IAA-L-0603

MISSION OPERATIONS FOR MARS OBSERVER

-- A Case Study

K. D. Erickson, F. J. Hammer, P. B. Kahn, G. J. Kazz
Jet Propulsion Laboratory, California Institute of Technology
4800 Oak Grove Drive
Pasadena, California, 91109

ABSTRACT

Mission operations for the Mars Observer project were patterned after the low-cost approach proposed under the Planetary Observer program of the early 1980s. That approach was based on: a mission with focused science objectives; a repetitive mapping operation; a high-heritage spacecraft design; a science payload with low demands on the spacecraft for resources and control; utilization of data standards throughout the information flow - from instrument to receipt of data by the planetary science community; a distributed ground system with multimission support for spacecraft monitor and control; remote science operations with non-interactive commanding; and data transfer and data loss criteria consistent with mission goals.

This paper examines the operation architecture, ground system technology, and the management engineering and information flow processes. The successes, drawbacks, and lessons learned of the mission operations low-cost approach are described and evaluated.

BACKGROUND

Mars Observer was launched on September 25, 1992. Unfortunately all communication with the spacecraft was lost on August 21, 1993, three days prior to going into orbit around Mars.

Mars Observer was the first of a series of planetary observers recommended by the Solar System Exploration Committee report.[1] The report, responsive to the cost pressures of the 1980s, proposed low-cost missions with focused science, spacecraft bus heritage of Earth-orbiting missions, and followed the data archiving and distribution recommendations of the Space Science Board's Committee on Data Management and Computation.[2]

At a high level, the functions performed by mission operations can be seen in the simplified end-to-end data system diagram of Fig. 1, The center of the project activity is located in the Project: I meal and Project: Remote boxes, Local refers to those elements at the Jet Propulsion Laboratory (JPL), and remote refers to elements located at the home institutions of the science investigators. Multimission services of Deep Space Network (DSN) provide for acquisition and handing of science and engineering telemetry, radiometric and very long baseline inferometry data, and radio science occultation data. The balance of the cud-end data system is traceable to Advanced Multi-Mission Operations System (AMMOS), a distributed ground data system extendible to support several concurrent missions, These multi mission services provide support to the project on a 24-hour basis and/or when the spacecraft is being tracked by the DSN. The planetary data system, included for completeness, is chartered by the National Space Science Data Center to be the long-term archive for planetary science data.

The organization to perform these functions is shown in Fig. 2. These teams with the exception of DSN Operations, Operations Planning and Control, and Multimission Control, were staffed by the project, All teams except for the 13 science investigation teams, were located within the mission support area at JPL.

I. OW-COST APPROACHES

‘he low-cost approaches taken by Mars Observer are summarized in the following 6 categories. Space limitations prevent detailed discussion. The reader is encouraged to contact the authors for more information.

Distributed Information Architecture

1. Remote Science and Engineering Operations

Description

Mars Observer was the first JPL mission to use a fully distributed information system approach for science and engineering operations (note: Magellan also had its Spacecraft Team remote from its main operations center). The project philosophy involved taking a hierarchical approach to mission operations thereby distributing it's operational processes and support to numerous teams, including remote science

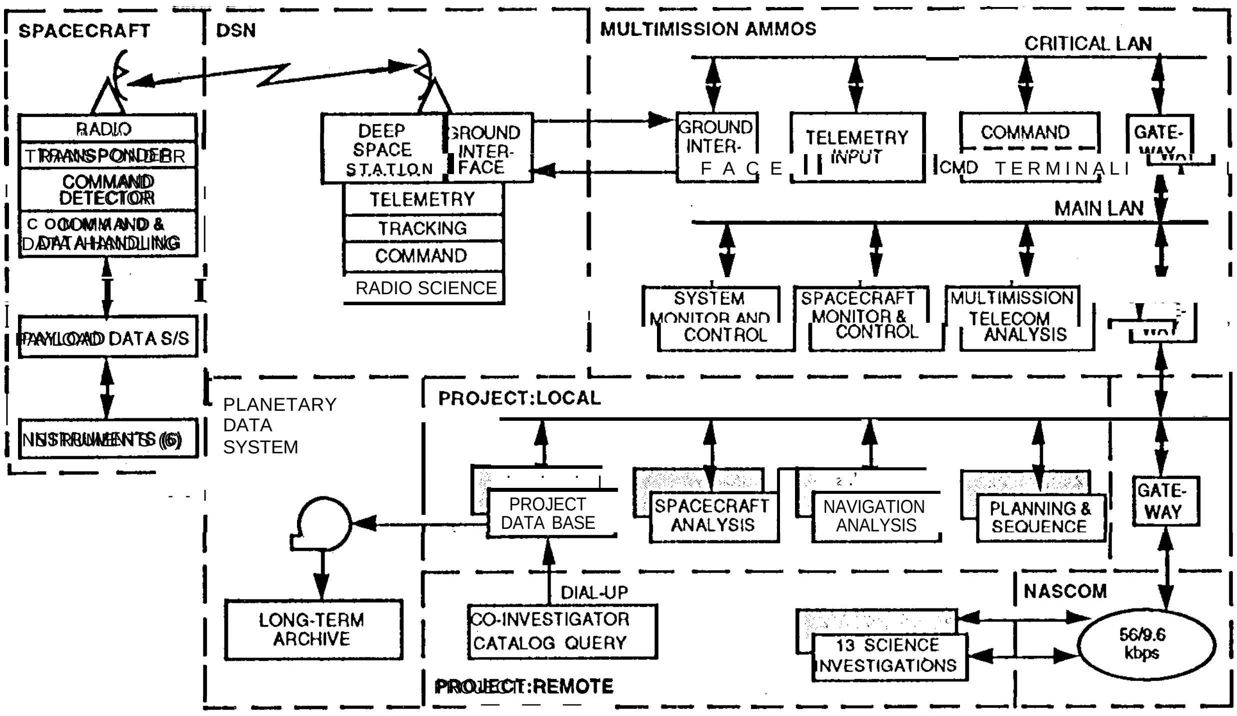

Fig. 1 End-to-end Data System

teams. The science and engineering teams further distributed the operational functions of their particular system to a variety of subsystem components within their own internal organization.

Some of the principles driving distributed operations were to place technical responsibility in the hands of those with the most expertise. In addition, client-. server architecture designs and increasing processing power have revolutionized data processing roles and made distribution of many tasks possible and desirable. This is due to the decreasing cost of computational power, the widespread use of communications infrastructures such as local and wide area networks, availability of commercial communications standards, financial constraints to keep staffing levels down and utilization of database technology.

Expected Advantage

‘his concept takes advantage of local expertise without the expense of transferring that knowledge-base to JPL for the life of the mission. It allows the developers of a subsystem to provide the operational support and expertise required after development has been completed. Any translation of technical expertise to another implementing or operating agency will raise costs and reduce flexibility.

One benefit of a distributed operations system is that it provides for faster science team response to changing instrument conditions. By providing the capability for the remote teams to monitor their instrument parameters in near red-time, engineering analysis and response times are reduced. The data are provided to those with the most expertise and knowledge of the instrument without incurring significant time delays that would otherwise be imposed in a more centralized system,

The overall effects of these trends were to functionally distribute system processes within the project where they made the most sense, The goal of this distributed approach was to setup a process that creates a satisfactory product in a minimum number of steps as opposed to a process that reshapes a product via rework into one that is ultimately satisfactory.

Result

The resultant system provided the flexibility and expertise as envisioned. Utilization of networking and electronic communications tools facilitated mission operations in an expedient manner given the geographic distribution of the project teams. It also achieved lower operating costs and improved productivity by not requiring investigators or their designates to be collocated at JPL.

2. Science Operations and Planning Computer (SOPC)

Description

The fundamental concept of the SOPC is that for a multi-year long mission in an era of widespread computing, the scientists are able to conduct most project-related science instrument operations from their home institutions via networked connections to a project information system.

Since the Principal Investigator or Team Leader is responsible for overall instrument operation, it was thought that providing a workstation with a suite of standard capabilities would be of assistance to him, The primary functions of the SOPC workstation include planning, sequence design and integration, retrieval of data packets and associated ancillary data from the project database and transfer of reduced data products. Although not a primary function of the SOPC, an investigation may perform science data processing on it.

Expected Advantage

Providing the same platform and tools to all investigators would reduce or eliminate customized developments. It would also make for a more efficient operation, and ease of anomaly investigation.

Result

The SOPCs provided the capabilities and support envisioned, Some investigators used the SOPC to its fullest and planned to perform analysis tasks on it whereas others limited it to interfacing with its own host computers.

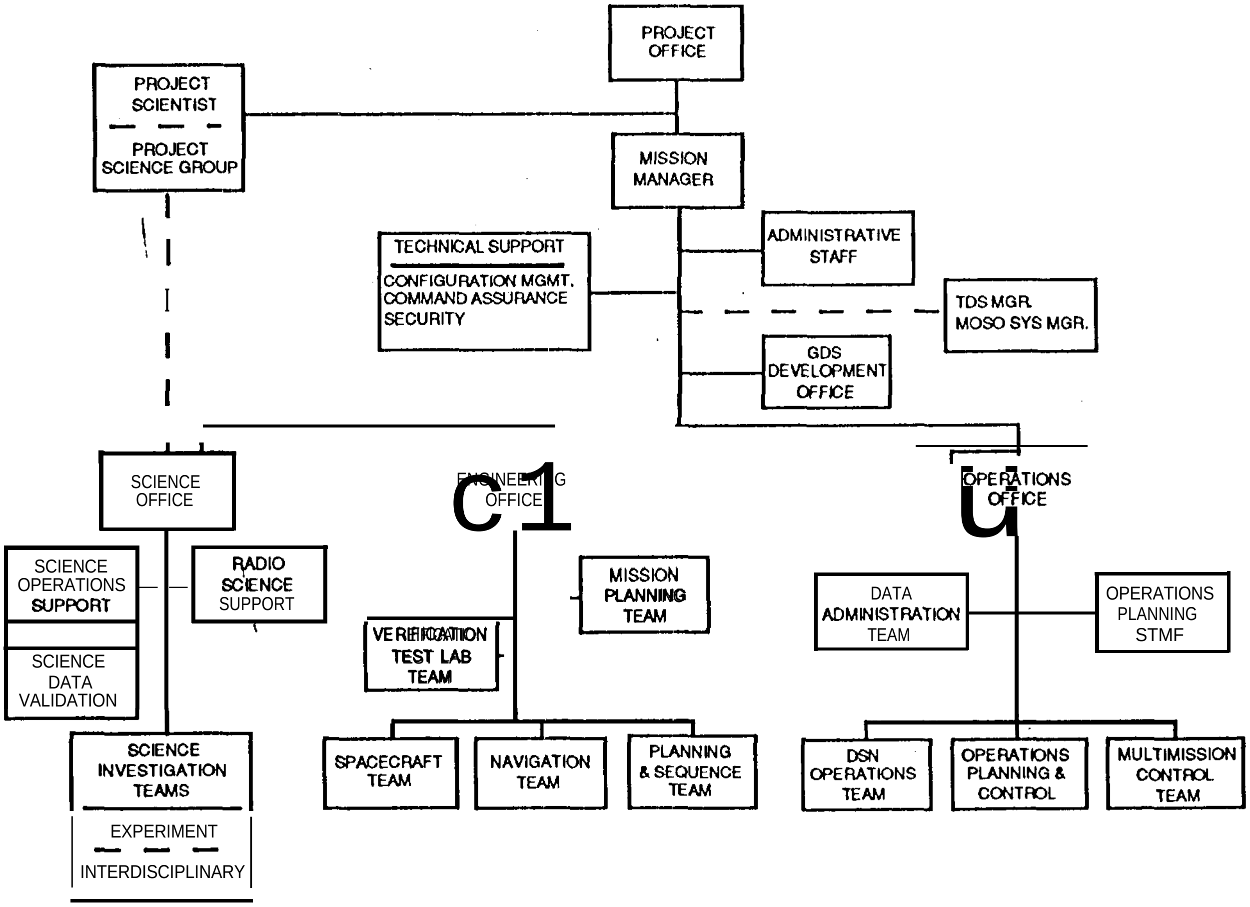

Fig. 2 Mission Operations Organization

3. *Project* Data Base

Description

To facilitate the distributed operation, the project provided a data base i.e., PDB. The purpose of the PDB was to provide a central repository to hold and provide access to all project data i.e., planning, acquired, processed, and ancillary.

Expected Advantage

The primary operational advantage was the central point for interchange of information, Administering one data base rather than several, possibly uncontrolled ones, was simpler, Also interface' formats could more easily be established and maintained.

Result

The PDB had its growing pains. The volume of information constantly increased to the point where the performance was far below its intended level. Changes made during cruise corrected the problem and performance tests confirmed the PDB would adequately support the mapping phase loads.

Multimission Support

Experience from previous flight projects suggested that project and JPL costs could be reduced, overall, by using a core set of multimission capabilities and services.

Description

Mars Observer used multimission components and services provided by:

- Deep Space Network
- Advance Multi-Mission Operations System
- Multimission Navigation Organization

The multimission components included a PDB, adaptable sequence software, telecommunications performance software, science and engineering workstations, data network, and multimission navigation facility and software.

The multimission services included telemetry, tracking, radio science, command, data system operations, and Multimission Control Team.

The project adapted some of the multimission components principally in command and telemetry formats, sequence software, science and engineering workstation integrated environment, and navigation software.

The project augmented the above capabilities with spacecraft analysis software, commercial software, spacecraft, sequence and navigation teams, and instrument-specific and investigator-supplied components and services for instrument operations and science analysis,

Expected Advantage

Project development and operations costs would reduced by using the multimission capabilities and services respectively.

Result

Mars observer was the first to use the full set of the multimission capabilities. Multimission capabilities (including project adaptations) and services were available, as needed, for training and flight support.

Project development costs relating to multimission development, were somewhat higher than anticipated. Also, changes to multimission capabilities during flight, were more difficult and intrusive than anticipated.

The cost advantage of using multimission components and services far outweighed the project cost to develop, test and operate a similar system,

CCSDS Data Standards

The project utilized the recommendation of the Consultative Committee for Space Data Systems (CCSDS) for packet telemetry,[3] telemetry channel coding,[4] and standard data format unit,[5] for data distribution as a cost savings strategy. These recommendations allowed the project to remain flexible to instrument change, plug into multimission downlink capabilities, and implement the distributed science operations approach. For command, the project chose to remain with the existing NASA planetary standard since the CCSDS telecommand standard was only in its conceptual stage.

1. Packet Telemetry

Description

Packet telemetry, along with the distributed character of the flight data system and the capability to buffer science measurements, effectively eliminates the coupling between the data rate of each instrument's operating modes and the output data rate of the data handling subsystem. The data handling system collected data based upon a programmable but deterministic collection table. The instrument could choose to provide data when polled or allow the data handling system to create a dummy packet for it.

Expected Advantage

The DSN and AMMOS base their core telemetry processing functions upon the CCSDS recommendations.[3,4,5] Missions which utilize these core capabilities enjoy the advantage of essentially a "free service."

Mission operations would have flexibility in adapting to changes made in the flight data system instrument complement, data modes and rates.

Investigator teams would have flexibility to vary their instrument data rate to meet observational needs.

Less resources would be required for specification, implementation and testing.

Result

Relatively late in the project development, an instrument was deleted. Its bandwidth was reallocated to the remaining payload with minimal impact to the instruments and mission operations.

Still later in development, a new packet type was added by the camera. This was to accommodate the instruments ability to capture two distinct data streams simultaneously, one for real-time downlink, the other for the recorded stream. This change was accommodated quickly by means of simple table changes to the flight and ground software.

One of the key characteristics of the project's science approach was the decentralization of science operations. The self-descriptiveness inherent in packet telemetry was the key ingredient in facilitating instrument packet routing, processing, and testing.

Being the initial packet telemetry mission at JPL, the project invested more resources in specifying, developing, and testing ground telemetry processing software than expected.

2. Channel Coding

Description

Mars Observer utilized a concatenated coding scheme with a rate 1/2, constraint length 7 convolutional code, and two independent outer coding techniques with totally different operating characteristics: 1) the engineering only CCITT error detection code; and 2) the science and engineering R-S (250,218) error correction code. Spacecraft development costs prohibited R-S encoding both streams.

Expected Advantage

The concatenated code provides high data integrity especially important for instruments utilizing adaptive compression,

The decoding process returns essentially perfect or no data to the end user. The undetected frame error rate, given correct frame synchronization is less than 10^{-12} frames.

Costly post decoding correction algorithms critical to adaptive telemetry can be eliminated,

Errors detected in the downlink are extremely likely to be real and not channel errors. his feature allows for cleaner diagnosis of spacecraft induced errors.

Result

The R-S encoded telemetry processed and returned to the principal investigators during cruise was error free. Comprehensive error statistics for the CCITT encoded telemetry is not available,

Ground telemetry corruption affecting the individual instruments distribution of data loss was unexpected. (See Lessons Learned). Corrupted telemetry in the ground processing chain was identified by comparing pre and post R-S decoded output.

Key field correction algorithms of engineering only telemetry were not implemented by the project. However the decision whether to process engineering data detected to be in error ("suspect data") was up to mission operations based upon the data criticality. Two problems arose from this processing approach: 1) suspect data was routinely screened and for most of cruise statistical analysis was not performed on it; 2) the traditional methods of storing and displaying suspect data was problematic and required unexpected operational workarounds.

3. Standard Formatted Data Unit

Description

The Standard Formatted Data Unit (SFDU) provides standardized techniques for the automated packaging and interpretation of data products. A characteristic of the SFDU is that it provides for self-identification, packaging, and registration of data products in order to facilitate data interchange from multiple sources.

Due to the correlative nature of the project science investigations, and the cross support required from the engineering teams, the mission data interchange requirements were very demanding. To be effective, Mars Observer took an automated operational approach to data interchange, in which subsystem interfaces were negotiated up-front, so that users could benefit from automated data processing and product generation.

Expected Advantage

Provides mission data in a format that will be reusable by future researchers in the international science community,

Facilitates end-to-end data interchange across heterogeneous platforms and organizations.

Provides the project with an end-to-end standard stream and tile interface.

Anticipated to be compatible with the existing capabilities of the Planetary Data System (l'DS).

Anticipated a standard set of generic software tools to be available to the project and extended mission community to support the retrieval, editing, parsing and presentation of SFDU data objects.

Accommodates the inclusion of existing software interfaces not previously defined as SFDUs with minimal impact.

Result

Cruise science and engineering data products were encapsulated into SFDU format and archived on CD-ROM by the PDS.

Both stream and file SFDUs were in general successfully interchanged across project data interfaces.

The project inherited from Magellan a telemetry stream SFDU format, which required minimal adaptation to fit the packet telemetry structures i e., frames, packets, and decommutated packets.

The project ran into some difficulty in establishing the data language used to describe the contents of the SFDU. Existing implementations and emerging standards led to the compromise and use of a parameter value like language for keyword data description.

Software file interfaces required a different SFDU structure: files were delimited by marker and contained a set of parameter value like keywords, used to catalog files into the project database. This approach worked, however, the full power of the catalog, based upon keywords, was not realized.

SFDU tools were developed rather late. Due to the emerging standard, it was unclear whether they would be developed on an individual basis or as a multimission capability. The later was chosen and provided,

Operating Strategy

Experience obtained on earlier Mars missions suggested that operating costs could be reduced if in its operating plan, Mars Observer would structure its operating philosophy to take advantage of the repetitiveness of the mapping mission, the services available through multimission support, and the heritage of the spacecraft

1. 85% Data Return

Description

The project believed that by relaxing the requirement to return "every last bit of data" it could reduce its development and operating costs. As a result it formulated an "85% data return policy." That policy allocated 5% loss to each of the areas: spacecraft-to-instrument hardware and software; project operations; and the ground services of the multimission DSN and AMMOS organizations. The important features that led to this areas follows:

- The mission with its 687 Earth days in orbit, provided several opportunities for obtaining measurements of the same areas. Thus in general, the data obtained on any particular day had the same importance as any other day.

- The telecommunication downlink insured virtually error free data with its Reed-Solomon and convolutional encoding technique.

- Reliable and error free data capture, processing and transfer would be afforded by the ground system using latest advancements in computer and data handling technology.

- Sequencing of the spacecraft tape recorders to record and dump the daily observations would not be interrupted or changed to accommodate loss of a scheduled DSN station view period. Losses caused by tape recorder track changes and start / stop cycles would be acceptable.

- The spacecraft provided a reliable interface with the instruments for the transfer of data and commands.

Expected Advantage

This scaled back approach would result in simpler sequences being developed, a simpler ground data system, and lower staffing levels in the sequence and data management teams. Specifically, the sequence team would not have to accommodate a late DSN schedule change or a missed spacecraft tape recorder playback. The project would not routinely "hunt down" every last packet of missing data that may be recoverable from the DSN; a scientist would be responsible to alert the project if data deemed important were missing.

Result

The sequence development and the team staffing levels were in essence in agreement with the approach. Unfortunately, the ground system did not become as robust as originally thought. Although the percent of data returned during cruise was generally above the 95% level, an arduous work around was needed to obtain the data completeness required by the science. The problem was identified and a solution was in process to correct, For more detail see Lessons Learned, Data Quality.

2. Single Shift Operations

Description

The project plan was to use the multimission services of the DSN and AMMOS to the maximum extent possible and thus reduce the number of tasks the project would directly perform. The spacecraft would be tracked 7 days a week and at times up to 24-hours per day. The project believed that the multimission services could perform specific tasks when the project was not on duty; in fact these services could be used at all times and the project would if their work period mirrored the spacecraft tracking period, observe the activity. The multimission teams would handle the tracking, spacecraft health monitoring, and command operations based on procedures and data files provided by the project. With this approach the project could staff for a single shift 40-hour week, For critical periods the project would arrange its work periods to cover these times,

Expected Advantage

Project staffing level would be for a 40-hour work week; it would not have to staff for a 7-day, 24-hour operation. Multimission services would perform some of the typical rest-lime functions; therefore the project could further reduce its staffing level by assigning responsibility to the multimission teams.

Result

The 40-hour week staffing plan was realized. Though the multimission teams provided the rerd-time monitoring, the project chose to "closely observe" the spacecraft and consequent] y some savings were not completely realized at launch. However during cruise good results suggested a future reduction would probably occur during the mapping phase.

3. Spacecraft Performance Analysis Tools

Description

The project believed that the in-flight assessment of a spacecraft of known design with few technology or design changes should be straight forward. Further, that the process be systematic and performed by system personnel rather than subsystem experts. A suite of tools organized in a windows environment using pull-down menus directing specific functions would assist the analyst in performing specified duties, These tools, taken from former missions, would be changed to provide more trend type of output indicators. Options would be available to deviate from the standard routines should the need require it.

Expected Advantage

Development costs would be kept low by the use of existing programs, and the utilization of commercial analysis and display packages, The spacecraft team staffing level would be smaller by cross training subsystem experts and using system personnel. Consistent with single shift operations the functions would be performed off-line.

Result

Mixed results were achieved, The activity led to the development of an integrated and highly interactive computer based system which assisted an analyst in reconstruction of past subsystem behavior, monitoring of current status, prediction of future subsystem behavior. The concept worked but several stumbling blocks prevented full realization. In particular most analysts were not familiar with the UNIX computer environment and therefore development staff personnel had to support early operations. Also most thought to be applicable software programs had to either be rewritten or did not exist for the required function; this was partly caused by the design changes in the mission. Finally some functions because of their special application e.g., thermal model, were kept outside of this integrated program set,

Sequencing

The project postulated that mission objectives could be achieved without having to perform complex sequence operations i.e., operate the spacecraft and payload in a straight-forward, simple manner. Mission characteristics to support this included:

- The ability of the instruments to perform their own sequence activities – instruments were microprocessor based and thus could function independent of spacecraft bus.
- The mission was non-adaptive to observations - individual instruments could however, change their activities based upon observations.
- Spacecraft data system architecture - robust script (macro) capability – on-board autonomous control of antenna and solar panel positioning.
- During orbit, each day's activity was essentially same as previous day – many repetitive bus operations i.e., record /dump recorders.
- Features previously identified under Operating *Strategy*, Independent Instrument Operation, and Distributed Information Architecture.

From this, a sequence'development and operating strategy was formulated which would reduce the effort previous missions expended in this area.

1, Sequence Development and Operation

Description

A mapping sequence was defined to cover a 28-day period. The number was derived from the spacecraft orbit at Mars which had a 56-day ground track repeat cycle. This provided approximately 27 sequences for the mapping phase. Cruise sequence duration varied to accommodate maneuvers and special calibrations.

The repetitiveness of the mission kept the differences between the mapping sequences very small. Within a sequence, the daily spacecraft bus activities were almost identical, Furthermore, since the instruments operated independently from the spacecraft bus, their activities would not have to be included in the sequence.

Therefore the strategy was to develop skeleton sequences before launch and populate (update) the appropriate parameters during the mission, These parameters e.g., time would provide the values needed to dump the tape recorders, and perform small orbit trim maneuvers.

During the mission, the plan was to precede each 28-day observation period with a 28-day preparation period in which specified parameters would be input to the sequence process and validated. Scientists would have the option to include instrument commands in these sequences, but would be constrained to the 56-day period.

Expected Advantage

With the operations of the spacecraft bus planned and sequences developed, the staffing to perform this function post launch would not be required.

Changes and increased costs caused by being observation adaptive would be mitigated. Science would have the flexibility to be adaptive within the constraints of their own instrument (refer to Independent Instrument Operation).

Result

Development and operations staffing levels were kept low, although the levels were higher than anticipated.

Most investigators did choose to operate their instruments directly i.e., not use the sequence process.

Before launch the knowledge of the spacecraft behavior (operating characteristics) kept changing as the spacecraft development and testing progressed. This resulted in having to change several of the sequences late in the development program,

The spacecraft capabilities became more robust – an autonomous downlink control was added, thus reducing the need for sequences to turn the spacecraft transmitter on/off, While this had a positive effect, the capability came too late to take full advantage of.

The 56-day period required navigation to improve its orbit prediction estimates which resulted in a higher demand than expected for navigation resources. Also the uncertainty of the gravity field increased the number of orbit trim maneuvers which led to a higher level of involvement by the project.

2. Sequence Testing

Description

With the concept of developing simple and repetitive sequences before launch, the plan was to complete this approach by testing them on the spacecraft, again before launch.

Expected Advantage

Not require development or operation of a command sequence simulator,

Result

Unavailability of the spacecraft kept delaying the tests to the point where only 5 key sequences were ever attempted to be tested on the spacecraft. Four of these were successful; the fifth was never run to completion duc to its length and constant interruption by storms at the launch site.

A reverse command translator to assist in validation of the commands being generated was developed.

The project originally did not fund a simulator; late in development a verification test laboratory, comprised of selected spacecraft subsystems was assembled together with software models to stimulate and control the activities. The test lab or simulator was primarily developed to support flight software developmen and testing, as such it operated like the spacecraft in real-time. Selected adaptations were made to enable mission operations sequences to be loaded and executed on the simulator, Approximately 8 months before launch mission operations began using the simulator to test its sequences. Mixed results were obtained until the simulator was validated against the flight spacecraft. The simulator was retained after development and used during the mission to test sequences. As a result staffing levels increased to support this activity,

Independent Instrument Operation

1. Non-interactive Commanding

Description

The project believed the instruments could be operated independent of one another and the spacecraft bus.

An instrument would have an allocation of spacecraft resources (power, thermal, bandwidth), It would be free to change its operation so long as the change did not cause the instrument to go outside its allocation. Working with the science investigators, a set of commands which met this criteria were identified and later designated as non-interactive commands.

Since the science investigative teams design the observations, determine the instrument-internal sequences, and validate the requested actions, it seemed appropriate for this activity to continue through to the instrument with minimum involvement by the project. Therefore as part of the distributed operations and the SOPC computers, the project provided the capability for an investigator to command his instrument via non-interactive commands with minimum project validation.

Expected Advantage

Reduced project involvement would yield lower operating costs and a shorter turn-around time for commanding an instrument, Up to 5000 bytes pcr day were expected to be sent to the instruments.

Result

Initially the process was plagued by a large number of project checks and validations, thus causing delay in getting the commands to an instrument. Changes were made to improve the process and thereby reduce the delay to the point where the investigators were satisfied with the performance.

LESSONS LEARNED

Effect of 85% Recovery Policy on Data Quality

Description

Based upon experience obtained on previous missions, it appeared that the volume of telemetry recovered was the main driver on containing development and operations costs in the downlink area. *In order to be cost effective, the project adopted a fundamental policy to recover 85% of the telemetry acquired by the instruments and spacecraft bus (instead of the nominal 95%) over the course of the mission.* It was believed that this relaxed requirement provided for a flexible and less costly response to faults affecting the downlink process.

Expected Advantage

Provided a traditional means of allocating data loss responsibility amongst ground multimission and project organizations.

Provided a metric to award the spacecraft contractor a performance fee based upon the data volume returned.

Required only regular support of the manually operated telemetry recall capability. No additional telemetry recall capabilities were envisioned.

Made it less likely for end data system users to request additional operation support to go after every telemetry packet acquired,

Limited project staffing in the planning and sequencing and data management areas. Data management would not track every packet lost and sequencing would not accommodate minute sequence changes to save data,

Reduced the probability that ground induced telemetry processing problems involving missing or corrupted data would drive the ground system design.

Result

The flexibility inherent in interpreting the data volume requirement facilitated its acceptance by the supporting organizations and the spacecraft contractor.

The distribution of data loss by the end-to-end ground telemetry system in concert with the camera compression design amplified the imaging loss in cruise to an unacceptable level. This surprising result is understood by examining the true data loss characteristics of the ground system and the camera compression scheme.

It was understood by the project that generally telemetry loss would not occur in small distributed outages. In fact, most telemetry outages occurred in large numbers i.e., greater than 100 frames. However, faults throughout the ground telemetry processing chain together with the lack of a guaranteed ground data transport delivery system created a telemetry stream in early cruise with a missing camera packet on average in every 500 packets recovered,

The preferred camera data mode is predicative (noiseless) compression which is reinitialized each 128 lines of an image (fragment). The compression algorithm resynchronized on such a large interval because as stated above, telemetry outages were thought to occur in large numbers. The loss of any portion of data comprising the fragment resulted in the non-usability of all the subsequent data received for that fragment. Therefore, although more than 85% of the camera packets were recovered during early cruise, an average of 70% of the data could not be placed into images. Visually this resulted in many wide black lines throughout the image.

To solve the problem, several enhancements were made in the ground telemetry processing chain including the camera. The on board camera compression scheme was not changed. However, even with these enhancements in place, operations support increased dramaticall y. In order to recover "every last camera packet" acquired by the DSN, operations intensified their activity of manually recalling telemetry dropped by the ground communication service. In total, these ground changes reduced the telemetry distribution loss rate on average to 1 packet unrecoverable in 10,000 packets acquired by the end of cruise. Numerically this ground loss resulted in 6% of an image loss over an average of five images transmitted,

The other non-compression based instruments were in general not effected by the distribution of data loss in the ground system, since their data reconstruction was more fault tolerant of small data loss.

Other contributing factors to data quality:

As previously stated, the 85% data volume requirement applied to all telemetry sources on the spacecraft. A precise definition of what 85% represented was not agreed to. Therefore each instrument team interpreted the requirement to its own advantage. Instrument compatibility with respect to data loss was not evaluated by systems engineering on a instrument basis. The 85% requirement was viewed as a blanket that covered, each of the instruments, but did not require further penetration of their designs.

The data handling system mandated the use of fixed size packets, since the designers believed collecting non-deterministic variable length packets would be untestable and too costly.

The mission was originally planned without encoding the science data with an error correctional code i.e., Reed-Solomon (R-S). The key characteristic of this code is that the user either receives "perfect data" or none at all. Moreover, data quality has traditionally been specified in terms of bit error rate (BER). However, once the R-S code was chosen, the instrument data quality requirements were never updated to reflect the code's key characteristic, Of importance, was the fact that no other metric of data quality was readily available at the time.

Lessons Learned:

- The traditional data volume requirement alone is insufficient to specify data loss. At a minimum, the distribution of data loss requires specification.[6]

- It is essential to do end-to-end information systems engineering on an instrument to ground data system basis as well as considering the entire system.

- Fixed sized packets and compressed data don't match, Variable length compression is best accommodated by a variable length packet.

- Defining telemetry performance in terms of the traditional BER for missions using error correctional codes is meaningless, since the BER of all recovered telemetry is zero. More meaningful metrics should be specified in terms of transfer frame and packet deletion rates,

- An in-order. delivered once, automated recall telemetry service is much more cost effective than a cumbersome mix of a manually operated real-time and non-realtime recall system.[7]

Test Time with Spacecraft

Mission operations was unable to conduct a thorough spacecraft compatibility test program due to insufficient spacecraft time availability. These tests were a series of activities demonstrating data format, command, sequence and operations compatibility.

Difficulties

It was originally planned to develop and test all sequences with the spacecraft before launch. That plan eroded to the point where only a few critical sequences: first cruise, first maneuver, orbit insertion, deployment and mapping were attempted, Success was achieved only after multiple attempts; the mapping sequence was never run to completion. Test activities to validate ground processing were also hampered by constant data link problems between the spacecraft contractor and the mission operations facilities,

A spacecraft bus simulator was developed late in the program to aid spacecraft development. Mission operations had limited access to it approximately 8 months before launch to start validating sequences. Differences between the simulator and the spacecraft reduced its effectiveness.

With spacecraft test time at a premium, some tests were deleted while others were combined with spacecraft integration and testing, and launch site activities. This combination did not always work as there were differences between the spacecraft test configurations and the expected flight sequence configuration. Thunderstorms at the launch site plagued the test program by constantly interrupting the activity before completion. Most tests required a couple hours to configure the spacecraft and the sequences themselves ran 12 to 24 hours. No sequence test was ever completed before the weather forced the spacecraft test activity to shutdown. Thus the end-to-end tests were severely curtailed because of this.

Recommendation

- Plan short tests; develop sequences that can be easily restarted following an interruption,

- Start testing as soon as possible; mandate early interface tests between the spacecraft and ground system.

- Keep the tests simple; do not attempt to accomplish everything in one test.

- Structure tests to minimize special set-ups or spacecraft configurations.

- Work earlier with spacecraft developers to put together a common or compatible test program.

SUMMARY

Overall, the low-cost approaches the project pursued were successful, There were some technical challenges i.e., PDB; also some short-sightedness in the applications i.e., data standards, and in expected performance i.e., ground data transport process.

Some approaches definitely provided a savings i.e., packet telemetry, or mitigated cost growth by either providing a check-valve or making the change trivial compared to similar functions on previous missions.

Others, were by themselves successful, but when implemented with supporting activities yielded a net result lower than expected. For example, multimission support and single-shift operation - the plan worked, but the concern for risk in light of spacecraft complexity maintained a higher than expected workforce.

The lower than expected success level was not in the approach, but rather in the paradigm of the existing processes in place to support the approach and in the changes that occurred in the mission. This can be thought of as doing the "wrong thing right."

Table 1. presents the results in a Total Quality Management (TQM) view of "right and wrong things" and "right and wrong methods." The arrows indicate the direction of continuous improvement,

Absolute numbers are difficult to obtain due to the complexity, interleaving, and dependency of the approaches with one another and supporting areas. The following nomenclature is used:

- High indicates:
  - Reduction in costs for functions performed on similar mission
  - Enabled improvement in other areas
  - Productivity increased as a result
- Moderate indicates:
  - Mitigated cost increases
  - Approach worked but higher than expected costs were expended to make it happen
- Low indicates:
  - Approach worked but the cost savings were not directly realized due to supporting area costs increasing

Future missions under development or in the planning stage are benefiting from the innovative and cost saving approaches applied first by Mars Observer. With that legacy, the low-cost operating visions of Mars Observer will become a reality.

ACKNOWLEDGMENTS

This research was carried out by the Jet Propulsion Laboratory, California Institute of Technology, under contract with NASA. The results represent the efforts of many members of the former Mars Observer project. The authors wish to thank them and Phil Varghese for their contribution to this publication.

REFERENCES

[1] Solar System Exploration Committee, NASA Advisory Council, "Planetary Exploration through Year 2000–A Core Program," Washington, DC, 1983.

[2] Space Science Board Committee on Data Management and Computation, Assembly of Mathematics and Physical Science, National Research Council, Data *Management and Computation, Vol. 1: Issues and Recommendations,* National Academy Press, Washington, DC, 1982,

[3] "Packet Telemetry," *Recommendation for Space Data System Standards,* Consultative Committee for Space Data Systems, NASA, Washington, DC, CCSDS 102.O-B-2, Jan. 1987.

[4] "Telemetry Channel Coding, " *Recommendation for Space Data System Standards*, Consultative Committee for Space Data Systems, NASA, Washington, DC, CCSDS 101 .0-B-2, Jan. 1987.

[5] "Standard Format Data Units, Structure and Construction Rules," *Recommendation for Space Data System Standards,* Consultative Committee for Space Data systems, NASA, Washington, DC, CCSDS 620. O-B-1 , Feb. 1988.

6,7 "GTS PAT Technical Topics Report", JPL D-11436, Jan. 12, 1994.

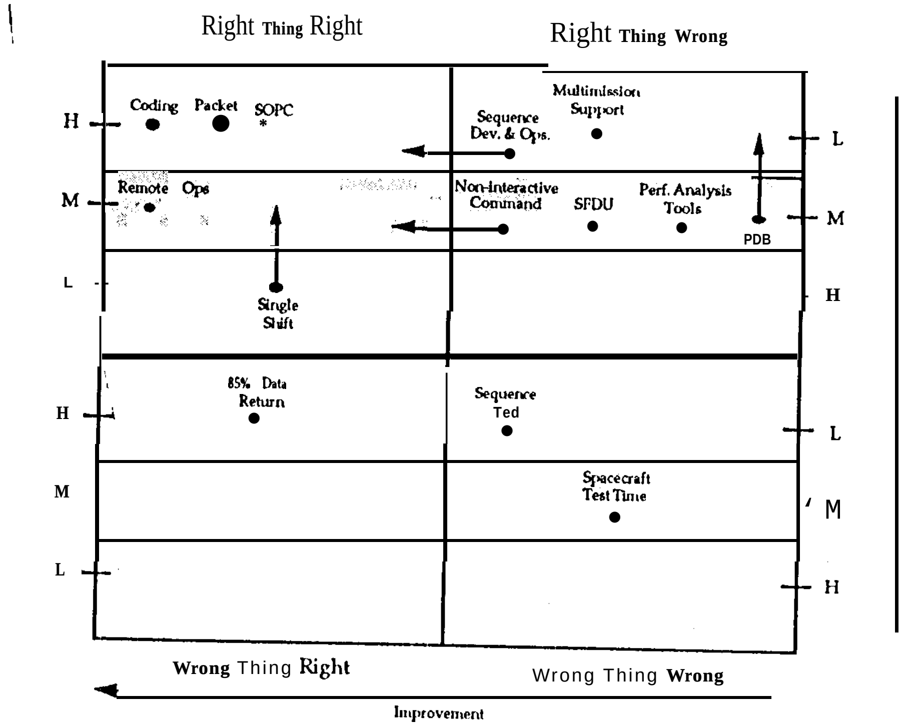

Table 1. Approach Summary