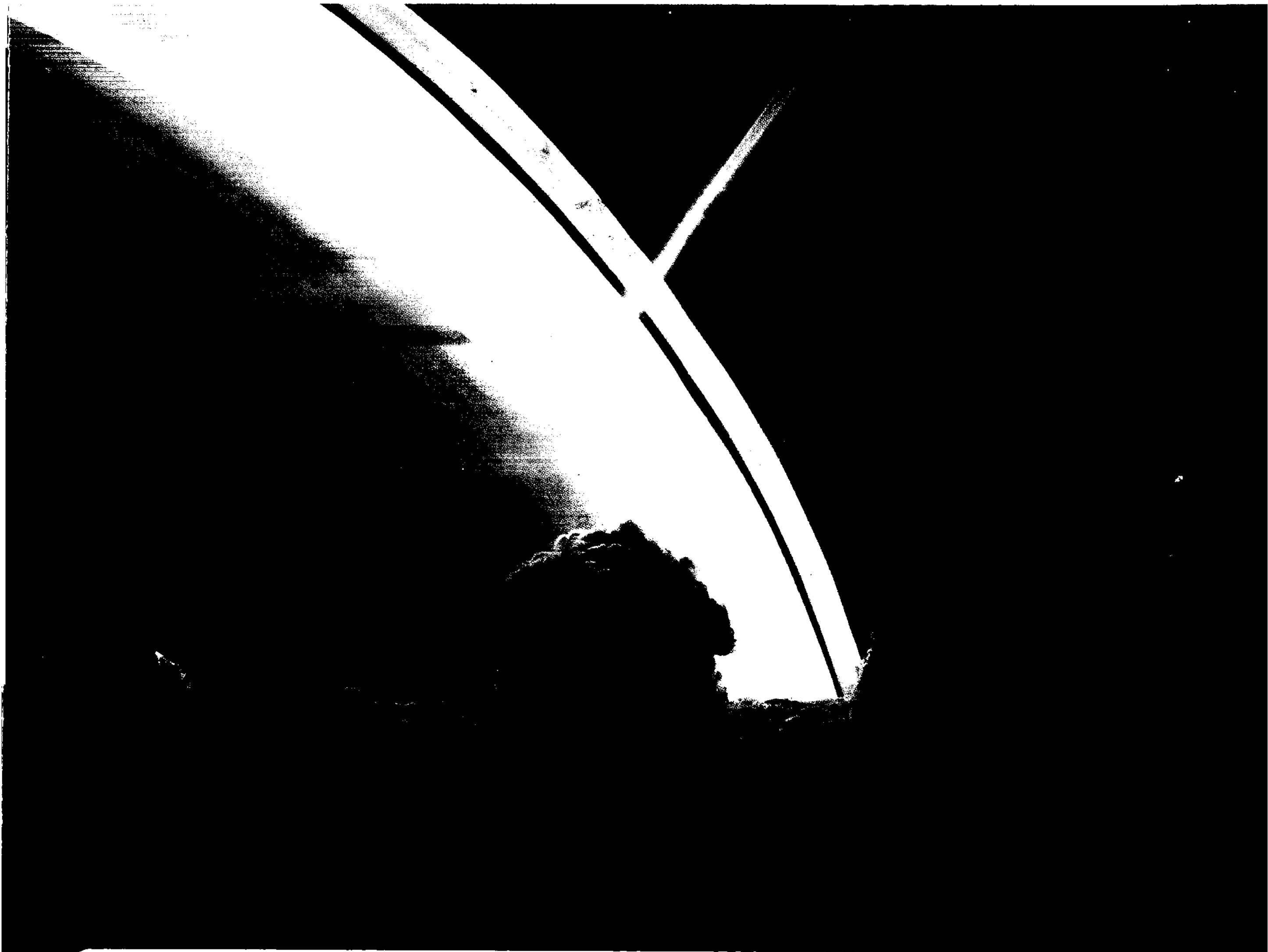
PLANETARY EXPLORATION THROUGH YEAR 2000

A CORE PROGRAM: MISSION OPERATIONS

A REPORT BY THE SOLAR SYSTEM EXPLORATION COMMITTEE OF THE NASA ADVISORY COUNCIL



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Cover *A probe begins its investigation of Saturn's turbulent atmosphere, with the vault of Saturn's rings in the background. Painting by Ron Miller.*

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A REPORT BY THE SOLAR SYSTEM EXPLORATION COMMITTEE OF THE NASA ADVISORY COUNCIL

WASHINGTON, D.C., 1986

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Executive Summary

In 1980 the NASA Advisory Council created the Solar System Exploration Committee (SSEC) to formulate a long-range program of planetary missions that was consistent with likely fiscal constraints on total program cost. The SSEC had as its primary goal the establishment of a scientifically valid, affordable program that would preserve the nation's leading role in solar system exploration, capitalize on our two decades of investment, and be consistent with the coordinated set of scientific strategies developed earlier by the Committee on Planetary and Lunar Exploration (COMPLEX), a part of the Space Science Board of the National Academy of Sciences.

The result of the SSEC effort was the design of a Core Program of planetary missions to be launched by the year 2000, together with a realistic and responsible funding plan. This Core Program consists of cost-constrained missions that address key scientific objectives. A hallmark of the Core Program set, which is defined in detail in Appendix I of this report, is that only two classes of spacecraft, *Planetary Observers* and *Mariner Mark IIs*, are required to implement the entire program.

The *Planetary Observer* spacecraft are generally intended for inner planet and lunar exploration and are characterized by focused flight objectives, relatively few instruments, no scan platforms, and modest data rates. The *Observer* spacecraft can be easily derived from existing Earth-orbital systems. The *Mariner Mark II* spacecraft would have higher data rates, larger science payloads, and a scan platform, as well as a modular design that would be simply reconfigured from mission to mission.

In developing the Core Program, the SSEC proposal constrained the total costs for Mission Operations and Data Analysis (MO&DA) to $60 million per year, recognizing as they did this that planetary mission operations methods would have to be changed.

The SSEC established the Mission Operations and Information Systems (MOIS) Subcommittee in early 1983 to provide SSEC oversight of Jet Propulsion Laboratory (JPL) efforts to achieve lower-cost mission operations. In addition, the Subcommittee supported additional studies and developments in such diverse areas as mission operations strategies, technology and resource requirements to implement lower-cost operations, and the scheduling interaction between ongoing missions, the SSEC Core Program, and the implementation of a "new" mission operations system. The recommendations at the end of this summary represent the primary output of the MOIS Subcommittee effort.

The earliest planetary missions had a very simple operations phase because sequencing options were extremely limited and data rates were comparatively low. Later missions like *Viking* and *Voyager*, however, had powerful on-board computers (which provided sequencing flexibility) as well as a dazzling array of scientific instruments with high and variable data rates. Large numbers of people, computer programs, and procedures were necessary to achieve a balance between acquiring the proper quality and quantity of scientific data and operating the engineering systems of the spacecraft in a prudent way.

The first major activity of the MOIS Subcommittee was to participate with the JPL team in a thorough survey of the ways in which spacecraft operations are currently conducted, at JPL and other NASA centers, such as Ames, Johnson, and Goddard, and at non-NASA facilities in Europe (the European Space Agency (ESA) and centers in West Germany and England) and the United States (Air Force Satellite Control Facility and the University of Colorado). Once the survey was complete, the Subcommittee and JPL turned their attention to the identification of those major cost "drivers" that significantly influence overall operations costs. Since so many of these drivers are science-related, a special science subgroup of the MOIS Subcommittee, consisting of scientists with considerable past experience as investigators, was created to ensure proper assessment of the science issues.

A computer model was developed and validated to provide a reasonably fast, accurate method of estimating operations costs as functions of operations techniques and methods. As part of an ongoing effort to reduce the cost of planetary operations, the JPL Flight Projects Support Office (FPSO) provides multi-mission services to all the projects for those operations functions that can be most cost-effectively performed by a central organization. Additional savings can be achieved by expanding the role of the FPSO to include more activities like image processing, maintenance of data records, and mission control. Another important cost reduction activity at JPL is the design and development of a "new" mission control center, called the Space Flight Operations Center (SFOC), that will use new minicomputers, microcomputers, remote terminals, and other modern techniques to reduce the number of people needed in operations. Identification of the major cost drivers affecting operations costs led to the establishment of a number of study tasks, conducted by the JPL team with MOIS Subcommittee oversight.

The first of these tasks involved an investigation of the ways in which JPL could organize itself to conduct mission operations for the SSEC Core Program and how multi-mission or shared operations would fit into the various proposed organizations. Several different organizational structures were proposed, and three candidates were evaluated in detail. Based on several criteria, including the difficulty of transition from the present JPL organization and the likelihood of the organization rewarding cost-saving suggestions, an organization was selected that creates a *Planetary Observer* and a *Mariner Mark II* program operations office (rather than individual project offices). Such an organization should be maximally efficient in the deployment of "shared" personnel; that is, people working on more than one spacecraft at a time. The second task looked at spacecraft commonality and was aimed at determining how the use of the same systems and/or subsystems on different spacecraft could reduce the overall MO&DA costs. This task led to two interesting observations. First, unless science instruments are also identical, having identical spacecraft subsystems is unlikely to reduce total operations costs by more than ten percent. Second, the real payoff from spacecraft commonality is in the reduction of development costs, which was not considered to be part of the MOIS Subcommittee purview, but is recommended for additional study. A third task was to determine which of the many proposed means of automation have the most potential for overall cost reduction. The automation task identified six computer tools (out of 32 studied) that have the potential for producing operations cost savings significantly greater than their development cost. Four of the tools are aimed at automating the sequence development process and thereby reducing the number of people needed to do sequencing. The other two automation tools that passed the cost-effectiveness test involved a telemetry monitor and fault analyst and a remote, non-interactive command manager. All the automation tools together have the potential to reduce the operations costs for a complex *Mariner Mark II* mission by as much as ten percent. The purpose of the fourth task was to determine the way in which the adoption of specific data system standards for planetary missions could simplify the operational activities. This study explored the cost benefits that might accrue if the operational data and the processes for handling data during mission operations were designed to conform to a set of standards. Seven data system standards were considered in the task, including such areas as packet telemetry and the use of a standard format data unit. The results of the task showed that although it is not possible to quantify, in terms of a percentage reduction in overall operations costs, the degree to which use of the standards would reduce the expense of operations, it is clear that use of the standards would result in increased operational efficiency, enable more automation for routine activities, allow for more sharing of personnel and equipment between missions, and simplify many of the operational activities.

The science subgroup of the MOIS Subcommittee considered a wide range of topics before selecting several areas of concentration based on maximum potential to reduce overall operations costs. The areas selected included: (1) the process by which the investigations and investigators are selected for participation in the missions; (2) the way in which scientists are involved in the operations themselves; (3) image processing costs; (4) sequencing costs; (5) the process by which Supplementary Experiment Data Records (SEDRs) are provided to the investigators during a mission. For example, science proposals are currently written against a spacecraft design included in the AO (Announcement of Opportunity), but no operational impacts of an experiment are considered until after the selections have been made. Requiring potential investigators to also propose against a mission operation system would be a significant step toward bounding operational costs. As another example, SEDR costs are, in the opinion of the scientist subgroup, much higher than they need to be because the data are not provided in a timely and accurate manner. In addition, many unnecessary parameters are provided to each investigator because the project SEDR contains all parameters requested by all investigators. One suggested way to reduce SEDR costs is to distribute the SEDR generation process and give each investigator the capability of producing his own SEDR. Additional study of this activity is recommended.

After all the specific study tasks were completed, the MOIS Subcommittee and the JPL study team worked together to synthesize the results of the tasks. To assist in this synthesis, the operations cost computer model was exercised in a parametric mode to determine the estimated annual operations costs for the Core Program Missions using present (that is, *Voyager* and *Galileo*) operations technology. The results were not surprising; they indicated that the MO&DA costs would prohibitively exceed the target $60 million per year. Next, the model estimated the average annual operations costs for the Core Program assuming: (1) successful implementation of SFOC and the expansion of the multi-mission role of FPSO; (2) use of shared operations; (3) implementation of the six automation tools identified in this report; (4) personnel productivity increases due to an efficient organizational structure that allows a normal "learning" process to occur. It is clear that when the above methods and techniques are implemented, total operations costs for the SSEC Core Program can be considerably lower than $60 million per year.

The MOIS Subcommittee concluded its activities by developing a set of recommendations. These recommendations are based on two kinds of conclusions: those directly derived from the specific study tasks performed during the effort, and those that were more general and qualitative in nature.

The specific recommendations were as follows:

1. The SFOC development and the FPSO plans to accommodate additional multi-mission tasks should become high-priority projects, and a regular set of reviews should be established to ensure their timely completion.

2. NASA and JPL should continue to move rapidly to establish an organizational structure for the SSEC Core Program that merges each family of spacecraft into a single program office.

3. NASA and JPL should continue a vigorous effort to implement automation tools that result in lower total MO&DA costs.

4. The current data system standards activity should be continued and extended to other areas where data standards might lead to additional operational simplification.

5. The operations cost computer model that permits fast, accurate estimation of operations costs should be maintained and updated as required and used regularly.

The general recommendations were as follows:

1. Regular independent reviews of all categories of mission operations costs should be continued to stimulate the identification of further cost-saving methods and technologies.

2. A study should be initiated to identify specific means by which the operations staff and activities can be "incentivized" to provide motivation for finding additional ways to reduce costs.

3. All Announcements of Opportunity for planetary missions should include operations plans and system definitions so that investigator proposals can respond to them as well as to the spacecraft descriptions.

4. NASA should consider creating a way by which planetary mission operations *development* costs for the SSEC Core Program can be reviewed systematically to identify additional program cost reductions.

5. A study should be undertaken to review the present SEDR generation techniques and to analyze alternate, more cost-effective ways of performing the SEDR function.

6. NASA should investigate the benefits of conducting mission operations for the simplest spacecraft at universities or NASA centers other than JPL.

1. Introduction

The exploration of the solar system by spacecraft has now spanned more than two decades and produced an avalanche of exciting discoveries and a wealth of data. More than two dozen unmanned spacecraft have transformed our view of the planets from one of shimmering, telescopic images to one of crisp, global perspectives. These new worlds amaze us with their beauty and awesome landscapes, which are the products of powerful, complex forces.

During the 20 years from the first *Mariner* flyby of Venus to the second *Voyager* encounter with Saturn, robot craft visited every planet known to ancient peoples, from Mercury to Saturn. Most of these spacecraft were launched by the United States, bearing such names as *Lunar Orbiter, Ranger, Surveyor, Pioneer, Mariner, Viking*, and *Voyager*.

As the planetary program has become more sophisticated, the actual planning of missions has progressed from a simple survey of available launch vehicles and tracking stations to careful, detailed analysis of the scientific goals and objectives of a set of planetary missions. The missions of the 1970s, including *Viking, Pioneer Venus*, and *Voyager*, were designed as an integrated set by the Lunar and Planetary Missions Board. Missions in the 1980s were based upon a coordinated set of scientific strategies developed by the Committee on Planetary and Lunar Exploration (COMPLEX), a part of the Space Science Board of the National Academy of Sciences. To respond to the COMPLEX recommendations for the 1990s in a way that was consistent with changing fiscal conditions, the NASA Advisory Council in 1980 created the Solar System Exploration Committee (SSEC) to formulate a long-range program of planetary missions.

The SSEC undertook a review of the U.S. planetary program aimed at ensuring that the nation could preserve its role in solar system exploration and capitalize on its two decades of investment. The SSEC took a fresh approach to planning, with its main goal being the establishment of a scientifically valid, affordable program of planetary exploration that was consistent with the scientific strategies outlined by COMPLEX. To achieve this goal, the SSEC emphasized

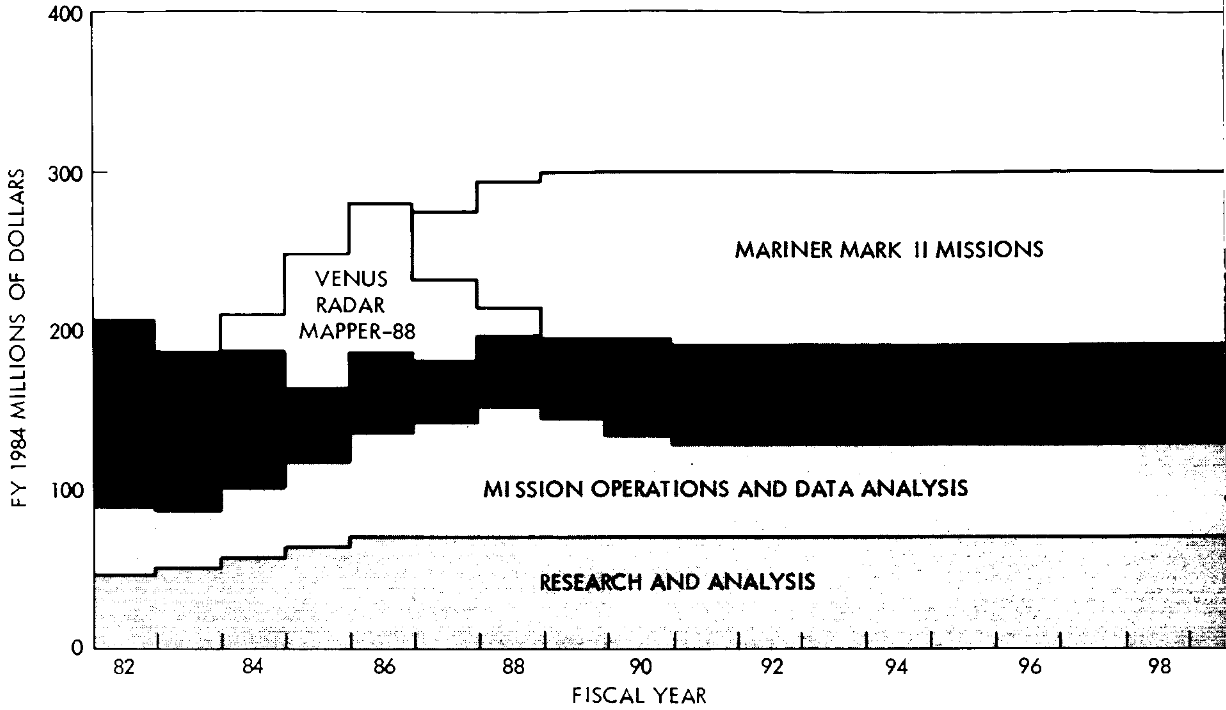

Figure 1. Funds Required for Core Program

overall program cost, rather than the cost of any individual mission, and encouraged the development of lower-cost, more innovative implementation approaches. One of the primary areas singled out by the SSEC for cost reduction was mission operations.

The SSEC deliberations produced both a Core Program set of planetary missions to be launched by the year 2000 and a realistic and responsible funding plan to accompany the Core Program. The Core Program Mission set is identified in Chapter 3 of this report and is discussed in detail in Part One of the SSEC Report, *Planetary Exploration Through Year 2000*. The budget projections for this recommended set of missions are shown in Figure 1. In order to perform the proposed missions within the allocated budgets, the SSEC constrained the total costs for Mission Operations and Data Analysis (MO&DA) to $60 million per year, recognizing as they did this that the constraint implied a significant, but achievable, change in the way planetary mission operations were conducted.

The SSEC recognized that mission operations cost growth has been compounded by several factors, including but not limited to: (1) the need to develop essentially unique operations and information systems for each planetary mission; (2) gradual antiquation of existing ground data systems that are characterized by labor-intensive operations and high maintenance costs; (3) insufficient end-to-end analysis of the complexities of deep space mission operations, including the handling of large volumes of data from many instruments.

The SSEC, cognizant of the success of the *Mariner* and *Pioneer* programs, suggested that a multi-mission operations system might be one way to significantly reduce overall program costs. The Committee noted that work was already under way at JPL to develop multi-mission methods and technologies that might permit achievement of the Core Program Missions within the MO&DA budget assigned by the Committee. From the early results of the work at JPL, the SSEC had developed confidence that the MO&DA cost problem was tractable.

To assist in the definition of lower-cost methods for planetary mission operations, the SSEC established the Mission Operations and Information Systems (MOIS) Subcommittee. The overall functions of the MOIS Subcommittee were to provide a critical assessment of current efforts to achieve lower-cost mission operations, to recommend areas for further studies and development, and to provide SSEC oversight of ongoing JPL activities in these areas.

Among the areas in which the MOIS has gathered information and is providing both assessments and recommendations to the SSEC are: (1) current and proposed organizational arrangements and management structures for conducting planetary mission operations; (2) mission operations objectives, priorities, implementation plans, and strategies; (3) impact of the SSEC Core Program on the schedule and requirements of any "new" mission operations system; (4) both technology and resource requirements to implement lower operations costs; (5) possible alternative approaches to lower-cost systems.

The specific scope assigned to the MOIS Subcommittee involved those items that comprise the MO&DA budget. This budget covers all the costs of operating planetary spacecraft after launch, including data distribution to scientists and preparation of science reports. There are two significant cost areas generally associated with operations that are *not* included in the MO&DA budget and hence were not considered to be part of the MOIS Subcommittee purview. These two areas are preparation of science data for distribution and archiving, and the mission operations prelaunch development budget, which includes, among other things, the design, test, and validation of the ground software system used during operations. Methods of reducing costs in these areas are clearly worthy of study.

2. Planetary Mission Operations

For the earliest planetary missions, the operations phase was very simple. Generally, there was a predetermined sequence, designed at the same time as the spacecraft, that was thoroughly tested during the system test phase. Only minimal changes in the sequence were allowed once the mission was launched. With the advent of powerful on-board computers and more complex missions, however, the number of real-time commands that could be executed by the spacecraft became very large. This has created a concomitant need for an advanced mission operations process on the ground to decide how the spacecraft and its instruments would be used.

Both *Viking* and *Voyager* were extremely complex, sophisticated missions carrying a dazzling array of scientific instruments. To operate these spacecraft safely and proficiently, a mission operations process was designed that attempted to balance acquiring the proper quantity and quality of science data with operating the engineering systems of the spacecraft in a prudent way.

The mission operations for both *Viking* and *Voyager* were extraordinarily successful; they were also very expensive. This experience has prompted the search for ways to conduct operations that are less expensive without sacrificing the scope and flexibility required by modern missions.

Many of the fundamental terms and definitions used to describe the mission operations process originated from the *Viking* and/or *Voyager* activities. For a planetary mission, the term *operations* is usually defined as the collection of people, procedures, computer hardware and software, and analysis techniques used to send commands to the spacecraft and to both receive and evaluate spacecraft data sent to Earth. Essentially, then, there are two major parts to the operations process: *uplink,* which is the set of activities associated with defining the proper commands, putting them into sets of commands called *loads,* and transmitting these loads to the spacecraft; and *downlink,* the set of activities that begins with the receipt of data by a ground station and ends with the systematic analysis of subsystem health and delivery of all required data to the scientific investigators.

Figure 2 is a general schematic of the principal components of the operations process. The uplink activity is shown across the top and the downlink is shown on the bottom. The uplink can be divided into three major functions: (1) determination by the scientific investigators of what observations they can acquire and would like to make during a given time period (mission analysis and science planning); (2) conversion of these science desires into commands to be sent to the spacecraft (sequencing); (3) actual command of the spacecraft. Similarly, the downlink can be divided into three major functions. The

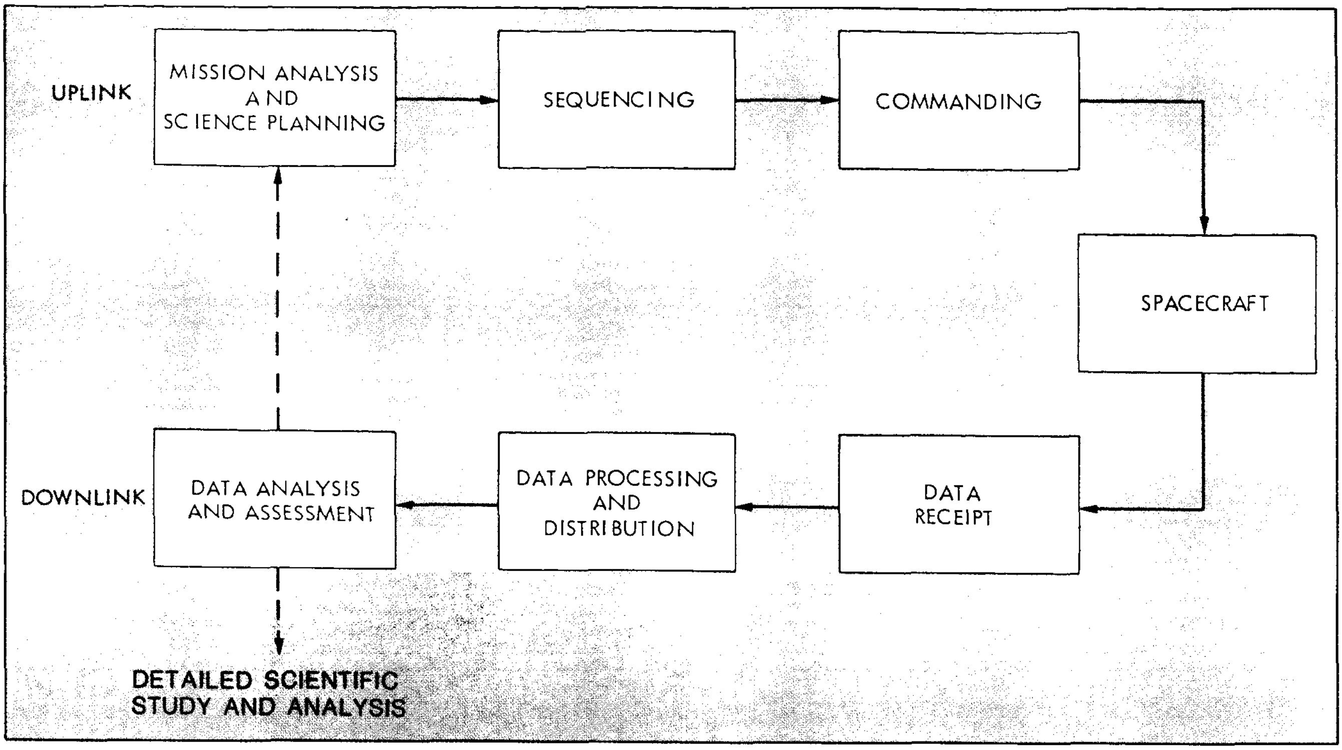

Figure 2. Generic Model of Mission Operations Process

first is data receipt or capture, which refers to the physical process of actually ensuring that the data transmitted by the spacecraft have been properly received on Earth. Data processing and distribution covers the activities necessary to separate the data into subsets which are then provided to the engineering subsystem analysts and scientific investigators. The third downlink function involves actual analysis of the data by the elements of the flight team to determine the health and operating characteristics of the components of the spacecraft, and by scientific investigators to assure the validity of subsequent sequences. In fact, a portion of this analysis is done in real time, but most of it is done after the data processing and distribution have been completed. Note that detailed scientific analysis is not considered part of the downlink process and is not considered in this report.

Several other definitions are important for the reading of the rest of this report. The Space Flight Operations Center (SFOC) is the "new" mission control center which is currently being designed and developed at JPL and which will be operationally certified by 1988. Two of its most significant features are the use of new and modern minicomputers and microcomputers and the ability to accommodate remote work stations. The Flight Projects Support Office (FPSO) is the organization at JPL that manages the multi-mission operations functions and provides them to the flight projects.

A planetary mission is said to be in its *cruise* phase if it is traversing the space between two target bodies (or Earth and a target body) and is acquiring only a limited amount of scientific data. The *encounter* phase of a planetary mission is the high-activity phase surrounding the spacecraft's closest approach to one of the target bodies of its mission. *Encounter* also includes orbital operations.

3. SSEC Core Program Missions

When the Solar System Exploration Committee (SSEC) was formed in 1980, its primary purpose was to address a growing concern over the viability of the planetary program. Working with the science community, the SSEC took a fresh look at the program, reviewing its goals, identifying those attributes that would ensure its viability, and proposing approaches to reduce the costs of the planetary program. The Committee endorsed three long-standing goals of the program and added a fourth. These goals are as follows:

1. To continue the scientific exploration of the solar system in order to comprehend its origin, evolution, and present state.
2. To gain a better understanding of Earth by comparative studies of other planets.
3. To understand how the appearance of life relates to the chemical and physical history of the solar system.
4. To survey the resources available in near-Earth space in order to develop a scientific basis for future utilization of these resources.

It was apparent to the SSEC participants that the present program had become too expensive in its pursuit of this challenging array of objectives. In fact, individual missions had become so complex and costly and so dependent on enabling technologies that new planetary projects were no longer being approved, and existing projects were encountering serious delays. To break the vicious circle of deferred approval, leading to higher mission cost, leading to further deferral, and to establish a stable base of continued mission activity, the SSEC recommended the concept of a Core Program. This Core Program would consist of coordinated low-cost missions that addressed key scientific objectives. These missions would be clearly defined from the outset and would employ new technologies only when their potential for reducing cost was clearly demonstrated. To implement such a program only two classes of spacecraft design were recommended: (1) *Planetary Observers*; (2) *Mariner Mark IIs*.

The *Planetary Observer* spacecraft are intended for the exploration of the inner planets and small bodies, including Venus, the Moon, Mars, near-Earth asteroids, and comets. These *Planetary Observers* were to be derived from existing Earth-orbital spacecraft systems; they would not have scan platforms and would carry relatively few instruments (four to seven per spacecraft) which would address focused flight objectives, such as global geochemical surface mapping. They would make only modest demands on tracking capabilities, and only modest data rate capability (less than ten kilobits per second) would be allowed. A development cost goal of $150 million to $200 million (FY 1984 dollars) per flight system was projected as being consistent with these design objectives.

The *Mariner Mark II* class of spacecraft is characterized by a new modular design which could be simply reconfigured from mission to mission. Its application is envisioned for outer planet exploration as well as higher-level small body investigations, such as extended rendezvous and stationkeeping at comets and asteroids. These *Mariner Mark II* spacecraft would have larger science payloads (seven to 12 instruments per spacecraft), include a scan platform, and provide data return rates of up to 50 kilobits per second. A development cost goal of $250 million to $300 million (FY 1984 dollars) per spacecraft was expected for these systems.

In initiating the *Planetary Observer* and *Mariner Mark II* missions, the SSEC recommended maximum usage of existing hardware spares and duplicates from previous programs such as *Viking*, *Voyager*, and *Galileo*, as well as from available Earth-orbital systems. New technologies and associated subsystem designs were only to be applied when a clear cost benefit could be demonstrated. At the program level, several additional constraints were imposed by the SSEC to bound the Core Program. Specifically, a plan encompassing all launches before the year 2000 was imposed, and annual funding was to be limited to $300 million (FY 1984 dollars), plus or minus ten percent.

With these definitions and constraints, a set of 11 Core Program Missions was evolved through an extended process of definition, assessment, and iteration, including review by a broad representation of members of the science community. The selected missions are presented in Figure 3, along with the spacecraft class designated for each mission. The first three missions listed are of the earliest priority, to be performed in the order shown, with the approximate launch dates indicated. Note that they include an inner planet, small body, and outer planet mission. The comet Wild 2 has recently been selected as the rendezvous target for the *Comet Rendezvous/Asteroid Flyby* (CRAF) mission. The remaining eight missions are proposed at this time in no particular order, but are all intended to be launched by the end of the century. Brief descriptions of each of the Core Program Missions are

INITIAL MISSION SET	S/C CLASS	LAUNCH
Mars Geoscience/Climatology Orbiter	Planetary Observer	1990
Comet Rendezvous/Asteroid Flyby	Mariner Mark II	1990
Saturn Orbiter and Titan Probe	Mariner Mark II	1993
SUBSEQUENT MISSION SET	**S/C CLASS**	**TARGET**
Lunar Geoscience Orbiter	Planetary Observer	Inner Planets
Venus Atmospheric Probe	Planetary Observer	Inner Planets
Dual Mars Aeronomy and Network Orbiters	Planetary Observer	Inner Planets
Earth-Approaching Asteroid Rendezvous	Planetary Observer	Small Bodies
Comet Atomized Sample Return	Planetary Observer	Small Bodies
Main Belt Asteroid Multiple Orbiter/Flyby	Mariner Mark II	Small Bodies
Saturn Flyby/Probe	Mariner Mark II	Outer Planets
Uranus Flyby/Probe	Mariner Mark II	Outer Planets

Figure 3. Core Program Mission Set

included in Appendix I. Detailed mission descriptions for each of these missions, including operations profiles, communications timelines, and data requirements can be found in JPL Report No. D-1703, *Lower-Cost Operations for Planetary Exploration: Report for the Mission Operations and Information Systems Subcommittee*, August, 1984.

In order to assess the MOIS requirements to support this set of Core Program Missions and to formulate a cost-effective plan for implementing those requirements, it is necessary to cast the full mission set into a mission model. Such a mission model, though by no means absolute, can be representative of the time-phased loading of mission operations activities, and can thus provide valuable insight into the formulation of an effective MOIS plan to match Core Program needs. The baseline mission model evolved for the subject MOIS assessment is presented in Figure 4. The model begins in 1988 with several already approved missions which precede the Core Program. These include the *Voyager Neptune Flyby*, the *Galileo Jupiter Orbiter/Probe*, the *Venus Radar Mapper*, and the *Ulysses* mission (formerly the *International Solar Polar* mission). The remaining 12 launches are Core Program Missions. Note that two *Main Belt Asteroid Rendezvous* missions are included in the model. This change is the result of the desire to provide an adequate number of asteroid rendezvous targets, while preserving a completely "ballistic" mission model.

For each mission presented in Figure 4 a timeline is given, beginning with project start (S) and including system test (T), launch (L), encounter (E), and, when appropriate, Earth return (R). The last launch actually occurs at the beginning of 2001. Mission encounters continue through 2008 for the last asteroid rendezvous mission. This model is the key to the determination of additional operations

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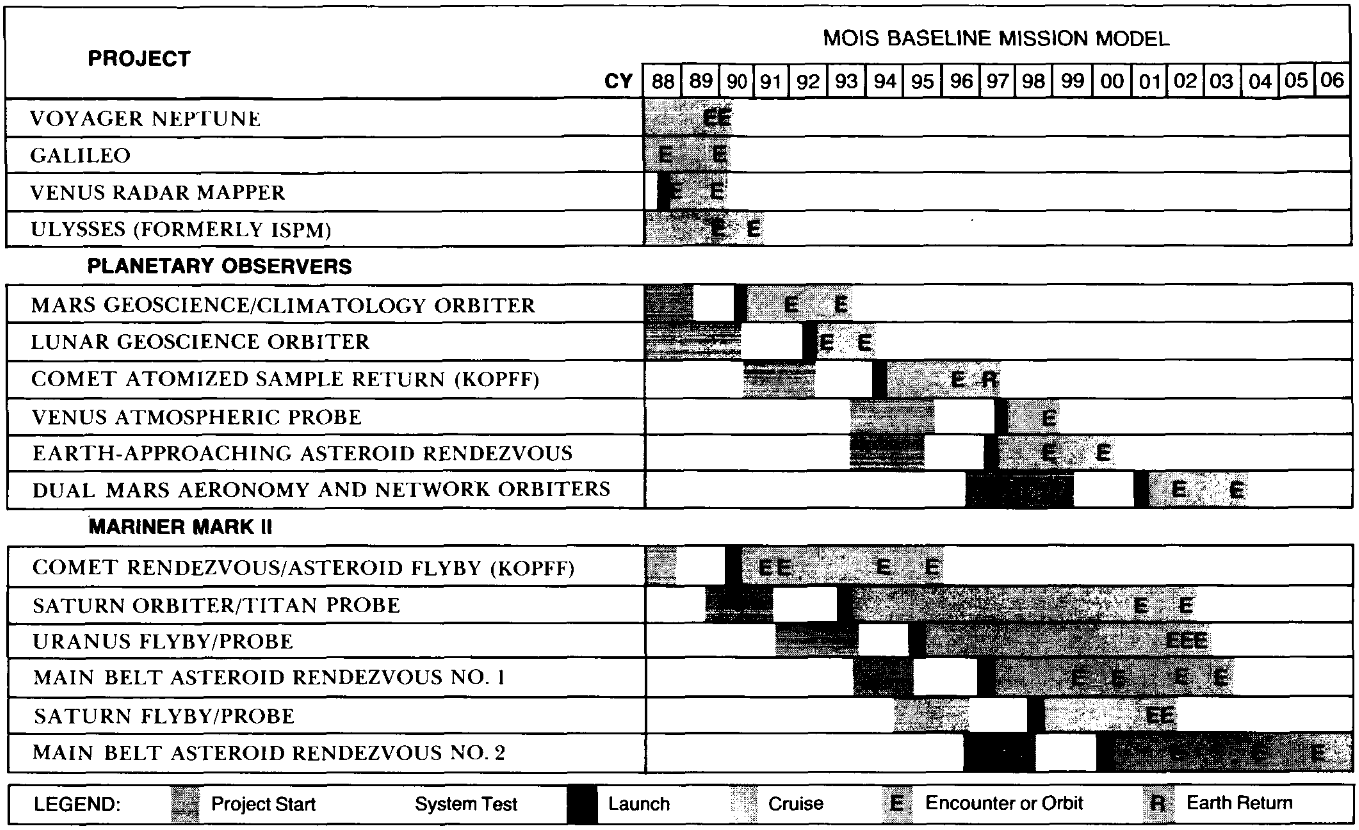

Figure 4. Baseline Mission Model

development requirements and manpower staffing requirements, as well as the trade-off studies that were conducted to assess the cost-effectiveness and sensitivity of the proposed MOIS plan for the Core Program.

One additional point must be mentioned in concluding the description of the mission model. The SSEC has also recommended a set of more complex, more capable, and more expensive "Augmentation" Missions. These missions include a *Mars Sample Return*, a *Comet Nucleus Sample Return*, and several outer planet initiatives. It is the intent of the SSEC that these missions augment, or be added to, the Core Program as resources and opportunity avail themselves. The scope of the MOIS Subcommittee's charter and subsequent assessments does not include any of these augmentations to the mission model, although it is clearly recognized that such additions may have an impact on mission operations. For the moment, it has been assumed that the impact would be addressed on a case-by-case basis if and when such augmentations actually occur.

4. Subcommittee Activities

One of the most important functions of the MOIS Subcommittee was the assessment of methods by which the operations costs of the Core Program set of planetary missions can be reduced. To meet this objective, it was first necessary for the Subcommittee to understand the fundamental tenets of the operations processes that have been used at JPL and other mission control centers to fly planetary missions in the past. A key element of this understanding involved the identification of those major cost drivers that significantly influence the overall cost of planetary mission operations. Once the most important cost drivers had been identified, the major thrust of the Subcommittee activity was participation in the definition and review of results of trade studies, conducted by JPL personnel, that were aimed at identifying changes that could be made in the operations process to reduce cost without measurably increasing risk.

The first phase of the Subcommittee activity was primarily an information-gathering process. Mission operations costs for expensive missions like *Viking*, *Voyager*, and the upcoming *Galileo* were studied, along with costs for simpler missions like *Pioneer*, *Mariner Venus-Mercury*, and the proposed *MGCO (Mars Geoscience/Climatology Orbiter)*. Of considerable importance in this effort was learning the way that JPL breaks down mission operations costs. The uplink and downlink activities associated with operations are divided, in the JPL system, into several different subtasks or groupings as shown in Figure 5. Spacecraft planning and analysis, for example, covers both the uplink and downlink activities related to the calibration, use, and health of the engineering systems on the spacecraft. The JPL system of accounting for costs in operations also splits out those functions that are funded on a multi-mission basis by the Flight Projects Support Office (FPSO) from those operations functions funded by each individual project. The division of responsibility between the FPSO and the individual project for a typical project like *Galileo* is also shown in Figure 5.

Once the Subcommittee understood how the fundamental functions of mission operations were costed by JPL, they studied other organizations and facilities that were engaged in operations activities similar to those at JPL. Fact-finding trips to NASA centers (Goddard, Johnson, and Ames), Air Force operational facilities, and even European agencies (ESA and agencies in West Germany and England) were made so that the Subcommittee could understand different techniques that were being used to fly space missions. The space missions studied covered the entire gamut of complexity, from the *Space Shuttle* to the *Solar Mesosphere Explorer* operated by the University of Colorado. An important part of this fact-finding effort was understanding the mission requirements and spacecraft designs for these missions and the way these requirements established the design and complexity of the mission operations. In addition, the

- PROJECT MANAGEMENT
- MISSION CONTROL AND COORDINATION
- NAVIGATION PLANNING AND ANALYSIS
- SPACECRAFT PLANNING AND ANALYSIS
- MISSION PLANNING
- SEQUENCE DESIGN AND IMPLEMENTATION
- DATA RECORDS
- IMAGE PROCESSING
- SCIENCE PLANNING AND ANALYSIS
- MULTI-MISSION GROUND DATA SYSTEM DEVELOPMENT
- MULTI-MISSION GROUND DATA SYSTEM OPERATION
- MULTI-MISSION MANAGEMENT

FUNDED BY FPSO

Figure 5. Major Operations Tasks

Subcommittee carefully reviewed the plans under way at JPL for the development of the new Space Flight Operations Center (SFOC) and the transfer of additional functions to FPSO.

One of the major tasks performed by the JPL study team under the aegis of the Subcommittee was the development of a computer model for studying mission operations costs. Early in the activity, it was clear that there existed no reasonably accurate, reasonably fast method for calculating total operations costs as a function of the defining parameters of a mission and the way in which operations were conducted. Such a model was deemed essential for the business of the Subcommittee, for without it there was no way the Subcommittee could understand the total cost changes which would result from a proposed set of amendments to the way operations were being planned. The cost estimating model was developed and validated as part of the Subcommittee activity and was then used to quantitatively substantiate some of the recommendations made by the Subcommittee. A brief description of the model appears in Appendix II.

Once the information-gathering effort was essentially complete and the Subcommittee had commissioned the development of the computer model to assess operations cost as a function of a host of mission variables, the Subcommittee, working with the JPL study team, began to isolate those critical cost drivers that play a major role in determining total mission operations costs. It became clear very quickly that many cost drivers were associated with the science element of the operations. As a result, a special science subgroup of the MOIS Subcommittee was established to study in detail the primary science issues that impact operations costs. The findings of this subgroup are contained in Chapter 6 of this report.

For the rest of the critical cost drivers, a group of study tasks or trade studies was defined, the output of which was designed to compare the costs and risks of several different ways of conducting mission operations. The next section of this report discusses each of the major trade issues, and the penultimate section gives a synthesis of the significant results from the trade studies.

5. Major Studies

The primary thrust of the MOIS Subcommittee was the identification of study tasks, to be carried out by the JPL team and reviewed by the Subcommittee, that seemed to have the largest potential for reducing MO&DA costs. The first of these tasks involved an investigation of the ways that JPL could organize itself to conduct mission operations for the SSEC Core Program and how multi-mission or shared operations would fit into the different proposed organizations. The second task was called spacecraft commonality and was aimed at determining how the use of the same systems and/or subsystems on different spacecraft could reduce the overall MO&DA costs.

A third task was to determine which of the many proposed means of automating the business of mission operations had the most potential for overall cost reduction. The purpose of the fourth task was the determination of the way in which the adoption of specific data system standards for planetary missions could simplify the operational activities. The major results of each of these tasks are contained in subsequent sections of this report.

Organization

The study team visited several other mission control centers to learn about the ways in which these organizations were conducting mission operations and to understand whether any of these different modes of organizing for operations might offer significant advantages to JPL. The centers visited were Johnson, Goddard, and Ames of NASA, the Air Force Satellite Control Facility, and the European and German Space Operations Centers.

The visits resulted in the following observations:

1. For those operations functions common to all centers, namely real-time mission control, telemetry processing, satellite monitoring, command transmission, and some routine navigation functions, the study team found no significant difference in staffing levels from center to center.

2. Most of the other centers placed as much of the operation as possible in a single multi-mission operations organization.

3. The more complex planetary missions have several unique facets, not found in most Earth-orbiting missions, which add significantly to the operations staffing requirements. For these missions, which feature several complex science instruments with competing requirements integrated into a single spacecraft, additional staffing is necessary due to:

- the large amount of science and mission planning required;
- long communication distances;

- spacecraft fault detection and correction capabilities;
- in many cases, only a single limited opportunity to acquire the most important scientific data.

Three separate candidate organizational structure options for conducting planetary mission operations at JPL were analyzed. These options were then compared based on the criteria of whether or not the organization defined provided the proper incentives for choosing to do the "right things" as well as the capability for actually doing them. For example, it is important that the organizational structure be one which provides strong incentives to apply inheritance from previous and ongoing projects in the selection of spacecraft systems, operational facilities, personnel, procedures, and software. The organizations should also encourage the sharing of facilities and people which, during "slow" mission phases of a single project, would be underutilized.

Option 1, shown in Figure 6, is the current organizational arrangement at JPL. Each Project Manager has a Mission Operations System (MOS) organization which is staffed and funded to develop the capability needed to carry out project-peculiar operations functions. Multi-mission services are supplied by a separately funded Flight Projects Support Office (FPSO) which is organizationally at the same level as each of the Project Offices. Multi-mission services are those that can be provided by facilities and staff that are judged to be acceptably common to two or more projects.

The second option (Figure 7) is a variant of the first which groups together similar projects into Program Offices to utilize the benefits of their commonalities. Using the SSEC Core Program as a basis, this option naturally results in a single *Planetary Observer* Program Office and a single *Mariner Mark II* Program Office. This organizational structure still retains the FPSO. A third option, shown in Figure 8, goes a step further and creates a single dedicated Flight Operations organization by combining all of the MOS operations functions and personnel for all the programs into a giant FPSO.

Both the JPL study team and the MOIS Subcommittee believe that Option 2 is the best of the three for the SSEC Core Program. It is not a radical departure from the current JPL arrangement and is therefore relatively straightforward to implement. What is more important, each program office is responsible for a single mission class and a single spacecraft type. There is, therefore, ample opportunity to carry out cost-saving trade-offs involving spacecraft systems and operations as well as the incentive and capability for taking the appropriate actions. Some of the more obvious advantages of this organization are as follows:

1. The responsibility and authority for project management resides with the Program Manager, who is motivated to optimize a series of projects rather than each project individually. Responsibility for this series of projects also makes planning more prominent.

2. There is an incentive to keep project costs low, assuming that the savings are kept within the program, to permit extended missions and the start-up of new projects.

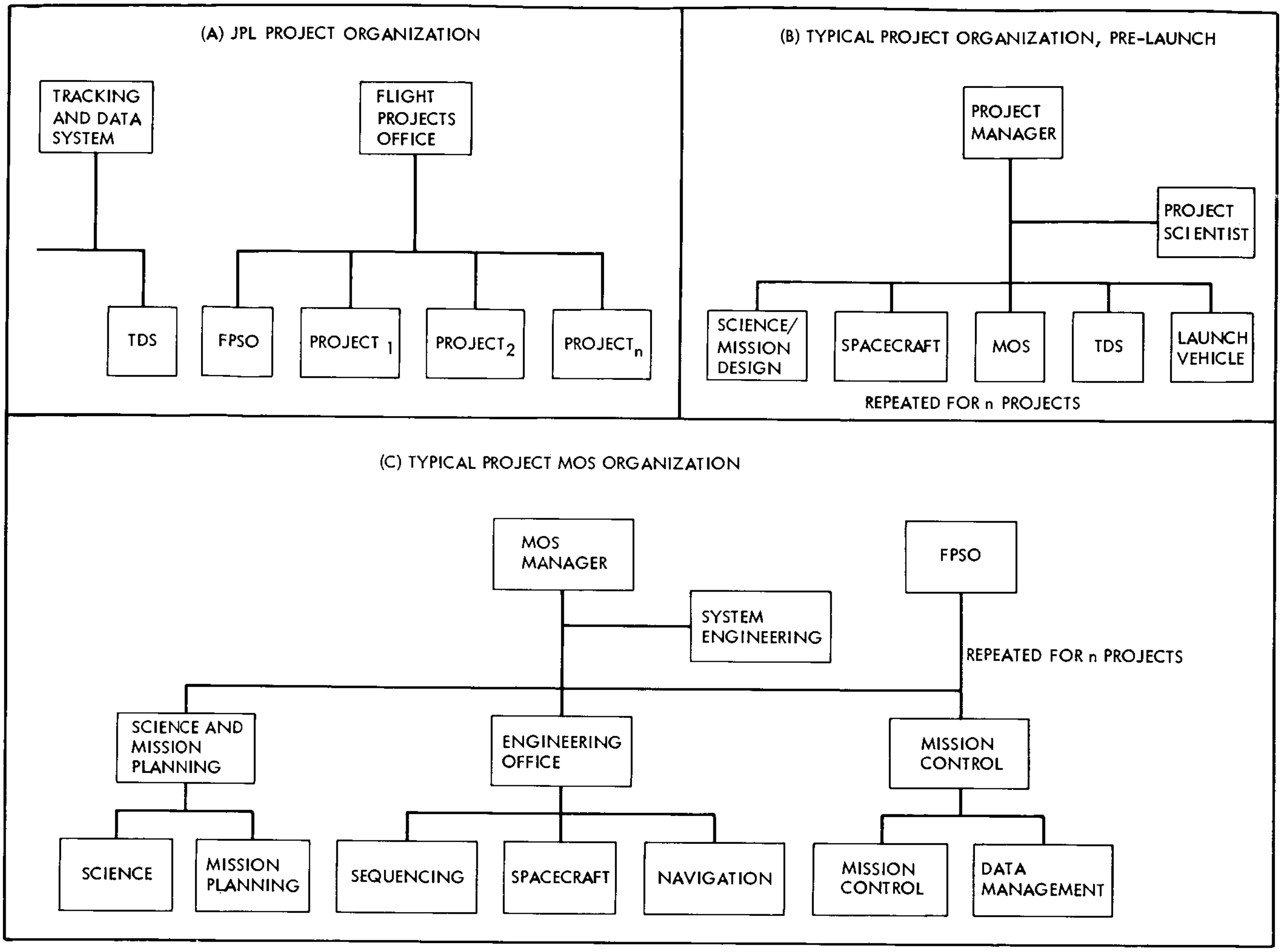

Figure 6. Option 1: Current Project and Operation Organization at JPL

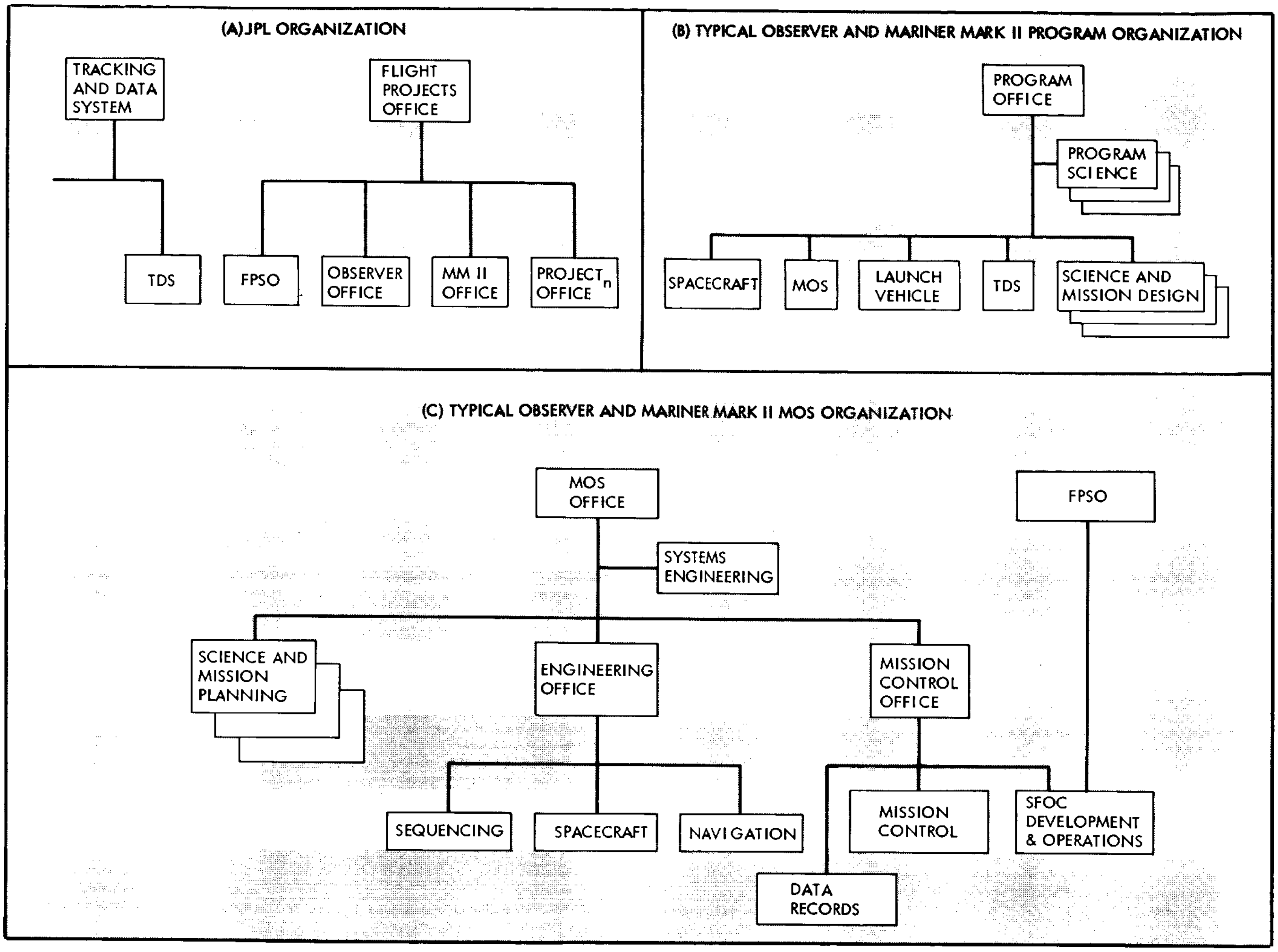

Figure 7. Option 2: Combined Project Office Operations Organization

3. There is an incentive to maximize spacecraft commonality because this reduces both spacecraft development and operations costs. This will be discussed further in the section entitled "Spacecraft Commonality."

4. Because the same people will perform the flight operations for all similar missions, the operations team will already be experienced even at the beginning of operations for new projects.

5. There will be a strong tendency to maintain standard operations hardware and software, thereby reducing MOS development costs.

6. The organization will foster the natural development of "shared operations." Shared operations involve the use of a single team of operations personnel and common facilities for several missions flying at the same time. It provides an ideal opportunity to reduce the "taximeter" effect that occurs during the less demanding mission phases, when Project Managers are forced to retain personnel they do not currently need in order to be staffed for future high-activity phases such as encounters.

The cost assessment models developed during the MOIS Subcommittee effort are not able to yield precise quantitative data about cost reductions resulting from organizational changes. They have, however, been applied to proposals for greatly increased multi-mission or shared operational activity, which is one of the natural outgrowths of the suggested organizational changes. If shared operations are pushed to their limit for two identical spacecraft, it appears likely that the cost of flying two spacecraft would only be 1.4 to 1.6 times the cost of flying a single spacecraft.

Finally, although the MOIS Subcommittee was not asked to assess the development aspects of mission operations, it should be mentioned that the Option 2 organization may result in substantial savings during the operations development activity, primarily because the organization is structured to encourage interaction between operations personnel and development personnel working on similar missions and spacecraft.

Spacecraft Commonality

Under this task, the JPL study team and the MOIS Subcommittee assessed the MO&DA cost savings that would be realized if two or more spacecraft or major spacecraft subsystems were identical. As part of this task, the reduction in costs due to specific identical subsystems and/or identical scientific instrument packages was also analyzed. Both hardware and software commonality were considered. Although the substantial savings that would result during the development of the spacecraft and its operational system were *not* assessed (development was outside the purview of the MOIS Subcommittee), the impact of spacecraft commonality on the MO&DA costs alone can still be considerable.

The greatest value of spacecraft commonality in the reduction of MO&DA costs comes from the *Mariner Mark II* class of missions in the SSEC mission model. This occurs because of the substantial overlap in the *Mariner Mark II* missions. The schedule for the SSEC Core Program

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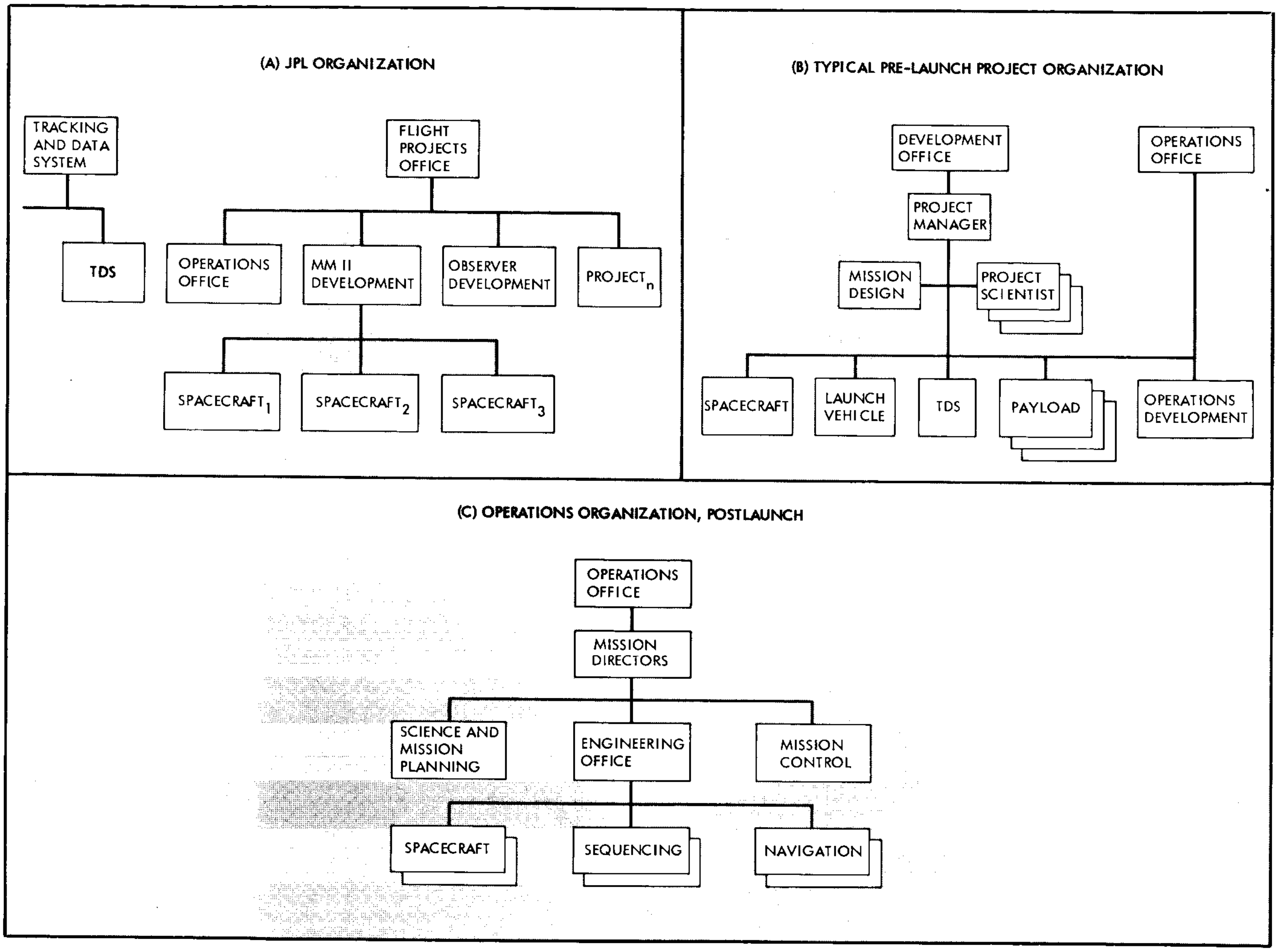

Figure 8. Option 3: Single Operations Organization

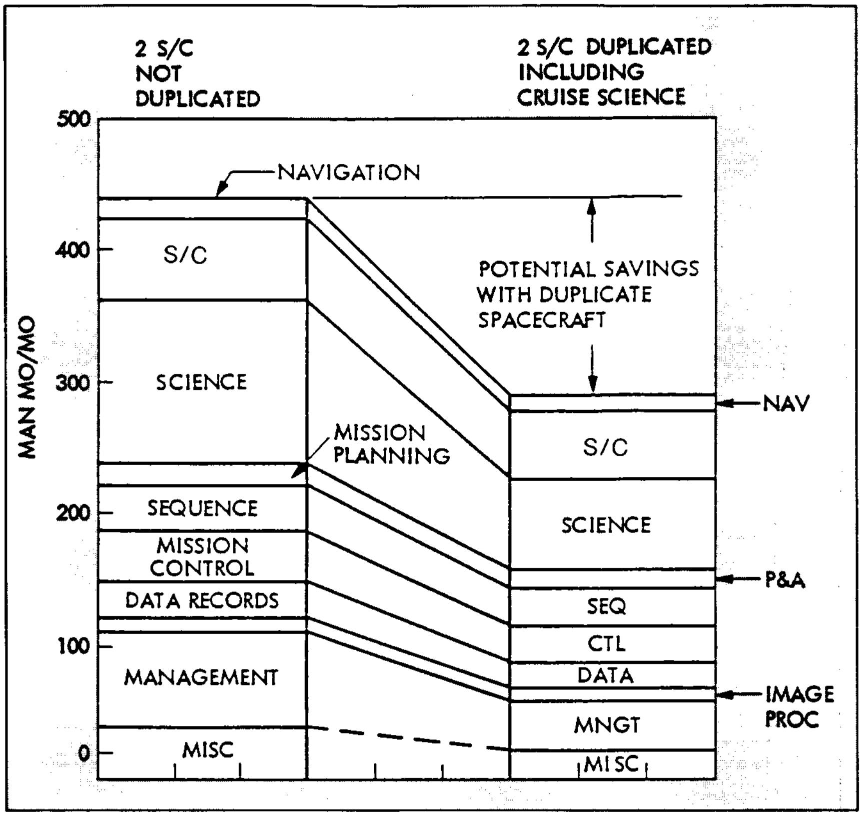

Figure 9. Cruise Operations, Potential Savings, Using Two Duplicate Spacecraft

Missions shown in Figure 4 indicates that over a period of about 12 years there are cruise and encounter overlaps for the *Mariner Mark II* spacecraft. For two *Mariner Mark II* spacecraft in cruise, assuming no other cost savings, the use of identical spacecraft means that the total MO&DA cost for the two spacecraft can be reduced by four percent. If the science instrument packages were also the same, another ten percent of the total cost of operating the two spacecraft could be saved. The individual elements whose costs could be reduced are shown in Figure 9. The use of common spacecraft noticeably lowers the costs associated with both spacecraft analysis and sequencing.

Encounter operations for *Mariner Mark II* spacecraft can also be accomplished more inexpensively when identical spacecraft are being flown. As graphically illustrated in Figure 10, the total MO&DA cost for two spacecraft in encounter operations can be reduced by as much as nine percent. The figure also illustrates the substantial cost reduction (as much as another 12 percent) that would come from using duplicate science payloads. Although duplicate science payloads may not be possible due to the diversity of missions, commonality of science instruments should be considered a viable way to reduce mission costs.

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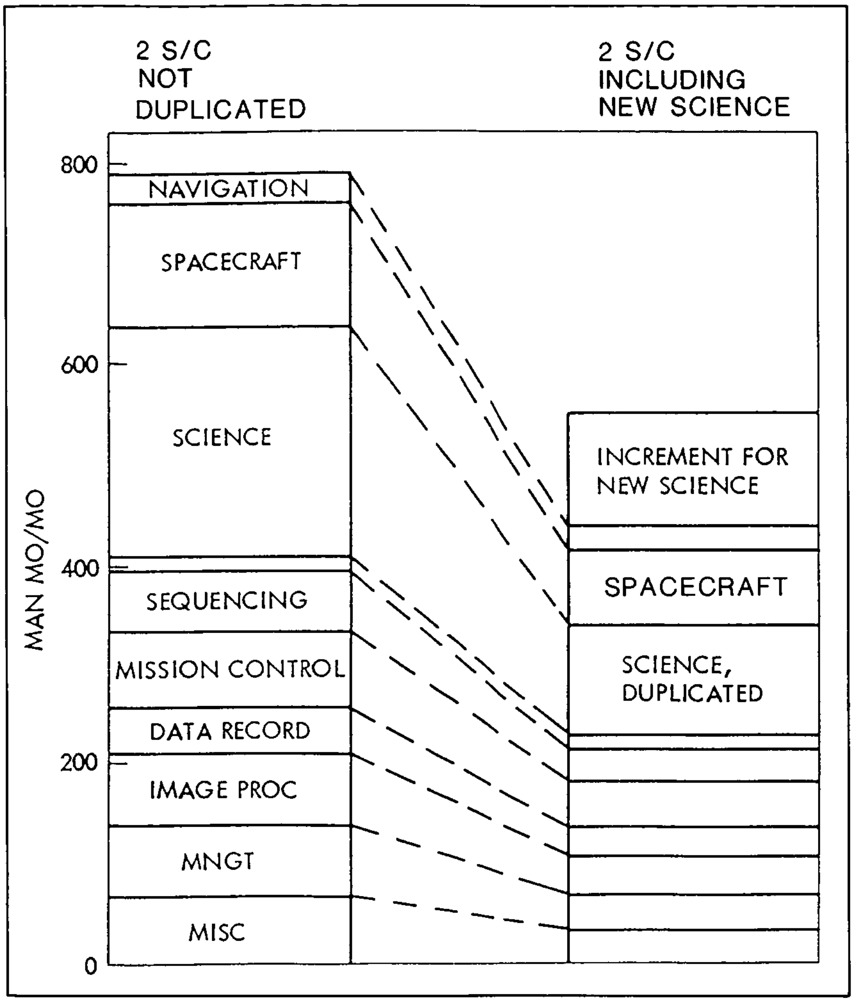

Figure 10. Encounter Operations, Potential Savings, Using Two Duplicate Spacecraft

Automation

Many aspects of mission operations are labor-intensive, and significant cost savings could be realized if some functions were more fully automated. Automation has always been a vital part of mission operations, but the advent of minicomputers and microcomputers has changed the environment in which automation is implemented. Functions that were formerly impractical or too costly to perform on mainframe computers may now be amenable to automation in the more flexible microcomputer environment. The various functions performed during mission operations were therefore reexamined to determine how existing tools might be improved and what new tools might be developed in order to reduce costs.

To determine areas where increased automation might be beneficial, all aspects of the MOS were systematically examined. Tasks were identified which could be more fully automated and tools that might perform these tasks were tentatively proposed. After merging tools where appropriate, the manpower reductions that would result from the implementation of each potential automation tool were estimated as a function of mission phase. The reductions were then compared with the SSEC mission model to obtain a time profile of the potential cost savings. Such savings must be balanced against the estimated costs of implementation, which are much more uncertain and subjective. Thus, for each automation candidate, software development costs, as well as computer operations and software maintenance costs, were estimated. As a result of this process, six automation tools out of 32 originally considered were thought to have significant potential for reducing operations costs. Most of the tools are directed toward streamlining sequencing, which is now a highly iterative and labor-intensive process.

The automation tools identified are as follows:

1. *OBSERVATION DESIGNER:* This computer program is an improved version of POINTER, the standard *Viking/Voyager* program for designing scan platform sequences. It generates a scan platform sequence, given the type of observation required and the geometry at the target. Flight sequences are generally the products of numerous iterations in which science requirements are translated into sequences that are implementable. Observation Designer will cut the time required to generate scan platform sequences. Because the program is designed to operate on minicomputers, the scientist can, at his home institution, perform preliminary design of sequences before large investments are made by sequence teams. As a result of Observation Designer, cost savings of ten to 15 percent in sequence development and integration and 50 percent in the design of scan platform observations can be expected.

2. *TIMELINE GENERATOR:* Sequencing is primarily a scheduling problem. Observation requirements of different instruments commonly conflict with one another. Sequence teams must constantly shift observations to eliminate conflicts and to better satisfy geometric and timing requirements. Most timelines are currently generated manually. The process is slow, requiring extensive redrafting between successive versions so that designers are often working with out-of-date timelines. The timeline generator will bypass the time-consuming process of manually updating timelines and it is expected to reduce the costs of integrating sequence requests by 35 to 60 percent. It will also have more general application in the scheduling of all mission support activities.

3. ***SCIENCE OPPORTUNITY ANALYST:*** Several requirements normally have to be met for a successful science observation. Commonly, a specific part of an orbit must be viewed within a certain range and under particular viewing and illumination conditions. The viewing conditions and opportunities are generally changing rapidly as the spacecraft position changes. Scheduling the observations so that all the requirements are met is normally done by trial and error and commonly depends on an analyst's intuitive grasp of all the motions. The Science Opportunity Analyst will reduce the time it takes to find opportunities by taking the science requirements and systematically searching the timeline to place the observations. Manpower savings could be as much as an additional 18 percent in the area of sequence development.

4. ***TELEMETRY MONITOR AND FAULT ANALYST:*** This tool examines the telemetry stream from the spacecraft and compares it with the timeline. It then gives an alarm if discrepancies are found between the anticipated and actual telemetry streams; the tool also begins the fault diagnosis activity. Automated alarm systems are currently used to monitor spacecraft, but these are static systems which simply alert analysts when spacecraft limits are violated. This new program compares expected spacecraft activity as indicated by the command sequence with actual activity, a job currently performed manually. Expected savings are 30 to 40 percent in real-time operations support.

5. ***REMOTE NON-INTERACTIVE COMMAND MANAGER:*** This tool permits a scientist to send certain commands to his instrument without time-consuming interaction with the spacecraft command team. Commands will be restricted to those, such as changing a gain state, that have no effect on the rest of the spacecraft. The procedure was followed on *Pioneer Venus* and is standard practice on many Earth-orbiting satellites. The tool receives a command from an authorized user, checks the command against an approved command list, requests time for transmission, and, after other appropriate checks, allows the command to be sent to the spacecraft. It is expected to result in 35 to 50 percent savings in spacecraft commanding.

6. ***SEQUENCE PLANNER:*** During sequencing, analysts receive large numbers of activity requests, each having a specific set of requirements. The analyst must search files to find opportunities, and check to ensure that the observation or activity does not clash with some other activity or violate some mission constraint. Currently, the process is iterative, time-consuming, and manual. This tool assists the analyst in providing possible solutions to difficult scheduling problems. Manpower savings range up to 30 percent in sequence development, integration of sequence requests, and preparation of flight operations schedules. Some of the same techniques used for the Timeline Generator would also be used by the Sequence Planner.

Taken altogether, these six specific automation tools represent a package that would greatly improve the efficiency of the sequencing process and hence reduce operations costs. The savings to the total MO&DA budget for a typical, complex *Mariner Mark II* mission like the *Comet Rendezvous/Asteroid Flyby* mission might be as much as nine percent.

Data System Standards

This task explored the cost benefits that might accrue if both the operational data and the data handling processes during the mission operations were designed to conform to a set of standards. The seven data system standards considered in the task were as follows:

1. *Telemetry Channel Coding.* This standard would require all data coded on a spacecraft to use one of a predetermined set of coding algorithms.
2. *Packet Telemetry.* This standard would require data generated by the science instruments and engineering subsystems on-board the spacecraft to conform to a common data structure.
3. *Packet Telecommand.* This would require all ground commands to any spacecraft to conform to a common data structure.
4. *Time Code Formats.* This would require all spacecraft and ground systems to use a common format for time, and to select that format from a predetermined set of formats.
5. *Standard Format Data Unit.* This would require use of a common data structure for transfer of data between any and all elements of the ground data system.
6. *Radio and Frequency Modulation.* This would require usage of common frequency bands, ground timing stability criteria, and command, telemetry, and ranging bandwidths between and within all facilities and agencies participating in the planetary mission operations.
7. *Radiometric and Orbit Data Formats.* This standard would require the use of a common data structure for the radiometric data and a common set of conventions for the models and coordinate systems used to process the radiometric data by all agencies participating in the planetary mission operations.

These standards would have to be implemented during the spacecraft and ground system design and development processes; benefits during mission operations would come from simplification of the operations process.

The results of this task indicated that it is not possible to quantify the degree to which the data system standards would reduce the cost of mission operations. Use of the standards would, however, provide a mechanism for achieving effective cost reductions in the mission operations, and would result in the performance of certain operational tasks in a more efficient manner. Imposition of these data system standards would also enable more use of automation for routine activities, allow for greater sharing of trained personnel and equipment between projects, and simplify the operational planning, testing, and execution processes. In addition, using the standard format data unit will greatly simplify the entire process of archiving data.

6. Science Issues

In the course of the MOIS Subcommittee activities, many issues were raised that required responses from the scientific community. Several members of the MOIS Subcommittee have served as principal investigators on one or more of the NASA planetary missions, and it was their role on the Subcommittee to represent the science position. In this chapter, the most important points made by the scientific members of the Subcommittee on the science issues raised during the Subcommittee's discussion have been summarized.

SCIENTISTS' INVOLVEMENT IN MISSION OPERATIONS

One of the characteristics of the SSEC Core Program concept is the increased emphasis on controlling costs in the definition and implementation of planetary missions. It is likely that, early in the process, trade-offs will be made that significantly affect the scientific return from many missions. To ensure that the effects on science return are understood, it is important that scientists with appropriate experience be involved in all stages of mission operations. This involvement should include system planning (at both the broad mission class level and the more detailed level of individual missions), implementation (particularly in sequencing, uplink and downlink control, data rate, and data storage), and execution. It will be the function of these scientists to represent and protect the interest of the investigator; to understand the cost/risk/schedule/science trade-offs and to convey this understanding to the larger investigator community; and generally to advance the concept of "most science for the dollar."

ANNOUNCEMENT OF OPPORTUNITY (AO) AND SELECTION

During the execution of the SSEC Core Program Missions, especially for the later missions in the *Planetary Observer* and *Mariner Mark II* classes, the basic Mission Operations System (MOS) will already be in place at the time of issuance of the mission AOs. Because MO&DA activities form a substantial portion of science investigation costs, it is desirable that respondents to the AO be able to make realistic estimates of their MO&DA costs. The AO should therefore contain an adequately detailed description of the MOS. Proposals should contain an outline of the investigation operations plan and should identify those elements of it that exceed the capabilities of the MOS described in the AO, together with the importance of such elements to the investigation. The selection process can then include estimates of the cost to the project of operating each investigation, and these estimates would be factored into the selection in much the same way as integration costs.

We also note that a careful match of the mission resources envelope and the selected payload's resource requirements is important, since the resource partitioning and scheduling required by an oversubscribed envelope have a substantial adverse impact on operations costs.

IMAGE PROCESSING COSTS

The costs of processing the imaging data from planetary missions have in the past been much larger than for other kinds of data. These costs are driven partly by the sheer volume of the data, and partly because the very great scientific and public interest in the images has led to a processing system geared to the rapid production and wide distribution of a complex set of finished image products. Other cost drivers include the use of high overhead general-purpose mainframe computers in the production process, and the reprocessing necessitated by revisions, frequently long delayed, to the SEDRs.

The Subcommittee believes that there are substantial cost savings to be made by rethinking the image processing system in the light of modern computer technology. The advent of efficient minicomputers makes possible a distributed processing system, which can take advantage of computing power already existing at investigator institutions. It also allows the replacement of image hard copy in scientific analysis by computer-compatible and "volatile" images. Both of these considerations reduce the pressure on (and therefore expense of) the primary image processing system at JPL, allowing this system to take efficient account of production factors when determining its scope and throughput. The Subcommittee also feels that it would be worthwhile to consider relaxing the time requirement on the mission Preliminary Science Reports, in the interests of further reducing throughput demands on the image processing system.

SEQUENCING

Sequencing, the translation of plans for observations and for spacecraft and instrument operations into a detailed command stream that will be uplinked to the spacecraft, involves the balancing of an exceedingly complex set of requirements and constraints imposed by the many parts and subsystems of the spacecraft. Because both the understanding of spacecraft characteristics and the observing requirements change with time as the mission progresses toward encounter, sequencing is necessarily an iterative process. The complexity and the need for iteration are both significant cost drivers in the sequencing process.

There are several ways in which the process can be simplified; some of them are already being used in the design of new sequencing systems. The complexity and some of the need for iteration can be reduced by making maximum provision for "non-interactive" instrument commands (that is, commands which have no effect on other spacecraft subsystems) and by providing to the investigators the tools for "pre-sequencing," by which the investigator can "wring out" his observing requirements before submitting them to the sequencing team. On flyby or rendezvous missions, where the need to maximize the science return requires the full utilization of all sequencing and uplink resources, it may be useful to explore the sequencing of certain key observations first, so that conflicts are uncovered early and can be resolved with minimum impact. On mapping missions, where the scientific return depends heavily on the completeness and uniformity of the acquired data set, greater resource margins should be retained during sequencing so that unforeseen events can be accommodated without an adverse effect on the scientific return.

SUPPLEMENTARY EXPERIMENT DATA RECORDS

Many scientific analyses performed on data from planetary missions require the accurate location of individual instrument measurements in a particular frame of reference (most commonly, on the surface of the target body, but also in such frames as the rotating magnetic frame of Jupiter). This information is traditionally supplied to the investigator in the Supplementary Experiment Data Record, or SEDR, the format and content of which is determined early in mission development. SEDRs contain a very large number of geometric parameters that are derived from the basic trajectory and pointing information. This is because, since the SEDR is the only means by which their data location needs will be met, investigators request a larger set of parameters than they ultimately need. The SEDR system has become very costly and inefficient because of its large size, wide distribution, and frequent revision as the basic information set (trajectory and pointing) is improved.

The Subcommittee feels that the impact on data analysis costs of alternative means of providing data location information should be examined. One such alternative is to provide the investigators with access to current trajectory and pointing information, so that they can compute their own location parameters, thus avoiding the updating delays involved in the SEDR production system. Resources currently expended in the production and distribution of SEDRs could then be used instead to accelerate the production of the definitive version of the basic trajectory and pointing information sets.

7. Transition Period Assumptions

One of the primary functions of the MOIS Subcommittee was the determination of methods by which mission operations costs can be reduced for the SSEC Core Program Missions. The first two of these missions, the *Mars Geoscience/Climatology Orbiter (MGCO)* and the *Mariner Mark II Comet Rendezvous/Asteroid Flyby (CRAF)*, are scheduled to be launched in 1990. As the work of the Subcommittee progressed, it became apparent that a significant key to achieving lower-cost mission operations in the 1990s was the successful completion of several activities during the time between 1984 and 1990. This time period has been called the Transition Period.

The quantitative results presented in this report are dependent upon all of the following activities being completed prior to 1990:

1. Design, development, and implementation of the Space Flight Operations Center (SFOC).

Work on the SFOC (Space Flight Operations Center) is currently under way at JPL and operational certification is due in 1988. This major update to the planetary operations capability at JPL, among other things, replaces outdated computing equipment with more modern machines and makes use of state-of-the-art interactive data base systems. It also allows both science and engineering personnel to live in a location remote from the SFOC and to communicate with it electronically. The SFOC is basic to the operational concepts suggested in this report. Without substantial implementation of the SFOC, the total costs of mission operations for the FPSO component of the MO&DA costs during the 1990s will be higher.

2. Expansion of Flight Project Support Office (FPSO) multi-mission functions.

It is currently planned that the data records, mission control, and image processing functions, all of which have been funded directly by the flight projects in the past, will be transferred to and integrated into the FPSO prior to 1990. The costs allocated to FPSO in the charts in the next section assume all these functions are part of FPSO during the mission operations for the SSEC Core Program Mission model.

3. Development of automation prototypes.

At the present time design of the kernels of the automation tools that will reduce costs for the planetary missions of the 1990s is progressing at JPL. The MO&DA cost calculations for the SSEC Core Program Mission set in some places assume that prototypes of these automation tools exist by the late 1980s and that individual flight projects need only do modest customizing of them to reap the reduced operations costs. To achieve these prototypes, the current program of automation tool design and development must be continued.

4. Organization of **Planetary Observer** *and* **Mariner Mark II** *projects.*

To benefit in a major way from shared operations, changes must be made in the way that JPL organizes its flight projects. Another of the transition period assumptions made by the MOIS Subcommittee is that the Option 2 organization (or something similar) discussed earlier in this report will be in place prior to 1988.

5. Data system standards and spacecraft commonality.

During the Transition Period, those activities necessary to ensure that data system standards can be adopted and common spacecraft can be flown during the 1990s are assumed to take place.

8. Synthesis of Trade Study Results

As part of the MOIS Subcommittee activities, various past missions were studied to understand which operations functions contributed the largest portion to the overall mission operations costs. Using the cost category breakdowns adopted by the JPL study team and the Subcommittee (which are given by Figure 5 in Chapter 4), the percentages of total costs that can be attributed to each category for the *Voyager* mission, for example, are shown in the pie chart of Figure 11. Of particular interest in this chart are the costs for the spacecraft planning and analysis task and the sequencing task; most of the significant cost reduction suggestions are aimed at these two categories. Another significant area of cost is image processing. One measure of the increased operational efficiency that will result from the implementation of the SFOC is that, after the SFOC is operational, the multi-mission FPSO (of which SFOC is a part) will be able to absorb the image processing functions—as well as the data records and mission control functions—with no net increase in the FPSO budget.

At the urging, and under the supervision, of the MOIS Subcommittee, JPL designed and implemented a software model that would quickly and accurately estimate the MO&DA costs for planetary missions. This model, which operates on a set of parameters that describe a mission or set of missions, was validated against the *Voyager* and *Galileo* data bases and then used, as part of the Subcommittee effort, to evaluate the impact of proposed mission operations changes on MO&DA costs. All of the quantitative results discussed in this section came from the model. A brief description of this computer model has been included as Appendix II.

The basic goal of the Subcommittee in using the model was the determination of the MO&DA costs for the entire SSEC Core Program Mission set as a function of the way that mission operations would be conducted. To accomplish this, the key parameters for each of the Core Program Missions were defined and used in the model under several different assumptions about mission operations. To establish a baseline (and also to calibrate the model), the first study estimated the MO&DA costs of flying the SSEC Core Program Mission set (given in Figure 3 of Chapter 3) using today's mission operations technology. Figure 12 shows the results of that study, indicating that the average MO&DA costs without improvement would be above the SSEC guideline.

The second study changed the governing assumptions about the mission operations system that would be used during the SSEC Core Program Mission Model time period. For this second study, it was assumed that all the significant elements of the SFOC (Space Flight Operations Center), currently in its initial development phase at JPL, would be in place and that the multi-mission FPSO, now more efficient as a result of SFOC, includes as planned the functions of image processing,

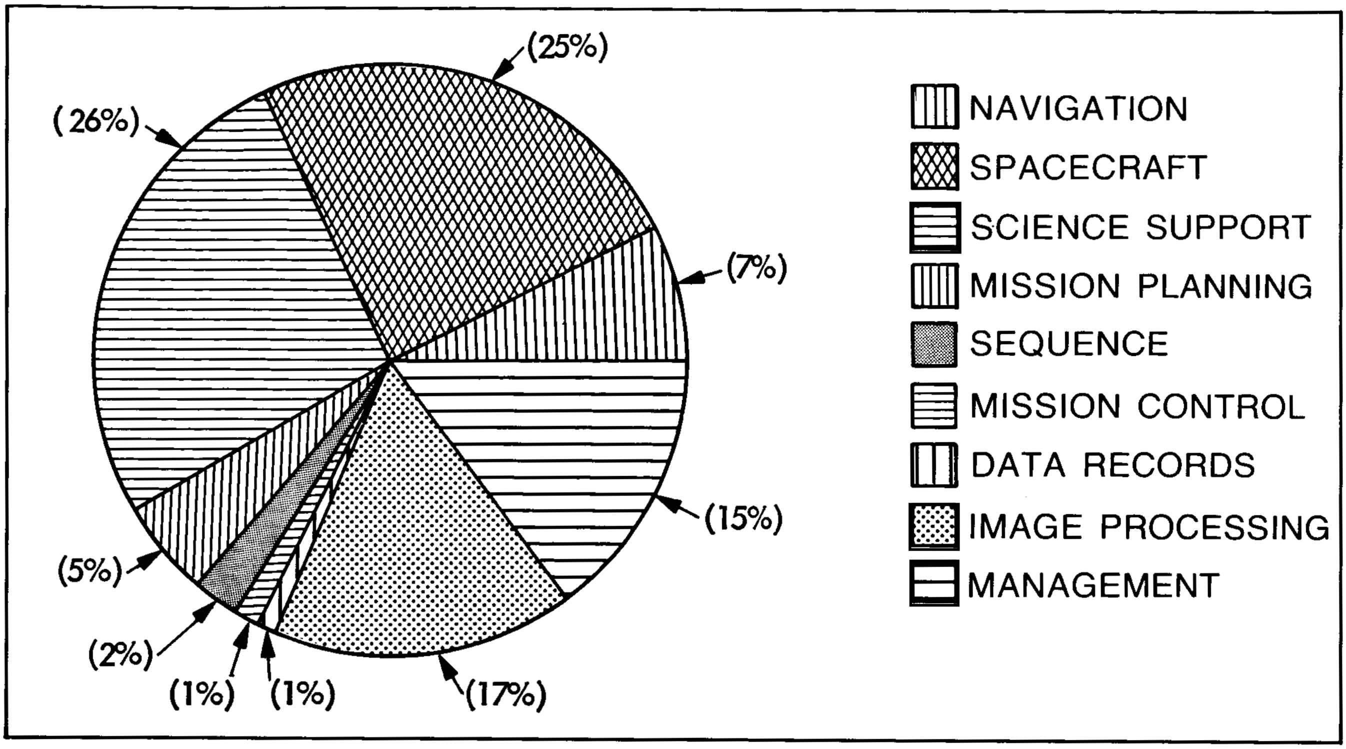

Figure 11. Cost Breakdown for *Voyager* Mission Operations

mission control, and data records. Figure 13 compares the resulting MO&DA costs for the SSEC Core Program Mission Model with the costs obtained if today's technology were used. Clearly, the successful implementation of SFOC and the transfer to FPSO of additional functions are vital contributions to reducing operations costs in the 1990s.

The model was also used to determine the MO&DA cost reductions that would result from the automation and shared operations concepts studied as part of the Subcommittee effort. Figures 14 and 15 demonstrate the additional operations cost savings that could be achieved for the SSEC Core Program as a result of automation and shared operations.

One additional cost analysis was performed using the model. Based on an analysis of the *Voyager* mission operations, it is clear that "learning" acts, after a period of time, to reduce the manpower required (and hence the costs) to fly planetary missions. If the *Mariner Mark II* and *Observer* spacecraft designs adhere to standards, and each family of spacecraft has a significant degree of commonality within the family, then "learning" will play a significant part in reducing operations costs for each member of the family (either *Mariner Mark II* or *Observer*) launched after the first one. The maximum potential savings from "learning" are indicated in Figure 15.

From these charts, one striking conclusion is apparent. Methods that should significantly reduce MO&DA costs for the SSEC Core Program Missions have been identified. The challenge now is to implement these methods and continually search for additional techniques to lower the costs of operations.

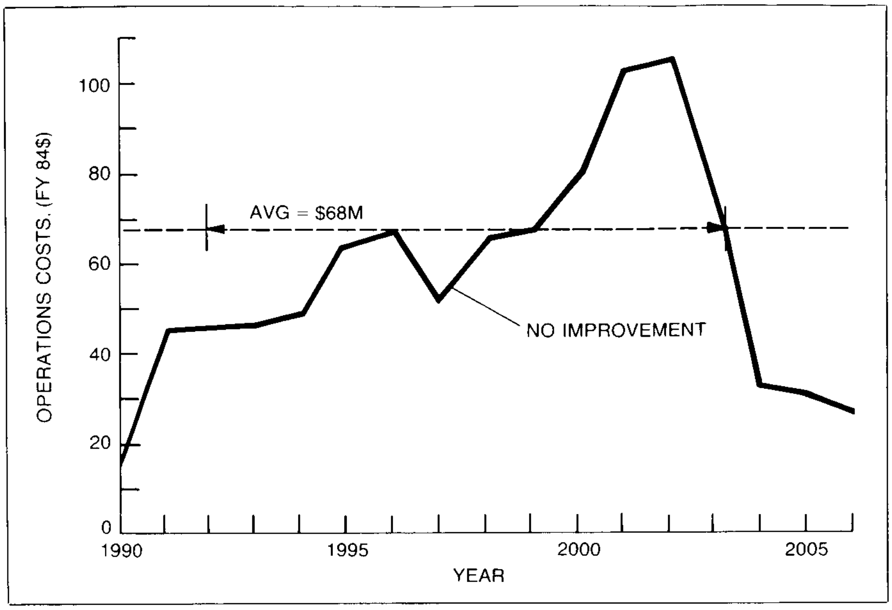

Figure 12. Estimated Operations Costs for SSEC Core Program Missions with No Improvements

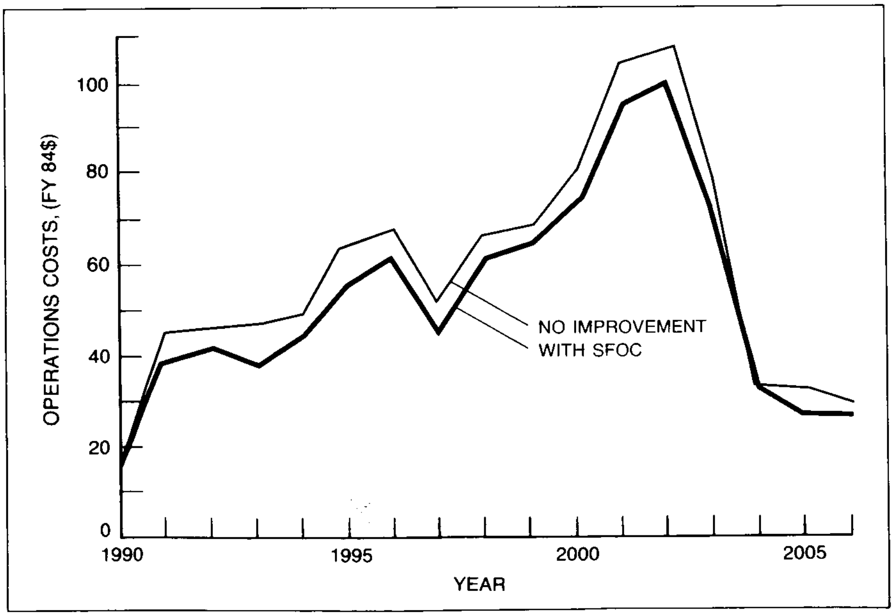

Figure 13. Estimated Operations Costs for SSEC Core Program Missions with SFOC

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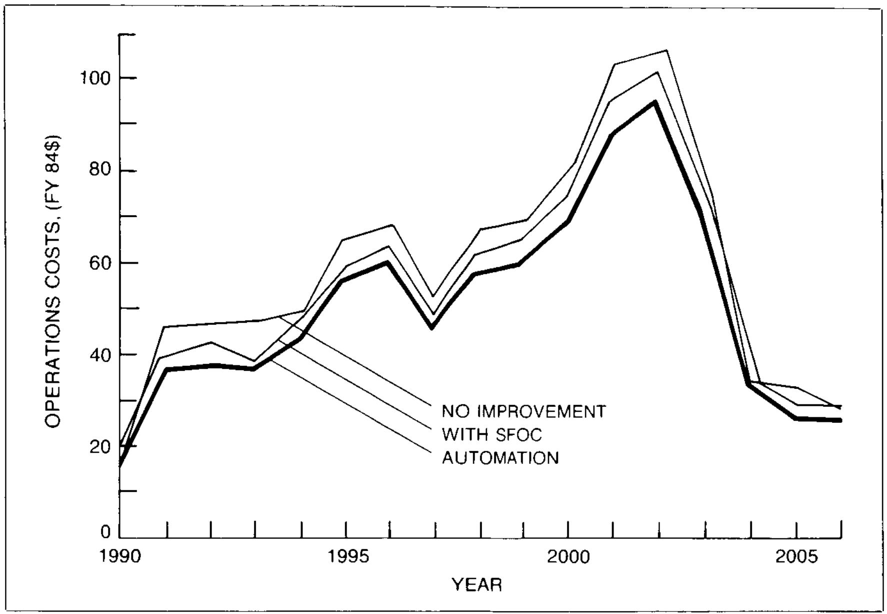

Figure 14. Estimated Operations Costs for SSEC Core Program Missions with SFOC and Automation

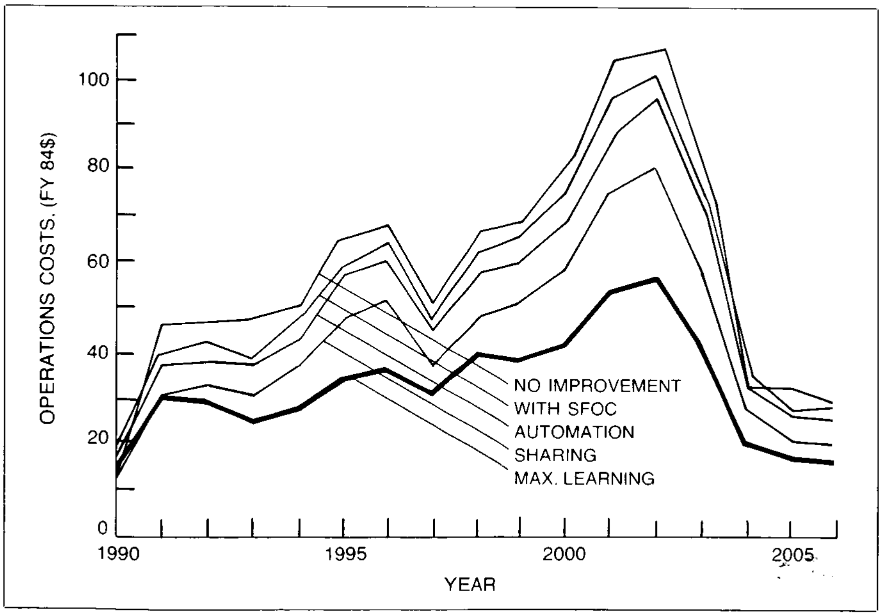

Figure 15. Estimated Operations Costs for SSEC Core Program Missions with SFOC, Automation, Sharing, and Maximum Learning

9. Conclusions and Recommendations

The major conclusions of the MOIS Subcommittee are of two fundamentally different types: those that are derived directly from the specific study tasks performed during the Subcommittee activity; and those that are more general and qualitative in nature. Recommendations have been formulated based on both kinds of conclusions, and the two types are presented separately in the discussion below.

Specific Recommendations

The MOIS Subcommittee, having assessed the results of the JPL study, finds that the SSEC MO&DA target cost will clearly support the SSEC Core Program during the period 1990 to 2000. In fact, expenditures were conservatively estimated to average $55 million per year, based upon the JPL study results.

This result is strongly dependent on JPL's continuing implementation of SFOC plans and on the incorporation of organizational changes, mission operations sharing, automation, spacecraft commonality, and the transfer of additional functions to FPSO. The result is also dependent on retaining the key constraints that define the characteristics of the missions in the SSEC Core Program.

The Subcommittee believes, if the above activities are carried out, that a combination of reduced conservatism in the estimation process and the identification of additional savings will result in further reductions of $5 million to $10 million per year.

We recommend that NASA continue to fund, in a timely manner, those activities which will lead to the realization of these MO&DA cost savings.

1. Based on the data shown in Chapter 8, it is clear that the modernization of the existing operations facilities at JPL and the transfer to the multi-mission FPSO of the image processing, mission control, and data records functions will powerfully reduce the costs of mission operations for the SSEC Core Program. The new Space Flight Operations Center (SFOC) will be modular in nature, will perform the telemetry and command functions for all missions using a new generation of commercial minicomputers and microcomputers, and will be designed to accommodate remote work stations. Once the SFOC is completed, significant manpower savings in hardware and software maintenance as well as software development and sustaining engineering will be realized. These manpower savings will allow FPSO to perform the added multi-mission tasks with no net increase in staffing.

We recommend that the SFOC development and the FPSO plans to accommodate the new multi-mission tasks become high-priority projects and that a regular set of reviews be established to ensure their timely completion.

2. One of the major findings of the MOIS Subcommittee is that the efficiency of the implementation of the cost reduction concepts is a function of the organization structure used for development and operations. To reduce costs, it is clear that both the *Planetary Observer* and *Mariner Mark II* programs must be organized to provide a common focus and incentives for such activities as: personnel sharing between projects; development and use of common spacecraft subsystems, software, and even science instruments; optimization of the total mission costs by "correct" trade-offs between development and operations; and maximization of the benefits of the learning process by the operations team.

We recommend that NASA and JPL continue to move rapidly to establish an organizational structure for the SSEC Core Program that merges each family of spacecraft into a single program office and provides appropriate incentives so that cost reduction concepts can be easily implemented.

3. The primary category of costs for planetary mission operations is manpower. Automation offers the potential to replace some labor-intensive tasks with computer models and tools. The automation effort under way during the past couple of years has identified several tools which, when their combined effort is analyzed, could significantly reduce MO&DA costs.

We recommend the continuation of a vigorous effort to determine those functions in mission operations that can be replaced by automated tools in such a way that total MO&DA costs are reduced. We also recommend timely implementation of the specific automated tools that are identified in this report as having significant potential for reducing costs.

4. The international community is already moving toward the adoption of data system standards. These standards will greatly simplify the mission operations process and will lead to cost reductions by encouraging personnel sharing across projects as well as the development of common software for such tasks as sequencing and data records. Data analysis will be simplified as a result of the ease with which different data sets can be reduced and compared. Science data archiving will also be simplified.

We recommend that the current data system standards activity be extended to search for other areas where data standards might lead to additional simplification in the mission operations program.

5. One of the most valuable results of the work between the MOIS Subcommittee and the JPL study team was the creation of a computer model that allows reasonably fast, reasonably accurate computation of mission operations cost as a function of the mission being flown and the underlying mission operations process. The model is extremely helpful in understanding the way in which mission design and/or mission operations design changes impact total mission operations costs.

We strongly recommend that this computer model be maintained and updated as required, and that it be used regularly to evaluate mission operations costs for planetary missions.

General Recommendations

In addition to the quantitative results and specific conclusions of the preceding section, the MOIS Subcommittee arrived at a number of more general assessments. The Subcommittee believes that the adoption of the recommendations based on these assessments will create an environment conducive to realizing the cost savings identified in the preceding section, as well as additional savings not quantified in this study. The topics of these recommendations are as follows:

1. CONTINUED INDEPENDENT REVIEW

The activities of the MOIS Subcommittee have resulted in an increased and sharpened focus on the issues influencing MO&DA costs for planetary mission operations. The results suggest that broad, generic analysis of the factors affecting mission operations costs by people with experience outside JPL can help identify ways in which operations costs can be reduced.

We recommend continued independent review of all significant mission operations development costs and ongoing planetary mission operations costs as a stimulus to the development of a regular and orderly process for identifying additional methods and technologies to achieve overall cost reduction.

2. MOTIVATION AND INCENTIVES

One of the major thrusts of the MOIS Subcommittee discussion about organizational structure was an attempt to define the characteristics of operational organizations that would result in personnel being motivated, while performing their operational tasks, to seek ways of reducing their costs without measurably increasing mission risk. It was suggested that perhaps some way of creating cost-related performance incentives inside the organization might be an additional way of obtaining that motivation.

We recommend that a study be initiated to identify means by which the operational activities can be "incentivized" so that the members of operational teams are additionally motivated to find ways of reducing costs.

3. SCIENTIST ROLE EXPANSION

Almost all the costs of planetary mission operations are associated, in one way or another, with the acquisition and/or distribution of science data to the investigators. Cost/performance trade-offs for individual missions or across a class of missions inevitably involve questions of science value that can best be addressed by representatives of the investigators. Operations plans directly impact science return and should be discussed in detail with the investigator community before and during development, instead of after the Announcement of Opportunity (AO), as is the current practice.

We recommend that all AOs for planetary missions include operations plans and system definitions and that the investigators' proposals respond to these plans, as well as to the spacecraft

descriptions. We further recommend that a mechanism be created to ensure the participation of the investigator community in the development of these operations plans.

4. DEVELOPMENTAL ISSUES

Although the MOIS Subcommittee charter limited its purview to the MO&DA cost elements for planetary missions, many of the factors that will reduce MO&DA costs (for example, personnel sharing, organizational changes, and spacecraft commonality) will also significantly reduce MOS and spacecraft development costs. The cost reductions in the development area resulting from the MOIS Subcommittee recommendations, as well as the possible identification of other major cost reduction factors, suggest that a thorough look at planetary mission development costs might also be warranted.

We recommend that NASA consider the creation of mechanisms by which planetary mission development costs for the SSEC Core Program can be reviewed systematically to identify additional ways of reducing the overall costs of the program.

5. SUPPLEMENTARY EXPERIMENT DATA RECORDS

A major source of significant expenditures of MO&DA money in the past has been the lack of timeliness and accuracy in the Supplementary Experiment Data Records (SEDRs) provided to the investigators by the flight projects. Many suggestions were made during the MOIS Subcommittee discussions on ways to reduce the SEDR costs. One such suggestion involved the project providing the investigators with navigation state vectors and the requisite set of computation algorithms so that the investigators could make their own SEDR.

We recommend that a study be undertaken to review the present SEDR generation techniques, as well as their costs, and to analyze alternative ways of performing the SEDR function that might substantially lower the overall costs.

6. OPERATIONS OF SIMPLE SPACECRAFT

The recent rapid advances in minicomputer and microcomputer hardware, software, and data base management techniques, as well as Earth-orbiter experience, suggest to the MOIS Subcommittee that low-cost mission operations systems for simple spacecraft can be quickly and inexpensively developed. The experience level and quantity of manpower required to operate these highly automated ground systems should be greatly reduced, and the resulting operations costs should be correspondingly low.

We recommend that NASA investigate the benefits of conducting mission operations for the simplest spacecraft at universities or NASA centers other than JPL.

APPENDIX I: Core Program Mission Summaries

Mars Geoscience/Climatology Orbiter

Target: Mars

Spacecraft Class: *Planetary Observer*

Mission Duration:

Cruise	1.0 years
Encounter	1.9 years
Total	2.9 years

Candidate Science Investigations

Gamma-Ray Spectrometer
Mapping Visual and Infrared Spectrometer
Pressure-Modulated Infrared Spectrometer
Radar Altimeter
Ultraviolet Spectrometer
Ultraviolet Photometer
Magnetometer
Radio Science

Mission Strategy

The *Mars Geoscience/Climatology Orbiter* mission will deliver a single spacecraft to Mars for an extended orbital study of the planet's surface, atmosphere, and gravitational and magnetic fields. The spacecraft will operate from a near-polar, sun-synchronous circular orbit at low altitude (350 kilometers) and collect data in a repetitive daily cycle over one Mars year (687 days). Except when performing maneuvers, the spacecraft remains nadir-oriented and points the instruments to the ground track. All of the instruments are self-articulating. Data are collected at a low data rate and recorded over a 24-hour period. Once a day, the recorded data are dumped to the ground over an eight-hour Deep Space Network pass, as data collection continues with recording on the second tape recorder. All engineering and science data will be assembled on the ground in an electronic data base.

Lunar Geoscience Orbiter

Target: Moon

Spacecraft Class: *Planetary Observer*

Mission Duration:

Cruise	5 days
Encounter	1 year
Total	1 year

Candidate Science Investigations

Gamma-Ray Spectrometer
Mapping Visual and IR Imaging Spectrometer
Radar Altimeter
Magnetometer
Electron Reflectometer
X-Ray Spectrometer
Solid State Imager

Mission Strategy

The *Lunar Geoscience Orbiter* mission will deliver a single spacecraft to the Moon for an extended orbital study of the lunar surface and gravitational and magnetic fields. The spacecraft can be launched at almost any time and inserted into a 100-kilometer circular polar orbit. This will be followed by a one-year observation period with data collected on a repetitive cycle. Except when performing maneuvers, the spacecraft remains nadir-oriented and points the instruments to the ground track. All of the instruments are body-fixed or boom-mounted. Data are collected at a single data rate (6,000 bps) and recorded over a 24-hour period. Once a day, the recorded data are dumped to the ground over a ten-hour 34-meter Deep Space Station pass at 32 kbps. Data collection would continue in a simultaneous record and playback mode. All engineering and science data will be assembled on the ground in an electronic data base.

Comet Atomized Sample Return

Target: Kopff 1996 Apparition

Spacecraft Class: *Planetary Observer* (assumes a complementary comet rendezvous mission reaches the comet before perihelion to provide essential ephemeris information).

Mission Duration:

Cruise Outbound	1.6 years
Encounter	25 days
Cruise Return	0.3 year
Total	2.0 years

Candidate Science Investigations

Sample Collector
Dust Counter
Solar Wind Collector

Mission Strategy

The *Comet Atomized Sample Return* mission will deliver a single, spin-stabilized spacecraft for a fast flythrough of the coma of the periodic comet Kopff. During the brief flythrough at a speed of 14 to 22 kilometers/second, a collector obtains samples of the gases and solid particles within the coma. The solid particles are either captured intact or vaporized upon impact with the collector, which entraps the dust or the resulting condensate. Following the encounter, the sample collector is packaged into an entry capsule for return to Earth. The interplanetary trajectory has a resonant period, so that following the intercept of the comet at perihelion, the spacecraft returns to Earth in a whole number of years after launch. As the spacecraft returns to Earth, the entry capsule is targeted into the atmosphere for surface recovery. The principal complexity of the mission will be the accurate targeting maneuvers for the encounter at the proper distance from the comet nucleus and for the entry capsule trajectory at the end of the mission. The encounter sequence is very simple, requiring only the proper pointing of the spacecraft so that dust impacts occur on the shielded side of the spacecraft where the sample collector is located. The only other instrument is a low data rate impact counter, and there are no requirements for articulation of the instruments or cruise science. A solar wind collector may be added as an enhancement. The simplicity of this mission depends on the assumption that optical navigation is not required by the *Comet Atomized Sample Return* spacecraft to determine the ephemeris of the comet, because a comet rendezvous mission has reached the comet before perihelion. With accurate ephemeris data from the comet rendezvous mission, radio navigation is sufficient for this mission.

Venus Atmospheric Probe

Target: Venus

Spacecraft Class: *Planetary Observer*

Mission Duration:

Cruise	4 months
Encounter	1 hour
Total	4 months

Candidate Science Investigations

Neutral Mass Spectrometer
Gas Chromatograph
Pressure, Temperature, and Accelerometer
X-Ray Fluorescence
Visual Spectrometer
Cloud Particle Counter

Mission Strategy

The *Venus Atmospheric Probe* mission will deliver one probe into the venusian atmosphere to obtain *in situ* measurements of noble gases, cloud particles, sulfur compounds, and the nature of lower atmospheric oxidation/reduction. The mission can be launched during any of the Venus opportunities, which occur every 19 months. The probe will be carried to Venus on a simple, spinning spacecraft. All science instruments are contained in the pressure vessel body of the probe and are sequenced by a predetermined load. The probe's shape is designed to perform a pull-up maneuver during entry to prolong high-altitude measurements. Data will be transmitted directly from the probe to Earth at one kilobit per second in RAM at 512 bps. The encounter will be supported by two stations of the Deep Space Network, at least one of which is a 70-meter station, to obtain angle data (NΔ VLBI) and to compensate for the probe's low-gain antenna. Data will be transmitted for a total of one hour during entry and descent to the surface. The probe is not designed to survive surface impact, but if it should, two hours of science data could be received.

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Earth-Approaching Asteroid Rendezvous

Target: Anteros

Spacecraft Class: *Planetary Observer*

Mission Duration:

Cruise		1.2 years
Encounter		0.5 year
Total		1.7 years

Candidate Science Investigations

Gamma-Ray Spectrometer
X-Ray Spectrometer
Radar Altimeter
Multispectral Mapper
Magnetometer
Charge Coupled Device Imager

Mission Strategy

The *Earth-Approaching Asteroid Rendezvous* mission will deliver a single spacecraft to rendezvous with an Earth-approaching or Earth-crossing asteroid. For this study, a rendezvous with Anteros in 1998 is assumed. The spacecraft will be launched from the *Space Shuttle* by a Transfer Orbit Stage. After a cruise of about 14 months, the spacecraft will perform a rendezvous burn to change its orbit from the transfer orbit to that of the asteroid. This initial rendezvous is a few thousand kilometers from the asteroid itself, outside of its sphere of influence. At this point, the asteroid will be the brightest object in the sky, so the imaging system will be used to help with the final approach navigation. Once inside the asteroid's sphere of influence, several scenarios are possible, due to the relatively weak gravitational attraction and low maneuver energy requirements. Stationkeeping, however, may be impractical due to propellant demands. It is likely that the spacecraft would make a series of ever-closer long hyperbolic passes at the asteroid, during which much of the surface would be mapped and an optimum orbit determined. The spacecraft would then either orbit the asteroid at an altitude as low as ten kilometers or execute a series of interrupted free-falls into the asteroid. At the end of the mission, an "as-soft-as-possible" landing on the asteroid may be attempted.

All science instruments are body-fixed or boom-mounted and the spacecraft is nadir-pointed. Data are collected in both real time and by tape recorder, and both real-time and playback data are received during a single eight-hour per day pass over a 64-meter Deep Space Station. Data collection would continue during the pass in a simultaneous record and playback mode to protect against a missed track. All engineering and science data will be assembled on the ground in an electronic data base.

Dual Mars Aeronomy and Network Orbiters

Target: Mars

Spacecraft Class: *Planetary Observer*

Mission Duration: Cruise .... 0.8 year
Encounter .... 1.9 years
Total .... 2.7 years

Candidate Science Investigations

Orbiter

Neutral Mass Spectrometer
Ion Mass Spectrometer
Ultraviolet Visible Spectrometer
Infrared Sounder
Retarding Potential Analyzer
Plasma Particle Analyzer
Electron Langmuir Probe/Plasma Wave Analyzer
Magnetometer
Radar Altimeter
Doppler Ranging

Penetrators

Fluxgate Magnetometer
Seismometer
Heat Flow
Stratigraphy
Imager
Meteorology
Geochemistry
Sun Aspect
Water Detector

Mission Strategy

This mission represents a combination of two Core Program Missions, the *Mars Aeronomy Orbiter* and the *Mars Network.* It will be a joint NASA/ESA mission with the objective of sending two coordinated spacecraft to Mars. Both spacecraft, the *Mars Aeronomy Orbiter* and the *Mars Surface Probe,* are based on ESA's Kepler design.

The *Mars Surface Probe* will carry four surface penetrator probes that will be independently targeted on approach to the planet for atmospheric deceleration and surface impact. It will then perform an orbit insertion burn so that it can relay data from the penetrator to Earth and vice versa. The *Mars Aeronomy Orbiter* will follow 132 days later and release four more surface penetrators in a similar fashion. Each surface penetrator will perform geochemical analysis, water identification, heat flow measurements, stratigraphy, imaging, and biochemistry. As a network they will collect information on seismology, meteorology, and magnetometry.

Two days after the *Mars Aeronomy Orbiter* has released its penetrators it will perform a capture burn at Mars and begin taking aeronomy data on the magnetosphere, solar wind interactions, upper and lower atmosphere, and surface topography.

Comet Rendezvous/Asteroid Flyby

Target: Comet Kopff, Asteroids Namaqua and Lucia

Spacecraft Class: *Mariner Mark II*

Mission Duration: Cruise .... 4.0 years
Encounter .... 2.3 years
Total .... 6.3 years

Candidate Science Investigations

Narrow-Angle Imaging
Spectral Mapper
Gamma-Ray Spectrometer
X-Ray Spectrometer
Dust Counter
Neutral Mass Spectrometer
Ion Mass Spectrometer
Dust Analyzer
Magnetometer
Plasma Wave Receiver

Mission Strategy

The *Comet Rendezvous/Asteroid Flyby* mission will deliver a *Mariner Mark II* rendezvous spacecraft for a 2.3-year detailed study of the periodic comet Kopff during its 1996 apparition. It will investigate the evolution in Kopff's activity as the solar heating changes during its orbit. En route to Kopff, the spacecraft will fly past the asteroids Namaqua and Lucia at a distance of 350 kilometers and 2,000 kilometers, seven months and 12 months after launch, respectively. At about perihelion minus 720 days, the spacecraft will rendezvous with Kopff at a range of 100,000 kilometers. After the safety of the spacecraft has been ascertained, the spacecraft will make several incursions into the comet at a range of distances from 1,000 kilometers down to 25 kilometers. Upon completion, the spacecraft will be placed into an orbit about the comet with a semimajor axis of 50 to 100 kilometers. Then, safety permitting, the altitude will be reduced to three radii of the nucleus in order to obtain optimal data for the gamma-ray spectrometer. From this orbit, it will be able to observe the comet from different vantage points with high resolution which will allow high-precision measurements such as density to be made. As the comet nears perihelion, the spacecraft will be repositioned 4,000 to 5,000 kilometers from the comet on the sunward side in order to avoid the hazards due to the increasing activity of the comet. Just before and after perihelion, the spacecraft will make several drops into the comet at a distance of ten kilometers to observe comet changes. Post-perihelion, the spacecraft will be placed into a ten-kilometer orbit about Kopff. The finale will be to place the spacecraft in a stable trajectory in the vicinity of the comet.

Saturn Orbiter/Titan Probe

Targets: Saturn and Titan

Spacecraft Class: *Mariner Mark II*

Mission Duration: Cruise .... 6.5 years
Encounter .... 3.0 years
Total .... 9.5 years

Candidate Science Investigations

Orbiter

Narrow-Angle Imaging
Radar Mapper
Magnetometer
Plasma Analyzer
Plasma Wave Receiver
Energetic Particles
Infrared Radiometer
Visible/Ultraviolet Photometer

Probe

Atmosphere Structure Instrument
Nephelometer
Helium Abundance Detector
Net Flux Radiometer
Neutral Mass Spectrometer
Gas Chromatograph

Mission Strategy

This mission, now referred to as *Cassini,* will deliver an orbiter spacecraft to the Saturn system for a three-year orbital study of the planet and its rings, satellites, and magnetosphere. A Titan atmospheric probe will be carried by the spacecraft and targeted into the atmosphere on approach to the planet in a sequence similar to the *Galileo* probe delivery. Note that this mission combines two SSEC Core Program Missions, the *Saturn Orbiter* and the *Titan Flyby/Probe,* into a single initiative. Probe measurements of the atmosphere during a two-hour descent will be relayed through the orbiter and back to Earth. After orbit insertion and a 160-day initial orbit, the spacecraft will conduct repeated close encounters with Titan, using the gravity of the satellite to vary the orbit geometry and to target for other satellites. The orbit period will be reduced to typically 32 days between Titan encounters with the periapsis at Saturn closest approach between three and six radii. This will allow close-in observations of the rings and the inner satellites on each orbit. During the flybys of Titan at altitudes of 500 to 1,000 kilometers, a radar instrument will map the hidden surface of the satellite. In addition to the radar experiment, a narrow-angle imager, an infrared radiometer, and a photometer are mounted on the scan platform.

Uranus Flyby/Probe

Target: Uranus and Uranian System

Spacecraft Class: *Mariner Mark II*

Mission Duration:

Cruise	7.0 years
Encounter	3 months
Total	7.2 years

Candidate Science Investigations

Bus

Imaging
Magnetometer
Energetic Particles
Infrared Radiometer
Dust Counter

Probe

Atmosphere Structure Instrument
Nephelometer
Helium Abundance Detector
Net Flux Radiometer
Neutral Mass Spectrometer
Gas Chromatograph

Mission Strategy

The *Uranus Flyby/Probe* mission will deliver a single spacecraft and a Uranus atmospheric probe to the Uranian system for a close flyby encounter of Uranus. The spacecraft will approach Uranus from about 30 degrees above the equatorial plane so that the probe can be easily targeted to the equatorial region of Uranus. The probe will be dropped at about minus 30 days from closest approach for a one-hour (20-atmosphere) descent mission during which the probe data are relayed through the spacecraft to Earth. The spacecraft trajectory is adjusted so that the probe entry occurs about two hours prior to closest approach. Following this event, there are several close approaches to satellites (probably Ariel and Miranda). After this, the probe relay data return, ring plane crossing, closest approach to Uranus, and the Sun/Earth occultations occur in quick succession. The five instruments on board will address the questions unanswered by the *Voyager* encounter with Uranus in 1986.

Main Belt Asteroid Multiple Orbiter/Flyby Missions

Targets: TBD*

Spacecraft Class: *Mariner Mark II*

Mission Duration:

Cruise	2 years	2.6 years
Encounters Phase	4.6 years	6.0 years
Total	6.6 years	8.6 years
Total Encounters	4	5

Candidate Science Investigations

Imaging
Magnetometer
Infrared Reflectance Spectral Mapper
X-Ray Spectrometer

Mission Strategy

The *Main Belt Asteroid Multiple Orbiter/Flyby* missions will deliver twin spacecraft (launched from the *Shuttle/Centaur*) to visit several different types of asteroids in the Main Belt. The cruise time to the first asteroid for both spacecraft will be about two years, with a 90-day encounter. The rendezvous will occur on the sunside of the asteroid at about 3,000 kilometers, slowly moving in to about 500 kilometers (permitting imaging at a resolution of about five meters per line pair). This close approach also allows the other instruments to map the surface of the asteroid. After this observational period is over, the spacecraft is placed on a new trajectory, flying past several representative asteroids on its way to a second rendezvous with another body.

* Targets are to be determined. The MOIS cost model is not sensitive to the specific targets selected, but it is sensitive to the length and spacing of the encounters. The current assumption is one 60-day encounter every 18 months for each mission.

Saturn Flyby/Probe

Target: The Saturn System

Spacecraft Class: *Mariner Mark II*

Mission Duration: Cruise .... 2.8 years
Encounter .... 80 days
Total .... 3.2 years

Candidate Science Investigations

Bus

Narrow-Angle Imaging
Infrared Radiometer
Radar Mapper
Energetic Particle Detector
Dust Counter
Magnetometer

Probe

Atmosphere Structure Instrument
Nephelometer
Helium Abundance Detector
Net Flux Radiometer
Neutral Mass Spectrometer
Gas Chromatograph

Mission Strategy

The *Saturn Flyby/Probe* mission, planned for launch in May, 1998, will have a mission strategy very similar to that of the *Uranus Flyby/Probe* mission. Therefore, with the exception of launch and arrival dates, the *Saturn Flyby/Probe* mission is assumed to have the same operational characteristics as the *Uranus Flyby/Probe* mission (described earlier in this appendix). The Saturn encounter in March, 2001 will occur while the *Cassini Orbiter* is still active at Saturn, so coordinated measurements by the two spacecraft are expected to enhance the encounter science during the flyby phase of the *Saturn Flyby/Probe* mission.

APPENDIX II: MO&DA Cost Model Description

Early in the MOIS Subcommittee's activities, it became apparent that a fast, accurate representation of mission operations cost as a function of basic mission design, spacecraft design, and mission operations parameters was necessary to aid in the process of determining methods by which overall operations costs could be reduced. A computer model was developed that featured the computation of estimated MO&DA costs for a wide range of mission and spacecraft types and different operational concepts. The model was structured in such a way that it could estimate costs for individual areas of operations (such as navigation, sequencing, etc.) to gain insight into the cost drivers for any particular mission. Because the model was to be used to estimate costs for missions conducted at JPL, the computational algorithms acknowledged the division of operational responsibilities between the projects and the multi-mission support organization (FPSO).

The basic flow of the computer model is straightforward. For each fundamental function that must be performed during operations, an algorithm exists in the model that relates the number of people required to perform that function to the spacecraft and mission type, the mission phase, and the underlying operations concept. To determine the total manpower requirement (and hence the cost) of any specific mission, the personnel required to perform each function are simply summed across all the functions. Changes in the operational costs for a given mission as a result of adding or subtracting science instruments, adding target body encounters, or shortening the mission, are easy to compute.

Depending on the function, the algorithms are quite varied in structure. The primary characteristics of the algorithms for project-funded operations functions are shown in Figure II-1. For multi-mission functions, the algorithms are more complex and involve assumptions about whether the institutional capability with its baseline staff is or is not saturated at various phases of the mission or mission sets under study.

The operation of the model in the single and multi-mission configurations is shown in Figures II-2 and II-3. From the definitions of the mission, spacecraft, and operations concept, 110 individual input parameters for the project-funded algorithms can be specified, as well as another 40 input parameters for the multi-mission algorithms. Before using the model to assess the costs of the SSEC Core Program, it was validated against a range of past missions of varying complexity. The validation activity, which used the "as-flown" data bases from *Voyager* and the *Pioneer Venus Orbiter,* found that the estimates of mission cost per fiscal year were accurate to plus or minus 20 percent.

The overall structure of the cost model proved very useful in analyzing the cost reductions that would result from shared operations, spacecraft commonality, and automation. Since the model is modular in form, it is easy to change input paramaters and/or individual algorithms to compare the costs of different operational approaches.

FUNCTION	CHARACTERISTIC
MANAGEMENT	• LOOKUP TABLES AND SWITCHES
MISSION CONTROL	• SIMPLE EQUATIONS
SEQUENCE GENERATION	• LOOKUP TABLES FOR WEIGHTING FACTORS • OVERALL WEIGHTING/COMPLEXITY FACTOR DERIVED • MULTIPLIES BASE-LEVEL TEAM SIZE BY WEIGHTING/TASK CONCURRENCY • DIRECTLY SCALED TO VOYAGER ENCOUNTER STAFFING
SPACECRAFT P&A	• LOOKUP TABLES AND EQUATIONS • UTILIZES EASILY MEASURED INPUT PARAMETERS DESCRIBING MISSION • GENERIC PHASE DEFINITION • BASE TEAM SIZE CONCEPT (IN PART)
NAVIGATION	• LOOKUP TABLES (MOSTLY) AND SIMPLE EQUATION • GENERIC PHASE DEFINITION • BASE TEAM SIZES DEPENDENT ON MISSION/ENCOUNTER TYPE
MISSION PLANNING	• EQUATIONS INVOKING LOGARITHM AND SQUARE ROOT DEPENDENCIES • COMPLEXITY FACTORS FOR WEIGHTING • GENERIC PHASE TYPES BUT NOT GENERIC DATES
SCIENCE	• BASE TEAM SIZES SCALED BY MISSION • PHASE/TYPE/TASK CONCURRENCY • GENERIC PHASE DEFINITION • UTILIZES EASILY MEASURED INPUT PARAMETERS DESCRIBING MISSION
DATA RECORDS	• ALMOST A MULTIMISSION FACILITY • NO GENERIC ALGORITHM • PROJECTS SELECT FROM A SHOPPING LIST OF AVAILABLE SERVICES
IMAGE PROCESSING	• ALSO INCLUDES PHOTOLAB SUPPORT SERVICES • EASILY MEASURED INPUT PARAMETERS BUT HARD TO ESTIMATE IN EARLY PHASES OF PROJECT DESIGN • HIGHLY PEAKED INPUTS SMOOTHED BY FEASIBLE STAFFING PRACTICES • COMMERCIAL-TYPE ACTIVITIES SHOULD YIELD GOOD COST ESTIMATES

Figure II-1. Project Algorithm Characteristics

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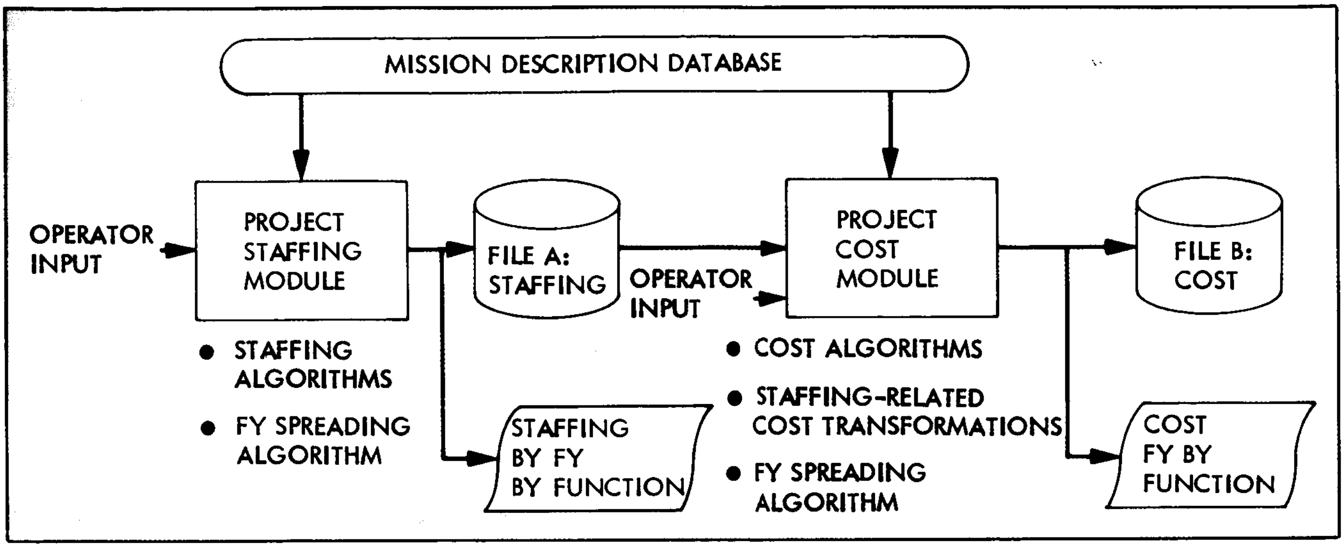

Figure II-2. Single Project Configuration

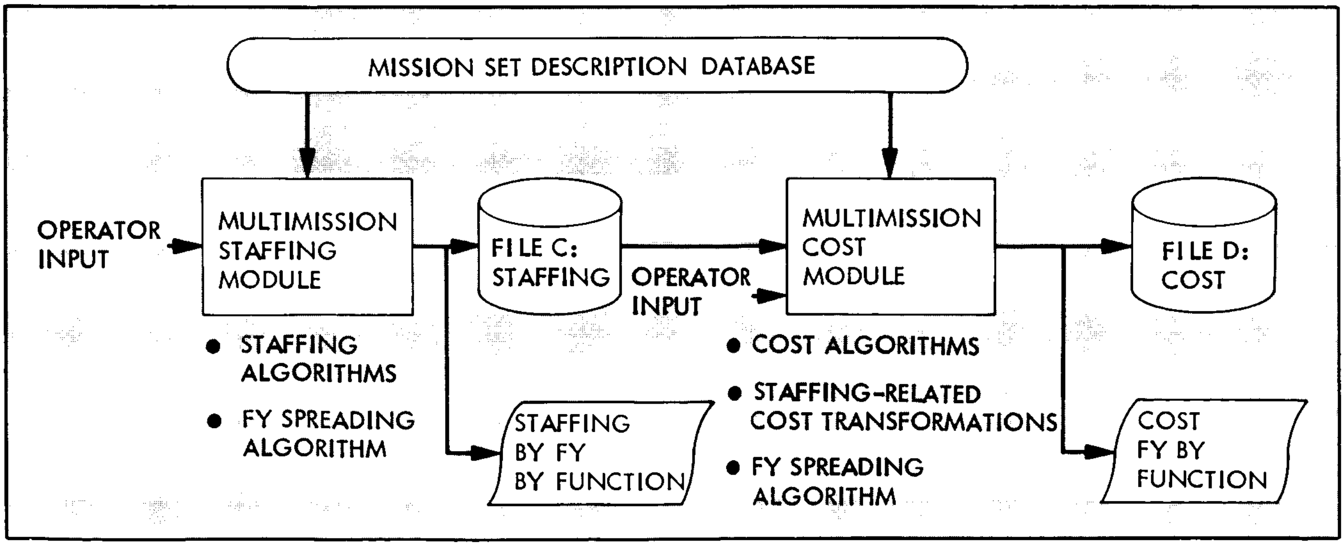

Figure II-3. Multi-Mission Configuration