1630-112

MAGELLAN LESSONS LEARNED
PROCEEDINGS OF THE MAGELLAN LESSONS-LEARNED WORKSHOP HELD DECEMBER 1991

14 APRIL 1992

NATIONAL AERONAUTICS AND
SPACE ADMINISTRATION

JET PROPULSION LABORATORY
CALIFORNIA INSTITUTE OF TECHNOLOGY
PASADENA, CALIFORNIA

JPL D-9643

1630-112

MAGELLAN LESSONS LEARNED
PROCEEDINGS OF
THE MAGELLAN LESSONS-LEARNED WORKSHOP
HELD DECEMBER 1991

K. W. LEDBETTER

S. D. WALL

14 APRIL 1992

APPROVED:

J. F. SCOTT
MAGELLAN PROJECT MANAGER

JPL D-9643

Distribution

S. Barry (HAC)
J. Carter
J. Casani
J. Clark
B. Compton
S. Dallas
P. Doms
C. Elachi
D. L. Evans
Dave Evans
T. Farr
J. Gunn
D. Griffith
R. Halverstat
N. Haynes
R. Heacock
M. Hill
R. Laeser
N. Lawson
K. Ledbetter (MMAG)
D. H. Lehman
K. Leung
D. Linick
R. Lock
T. Marsh (MMAG)
J. S. Martin
J. McCarthy (HAC)
F. McKinney(MMAG)
J. Miller
R. Morris
A. Morrison
J. Neuman(MMAG)
D. Okerson
R. Piereson
L. Pieri
D. Quinn
M. Sander
S. Saunders
J. Savino
A. Schallenmuller (MMAG)
J. Scott
A. Spear
J. M. Stewart
E. Stofan
A. Tavormina
G. Textor
T. Thompson
D. Villani (HAC)
S. Wall
D. Woerner

JPL Vellum Files (original)

Table of Contents

Section	Page
Introduction	2
Executive Summary	6
Session 1: Spacecraft Flight System Development	16
Program Philosophy Issues	16
Contractual Issues and Technical Contract Monitoring	23
Flight Software and Fault Protection Issues	27
Flight Hardware-related Issues	31
Session 2: Assembly, Test and Launch Operations	35
Program Philosophy Issues	35
ATLO Testing Issues	37
Spacecraft Assembly Issues	44
Launch Operations Issues	45
Session 3: Mission Operations System Development	48
Program Philosophy Issues	48
Organizational Issues	52
MOS Design Issues	53
Sequence and Command Related Issues	57
Ground Data System Issues	60
Session 4: Mission Operations Conduct	71
Program Philosophy Issues	71
Operational Issues	76
Ground Data System Maintenance Issues	78
Session 5: Science Data Processing, Distribution and Analysis	80
Philosophy and Organization Issues	80
Operations and Operations Design Issues	83
Ground Data System Issues	87
Acronyms and Abbreviations	89
Index	92

Introduction

In November 1991, the authors of this document were requested by the Magellan Project to develop a set of "lessons learned." A "lesson learned" is a statement describing a recommended course of action for future projects or tasks based on specific experiences from a current project task or activity. Accordingly, we held a series of interviews, meetings, and workshops to review the mission's performance and to record those parts of the mission which the team felt were either: (a) done well and in a way worth recommending to future missions; (b) done in a less-than-optimum way and worthy of comment to allow future missions to correct the approach; or (c) likely to be among the "close calls" that missions face and for which some constructive comment might be made about how to make those calls in the future. This document represents the outcome of those workshops and is intended to contain those recommendations the Magellan project has to pass on to those who design, operate or analyze data from future remote sensing missions.

This "Lessons Learned" activity was carried out in three phases. First, the authors of this document conducted several dozen one-on-one interviews with other Magellan or ex-Magellan team members. These interviews concentrated on the development of lists of "what we did right" and "what we did wrong." Each listed entry was taken as a starting point for a recommendation to future missions. As these interviews progressed, any listed entry about which the interviewees disagreed, or for which there were opposing recommendations, was noted and developed into an argument and a counter-argument. Second, small groups were assembled from Magellan offices to discuss the listed entries and recommendations. In these meetings we attempted to determine the level of support for recommendations, and for those where there were opposing viewpoints tried to discern whether clear majority and minority opinions existed.

Each listed entry and the related recommendation or set of arguments was distilled into a single page, and a rationale for the recommendation was created from the discussions based on specific Magellan experience. The pages were sorted into five programmatic divisions:

(1) Spacecraft Flight System Development
(2) Assembly, Test and Launch Operations
(3) Mission Operations System Development
(4) Mission Operations Conduct
(5) Science Data Processing, Distribution and Analysis.

Each entry was graded for value in each of three categories with three levels in each category, as described by Table 1.

Table 1: Lessons-Learned Value Assignment

	A	B	C
1 Applicability to future projects:	Applicable to all or nearly all projects and to multiple areas within a project	Applicable to many projects (but not all) with potential to apply to several areas	Applicable to only a few projects or applicability to only one area.
2 Potential increase to mission success and/or reduction of risk:	High probability of increasing mission success or reducing risk of operations	Possible benefit to project if implemented by either increasing success or reducing risk	No (or very small) impact on mission success or risk reduction.
3 Potential contribution to reducing total costs	Major cost reduction is a definite possibility	Some cost reduction is possible	No cost advantages, or an expected increase to cost

For each of the five divisions, a workshop was held at a conference room remote from the mission support area. To each workshop was brought the one-page summary of each listed entry, and our initial estimate of the above value assignments. Each original interviewee was invited to one or more of the workshops, along with selected other flight team personnel.

Basic objectives of the workshops were to make each recommendation a concise encapsulation of the Magellan experience, selecting only those key items with the greatest potential for positive impact on future projects. Attempts to criticize each other, retroactively improve Magellan for its own sake, or to make points from "old wounds" were discouraged. Following a short introduction, each summarized item was presented and discussed. Factual errors were corrected, and agreements or disagreements were solicited for recommendations and arguments. Where strong minority opinions existed they were recorded, and where there was no clear majority, an argument-and-counterargument format was created. Estimated value assignments were discussed and modified where appropriate. New recommendations were formulated as they surfaced, and value assignments were made during their discussion.

Finally, the initial recommendations and value assignments were revised according to comments received at the workshops. One final editing was made by the authors to combine similar recommendations and to remove any for which we felt there was no clear consensus reached at the workshop for either a recommendation or a set of contrasting positions. The results were then sorted using a grade calculated by giving each "A" value three points, each "B" two points, and each "C" one. Recommendations are presented herein in that order within each of the topics and subtopics used in the workshops.

After applying the revisions suggested at the workshops, the statistics of the value assignments are as shown in Table 2.

Table 2: Number of Recommendations in Each Value Assignment

Category	A	B	C
Applicability to Future Projects	114	44	8
Potential Increase to Mission Success and/or Reduction of Risk	43	89	36
Potential Contribution to Reducing Total Costs	19	61	84

The value-assignment scheme requires two comments. First, several recommendations were initially thought likely to increase cost but were reconsidered as likely to reduce total (*i. e.*, runout) mission cost as a result of the initial "investment". But, rather than automatically change the third value assignment of such recommendations to "A" or "B", it was agreed to leave the cost value of any recommendation involving even an initial increase in cost at "C" unless the downstream cost-savings could be reasonably well quantified and were thought to definitely exceed the initial increase. Naturally such judgments were subjective, and the application of such judgments to other missions must be made individually. Second, during discussions in the fifth (science) workshop, the word "success" in category 2 was interpreted as applying to scientific return; *i. e.*, an increase in science return was treated as an increase in mission success.

The results of this activity are presented in this report. The immediately following section is an executive summary where the authors have tried to summarize the most significant points from the entire activity in as few words as possible. Hopefully we have captured the essence of the workshop's principal recommendations to future projects. Since the emphasis now seems to be on achieving low-cost spacecraft and low-cost operations, this executive summary is biased toward those recommendations that are likely to reduce cost. Further details for any item are found in the body of the report at the location of the item number specified in the summary.

The text of the report is divided according to workshop session and subtopic as shown in the table of contents. The format is the same as that used in the workshops where the recommendation is stated first followed by the rationale from specific Magellan experience. Lastly the "value" is given, which has been used as a sort key, such that (if it worked properly) the most important items are addressed early in a sub-section.

We would like to express our thanks to all the Magellan flight team members who participated in Lessons Learned, whether in the initial interviews, meetings, workshops, or through the many written comments we received. With only minor exception, the exercise was thought to be worthwhile by its participants. We sincerely hope that the document will prove so to its readers. It was noted that, as with most parents and their children, past projects have more often felt it worthwhile to document their learned lessons than they have been willing to read and accept those of their predecessors. And, like most parents, we feel certain that this document will reverse that trend.

Ken Ledbetter
Steve Wall
March 1992

Executive Summary

This summary is divided into two parts. A summary of those recommendations judged to be most significant is presented first. Many of these are items relating ways to reduce or contain cost. Others include items related to communications, common designs, process simplification, and common resources during various program phases. Also included is a section of recommendations resulting from some specific Magellan situations. Part I is followed by a summary of the most-often mentioned subjects during the Lessons Learned Workshop, if they have not already been covered by Part I. These reflect the concerns of the Magellan project whether or not they directly impact the cost of the mission.

In both parts of the summary, references are made in parentheses to the item numbers of the individual recommendations, some of which are quite detailed and specific. For those subjects of interest to the reader, we suggest that a reading of the actual wordings in the latter part of this report would be worthwhile. Also, note that many topics are covered by the grouping of items in the separate sessions and subsections of the report. (see the Table of Contents) For example, flight software and fault protection items are covered together in items 1-24 through 1-34; spacecraft system testing issues by items 2-8 through 2-23; and contractual issues by items 1-14 through 1-23.

Part I: Most Significant Subjects

Common Spacecraft, Mission and MOS Designs.

Projects must find ways to design the spacecraft, mission and the mission operations system together, with cost minimization as a project objective (1-3). Decisions made in spacecraft or mission design should always be considered for their subsequent MOS impact. A prime example is the design of the functional command blocks during spacecraft development that must be implemented in the sequencing software of the MOS ground system (3-25). With mission durations now commonly extending for years or even tens of years, no longer can NASA afford to design the MOS last. A detailed operations concept, developed early and maintained, would help keep operability a focus during spacecraft and mission design phases (3-1, 3-5).

Making Things Simpler.

With the move of the future being toward missions that are lower cost, of shorter duration and less complex, many items at the workshop dealt with simplification of processes. One item (1-1) recommended a complete reevaluation of a program after Phase B to see if a major cost reduction could be achieved through simplification. Others concerned simplification during the spacecraft development phase, with a recommendation to use proven technology rather than new development whenever possible (1-6), and one to streamline the process for handling various required technical reports (1-38). Reducing the number of approval signatures on documentation, all throughout spacecraft and MOS development (3-52), will speed up the process, give more responsibility to the writer, and reduce cost. Relaxing of controls of certain test software was considered to be a potential cost saver (1-33), as was moving the responsibility for control of development and maintenance of project-funded MOS software onto the operations team where the software's users will reside during operations (3-3, 3-29).

A number of suggestions to simplify spacecraft system testing were discussed, with an objective of lowering cost. Implementation of a "ship and shoot" philosophy where activity at KSC is minimized (2-5) was recommended by some to cut costs. Using a modified protoflight approach to system testing (2-7), modifications to structural static loads tests (2-16), and simplifying solar thermal vacuum testing (2-19) were suggested. Magellan showed that development of a standard spacecraft configuration script for returning the vehicle's state to one that is fixed and known after each test helps to simplify interfaces between tests (2-10) but caution must be exercised when designing the tests. It was also felt that there were too many Quality Assurance people at KSC (2-28).

Other simplification items were recommendations to use simpler command mini-blocks for sequence design (3-24), to implement the Magellan non-standard command process for non-sequence commands (3-26), even to the extent of using pre-approved and validated "express commands" to be requested by specific flight team members (3-28). For downlink, develop a user-friendly, front-end processor for the SFOC workstations so real-time users, such as the flight controllers, would not have to be experts in UNIX and SFOC workstation languages to monitor a spacecraft, yet the more flexible capabilities would be there for the detailed analysis performed by spacecraft analysts (4-15). Lastly, there was a recommendation to minimize paper interfaces by using the workstation electronic systems that are already in place on most projects (5-18).

Communications.

Communication between teams and members of a flight team is one of the keys to a cohesive, effective unit. This issue permeated many of the recommendations provided to the Lessons-Learned Workshop, from the conduct of informal work unit meetings between JPL and contractor work unit managers prior to formal monthly management reviews during spacecraft development (1-18) to the regular dissemination of science analysis results to the flight team (4-1, 5-9, 5-14). On the latter subject it was felt that Magellan's science briefings and NASA Select TV programs were effective ways of communicating science results. Communication between remote sites and JPL central control, both in the form of teleconferences and status reports, is essential to maintaining a healthy working relationship (4-2). Communication within structured project meetings was addressed (4-13) as was the recommendation that decision-making should be forced down to the lowest level possible to empower the team and enhance communications (4-7).

Other topics were discussed that help to enhance communications without directly specifying communications recommendations. One item (3-45) pointed out it is important to carefully specify up-front which team or subteam is responsible for which data product. Another discussed the problems that physical barriers (e.g locked doors, different floors) can cause with intrateam communications (4-8). Still others dealt with supporting personnel needs (4-4), and involvement and cross-training in areas other that a person's speciality to keep the team sharp and involved (4-3, 5-10, 5-11). Teamwork and sharing of responsibility between JPL and its prime contractors also enhances communication (1-15).

Common Resources During Multiple Program Phases.

One way to reduce cost is to share common resources, whether those resources are hardware, software or people, and in particular, to use common resources between two sequential phases of a mission. Suggestions were made to ensure carryover of personnel from spacecraft development onto the MOS teams and/or to use people destined for MOS during spacecraft testing to gain the training benefit (2-3, 2-6, 3-11, 3-18). In fact, one recommendation (3-12) suggested making the pre-launch development organizational structure like that to be used in MOS. The issue of how ground software is done was discussed, with a suggestion that project-funded software be under the control of the using teams (3-3), which effectively combines certain ground data system functions with MOS team functions. Another insisted that the same systems engineer (user) that defines the software requirements should be the one to define and perform the final user acceptance testing (3-46). Commonality of software tools for development was pointed out to be a potential reducer of risk and cost (3-50).

In the realm of hardware/software systems, several recommendations were listed that would provide both cost savings and risk reduction by using them during both the development phase and mission operations. These are: a) using the MOS command database and the RF command system to send commands to the vehicle during system test (2-14); b) using a common telemetry processing system for spacecraft system test and mission operations (2-18); and c) building a breadboard simulator to be used for hardware/software integration and spacecraft sequence testing during system test and retained for use during mission operations (2-12). For testing of selected ground data system components, combined SFOC-DSN-Project testing was accomplished on Magellan which successfully saved budget (3-34).

Recommendations Arising From Specific Spacecraft Anomalies or Incidents.

The several anomalies Magellan experienced during spacecraft assembly and mission operations led to recommendations to alleviate such problems on future projects. Avoiding asynchroneous interrupts in flight software design (1-28) would help avoid the runaway program executions that plagued the prime mission. Avoiding glass-fiber thermal surfaces (1-42) would have mitigated one cause of star scanner false interrupts. Having the cognizant engineer on the spacecraft assembly floor during critical operations (2-24) would probably have prevented misconnection of the solid rocket motor. Avoiding blind electrical connections (2-25) could have prevented damage to the electric power subsystem. The design of single activity command mini-blocks (3-24) would have avoided much of the hand editing of sequences during the mission and mitigated the risk of command errors. Command errors themselves should be categorized by criticality (4-10). The addition of a non-sequence command validation and approval process for quick response during anomalies was recognized after launch and is a strong recommendation for implementation by future projects (3-26).

There are also some positive actions that Magellan implemented that were significant aids to anomaly recovery. The most significant was the incorporation of a ROM safing capability in fault protection (1-26). Had that not been present, the Magellan mission would have ended prematurely. The construction and use of the Systems Verification Labratory out of the test bed simulators (2-12, 3-27) was a benefit to operations by allowing command sequence and flight software change verification. During spacecraft development, early interface testing between subsystems and the flight computers was instrumental in driving out potential problems (2-13). Lastly, the practicing of hazardous operations to be performed during preparation for launch operations prior to their actual use (2-27) allowed the schedule to be maintained with few hitches.

An item that arose after the Lessons-Learned Workshop relates to the failure of radio transmitter A in January 1992. An additional recommendation not included in the body of this document is to severely limit thermal cycling of the radio frequency subsystem during mission operations. Magellan cycled the RF subsystem on and off every 3.25 hour orbit during the first 15 months of orbital operations. No other NASA standard transponder on a planetary mission has cycled with such a frequency. While it cannot be proven that this caused the failure, our recommendation is not to allow the cycling wherever possible.

Part II: Most Common Subjects

Each of the most commonly-mentioned subjects is listed below, followed by the total number of recommendations and a summary of their content.

1. Systems Engineering (15 recommendations)

Items related to systems engineering varied from general pleas to staff systems engineering roles early and to retain them in times of budget cuts (1-9, 1-41, 3-10) to the more specific suggestions that follow. Failure to provide project-level systems engineering can force inter-system technical decisions to be made by project management, and problems develop between groups representing different subsystems (1-9, 2-17). A system design team could be used to develop test requirements, resulting in less effort during both ATLO and MOS GDS development (2-8). MOS system-level requirements definition should also begin early so that subsystem requirements can follow them instead of being simultaneously developed (3-9). Similarly, subsystems engineers should follow subsystems from development all the way through to flight (1-4, 3-47), especially in the case of inherited items (1-10, 1-11, 2-9). Lastly, systems engineering should not be left to subcontractors (1-16, 1-23).

In the sequencing software area, Magellan felt that a single cognizant systems software engineer could save effort and complexity during software development (3-13). Likewise, the division of the ground data system into FPSO- and project-supplied functions would benefit from a single systems engineer and might reduce the total effort (3-32).

2. Effects of Change and Preparation for Change (14 recommendations)

Unexpected changes to the Project occurred as a result of budget reductions, design improvements, and Magellan's erroneous preconception that mapping would be a highly repetitive, uneventful process. These affected the course of operations considerably and inspired much discussion at the Lessons Learned Workshop. Design changes need to be made only after sufficient revision of high-level analysis (1-5, 1-21). Missions should retain management capability to replan during system test and assembly (2-2) and capability to change GDS software (3-37, 4-20). A provision for special, rapid deliveries of GDS subsystems should be developed (4-19).

Spacecraft command blocks need to be flexible, even when they are built for a repetitive process. They must accommodate the realities of, for example, a changing thermal environment or spacecraft anomaly correction (3-24) to avoid the risk of hand-edited sequences. Closer interaction with science groups, however, might better determine the necessity for such extreme activity by more carefully defining science priorities for collecting the data obtainable with the edited block versus the risk for performing the edits (3-7, 4-9).

The lack of either an efficient real-time (non-sequence) command process or manual command translation capability created unworkable situations early-on, and both had to be developed later (3-26, 3-28, 4-18). In data management, uplink, and image processing subsystems, hardcoded parameters were often found to require changes or overrides (3-40). In general, the advice was that being prepared for change saves runout cost (4-6, 4-12).

3. Product Walkthroughs and Reviews (11 recommendations)

One thread found in all five sessions was a focus on product reviews or walkthroughs. In general, the belief was that early tabletop walkthroughs, with the correct people in attendance, were essential to achieving a quality product at a reasonable cost. For hardware, regular reviews with the product integrity, materiel, and quality engineers help to avoid problems and keep development moving (1-12). For either flight or ground (GDS) software, tabletop walkthroughs should be held at all phases from initial algorithm development to final code and test plans. Hardware engineers should review all flight software math models. Walkthroughs should be attended by members of the hardware, software, systems engineering, quality, analysis and mission operations portions of the team, and also science personnel if the software is science related. Without all the proper personnel in attendance, flaws can go unnoticed, causing difficulties later (1-24, 3-49).

Three areas, in particular, were singled out for special attention related to walkthroughs. It was a general belief that for missions that require a significant amount of on-board fault protection, this area should be treated like another subsystem, with its own PDR and CDR and appropriate walkthroughs at various stages of development (1-25). The second area concerned flight software parameters changeable by ground command during operations. Tabletop walkthroughs to verify the correct value of each parameter for each phase of the mission is essential prior to entering that phase of the flight (1-30). In a different vein, conducting early around-the-table walkthroughs of simulated deliveries with real or simulated products helps to define team-to-team interfaces and drive out interface problems (3-16).

Reviews, despite the work required to prepare, were felt to be necessary, in particular, special activity reviews such as single point failure reviews (1-36). For all reviews, several related items were noteworthy. Informal work unit discussions should be held between contractor and customer prior to all formal reviews, especially monthly management reviews (1-18). Timely closeout of failure reports and design analyses soon after the review is important to minimizing the cost impact of the solution (1-13). Some reviews, such as those for launch, may require extra attention to ensure maximum benefit for optimum cost. Plan for additional pre-launch activity for launch reviews since they occur surrounded by hectic activity preparing for launch (2-29). Ground Data System subsystem reviews need both development and operations people on the review board to ensure that both developer and user points of view are represented (3-48).

4. Team Structure and Retention of Personnel (11 recommendations)

Creating a single "team" out of personnel from diverse backgrounds and contractor facilities was considered important, as was the retention of personnel (2-1). The following specific comments were received.

Contract monitors should be senior people (1-22). Advantage should be taken of past experience where it is similar (2-30). Carryover of development and test engineers into flight team positions should be maximized (2-3, 3-11). Efforts should be made to maintain a high personnel interest in the goals of the mission through seminars, career advancement, co-location of work areas within sites (4-1, 4-4, 4-8, 5-14). However, remote-site operation was thought advisable from both cost and personnel convenience viewpoints, with the caveat that on-site representatives and (emphatically) the highest quality teleconferencing, voice and data networks should be implemented (4-2, 4-17, 3-22). Cross-training between functions should be emphasized (4-3, 5-16).

Use of graduate students and post-doctorals, not only in the science area but throughout operations, is recommended (5-5, 5-15).

5. Inheritance of Existing Hardware, Software or Designs. (8 recommendations)

The Magellan spacecraft was designed to take maximum advantage of inherited components from prior missions. Several of the suggestions from the workshop concerned inherited hardware or software, or in some cases inherited hardware designs. Foremost on the list was the admonition to carefully investigate the history and limitations of existing hardware or designs to determine if applicability to the new situation is justified (1-2, 1-39). Just because a design or component actually flew on one mission doesn't mean it will function correctly for a new mission and environment. When inherited components are used, a strong systems engineering analysis needs to be accomplished to make fixed components play together with new the designs of the rest of the vehicle (1-11). Thorough subsystem integration should be accomplished, including component characterization tests (2-9), to understand performance and interfaces prior to moving to systems tests. Inherited or GFP hardware or software should always be accompanied by appropriate documentation (1-21, 3-39), and wherever it meets the requirements, hardware and software should be considered a package (1-32). The use of new technology designs was advised only when absolutely necessary, and then with specific acknowledgement of the additional effort to qualify those designs (1-6).

6. Operations Scheduling (8 recommendations)

Several suggestions related to development and maintenance of operations schedules. The most important were those to develop a set of networked schedules across the project so all dependencies could be accurately tracked (3-4) and to maintain schedule history on all schedules by indicating slips and changes rather than generating new versions for each status review (1-14). Budget reductions or task delays should always be quickly reflected in the schedules (5-13, 3-6). For ground software, prioritize the development efforts early and phase deliveries to meet project need dates (3-37, 3-38). Carefully established software metrics can assist the schedule tracking process (3-51) and appropriate selection of the level of control will help to maintain schedules (1-33).

7. Standards (5 recommendations)

Recommendations relating to standards fell into two categories: those recommending them and those opposing them. In the former category was applause for standard review processes, document formats and procedures (3-2). Standards for software engineers, even though simplistic, were thought to be worthwhile (3-44).

In the latter category was a recommendation to not require JPL's standard problem (failure) reporting system for contractors, but to either allow them their own system or to adapt JPL's to them (1-20). Adapting "almost completed" standards should be avoided due to the increased cost and effort when these standards change (3-33).

8. Configuration Control (4 recommendations)

Most recommendations concerning configuration centered around areas of "too much" and those of "not enough", with emphasis on the former. Flight software parameters need to be carefully controlled (1-30), where ground software needs more levels of control to allow informal software to be recognized in some way (3-29, 3-30). Some provision for special deliveries of portions of GDS software is essential. In general, the configuration control process must have the ability to quickly approve needed changes (4-20). Where changes are approved appropriate links to budgets must be made (3-8).

9. Quality Assurance (4 recommendations)

Quality assurance was implemented in both uplink and downlink processes. Generally, uplink and hardware QA took the form of well-established JPL procedures such as MOCA and the various problem reporting systems, whereas in the downlink process Magellan attempted to devise a new system.

Launch-site integration should employ a minimum of hardware quality inspectors(2-28). Uplink quality assurance should be specific toward the more critical errors rather than insist on "zero command errors"(4-10). The MOCA system should be only used in prevention of startup errors and then phased out (4-5). Downlink QA requirements should be incorporated in initial requirements rather than be incorporated later (3-17).

Session 1: Spacecraft Flight System Development

This session covered topics relevant to the design and implementation of the Spacecraft Flight System, which for Magellan included the spacecraft, its flight software and the radar system. Included in this session were issues which pertained to fault protection as implemented in flight software. Since the Spacecraft Flight System was built by Martin Marietta Astronautics Group as a contractor to JPL, and included the radar system built by Hughes Aircraft Company, this session also dealt with the contractor-contractee relationship.

Program Philosophy Issues During Spacecraft Flight System Development

1-1. Recommendation: In cases where a new program is under cost pressure or is anticipating significant cost pressures the following technique should be applied. At the end of Phase B, program management should perform a "compression stroke" on the program by asking what mission could be accomplished for half the price, forcing the issue of mission simplification.

Rationale: The cancellation of VOIR and subsequent resurrection of VRM (aka Magellan) forced the redesign of a much lower cost mission that in the end, accomplished nearly the same objectives as the original. Even though Magellan suffered cost growth, the super elegant VOIR would have been a billion dollar plus mission, with probably no greater success. The externally-forced Magellan "compression stroke" caused intense pressure on the design team, but they emerged well and tested by the fires of experience.

Value = A B A

1-2. Recommendation: For components inheriting "existing designs" from other programs, the project needs to penetrate those designs for full understanding of their history and limitations. We should not accept that just because a design actually flew it will work correctly for our mission and environment.

Rationale: Someone knew from prior flights that the Magellan star scanner was sensitive to high energy protons. If we had discovered this fact early enough, the cruise star scan false interrupt problems might have been mitigated. Similarly, the power distribution unit design was developed and tested for the P80 Program, however during Magellan development, the unit had to be returned to the vendor multiple times to correct Magellan application problems. These returns might have been eliminated if early investigation of the prior design had been thorough. A third example is the Odetics tape recorder that exhibited similar data corruption problems on the GEOSAT Spacecraft in 1987, well before Magellan launch.

The Magellan radio transmitter used a NASA standard transponder, flown numerous times on other spacecraft. Its heritage was well researched, but this has been Magellan's most serious on-board failure to-date.

On the other hand, the CDS flight software inherited from the Galileo project is a positive example, where the designs were properly penetrated.

Value = A A C

1-3. Recommendation: Projects must find ways to design the mission, the spacecraft flight system and the mission operations system together, with cost minimization as a project objective. Decisions made in spacecraft design should be considered for their subsequent MOS impact.

A mission operations concept document should be written early and made available to spacecraft designers, or some other early method of specifying operations requirements to spacecraft designers should be implemented.

Rationale: Usually, the spacecraft is designed first, around the planned mission, and sometime later, the MOS is designed. Many times, decisions made in spacecraft design require difficult and costly implementations in the command and telemetry systems on the ground, whereas a different but equally sufficient solution for the spacecraft would reduce the complexity on the ground. Even in cases where the spacecraft and MOS designs proceed together, spacecraft activity wins the competition for resources, MOS having much lower priority. Magellan experienced some of this, for example in the design of the radar engineering telemetry frame to repeat asynchronously with the spacecraft engineering frame. The radar cycle period of 24 is not a submultiple of the spacecraft's 91. This was a contributor to the lack of pre-launch discovery of the spiral-wrap commutation problem discovered in cruise. Another example was the specification of the same frame synch id word for the radar and spacecraft telemetry frames.

Value = A B B

1-4. Recommendation: For each work unit, a subsystem cognizant engineer should be assigned to follow the subsystem progress from requirements and design to delivery. This is especially important for one-of-a-kind builds. Subcontractors should follow this procedure also.

Rationale: Magellan examples: The DMS (tape recorder) cognizant engineer did not follow the recorder through to delivery. The Motorola chief design engineer for the transponder did not follow it through development. Although perhaps not connected, these are our two spacecraft hardware failures.

There are several positive examples of subsystems where a subsystem cognizant engineer did follow the subsystem throughout the process, specifically propulsion and structures/mechanisms. These subsystems have had fewer and less serious internal (hardware) problems.

Value = A A C

1-5. Recommendation: Ensure that proper analysis is re-done when major requirements or design changes are made. Allow contractors time and money to re-evaluate the system's architecture. This should be accomplished early enough to implement the necessary modifications if problems are discovered. Do not allow band-aid approaches.

Rationale: The solar cells on the Magellan solar panels were changed from 2cm x 4cm to 4cm x 4cm in size, but the same interconnects were used. Analysis indicated that flexure of panels might cause a disconnect as early as cycle 4, but no changes could be made because the analysis was completed too late (i.e too close to launch).

When the SAR resolution requirement changed, for the Hughes contract, not enough thought went into evaluating the impact on the timing margins due to lack of time and money.

Value = A A C

1-6. Recommendation: Use existing, proven technology when it meets the requirements rather than developing new technology unless new technology is essential or offers major functional or cost advantages. If development must be done, it needs to be widely recognized, the risk quantified, and additional planning for the unexpected accomplished. (e.g. additional testing planned)

Rationale: The use of Astroquartz blankets on Magellan was in actuality technology development. Numerous problems were experienced in development (e.g. blanket fraying, layer debonding) and in flight (e.g. hot spacecraft surfaces, particle shedding in star scanner field of view.) Although much testing was done, these problems were not caught. Additional testing might have caught them.

Value = B B A

1-7. Recommendation: Develop a written project policy defining the criteria for use of protoflight components versus the need to build a development unit. Each element of a spacecraft should be evaluated individually against the criteria checklist before protoflight status is granted.

Rationale: All Magellan mechanisms had design development units and have experienced no in-flight problems. The Rocket Engine Modules (REM) were declared protoflight (without a development unit) and had problems in flight.

Value = A B C

1-8. Recommendation: Do not delete engineering models (EM) for major developments. If the EM is deleted, then more design effort needs to be expended to analyze and test the development unit.

Rationale: The radar sensor engineering model (EM) was deleted due to cost constraints. The result was a very immature and poorly tested design. This design was then used to build the flight units. This caused changes to be incorporated on flight hardware late in the program (averaging 300 changes per month) with the resultant high cost. The developmental model breadboard testing program was weak, further compounding the problem. Due to schedule slippages and forced workarounds, some units later did have engineering models built. The cost saving planned was not realizable and, in the end, deletion of the EM resulted in a higher developmental cost.

Value = A B C

1-9. Recommendation: Provide a strong project-level system engineering capability early.

Rationale: The project was organized around several systems (Spacecraft, Radar, Mission Operations...), each of which was well staffed technically. However, technical decisions at the project level (i.e., between systems) were handled either by the project manager or by consensus of the affected systems. While this usually worked, it created an extra load on project management and opened cracks between the systems for problems to drop into.

Value = A B C

1-10. Recommendation: The prime contractor should have an on-project design team designated early in the program to integrate between work units. Such methods to resolve problems should be formal and visible to JPL representatives.

Rationale: Some disagreements between work units were not solved in a timely and cost effective manner, and many had to compete for program managers' time for a resolution. The compromise resolutions were not always visible to JPL, and may not have always been correct for the situation.

Value = B B B

1-11. Recommendation: Whenever a subsystem is planned to be assembled from a mixture of inherited components from different programs, inherited designs, and new builds, a very strong systems engineering design must be accomplished up front to avoid serious problems during development.

Rationale: The Magellan electrical power subsystem experienced numerous problems in development due to insufficient systems engineering. Component sources were as follows:

- Power conditioner and shunt regulator from P-80 program.
- Inverter, pyro switching unit and power distribution unit from Galileo.
- Power requirements determined by inherited equipment (e.g. AACS & CDS).

Problems were experienced in the power regulation scheme, the addition of a soft ground, and fault protection for the pyro switching unit. Changes to the design to fix these problems caused a significant increase in cost. (e.g. modification to the signal conditioning unit.)
(Note: The power system was a fixed price contract.)

Value = B B C

1-12. Recommendation: Hold subcontract product integrity enginer (PIE) day reviews frequently with project technical, materiel and quality assurance personnel in attendance.

Rationale: Magellan held these on 3 week centers to give the PIE's airtime on their issues. This communication technique identified difficult areas for solution before they became problems. PIEs tend to be ignored unless they are in trouble.

Value = B B C

1-13. Recommendation: Provide the resources for timely review and closeout of failure reports and design analysis.

Rationale: During radar sensor development, review and closeout of failure reports and analyses was delayed by a lack of resources. Often the review would occur many months after submittal and would be accompanied by requests for more information and analyses. This delay caused inefficiencies due to the need to remember the details of the failure report or analysis.

Value = B C C

Contractual Issues And Technical Contract Monitoring

1-14. Recommendation: Project monitoring of both internal and contracted effort should require schedule history to be maintained. Schedule slips should be shown and not just updated each month. Differentiation should be made between slips due to late input versus slips from late performance.

JPL and the contractor should co-own each schedule. It may require contractual changes, adding scheduling guidelines, to make this happen.

Rationale: Many schedules tracked monthly were simply updated to show new completion dates without indicating the slip. This causes a loss of visibility into developing problems. (Some work units did this better than others)

Value = A A B

1-15. Recommendation: JPL and prime contractors need to establish an environment of teamwork and mutual respect. The strengths of both organizations should be used where needed to solve problems. Contractors should be encouraged to ask for JPL help in areas where they can contribute. In-residence people from one organization should be prepared to step in and help out when it is mutually agreed. It's also important to have lateral communications within and between organizations.
Corollary: The contract (and award fee process) should be structured to accommodate this.

Rationale: This concept worked reasonably well with Martin Marietta; not quite so well with Hughes.

Positive Examples:

- The CPAF contract structure allowed the flexibility to get the job done right.
- Cooperative work to get the structural verification plan approved by JSC prior to launch.
- Rocket Engine Module testing at Edwards AFB during cruise.
- AACS memory chip testing after VOI back-up memory glitch.
- Star scanner sun avoidance calculations during mapping.

Value = A B B

1-16. Recommendation: Do not allow contractors to let out-of-house (to a subcontractor) a systems level integration function, or if it is done, a careful monitoring process should be put in place.

Rationale: For subcontracted systems-level integration activities, neither the prime nor JPL can maintain quality control over the systems engineering and integration functions. Subcontractor reviews, in general, are not sufficient to discover problems. Magellan rocket engine modules were given to Rocket Research. Their thermal analysis was not sufficiently complete to catch the REM overheating problem that developed in cruise. In this case, the project let a subcontractor do a task the prime contractor could have done better.

Value = A B B

1-17. Recommendation: Carefully construct the award fee in the contract of prime contractor such that there always remains an incentive to get the job done. JPL should retain adaptive control of award fees, permitting subjective evaluations.

Rationale: The construction of the Magellan award fee for the Martin Marietta contract was counter to what had to be done in 1987 and 1988. It was set up such that "if you overrun, you get zero fee", which eliminates the incentive to perform or to solve problems as soon as an overrun state is reached, regardless of the cause of the overrun. (Fortunately, Martin continued to perform, trusting JPL to eventually make it right.)

The construction of the award fee procedure for the Hughes radar contract was too results-oriented, prohibiting measurement of internal relevant factors.

Value = A B B

1-18. Recommendation: Encourage contractors to hold informal discussions with the JPL work unit representative prior to each formal management review. (Formal management reviews should be regularly held.) Details of problems and recovery efforts should be mutually discussed before formal presentations.

Rationale: Most Magellan spacecraft development work units held splinter sessions with the JPL work unit technical monitor prior to each monthly management review (MMR). In general, these were open and candid work unit progress reviews that worked well for Magellan. The JPL representative was not subsequently surprised by the material presented at the formal MMR. This fostered a team spirit during development.

Value = A B B

1-19. Recommendation: JPL should review contractors' key personnel prior to contract negotiations. Recommended changes should be presented to the contractor. The contract should not be executed until JPL is satisfied with the personnel qualifications. (i.e. make it a part of negotiations.)

Rationale: During the re-classification of the program from VOIR to VRM, Hughes key contractor personnel, who had participated in the study phases and were identified in the VOIR proposal, were replaced with less experienced personnel. As a result, the technical head start that appeared in the proposal was not there and much of the engineering had to be re-done, including bring the digital unit in-house at JPL.

Value = A B C

1-20. Recommendation: JPL should not force a "JPL standard" problem or failure reporting system on its contractors. The contractor's existing process should be examined and suggestions made (if necessary) to make program-specific modifications to satisfy JPL needs.

Minority Opinion: JPL should do the adapting. It is too difficult to change a contractor's standard procedures. Each project should establish a "screening" process to limit the amount of duplicate paperwork to the absolute minimum necessary.

Rationale: Magellan used the Martin Marietta anomaly reporting system (MARS) without requesting modifications. Selected MARS were turned into JPL PFRs, creating duplicate sets of paperwork. Most other MARS were only "inspection reports" and should have been classified differently.

Value = A C B

1-21. Recommendation: If JPL (or a system prime) provides GFP hardware to a contractor, special provisions should be made in the contract to also provide all or some of the following:

1. Up-to-date documentation (both design and as build)
2. Unit replaceable spare components
3. Access to knowledgeable repair personnel
4. Support for modifications

Rationale: Magellan used numerous GFP components, most with inadequate documentation, no spares and minimal repair capability. In some cases, like the high gain antenna (HGA), where documentation wasn't available, this process was made to work with difficulty. In many other cases, the lack of this additional support created numerous problems. On the other hand, in cases where all of this support was provided, such as for the propellant loading ground equipment, problems were avoided and operations went smoothly.

Value = B B B

1-22. Recommendation: Carefully select the JPL contract monitors for each work unit considering the nature of the subsystem's complexity and difficulty to build. The more senior people should handle the most difficult/complex subsystems. Function experts may need to be used (perhaps part-time sharing over several projects) for certain very complex spacecraft functions.

Rationale: Subsystem monitoring of the Martin Marietta contract worked well with the senior people; not so well with junior people. A "function expert" was developed for fault protection which yielded benefit in fault protection design. A similar expert in attitude determination would have been helpful.

For the Hughes radar contract, JPL early technical penetration was inadequate to allow early detection of problems to come. JPL did not staff to the original plan.

Value = B B C

1-23. Recommendation: Use cost plus contracts on development subcontracts. Examine amount of required development to determine if fixed price is manageable.

Rationale: The power subsystem contract was fixed price, requiring the integration of GFE, military hardware and new designs. The systems engineering was not well done and requirements not well defined. Changes were costly, too slow and painful to implement.

Value = B B C

Flight Software and Fault Protection Issues

1-24 Recommendation: Design walkthroughs should be held for all phases of algorithm and flight software development. These must include a hardware engineering review of all math models used in design analysis simulations and in flight software. These should be attended by hardware cognizant engineer, software developers, algorithm analysts and systems engineers.

Rationale: Magellan attitude and articulation control flight software development did this well, resulting in more efficient and cost-effective flight software.

Value = A A B

1-25. Recommendation: As on-board fault protection complexity increases with ever growing flight computer memory size and capability, spacecraft fault protection should be treated like another subsystem with its own requirements review, PDR and CDR. System-level design walkthroughs are essential. Begin fault protection design early in the program and consider testing implications.

Rationale: Magellan, unlike its predecessors Voyager and Viking, had multiple levels of spacecraft fault protection and numerous interactions with various spacecraft states. This complexity made an independent fault protection review necessary, which proved very beneficial. (A minority opinion was expressed that Magellan's fault protection was overly complicated.)

Fault protection design on Magellan could have significantly benefited by starting earlier, in parallel with subsystem designs and receiving more attention at the system level.

Value = A A C

1-26. Recommendation: Read-only memory (ROM) is necessary, especially ROM fault protection in non-volatile memory. It provides a system-level safety net.

Rationale: At one time, Magellan was going to remove AACS ROM from the design due to delivery schedule problems. It was believed not much could be done with "only a thousand words." Without ROM safing Magellan would never have mapped Venus.

Value = A A C

1-27. Recommendation: Develop, document and implement a process for maintaining margin estimates for flight software development. Software metrics should be defined against which to regularly measure progress. Rationale should be specified for tolerances on estimates during different phases.

Rationale: The AACS flight software development work unit did this right. Tolerances were established early, defined carefully, and decreased with time as the software matured. This gave reality to the software estimates. Software metrics were both imaginative and informative.

Value = A B B

1-28. Recommendation: Develop a flight software design that protects from asynchronous interrupts. Avoid common stacks and registers. Make sure overwrites cannot occur. Follow standard software design practices. Careful design and adequate testing must be accomplished.

Rationale: The five loss-of-signal anomalies during the Magellan prime mission were AACS runaway program executions (RPE) resulting from improper asynchronous interrupt handling logic.

Value = B A C

1-29. Recommendation: Fault protection design should include a "layered" approach, particularly where attitude control faults are involved. Multiple levels of sophistication should be coded where the most primitive level is in read-only memory (ROM) and the most sophisticated is in random access memory (RAM).

Rationale: Magellan had two-star RAM safing, backed up by one-star RAM safing, backed up by RAM coning, backed up by ROM coning. This approach was successful in the face of unanticipated star sensor problems and multiple computer failures, both hardware and software.

Value = B A C

1-30. Recommendation: Start early to maintain a database for configuration control of flight software parameters. Conduct parameter reviews at various stages of development and before each phase of the mission to validate expected values of parameters, and their use in flight operations plans and flight software code. Assign responsibility for certain parameters to specific people. Control of certain test software parameters is also important.

Rationale: Magellan had 1700 parameters that could be changed inflight. Managing the values for these parameters was recognized to be a formidable task and a series of parameter reviews was instituted. This activity proved extremely beneficial, although begun too close to launch.

Value = B A C

1-31. Recommendation: For critical flight software functions where subtle errors may not be visible in systems testing, an independent coding of key algorithms should be performed to compare numerical output with that from flight code. This software is not elegant, formal or compact and is not subject to project controls.

Rationale: In the Magellan AACS system, many small factors contribute to the attitude determination accuracy necessary for mapping the planet. Most of these are too small and subtle to be able to verify during either flight systems test or computer simulation. The AACS group effectively used independently coded software to verify the correctness of flight algorithms. The FPSIM program was created primarily for this purpose and functioned well.

Value = C A C

1-32. Recommendation: When inheriting flight computer hardware from other programs, consider inheritance of flight software also. Analyze applicability of fault protection code. However, prior to accepting software for inheritance or reuse from another project, an in depth understanding of requirements for both software and hardware should be attained.

Rationale: Requirements for CDS-type functions from mission to mission have many similarities. This provides for use of consistent and proven command/telemetry ground systems for ease of standardization. Nearly 50% of the Galileo flight software was incorporated unmodified into Magellan. The flight software development cost reduction was dramatic.

The Magellan AACS test software originally relied on heavy inheritance from Galileo with some modification. Based on this, Martin Marietta purchased two PDP-11/44's for development and execution of this software. As development progressed, less than 20% of the Galileo software was inherited. The PDP-11/44 proved to be slower than the PDP-11/60 used on Galileo, resulting in considerable effort just to get the Magellan software to execute. Together, these two factors resulted in cost overruns, late delivery and incomplete software, and continues to impact software efforts during operations. Better understanding of this task would have indicated a different computer with a new development effort to be more cost effective.

Value = C C A

1-33. Recommendation: Establish informal controls for the development of spacecraft test software such that its schedule is maintained and doesn't impact flight hardware/software schedules. Apply software management tools to maintain the rigor without the formality. Recognize that there are various grades of test software.

Minority Opinion: All spacecraft test software should be under formal control.

Rationale: When test software is not subject to rigorous controls similar to flight software, it can lead to a disregard of prudent software management. This results in problems with test software that impacts the progress of the flight systems.

Value = C C B

1-34. Recommendation: For spacecraft with multiple flight computers, design into flight software the capability for one computer to reset ("warm boot") the others.

Rationale: Magellan has to command a hardware configuration change in order for the CDS computer to reset the AACS computer.

Value = C B C

Flight Hardware Related Issues

1-35. Recommendation: Vendor subcontractor requirements specifications for certain component manufacture must clearly identify the difficult or special nature of the task, to prevent cost overruns.

Rationale: A battery packaging technique from Viking was selected for the battery chassis, however the requirements document was not sufficiently detailed to reflect the very difficult machining job. This led to both cost and schedule problems.

Value = A B B

1-36. Recommendation: Conduct single point failure reviews.

Rationale: Magellan held an initial overall single point failure review and then later had focused reviews for critical phases. All were worthwhile because they uncovered potential problems that could have impacted the mission.

Value = A A C

1-37. Recommendation: Establish a clear parts policy at the outset of the program and stick to it.

Rationale: Magellan planned class B parts and made schedules accordingly, but changed to Grade 1, incurring additional cost and schedule impacts.

Value = A B C

1-38. Recommendation: Streamline the process for certain subsystems technical reports such as worst-case analysis, FMEA reports, and reliability analysis reports. JPL should trust its contractor for these without having to approve everything. (May have to accept increased risk, especially to achieve low cost.)

Rationale: Magellan required JPL review and approval on most of these analysis reports adding time delay and additional cost.

Value = A C B

1-39. Recommendation: Investigate components to the level required to fully understand their operation as well as any required protective measures prior to integration and testing. This applies to both new items and those with heritage. Also, have more highly qualified personnel on hand at least in a supervisory role during integration and handling of unique hardware.

Rationale: Failure to fully understand reaction wheel circuitry resulted in damage to a prototype, when allowed to freely spin down. Unknown to the project, it became a generator if power is totally removed. Due to this lack of understanding, the spacecraft wiring had to be redesigned to preclude damage if power was lost in flight.

Lack of experience resulted in connection of the PDP-11 to an incorrect power source in the clean room, damaging it.

On one occasion a more experienced person asked to take the extra time to recheck a cable harness after a lengthy storage, prior to connection to flight equipment. An electrical short was found that would have resulted in damage to hardware.

Value = A B C

1-40. Recommendation: Negotiate margins and environmental parameters with program systems engineering and JPL counterparts early. This will aid in establishing the widest possible parameter ranges. (e.g. temperature ranges)

Rationale: Magellan thermal worked with their JPL counterparts early and kept them informed and involved in the decisions made. This made for well informed customer contacts and few surprises at monthly meetings.

Value = A C B

1-41. Recommendation: Make sure that the instrument telemetry system (on-board) receives proper system engineering attention.

Rationale: The Radar Sensor engineering telemetry system is not as good as it should be. The current measurements for roughly half the units have poor resolution, and the reverse power telemetry is insensitive. The root cause is a lack of adequate sensor level requirements upon the unit designers. This would significantly affect anomaly resolution efforts.

Value = A B C

1-42. Recommendation: Avoid the use of glass-fiber mat thermal surfaces wherever possible or treat them to prevent dust. Untreated, these materials generate large quantities of dust, which will cause problems with any nearby optical sensors.

Rationale: Blankets made from glass fibers are notorious dust producers. ATLO technicians and engineers were aware of that before launch. Although the engineers worried about its effects and did some testing for it, the decision was that it would not be a significant problem. As it occurred, glass dust from astroquartz blankets caused Magellan severe problems with star scans until an operational work-around was designed.

Value = B B C

Session 2: Assembly, Test and Launch Operations

A critical phase of Magellan was the period during which the spacecraft was assembled from its component parts, tested, and readied for launch. Much of the assembly and test occurred in Denver prior to shipment to KSC. Final assembly and test, including MOS compatibility testing was conducted at KSC. Although most of the actual launch was controlled by Kennedy Space Center, Magellan provided a launch operations flight team to support launch activities. A subtopic within this session was dedicated to launch operations activities.

Program Philosophy Issues During ATLO

2-1. Recommendation: Work hard at team building to accomplish an effective merge of the various disciplines needed by an ATLO operations. Plan the organization well in advance.

Rationale: Magellan achieved a good meld of multi-discipline subsystems engineers, science system developers, environmental test laboratory technicians, product assurance, transportation and handling, and JPL team members.

Value = A A B

2-2. Recommendation: Project management must be receptive to numerous replans during assembly and system tests if the overall schedule is to be maintained and maximum testing accomplished. The available contingency time and resources must be carefully managed.

Rationale: The Magellan program, during its last year before launch, was able to maintain momentum by a continuous process of planning based on the present condition of the hardware and software, lessons learned from previous tests and the current assessment of what must be done to meet the critical requirements of the verification program.

Value = A B A

2-3. Recommendation: Use the mission operations system and team for all launch operations and to support as much pre-launch testing as possible.

Rationale: Magellan utilized mission operations people and ground systems only to a limited extent, but the benefit from this experience was still visible during in-flight mission operations.

Value = A B B

2-4. Recommendation: Schedule the assembly and system test activities for no more than 2 shifts per day and five days per week. This leaves margin for expansion when the schedule is threatened. Also, staff shifts sufficiently to avoid excessive overtime. Careful use of overtime can be used to maintain schedule.

Rationale: For many periods, Magellan planned and staffed three shifts per day and seven days a week. Not only did this leave no schedule room to absorb problems, but usage of personnel on third shifts and weekends was not efficient, leading to higher cost. It also contributed to excessive fatigue for personnel working on flight hardware.

Value = A C A

2-5. Recommendation: Plan to minimize time at the launch site. Develop a "ship and shoot" philosophy. Transfer to the launch site only the necessary hands-on personnel and management, and minimize launch support equipment.

Rationale: Magellan did not attempt this approach, however, much of Magellan testing done at KSC could have been accomplished less expensively in Denver if there had been time prior to shipment.

Value = A C A

2-6. Recommendation: For prelaunch spacecraft systems testing, use engineers for test operators of the most complex subsystems, rather than technicians. Each project should carefully understand and define the responsibilities for each testing position, then secure the correct staffing mix.

Rationale: For AACS, CDS, Thermal and Systems engineering, Magellan used subsystem engineers rather than technicians for testing operations. This approach provided two benefits:

1. Allowed better and faster troubleshooting.
2. Created a very experience team which transitioned into flight operations.

Value = A B C

2-7. Recommendation: Use a modified protoflight approach to spacecraft development which builds one flight system, and a separate non-flight structure and cable harness to support early hardware and software integration.

Minority Opinion: This is a good approach only if time is very short. It's not good if time is available to support integration on the flight vehicle.

Rationale: Magellan attempted to develop only the single flight unit and perform all necessary testing sequentially. Early integration of subsystems could have been accomplished on a reproduction structure and cable harness avoiding the additional work of disassembling the spacecraft for modal survey.

Value = B C B

ATLO Testing Issues

2-8. Recommendation: Systems and subsystems engineers need to pay particular attention to developing clear and complete test requirements for all aspects of testing. It is difficult to have a well-defined and well-planned test program when test requirements are poorly defined. Requirements writers need to work closely with test plan developers. A "system design team" should be responsible for specifying verification and test requirements.

Rationale: A verification plan for system level requirements was not accomplished seriously. Consequently, system test requirements were initially poorly defined. This resulted in significantly more effort than necessary to develop and approve ATLO test plans and procedures. The test requirements had to be cleaned up first.

Value = A B B

2-9. Recommendation: Do a very systematic and thorough subsystem integration to characterize interfaces and functional performance prior to moving to spacecraft systems test. This is true even for subsystems with "inherited" components. Be cautious about eliminating any characterization for such "inherited" subsystems.

Rationale: The subsystem integration test for the electrical power subsystem (EPS) was eliminated to save cost and schedule. Its first system test was on the spacecraft. The subsequent troubleshooting of EPS problems took a lot of spacecraft time and cost the program in both schedule and money.

For the other Magellan subsystems, this integration provided a baseline for performance during subsequent system integration and a baseline for any potential degradation during system environmental testing.

Value = A B B

2-10. Recommendation: Develop a script or command file which can quickly and safely configure the spacecraft from any unknown state to any reference state. (i.e. launch, cruise, on-orbit ops) Occasionally vary this configuration state to prevent masking a problem.

Rationale: Most ATLO procedures and sequence tests require a well defined spacecraft configuration. Magellan's "CONFIG script" enabled ATLO personnel (and procedure authors) to not worry about how to transition from a previous test's final state to the next test's initial state. Savings were realized in risk, time, and cost.

After launch, Magellan discovered a radar "spiral-wrap" telemetry commutation problem. Although not caused by "CONFIG", the problem had been masked by always using the same script. Therefore, caution must be exercised to prevent this from restricting test cases.

Value = A B B

2-11. Recommendation: The testing of spacecraft fault protection (FP) is most efficient and effective using the following guidelines:

1. Use a building-block approach where different aspects of FP are tested on different test beds.
2. Pre-test FP tests on a test bed before executing on the spacecraft.
3. Test the sequence and injected fault independently at first.
4. Strictly maintain procedure development folders
5. Make sure at least one test is with final flight software.
6. Make FP description document available to test personnel.
7. Write a FP test plan.

Rationale: These guidelines were used effectively by Magellan. Systems Verification Lab (SVL) FP pre-testing saved considerable time in the spacecraft critical path and allowed us to test the minimum set of FP necessary on the flight vehicle. Tests beyond the minimum were defined for subsequent testing in the SVL.

Value = B A B

2-12. Recommendation: Build a system test bed to use for early hardware/software integration and retain for use during mission operations for verification of command sequences and flight software changes. Make it run faster than real-time or have a separate test capability that does.

Rationale: Magellan initially did not plan to have a system test bed, but finally cabled the AACS and CDS test beds together, added a simulation system for the rest of the spacecraft and retained the resulting Systems Verification Laboratory in operations. From Magellan's experience, sequence simulation is mandatory to maintaining the integrity of mission operations. However, the inability to execute tests faster than real-time has made the test bed a bottleneck for some activities.

Value = A A C

2-13. Recommendation: During subsystems testing, interface testing with the flight computer should be done as early as possible. Then, in systems test, at least one test should be run where all non-flight access is removed.

Rationale: Magellan radio frequency (RF) subsystem testing was done well. Early interface testing with the flight computer provided early identification of problems that could be resolved while they were still small. Plugs-out testing with all direct memory access and auxiliary input removed provided valuable data. Also, using the RF subsystem to send commands during spacecraft system tests was a significant plus for the test program.

Value = B A C

2-14. Recommendation: Use the RF command subsystem during system test and send multiple commands, not just single no-op commands.

Rationale: For many of the tests, Magellan used the flight RF command subsystem and the actual command database to not only test the subsystem, but to ferret out errors in command and sequencing software and in operations procedures. This proved very beneficial. However, in spite of all this testing, Magellan still discovered RF interference at KSC from the MILA installation when on the launch pad. A launch-day dress rehearsal would have uncovered this problem.

Value = A B C

2-15. Recommendation: Don't use system level environmental tests to verify workmanship. Ferret out workmanship effects at the subsystem level prior to system integration.

Rationale: Magellan's system level environmental tests were designed to validate the mathematical models for thermal and structural dynamics and demonstrate system performance during the expected mission environment (with some margin) and as such did not expose the subsystems to levels or variations necessary to drive out workmanship problems. In addition, the Magellan spacecraft was completely disassembled following the system environmental tests, negating the value of system workmanship.

Value = A C B

2-16. Recommendation: Conduct structural static loads test only if mass constraints force a minimum design margin.

Minority Opinion: Static load testing is necessary. In most cases a 2.25 margin would be required to enable elimination of this test.

Rationale: Magellan's non-destructive tests and process controls provided proof of workmanship and mitigated the need for a static loads test. The Magellan modal survey and acoustic test demonstrated that loads during the launch phase would not exceed the expected value. Because of schedule constraints, Magellan built a structural test article to conduct static loads testing, adding cost to the program.

Value = B C A

2-17. Recommendation: Develop a top-down plan for each subsystem to verify the electrical phasing. (i.e. polarity checking). Definitions of + and -, clockwise, left and right, etc need to be clearly defined and understood by everyone early in the program. Testing should be planned at several stages during development and a true end-to-end test conducted that involves both flight hardware and software. The effect of test equipment on phasing data in documentation should be kept up-to-date.

Rationale: The Magellan AACS group planned and accomplished phasing verifications very well, yielding a reliable system. As an example, they were confident that the star scanner phasing was correct when the first starcal after deployment from the shuttle failed, despite the star scanner subcontractor insisting it was incorrect. This confidence allowed us to command a correct starcal. The actual cause of the starcal failure was an incorrect star magnitude in the on-board database.

Value = B A C

2-18. Recommendation: Strive to utilize the same (or a very similar version with a common format) telemetry processing system in ATLO as in MOS. The enhanced capabilities will help ATLO and the familiarity will assist personnel transition to MOS. This applies to both spacecraft test equipment as well as to a verification test bed.

Corollary: Automate the test analysis process

Rationale: The SVL during ATLO collected data by printing out a limited number of engineering channel values once a major frame. This meant problem discovery was sometimes delayed until testing on the spacecraft or went undiscovered. During ATLO, the telemetry data from the spacecraft was collected by the system test support equipment, which was hard to use and had limited capabilities. After launch a telemetry processing system was implemented which had capabilities similar to SFOC but did not use a central data base. This new system has increased the analysis capability of the SVL, has reduced the time and personnel required for this analysis, and has been successful in catching problems before they get to the spacecraft.

Value = B A C

2-19. Recommendation: Simplify solar thermal vacuum testing to that necessary to verify the thermal models and to verify the functional performance of the spacecraft. The latter should be done in a mission-like environment, preferably with one hot and one cold cycle.

Rationale: For Magellan, one hot and one cold case might have provided sufficient data to verify the thermal model and characterize system performance. Magellan spend 19 days in the solar thermal vacuum chamber and yet further characterization was still necessary in flight. Since characterization is almost always necessary in flight, minimizing the number of cases in STV is cost effective.

(See also Item 2-20 for minority opinion)

Value = A C A

2-20. Recommendation: Solar thermal vacuum (STV) testing of complex forms and any exposed metal surfaces should be done at multiple attitudes with respect to the sun. Design both spacecraft and test fixtures to allow this.

(This is minority opinion to item 2-19)

Rationale: The Magellan rocket engine modules (REMs) were not tested at the subcontractor level with solar illumination. Magellan's STV did not expose much of the REMs to solar illumination since the aft end of the spacecraft was not exposed to solar intensity. This was a major problem until additional testing was done at Edwards AFB after launch. Also the medium gain antenna experienced a solar entrapment problem similar to the REMs. The aft end of the spacecraft, where the Inertial Upper Stage and the solid rocket motor separation pads were located, also exposed bare metal (although supposedly clear anodized) and were not adequately characterized prior to launch. This caused the Magellan team to develop an additional mapping sequence in an accelerated schedule to cool down the aft end of the spacecraft.

Value = B B C

2-21. Recommendation: For subsystem testing, understand and characterize the test setup and associated ground system to the point that problems discovered during the test can be quickly isolated to flight system or test system.

Rationale: Magellan high gain antenna testing experienced RF breakdown of feedthru connectors on the test setup.

Value = B B C

2-22. Recommendation: External surfaces (e.g. OSRs) should be extensively tested in a representative test configuration (e.g. with adhesives and solar) so that degradation in optical properties can be properly characterized. Also exposed metal surfaces (REMs, SRM adapter ring, etc) should always be tested in a solar environment.

Rationale: The optical solar reflectors (OSR) were tested in flight configuration during environmental tests before flight (including solar thermal vacuum) and yet the OSRs have made the thermal subsystem the most constraining subsystem on the spacecraft. There is speculation that the excessive degradation being seen is due to interaction between the adhesives and the optical surfaces. Perhaps additional testing could have discovered this. The exposed metal surfaces have also been a source of problems. (e.g. the REMs and inferior conjunction problems with the SRM attachment ring.)

Value = B B C

2-23. Recommendation: Design a separate propulsion module that can be used for testing apart from the rest of the spacecraft.

Rationale: This allows hazardous tests to be performed independent of the rest of the spacecraft. (hazardous tests: tube x-rays, pressurization, propellant loading, pyrotechnic installation)

Value = B B C

Spacecraft Assembly Issues

2-24. Recommendation: Always have the cognizant engineer present on the floor when conducting critical assembly operations. The subsystem product integrity engineer should define "critical".

Rationale: The Magellan solid rocket motor safe and arm mechanical connections were initially made incorrectly at KSC. The cognizant engineer was in Pasadena on other Magellan business.

The Magellan thermal engineers were present and did most of the blanket installation themselves or assisted the blanket subcontractors.

Value = A A C

2-25. Recommendation: Don't perform blind electrical connections during assembly or system tests when live power is present. Battery and test connectors should all be scoop-proof, and similar-function connectors be keyed sufficiently differently as to prevent an incorrect electrical mate.

Rationale: Magellan, under pressure to maintain schedule, failed to move the obscuring components and incorrectly performed a blind battery mate of a non-scoop proof connector, shorting the battery and damaging the spacecraft.

Value = A A C

2-26. Recommendation: Pay particular attention to requirements that specify how to mechanically implement electrical connections. Assembly techniques should be designed around worst-case operational conditions.

Rationale: Power Control Unit ring terminals were soldered before being bolted down. Lumps of solder gave poor electrical connections for worst-case conditions and had to be reworked. This assembly technique assumed that the maximum current load was the most stringent requirement when upon further analysis, the trickle charge was more challenging.

Value = A B C

Launch Operations Issues

2-27. Recommendation: Practice hazardous operations prior to actual use. Procedure changes during the operations will stall the activity and waste precious time. Nothing should be new during KSC operations.

Rationale: Propellant loading went without a hitch because all errors had been removed prior to actual operation through testing.

The only problem was during cart loading when using EG&G personnel who had not practiced their part.

Value = A B C

2-28. Recommendation: Keep the number of Quality Assurance (QA) inspectors to the absolute minimum necessary to do the job. Too many QA people is detrimental to integration and test.

Rationale: Too many quality inspectors confused the integration of the radar data formatter unit at the launch site.

Value = A C B

2-29. Recommendation: Realize and plan for the additional activity associated with formal reviews and action item closeouts, especially those occurring just prior to launch. Develop a method of tracking open items, daily if necessary.

Rationale: Time to create presentation materials, participate in informal reviews and answer action items took away from actual spacecraft and team preparation for Magellan launch. This effort was underscoped and as a consequence, much work was postponed until after launch which should have been accomplished before.

Value = A C C

2-30. Recommendation: Consult prior missions that have flown on the space shuttle (SIR, MGN, GLL, ULS) to accurately scope the amount of work to be done.

Rationale: Magellan didn't take advantage of the SIR A and B missions' experience and severely underscoped the work to be accomplished to fly as a payload on the shuttle. KSC interfaces were difficult and time consuming. Facilities, meetings, plan generation, and document review were all underscoped.

Value = C B C

2-31. Recommendation: For any future JPL missions flown on the Space Shuttle (e.g. SIR-C) the project needs to be proactive with JSC in working STS interfaces (e.g. structural verification, failure mechanisms, safety, procedure development, etc) to smooth the mission operations interface. JPL also needs to recognize and plan for the significant amount of work involved in launching on the shuttle, particularly for STS safety issues.

Rationale: Magellan worked this interface well, which made JSC pro-Magellan and in our camp on many issues. The project did underscope the effort required to achieve a successful launch.

No significant problem occurred with KSC or JSC reviews or during launch operations.

Value = C B C

Session 3: Mission Operations System Development

The Magellan Mission Operations System was developed over a period of several years. The project held MOS Design Team meetings, and while Team Chiefs and Subsystem Engineers defined their tasks they reviewed each others' plans at these meetings. Both team-to-team and software-to-software interfaces were conceived, defined and developed, the necessary documents were written and approved, and subsystems and teams were built. Information from the spacecraft build activity, occurring in parallel, was fed into the MOS implementation process. This session dealt with issues relating to that development and implementation process.

Program Philosophy Issues

3-1. Recommendation: Find a way to design the Spacecraft Flight System and the Mission Operations System together, with cost minimization as a project objective. Decisions made in spacecraft design should be considered for their subsequent MOS impact.

Rationale: Usually, the spacecraft is designed first, and sometime later, the MOS is designed. Many times, decisions made in spacecraft hardware and software design require difficult and costly implementations in the command and telemetry systems on the ground, whereas a different but equally sufficient solution for the spacecraft would reduce the complexity on the ground. Even in cases where the spacecraft and MOS designs proceed together, spacecraft activity wins the competition for resources, MOS having much lower priority. Magellan experienced some of this, as discussed under item 1-3.

Value = A B A

3-2. Recommendation: Define standard processes, schedules and document formats early in the design and enforce them.

Rationale: Magellan MOS defined and enforced standards for:

- All review processes (PDR, CDR, ATR, etc)
- Documentation (Content & format)
- Configuration Control (and CCB Procedure)

- Hierarchical set of schedules

These improved efficiency during MOS development.

Value = A B A

3-3. Recommendation: Place project-funded GDS subsystems development under management of the using team. The users know what their software must do. A GDS organization still should remain to monitor adherence to format and completeness of software documentation and conduct systems level testing. Team staffing levels should reflect the need to perform both the software and operational jobs.

Rationale: Magellan's ground data subsystems were divided about equally between those where the team chief had control of the software development and those where software was developed in a completely separate organization and the team users had little voice. Those under the team's authority seemed to have fewer problems during operations. The groups that have followed this approach have been able to respond to changing conditions and have delivered more usable software. Those in separate organizations were in many cases, insufficiently responsive to team needs, or created their own agendas.

Multimission software may be a valid exception to this recommendation.

Value = A B B

3-4. Recommendation: Build a networked set of MOS schedules for pre-launch development and define a consistent set of milestones for application across all implementation elements of the MOS.

Rationale: Magellan MOS schedules were not networked at any level and no consistent set of schedule milestones was defined to apply to all elements. Schedule slips were allowed without management assessment of the impact. Post-launch, a networked schedule system was added that improved this situation.

Value = A B B

3-5. Recommendation: Develop an Operations Concept document at the beginning of the program. It should summarize the objectives and constraints of the mission; document the intended operational approaches; and define how users will operate and maintain both spacecraft and MOS. This document will guide the program design (both spacecraft and MOS) to satisfy the objectives, keeping the focus on system operability.

Rationale: Magellan did not have such a document. The science and mission plans which came later, identified mission objectives but did not address operational approaches. An operations concept would have given a common starting reference for all the functional requirements and interface requirements documents and operations plans developed later. It might also have sensitized the spacecraft designers to operations issues earlier.

Value = A B C

3-6. Recommendation: For activities that are delayed due to higher priority, make-play, situations, plans should be identified to resolve them (e. g., by discarding or developing an accomplishment schedule) at the time of the postponement. Don't assume that you will be any less busy later. When necessary to delay software generation due to budget problems, postpone development but keep a person active on requirements refinement

Rationale: As launch approached, many MOS development tasks were "tossed over the fence" to be accomplished during cruise, without further consideration of future schedule and manpower impacts. Some were never accomplished; others ran into similar schedule crunches later. This applies to both project-funded efforts as well as SFOC efforts to support Magellan.

Radar analysis system software development was abruptly cut off due to budget cuts. Two key software development experts were kept and they continued talking to the end users, and refining test plans. When it was finally turned back on again, coding and testing went quickly, and the software was what was needed.

Value = A B C

3-7. Recommendation: For projects willing to accept higher risk in exchange for lower cost, the risk versus cost trades need to be made early and documented clearly, so that later, NASA management and the various review boards will remember and consider this scope in their actions. As risk vs. cost trades are re-made during development, sponsor involvement (via the Project Manager) is important.

Rationale: Magellan, when resurrected from VOIR as the Venus Radar Mapper, was intended to be a low-cost mission where mission operations short cuts that added some risk could be taken in the interest of cost savings. However, when critical reviews were held, review boards and upper management decisions forced operations down the path of a "Class A" mission. Increased team sizing, certain formal software controls, additional testing of subsystems, additional reviews and checks of the uplink process, and mission operations command assurance involvement in the project are several examples of the transition from class C to class A.

Value = B C A

3-8. Recommendation: Reflect approved change paper in corresponding change to budget accounts.

Rationale: For Magellan, there was minimal attempt to link approved change summaries to the corresponding budgets. This led to overruns, schedule slips and inappropriate prioritization of work to be done.

Value = A C B

3-9. Recommendation: Develop early the system level requirements for the MOS, including those defining the teams and GDS subsystems. Then, the detailed team requirements should be a level above the subsystem requirements with requirements traceability appropriately indicated.

Rationale: For Magellan, few mission operations system requirements were defined, mostly limited to those allocated to teams and subsystems, although the teams and subsystems themselves were not identified at this level. Requirements documents for teams and subsystems were on the same level, making traceability difficult if not impossible.

Value = A C C

3-10. Recommendation: In an effort to reduce the cost of implementation, don't eliminate the system engineering.

Rationale: In an effort to save development costs the original development of the CD-ROM science data product capability was not system engineered and was implemented on an uncontrolled "best efforts" basis. JPL suffered unnecessary embarrassment because the capability to be implemented was not well understood by parties not directly involved. Headquarters and science expectations were greater than the implementing parties could have met.

Value = B B C

Organizational Issues

3-11. Recommendation: Maximize the carryover of spacecraft and instrument engineers from spacecraft system development and test onto the flight team. Also, retain some of the flight and ground software developers on the flight team for software maintenance and SFOC interface.

Rationale: The experience gained by the spacecraft engineers during spacecraft development and test was invaluable when Magellan experienced inflight anomalies.

Flight software engineers were indispensible in dealing with the many changes in both of the flight software systems during Magellan's prime mission. Ground software engineers have been able to enhance the flight team's capabilities through automation development. Also, flight team software engineers were crucial in initializing the Unix-intensive SFOC system for operations.

Value = A A B

3-12. Recommendation: Make the MOS Design Team a skeleton of the Flight Operations Team by appointing Team Chiefs and GDS Subsystem Engineers early.

Rationale: This makes the transition to operations easier (though not painless), and results in earlier designs of operational products. Magellan found this approach to be very beneficial.

Value = A B C

3-13. Recommendation: Put all sequencing-related software under one Cognizant Engineer.

Rationale: Magellan had three different engineers responsible for the SGS, MSDS, and SEGS. This made it difficult to make tradeoffs between them. Voyager had POINTER, SCANOPS, SEQGEN, SEQTRAN and SEGS all under one Cognizant Engineer, which worked much better.

Value = B B B

3-14. Recommendation: Have the TDA Manager report to the MOS Manager, not the Project Manager, during development.

Rationale: Interfaces with the DSN, a part of the MOS, should be handled at a level compatible with other MOS components, making resolution of problems easier. Magellan did not do this.

Value = B C C

MOS Design Issues

3-15. Recommendation: Use distributed computer systems for MOS designs. This provides standardization and growth potential, and provides a host for relocating software from expensive mainframes.

Rationale: The SFOC distributed data system was a plus for Magellan in spite of the initial start-up problems. Also both navigation and thermal analysis software were re-hosted from mainframe computers to Sun systems resulting in a significant savings to the Project.

Value = A B B

3-16. Recommendation: Conduct early walkthroughs of simulated deliveries using either real or simulated interface products between teams. Continue these until system is developed and repeat them when major changes occur and after data products are defined.

Rationale: Magellan conducted several "interface fairs" early in the MOS development process. These round-the-table discussions of the content, format and delivery frequency of data products helped development of operations procedures and drove out interface product problems early.

Value = A B B

3-17. Recommendation: Include data quality assurance requirements in the design from the beginning and as close to the source as possible. Operations teams should take the time (and have the appropriate tools) to validate their own products.

Rationale: Radar system quality assurance was a late addition to the design of the MOS. The need for such activities was not appreciated until quite late in the design and development phase. The usefulness of such a process has been demonstrated, for example, by the early detection of the degradation of one of the tape recorders. It was noted that procedures by themselves are not validators - independent validators are needed, too.

Value = A A C

3-18. Recommendation: Ensure mission controllers are brought on the flight team sufficiently early to obtain spacecraft subsystem familiarization training. This could be accomplished by at least three different methods: 1) Provide early spacecraft training sessions; 2) plan to staff the Mission Control Team partially with people from the spacecraft development or ATLO areas; or, 3) provide future mission controllers to ATLO to assist in spacecraft testing.

Corollary: Put this support for mission controller spacecraft familiarization in the spacecraft developer's contract to ensure participation.

Rationale: Magellan did not do a good job of training mission controllers on specific spacecraft operation until far after it was really needed.

Value = B A C

3-19. Recommendation: Perform pre-launch contingency planning at a high level. It is more important to cover many possible contingency situations at a cursory level than to delve into the details of a very few. The thinking process is more important than the written plan. Only short duration, high criticality periods (e.g., launch, VOI) should have detailed contingency plans.

Rationale: From Magellan's experience, the contingency situations that developed were always different than those considered pre-launch. The contingency process, however, helped in developing the loss-of-signal recovery plans during flight operations.

Value = A B C

3-20. Recommendation: A mission should carefully examine its tracking requirements if something more than Doppler tracking is requested. A careful analysis of the trade-offs between accuracy requirements, alternative data types, flight team operational impacts, and DSN loading projections must be made.

Rationale: Magellan, with its precision requirements on spacecraft position and pointing for mapping operations, initially thought VLBI tracking would be necessary, at the added expense of multiple, simultaneous tracking antennas. As it happened, differenced Doppler (2-way and 3-way) was determined to be sufficient, resulting in much easier operations.

Value = A C B

3-21. Recommendation: For future missions with spacecraft which require accurate ephemeris predictions over extended on-board sequence execution periods, the following should be accomplished pre-launch:

1. Dynamic models (e. g. gravity fields) should be carefully investigated for deficiencies and plans initiated for model improvement.

2. The sequence generation lead time should be shortened as much as possible and still satisfy requirements.

3. A sequence tweaking process should be designed into the spacecraft and ground processes to make changing on-board navigation parameters operationally simple.

Rationale: Magellan's long lead time for sequence generation along with the dynamic close-approach elliptical orbit posed a significant challenge to navigation. All three of the above items were addressed during the Magellan mission and resulted in significant improvement in orbit determination. It would have been better still if they had been addressed pre-launch.

Value = B B B

3-22. Recommendation: During development, test, and operations for a MOS containing remotely located components, there should be an individual at each remote site assigned as the focal point for all data-network related issues. Responsibilities should include LAN and computer hardware installation (and associated verification). During anomaly resolution such an individual would also be helpful on each team that has a sub-net.

Corollary: A "ping" capability for signal return should be maintained for all remote GDS areas to ensure minimum time to isolate problems.

Rationale: A single point of contact (i.e. the system administrator) at each site greatly reduced the amount of time spent trying to contact each individual at a remote site to determine if their workstation was functioning correctly. Also, Magellan did not initially have a "ping" capability and isolation of failures between Denver and JPL was much more difficult than necessary. Its installation improved this process tremendously.

Value = B B C

3-23. Recommendation: When downlink data rates are high, do away with magnetic tapes. Design data storage and transfer around high density optical media.

Rationale: At Magellan's high science data rate and total data quantity, tapes are not efficient media. Tapes suffer from access, storage, and survivability problems.

Value = B C B

Sequence and Command-Related Issues

3-24. Recommendation: Build single-activity command blocks, with minimal options, that can be stacked together in various ways to form sequences. Plan and execute tests that will verify the resultant sequences.

Rationale: Magellan developed large blocks with many options. (Example: The "orbit" profile activity called just two blocks to perform daily mapping operations, "mapping" and "playback".) These inflexible blocks would have worked just fine in a perfect world. Since Magellan had many anomalies and required changes due to geometry, special tests, and other reasons, the sequence generation software engineers were continually modifying block software to account for anomalies, like "hiding" for thermal reasons. Many sequences had to be hand-edited due to lack of flexible blocks, increasing the risk to the mission.

Value = A A B

3-25. Recommendation: During spacecraft development, the parallel design of the command blocks must consider mission operations implementation. Sequence software engineers should be involved in block design and walkthroughs. Then, as soon as they are designed, the blocks should be released to mission operations software engineers for implementation in ground software. Guidelines and requirements for block design should be well documented ahead of time.

Rationale: The Magellan command blocks were designed with minimal consideration of implementation in the sequence generation subsystem, with minimal input from MOS personnel, and delivered too late to prevent serious schedule impacts on the ground system. Changes to the block dictionary throughout the development cycle caused a lot of re-coding and retesting.

Value = A B B

3-26. Recommendation: Recognize that a quick-response command system is necessary. Devise both a spacecraft sequencing process and a solid real-time or non-sequence commanding process prior to launch and test the entire processes thoroughly. Also, the sequencing process must allow late breaking command sequence changes requiring low level sequence edits or entire sequence re-deliveries.

Rationale: Although a very good sequencing process was designed, there was much less emphasis devoted to non-standard commanding prior to launch, including no process for validation and approval of non-standard commands. Magellan implemented a very systematic and detailed process for non-standard command uploads approximately half way through cruise. This new process resulted in many benefits. First, it brought in the flight team at the early stages of command development and saved valuable engineering time by getting approval at an early stage. Second, this process reduced command errors. Many checks and balances were incorporated to ensure that commands were well thought through and correctly implemented. The Magellan non-standard command process was used more frequently than the standard sequence process, despite pre-launch predictions. The standard sequence process was developed prior to cruise and was reevaluated prior to mapping operations. By establishing these uplink processes in advance, the cruise sequence uploads went very smoothly and the mapping sequences have and are continuing to proceed nominally.

Despite the impacts to the rest of the MOS, Magellan found that late, quick changes in the sequence were necessary to:

A) Respond to spacecraft anomalies,
B) Correct undiscovered on-board sequence errors,
C) Save key science data, or
D) Avoid potential spacecraft problems

Value = A A C

3-27. Recommendation: Plan for and develop a spacecraft simulation capability for command sequence verification and flight software change validation. Use flight system breadboards wherever possible to reduce cost and implement a "halt, checkpoint, restart" capability to facilitate testing. If possible, design the system to run faster than real-time. Use a software CDS simulator for sequence testing to offload simulation hardware.

Rationale: Initially, there were no plans for the Magellan systems verification laboratory, and when the need was recognized, the lab was incrementally developed without a master plan. This led to parallel development and use, needed capabilities that were usually one step from completion, and a resource that was always oversubscribed. Early recognition of the need for the SVL and up-front planning would have reduced both the cost and the risk to mission operations. The Magellan SVL has been an essential tool for verification of both command/sequence loads and modified flight software. Also, the program CDSSIM was used to offload the "bread board" simulator and work around a bottleneck in the process.

The radar testbed proved to be invaluable during operations for verifying and locating missing pulse frequency and range gate commands.

Value = A A C

3-28. Recommendation: Devise a simplified, non-standard command process to accommodate spacecraft maintenance, with a minimum of flight team involvement. Maintain and control these types of commands on the command system or a storage medium readily available to the command system.

Rationale: Development of "express commands" provided a more efficient process to handle a small subset of commands that were being repeatedly sent to the spacecraft. "Express commands" are a pre-tested, pre-approved, precisely determined, set of commands that can be sent to the spacecraft by a single subsystem in response to a predetermined situation.

Value = B B B

Ground Data System Issues

3-29. Recommendation: Provide a mechanism for team or other local control of software below a certain level of criticality. Software should have only an appropriate level of control.

Rationale: Treating all software as either Class A, B, or C is unrealistic. There is a wealth of software which is developed for special purposes (often used one time or experimentally) which lives an underground existence. This software often turns out to be extremely useful and should be acknowledged by the system in some way.

Value = A B A

3-30. Recommendation: Encourage the development of pre- and post-launch supplementary analytical software to relieve the flight team from the tedium of manual, repetitive operations and to improve efficiency.

Rationale: Through additional automation, the thermal group was able to increase their throughput from one program run per week prior to launch to one per day now. All subsystems have come to depend on "SEFCHECK" software to verify sequences in the Spacecraft Events File, a step performed manually during most of cruise. These would not have been possible without enhanced automation. It also greatly reduces the probability of an analytical error during labor intensive tasks. The same rationale applies to multimission software.

Value = A B A

3-31. Recommendation: Build prototypes of complex software.

Rationale: The Radar Mapping Sequencing Software (RMSS) system was intended to get the best possible performance out of a complicated and dynamic radar system. Given the complexity, it was impossible ahead of time to determine the software requirements. The prototyping stage allowed the radar team to experiment with different optimization schemes. In fact RMSS had two prototypes: RMSSTK and the Hughes prototype which ultimately evolved into the operational version.

Value = B A B

3-32. Recommendation: For FPSO-provided components of the ground data system for future projects, the following steps are essential to achieving a quality product on schedule and within budget:

1. Both FPSO and the Project must assign senior personnel who will commit to see the component through design, development and test.

2. Component functional requirements must be written clearly and completely and must be testable. There must be only one functional requirements document that both parties accept.

3. The FPSO implementers (especially programmers) and the ultimate project users (flight team personnel) need regular face-to-face discussions during implementation to verify interpretation of requirements.

Rationale: The requirements and design process between the project and FPSO for the Magellan telemetry processing subsystem was weak, confusing and difficult to resolve. Personnel changeover was rapid. Requirements were late and poorly specified, and made confusing by having both a project Functional Requirements Document (FRD) and SFOC FRDs. Discussions between implementers and users were discouraged. As a result, the Magellan Telemetry Processing System was late and over budget.

Value = B A B

3-33. Recommendation: Be wary of promises that evolving international standards are "almost" finalized. This can create a development dependency over which the project has no control. Recommend that a project not commit to a standard until it is in approved, final form. Project should establish a need date and use the "standard" that best suits project needs on the date.

Rationale: Changes to the Standard Format Data Unit (SFDU) "standard" resulted in unproductive reworking of documentation and software. Magellan also committed to an "evolving" standard of the Planetary Data System, and had to reconsider when the Project could not keep up with the changes.

Value = A B B

3-34. Recommendation: Use a combined test team approach for project, SFOC, and DSN testing, allowing single tests to satisfy the objectives of multiple organizations. This requires getting a DSN commitment to support testing early.

(This recommendation is not meant to replace earlier required subsystem-level testing.)

Rationale: Magellan's combined test team approach, forging a link between the project, SFOC and DSN was an innovation that worked well.

Value = A B B

3-35. Recommendation: Define and document all software interfaces during software <u>requirements</u> generation by writing formal software interface specification (SIS's).

Rationale: For SES software all software interfaces were well documented in detail by formal SISs or by formal software requirements (SRDs). Detailed definition meant not only file form and content, but all record and file structures, data types, data ranges, volume and size estimates, and order. The well defined interfaces facilitated the coding phase, producing accurate program-to-progıam interfaces that required little changing.

Value = A B B

3-36. Recommendation: Plan to oversize ground system computers (both development and test) to be prepared for the unknown during ground software development and mission operations. Similarly, be flexible when imposing hardware constraints: hardware is always less expensive than custom software.

Rationale: MIPL asked for more computer capability for Magellan data processing than management thought they needed, but it was approved anyway. It turned out to be very necessary, and the foresight prevented serous difficulties.

Size and throughput limitations of the PDP 11/44 computer in the Magellan LTS/SE used for subsystem testing, caused an inordinate expenditure of test software programming time to overcome those limitations.

SFOC Class 2 workstations could not keep up with incoming 1200 bps engineering telemetry and had to be replaced with Class 3 (larger) workstations.

Value = A C B

3-37. Recommendation: For GDS development efforts, prioritize work at the beginning. This should include prioritization of requirements to be implemented and tests to be performed. Phased deliveries consistent with the priorities should be planned.

Rationale: The tendency is to prioritize when development falls behind schedule. By this time effort has usually already been expended on partially implementing lower priority items when the time could have been better spend working on highest priority items. The SFOC Magellan implementation is an example of this. By the time the project was able to determine the extent of the slip in development schedule, significant time had been spent on lower priority items.

Value = A B C

3-38. Recommendation: Phase team and software development to match project need dates.

Rationale: The Radar System Engineering Team and Radar Engineering Subsystem development were originally scheduled to be completed at launch, leaving 16 months of inactivity during cruise. Programmatic pressures eventually slipped the schedule to May 1990, three months before arrival at Venus and the subsequent in-orbit checkout. (This schedule was tight, but not excessively so.) Unfortunately, shortly after the original development schedule was approved and workers recruited, the effort had to be aborted, leading to wasted effort and low morale.

Value = A C B

3-39. Recommendation: Ensure that inherited ground software is accompanied by appropriate documentation or lay plans to develop it.

Rationale: Inherited software was accepted from other projects with inadequate documentation that Magellan did not plan or budget to update. (e.g. Nav Subsystem, SGS Subsystem)

Value = A B C

3-40. Recommendation: Consider carefully any options relative to "hardcoding" of requirements, and maintain flexibility in software/hardware, particularly to be able to handle non-nominal spacecraft performance.

Rationale: Magellan "hardcoding" in DMAS created inflexibility in changing of data products. This subsystem was in the center of all data product flow, but it was difficult to interface, inflexible, and had little capability to perform mathematical operations.

Also, the hardcoding of items in command blocks that could have been block options decreased flexibility. As an example, the Magellan cat bed heater warm-up time was hard coded in the block to be 90 mins. There was no "operator override" capability for this constraint, which forced hand edit of the final product when thermal problems with the rocket engine modules reduced warm-up times to 45 mins.

Hardcoding of portions of the decommutation map in SFOC required additional software development and deliveries to correct for the radar spiral wrap commutation problem during cruise.

Value = A B C

3-41. Recommendation: Do as much testing at the GDS subsystem level or program set level as early in the development cycle as possible. (*i.e.*, don't put testing that can be accomplished earlier off until the system test phase.) All subsystems should provide, early in the project development process, test products for their associated team data processing and for down-stream processing.

Rationale: Magellan originally required inter-subsystem testing with actual interfacing subsystems (as opposed to simulated interfaces) for the first time during system test. The policy was later changed to require subsystems to do testing with interfacing subsystems prior to delivery for system test. This helped to identify more anomalies prior to delivery to formal change control.

Realistic test products were not always provided or were provided during cruise or later.

Value = A B C

3-42. Recommendation: Spend the necessary time to thoroughly define the Software Management and Development Plan (SMDP) prior to beginning *any* software development.

Rationale: The wisdom of having a thorough plan defined up front cannot be overemphasized. The SMDP was referred to constantly throughout the development effort, and even though minor updates to it were required, it still services as a surprisingly stable reference.

Value = A C B

3-43. Recommendation: Implications of "phased implementation" of software need to be addressed in SIS's and test plans. Balance is required between early and complete definition of requirements, and testability of partial deliveries.

Rationale: Early versions of Experiment Data Records (EDR), especially those provided for GDS testing, contained many dummy files and parameters. Software using these EDR's as input were sometimes written "per SIS," without the capability to ignore the dummy material, and would simply stop with error messages rather than continue processing. This required last-minute workarounds to enable the part of the software that was working to be tested.

Value = A C B

3-44. Recommendation: Before the start of the coding phase, establish a set of conventions, guidelines and rules for software engineers to follow.

Rationale: Rules covering program structure, segmentation and commenting rules, preface/prologue commentary, call/return and argument list conventions, file unit standards, and statement numbering were established and documented. It appeared to be overly simplistic, obvious, and not worth documenting at the time, but proved to be exceptionally effective in achieving uniformity, eliminating potential errors, and minimizing stylistic biases. This effort has also facilitated maintenance of the software during mission operations.

Value = A C B

3-45. Recommendation: Organizational boundaries (team-to-team, contractor-to-subcontractor, etc.) need to be distinct when determining who generates and delivers which products, but should not prevent technical interaction between working-level members of different organizations.

Rationale: Areas where this worked well for Magellan include the spacecraft flight system (during testing) and the RSET/AACS Group/Upload Preparation Group interaction during operations. It was not applied well between MIPL and RSET during operations.

Value = A B C

3-46. Recommendation: For the development of ground software, the system engineer that creates all system level (functional) software requirements should also perform final user qualification testing.

Rationale: By having the "same" individual write the requirements and perform final testing, the Magellan Spacecraft Engineering Subsystem (SES) has experienced very few failures during mission operations. The SES consists of 28 individual programs that support spacecraft subsystems analysis. 114 informal software anomaly reports were written during preliminary qualification testing. Two software anomaly reports were written during final qualification testing and less than 40 failure reports have been issued during the 3.5 years of mission operations. Not enough can be said for having clear and concise requirements and personnel knowledgable enough to perform comprehensive testing.

Value = A B C

3-47. Recommendation: During performance of the project, attempt to maintain consistent personnel throughout the entire software development lifecycle and into mission operations.

Rationale: Some software development life cycles advocate separate personnel for requirements, design and code, and acceptance test. For both the SES and SEGS, each engineer was responsible for all life cycle products beginning with software requirements and ending with program level acceptance testing. This consistency provided a strong software group that eventually transitioned into operations, providing significant positive impact to flight team operations. The developers familiarity and expertise played a big role in the "team" concept required in a flight team environment.

Value = A B C

3-48. Recommendation: GDS component reviews, with both development and operations personnel on the review board for GDS subsystem documentation and deliveries, contributes to implementation of a system that is responsive to operational needs.

Rationale: Magellan consistently found that operations involvement in defining GDS subsystem requirements was essential. Having operations personnel on the subsystem review boards ensures that they have read (and commented on) the proposed requirements.

Value = B B C

3-49. Recommendation: Have each GDS subsystem engineer hold software "walk-throughs", of both code and process, with MOS teams, GDS staff personnel, and, where applicable, science teams.

Rationale: "Walk-throughs" within IDPS/T were helpful and would have been more so with science team participation.

This activity would also make meetings (CCB, ATR) shorter since GDS subsystems engineers would spend less time defending their testing and implementation positions.

MSDS and SGS, in particular, should have had mutual walkthroughs.

Value = B B C

3-50. Recommendation: Spend the time and effort to carefully select tools for the software development environment with attention paid to tools that have the ability to increase productivity.

Rationale: Both the Lahey F77L FORTRAN compiler and its source level debugger were high productivity items. The compiler was fast, producing efficient code. The ability to build full breakpoint and monitoring features at the source level prevented significant time losses from the inability to track down obtuse bugs. This complete development environment allowed concentration to be focused on the major algorithm and code problems associated with each programs' functional requirements and minimized distraction from "details".

A decision was made to use LATEX for Radar Analysis Subsystem software documentation because it was the standard word-processing/publishing package on the Sun software development computer. The decision missed the point that much better, cheaper and more friendly word processing software was available on PC's.

Value = B C B

3-51. Recommendation: Develop a software metrics tracking scheme to allow all engineers and management to become involved in the status and tracking of individual responsibilities.

Rationale: The metrics scheme used by the Spacecraft Engineering Subsystem developers was a low level management tool that proved to be as useful to the individual engineers as it was to management. By requiring the individuals to provide minute tracking status on a weekly basis, they became precisely aware of how their assignment was affecting the aggregated task completion effort. If slippages started to creep in, the source was apparent and corrective measures addressed quickly. Moreover, by quantifying the amount of slip, each engineer was aware of how much schedule had to be made up and how soon. Each individual engineer was able to set or at least see their own goals for meeting final deadlines.

Value = A C C

3-52. Recommendation: Keep the number of signatories of software documentation to a minimum and have the documents signed at the lowest level of responsibility that makes sense.

Rationale: In some cases it took months to get documents through the signature cycle due to the large number of signoffs required. Before MGN modified its policy, an interface with three users required 14 signoffs on the SIS. The procedure was later modified to require only subsystem engineer and system engineer signoff reducing the required number of signoffs by 8, for the above example.

Value = B C C

3-53. Recommendation: Postpone ground computer hardware selections as late as possible without affecting schedules to ensure that the latest technology is used.

Rationale: DMAS hardware selection was made early, and more efficient hardware/software was available by flight time. Proper consideration was not made of ease of use, number of users, frequency of transactions, etc., in the choice of the entire hardware/software package.

The SFOC workstation host decision was also made early (Sun vs. Sparc) and Magellan now has an out-of-date workstation in relation to later versions of SFOC.

Value = A C C

Session 4: Mission Operations Conduct

After the spacecraft was launched, the operations phase began with a 15-month cruise period, followed by Venus Orbit Insertion. During the planetary orbital operations phase, the mission's mapping science objectives were met. Session 4 was concerned with recommendations about the activities related to operating the spacecraft and collecting the science data. Note that even though Magellan's development activities continued into the mapping phase, all development issues were relegated to Session 3, and only maintenance-related development activities are critiqued here.

Program Philosophy Issues During Operations

4-1. Recommendation: Efforts should be made from the very beginning to take advantage of the interest that all project workers (managers, engineers, secretaries...) have in the science goals. The project gets more free labor out of this than out of anything else!

Rationale: Science briefings remind all the workers what the ultimate results of their efforts will be. (1) After an informal science briefing/pep talk given to the Hughes people just before shipment to the Cape, several experienced test crew members (who were getting very tired of living out of suitcases) elected to remain with Magellan through launch instead of transfer to other programs that would let them live at home. (2) The radiometer mode of the radar got no real attention from the formal specifications; much of the success of the radiometer was due to effort put in by one individual who did it mostly because he was excited about the science goals. (3) The Spacecraft Team receives a regular revitalization when a science team member comes to Denver to status the science results in his area.

Value = A A A

4-2. Recommendation: Allow portions of the flight team to operate from a remote location if appropriate, to save cost and retain quality people. Emphasize development of high quality communications links and procedures to permit good exchange of information between sites. Have at least one representative in each site.

Rationale: Magellan's Spacecraft Team operated from a remote site in Denver during flight operations. This allowed a significant cost reduction and permitted retention of a quality team with access to critical spacecraft development experience. The major difficulties revolved around communications between Pasadena and Denver. The following capabilities were determined to be essential to making remote operations work:

1. A quick, clear and reliable station-to-station voice network.

2. A quality teleconferencing system allowing full audio participation in meetings.

3. Regular status reports (both verbal and written) on remote site activity.

4. Regular science results briefings

Value = A B A

4-3. Recommendation: Develop and implement a plan to achieve as much cross-training as possible, both among and between teams, with a goal of cost-reduction through staff minimization.

Rationale: Magellan flight team members are, in general, too specialized (as are most other JPL flight teams). The spacecraft team discussed cross-training many times, but never seemed to have time until cost reductions required it. Theoretically, there is no reason why a good spacecraft engineer couldn't be trained to handle multiple subsystems. The Mission Sequence and Design Team and Sequence Generation Subsystem operators could also be cross-trained.

Value = A B B

4-4. Recommendation: Be aware of personnel needs. Specifically, (1) provide and assist career advancement paths wherever possible, and (2) do not ignore the social aspect of team development. This means to encourage parties, of course, but it also means to encourage teams to give seminars on what they do and how they do it.

Rationale: Magellan recognized this need late in the operations phase and lost some key personnel before such recognition. Even then it was a good morale booster.

Value = A A C

4-5. Recommendation: Provide Mission Operations Command Assurance (MOCA) support at the beginning of operations to focus on elimination of startup errors, and then phase them out. This brings past experience to new flight teams.

Rationale: Magellan has had MOCA support throughout operations. Its usefulness appears to follow the law of diminishing returns.

Value = A B B

4-6. Recommendation: Plan on change during operations, even in "repetitive" missions. Nothing is ever as simple as it seems at the plan level. This impacts both team staffing levels and enhanced ground software designs to include options.

Rationale: Magellan, planned to be repetitive and boring, where "every orbit looks like every other orbit", found this not to be the case. Constant adaption and change resulted from anomalies, both on the ground and in flight. We had to maintain efficiently functioning ground and flight software support, throughout the mission.

Value = A A C

4-7. Recommendation: Force operational decision-making down to the lowest level consistent with application and personnel.

Rationale: The Magellan flight team sometimes let mundane issues and decisions rise up to the mission director, consuming the time of everyone in that particular chain of command. Finally Magellan reversed the trend. Express commands are a good example, where individual subsystem engineers can authorize pre-approved commands to be transmitted in certain instances.

Value = A C A

4-8. Recommendation: Keep all teams of the flight team that are at one site in one physical location for more operations efficiency.

Rationale: The Mission Control Team was on the first floor of SFOF with the rest of the team on the second floor, which created a separation.

Magellan's science area was located apart (through 2 locked doors) from the rest of the Science and Mission Planning Office, causing communications difficulties.

At Martin, the Systems Verification Lab and spacecraft subsystems were on different floors.

Both the SAR Data Processing and Image Data Processing facilities were separated from the science team

Value = A B C

4-9. Recommendation: Carefully define (at least qualitatively) how much effort the project is willing to spend to gain or recover science data. Guidelines need to be developed to find the right balance between extra work and additional data.

Rationale: Magellan sometimes went to great lengths, involving a lot of work by the flight operations teams, to achieve a small amount of science data (e.g. two-hide optimization). At times the extra effort was worthwhile.

Value = A C B

4-10. Recommendation: For those missions intended to be truly low cost, don't insist on "zero command errors" but categorize them, accepting efforts to minimize command errors with zero as a goal. Concentrate checking efforts to eliminate those errors that might cause damage to the spacecraft flight system or mission, while being less concerned about those that have no consequence to either.

Rationale: On Magellan, all command errors were equal. So much effort was spent trying to eliminate all types of command errors that there was concern that a really big one would slip through. As long as people are involved in spacecraft command and control, there will be human error. The objective should be to guarantee to catch *all* the big ones and don't sweat the little ones.

(Note: A minority opinion, submitted in review, states that "little" command errors might affect other things and result in "big" errors; i. .e., that the distinction is difficult to make ahead of time.)

Value = B C A

4-11. Recommendation: Be careful to allow for (potential) extended mission phases when planning primary missions. Take literally the directions to "not preclude extended mission."

Rationale: (1) Cycle-2 effects in image mosaicking operations required transition at the end of cycle 1, which Magellan handled well. (2) Thermal situations during extended missions were difficult to handle, but the thermal analysis software was capable of dealing with them. (3) Command blocks, as coded for primary mission, were not flexible enough to support extended mission objectives. (4) Orbit numbers and product labels required numerous software changes during extended mission. (5) The radar team required redesigns in the extended mission. (6) Key personnel were lost by the time required changes were identified.

Perhaps Magellan should have requested a modest extended mission planning effort throughout its existence.

Value = B C B

 1630-112

4-12. Recommendation: Keep all flight memories up-to-date during mission operations, even if they are "off-line."

Rationale: The Magellan AACS-B memory was not kept up-to-date after the anomalous Solid Rocket Motor separation event. Neither of the two on-board Attitude and Articulation Control systems had correct guide stars for RAM safing (i. e., the safing routine stored in random-access memory) after orbit insertion. This is likely the reason RAM safing did not work during the first so-called "Runaway Program Execution" event.

Value = A A C

4-13. Recommendation: Maximize communication through a combination of all-hands, focussed, and management (chain-of-command) meetings. Carefully structure meetings so that they minimize wasted time. Issue agendas, state goals, consider listing separately the "required attendees" and "come-if-you-want attendees". Start meetings on time.

Rationale: Magellan meetings were often populated by too many people, and yet often communications did not occur well, especially in the downward direction. Magellan meetings were perceived as inefficiently run, personnel felt that they were required to sit through meetings to see if there was any subject pertinent to them.

Value = A B C

4-14. Recommendation: Implement an automated on-line relational database for quick access at workstations during operations. This is especially important for command information such as command availability, structure and usage, and also to maintain an on-line history of commands transmitted. It is also useful for telemetry.

Rationale: The Magellan team realized the need for this during prime mission mapping operations and implemented it for extended mission.

Value = C A C

4-15. Recommendation: Design an automated "front-end" processor for implementation in the SFOC workstation (the workstation supplied by the multi-mission Space Flight Operations Center) to simplify the workstation interfaces and processes for real-time telemetry monitoring applications, but retain the full flexibility for the non real-time spacecraft team engineer's activity.

Rationale: For real-time activities, the SFOC workstation interface was too labor intensive, requiring far too much keyboard entry which detracted from spacecraft monitoring. For non real-time activities (e. g., spacecraft engineering analysis), the flexibility offered by multiple windows, user-changeable displays, rapid query access to a central telemetry data base, and other SFOC features, allowed the engineers to accomplish their jobs quickly and efficiently, especially during anomaly response.

Value = C A C

4-16. Recommendation: For programs having a test bed spacecraft simulator, use it as a training ground for replacement or additional mission operations personnel.

Rationale: As Magellan Spacecraft Team operations persons have left the program or as new people are required, SVL has been instrumental in providing personnel who are experienced in spacecraft operations to the spacecraft subsystems portion of the flight team.

Value = B B C

4-17. Recommendation: One individual or organization (company) should be assigned responsibility for troubleshooting an entire data link to remote support areas rather than have many individuals (and their respective companies) responsible for just their portion of the link.

Rationale: Before responsibilities were clearly understood for the JPL/Denver 56 Kbps data line interface, there was confusion as to who was responsible for resolving a particular anomaly. In several instances each of the parties responsible for a piece of the failed interface (5 different companies) reported that their piece was working and that it must be another piece that was not working.

Value = B C C

Ground Data System Maintenance Issues

4-18. Recommendation: Keep the flight team trained in the process for manual command translation so that this procedure can be used when needed, even if it is not the nominal process.

Rationale: Magellan did not initially use this capability. When a situation arose that required the manual process, the team was not able to respond. Later a training plan was developed and the translation process is now continuously used.

Value = A A C

4-19. Recommendation: Provide a method allowing special delivery of portions of the GDS quickly during operations. Put more interface testing responsibility on the subsystem engineers.

Rationale: Magellan found that due to the complex GDS testing process it was much quicker to update the flight software than it was to correct a problem in ground software (e.g. the desat block).

Value = A B B

4-20. Recommendation: Plan and budget for continued changes to GDS software after launch, and the associated re-deliveries. Plans should be able to support concurrent implementation, and test of GDS software along with flight operations. Budgets should not be structured such that subsystem development personnel are phased out prior to actual operational use of the subsystem. Ensure that adequate computer hardware is available for post-launch development. Also, consider modification of the nature of Acceptance Test Plans (ATPs) after initial software delivery.

Rationale: Resource planning for sustaining GDS subsystem engineering in most areas was inadequate, both in manpower available and in computer resources. Regardless of the quality of the implementation effort there is always a need for operational enhancements or anomaly correction following actual use. We naively assumed that once we were flying, the subsystem work would drop to near zero. Every subsystem required at least one re-delivery following its initial use.

ATPs are a necessary and useful part of testing. But testing an upgrade could be done less rigorously than an initial delivery. Full regression testing is usually unnecessary, as only a portion of a software set is affected. Usually the best person to define the portions affected is the cognizant engineer.

Value = A B B

4-21. Recommendation: When it is impossible to completely check out a GDS subsystem prior to operational use due to lack of test data or proper configuration, a period of subsystem checkout should be officially scheduled during which no routine operational activity is planned.

Rationale: Due to lack of radar test data it was impossible to completely check out the SAR data processing subsystem (SDPS, the subsystem that processes the radar (science) data) prior to-in-orbit-checkout. A three-week period following receipt of actual data was blocked out during which the SDPS developers ran acceptance tests under a modified change control process. At the conclusion of this period the development personnel documented changes made to the subsystem and delivered the subsystem to the change board. Without this checkout period data products with anomalies would have been produced which could have resulted in reprocessing across the downlink processing system. The Image Data Processing Subsystem (IDPS) should have been similarly planned.

Value = B B C

Session 5: Science Data Processing, Distribution and Analysis

Into Session 5 were put all recommendations involving the actual collection of science data during the mapping phase and the handling of science data products. This phase of Magellan saw the first production and distribution of actual data products, and the first science analysis. In this time period Magellan implemented the first effort to have a centralized data management and archive team, DMAT, and pioneered project distribution of data on digital compact discs (CD-ROMs).

In this session we repeated some subtopics from previous sessions, but here they are used to separate the science and data production issues rather than to re-address the entire subtopic. Note that in this session, the second value category was expanded so that the words "increase to mission success" were interpreted to include increase in science return. Thus some recommendations which increase mission success may actually involve an increase in mission risk, whereas in spacecraft safety issues the opposite is generally true. Note also that this session does not stand alone. Many of the topics that could be covered under science data processing, distribution and analysis have already been discussed either in MOS Development or in MOS Conduct, and are not repeated here.

Philosophy and Organization Issues

5-1. Recommendation: Negotiate science team contracts at a detailed level from the science office. Write contracts with specific deliverables and longer terms.

Rationale: Magellan experience worked well, allowing the Science and Mission Planning Office to monitor progress and provide and defend funding as required.

Value = A B A

5-2. Recommendation: Projects should consider carefully whether or not to separate data management, data archive and data distribution functions and, if they are separated, where to place them organizationally.

Rationale: (Argument 1) Data archive and distribution are more separable from science oversight than is data management. Science support personnel spent too much time doing data management functions which they were unable to delegate.

Rationale: (Argument 2) The tasks of management, distribution and archiving of the data are too related to separate them. Science oversight is requied for both. However there is some overlap between the Data Management and Archive Team (DMAT) and the Mission Operations and Science Support Team (MOSST) functions which is inefficient and could be addressed by better communication and a closer working arrangement.

Value = A B B

5-3. Recommendation: Consider carefully the relative advantages of having the Mission Planning Team (MPT) within the science organization versus as a staff position to the Mission Director.

Rationale: (Argument 1) The Magellan organization worked well, allowing MPT to function to maximize science results. During operations, the MPT evolved into a Mission Director-level forum anyway.

Rationale: (Argument 2) Too many studies were performed outside of MPT's cognizance. MPT should have directed such studies.

Note that Magellan maintained a Spacecraft Team representative on its Mission Planning Team to give a broader planning perspective.

Value = A B B

5-4. Recommendation: Organize the Public Information Office (PIO) under the Project Manager, retaining a public-relations type function in the science office.

Document PIO requirements early and plan accordingly.

Rationale: The PIO function could not be efficiently managed by Magellan Science and Mission Planning Office. Upper level management was required anyway.

Value = A B C

Operations and Operations Design Issues

5-5. Recommendation: Encourage graduate student and post-doctoral participation throughout the flight team, both early in the mission and throughout its duration.

Rationale: These people served Magellan very well as staff to Project Scientist and in operations team support roles.

Value = A B A

5-6. Recommendation: Design science inputs to uplink and downlink processes with a series of meetings which progress from heavy science participation to heavy operations participation.

Rationale: The Magellan system was organized this way and worked well for both processes.

Value = A A B

5-7. Recommendation: Data flow simulations ("sims") involving both teams and subsystems should be held which include science support personnel, both with and without contingencies. Encourage multi-day sims run at real-time speed in order to uncover data volume problems.

Rationale: Magellan's "startup" time in getting a smoothly operating data production was largely due to lack of practice. Magellan simulations were of limited scope due to the difficulty of creating simulated data that would flow through all software. But even crude simulations ("tabletop" or "paper" sims) would have revealed such problems as format errors in directory files. Sims with full data volumes would have uncovered the underscoped Data Management and Archive Team (DMAT) and other team and subsystem problems. Meeting-flow sims would have helped meetings such as the Data Products Management Meeting to be fully functional at start of mapping.

Value = A A B

5-8. Recommendation: Acknowledge early the need for archiving data products, and disseminate the information widely.

Rationale: Early effort by the Project relative to archiving gave everyone the knowledge that they needed to be concerned about archiving.

Value = A A B

5-9: Recommendation: Encourage timely release of science data, both digital and photographic. Allow minimal data validation period. Encourage monthly data (e.g., image) releases.

Rationale: Magellan process worked well - a six-month time period for data validation was a good balance. Magellan suffered because its digital data product releases lagged behind its photoproduct releases.

Value = A A B

5-10. Recommendation: Require science investigators to keep a strong involvement in project operations.

Rationale: Magellan science team members on occasion did not fully participate in operations-oriented meetings, especially after analysis phase began. As a result, necessary tradeoffs were never understood by science team members. Where the team did participate, they were a big help.

Value = A B B

5-11. Recommendation: Require that science support and instrument control personnel participate in science analysis.

Rationale: The support team was often so "out-of-touch" that direct team participation in operations meetings was required in order to make and/or justify decisions.

Value = A A C

5-12. Recommendation: Define ground system products (including media) early, and involve science in science data product definition early. Estimate carefully the scope of the data flow.

Rationale: Early consideration of data flow gave Magellan a "leg up" on defining a system. Scientists were asked to review and sign Software Interface Specifications for science-deliverable data products. Magellan recognized the complexity, but still underscoped the data flow requirement.

Magellan did not recognize the need for compact discs (CD-ROMs) until late in the development process, then tried to produce them informally. The result was that there was no well-thought-out development and operations plan. GDS had to take over the process after data acquisition had begun.

Science use of the Data Management and Archive Subsystem (DMAS) never occurred as envisioned. (Perhaps Overscoped?). Further science involvement in the design phase would have made science queries to DMAS more "user-friendly".

Value = A A C

5-13. Recommendation: When budget cuts come (as they will), immediately rescope documents, schedules, objectives, especially those that relate to data management/delivery, if you can't do the same task for less. If time absolutely does not allow updating of schedules or milestones, be sure to "invalidate" any commitments that may not be kept as a result.

Rationale: Unrealistic expectations led Magellan to be constantly behind. Commitments should have been more balanced with staffing. Magellan's failure to update the Project Data Management Plan after it became apparent that data production was behind led to missed milestones.

Value = A B B

5-14. Recommendation: Maintain a high level of science communication within the project, during all phases and at all locations. Establish regular science briefings by team members. Similarly, maintain internal communication of project status through dissemination of current activities ("experimenter notebook" level data).

Rationale: Flight team members appreciated knowing what results are found, and everyone benefitted from keeping current. However, science seminars were held at times when some personnel had to work or go to scheduled meetings. And, Magellan status reports did not emphasize planned events.

Value = A B C

5-15. Recommendation: Science investigator teams and the Project Scientist should have separate office space and sufficient staff.

Rationale: The Magellan Mission Support Area for science allowed efficient space for data validation and science analysis. Project Scientist staff were not planned for and had to be accommodated later.

Value = A C C

5-16. Recommendation: Within the science support function, emphasize cross-training, even at the expense of pyramid structure.

Rationale: Magellan science support suffered when personnel were absent.

Value = A C C

5-17: Recommendation: In designing data management teams such as Magellan's DMAT, consider carefully whether to integrate tasks horizontally (i.e., in "assembly line" fashion) or vertically (i.e., one person per product transaction).

Rationale: (Argument 1) Having a product pass through many hands seemed inefficient, spending too much time handing products from one desk to another. Vertical structure led to problems when people were ill or vacationing.

Rationale: (Argument 2) The nature of tasks in DMAT is such that the "assembly line" approach is most efficient for most tasks.

Value = B B C

Ground Data System Issues

5-18. Recommendation: Keep paper interfaces to a minimum. Requests and processing confirmations should all be electronic.

Rationale: Paper interfaces are slow, personnel-intensive, and cost-ineffective.

Value = A A B

5-19. Recommendation: Plan early to have all data-production teams validate their own output products, with coordination of the design at the system level.

Rationale: Magellan data product quality control was not incorporated into the early system design, and team product validation was in some cases not instituted. Producers of data products are not equivalent to product validators.

Value = A A B

5-20. Recommendation: Provide on-site workstation capability, with network access, to investigators even though they are not in residence. Include these in the GDS design.

Rationale: Magellan's science workstations were well-used and productive even though Magellan did not envision in-residence investigators. The workstations provided a means for network communications and transfer of data products to investigator's home-institution computers as well as a basis for in-house quality control and a facility for use during meeting times.

However, Magellan's GDS design did not originally include the workstations and was required to assume control of them late in the design phase.

Value = B B C

Acronyms and Abbreviations

AACS	Attitude and Articulation Control Subsystem
ATLO	Assembly Test and Launch Operations
Ace	(Lead) Mission Controller
ATP	Acceptance Test Plan
ATR	Acceptance Test Review
CCB	Change Control Board
CDB	Central Data Base
CD-ROM	Compact Disc - Read Only Memory
CDR	Critical Design Review
CDS	Command and Data Subsystem
Desat	Desaturation
DFU	Data Formatter Unit
DMAS	Data Management and Archive Subsystem
DMAT	Data Management and Archive Team
DMS	Data Management System (onboard tape recorder)
DPMM	Data Products Management Meeting
DSN	Deep Space Network
EDR	Experiment Data Record
EPS	Electrical Power System
FP	Fault Protection
FPSO	Flight Projects Support Office
FRD	Functional Requirements Document
GDS	Ground Data System
GLL	Galileo
HGA	High-Gain Antenna
IDPS	Image Data Processing Subsystem
IDPT	Image Data Processing Team
IOC	In-Orbit Checkout
IUS	Inertial Upper Stage
JSC	Johnson Space Center
Kbps	Kilobits per second
KSC	Kennedy Space Center
LAN	Local Area Network
MD	Mission Director
MGA	Medium-Gain Antenna
MGN	Magellan
MIPL	Multimission Image Processing Lab
MILA	Merritt Island Launch Area
MMR	Monthly Management Review
MOCA	Mission Operations Command Assurance
MOS	Mission Operations System

MOSST	Mission Operations Science Support Team
MPT	Mission Planning Team
MSA	Mission Support Area
MSDS	Mission and Sequence Design Subsystem
Nav	Navigation (Team or Subsystem)
OSR	Optical Solar Reflector
Ops	Operations
PCU	Power Conditioning Unit
PDR	Preliminary Design Review
PDU	Power Distribution Unit
PIE	Product Integrity Engineer
PIO	Public Information Office
PRF	(Radar) Pulse Repetition Frequency
PSU	Power Switching Unit
QA	Quality Assurance
RAM	Random Access Memory
RAS	Radar Analysis Subsystem
REM	Rocket Engine Motor
RES	Radar Engineering Subsystem
RF	Radio Frequency
RMSS	Radar Mapping Sequencing Software
RPE	Runaway Program Execution
RSET	Radar System Engineering Team
S/C	Spacecraft
S/S	Subsystem
S/W	Software
SAMPO	Science and Mission Planning Office
SAR	Synthetic Aperture Radar
SEF	Spacecraft Events File
SES	Spacecraft Engineering Subsystem
SFOC	Space Flight Operations Center
SFOP	Space Flight Operating Procedures
SGS	Sequence Generation Subsystem
SIR	Shuttle Imaging Radar
SIS	Software Interface Specification
SMDP	Software Management and Development Plan
STV	Solar Thermal Vacuum (Test)
SRM	Solid Rocket Motor
SRS	Software Reporting System
SRU	Shunt Regulator Unit
STDPS	System Test Data Processing System
STS	Space Transportation System
SVL	Systems Verification Lab

TDA	Tracking and Data Acquisition (Office)
TPS	Telemetry Processing Subsystem
VLBI	Very Long Baseline Interferometry
VOIR	Venus Orbiting Imaging Radar
VRM	Venus Radar Mapper

Index

AACS 28, 30, 76
acceptance Test Plans 78
acceptance testing 9
acoustic test 41
action item closeouts 46
algorithm 27
algorithm development 12
algorithms 30
"almost" finalized 62
analysis 11, 18, 22, 77
anomalies 9, 29, 59
anomaly 11
anomaly recovery 10
approval signatures 7
archiving 84
assembly 11, 35, 45
assembly line 86
astroquartz 19, 34
asynchronous interrupts 9,29
ata management 80
ATLO 10, 34, 35, 38, 42, 54
ATR 48
attendees 76
attitude 30
attitude control 29
automation 60
award fee 23, 24
band-aid approaches 18
battery 32
blankets 19, 34
briefings 71, 72, 86
budget 9, 50, 51, 64, 78, 85
budget cuts 10
budget reductions 11, 14
budgets 15
cable 33
career advancement 13, 72
carryover 52
carryover of personnel 8
CCB 48

CD-ROM 52, 80, 85
CDR 48
CDS simulator 59
change 11, 51, 73, 78
changes 14, 18
class A 51, 60
clockwise 41
close calls 2
co-location 13
cognizant engineer 9, 18, 44
command 9, 11, 40, 58
command blocks 6, 11, 57
command database 9
command errors 9, 15
command file 38
command information 76
command mini-blocks 7
command process 7
command validation 9
commands 40, 76
commitments 85
common resources 8
common stacks 29
commonly-mentioned subjects 10
communication 8, 21, 76, 86
communications 71
commutation 39
compact discs 80, 85
compatibility testing 35
component 61, 68
components 13, 33
compression stroke 16
computer 30
configuration 31, 79
configuration control 14, 29, 48
confirmations 87
connectors 45
contingency 35
contingency planning 55
contract monitors 13, 26
contractor 8, 13, 20, 23, 24, 25, 26, 32
contractor-contractee relationship 16
contractors 8, 18

contracts 27, 80
contractual Issues 23
control 31
controls 31
conventions 66
cost 8, 9, 14, 16, 17, 19, 32, 38, 51, 71
cost minimization 6
cost reduction 7
cost savings 9
cost-reduction 72
critical assembly operations 44
critical operations 9
cross-training 8, 13, 72
cycling 10
data 13
data archive 80
data distribution 80
data flow. 85
data link 77
data management 11, 80, 85, 86
data product 8
data production 83
data products 54, 80
Data Products Management Meeting 83
data quality 54
data validation 84
data volume 83
data-network 56
data-production 87
database 29
decision-making 8, 73
decommutation 65
deliverables 80
delivery 78
dependencies 14
design 13, 16, 18, 20, 22, 27, 29
design improvements 11
development 11, 13, 14, 19, 20, 27, 31, 37, 39, 52, 56, 57, 63, 64, 65, 67, 68
development phase 9
distributed computer systems 53
DMAS 64, 70, 85
DMAT 80, 81, 86

DMS 18
document 32, 48, 62
documentation 7, 14, 26, 49, 64, 69
documents 85
doors 8
downlink 7, 15, 83
downlink data rates 57
DSN 9, 53, 55, 62
dust 34
efficiency 74
effort 74
electrical connections 9, 45
electrical mate 45
electrical phasing 41
electrical power subsystem 21
engineering models 20
environmental 33, 38
environmental tests 40
ephemeris predictions 56
equences 9
errors 59
Executive Summary 6
expectations 85
Experiment Data Records 66
express commands 7, 60, 74
extended mission 75
failure 14
failure reporting system 25
failure reports 12, 22
false interrupt 9,17
fault protection 10, 12, 16, 21, 27, 28, 30, 39
flexibility 64
flexible 11
flight computers 10
flight controllers 7
flight hardware 20
flight memories 76
flight software 9, 12, 16, 17, 27, 29
flight systems 31
flight team 13, 71
FMEA 32
FPSO 11, 61
free labor 71

"front-end" processor 77
functional requirements 61
Galileo 30
GDS 10, 11, 12, 15, 49, 51, 63, 65, 68, 78, 79, 87
glass-fiber 34
glass-fiber thermal surfaces 9
graduate student 83
graduate students 13
gravity 56
ground data system 9, 61, 87
ground data system maintenance 78
ground software 9
ground system 85
hardcoded parameters 11
hardcoding 64
hardware 8, 12, 13, 26, 29, 31, 33, 35, 70
hardware) 18
hazardous operations 10, 45
heritage 33
hiding 57
high gain antenna 26, 43
history 16
Hughes 16,23, 27
Image Data Processing 74
image processing 11
implementation 16
independent coding 30
inheritance 13,16,30,38, 64
inherited components 11,21
inherited equipment 21
inspection reports 26
instrument control 84
integration 15, 33, 37, 38, 46
interest 71
interface fairs 54
interface testing 78
interfaces 7, 12, 38, 40,54,62, 87
interfacing 65
involvement 8
JPL 8, 14, 15, 20, 23, 24, 25, 33, 47
KSC 35, 40, 45, 46
LAN 56
LATEX 69

launch 12, 15, 30, 35, 36, 39, 50
launch operations 35
layered 29
lesson learned 2
loss-of-signal 29
low cost 7,74
magnetic tapes 57
management 10, 11, 20, 24, 31, 35, 49, 51, 69, 81
manual command translation 78
mapping 11, 80
margin 28, 33,41
MARS 26
Martin Marietta 16, 23, 24, 26
math models 12
medium gain antenna 43
meetings 8, 76, 83
memory 27
metrics 69
MILA 40
milestones 85
mini-blocks 9
minority opinions 3
Mission Control Team 54
mission controllers 54
mission operations 9, 12
Mission Operations Command Assurance 73
mission operations conduct 71
mission operations system 6, 36
Mission Planning Team 81
Mission Support Area 86
MOCA 15, 73
models 27
monthly management reviews 8,25
MOS 9, 10, 42, 48
MOS Design Team 53
MOSST 81
multimission 49
NASA 51
NASA Select 8
network access 87
networks 13
non-standard commanding 58,59
objectives 3, 85

office space 86
operability 6
operational issues 76
operations 11, 13, 14, 17, 29, 37, 45, 48, 50, 53, 55, 56, 57, 60, 63, 67, 68, 73, 76, 78
operations concept 6, 17, 50
operations team 7
opposing recommendations 2
optical media 57
optical sensors 34
optical solar reflectors 44
optimization 74
options 57
organizational boundaries 66
organizational structure 8
OSR 44
overtime 36
"paper" sims 83
paperwork 25
parameters 12
parties 73
parts 32
PDR 48
people 8, 71
personnel 13, 25, 26, 33, 67, 68, 72, 77, 84
personnel needs 8
PFR 26
phased implementation 66
physical barriers 8
physical location 74
ping 56
PIO 81
Planetary Data System 62
planning 35
policy 19
post-doctorals 13,83
postponement 50
power 9
pre-launch 8, 12 ,36,55
presentations 25
prior missions 46
priorities 11,50
prioritization 63

problem 14
procedures 14,38
processes 48
product assurance 35
productivity 68
profile activity 57
Project Data Management Plan 85
project manager 20
propellant 45
propulsion 18, 44
protoflight 7, 37
protoflight components 19
prototype 33,61
Public Information Office 81
pyramid structure 86
pyro switching unit 21
pyrotechnic 44
quality 12
quality assurance 7, 15, 46
quality control 87
quick-response 58
radar 16, 20, 22, 34, 50, 79
Radar Engineering Subsystem 64
Radar System Engineering Team 64
radio 17, 40
radio frequency subsystem 10
reaction wheel 33
real-time 11, 39
reference state 38
registers 29
relational database 76
release 84
remote location 71
remote site 56
repair 26
repetitive 11, 73
replans 35
reports 32
requests 87
requirements 15, 31, 51, 62, 64
reset 31
resolution 19
resources 8, 22, 35

respect 23
responsibility 8
review 14, 22, 27, 51, 68
reviews 12, 29, 32, 46
RF 40
risk 9, 32, 38, 51
risk reduction 9
RMSS 61
Rocket Engine Modules 19, 23, 24, 43
ROM safing 10
runaway program execution 9, 29
runout cost 12
safing 28
SAR 19
SAR Data Processing 74
savings 38
schedule 10, 14, 23, 32, 35, 36, 48, 49, 63, 64, 85
schedule history 14
schedule tracking 14
science 4, 8, 11, 12, 13, 52, 57, 71
science analysis 8
science briefings 8
science data 74, 84
science data processing 80
science inputs 83
science investigators 84, 86
science return 5, 80
science support 84
science workstations 87
science-deliverable 85
scoop-proof 45
script 38
SEFCHECK 60
seminars 13, 73, 86
sequence 9, 59
sequence design 7
sequence generation 56
sequences 57
sequencing 53
sequencing software 11
SFDU 62
SFOC 9, 42, 52, 61, 62, 63
SFOC workstation 77

ship and shoot 7, 36
shunt regulator 21
Shuttle 46, 47
signatories 69
simplification 7, 16
sims 83
simulate 12
simulation 59
simulations 83
simulator 9, 77
single point failure 12, 32
SIR 46
slips 14
soft ground 21
software 7, 8, 9, 11, 13, 15, 29, 30, 31, 35, 49, 52, 53, 60, 61, 64, 65, 66, 67, 69, 73, 78
Software Management and Development Plan 65
software metrics 14
software requirements 67
solar cells 18
solar panels 18
solar thermal vacuum testing 7
solid rocket motor 9, 76
spacecraft 6, 13, 16, 17, 25, 26, 27, 31, 37, 42, 45, 48, 59, 71
spacecraft analysts 7
spacecraft assembly 9
spacecraft configuration script 7
spacecraft development 7, 8
Spacecraft Engineering Subsystem 69
Spacecraft Team 72
spacecraft testing 8
spares 26
specifications 31
spiral-wrap 18, 39
staff 86
staffing 73
standardization 30, 53
standards 14, 62
star scanner 9, 17, 23, 29
starcal 42
startup errors 73
static loads 41
status 71

status reports 8, 72
status review 14
structural static loads tests 7
structure 66
subcontractor 11, 18, 31
subsystem 12, 13, 18, 21, 27, 40, 41, 43, 51, 68, 79
subsystem requirements 10
subsystems 10, 32, 35, 36, 40, 49
success 5, 80
SVL 42, 77
system 28, 42, 87
system design team 10
system engineering 20, 33, 52
system test 7, 9, 11 35, 45
system-level 10
systems 9, 24
systems engineer 9
systems engineering 10, 13, 21, 27, 33
Systems Verification Lab 10, 39, 74
tabletop walkthroughs 12, 83
tape recorder 17, 18
team 13, 35, 49
teamwork 8
technical contract monitoring 23
technical reports 7
technology 14, 19, 70
technology development 19
teleconferences 8
teleconferencing 13, 72
telemetry 9, 18, 33, 34, 39, 76
telemetry processing system 42
test 13, 31, 35, 36, 39, 41, 46, 56, 62, 63, 79
test bed 39
test bed simulators 10
test products 65
test requirements 10, 37
test software 7
testing 33, 65
thermal 33, 60
thermal cycling 10
thermal environment 11
thermal surfaces 34
thermal vacuum 42, 43

traceability 52
tracking 46, 55
training 8, 54, 77, 78
transmitter 10
transponder 10
troubleshooting 37, 77
tweaking 56
uplink 11, 15, 83
validators 87
value 4
verification 35, 38, 42
vertical structure 87
Viking 32
VLBI 55
voice 13
voice network 72
VOIR 16, 25, 51
walkthroughs 12, 27, 54, 68
warm boot 31
wasted time 76
wiring 33
work areas 13
work unit meetings 8
workstation 7, 70, 87
worst-case analysis 32
zero command errors 74