Mars Observer Mission Operations

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Mars Observer, planned for a launch in September 1992, will be the first deep space planetary mission to fully utilize a distributed operations concept for science planning, instrument control, and data distribution. In addition, several other concepts in the area of data handling and operations proposed by the Mission Operations and Information Systems Subcommittee of the Solar System Exploration Committee have been adopted for the purpose of improving the efficiency and reducing the costs of deep space mission operations. At the completion of its 687-day prime mission, Mars Observer will have produced and deposited a terabyte of information on its project data base.

Introduction

THE two primary mission operations processes of uplink and downlink can be represented by a simplified model, as shown in Fig. 1. Basically, the uplink process results in spacecraft and instrument control, whereas the downlink results in science and engineering data acquisition and analysis. Although preliminary science data analysis is necessary for the purpose of assessing instrument health, detailed science data analysis is not considered to be part of mission operations. The mission operations system (MOS) used to support this set of processes is comprised of the ground data system and the operational elements necessary to execute the mission plan. This definition excludes elements of the spacecraft and instrument data systems. However, for a full understanding of the Mars Observer MOS design, an appreciation of the end-to-end data system, including several features of the mission, spacecraft, and instruments, is important. Because the mission provides repetitive opportunities for science measurements, near-term feedback from the data analysis process to the mission analysis process is not critical to the mission operations design.

Selected Mars Observer Characteristics

Characteristics that provide the opportunity for the type of MOS described later include 1) a nadir-pointing spacecraft with instruments mounted to provide a continuous view toward the nadir, 2) a payload consisting of seven investigations with independent control requirements, 3) a packet-based flight data system, and 4) a repetitive, nonadaptive mapping mission. These characteristics combine to practically eliminate, with the possible exception of power, conflicts for spacecraft resources. The following subsections amplify these characteristics from an operations perspective. Further information may be found in Refs. 1–5.

Spacecraft and Instrument Characteristics

During the mapping phase of the mission, the $+z$ axis of the spacecraft will be continuously pointed in the nadir direction. The instruments are attached to the spacecraft in a manner that takes advantage of this geometry to achieve a nearly continuous opportunity for data acquisition. In particular, there is no articulating platform shared by two or more instruments that limits the observation opportunities available to each investigation. For the MOS, this represents a significant reduction from other missions, i.e., Voyager, in the complexity of the command sequences required to control the spacecraft and instruments.

Figure 2 shows a simplified view of the flight data system. Primary instrument control is effected via commands detected by the telecommunications subsystem and forwarded via the payload data subsystem (PDS) to the instruments. The PDS also polls the instruments for data to be downlinked. Other spacecraft control is via commands stored in the command and data handling (C&DH) subsystem memory for execution. The science instruments use dedicated microprocessor-based techniques for measurement control and data preprocessing. The PDS polls the instruments and formats the downlink data. The C&DH subsystem provides overall spacecraft management including altitude control. This system possesses many of the characteristics of a distributed data system. Instrument control commands do not, in general, require interinstrument coordination nor do they affect the PDS or C&DH. Thus, these data system features, combined with the nadir-pointing features noted earlier, allow nearly all day-to-day instrument control activities to be delegated to the respective instrument investigation teams.

Data Standards Characteristics

The Mars Observer project has elected to use the recommendation of the Consultative Committee for Space Data Systems for packet telemetry,[6] telemetry channel[7] coding, and standard data format unit[8] for data distribution. 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 C&DH subsystem. Thus, the downlink rate can be constant for extended periods of the mission, the extent of those periods being determined by the telecommunications link capabilities. Figure 3 shows this rate structure for the mapping phase of the mission. Reed-Solomon coding provides data integrity and allows instrument data compression as high as 15:1. The coding also provides for reduction in ground processing that would otherwise be performed to insure data integrity. The standard formatted data unit (SFDU) provides standard software interfaces and self-documentary capabilities for ground data handling.

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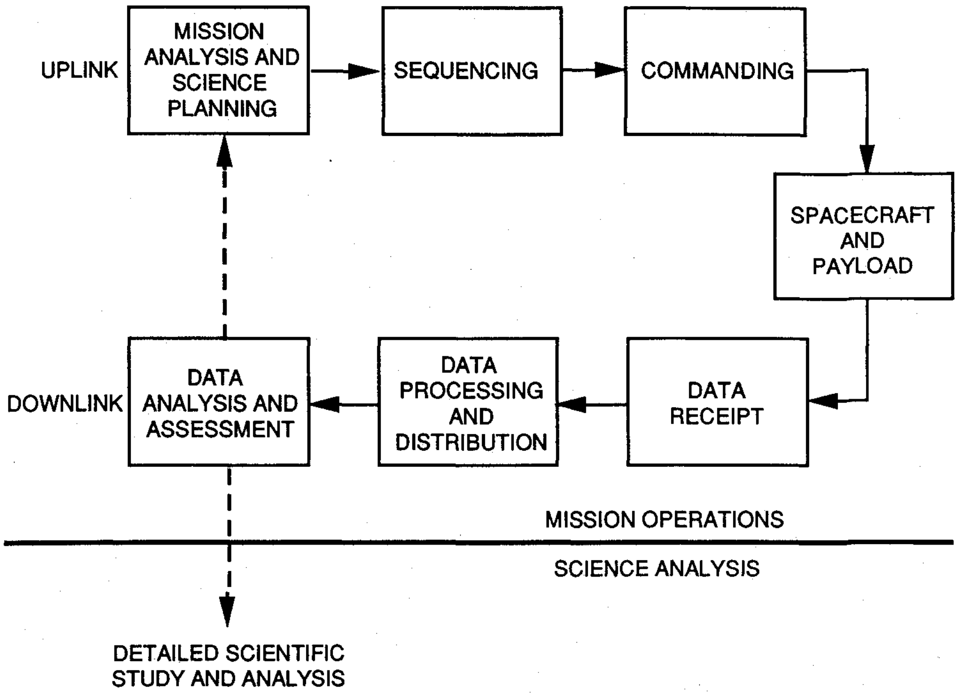

Fig. 1 Mission operations process model.

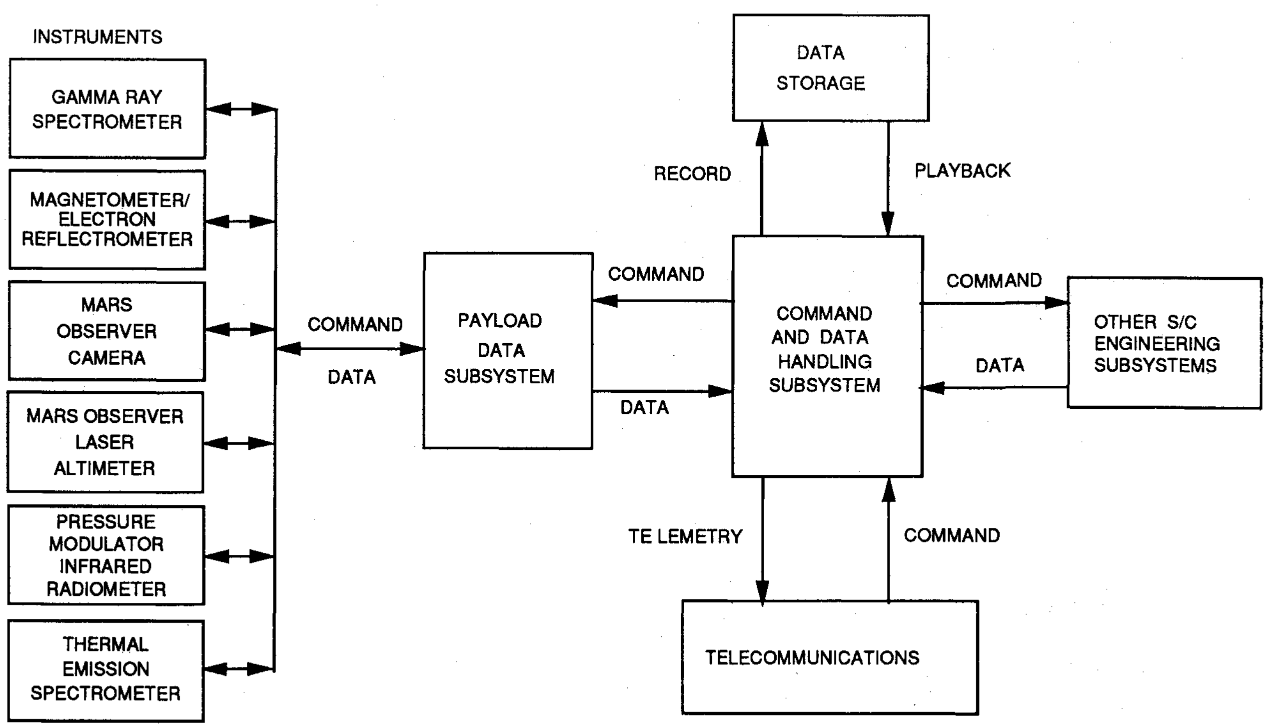

Fig. 2 Flight data system.

Mission Characteristics

Mars Observer consists of several mission phases (see Fig. 3). The most demanding phase for MOS is the mapping phase.

The mapping orbit is a low-altitude, nearly circular orbit with a ground track that will provide complete coverage of the surface to 3 km after nearly one Martian year. Thus, there are several opportunities to observe the same region of Mars. As a consequence, mission operations are not required to be adaptive.

Communication with the spacecraft is provided by the Deep Space Network (DSN). Coverage will be one horizon-to-horizon pass each day by a 34-m deep space station plus one additional pass every third day. To support continuous science and engineering data acquisition, the data are continuously recorded on the spacecraft for playback during the daily DSN pass. Earth acceleration interrupts telecommunications for as much as 41.4 min of the 118-min orbit period. Figure 4 shows the recorded data return strategy. The every third day pass provides high rate real-time data for the camera and thermal emission spectrometer. The data return is similar to that shown in Fig. 4.

End-to-End Data System

A simplified diagram of the end-to-end data system is presented in Fig. 5. The system consists of four major pieces: the flight data system discussed earlier, the tracking data system or DSN (including NASA communication circuits), the multimission Space Flight Operations Center (SFOC), and the project-unique ground portion. 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. It does not have an operational role, but at regular intervals during the Mars Observer mission, project data will be forwarded to this archive. Multimission capabilities include the DSN and the SFOC. PROJECT:LOCAL is located at the Jet Propulsion Laboratory (JPL), and PROJECT:REMOTE represents support elements located at the home institutions of the investigators.

Mars Observer places no unusual requirements on the DSN for acquiring and handling science and engineering telemetry, radiometric and very long baseline interferometry data, and radio science occultation data. The balance of the end-to-end data system is traceable to the SFOC, a distributed ground data system capable of being extended to support several concurrent deep space missions.

Mars Observer will be the first project to use nearly all of the SFOC uplink and downlink capabilities. Extension of the SFOC to a particular mission is achieved by 1) adapting core multimission software and, as necessary, hardware capabilities to project-specific requirements; 2) adding a project-dedicated physical extension to the core network; and 3) adding project-unique software.

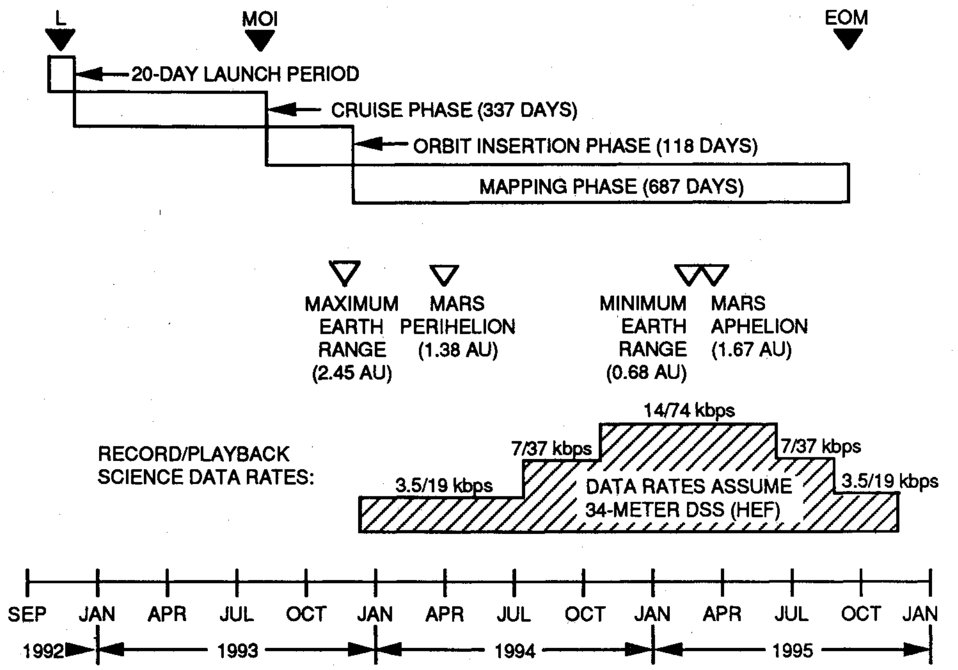

Fig. 3 Downlink plan supported by telecommunications.

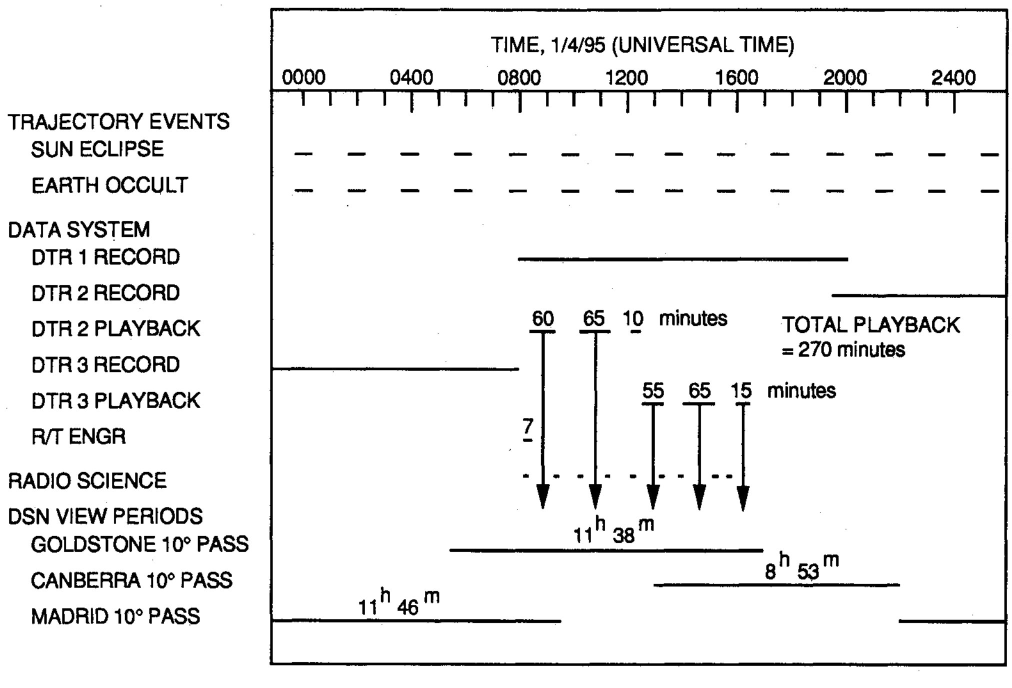

Fig. 4 Recorded data return.

Multimission Capabilities

As shown in Fig. 5, the multimission SFOC capabilities include telemetry processing, flight system commanding, data system operational control, telecommunications link performance assessment, and simulation of the ground portion of the data system.

Telemetry processing includes error detection and correction using the Reed-Solomon encoding information, depacketization of the transfer frames, placement of the packets into the project data base, channelization of the engineering data for display at an analyst's workstation, and monitoring of spacecraft engineering data for health assessment. Note the absence of any requirement to process the contents of the science data packets. That processing is the responsibility of the investigators.

Figure 5 does not faithfully reflect spacecraft commanding since the capability to enter command requests into the project data base is distributed to several project workstations. In particular, it is a capability of the science operations planning computer (SOPC) provided to the instrument investigators. (The distinction between principal investigator and team leader is not an MOS discriminator, and so the term instrument or lead investigator is used.) Instead, the command workstation shown in Fig. 5 will have responsibility for final formatting of the command requests and formal release of the request to the DSN for transmission.

SFOC system monitor and control is responsible for data system administration of the local area network and internode communication. Gateways will be used to provide isolation between networks.

A multimission deep space telecommunications performance analysis capability will be used to monitor the link performance. The multimission software will be adapted by supplying parameters describing the telecommunications subsystem of the Mars Observer spacecraft. The principal benefit is operational since real-time analysis costs are distributed across several projects. A similar condition exists with regard to the simulation capability required to support ground data system integration and test.

Project-Dedicated Extension

Those portions of the end-to-end data system annotated in Fig. 5 as PROJECT:LOCAL and PROJECT:REMOTE constitute a project-dedicated extension of the SFOC. The complement of hardware for this extension will be a competitive procurement. However, a representative range for the expected performance of the workstations is shown in Table 1.

Table 1 Representative workstation performance

Features	Class 10	Class 20	Class 30	Class 30 (SOPC)
CPU	12 MIPS	16 MIPS	20 MIPS	20 MIPS
Memory size	8 MB	24 MB	32 MB	32 MB
Disk storage	327 MB	2×327 MB	688 MB	688 MB
Tape storage	Cartridge (150 MB)	Cartridge (150 MB)	Cartridge (150 MB)	Cartridge (1500 MB)
	no	no	no	9-Track 1600/6250
Monitor	16 in. color	19 in. color 8 plane	11 in. color 24 plane	19 in. color 24 plane 1152×900
Keyboard/mouse	yes	yes	yes	yes
Laser printer	no	no	no	yes
CD-ROM	no	no	no	yes

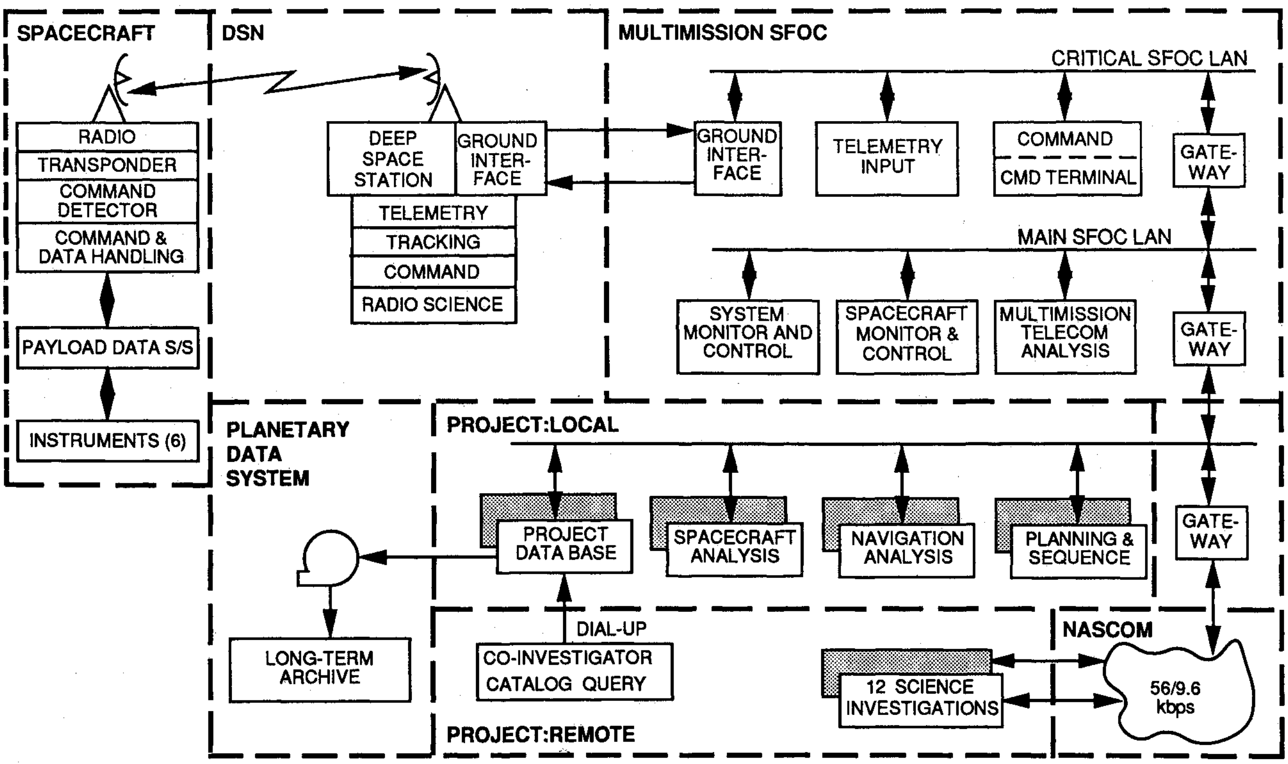

Fig. 5 End-to-end data system.

Table 2 Lead and interdisciplinary science investigators

Investigation	Investigator	Operations site
Gamma-ray spectrometer	W. Boynton	University of Arizona, Tucson, AZ
Magnetometer	M. Acuna	Goddard Space Flight Center, Greenbelt, MD
Mars Observer camera	M. Malin	Arizona State University, Tempe, AZ
Mars Observer laser altimeter	D. Smith	Goddard Space Flight Center, Greenbelt, MD
Pressure modulator Infrared radiometer	D. McCleese	Jet Propulsion Laboratory Pasadena, CA
Radio science	G. Tyler	Stanford University, Stanford, CA
Thermal emission spectrometer	P. Christensen	Arizona State University, Tempe, AZ
Climatology IDS[a]	J. Pollack	NASA Ames Research Center, Moffett Field, CA
Geosciences IDS	M. Carr	United States Geological Survey, Menlo Park, CA
Polar Process IDS	A. Ingersoll	California Institute of Technology, Pasadena, CA
Surface-atmosphere interactions IDS	B. Jakosky	University of Colorado, Boulder, CO
Data and Archiving IDS	R. Arvidson	Washington University, St. Louis, MO

[a]IDS = Interdisciplinary scientist.

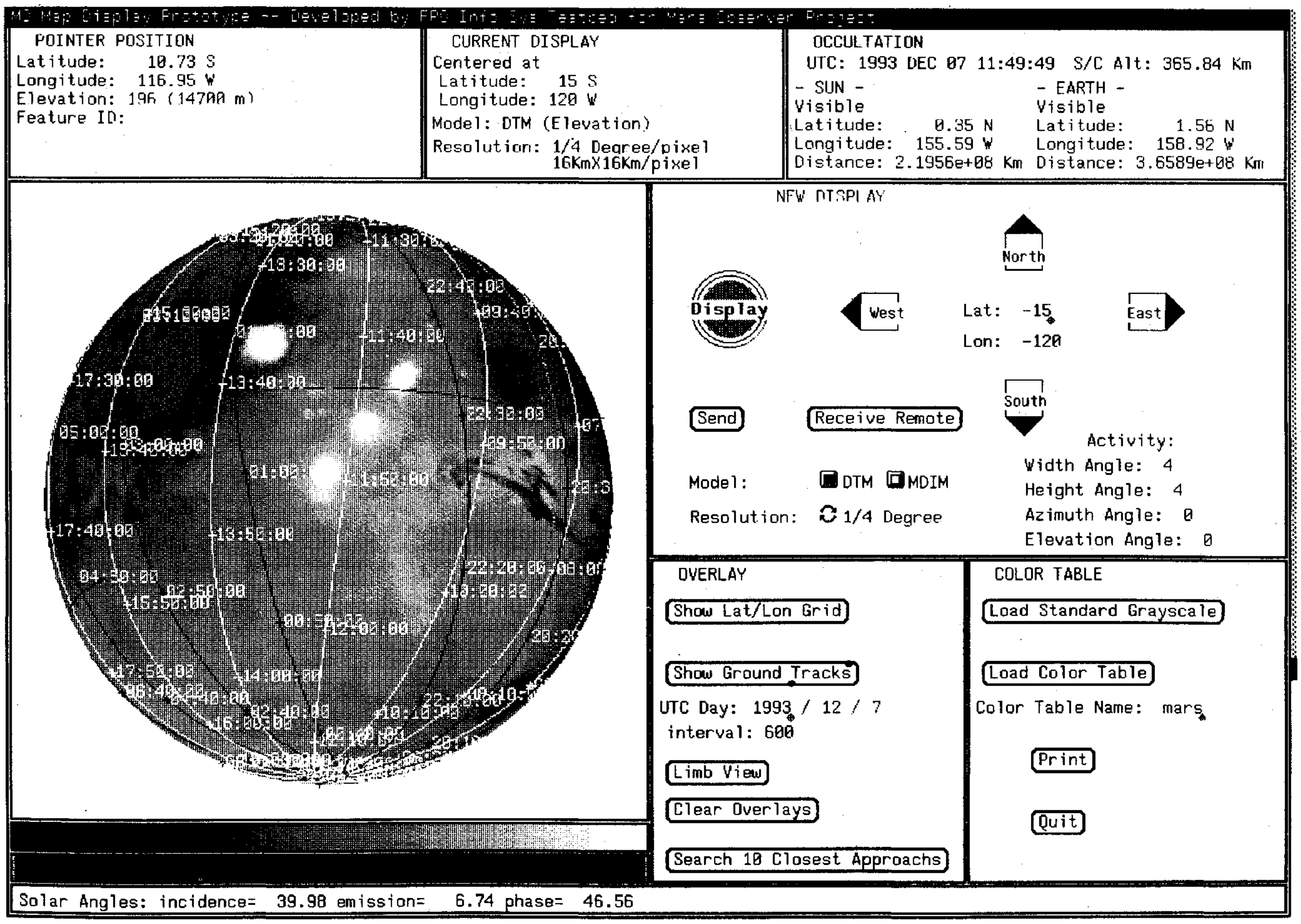

Fig. 6 Mars map display.

The extension accomplishes three major results: 1) it provides a set of workstations for performing the necessary flight engineering operations, 2) it provides a workstation at each lead investigator's home institution for supporting science operations, and 3) it provides a project data base that is accessible to users at JPL's support area and investigator's home institutions.

Engineering Support

The PROJECT:LOCAL extension consists of those capabilities required to perform the classical set of engineering operations functions in support of a deep space mission. These include spacecraft performance analysis, spacecraft navigation, and flight system command sequencing, primarily command sequencing of the spacecraft bus. Provisions are also made for a modest science support and operations planning capability.

The spacecraft performance analysis software consists of programs that model the performance of the attitude and articulation control, propulsion, power, and C&DH subsystems including the digital tape recorder assembly.

The navigation software includes orbit determination and various trajectory control programs. The core of the orbit determination program is a carryover from several previous missions, including Viking and Voyager. However, the Martian gravity field is highly irregular and will be a significant factor in orbit knowledge and control accuracy; therefore, a major activity will be the development of a 20th degree and order gravity model.

The planning and sequence command software will be an adaptation of multimission software that is presently under development by the SFOC. Developed in the object-oriented language C++, adaptation will consist of entering Mars Observer unique data into various tables and, in the case of the command sequence software, adding routines that characterize constraints imposed by the spacecraft and science instruments. Functionally, the software will be similar to the present command sequence software employed by Voyager and other projects. Architecturally, however, it will take advantage of current workstation and data base technology. These changes are central to Mars Observer since this software will also be hosted on the remote science workstations with the expectation that a remote user, in this case, a science investigator, participate in the command process. Clearly, all users must be able to conveniently access the set of data for a command sequence in its development phase.

Science Support

The PROJECT:REMOTE extension consists of those capabilities required to support instrument operational control and health assessment, transfer of science measurement packets and ancillary data to the investigators, and transfer of reduced science data products to the project data base.

The remote components consist of one SOPC located at the home institution of each lead and interdisciplinary investigator (Table 2). As noted in Table 1, the SOPC is a specially configured version of the Class 30 workstation. The SOPCs will be

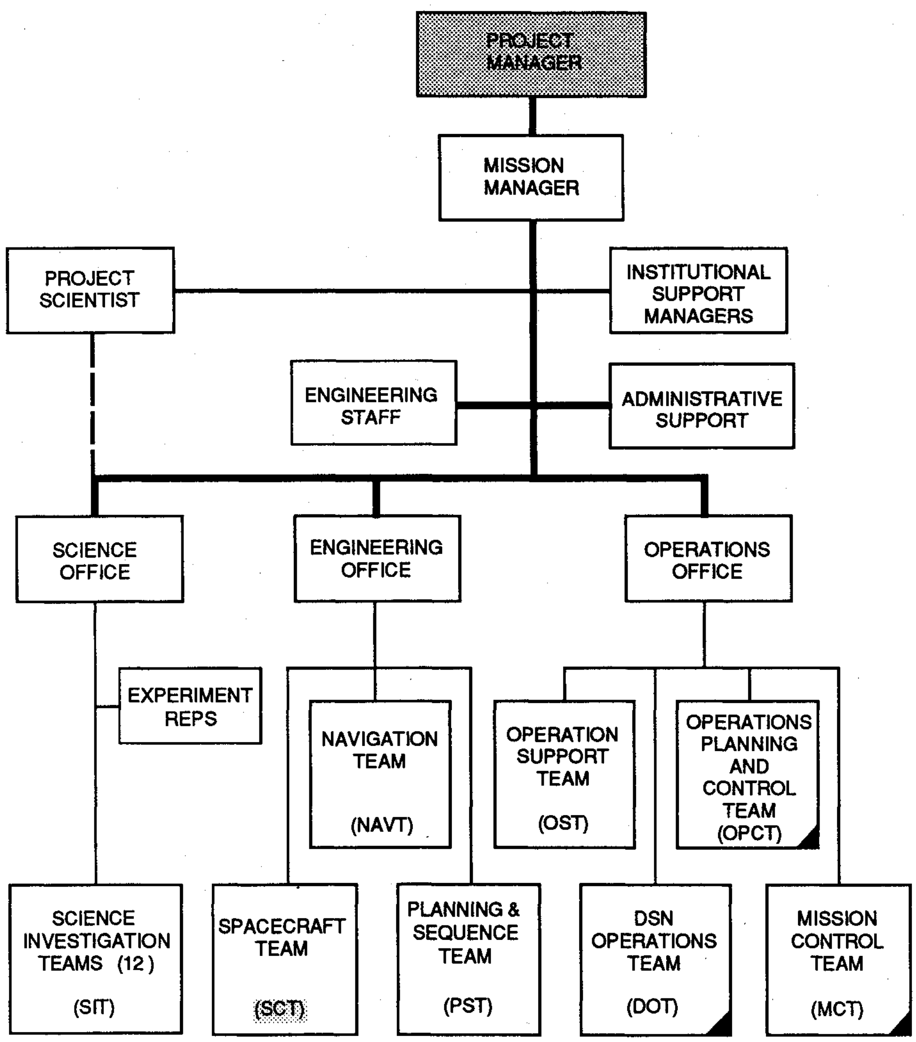

Fig. 7 Mission operations organization.

connected to the project data base via 56-kbyte/s, NASA-supplied communication circuits.

The SOPC will provide lead investigators with direct control of their instruments subject to certain MOS resource limitations and the capability to provide data system security and integrity. This will allow the lead investigators to prepare more than 95% of all of the commands required for their experiments and to forward those commands directly to the project data base command request file. Following some modest integrity checks and final formatting, the commands will be uplinked.

The SOPC will be delivered with a digital map of Mars and software tools to overlay user selected mission data (see Fig. 6). The map is being developed for Mars Observer by the U.S. Geological Service at Flagstaff, Arizona, using Viking images. Subject to storage and response time constraints, the map will be represented on the SOPC at various resolutions. Since a 1/64-deg/pixel map, corresponding to approximately 930 m on the surface of Mars, requires approximately 550 Mbytes of mass storage, substantial workstation performance vs resolution trades will be required. Prototypes of the SOPC are being used to help select the set of scales to be provided. Experiments to date suggest that achievement of a 2-s response time to a user request may limit map resolution to 1/32 deg/pixel (1860 m).

The trajectory overlay information will be derived from a set of tools provided by the Navigation Ancillary Information Facility.[9] These tools interface directly with the navigation ephemeris files in the project data base and can be used to compute a wide range of ancillary data. This capability will be especially useful for defining when a feature of interest is in an instrument's field of view.

The SOPC is required to provide the investigators with access to the science telemetry within 24 h of its receipt by the DSN and the SFOC. Nominally, the data will be available within minutes. As noted earlier, that data, in packet format, will be placed in the project data base upon receipt. The investigator may, at any time, query the project data base to ascertain the status of data and may then extract data of interest for which a read privilege is in effect. For the interdisciplinary scientists (those investigators not tied directly to an instrument), this process can be used to retrieve reduced science data products that have been returned to the project data base by the lead investigators. Coinvestigators and participating scientists will be able to query the project data base catalog via dial-up lines to determine availability of products and, subsequently, to request and obtain the relevant products from the cognizant lead investigator.

Data Base

Physically, the project data base will be located at JPL. As the earlier discussion implies, however, it will be electronically available to the entire project on a 24-h, 7-day-per-week basis. All ground-based software is required to operate via this data base for data retrieval and storage. This constraint, along with the data documentation features of the SFDU discussed earlier, should provide for effective administration of the project data.

The data base capability may be implemented using a network of workstation-class computers or, depending on the results of current data architecture studies, it may be a midframe. Initial sizing for 30 days of on-line mission and science data corresponds to approximately 28 Gbytes; 11 Gbytes being allocated to engineering and other mission support, and 17 Gbytes being allocated to science data.

Finally, standards applicable to most of the data in the project data base will conform to the formats being instituted for the planetary data system. This is intended to support efficient transfer of the data to that system for long-term archive. Since the mapping mission duration is approximately 1.9 yr with an average production of 1 Gbyte/day, it will be necessary to begin transferring products to the planetary data system prior to the end of the mission if that task is to be completed prior to the end of the project.

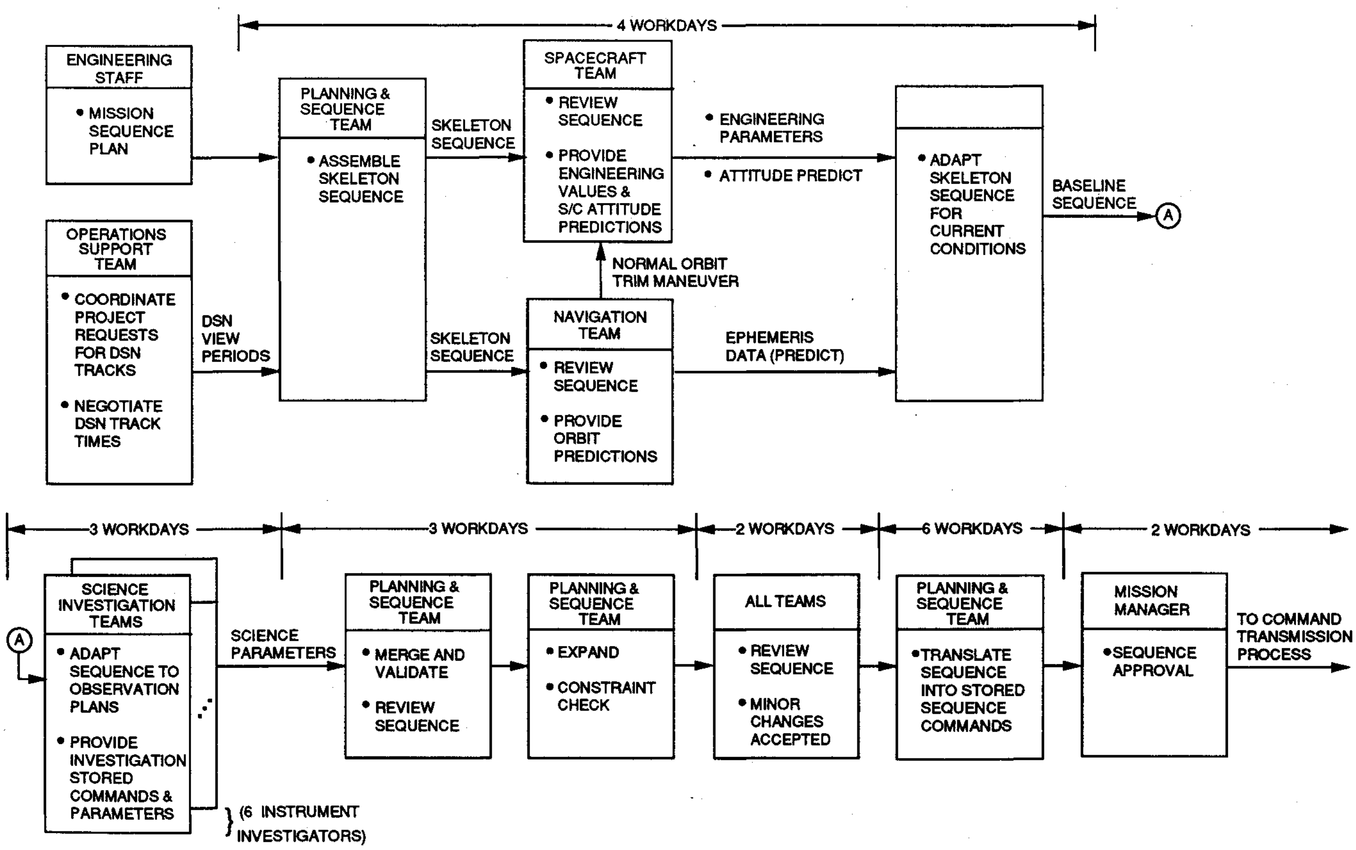

Fig. 8 Stored sequence process.

Operations

In this section, selected Mars Observer operational processes are described. The processes selected for description reflect time and space limitations for the article, not a judgment of the relative importance of one process with respect to another. The discussion illustrates the operations strategy and discusses the design of several operations processes that support the strategy. For convenience, the process descriptions are given in terms of the teams comprising the operations organization.

Operations Strategy

Mars Observer mission operations will be constrained to be considerably less adaptive than operations for most deep space missions. This has been noted earlier as a reflection of the repetitive character of the mapping phase trajectory and the recurrent data acquisition opportunities. The nature of the constraint is perhaps best illustrated by the spacecraft command sequencing (uplink) strategy that will be used; however, the data return (downlink) strategy, with its modest 85% data recovery requirement, is also indicative of the constraint.

Uplink Strategy

The uplink strategy consists of generating, on 28-day centers, a stored sequence command (SSC) load that will be used primarily to control spacecraft bus operations and update onboard spacecraft ephemerides and star catalogs. More significantly, however, each SSC load that is necessary for the support of the mission must be implemented and tested with the spacecraft prior to launch. This reflects a decision not to include a command sequence simulator in mission operations. Without a simulator, there is no reliable method for certifying untested command sequences, and without that certification, the risk to the spacecraft is deemed to be unacceptably high.

Thus, SSC load generation during mission operations is actually an adaptation process consisting primarily of revising the parameters of a skeleton sequence built prelaunch. These skeleton sequences are constructed to reflect an approved mission plan and, following test verification with the spacecraft, are documented as the mission sequence plan.

Since instrument operation is nearly independent of spacecraft bus operation, this design is appropriate. Each investigator may request transmission of noninteractive real-time commands (NRTC) to their instrument at any time subject to operations scheduling and spacecraft activities. The investigators are tasked with insuring that commands to their instrument will not endanger the instrument, a condition that will be demonstrated during instrument and spacecraft system testing. In addition, the real-time command process, discussed later, will insure that any NRTC request is addressed to the intended instrument.

Downlink Strategy

As noted earlier, the Mars Observer downlink strategy consists of a daily playback of the spacecraft digital tape recorders plus a real-time data return every third day. The principal downlink operations requirement is to recover 85% of the data acquired by the instruments. By the standards of most planetary missions, this is a relatively modest requirement. In-

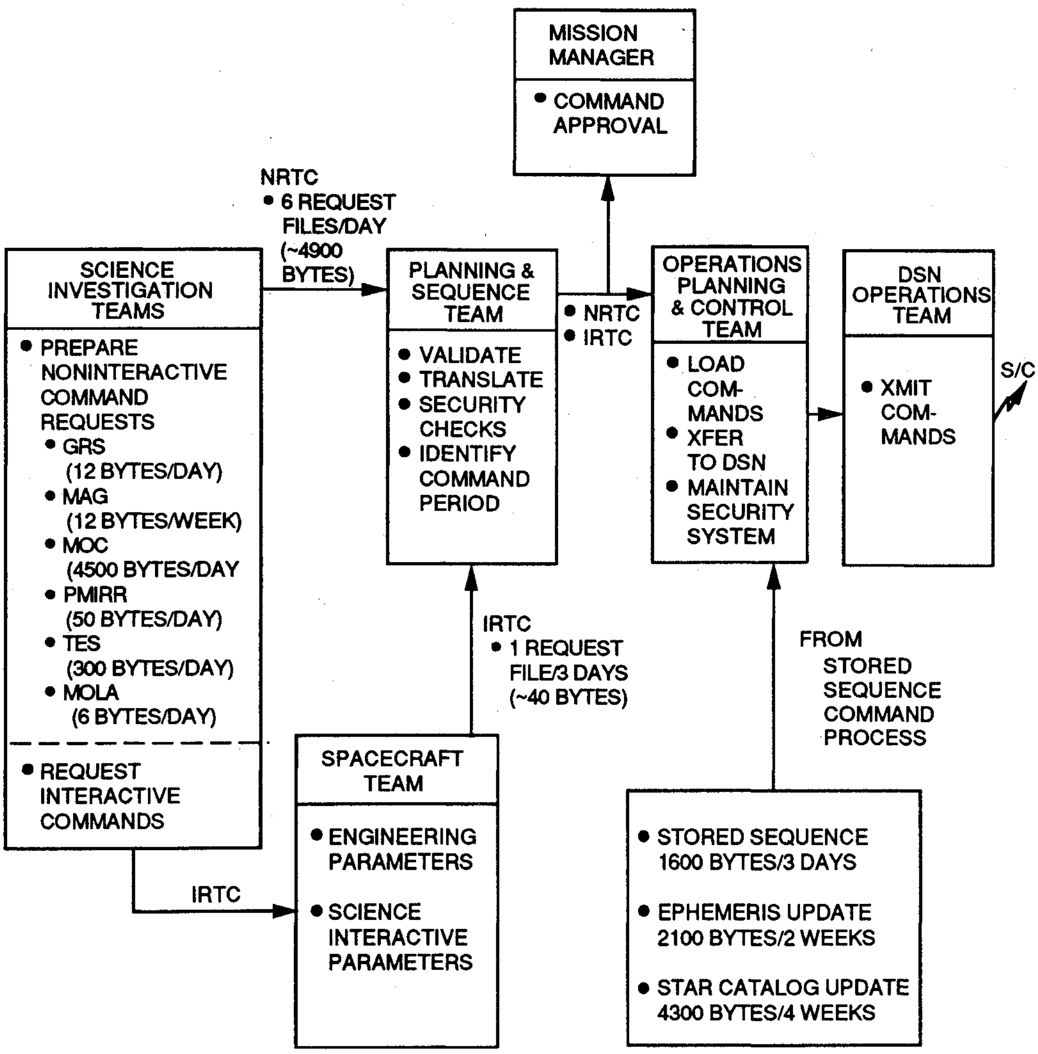

Fig. 9 Command transmission process.

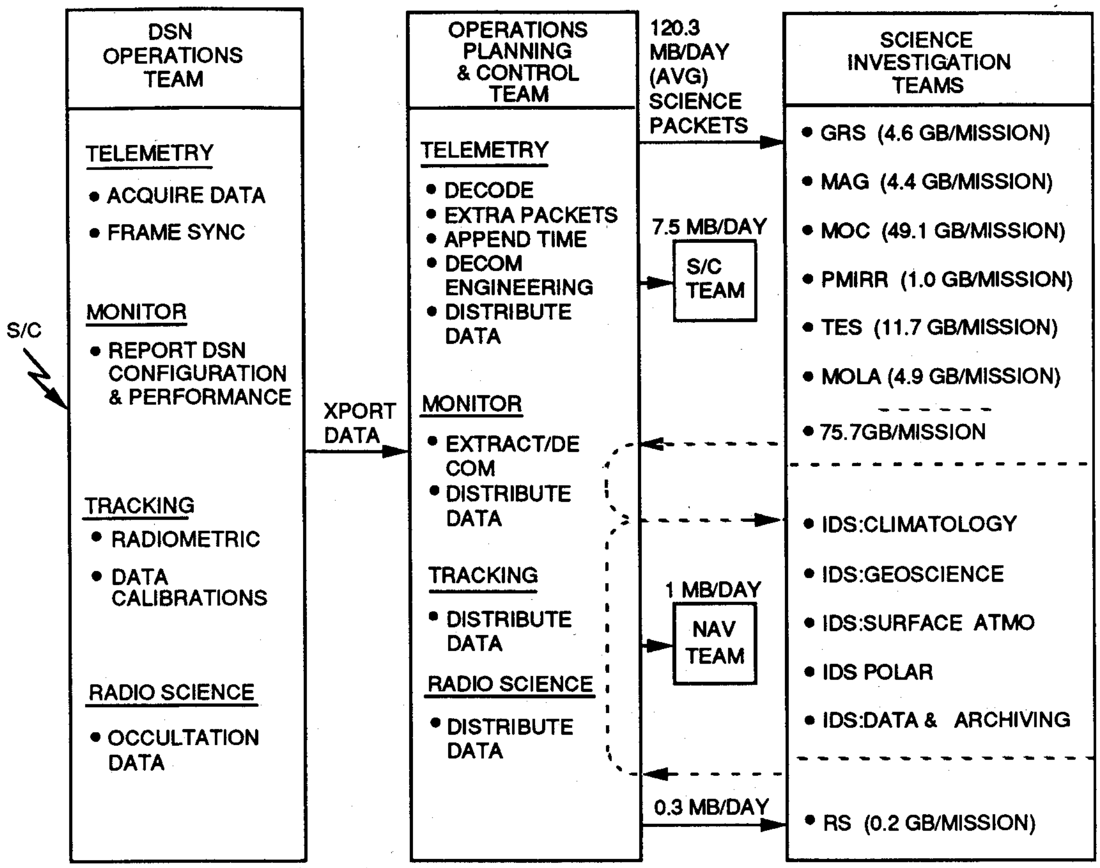

Fig. 10 Downlink process.

deed, present estimates for meeting this requirement indicate that more than 95% of the data will actually be recovered. However, the relaxed requirement is a key ingredient of the downlink strategy since it provides for a flexible and, it is hoped, a less costly response to faults affecting the downlink process.

Operations Processes

Figure 7 shows the operations organization. The 12 investigations listed in Table 2 are organized into a science office with responsibilities including instrument control and health and science data analysis and product generation. The engineering office is responsible for spacecraft bus operation and performance analysis, trajectory knowledge and control, and spacecraft bus and instrument sequencing. The operations office is responsible for operations planning and execution and project data base administration.

Uplink Processes

There are two key features of the uplink process: stored sequence command loads and NRTC. Provisions are also being made to accommodate interactive real-time commands (IRTC), even though they are expected to comprise less than 5% of all commanding.

Figure 8 shows the SSC adaptation process. It is applicable for the mapping phase, although there is nothing to preclude its use during other phases of the mission. The mission sequence plan provides the guidance for spacecraft operations including a definition of the SSC loads tested before launch. The operations support team negotiates the institutional support necessary to implement the plan, and the planning and sequence team proposes a skeleton sequence that reflects ground support capabilities. Further modifications of a similar nature are made by the spacecraft and navigation teams to reflect current capabilities and conditions in those areas.

With the skeleton sequence updated to current conditions (as opposed to the nominal conditions used for test verification), the science investigators develop their observation plans and reflect those plans as sequencing requests. It is expected that, with the exception of radio science, the remainder of the process will consist of using the sequence software to integrate the independently developed sequence requests, verifying that no spacecraft or mission constraints are violated, and translation of the sequence into a command file.

Figure 9 shows the command transmission process. Nominally, the SSCs are input to this process via a set of files produced by the sequence software and entered into the project data base. Each file in the set provides the operating instructions for the spacecraft bus spanning a period of approximately 3.5 days and is estimated to be 1600 bytes long. This 3.5-day period is limited by the spacecraft sequence buffer size and may be adjusted after the sequences are developed. In addition, updates to the spacecraft's ephemeris and star catalog are inputs to this process from the SSC process. These two products are updated at intervals of two and four weeks, respectively, and are estimated to be 2100 and 4300 bytes in length. Although instrument control can be accomplished via SSCs, most of the investigators will use NRTCs as the primary control mechanism.

NRTCs are developed by the instrument investigators using tools built to support implementation and test of the instruments. The tools, at the discretion of the investigator, may or may not be hosted on the SOPC. In the case where the instrument is commanded to only a few discrete states, SOPC-provided capabilities may be used. In either case, Fig. 9 shows the rate for this command type. NRTCs will be subjected to modest validation in the command process, the key objective being certification that the command request is indeed noninteractive and that the source of the request and the destination address are in agreement. Assuming that the validation proceeds smoothly, command approval will be reasonably pro forma.

IRTCs, by definition, are commands that cause more than one instrument or subsystem to respond in some significant way to the command. A classic example of an IRTC is a command to an instrument or subsystem that changes the power requirements. The use of this command type is primarily for engineering parameter updates and is not expected to exceed one request every three days. The nature of IRTCs requires that the spacecraft team be responsible for their design. The planning and sequence team translates the design to command bits for transmission by the DSN.

Downlink Processes

The Mars Observer downlink (Fig. 10) is reasonably straightforward. A new feature is the distribution of the science data to the lead investigators via the 56-kbyte/s lines (Fig. 5) in the packet format produced by the instruments and the subsequent return of processed data to the project data base. Averaged over the mission, the raw data rate is in excess of 120.3 Mbytes/day. Initial data reduction is performed by the lead investigators for several purposes, one being the return of products to the project data base for distribution to the interdisciplinary scientists (IDS). These transfers to the IDS are viewed as part of the downlink in the sense that IDS' measurements are the partially reduced data for a subset of the instruments. For this reason, Fig. 10 shows them as broken lines.

Other products are returned to the project data base as an intermediate step in the delivery to the planetary data system — the long-term data archive. These products comprise the principal science output and are presently being defined by the science data management plan. The volume of this data has been estimated to be in excess of 620 Gbytes.

Configuration Management and Security

The distributed system with its 40 plus workstations presents new challenges in maintaining system integrity. Configuration management for Mars Observer includes the hardware and its location, software, procedures, documentation, and accountability records. The level of control and its implementation will vary according to the prescribed functionality levels in the mission configuration management plan. For example, each science investigation will develop and administer a configuration management plan; changes in that facility or investigation can vary from requiring formal project change control board approval to only notification of a change.

The Mars Observer project will have its system in place to support early ground system software development and delivery. Since a substantial portion of the software and hardware is provided by SFOC, Mars Observer will use, to the extent permissible, the approach and tools being implemented by SFOC. As a further aid, each product with an SFDU label will carry software version numbers, thereby providing a genealogy of its generation. Although no formal development of software is planned after launch, changes will occur and this process will be followed throughout the duration of the mission.

Computer security in a distributed environment is a prime concern with the current outbreak of virus and information compromises. The Mars Observer project plans to implement physical, operational, and electronic controls to insure system operational authenticity and information privacy. The mission security plan specifies the criteria that the ground data system must meet. The specific techniques the project and SFOC will be using will not be discussed.

Summary

The Mars Observer mission operations represents a new and challenging approach to control of the instruments of a deep space mission. Inherent in this approach is the application of techniques intended to lower operations costs.[10] These techniques are distributed throughout the project and include the following: the mission with its repetitive mapping opportunities and nonadaptive operations policy; the spacecraft flight data system that separates bus and instrument operation; the ground data system with its widely distributed collection of powerful workstations giving instrument control authority to the investigators and near-real-time access to science measurements; the use of data standards (coding, packet, SFDU); and the centralization of data management using modern data base management tools.

Acknowledgments

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References

[1]Palocz, S., "Mars Observer Mission and Systems Overview," *Journal of Spacecraft and Rockets,* Vol. 28, No. 5, 1991, pp. 491–497.

[2]Komro, F. G., and Hujber, F. N., "Mars Observer Instrument Complement," *Journal of Spacecraft and Rockets,* Vol. 28, No. 5, 1991, pp. 501–506.

[3]Potts, D. L., "Mars Observer Spacecraft Description," *Journal of Spacecraft and Rockets,* Vol. 28, No. 5, 1991, pp. 507–514.

[4]Blume, W. H., Dodd, S. R., and Whetsel, C. W., "Mars Observer Mission Plan," *Journal of Spacecraft and Rockets,* Vol. 28, No. 5, 1991, pp. 522–529.

[5]Esposito, P., Demcak, S., and Roth, D., "Mars Observer Orbit Determination Analysis," *Journal of Spacecraft and Rockets,* Vol. 28, No. 5, 1991, pp. 530–535.

[6]"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.

[7]"Packet Telemetry," *Recommendation for Space Data System Standards,* Consultative Committee for Space Data Systems, NASA, Washington, DC, CCSDS 102.0-B-2, Jan. 1987.

[8]"Standard Formatted Data Units, Structure and Construction Rules," *Recommendation for Space Data System Standards,* Consultative Committee for Space Data Systems, NASA, Washington, DC, CCSDS 620.0-B-1, Feb. 1988.

[9]Action, C., "The SPICE Concept: An Approach to Providing Geometric and Other Ancillary Information Needed for Interpretation of Data Returned from Spacebourne Scientific Instruments, AIAA Paper 90-5082, Sept. 1990.

[10]"Lower-Cost Operations for Planetary Exploration," Rept. for the Mission Operations and Information Systems Subcommittee, Jet Propulsion Lab., Pasadena, CA, JPL Doc. S22-710, Aug. 1984.