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COST EFFICIENT OPERATIONS FOR DISCOVERY CLASS MISSIONS

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ABSTRACT

The Near Earth Asteroid Rendezvous (NEAR) program at The Johns Hopkins University Applied Physics Laboratory is scheduled to launch the first spacecraft in NASA's Discovery program. The Discovery program is to promote low cost spacecraft design, development, and mission operations for planetary space missions. In this paper, the authors describe the NEAR mission and discuss the design and development of the NEAR Mission Operations System and the NEAR Ground System with an emphasis on those aspects of the design that are conducive to low-cost operations.

INTRODUCTION

NEAR will launch in February 1996 and rendezvous with the asteroid Eros in January 1999. The spacecraft is to orbit Eros for up to a year, mapping the asteroid and collecting data on its gravitational and magnetic fields as well as its elemental composition. Significant challenges are anticipated in NEAR mission operations. NEAR will be the first spacecraft to conduct orbital operations around a small, irregularly shaped planetary body. Stringent orbital plane restrictions are required to simultaneously maintain instrument fields of view of the asteroid, communications antenna coverage of the Earth, and illumination on the solar panels. During certain portions of the year of asteroid operations, orbital maneuvers may be required every three days to maintain the orbital plane. Given the irregular shape and size of the asteroid, simple nadir pointing mapping strategies will not be sufficient for conducting operations at Eros; a flexible planning strategy must be implemented to coordinate scientific priorities given limited observation opportunities. These scientific observations must be combined with routine subsystem maintenance, orbital maintenance, and navigation requirements. A sophisticated sequence planning system with quick reaction capability is required (priorities and orbital dynamics can be expected to change on a continuous basis, requiring constant adaptation of operations to mission science needs).

These considerations generally increase the cost of mission operations in an era when Mission Operations and Data Analysis (MO & DA) costs are being scrutinized as never before. If NEAR and future Discovery class missions are to succeed, they must set new standards for cost efficiency. The goal of this paper is to show how mission operations costs can be controlled by the application of advanced technologies and operations concepts.

Organization of Paper

Following the Abstract and Introduction, this paper begins with a discussion of low cost mission operations. This is followed by a description of the NEAR Mission Operations System (MOS) which highlights those elements of the system design that contribute to low cost mission operations. Following the MOS description is a section detailing the design of the NEAR Ground System (NGS), again, with an emphasis on the low cost operations aspects of the design. Finally, we provide a summary of our recommendations for implementing low cost mission operations on Discovery class missions.

LOW COST MISSION OPERATIONS

The MOS is often the last element of the program to be developed; as such, the MOS frequently must make up for gaps and problems that have developed in the mission, spacecraft, and instrument designs. The MOS is generally custom developed for each mission, which is decidedly non-optimal from a cost-effectiveness viewpoint.

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Mission Operations costs can be divided into two major categories: development costs (mostly pre-launch) and operations costs (mostly post-launch). In the following discussion, potential cost saving measures are introduced in each category.

System Development

System development costs are primarily pre-launch and are generally incurred late in the pre-launch program. If a program gets into budget problems late in the spacecraft development phase (this is not uncommon), mission operations development costs frequently attract the attention of the budgetary ax-wielder. Saving money in development costs at the expense of repetitive costs in the post-launch mission operations phase is not cost efficient over the mission life cycle, yet this trade is frequently made. In the following, several approaches to saving costs in MOS development are discussed which do not compromise either mission capability or total life cycle cost.

Existing Infrastructure

Always take advantage of existing infrastructure where cost efficient. If an existing voice communications system or ground station network will work for your mission, why re-invent the wheel? It should be noted that existing infrastructure is not always cost efficient. Maintenance or personnel costs associated with outdated systems can negate their advantage. Each element must be individually evaluated on the basis of cost-efficiency.

Commercial-Off-The-Shelf Systems

Examine Commercial Off-The-Shelf (COTS) hardware and software systems for applicability to your program, again, on a cost efficiency basis. COTS systems have shown a tremendous growth in capability in recent years; low-cost programs can get a lot of bang for the buck compared to the development costs of custom systems. There are two major shortcomings of COTS systems. First, "COTS" elements for space mission applications are not the shrink-wrapped products we have come to expect in the truly commercial (i.e., PC) marketplace; they lack the smooth polish of a mass market product (e.g., documentation, on-line technical support) and must frequently be customized for each application. Make certain that the costs of these modifications are considered in the total cost of a COTS system. Second, many functions that are necessary to operate a complex space mission are not found in the COTS offerings. Straight-forward Telemetry, Tracking, and Control (TT&C) operations for a commercial satellite (such as a communications satellite) are significantly different from operations for a planetary exploration mission with complex planning tasks and command sequence development. COTS products tend to be stronger in meeting the needs of commercial users than scientific mission planners.

Concurrent Engineering

Use modern concurrent engineering development techniques. Traditional approaches to system development (requirement definition, specification development, preliminary and detailed design, fabrication, and test) are slow, cumbersome, and costly. Modern methods of system development such as concurrent engineering and rapid prototyping can be faster and cheaper. There are risks in this approach, however, the benefits generally outweigh these risks. For Discovery programs, higher risks must be tolerated to achieve the avowed goals of faster, better, and cheaper.

Design for Operability

Design the spacecraft and Mission Operations System for operability. Too often, flexibility and operability are relegated to the ground system and mission operations team to save development costs in the spacecraft. While this is an understandable approach (complexity vs. reliability tradeoffs in the spacecraft favor simplicity), this may not be the optimal approach. In some cases, relatively minor changes in spacecraft or instrument design can significantly save in operations costs (sometimes, over and over again). For example, thermal and power robustness may eliminate the need for complex analysis of every maneuver sequence, saving time and money in the development of sequence uploads. A mission level system engineer should have the authority and responsibility to perform such tradeoffs at a high level.

System Commonality

Build systems that achieve simplicity through the use of common architectures. Cost savings due to system commonality may not be apparent at the mission operations level, but are observable at the program level. Many Integration and Test (I&T) functions are duplicated in the Mission Operations System and vice versa. Why should these capabilities be developed twice? Using a common system design for Mission Operations (MO) and I&T saves money not only in design and development of the ground system, but in sparing, training of personnel, and staffing during test, launch, and mission ops.

Operations

The division of operations costs between pre- and post-launch is mission dependent. Pre-launch development of operations teams and processes, personnel training, and system testing can be significant cost items. If the mission is short, or if it can be staffed at a very low level, pre-launch costs can be a significant portion of overall operations costs to the program. If the mission is long, complex, or both, post-launch costs tend to be the driver of overall costs. In the sections that follow, we shall show how intelligent application of pre-launch funding can significantly reduce post-launch costs.

Low Staffing Levels

Minimize the number of personnel needed to operate the spacecraft during post-launch operations. The major post-launch cost item for most missions is personnel. In most programs, the key to lowering operations costs is to reduce the number of people required to operate the spacecraft.

Personnel reductions can be achieved merely by paying attention to the type and capabilities of personnel hired and the changes in skills needed during different phases of the mission. As teams become smaller, the competence and breadth of individual members becomes more important. Small teams can not afford to have members with specialized or limited skills; every team member must contribute significantly to the overall productivity of the team for operations to be cost efficient.

It is important to note that the skills required during design and development of the MOS are not the same as those required during post-launch operations. Personnel should be added as their skills are required and removed when their skills are no longer applicable to the needs of the program. This may conflict with the policies of some organizations, but is essential to controlling operations costs. Large institutions frequently utilize matrix management techniques that allow the program to draw from a broad mix of skilled personnel, paying only for the time charged to the program. Matrix techniques can be advantageous in the implementation of these practices.

Spacecraft Autonomy

Build spacecraft systems that require minimal operations support. Perhaps the most obvious way to reduce operations cost is to build a spacecraft that does not require operations! The more autonomy built into a spacecraft, the less the MOS needs to do. The prevailing view is frequently the inverse -- the more the ground does, the less the spacecraft needs to do. Mission system engineering of the spacecraft and MOS offers the capability to partition requirements between the ground and flight systems. If the optimization goal is to minimize overall program costs, operations costs will generally be lower. Even if cost is not an optimization parameter, the consideration of mission operations issues in the design of the spacecraft will generally result in cost savings (due to operability enhancements). Frequently, the spacecraft design team has options that have little impact on the spacecraft but significant advantage to mission operations.

Spacecraft autonomy features which simplify operations include: telemetry monitoring and alarming; processor memory management; anomaly detection, correction, and/or reporting; automated data handling; and multi-level autonomous safe modes. Each of these features are discussed below.

Autonomous telemetry monitoring and alarming reduces the work load on ground personnel, especially if the MOS is designed to communicate spacecraft generated alarms to operations personnel immediately. This reduction in the need for ground system monitoring reduces the number of personnel and the frequency of contacts required. During missions with long cruise phases and infrequent contacts, onboard alarming, coupled with storing alarm status in memory, can enable operations personnel to instantaneously assess the state of spacecraft health since the last contact. This reduces the contact time required, the operations load, and thus, the total cost to the program.

Automation of memory management allows the MOS to use lower fidelity models of onboard processors, thereby reducing development costs. Additionally, fewer commands are required for processor memory management, reducing the costs of testing those commands as well as simplifying operations.

Autonomous anomaly detection, correction, and reporting is similar to onboard telemetry monitoring and alarming with respect to operations. The potential reduction in operations workload and the increase in intervals between contacts results in a reduction in operations personnel.

Autonomous data handling, in which the spacecraft processes, stores, and retrieves data by instrument or subsystem without detailed operator intervention, allows the operations team to use contact time more efficiently and send fewer commands, reducing the workload and cost of operations.

Multi-level safe modes allow the spacecraft to assume intermediate modes of operation between fully operational and "cocoon" mode (minimal activity, awaiting ground command). For example, a failure in the data handling system may cause the spacecraft to shut down the data handling system, point the antenna at Earth (assuming guidance, navigation and control functions are unaffected), and await instructions. Allowing the good subsystems to remain operational means that the anomaly will be addressed more quickly than would otherwise be the case. This allows for longer intervals between contacts, which reduces operations loads and costs. This also reduces the time spent and the assets utilized in recovering from a failure.

Ground System Automation

Build ground systems that minimize personnel requirements. The use of automation in the ground system can significantly reduce requirements on operations personnel. Most apparent is the application of automated telemetry display and command generation capabilities. The use of high level command languages reduces operations personnel requirements, as do integrated databases, graphical user interfaces, and automatic report generation and transmission capabilities.

The next logical step in ground system automation is ground systems that autonomously receive, process, interpret, and respond to spacecraft telemetry. While totally automated operations are not yet feasible for scientific missions, many functions can be automated. Automated monitoring of telemetry can not only alert an operator to an out-of-bounds condition, it can spawn a process to advise the operator what to do (i.e., retrieve a contingency plan from a database), or even take action itself (depending on the nature and severity of the anomaly). Spacecraft data trending and analysis can be highly automated, generating formatted reports and delivering them electronically to the correct parties at the appropriate times (e.g., at shift changes or on Monday mornings). Clearly, all of these capabilities can be used to reduce the personnel otherwise needed to perform these tasks.

Advanced Technology

Utilize advanced technologies, where applicable, to enhance productivity in operations. The application of advanced technology throughout Discovery class missions has been mandated by NASA (the NEAR mission design predates this mandate, and NEAR is specifically exempted from this requirement). Advanced technology can reduce operations costs by enhancing productivity, i.e., allowing fewer people to accomplish more work with fewer resources expended. Two ways in which advanced technology can be used to enhance productivity are: 1) advanced technology can enable the use of higher level interfaces to gain insight into data and processes, and; 2) advanced technology can be used to assist in making decisions. The application of advanced graphical techniques to gain insight into complex data sets is called *visualization*; and the use of software to assist in decision making processes falls in the category of *expert systems*.

Visualization

Everyone has seen global maps with projected spacecraft ground traces, coverage circles of ground receiving sites, and perhaps time ticks indicating when a spacecraft will or did pass over a particular spot -- these types of displays were a staple of the highly publicized manned space missions of the 1960's. This type of display is a prime example of the use of visualization to provide insight into a complex data set -- in this case, the orbital ephemeris of the spacecraft, the locations and views of each of the ground network's tracking stations, and the time the spacecraft will be available for contact at each of the ground stations.

Humans excel at the assimilation of visual information. The recent trend in returning to traditional watches and clocks from the digital variety is evidence of this phenomenon. People easily interpret the time of day from the angles of clock hands, whereas a digital clock requires assimilation and interpretation to understand. Computer graphics are a powerful tool for taking advantage of this characteristic of the human brain to reduce operations costs. The trend in operations systems is away from alphanumeric screens with numbers and cryptic mnemonics towards graphical displays, including analog dials, graphs, and trees of color coded boxes representing spacecraft systems and subsystems, etc. Aircraft cockpits with modern CRT and flat-panel displays utilize representations of analog dials and "tape" gauges for the same reasons operations systems do; these displays rapidly and intuitively present more information to the user more quickly than alphanumeric displays, thus allowing fewer people to monitor a complex system more efficiently and completely -- and with fewer errors. Fewer people mean lower costs, and fewer errors mean greater spacecraft safety.

Expert Systems

More advanced than visualization (already in use in operations centers, albeit sparingly) is the use of expert systems to assist in decision making processes. Rule-based expert systems are currently in use in some operations systems to assist in telemetry monitoring and display functions. Rule-based systems may also be used in the near future to help diagnose spacecraft anomalies, again, based on interpreting spacecraft telemetry. In artificial intelligence circles, however, rule-based systems have fallen out of favor because of their inherent lack of robustness; these systems can only apply pre-programmed rules to a known data set, and can be very difficult to adapt rapidly to changing conditions. For complex systems, the rule sets can get very large and difficult to manage. Finally, rule-based systems require all rules to be programmed before the system is very useful.

Model-based systems are being investigated for spacecraft operations because they address these problems. Model-based reasoning (MBR) methods use models of systems and subsystems to make estimates of systems states. MBR allows incremental growth in capability as models are added, refined, or updated, and can provide answers that are both qualitative and quantitative. MBR can be used to diagnose problems based on spacecraft telemetry, but the models can also be used to support analysis in the sequence generation process.

Model-Based Reasoning appears likely to reduce MOS costs in two ways. First, it may allow the development of a single set of spacecraft models to perform planning, analysis, and assessment functions, thereby reducing system development costs over traditional MOS designs. Second, it may allow fewer analysts to generate very complex spacecraft sequences with greater confidence, thereby reducing personnel requirements while enhancing mission capability. MBR may be a suitable alternative to the building of costly hardware-based spacecraft simulators traditionally used for command sequence vetting.

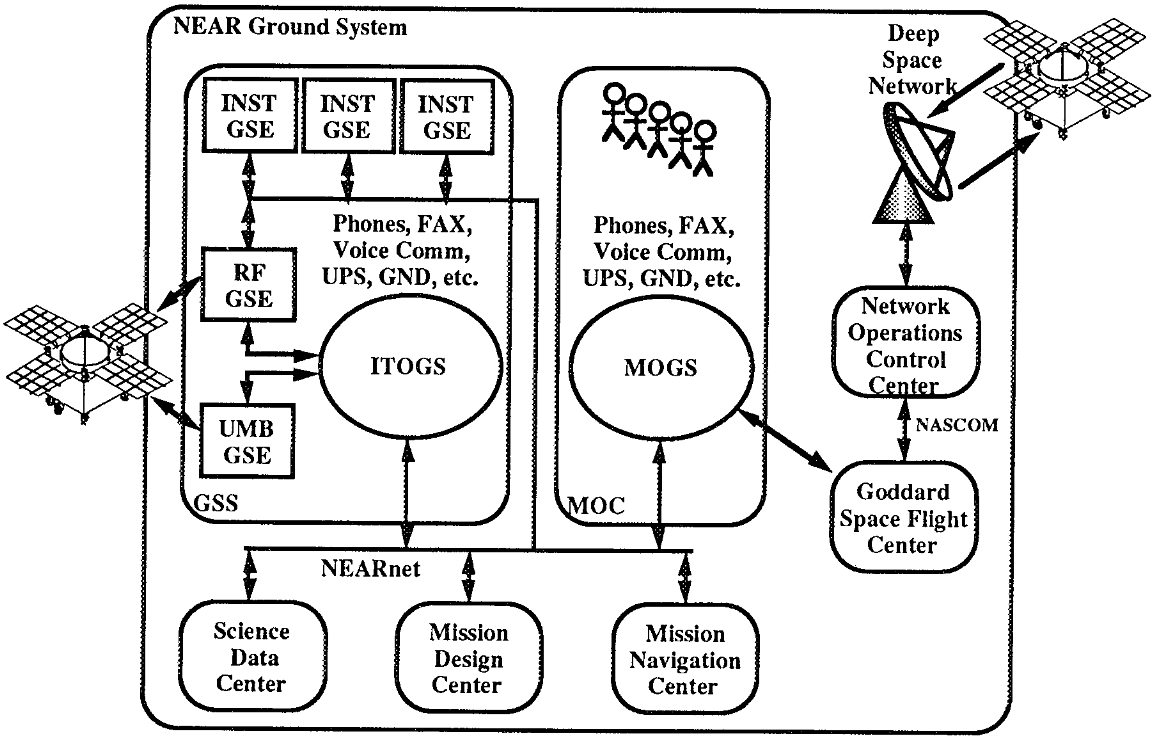

Figure 1. NEAR Ground System

MISSION OPERATIONS SYSTEM

Ground System

Figure 1 is a high level diagram of the NEAR Ground System (NGS). There are six major ground facilities: the Mission Operations Center (MOC); the Ground Support System (GSS); the Mission Design Center (MDC); the Science Data Center (SDC); the Mission Navigation Center; and the Deep Space Network (DSN), which is linked via NASA Communications (NASCOM) circuits at Goddard Space Flight Center (GSFC).

Mission operations will be conducted from APL. Therefore, the MOC and MDC are located at APL. The principal equipment in the MOC is a suite of interface equipment and high-end workstations, including software, known as the Mission Operations Ground Segment (MOGS).

The GSS includes a parallel construction called the Integration and Test Operations Ground Segment (ITOGS) as well as the Ground Support Equipment (GSE). The GSS is used to perform integration and test of the spacecraft at APL, environmental testing at GSFC, and prelaunch testing at the launch site. The ITOGS and MOGS are identical; by virtue of the interconnecting data network called NEARnet, each has controlled access to the spacecraft.

Science data received by the MOC is processed and passed on to the SDC, which further processes the data for dissemination to the science community. The Mission Navigation Center, located at the Jet Propulsion Laboratory (JPL), provides navigation data and products to the MOC, the SDC, and the MDC.

Existing Infrastructure

The NEAR Ground System maximizes the use of existing infrastructure, including the DSN and NASCOM. The DSN is used for all TT&C for NEAR. Operated by JPL, the DSN is a ground network primarily used for interplanetary missions, with ground station complexes in Barstow, California, Madrid, Spain, and Canberra, Australia.

Access to the DSN is provided via NASCOM. NASCOM will be used for virtually all NEAR communications. This includes extensions of the NEARnet to the

ITOGS as it moves with the spacecraft to GSFC and to the Kennedy Space Center (KSC) and Cape Canaveral Air Force Station (CCAFS). The cost effectiveness of using NASCOM for NEAR is multiplied because the arrangements for its use are provided by the DSN as a service.

A third major use of existing infrastructure is internal to APL. As discussed, the workstations, GSE, and peripherals of the MOGS and ITOGS are tied together as one large system via the NEARnet. Within APL, NEARnet uses an existing ethernet communications system called the APL Network Information System (APLNIS). APLNIS is ubiquitous throughout APL and supports multiple interface configurations. APLNIS supports TCP/IP protocols and has an existing connection to Internet, which provides off-campus access to the SDC. Connections of the ITOGS and MOGS to the APLNIS will utilize a router to provide protection against unauthorized access to spacecraft control and telemetry.

It should be noted that the NEAR spacecraft conforms to the standards of the Consultative Committee on Space Data Systems (CCSDS), and will be the first spacecraft to use CCSDS for uplinking. In using this system, NEAR is effectively making use of another set of existing infrastructure that results in reduced costs within the NGS.

Commercial-Off-The-Shelf Systems

An important aspect of the NGS implementation approach is the use of COTS mission operations systems. Although this industry is still young, a number of available systems offer capabilities in one or more aspects of spacecraft telemetry processing, performance assessment, and command and control. The core of the NGS is COTS. This core provides telemetry monitoring, alarming, and archiving, as well as spacecraft command and GSE control. Two systems are being procured for the MOGS and ITOGS; when augmented with additional workstations and custom software developed by APL, they will constitute the ITOGS and MOGS.

The core system includes a VME-based front-end, a workstation, and peripherals. The front-end provides the telemetry and command interfaces to the spacecraft (or more correctly, the spacecraft GSEs and/or the DSN via NASCOM) as well as realtime decoding, error correction, and data handling required to provide data for display on operator workstations. Workstation processing includes calibration, engineering unit conversions, display, alarming, and command script generation. Workstations may analyze realtime or archived data, or a combination. A large number of workstations can be supported on the NEARnet, and as described previously, these can be located anywhere.

Like many other current COTS systems, the NEAR MOC and GSS use networking and distributed processing. In each area, the workstations, peripherals, and command and telemetry interfaces are merely logical groupings of equipment on the NEARnet, with equal access to all data whether it enters the system via the MOC or the GSS. Each workstation has equal access to the "front end" of either area. The look and feel of the system remains the same in all locations; the parallel nature of the networked system provides a mutual backup capability.

This networked architecture permits the system to take advantage of distributed processing. The NEAR MOS has no large central computer with the resultant interference and speed problems as different workstations access and run processes on the central facility. These workstations simultaneously and independently run different processes on the same or different realtime or archived data. This permits a single database (e.g., telemetry and command dictionaries) to be accessed from any workstation, preventing the problems of maintaining multiple dictionaries. Incremental growth in the ground system can be easily accommodated without disrupting existing (operating) components.

The NEARnet extends beyond the MOGS and ITOGS, providing controlled (authorized) access to selected data on the NEARnet by other workstations or PCs. One recipient of data is the Science Data Center (which also has workstations and peripherals connected to the NEARnet).

The SDC is given essentially raw science data at the CCSDS Transfer Frame and Packet level and provides various levels of processing to generate products for the science community, which accesses these products via the NEARnet. Off-campus science teams may obtain access via the Internet. Two other Centers have access to the NEARnet Science Data Center. These are the Mission Design Center and the Mission Navigation Center.

One additional aspect of the ITOGS and MOGS worth noting is the use of an open operating system. All of the commonly recognized advantages of this approach are realized for NEAR. For example, access to commercial software is maximized; in-house software can be developed on non-NEARnet workstations or PCs with minimum problems in transporting these to MOS workstations. Further, the NEARnet configuration is much more supportable and expandable over the life of the mission.

Common architecture for I&T and MO

It is important to note that the MOGS and ITOGS are identical in configuration, software, hardware, and command and telemetry capability. This is significant in at least two aspects. First is the reduced development and maintenance costs resulting from identical workstations, front-end equipment, and peripherals. Because a single system design and architecture is used, overall complexity and design effort is reduced, as is the number and cost of procured components. Additionally, spares and maintenance costs are minimized.

The second significant aspect of using identical systems for I&T and MO is that the spacecraft will be flown as it was tested. The look and feel of the two segments is the same to the user. Since both sets of front-end equipment are also identical, (each supporting the three modes of interface with the spacecraft: RF GSE, umbilical GSE, and via NASCOM and the DSN), and since either can be accessed from a workstation in either the MOGS or ITOGS, the only distinction between the two is established by access authorization. While I&T activities will be principally controlled from the ITOGS due to its proximity to the spacecraft and GSE, considerable capability exists, and will be utilized, to exercise the spacecraft from the MOC during the I&T phase. When this commonality of hardware and software is considered in light of the current plan to have a number of mission operations personnel involved in integration and test, the transition from I&T to MO should be as seamless as is achievable. This blending of traditionally separate and distinct functions significantly reduces the total cost and development time for the ground support elements of the NEAR mission while improving the quality and reliability of the overall product.

SUMMARY

This paper began with a discussion of low cost mission operations, including a number of specific recommendations for controlling costs. These are summarized below: 1) Always take advantage of existing infrastructure where cost efficient; 2) Use Commercial Off-The-Shelf hardware and software systems where applicable and cost effective; 3) Use modern concurrent engineering techniques; 4) Design the spacecraft and Mission Operations System for operability; 5) Build systems that achieve simplicity through the use of common architectures; 6) Minimize the number of personnel needed to operate the spacecraft during post-launch operations by building spacecraft and ground systems that minimize personnel requirements, and; 7) Utilize advanced technologies, where applicable, to enhance productivity in operations. While these simple statements may seem obvious, they are frequently forgotten or overlooked as heritage often dictates the design and implementation of the MOS.

The second part of the paper included a description of the NEAR MOS and ground system with an emphasis on those elements of the system design that contribute to low cost operations. In the case of NEAR, we were able to apply almost all of the practices discussed in this paper. It is our hope that NEAR Mission Operations will introduce a new way of doing business for Discovery, and that this will lead others to identify even better approaches to controlling costs in today's cost-constrained environment.