A Technology Program That Rescues Spacecraft

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Abstract—There has never been a long-duration deep space mission that did not have unexpected problems during operations.

JPL's Interplanetary Network Directorate (IND) Technology Program was created to develop new and improved methods of communication, navigation, and operations. A side benefit of the program is that it maintains a cadre of human talent and experimental systems that can be brought to bear on unexpected problems that may occur during mission operations.

Solutions fall into four categories: applying new technology during operations to enhance science performance, developing new operational strategies, providing domain experts to help find solutions, and providing special facilities to trouble-shoot problems. These are illustrated here using five specific examples of spacecraft anomalies that have been solved using, at least in part, expertise or facilities from the IND Technology Program: Mariner 10, Voyager, Galileo, SOHO, and Cassini/Huygens.

In this era of careful cost management, and emphasis on returns-on-investment, it is important to recognize this crucial additional benefit from such technology program investments.

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1. INTRODUCTION

Deep space exploration is a complex and risky business. In fact, there has never been a long-duration deep space mission that did not have to solve unexpected problems encountered during operations. These unexpected events can be positive or negative. They include serendipitous scientific discoveries, degradations in system performance due to environmental effects, and failures of either spacecraft or ground system components.

The Jet Propulsion Laboratory (JPL) Interplanetary Network Directorate's (IND) Technology Program was put in place to develop new and improved technologies and methods of communication, navigation, and operations for NASA's deep space missions. The program can be traced back to 1959 when it was part of the Deep Space Instrumentation Facility (DSIF) operating plan. Later, after the Deep Space Network (DSN) was formally chartered in 1963, the program became the DSN Advanced Systems Program. Although the Program has had several names over its lifetime, the authors will refer to it as the IND Technology Program in this paper.

The IND Technology Program has been extremely successful in its main goals. It has increased communication performance from deep space by some eight orders of magnitude (between Pioneer IV and the present, there have been more than 11 orders of magnitude improvement with at least eight of those orders attributable to the IND Technology Program), improved angular tracking accuracy by six orders of magnitude [1], and enabled significant overall cost reductions in the DSN. Nearly all the systems used in both the DSN and in the communications portions of NASA's deep space missions can trace their heritage to the IND Technology Program.

The IND Technology Program has another, equally important, purpose that is less well recognized. It maintains a cadre of both human talent and experimental systems that can be brought to bear on unexpected spacecraft problems.

Solutions to spacecraft challenges during operations fall into four main categories – all of which have been supported by this technology program: applying new technology during operations to enhance science performance (could be on the spacecraft, on the ground, or both), developing new operational strategies (together with the mission team), providing domain experts to mission teams to help diagnose problems and find the best solutions, and providing special facilities to trouble-shoot problems.

In the following sections, we will examine five specific cases where the IND Technology Program was instrumental in solving such unexpected spacecraft problems. In some cases, the Program's influence was directly responsible for recovering from catastrophic spacecraft events and allowing the missions to complete much of their scientific objectives.

2. Mariner 10

Mariner 10 was launched in late 1973 and visited Venus and Mercury (it is sometimes called "Mariner Venus Mercury 73" or "MVM 73.") It became the first spacecraft to use the *gravity assist* technique when it used the pull of Venus to bend its trajectory toward Mercury.

Mariner 10 was also the first deep space mission to transmit full resolution images in real time from planetary distances. The spacecraft imaging system allowed transmission at only two data rates: 117.6 kbps and 22.05 kbps. The higher rate allowed real time image transmission, while the lower rate required images to be stored on the spacecraft's tape recorder for transmission later. These rates were chosen to provide good performance at Venus and Mercury distances respectively. In June of 1973 the Mariner project asked the DSN to investigate methods for using the higher data rate at Mercury. This would allow real time image transmission from that planet as well.

The DSN proposed using a new ultra-low-noise maser amplifier (ULNA) with an input noise temperature of 2.1 K on their 64m antenna in Canberra, Australia – which would be used for receiving the images from Mercury. In addition, the technology program proposed building an "ultracone" with a specially designed feed that would result in an overall operating system noise temperature of only 12.5K at zenith [2]. The Mariner project accepted the proposal, to be accomplished on a best-effort basis.

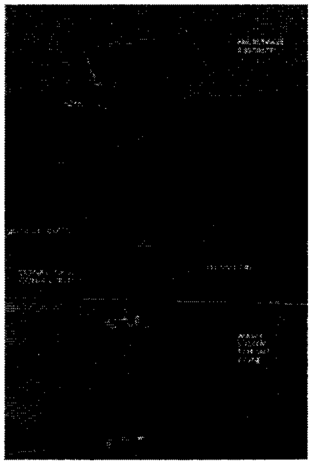

Figure 1 – S-band ultra-low-noise maser and feed under test

Unfortunately, just seven weeks after launch, the spacecraft antenna feed experienced a problem [3] that resulted in a 3 dB degradation in radiated power and changed the transmitted signal polarization from circular to linear, resulting in the loss of 3 more dB. The spacecraft communication system was now operating 6 dB below expectation.

In response to a request from the Mariner 10 Project Office, the DSN implemented special equipment at each of the three 64m antennas to receive the linear polarized signals. This recovered 3 dB of the loss. This improvement was sufficient to assure a successful Venus encounter.

The ultracone was then implemented at the 64m antenna in Canberra, which would be the principal receive site for the Mercury encounter.

With some exceptional luck (which the authors cannot attribute to the technology program) the spacecraft antenna problem corrected itself just 25 days before arriving at Mercury! Hence, the improved DSN system allowed the encounter to proceed at the 117.6 kbps data rate. The DSN and Project did some emergency replanning and the Mercury encounter was a complete success. Full resolution images of Mercury were transmitted in real time. Other images were recorded for subsequent transmission to Earth. The IND Technology Program efforts were directly responsible for the ability to receive the real time, full resolution images.

Because of the mission's success, NASA approved an extended mission to encounter Mercury two more times. However, between this time and the second Mercury encounter, the spacecraft's tape recorder failed [4]. With no ability to store images for later transmission, the success of the extended Mariner 10 mission rested solely with the improvements from the technology program.

The second encounter was also completely successful. For this encounter, the IND Technology Program was responsible for a five-fold increase in science data return.

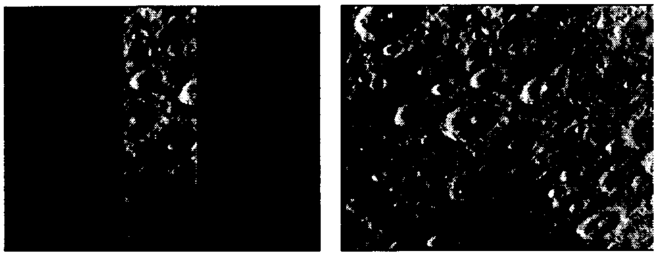

Figure 2 – A comparison of (left) mercury images that would have been returned to Earth after the spacecraft tape recorder failed and (right) the performance actually achieved using communication system improvements from the technology program

Unfortunately, the spacecraft antenna problem reoccurred just before the third Mercury encounter so that only the middle quarter of each image could be sent to Earth.

This example illustrates two mechanisms by which the IND Technology Program aided a mission in trouble. First, specialized systems (in particular the low-noise maser) that had already been developed were brought to bear. Second, new technology (in the form of the ultracone) was applied during operations.

3. VOYAGER

Most of us today recognize the Voyager 1 and 2 spacecraft as two of NASA's most successful explorers of the solar system and the fringes of interstellar space. When they were launched in 1977, however, their prime mission was to explore no further than the planet Saturn [5]. Luckily, their design did not preclude them from traveling on past Saturn.

Once the Saturn mission was complete, NASA approved the extension of the Voyager mission to Uranus and Neptune. This was good news for the science and the public, but it also presented a major challenge for the DSN to continue to support communications at these much greater distances.

Uranus is, on average, about 19 Astronomical Units (AUs) from Earth while Saturn is only about 9.5 AUs away (1 AU ≈ 150 million km). Hence the communications system for the Voyager spacecraft would have to improve by approximately 6 dB.

The additional 6.0 dB would have to be achieved through a combination of brute force techniques (e.g. increasing effective reception antenna area) and careful application of new technology developed in the IND Technology Program.

A new set of High Efficiency (HEF) 34m antennas was constructed by the DSN prior to the first Voyager encounter with Uranus. These were arrayed at baseband with the existing 64m DSN antennas and the 64m Commonwealth Scientific and Industrial Research Organisation (CSIRO) antenna at Parkes, Australia, to support the encounter. The algorithms for doing this were developed in the IND Technology Program [6]. It was originally thought that the radio signals would have to be combined before they were demodulated. However, research in the technology program proved that the signals could be combined at baseband with a tolerable performance loss. This system was much simpler to build and operate.

Before launch, a (255, 223) Reed-Solomon encoder was placed on the spacecraft to enable an additional 1.5 dB of performance over baseline coding system. However, when the Voyagers launched, there was no decoder for this code on Earth that could work fast enough to keep up with the Voyager signal. The technology program developed this decoder so that it was ready to receive data well before Voyager encountered Uranus. This gain was in addition to the data rate increase mentioned above.

The largest antennas in the DSN at the time of the Uranus encounter were 64m in diameter. The DSN rebuilt these into 70m antennas before the Neptune encounter. Rather than simply building bigger dishes, the DSN implemented a set of *shaped reflectors* (the main dish and the subreflector). The design for the shaped reflectors came from the IND Technology Program and it both improved the efficiency of the antennas and reduced the noise temperature [7]. The overall effect was a gain of about 2.0 dB (1.2 dB from the shaping.)

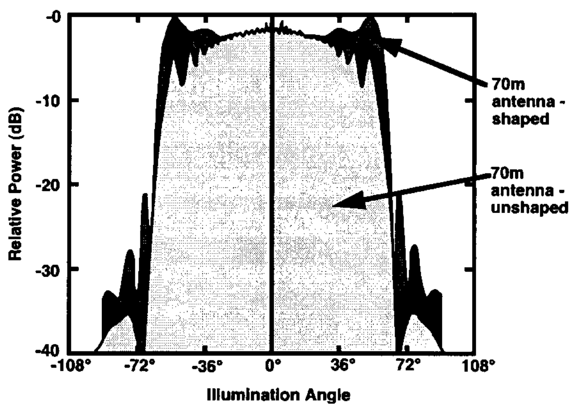

Figure 3 – 70m antenna energy distribution for shaped and unshaped reflectors

In addition to enlarging DSN antennas, many more antennas were arrayed in real time to provide an effective collecting area nearly equal to the sum of the individual dishes. The baseband arraying developed for the Uranus encounter was expanded to use additional antennas.

Many non-DSN antennas were used to support the Voyager Neptune encounter. One of these was the National Radio Astronomy Observatory's (NRAO) Very Large Array (VLA.) The VLA is a set of 27 antennas that are phased as a single large aperture. At the time these encounters, this phasing was accomplished by sending a periodic calibration signal to all the antennas. Whenever this signal was sent, the incoming telemetry from Voyager would be corrupted for a short time. Analysis from the technology program showed that the communications system could tolerate these outages as long as enough other antennas were used in the combining [8].

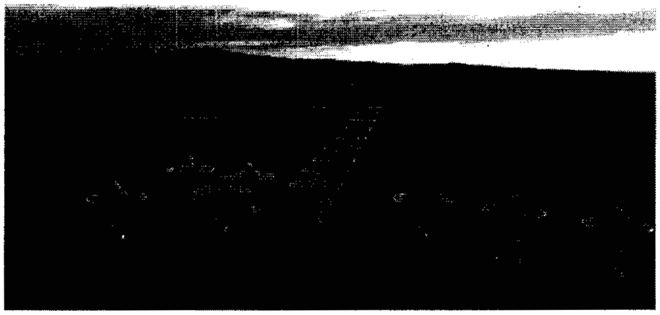

Figure 4 – The National Radio Astronomy Observatory's Very Large Array

The VLA was, at the time, not equipped to receive the X-band (8.4 GHz) telemetry signal from Voyager. High Electron Mobility Transistor (HEMT) amplifiers, based on prototypes developed jointly with NRAO and the IND Technology Program [9], were added to the VLA. In addition to supporting Voyager's Neptune encounter, these HEMTs enabled a new science capability at the VLA.

The Voyager mission's encounters with Uranus and Neptune were made possible, at least in part, through the introduction of new technology solutions developed in the IND Technology Program during operations.

4. Galileo

In the case of the Galileo mission to Jupiter, the technology program actually played a critical role in two phases.

After the launch delay caused by the destruction of the Columbia shuttle and subsequent investigation, the revised Galileo trajectory resulted in an arrival at Jupiter that was about 1.5 AU farther from Earth than originally planned. This, together with the fact that Galileo's Plutonium power source was several years more depleted, was going to result in a decreased data return from Galileo's only planned encounter with the Jupiter moon Io.

The Galileo project asked the IND Technology Program to develop a new error correcting code for inclusion on the spacecraft. The result was a (15, 1/4) convolutional encoder [10]. The prototype encoder was delivered to the Galileo project and a flight version was installed on the spacecraft before launch. It took the next two years for the technology program to develop a decoder for this code that could work at required data rates.

When the Galileo project commanded the spacecraft to deploy its high gain antenna (HGA), the prototype DSN decoder was ready for its initial testing (which was coupled to the use of the HGA through hardware on the spacecraft.) Unfortunately, the HGA did not deploy.

Figure 5 – Artist's conception of the Galileo spacecraft with the failed high gain antenna

Without an HGA, and if nothing else were done, the data rate from Jupiter would be about 10 bps rather than the planned 134 kbps. The same team that had been working on the (15, 1/4) decoder began immediately thinking of solutions to the HGA anomaly. This lead to a quick study conducted by the IND Technology Program office. The study showed that it was feasible, through extensive reprogramming of Galileo and an ambitious upgrade of the DSN, to increase the effective data rate to about 1 kbps, a 20 dB improvement!

This was followed by a joint study involving the Galileo project and members from the technology program. The resulting report outlined a design that would gain this 20 dB for an affordable cost, and achieve some 70% of the science objectives of the mission.

Among the solutions that came directly out of the technology program and used on the spacecraft were: an integer cosine transform (ICT) compression algorithm to achieve image compression ratios up to 20:1 [11], a (15, 1/4) convolutional code that made use of the hardwired (7, 1/2) encoder in series [12], a variable redundancy Reed-Solomon code, and a packet telemetry system.

Some of the solutions from the program that were implemented on the ground were: An updated version of the ultracone system, full spectrum combining of signals from multiple ground antennas [13], and a specialized demodulator that can work both forward and backward in time.

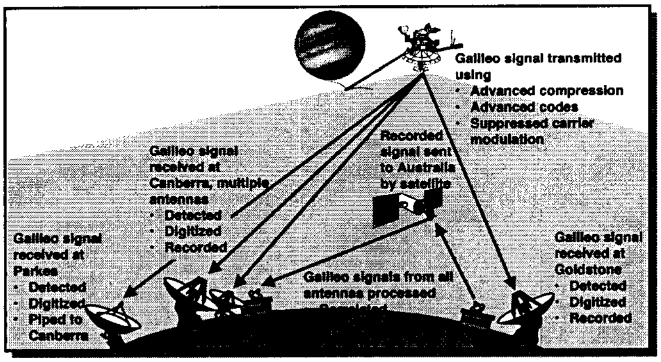

Figure 6 – Galileo communications system

The technology program was directly responsible for rescuing the Galileo mission. This was accomplished through the use of experts from the program and the insertion of new technology from the program, both on the ground and on the spacecraft.

5. SOHO

The Solar and Heliospheric Observatory (SOHO) is a joint mission of NASA and the European Space Agency (ESA.) The SOHO spacecraft was launched in December of 1995 and it travels in a highly elliptical Earth orbit. Since its orbit frequently takes SOHO well beyond the range of standard Earth tracking stations, the DSN uses its 26m antennas to track SOHO.

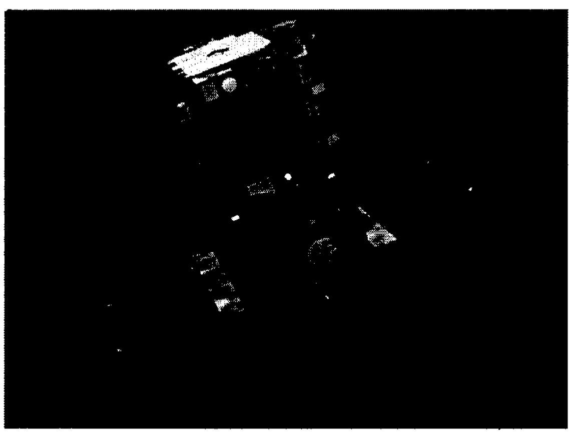

Figure 7 – The SOHO spacecraft

In June of 1998, one of SOHO's gyroscopes shut down during a routine maintenance procedure. This put SOHO into a spin and resulted in a loss of communications with Earth.

The IND Technology Program used its research and development antenna, Deep Space Station 13 (DSS-13) together with a high bandwidth and high-resolution spectrum analyzer it had developed to search for the SOHO spacecraft. In addition, the Goldstone Solar System Radar (GSSR) attempted to detect the spacecraft by transmitting a signal at 2.4 GHz and receiving echoes at the National Astronomy and Ionosphere Center (NAIC) antenna at Aericibo. Much of the technology in the GSSR has roots in the IND Technology Program.

The SOHO spacecraft was located using these techniques. Once it was found, the GSSR used a high-resolution signal at X-band to determine SOHO was rotating with a period of between one and two minutes.

This was enough information to reestablish communications between the DSN and SOHO. SOHO engineers were then able to slow the spacecraft's spin and recharge its batteries. The mission achieved a full recovery.

This is an example of using specialized facilities from the IND Technology Program to diagnose spacecraft problems and aid in their resolution.

6. Cassini/Huygens

The Cassini mission to Saturn carries the European Space Agency's (ESA's) Huygens probe, which will be released shortly before an encounter with Saturn's moon, Titan, in July 2004. As it parachutes towards Titan's surface, Huygens will acquire scientific information that will be relayed to Earth through Cassini. Comprehensive testing of this relay radio link was not performed prior to Cassini launch and cannot be done during cruise. A test using NASA's Deep Space Network (DSN) to mimic the probe's signal was performed in 2000 and uncovered an anomaly that, if unchecked, would result in nearly complete loss of the Huygens mission.

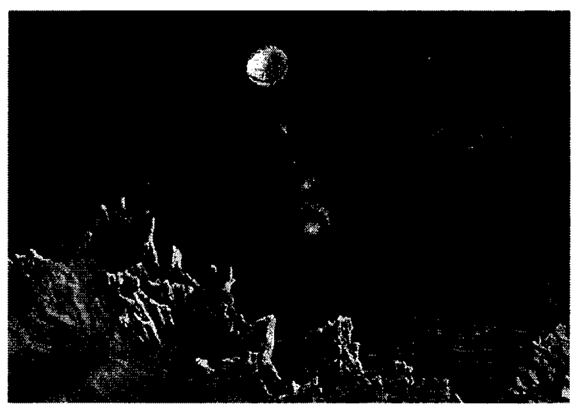

Figure 8 – Artist's conception of the Huygen's probe descending toward the surface of Titan

A NASA/ESA investigation analyzed the situation and concluded that several key parameters in the Cassini relay radio were in error, causing the radio to continually lose lock on the modulated signal under Doppler conditions that would be typical of the actual probe mission.

The IND Technology Program supplied several domain experts in communication systems to a joint NASA/ESA

Huygens Recovery Task Force (HRTF.) This task force performed additional tests, interviewed experts from the radio design team, and considered a host of possible solutions.

The HRTF recommended that the trajectory of Cassini be changed so as to carefully control the Doppler during the probe mission. In addition, several improvements in both onboard data management and ground decoding algorithms were identified that would further insure the integrity of the received data [14]. The Cassini project has adopted these recommendations and the implementation is now underway.

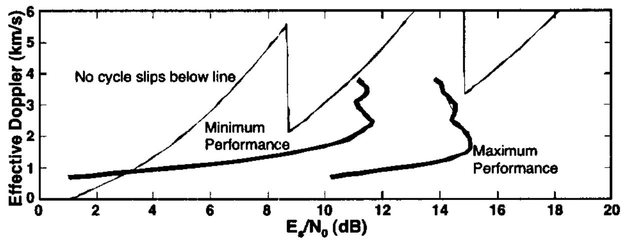

Figure 9 – Expected Huygens Doppler trajectory (bounds) showing regions where cycle slipping is predicted

This is an example of the technology program helping a mission to solve its problems by supplying expertise in the form of researchers who understand the latest technology.

7. CONCLUSIONS

We have examined five examples of instances where the IND Technology Program has aided in the resolution of serious spacecraft anomalies. In some cases (such as Galileo) the Program was responsible for saving the major science objectives of the mission. In others (such as Mariner 10 and Voyager) the Program was responsible for extending the useful life of the mission.

All four mechanisms for helping resolve such problems have been exhibited: applying new technology during operations to enhance science performance (Mariner 10 and Voyager), developing new operational strategies (Voyager and Galileo), providing domain experts to mission teams to help find the best solutions (Galileo and Cassini/Huygens), and providing special facilities to trouble-shoot problems (SOHO.)

The IND Technology Program has been in existence (under various names) since 1959. The program funding built up over the initial years and reached a sustained level of about \$30M/year (when inflated to FY03 Dollars), although the support level has fallen drastically in the past 10 years. Since the Program's inception, the integrated 45-year NASA investment (again scaled to FY03 dollars) is estimated to be on the order of \$600M. The program has paid for itself many times over in increased performance and reduced cost for the DSN through its normal technology development accomplishments. In addition, as shown here, the IND Technology Program has directly contributed to the resolution of serious problems on at least five missions, some of which may have resulted in total losses without this assistance. The worth of the recovered science is not easy to calculate – but it is clearly measured in billions of dollars in mission costs.

In this new era of extreme cost-consciousness, it is imperative that we compute the complete worth of our technology investments – which includes taking into account the inherent ability of these programs to solve critical mission problems during operations.

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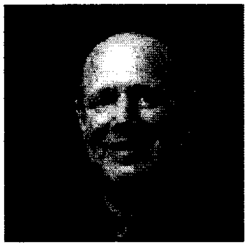

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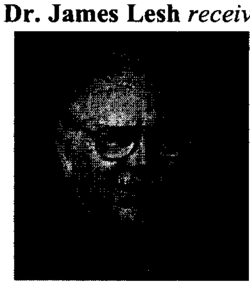

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He is a Fellow of the IEEE, a Fellow of the SPIE, a Charter Member of International Laser Communications Society, Co-chairman of the Government Lasercom Caucus, and the former Editor-in-Chief of the IEEE Transactions on Communications. He has three patents, over 120 publications, and 25 NASA Certificates of Recognition.