosphere; Tenuous rings; Weak magnetospheric activity; Volcanism on Triton; Nitrogen frost on Triton.</td>
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</tbody>
</table>

**Current Missions**

The planetary missions that are current, by being supported, include Magellan in orbit at Venus and Galileo enroute to Jupiter. By the time this paper is presented, the Magellan spacecraft will have entered the Venus atmosphere and be 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 kbit 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 the concept of aerobraking as a means of trajectory or orbit adjustment. The aerobraking technique allows the atmosphere of a planet to slow the spacecraft sufficiently to modify the flight path without a significant expenditure of on-board propulsion. The successful application of this technique may have significant positive impact on future missions in terms of weight tradeoffs between propulsion and instruments.

The Galileo spacecraft includes an orbiter and an atmosphere 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) 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 VOI at Jovian - 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 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 expand and refine the knowledge gained during the early Cassini missions.

To prepare for the Cassini Mission and to replace the aging 34 meter antennas, NASA is planning a new series of 34 meter Beam Waveguide Antennas at the current location.
In addition, a new digital receiver is being annealed.

Mars Global Surveyor - This mission, scheduled for launch in 1996, is intended to be the first of a series of low cost orbiters andlanders 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 missions on design studies are being conducted to determine the feasibility of sending a pair of small space craft 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 have yielded an enormous amount of data and knowledge about the planets and our solar system. The overall goal of the United States' civilian space program throughout the three decades of NASA's existence, has been the understanding of the birth and evolution of our planetary system (achieved by fast flybys), 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 significant 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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