# A Multi-Mission Operations Strategy for Sequencing and Commanding

Robert N. Brooks Jr. *
Telecommunications and Mission Operations Directorate
Mission Services and Applications
Service System Development Engineer
Jet Propulsion Laboratory
4800 Oak Grove Dr.
Pasadena, CA 91109
Mail Stop: 301/235
818-393-7856
Robert.N.Brooks@jpl.nasa.gov

Abstract - The Telecommunications and Mission Operations Directorate (TMOD) of the Jet Propulsion Laboratory is responsible for development, maintenance and operation of flight operations systems for several classes of science missions planned for the next several years. The Mission Services and Applications (MS&A) Office is responsible for a large group of operations tasks, most of which are oriented toward the uplink leg of flight operations. These include sequence design and command generation, flight engineering tasks such as spacecraft activity planning and performance analysis, mission planning, telecommunications link analysis and DSN resource scheduling and planning. In addition, MS&A is responsible for the software tools necessary for performing these functions.

The mission classes mentioned in the preceding paragraph are of the following four types. Shared operations class missions are characterized by the similarity and simplicity of their operational strategies. Most of these types of missions involve routine activities by both a spacecraft and its ground support teams. Another class of missions are those which will use the developing Mission Data System, a flight and ground operations system which will permit greater operations flexibility by developing a unified flight and ground architecture. A third type of mission is observatories. Examples of this class of mission would include SIRTF and SIM and would be characterized by heavy use of early observation planning and rapid turnaround flight sequence generation. Finally, the fourth class of missions involve mobile vehicles and sample returns. Operations for this mission type is planned for use beginning in 2001 and is currently in early development.

The various mission classes have operational requirements, which are in many ways similar but differ sufficiently from one another to warrant development of a different type of operations strategy for each. Each of these operations strategies uses a standard set of tools developed by TMOD. A sequencing operations organization under the auspices of the MS&A is now being built that will be responsible for the sequencing and commanding aspects of flight operations for all missions that subscribe to its services, including personnel, computer hardware and software, procedures and interfaces.

This paper will describe the various mission types projected through the year 2006. It will then describe how TMOD/MS&A is planning to accommodate these missions operationally by providing a multi-mission sequencing and commanding capability which will be accessible to both new and existing missions. Finally,

**the projected resource savings and increases in efficiency will be discussed.**

*** Jet Propulsion Laboratory**
**California Institute of Technology**
**4800 Oak Grove Dr.**
**Pasadena, CA 91109**
**The work described in this paper was carried out at the Jet Propulsion Laboratory/California Institute of Technology under contract with the National Aeronautics and Space Administration.**



## HISTORY OF SEQUENCING AND COMMANDING AT JPL

Sequence and command processing at JPL has, traditionally, been a very rigorous and time-consuming affair. For many years the large and complex missions flown by the laboratory used processes which required sequence development to begin several months prior to actual execution of the activities. Each sequence was manually constructed and heavily scrutinized by a project flight team consisting of a great many people. In addition, each project maintained its own sequence team consisting of specialist personnel from the various fields of expertise needed to fly a deep space mission. This, in turn, implied that a large amount of duplication of effort was occurring between the various projects.

JPL recognized this duplication of effort during the 1980s and an effort was begun to identify those processes, which could be performed in a multi-mission manner. Sequencing and commanding was one of the candidate processes to undergo this scrutiny. Several ideas were considered but none seemed viable at the time. Each was unacceptable due to increased risk levels to the missions it would support or impossible given the technology of the day. Major changes in the way sequencing and commanding was performed would not occur until the early 1990s and would be driven by the Mars program.

### *Current Architectural Approach*

JPL has embarked on the development of a truly multi-mission operations capability to be used for the vast majority of missions planned to be flown during the next ten years by the laboratory. The organization responsible for developing this capability is JPL's Telecommunications and Mission Operations Directorate (TMOD). TMOD is composed of several areas of expertise. Sequencing and commanding, navigation, software development and DSN operations are just a few. Until recently mission sequencing and commanding has been a project specific function. With the exception of the Mars Surveyor Operations Project (MSOP), each flight project maintained its own sequence and command generation processes and each of these was custom tailored to the needs of their specific mission. With the advent of NASA's aggressive frequent launch strategy for space science missions it became necessary to devise a multi-mission operations service that could support several similar missions simultaneously.

Any good operations service must rely on an equally reliable set of tools with which it can perform the tasks it is assigned. TMOD's Mission Services and Applications (MS&A) organization has spent the past several years working closely with active and developing flight projects to develop just such a tool set. This tool set consists mostly of software elements which are readily adapted to the needs of generic mission types. With the availability of this tool set the stage was set to begin development of a multi-mission sequence operations service.

The most successful attempt at developing a multi-mission sequence operations strategy was the one developed by the MSOP. From its very inception, the MSOP sequence operations team was designed to support multiple spacecraft in various stages of development and flight. At the heart of this highly efficient operations approach are some very basic rules. These rules include standardization of all procedures and interfaces, even down to the level of file naming conventions. However, it was realized that standardization could not imply rigidity or the system would be unattractive at best to prospective customers. The MSOP sequencing team worked very closely with TMOD's MS&A organization during the above mentioned development period to assure that all procedures and interfaces were fully integrated with the MS&A provided ground data system.

Another factor which has made MSOP's sequence and command processing system so useful has been its heavy use of automation in its processing. The type of automation employed by the MSOP sequence team was engineered from the beginning to reduce the risks inherent in operating deep space missions. Every procedure used by the team was analyzed in minute detail and, where it was deemed appropriate and safe, automation replaced human intervention in the process. At the heart of this automation is a tool known as the Automated Sequence Processor (ASP). The ASP had its beginnings during flight operations of the Mars Observer (MO) mission. Prior to the loss of the MO spacecraft to a spacecraft propulsion system failure, the project manager had assembled a group of flight team members whose task was to review all procedures associated with the project's uplink process and recommend improvements which would increase efficiency and processing speed. From this effort the concept for the ASP was born. The ASP is actually not a specific tool but is, rather, a method for linking all of the components of the sequence and command generation processes together and providing a mechanism for external users to submit command or sequence requests and have them prepared for transmission to the spacecraft. The same process performed manually on MO required two engineers approximately 2 hours to process one command file. The manual process was only available during standard work hours (8 hours per day, five days per week). The ASP replaced all manual processing, was available 24 hours per day, 7 days per week and could complete all processing in 1 to 3 minutes depending on file size and machine load.

These generic formats along with equally adaptable operational procedures and its long term use in a multi-mission environment made the MSOP system the system of choice as MS&A began to develop its own multi-mission capability.

In addition, the MSOP sequencing system had been designed to be so generic that many of its components could be slightly modified or taken as is and used to operate missions with little similarity to the relatively simple missions supported by MSOP. MSOP's charter was originally to operate the planned set of missions included in NASA's Mars Surveyor Program (MSP). However, as various new missions were approved and they became aware of the reliability and versatility of MSOP's sequencing capabilities, projects outside of the MSP were added to the list of MSOP supported projects. At this writing, the MSOP sequencing team is supporting more than 10 spacecraft in various stages of development and flight. All of this is made possible by the above-mentioned use of TMOD/MS&A standard tools, MSOP standard procedures and interfaces and heavy use of risk reducing automation.

## NEW MISSION TYPES

The MS&A organization within TMOD is tasked with developing a sequencing operations capability for all flight missions planned for the next decade. The set of missions, both planned and in flight, are diverse in their goals as well as their complexity. Some are simple flybys of primitive bodies in the solar system while others are major observatories or sample return missions. Still another class will use common software for both their flight software and ground software systems. This last class of mission is entirely new for JPL and is currently in development.

### *Shared Operations Class*

By far the Shared Operations class of mission is the one with which JPL has the most experience. As mentioned earlier, the MSOP developed a multi-mission sequence operations capability beginning immediately after the loss of the Mars Observer spacecraft in 1993. NASA had decided to focus a major portion of its solar system exploration attention on Mars. This approach would be supported by at least one if not more launches at each Mars launch opportunity. The implication of this strategy was that several spacecraft would be in development or flight simultaneously and a ground sequencing system was needed to support all aspects of these missions. The resulting MSOP system provided all of the required capabilities and did so in a very efficient, rapid and cost effective way.

The author was a principle player in the development of the MSOP sequence team. That same author has now been given responsibility for developing TMOD MS&A's equivalent capability. The high quality and reliability of MSOP's sequence team and its associated software, procedures and interfaces has made it a very attractive model for this multi-mission capability. MS&A has decided to use MSOP's sequence team as the model for its first fully functional multi-mission sequence operations service.

### *Observatory Class*

The Observatory class of mission requires another completely new approach to sequencing for JPL. TMOD MS&A is working closely with the Space

Infrared Telescope Facility (SIRTF) project to develop the basis for this type of mission. Effectively, SIRTF is being used as the model from which MS&A will derive its sequencing operations system for observatory missions.

At the heart of this mission type is a requirement by SIRTF to have sequence operations performed by the science community. In essence, the science organization on the project will be providing the vast majority of activity requests for the spacecraft and will require a very rapid turnaround. This, and the fact that non-project affiliated observers will be permitted to submit requests for telescope use time and these requests will require careful integration by the science team have resulted in a planned operations strategy which will look very different from past JPL missions.

One extremely important aspect of a sequence operations service for these types of missions will be their activity planning and scheduling. Because several external requesters will submit activity requests it is expected that all sequences will be "over-booked" with respect to their available resources. Heavy use of automated tools which will collect a set of approved observations defined at a high level, build a plan for their implementation based on spacecraft resources, activity priorities and other parameters and then generate all necessary uplink and ground support products are all requirements on the system which will be needed to support such missions. In fact, a prototype of just such a system has already been developed by the combined efforts of TMOD MS&A personnel and SIRTF project staff. Even in its prototype form it has proven to be extremely efficient and capable of building very complex sequences in a very short time, on the order of several minutes.

Another significant difference between traditional sequencing and that being deployed by this new class of mission is their need for non-deterministic sequencing. By this is meant that a sequence being flown would be responsive to stimuli from spacecraft states and environmental triggers. Near-term missions of this type are not planning to make use of this capability but future observatory class missions will certainly use it. This method of sequencing has never been implemented as a standard mode of operating a spacecraft by any JPL mission and a great deal of study is being focused on it for several future missions.

***MDS Class***

The Mission Data System (MDS) is a totally new approach to both ground and flight operations. MDS is currently under development at JPL and, as such, not yet ready for actual flight use. However, it is planned to be available for use on missions beginning in 2002 when it would be used in support of Europa Orbiter's Assembly, Test and Launch Operations (ATLO) effort.

MDS departs from more traditional techniques of sequencing in at least two ways. First, it is being designed to use goal oriented sequencing and high level commanding. With this technique, a flight team member would specify some specific goal they want the spacecraft to accomplish and express that goal in a "language" used by MDS for this purpose. A goal could be as simple as "Issue command xyz" where the goal would result in a single command (called xyz) being issued or as complex as "perform science instrument A calibration number 5" which could generate a sequence of several, perhaps hundreds, of commands all designed to accomplish the calibration of science instrument A in calibration mode number 5. Still further, MDS is planning to provide the ability to specify a goal and then permit the spacecraft to determine autonomously from several spacecraft and environmental states when to execute the activities associated with the goal.

The second way that MDS deviates from JPL's traditional sequencing methods is that the ground software and the flight software will be the same software. Programs used in the sequencing process will be usable on both platforms. This is expected to allow migration of some tasks currently performed exclusively on only one of these platforms to be optionally performed on either or both, depending on the project's planned modes of operation.

Sequence operations for a mission using MDS will be radically different from JPL's more familiar methods. To begin with, the sequence team member responsible for generation of a flight sequence will no longer be required to specify exact times and parameters. A simple request for some high level goal will suffice to trigger a set of commands that will yield the desired outcome. Also, the types of products produced by the more traditional methods will not be necessary. In fact, it may not even be possible to generate many of them because of events being triggered by spacecraft and environmental states. These two characteristics of the MDS approach to sequencing amount to a significant change in paradigm for JPL sequence operations and promise to be the most challenging to solve as they will require a basic change in attitude on the part of sequence team members as well as other members of the flight team.

***Mobile Vehicle/Sample Return Class***

By far the most unfamiliar sequencing territory for JPL is the operation of mobile vehicles and sample return vehicles.

Mobile vehicles would include rovers, aerobots, submarines and balloons. The great challenge for MS&A in developing a sequencing capability for these types of vehicles is that JPL has very limited experience with such vehicles and, so, must work closely with developers of such missions from a very early stage of development to assure that all of the project's requirements are met. The experiences gained from both Mars Pathfinder and the Mars-01 mission will be of great importance in developing a responsive, reliable and high quality sequence service for these missions.

In fact, at this time it is unclear exactly what it means to "sequence" a mobile vehicle. A truly mobile vehicle may require a large degree of onboard autonomy so it may respond to situations it encounters during its journey. Prior missions of this class used a "one step at a time" approach to control the motions of their spacecraft. A ground based operator would use an onboard camera to survey the rover's surroundings. These images would then be used to determine a safe direction for the spacecraft to move. Once this path was determined commands would be generated and sent to the vehicle to instruct it to move several centimeters or even a few meters. This process would then be repeated until the rover had reached its ultimate destination. Most vehicles of this class never journeyed more than a few meters from their initial starting point.

Future mobile vehicles will not be operated in this manner. Instead, they will need to be able to check their own surroundings, use onboard autonomy to determine a safe route to a destination and then generate its own commands to accomplish that goal. Dangerous conditions will need to be detectable as well and replanning of the original plan initiated. This will permit such mobile vehicles to navigate themselves far beyond the limits of their landing site. Excursions of several kilometers are envisioned and a sequencing and commanding system compatible with such a strategy must be developed.

One possible scenario for this type of sequencing operations may involve the use of the above mentioned Mission Data System (MDS). MDS will permit the specification of "goals" in a sequence. These goals could be very high level, perhaps instructing a vehicle to drive from its current location to a mountain some distance away. Using onboard navigation and imaging systems, the rover could plot a course for it to take which would end with it at the designated mountain.

## PROJECTED OPERATIONS SAVINGS

Incredible savings have already been realized from the use of the MSOP sequence operations system. These savings have manifested themselves not just as lower dollar costs for the missions supported by MSOP but also in reduced workforce levels required to operate these missions. The MSOP sequence organization keeps a baseline staffing level of six members, four of whom perform sequencing tasks and two who maintain DSN schedules for the supported missions. Adding small fractional workforce levels to this baseline supports additional missions. These savings are a result of the well system engineered, highly efficient and low risk automation used by the MSOP team. Use of this same approach for MS&A's sequencing team will give similar results.

Early costing exercises for the Observatory and MDS class missions indicate that many of the proven sequencing procedures used on MSOP will be directly applicable to these two other mission types. SIRTF, and to some extent SIM, have been used as the models for the Observatory class missions. Europa Orbiter has been the only example for an MDS mission available thus far. Especially for the MDS type of mission, there is still much development to be completed and operational savings for sequencing may range from conservative to optimistic. MS&A is working very closely with MDS personnel to make certain that MDS development is in alignment with MS&A's planned sequencing strategies.

Finally, the mobile vehicle/sample return class of missions present JPL with its greatest challenge to develop a sequencing and commanding strategy which will support these missions in the manner needed to accomplish their goals while minimizing costs and risks. This development is in its early stages and is expected to be ready for use in 2002 when the Mars-03 project begins its spacecraft Assembly, Test and Launch Operations period of development.

By carefully system engineering the MS&A sequence operations and flight engineering services large savings will be realized in the flying of a multitude of planetary and science missions. This will, in turn, make space much more accessible to the entire science community.

## BIBLIOGRAPHY

1) R. N. Brooks Jr. and J. L. Torgerson, "Increases in Efficiency and Enhancements to the Mars Observer Non-stored Commanding Process", OP.2.b, Proceedings of the Third International Symposium on Space Mission Operations and Ground Data Systems (SpaceOps 94), NASA Conference Publication 3281, Part 1, Greenbelt, Maryland, November 1994.

2) R. N. Brooks Jr., "A High Efficiency System for Science Instrument Commanding for the Mars Global Surveyor Mission", RAL.GS.36, Proceedings of the First International Symposium on Reducing the Cost of Ground Systems and Operations, Rutherford Appleton Laboratory, Chilton, Oxfordshire, UK, September 1995.

3) R. N. Brooks Jr., "The Mars Surveyor Flight Operations Project Command Generation Process", SO96.8.05, Proceedings of the Fourth International Symposium on Space Mission Operations and Ground Data Systems (SpaceOps 96), Deutsches Museum, Munich, Germany, 16-20 September 1996.