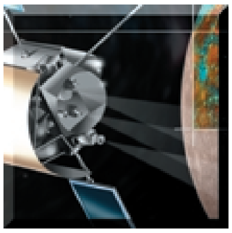

Mission Operations

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Space mission operations have evolved over the years as both spacecraft and ground system technology have matured. APL has been at the forefront of the U.S. space program since its inception in the late 1950s, and, therefore, has been a driver in developing and implementing space technology. From the early days of handheld ground antennas tracking Sputnik to today's automated, Web-based mission control centers, APL has helped pioneer that progress. The capabilities of both the spacecraft and ground systems have increased so much that we are able to collect significantly more science data and to control military operational satellites with greatly reduced staff, which lowers the overall program costs. This article examines how mission operations are handled at APL, with an emphasis on how the technology and processes have evolved. We also glance at the future to predict how further technology development will affect the way APL operates future missions. (Keywords: Autonomous operations, Mission operations, Spacecraft ground systems, Spacecraft operations.)

INTRODUCTION

The traditional philosophy developed in the early days of the space business was to build as simple a spacecraft as possible and put as much of the mission complexity in the ground system where humans had direct access, control, and the ability to fix things. This philosophy stemmed from the immature state of space technology and its inherent risk, the cost of implementing new space technology, launch costs, and launch risk despite the relatively lower costs of building the complexity into the ground systems. However, this paradigm has changed. Most functions have migrated to the spacecraft, thereby reducing the number of ground operators significantly. NASA programs such as Cassini and the Near Earth Asteroid Rendezvous (NEAR) are good examples of this contrast. Cassini literally has hundreds of people on the mission operations team, whereas NEAR had only seven people during the cruise phase. The number of personnel for NEAR increased to 20 during the orbital phase at the asteroid Eros.

APL has been involved in many spacecraft operations throughout the history of the space program, as shown in Fig. 1. The evolution of some of the major technologies incorporated is also shown.

One major change over the years has been the inclusion of the mission operations personnel at the concept of operations phase of the program. Concurrent engineering, with the mission operations engineer as part of the mission design team, allows life cycle trade-offs to be

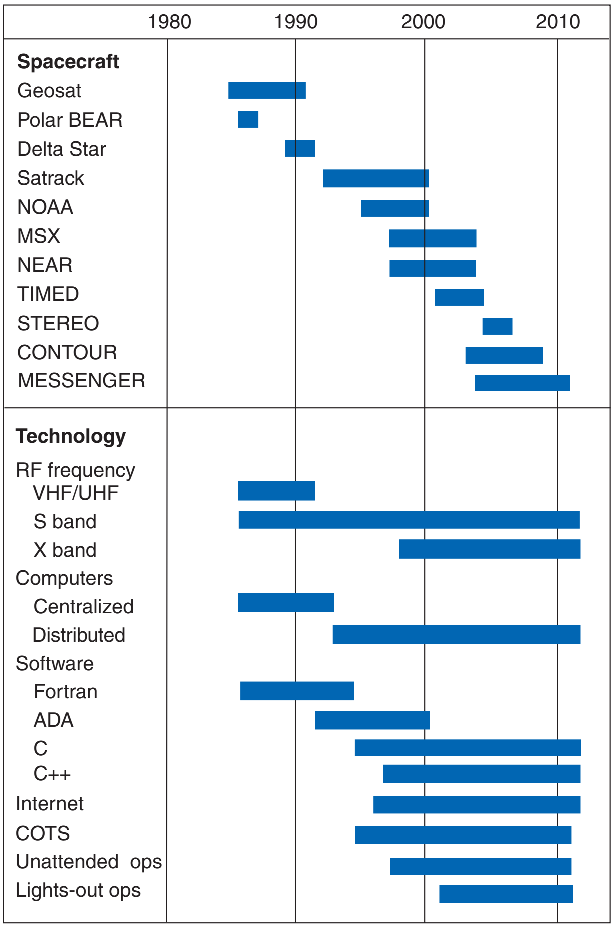


Figure 1. APL spacecraft operations, past and present, and the technologies incorporated.

made between the mission design and the operations concept as well as the spacecraft and ground systems. The operations team is also able to influence the design of the spacecraft and instruments for operability. The result is an optimized minimum cost for the overall program.

Levels of autonomy (some very sophisticated) are now implemented on APL spacecraft. However, much greater levels will continue to be developed to replace many routine ground operations. Automated planning and scheduling tools are being developed for ground use that will eventually migrate to the spacecraft. Event-based commanding, a subset of an automated planning and scheduling system, is already being implemented onboard the Thermosphere-Ionosphere-Mesosphere Energetics and Dynamics (TIMED) spacecraft. Autonomy has already made the greatest inroads in the real-time control and assessment phases of operations. Continued development here will result in what is called “lights-out operation,” where contact with the spacecraft is made in an unmanned control center, yet real-time performance assessment is still conducted. The NEAR Program is already making unattended Deep Space Network contact, the National Oceanic and Atmospheric Agency Program makes approximately 14 unattended contacts per day, and the TIMED Program is designed to do both nighttime and weekend tracks unattended. Future programs will implement concepts where the spacecraft will “take care” of itself and contact the ground when it needs to be serviced, either for reasons of health or for science data dumps.

Greater levels of spacecraft autonomy will ease the load of ground operators so that they can take on multiple spacecraft. However, both spacecraft and ground systems must be standardized. The Consultative Committee for Space Data Systems, a standards committee representing many organizations, has taken us a long way there by defining data interface standards. However, deeper levels of standardization on the spacecraft and ground systems are needed to fully realize the multimission operations environment.

Also, higher levels of autonomy will enable the ground operators to work at a much higher level of abstraction, where they are dealing with spacecraft and instrument functions as opposed to minute details at the bit level. This level of abstraction will allow the operators to control many different spacecraft since the very complex bit-level differences can be transparent. For operators to work at this level requires a robust spacecraft safing system and the close and immediate availability of the spacecraft engineering team, both of which are readily available to APL.

Although APL traditionally has had relatively small mission operations teams compared with other organizations, we continue to reduce required team size through spacecraft automation. APL has been a leader in applications of spacecraft autonomy since the late 1980s. The Midcourse Space Experiment (MSX) and NEAR have incorporated onboard rule- and model-based reasoning. Along with more onboard autonomy come fewer requirements for ground intervention as the spacecraft takes responsibility for its own health and safety. The result is a smaller mission operations team.

For decoupled instrument operations, which are being implemented on TIMED and are planned for the Solar-Terrestrial Relations Observatory (STEREO), all the instrument commanding responsibilities are delegated to instrument and science teams. With the more sophisticated tools, the tasks of science analysis, instrument configuration, and commanding are becoming amorphous. Scientists can thus work more closely with instrument operations personnel without the need for large instrument operations and mission operations teams to support them. Future work will extend this model to the point where instruments can be a node on the Internet, and the Mission Operations System (people, processes, and ground systems needed to perform the mission operations function) will become totally transparent to the scientist.

Overcoming new challenges in the operations world of the future will permit the space community to provide more capable and complex missions at a lower cost. The bottom line, in our case, is a much greater return of scientific data to our research customers.

Mission operations have traditionally been separated into three functions: planning, control, and assessment (Fig. 2). In this article, we will explore further details about each of these functions. We will also examine the ground system that provides the mission operations teams with the tools needed to perform their functions. These systems have evolved significantly over the years, riding on the explosion of new capabilities in the computer and networking industry. This trend is guaranteed to continue with further advancements in information technology. The explosion of the commercial space business is driving the startup of many small commercial off-the-shelf (COTS) ground system suppliers, and will continue to provide systems with ever-increasing capabilities at lower costs and quicker availability.

The final section discusses testing and training issues. Good test programs are essential for successful on-orbit operations, especially when lifetime is limited, as was the case for the MSX cryogen phase. Future systems, with their greater complexity, higher levels of autonomy, and reduced operations staff, will require commensurately more complex test programs. The implementation of a new industry trend of combining integration and test (I&T) and mission operations teams and their use of a single ground system is also discussed.[1] The use of a single ground system requires the implementation of remote testing. Cost savings are achieved in several ways from this integration: (1) only a single ground system is purchased, (2) smaller teams are required for I&T and mission operations, and (3) fewer staff travel to field test and launch sites. Also, getting the mission operations team involved in I&T provides valuable spacecraft training that would be difficult to do any other way.

MISSION OPERATIONS FUNCTIONS

Planning and Scheduling

Planning and scheduling within mission operations refers to the process of evaluating which future activities should be conducted on a mission over a particular time period. Activities include both spacecraft housekeeping functions and instrument payload activities. The planning and scheduling process required for APL missions has evolved considerably. Today, planning for missions often involves linking people and software that are geographically dispersed all over the country and the world. Using the Internet has become a key facilitator in this process.

In general, APL missions have become more sophisticated, with multiple instruments and increased onboard capabilities. As a result, the number and complexity of activities planned have increased significantly. Housekeeping activities typically include orbital maneuvers, spacecraft data recorder management, reconfigurations of RF and other subsystems for real-time ground contacts, flight software loads and data structure management, and attitude maneuvers.

Payload activities depend on the type of instruments being flown, and both have been diverse in nature. For Geosat, a typical payload activity placed the radar altimeter (the sole instrument on Geosat) in calibration mode and then back into its normal operating mode. This change in mode was accomplished with only a few commands. Today, the number of possible combinations of configurations on MSX's Ultraviolet and Visible Imagers and Spectrographic Imagers (UVISI) suite of sensors ranges in the hundreds.[2] For NEAR,

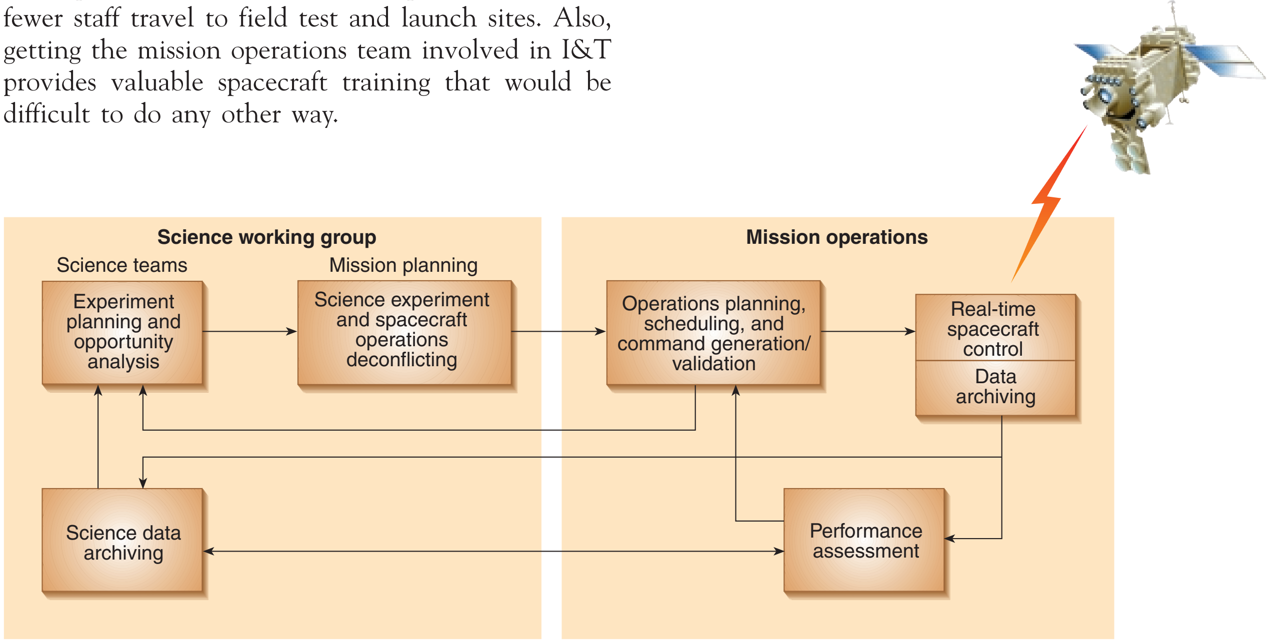


Figure 2. Concept of operations flow showing the planning, control, and assessment functions within the mission operations system. It also shows the close coupling of the mission operations teams with the science teams.

a typical activity is turning on the Multispectral Imager (MSI) to image a target. This activity is also linked with pointing the imager at the target, recording the imager data with onboard solid-state recorders, and then performing an attitude maneuver to point the satellite's high-gain antenna at Earth for transmission of the science data.[3] The difference between these examples is dramatic and typical of the evolution that has taken place from the days of Geosat instrument operations to modern-day NEAR and MSX operations.[4] Conducting the NEAR MSI and MSX UVISI activities requires planning and coordination of all supporting activities. Furthermore, safeguards must be taken to ensure adequate power availability and thermal control. Future projects like MESSENGER or Comet Nucleus Tour (CONTOUR) will simplify the planning of types of operations through increased onboard autonomy, event-driven commanding, and closed-loop controls.

Opportunity Analysis

Planning and scheduling can be divided into several stages, as shown in Fig. 2. The planning process starts with opportunity analysis, a process to determine how and when an instrument can support a data-gathering exercise, given the geometric and operational constraints of the instrument and spacecraft. For missions requiring the integration of payload and spacecraft operations, such as on the NEAR Project (left part of Fig. 2), the success of the instrument operations depends on spacecraft performance factors and the availability of resources. Interdependencies with pointing accuracy and stability, onboard data management, and onboard autonomy have made the planning process more complex for these types of missions. Sophisticated tools that model spacecraft behavior permit scientists to analyze new approaches before they are transmitted to mission operations. Such tools include software models of the spacecraft and orbital geometries. Conversely, the TIMED mission will permit instrument operations to be planned and conducted virtually independent of each other and of spacecraft housekeeping functions. Instrument teams are given individual allocations of onboard resources like recorder space and can control instrument operations independent of other ongoing activities, assuming they stay within these allotments. These allocations greatly streamline and simplify the process by reducing the simulation tools required for planning and the "horse trading" that often goes on to trade onboard resources for missions such as NEAR.

Whether we are talking about TIMED or NEAR, mission planning at APL has entered a new age compared to past missions like Geosat. Multiple concurrent instrument operations, precise 3-axis attitude control systems, and sophisticated onboard processing have added complexity to the planning process and, at the same time, put valuable science data unobtainable with past technologies in the hands of scientists.

Activity Request Generation

After a scientist or an engineer has designed an activity, it must be communicated to the spacecraft, which is the next step in the planning and scheduling process. Now scientists use their own systems or link with mission operations control (MOC) systems to generate their own command sequences. For the NEAR mission, a centralized method of control and command verification requires that all housekeeping and instrument commands be integrated at MOC and tested before being uplinked to the spacecraft. This centralization prevents oversubscribing of spacecraft resources shared among instruments. On the TIMED mission, instruments will be controlled independent of each other. Commands originate from the Instrument Flight Payload Operations Center and are transmitted electronically to MOC, which forwards them directly to the spacecraft. Spacecraft housekeeping commands are sent separately to TIMED without regard for the instrument commands passing through MOC.

Over the years, the trend has been to increase the level of abstraction of payload activities as viewed by the mission operations team. In the early years they did it all, developing both spacecraft and instrument command sequences together. For NEAR, the team still builds all spacecraft housekeeping activities and assists instrument teams in constructing canned activity sequences (CASs) that use the spacecraft housekeeping activities and also fold in instrument commands. The actual instantiation of these activities appears to mission operations as a steady stream of incoming CAS requests. The intimacy with the instrument commands slowly fades. On the TIMED mission, the level of abstraction will be much higher, with instrument teams developing command sequences and initiating them entirely on their own. They will be viewed as command packets flowing through the TIMED MOC and directly up to the spacecraft. Other than their origination and destination, little else will be known about the contents of the packets sent. This tendency to move away from a centralized control system to a distributed one puts the ability to operate instruments directly in the hands of the scientist and reduces the overhead associated with coordinating activities with other teams. Final results from the request generation process are now communicated from remotely located scientists to the spacecraft MOC System via the Internet, where commands are validated and transmitted to the spacecraft (Fig. 3).

Command Load and Validation

Before commands are uplinked to the spacecraft, they must be tested to verify proper execution within the operational limits of the spacecraft. Regardless of the type of mission, past or present, one constant is that all commands must pass through a MOC system, where the final validation of the commands is performed. As the number of commands has increased, so has the sophistication of techniques used to test them. In the past, command loads were limited to tens or hundreds of commands, each given a visual check by ground controllers. Today's command uplinks may include thousands of commands. Manual (visual) checks of the loads are no longer practical, owing not only to the sheer number of commands being sent but also to the indirect effects that commanding one system can have on another. Also, reduced operations budgets no longer permit "throwing more people at the problem."

Simulators and models now replace the mundane work once done by those who reviewed command loads. Command-load checking now goes beyond simple format and content and also includes system-level checking. An entire week's command loads are now run through a spacecraft software simulator for NEAR in a matter of minutes.[5] Passing all commands through copies of flight software before uplink now permits a thorough check of each command. Furthermore, models of subsystem performance can easily be appended to the software simulator to give even more information about the expected operation of a command load before uplink. For NEAR, predictions for vehicle attitude, RF system performance, and spacecraft system performance are produced as part of the command-load verification process. These predictions can be given to flight controllers to verify that the actual performance equals the expected performance during command execution in flight.

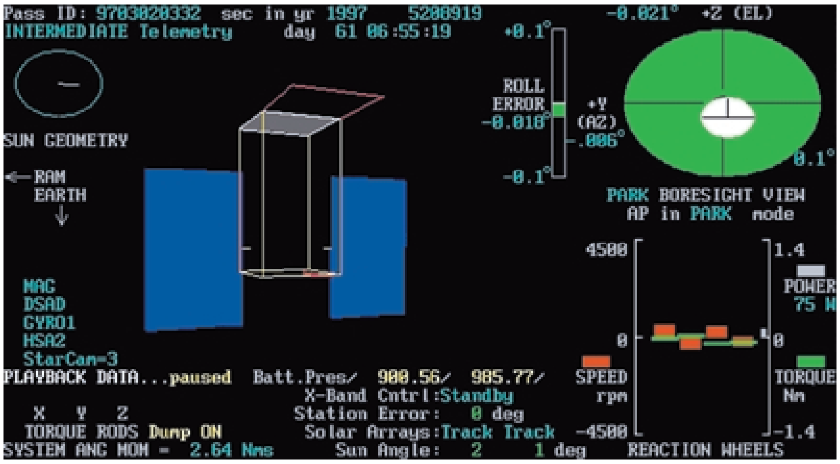
Control

The MOC function involves the interactions that take place during contact between the ground and the spacecraft. The control team, consisting of flight and ground controllers, occupies the Control Center. Here, housekeeping telemetry from the spacecraft is analyzed to assess its real-time state of health, and performance and uplink commands are generated to instruct the spacecraft to perform the desired activities.

Although many things have changed in the APL Control Center environment over the years, the range of excitement of real-time controllers analyzing real-time telemetry has remained constant. Whereas routine operations have always been the expected, nominal, and sometimes boring occurrence, anomalous conditions always raise adrenaline levels in all flight controllers, regardless of their experience. The technology has evolved to make the viewing of telemetry not only more user friendly but also quicker, easier, and more accurate. For example, taking the place of strip chart recorders, to indicate a voltage as the page sweeps under the needle are large heads-up displays showing green, yellow, and red indicators of every spacecraft subsystem and instrument in schematic fashion. A click of the mouse brings up more detailed information (Figs. 4 and 5). Also, in place of complicated plots indicating derived roll, pitch, and yaw are "stick" figures illustrating the spacecraft's attitude with respect to the Sun, Earth, and Moon, making real-time evaluation much more intuitive.

Furthermore, from the planning effort and the use of models, much more sophisticated information is available to real-time controllers regarding the expected state of the spacecraft. State simulators that include RF, recorder, attitude and power, and thermal modeling yield highly accurate real-time performance metrics. With sophisticated software tools that can quickly perform real-time analysis has come a reduction in the number of personnel required in the Control Center. The TIMED Program will even demonstrate "lights-out" operations where contact with the spacecraft is made without any personnel in the Control Center, yet real-time control and performance assessment is still conducted.

Figure 3. NEAR Mission Operations Center in the real-time control pit. The flight controller interfaces with a three-monitor display system to keep track of all operations.



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                        Station Error:   0 deg
TORQUE RODS Dump ON     Solar Arrays:Track Track
SYSTEM ANG MOM =  2.64 Nms   Sun Angle:   2     1 deg
PARK BORESIGHT VIEW
AP in PARK  mode
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Figure 4. MSX SeeMSX Attitude System graphical telemetry display, which allows a quick real-time assessment of the health and status of the spacecraft attitude control system. It also shows solar arrays properly aligned with the Sun.

Figure 5. MSX Mission Control Center showing the DataViews and SeeMSX overhead displays that enable very fast real-time assessment of the spacecraft's health. It allows flight controllers to quickly move from assessment to the command loads and tape recorder playbacks. Speed is critical in low-Earth-orbit missions where contacts only last about 10 min.

At the front end of the control function is the antenna used to receive telemetry and uplink commands. In the early days of the space program, APL spacecraft operations were conducted using relatively primitive antennas. For their earliest receipt of Sputnik signals, Guier and Weiffenbach used a 2-ft wire hanging from their 20-MHz receiver.[6] Operations that were initially limited to functional spacecraft checkout today include the continuous operation of spacecraft by a team of highly trained personnel working from an on-site control center. Future plans include automated spacecraft operations and automated operation of the ground station for contacting the spacecraft.

The ground station has evolved from one with a 60-ft antenna, minimal equipment, and with many personnel to review data to a suite of three antennas (Fig. 6), as well as a classified and unclassified Control Center capable of conducting operations without operators. All aspects of the ground station have progressed to a complex automated system that can conduct an unattended spacecraft contact.

Antenna operations, which originally required several operators to schedule and then operate an antenna that followed a "program track," now require only a few minutes of an operator's time to schedule a contact. Computers then follow the schedule and have the antenna autotrack the spacecraft RF signal. The Geosat mission, which began in 1985, used the 60-ft antenna that program tracked and a 5-m antenna that autotracked the Geosat downlink signal. The Satrack Program upgraded the 60-ft antenna to autotrack the launch of Trident missiles from Cape Canaveral to receive data for real-time delivery to the Satrack data-processing facility at APL. The MSX Program installed a 10-m antenna that can automatically conduct spacecraft contacts based on a daily schedule. The 10-m antenna has the ability to autotrack first on the wider beamwidth S band signal and then transition to the much narrower X band signal. The desire to obtain National Oceanic and Atmospheric Agency weather data without an operator setting up the 5-m antenna resulted in the installation of a control computer that schedules, configures, and conducts automated contacts. These features allow real-time weather data to be posted on a Web site maintained by APL that is accessible to the public.

Spacecraft initially designed by APL used very-high or ultra-high frequencies for command and telemetry. APL also designed both the command and telemetry streams. Although these unique designs provided a level of safety to the spacecraft that prohibited unauthorized users from either commanding the spacecraft or using the telemetry, they lacked standardized command and telemetry streams. The MSX Program used standard Air Force Space/Ground Link Subsystem (SGLS) command and telemetry designs. SGLS enabled MSX to be contacted via the Air Force Satellite

Figure 6. Collage of the APL 60-ft (left), 10-m (center top), 5-m (center bottom), and Deep Space Network 34-m (right) antennas. All are currently supporting APL mission operations. Not shown is an AFSCN network antenna, which is also being used to support MSX.

Control Network. It also allowed the APL Satellite Communication Facility (SCF) to communicate with any SGLS spacecraft. The MSX Program also added X-band telemetry capability for high-volume data transmission to the SCF. The TIMED Program has upgraded the 60-ft antenna to be fully compatible with Consultative Committee for Space Data Systems recommendations. This included adding NASA S-band commanding capability. These changes give the 60-ft antenna the ability to be used as a fully autonomous, shared services, multiuser ground station. Future enhancement will provide external users the ability to schedule contacts via the Internet.

Military programs like MSX require the routine use of encryption and decryption equipment. This capability safeguards data, as directed by the federal government. Whereas early programs such as Transit did not encrypt data, MSX encrypted both commands and telemetry. Encrypting a 25-MB telemetry stream presented a challenge. Therefore, special encryption devices were developed in conjunction with NSA that are now used daily for safeguarding science data from MSX. These encryption and decryption devices require "closed" areas for housing and operating.

Performance Assessment

The function of performance assessment involves analyzing the housekeeping telemetry from a spacecraft to determine whether it is operating in the desired manner, how well it is working, and what its state of health (present and long-term) is. Traditionally, there have been two types of spacecraft performance assessment: realtime and off-line. Real-time assessment involves viewing the spacecraft housekeeping telemetry in the Control Center and responding as necessary to the information provided, whether it is a routine operation or an anomalous condition. Real-time performance assessment is a major component of the control function and was discussed earlier in this article. Off-line spacecraft performance assessment deals with the short-term comparison of expected and actual operations and the long-term trends of spacecraft systems.

Off-line performance assessment has traditionally been conducted by several spacecraft engineers working outside the Control Center environment. These engineers analyze housekeeping data for long-term trends to detect and account for spacecraft aging characteristics before they become problems. Where this once involved the laborious task of drawing plots by hand 20 to 30 years ago, by the mid-1980s the first PCs were being used to provide simple graphs from a spreadsheet. However, just getting the data into the spreadsheet was difficult. It involved using "sneaker net" to deliver a tape to APL's McClure Computer Center and then waiting at the PC for the tape to be loaded so that the housekeeping telemetry points required for the analysis could be specified by the engineer via a telephone modem. Thereafter, data were imported into the spreadsheet. As PC capabilities grew, they became the engineer's analysis tool and were programmed by the users themselves to produce the desired output. Today, more COTS are used on much faster machines with large disk arrays to allow the engineers online access to any housekeeping telemetry point over the entire mission. A plot of an instrument's temperature over a 3-year mission could have taken weeks to obtain off tape backups in the mid-1980s, but in the mid-1990s it could be generated in a matter of minutes. In addition, the ground software now processes the data directly into a database, generates the required plots according to the time line, and prints them for quick analysis. In place of the hand-drawn plots from the early days of the space program are today's plots that include color with multiple y axes and three-dimensional versions conveying much more information for quicker, more thorough analysis.

As ground systems capabilities have increased over the years, spacecraft telemetry has become more sophisticated. Where once there were simply housekeeping telemetry channels with associated voltages, now there are mnemonic names with engineering units, data summary tables, command execution history buffers, and much more to analyze to determine the cause of a problem and help re-create an anomalous situation as it occurred onboard. A recent trend at APL is toward downlinking high-level status telemetry to indicate whether further analysis is required. Again, this places more requirements on the "smart spacecraft," which further reduces the size of the operations team.

Another function of off-line performance assessment is model validation. As prelaunch models have become more essential due to increasing spacecraft complexity, so has the postlaunch validation and update of these models. In these situations, the planned activities are used along with housekeeping telemetry to compare the modeled results with real data.

The responsibility of the off-line engineers is to act as resident spacecraft experts, on-call around the clock in case of spacecraft emergencies. In the past, the control team would page the off-line engineers. Now TIMED is implementing automated paging by the ground system during lights-out operations. A short message or code will be forwarded to indicate the problem, allowing the engineer to decide what is critical. APL mission operations teams have always had a distinct advantage over more traditional organizations, since the spacecraft engineering design team is at their disposal for emergencies.

TESTING AND TRAINING ISSUES

Test and Operation

APL has built and operated spacecraft since 1959. The APL SCF, or the Injection Station as it was called, was built along with APL's 60-ft satellite communications dish to test and verify the Transit satellite navigation system. The early satellite systems operated using analog uplink and downlink for communications.

Since then, APL has built ground systems to operate Geosat, MSX, NEAR, and TIMED. Each of these systems is different, yet they perform many of the same functions that are necessary to test and operate a spacecraft. The Laboratory has been at the forefront of the spacecraft industry as one of the first spacecraft developers to use the same computer systems for spacecraft I&T as well as mission operations. On all four of the spacecraft operated from APL, and one that is operated by NASA-Goddard Space Flight Center (the Advanced Composition Explorer),[7] the same system was used for I&T and mission operations.

Each of these systems provided the following features for the engineers to successfully test and operate the spacecraft:

- Telemetry data storage
- Telemetry data display
- Telemetry data conversion
- Telemetry limit checking and alarm notification
- Telemetry playback
- Telemetry database
- Command database
- Command parameter conversion
- Command scripting language
- Memory load, dump, and compare utilities
- Event logging
- Planning and scheduling

After the Transit Program in the mid-1960s, it was not until the Geosat Program in the mid-1980s that APL operated another spacecraft. Digital communications had become the mode of operation by then, and minicomputers were used to control Geosat during I&T and mission operations. A Systems Engineering Laboratories (SEL) real-time minicomputer was used to operate Geosat. The system software was written mostly in Fortran, with some assembly language for compactness and efficiency where necessary. To allow spacecraft testers and operators to control the spacecraft and display telemetry data, APL created a language called APLCOM (APL communications language). This language used a simple syntax that engineers could employ to write test programs and operational scripts. Operators used ASCII terminals to edit and execute scripts. These terminals were also used to display spacecraft telemetry one window at a time.

The core system was developed and used to test and verify the operation of the command, telemetry, and tape recorder subsystems. Then the system was enhanced to support spacecraft I&T. A separate system using similar computers but the same APLCOM language was prepared for use during mission operations. The SEL minicomputers were physically large systems and were housed in their own temperature- and humidity-controlled rooms the size of a very large walk-in closet. The operator terminals were in a separate room and were wired into the main SEL computers.

The next major satellite program to operate from APL SCF was MSX, which was launched in April 1996 and is still being operated from the facility. The spacecraft began development in the early 1990s. MSX is a Ballistic Missile Defense Organization mission and, along with other military development programs at that time, APL was directed to use the ADA programming language for all software development on the satellite program. Digital Equipment Corporation workstations running the VMS multi-user operating system were selected as the platform to test and operate the MSX spacecraft. The initial series of workstations, with black-and-white video monitors, were purchased before the current era of inexpensive color workstations. The black-and-white systems were selected to minimize the cost of the control system. The length of the MSX Program has allowed some of the computer systems originally used on MSX to be replaced by newer color workstations with more computing power.

The MSX control system was the first developed at APL to take advantage of multiwindow graphical user interfaces. The software was designed to be used on multiple missions with ASCII configuration files. The system allowed multiple data displays on the screen simultaneously. Telemetry could be automatically monitored for out-of-limit conditions, and data could be replayed through the system as if it were live. Several system utilities were developed, including a graphical display editor that allowed data displays to be created and edited easily.

The NEAR mission began at APL with a goal of launching the spacecraft a little over 2 years after beginning the program. This time frame meant that spacecraft integration would have to begin in 1.5 years. To meet that very ambitious schedule, APL for the first time chose to purchase a COTS product instead of developing a spacecraft control system in house. Following an extensive market survey, the EPOCH 2000 system from Integral Systems in Lanham, Maryland, was selected. By purchasing EPOCH 2000, the NEAR Project could immediately use the existing capabilities of the system to display data, perform limit checking, archive and replay data, and create automated command scripts.

The money spent on previous programs to develop a system from scratch was spent enhancing EPOCH 2000 to meet the specific needs of the NEAR mission. Several tools not included with the control system but needed by NEAR's mission operations team included memory load, dump and compare utilities; trend and health assessment utilities; planning and scheduling tools; and spacecraft time correlation utilities.

Hewlett-Packard workstations running HP-UX UNIX and DEC Alpha workstations were selected for use in the NEAR Mission Operations Center. Each system had a 21-in. color monitor. Color X-terminals were also integrated into the mission operations ground system to provide cost-effective user seats. In 1998, as the NEAR spacecraft approached the asteroid Eros for a rendezvous, its network was divided into a secure NEAR-Net and a more open Rear-Net that provides network access to system data and resources by those who need it.

The TIMED spacecraft is being developed at APL and is scheduled to launch in May 2000. Once again, EPOCH 2000 is being used as the core of the TIMED control center software system. However, on TIMED, in-house developed software has been designed to surround the EPOCH 2000 system to control the telemetry and command data streams. This system design, a part in-house–development and part COTS product, is intended to take advantage of the cost-effective COTS software for functions that are generic across spacecraft and allow in-house developers to customize software to meet the specific requirements of the TIMED mission. This approach limits the need to renegotiate contracts because of a change of scope, but allows for software changes under in-house control as the spacecraft system design evolves.

Similar to NEAR, TIMED uses color workstations and X-terminals. However, Sun Ultra SPARCstation workstations running Solaris UNIX are being used on TIMED. Just as MSX and NEAR used the same ground system for I&T and mission operations, TIMED is also using the same system for both phases of the mission. In fact, for the first time, the ground system was also used by three development teams for subsystem bench testing and flight qualification.[8,9] Also, like NEAR, an internal secure network was created to maintain the command integrity of the control system.

Validation

Mission operations testing validates the MOC System before launch to ensure its ability to support spacecraft on-orbit operations. Once the planning, control, and assessment functions are integrated together into the system, testing becomes necessary to verify proper operation. Mission operations testing is done through the use of simulators at various stages in program development. The process consists of stand-alone testing and also testing with the spacecraft.

Stand-alone testing consists of testing individual components and systems. Component testing involves database validation along with the testing of individual functions and tools within the planning, control, and assessment areas. System-level testing typically involves simulating operations for days and weeks at a time. Hardware and software simulators can be used in place of spacecraft components not available for mission operations testing. Historically, APL programs have not built spacecraft simulators during the system development phase. Instead, spacecraft telemetry recorded during I&T or simulated spacecraft telemetry would be played back as though it were being downlinked from the spacecraft in real time. Recent programs such as NEAR and TIMED have chosen to integrate the engineering model and breadboard units fabricated during spacecraft subsystem development to create a spacecraft on the ground. These hardware-in-the-loop simulators run in real time and provide a realistic test bed for system testing.

Mission operations testing with the spacecraft consists of commands generated from the MOC System, which originates from the Control Center and transmits through ground links to the spacecraft. These tests, called mission simulations, involve a "test it as you will fly it" approach. They characterize the performance of the spacecraft as it will be operated on orbit to the extent possible while still on the ground and simultaneously provide valuable training for the mission operations team. These mission simulations are run during spacecraft thermal-vacuum testing and provide realistic characterization of on-orbit performance.

In the past, spacecraft test time allocated to mission operations testing was minimal. On the last several spacecraft built at APL, more mission operations tests have been performed before launch, as the benefits of additional testing have recognized.[10] Before the TIMED mission, a separate mission operations team using a separate MOC system from that of the I&T team, was allowed a small amount of time to perform what amounted to compatibility tests with the spacecraft. In these cases, the Control Center would be allowed to execute a few commands on the spacecraft to verify that the commands were formatted, transferred, transmitted, received, and executed properly. On MSX, because of delays in the launch schedule, many mission simulation tests were performed. These operated the spacecraft as a system using dynamic simulators to make the tests as realistic as possible. The system-based simulation tests are different from sub-system functional and performance tests, where a unit is tested independent of other subsystems. It became apparent from the experience on MSX that mission simulation tests were beneficial in the testing of not only the MOC System but also the spacecraft itself. Several flight software bugs were uncovered during MSX mission simulation testing that had previously gone undetected because the spacecraft was operated differently than it had been in the standard I&T functional and performance tests. With mission operations teams becoming more integrated with the I&T team, TIMED is the first APL program to allocate time in its schedule for mission simulations to be run as part of spacecraft baseline performance testing.

Another industry trend in which APL has been a pacesetter involves combining I&T and mission operations teams. Although these teams were once separate and used separate systems, the TIMED Program (as well as future programs) uses one integrated team and one ground system. The same system used for I&T will also be used for postlaunch operations. This change is cost-effective since only one ground system is developed. Also, the total team size is smaller. The early involvement of mission operations personnel provides invaluable training for the team, as well as an early mechanism to influence the design of the spacecraft for enhanced operability.

Over the years, as spacecraft and missions have evolved into more complex systems, so have the simulators required to conduct realistic mission simulations. Simulators are needed to mimic what the sensors would detect on orbit to permit the closed-loop testing required to run mission simulations. On previous APL missions (MSX and NEAR), only attitude simulators were developed. TIMED, however, is building a “Ground-Sat” from subsystem engineering units. This simulator will facilitate spacecraft testing and act as a test bed for use by both I&T and mission operations teams for team training. Using the simulators and spacecraft, these teams will be able to validate operational procedures as well as verify proper operation of hardware and software. Mission Operations Control system testing with the spacecraft will also be used to validate the performance of the “Ground-Sat” used in the stand-alone system testing. This effort helps mission operations teams gain confidence in their system and further ready themselves and their system for postlaunch operations.

REFERENCES

[1] Harvey, R. J., and Huebschman, R. K., “Applied Physics Laboratory Integration and Test: Lessons Learned and Applied,” in *Proc. 18th Aerosp. Testing Seminar,* Manhattan Beach, CA pp. 455-463 (Mar 1999).

[2] Heffernan, K. J., Heiss, J. E., Boldt, J. D., Darlington, E. H., Peacock, K., et al., “The UVISI Instrument,” *Johns Hopkins APL Tech. Dig.* **17**(2), 198–214 (Apr 1996).

[3] Harch, A., and Heyler, G. A., “Design and Execution of the Asteroid Mathilde Flyby,” in *Proc. 3rd IAA Int. Conf. on Low-Cost Planetary Missions*, pp. 5-1–5-8 (Apr 1998).

[4] Nordeen, R. D., Barnes, V. B., Good, A. C., and Harvey, R. J., “The MSX Flight Operations System,” *Johns Hopkins APL Tech. Dig.* **17**(1), 102–116 (Jan 1996).

[5] Carr, P. D., and Kowal, C. T., “NEAR Cruise and Mathilde Flyby Mission Operations–Report from the Front Lines of Low Cost Missions,” in *Proc. 3rd IAA Int Conf. on Low-Cost Planet. Missions*, pp. 8-1–8-8 (Apr 1998).

[6] Guier, W. H., and Weiffenbach, G. C., “Genesis of Satellite Navigation,” *Johns Hopkins APL Tech. Dig.* **18** (2), 178–181 (Apr 1997).

[7] Rodberg, E. H., “The Ground Support System Used to Test the Advanced Composition Explorer Spacecraft,” in *Proc. 21st Int. Symp. on Space Tech. and Sci.*, Omiya, Japan (May 1998).

[8] Dove, W. C., and Mitnick, W. L., “The TIMED Mini-Moc and Beyond,” in *Proc. 21st Int. Symp. on Space Tech. Sci.,* Omiya, Japan (May 1998).

[9] Mitnick, W. L., “The TIMED Mini-Moc Grows Up: A Successful Strategy for Reducing the Cost of Spacecraft Testing and Operations,” in *Proc. 18th Aerosp. Testing Seminar,* Manhattan Beach, CA pp. 449–454 (Mar 1999).

[10] Harvey, R. J., “The Role of Mission Operations in Spacecraft Integration and Test,” in *Proc. 3rd Annual Symp. on Space Mission Operations and Ground Data Systems*, Part 1, pp. 361–369 (15–18 Nov 1994).

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