N93-24693

REPORT OF THE SEASAT FAILURE REVIEW BOARD

158585

P-15

by the NASA Investigation Board

The Seasat spacecraft failed on October 9, 1978, after satisfactory operation in orbit for 105 days, as a result of a loss of electrical power in the Agena bus that was used as a part of the spacecraft. The loss of power was caused by a massive and progressive short in one of the slip ring assemblies that was used to connect the rotating solar arrays into the power subsystem. The most likely cause of this short was the initiation of an arc between adjacent slip ring brush assemblies. The triggering mechanism of this arc could have been either a wire-to-brush assembly contact, a brush-to-brush contact, or a momentary short caused by a contaminant that bridged internal components of opposite electrical polarity.

The slip ring assembly, as used in the Seasat spacecraft, was connected into the power subsystem in such a way that most of the adjacent brush assemblies were of opposite electrical polarity. This wiring arrangement, together with the congested nature of the design itself, made the Seasat slip ring assembly a unique, first-of-a-kind component that was particularly prone to shorting.

The possibility of slip ring failures resulting from placing opposite electrical polarities on adjacent brush assemblies was known at least as early as the summer of 1977 to other projects within the contractor's organization. Furthermore, failures of slip ring assemblies due to shorting between brushes had been experienced by the prime contractor on the slip ring assemblies used by other programs. That the Seasat organization was not fully aware of these potential failure modes was due to a breakdown in communication within the contractor's organization.

In addition to this small, though fatal, breakdown in communications, the failure to give the slip ring assembly the attention it deserved was due, in large part, to an underlying program policy and a pervasive view that Seasat's Agena bus was a standard, well-proven piece of equipment that had been used on other programs. In actuality, however, three major subsystems—the electrical power subsystem, the attitude control subsystem, and the data subsystem—were substantially modified for use on Seasat's Agena bus. So firmly rooted was this principle of using a "standard Agena bus" that, even after the engineering staffs of both the government and the contractor were well aware of the final uniqueness of their bus, the words, and the associated way of doing business, persisted to the end.

The point of view that the Seasat bus was flight proven, standard equipment proved to have far-reaching consequences. It became program policy to minimize testing and documentation, to qualify components by similarity wherever possible, and to minimize the penetration into the Agena bus by the government. It led to a concentration by project management of the sensors, sensor integration, and the data management system to the near exclusion of the bus subsystems. Important component failures were not reported to project management, a test was waived without proper approval, and compliance with specifications was weak. The component that failed—the slip ring assembly—was never mentioned in the briefing charts for either the Consent to Ship meeting or the Critical Design Review.

The Failure Modes, Effects and Criticality Analysis that was conducted for the electrical power subsystem did not consider shorts as a failure mode and thus did not reveal the presence of single point failure modes in the system or provide a basis for the development of a full complement of safing command sequences that could be used by the flight controllers in responding to

PRECEDING PAGE BLANK NOT FILMED

200 INTENTIONALLY BLANK

anomalies in the power subsystem. A lack of clarity and rigor in the operating requirements and constraints documents for the power subsystem of the bus, together with this lack of safing command sequences, prevented the flight controllers from having all the tools they needed to do their job. The flight controller for the power subsystem was also new to his job at the time of the failure and thus was not sufficiently knowledgeable of the system he was controlling. While no action of the flight controllers contributed to the failure, they did fail to follow the prescribed procedures in response to the information available to them at the time of the failure.

The advantages of using standard, well proven equipment in terms of both cost and mission success are well recognized. But the experience of Seasat illustrates the risks that are associated with the use of equipment that is classified as "standard" or "flight proven." The uncritical acceptance of such classifications by the Seasat engineering staff submerged important differences in both design and application from previously used equipment. It is therefore important that thorough planning be conducted at the start of a project to fully evaluate the heritage of previously used equipment and to establish project plans and procedures that enable the system to be selectively penetrated.

THE SEASAT MISSION AND ITS SPACECRAFT

The Seasat Project was a proof-of-concept mission whose objectives included demonstration of techniques for global monitoring of oceanographic and surface meteorological phenomena and features, provision of oceanographic data for both application and scientific areas, and the determination of key features of an operational ocean dynamics monitoring system.

To fulfill these objectives, the Seasat sensor complement comprised a radar altimeter (ALT), a synthetic aperture radar (SAR), a Seasat-A scatterometer system (SASS), a scanning multichannel microwave radiometer (SMMR), and a visual and infrared radiometer (VIRR). All of these sensors except the SAR operated continuously; telemetry from them, as well as from all engineering subsystems, was sent in real-time when over a ground station and recorded on a tape recorder for later transmission to provide data for a full orbit. SAR data had to be transmitted in real-time, without the use of the onboard recorder, to specially equipped stations because of its high data rate. The normal duty cycle for the SAR was four percent.

The five sensors were integrated into a sensor module that provided mounting, thermal control, power conditioning, telemetry, and command support to the instruments. The second major element of the spacecraft was an Agena bus which provided attitude control, electrical power, telemetry and command functions to the sensor module. In addition to these on-orbit functions, the Agena bus also provided injection stage propulsion and guidance to orbit. The spacecraft was three-axis stabilized with all sensors Earth pointing and is shown in its on-orbit configuration in Figure 1. To provide near global coverage, the spacecraft was injected into a 790 kilometer, near circular orbit with an inclination of 108 degrees and a period of approximately 101 minutes. Design lifetime was one year on orbit, with expendables provided for a three-year life.

The sensors were provided by various NASA Centers. The sensor module, the Agena bus and the integration of the sensors, sensor module and Agena bus into a spacecraft was provided by the Lockheed Missles and Space Company under contract to the Jet Propulsion Laboratory (JPL).

Responsibility for Seasat project management, mission planning and direction, mission operations and experiment data processing resided at JPL. The Goddard Space Flight Center (GSFC) provided network support and spacecraft orbit and attitude determinations; use was therefore made of the existing Spaceflight Tracking and Data Network, the NASA Communications (NASCOM) network, and the Project Operations Control Center that are operated by GSFC.

To place this failure review in a proper perspective, it is noted that the Seasat spacecraft operated in orbit in a generally satisfactory maneuver for over three months and provided a large amount of scientific data. The sensors represented a significant advance in technology and their integration into the sensor module, a large engineering challenge. In addition, Seasat also required the creation of significantly enlarged capabilities in the acquisition and processing of flight data. That the important and significant technical and engineering advancements were achieved is a tribute to the skill and dedication of all who were associated with this program.

The Seasat spacecraft was successfully launched on June 26, 1978, and thus operated for 105 days until the failure occurred on October 9, 1978. During this time in orbit, the spacecraft operation was generally satisfactory with considerable data being obtained from all of the sensors. Three significant anomalies were experienced during the life of Seasat in orbit, one involving sun interference in the attitude control system scan wheels, one caused by a sticking thermostat in a sensor heater circuit, and one in which the spacecraft suffered an abnormally low bus voltage for several orbits. Because of a possible relationship of these latter two anomalies with the failure of October 9, 1978, they were specifically investigated by the Board.

PROGRAM HISTORY AND MANAGEMENT

The Seasat program was conceived and initiated in a period of transition in the philosophy of management of NASA programs following the Apollo program. Apollo, and to varying degrees other NASA flight programs, were characterized by extensive test programs, large formal documentation systems, and comprehensive and frequent technical and management reviews. A large in-house staff was required in order to implement this approach. The high cost of conducting space programs in this mode severely constrained the future uses of space. During the final phases of the Apollo program, NASA management accordingly instituted a policy aimed at reducing the cost space missions. This policy was aggressively pursued by the highest levels of management.

A Low Cost Systems Office was established in Headquarters to oversee a standardization program and to encourage the use of existing hardware. This program included the development of standard components as well as a multimission spacecraft.

A major emphasis was placed on shifting work from in-house to out-of-house in consideration of reducing the NASA manpower base. Design-to-cost techniques and cost benefits of heritage through the use of hardware and software developed for other programs were subjects to be addressed at each step in the approval cycle.

The basic philosophy of the Seasat program was thus established in an environment in which management emphasis was shifting from one of demonstrating a national capability to operate reliably in space to one of reducing the cost of utilizing space. Design-to-cost was a fundamental tenet of the Seasat project definition. A cost estimate of $58.2 million was established as a target cost at the end of the feasibility study phase in mid-1973 and was imposed as a design-to-cost ceiling in December 1973 by NASA management. Any overruns were to be offset by descoping the mission content.

In attempting to define a program which would both satisfy the user community and live within the ceiling cost, the concept of making maximum use of proven existing hardware and software was adopted early in the program planning phase. This in turn provided for a reduction in design and development effort and in the size of the in-house staff needed to monitor the activity.

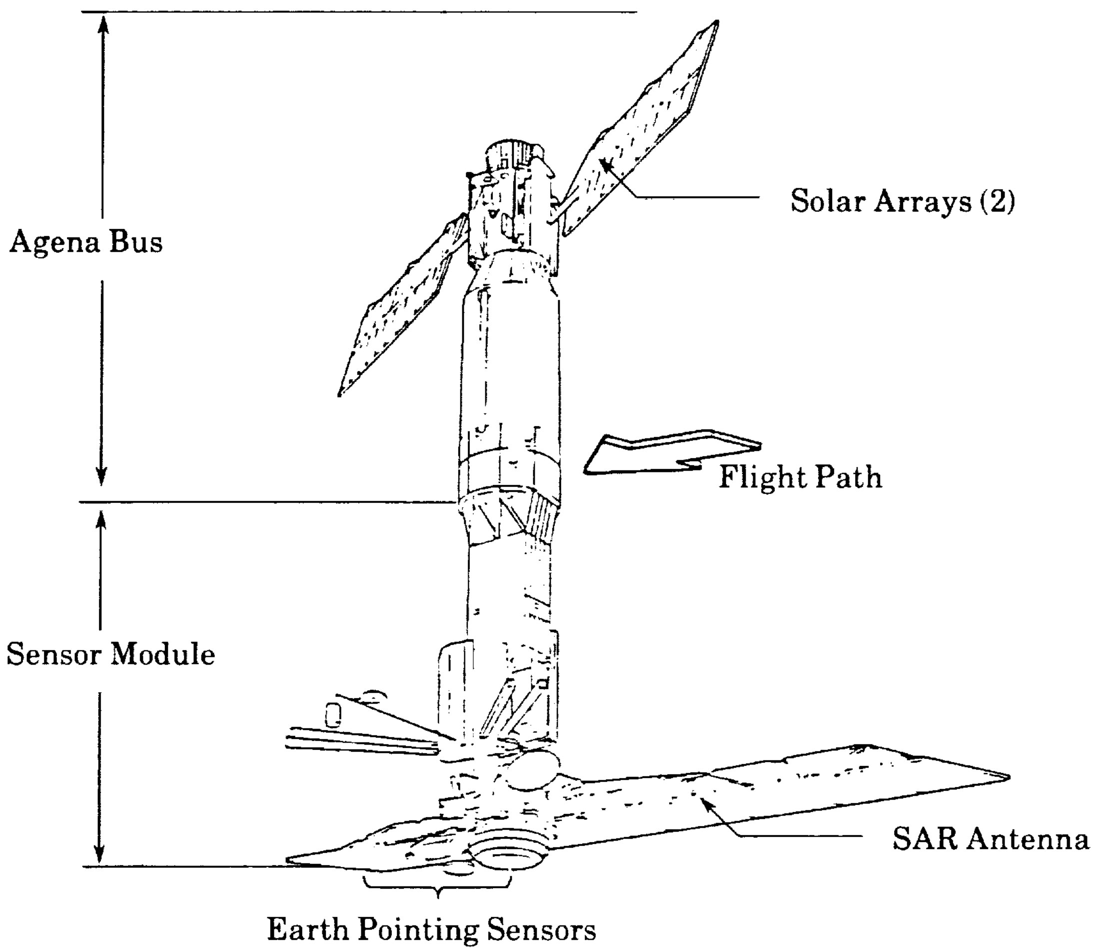

Figure 1 On-Orbit Configuration of the Seasat Spacecraft

These were key elements of the management philosophy which influenced the structure and conduct of the program.

PROGRAM PLANNING

Feasibility Studies (Phase A) - Feasibility for the Seasat mission was established in '73 through three studies conducted by the JPL, GSFC, and the Applied Physics Laboratory of the Johns Hopkins University. These studies were aimed at meeting the set of user requirements generated at a series of meetings held in the first half of 1973 among NASA and representatives of the governmental, commercial, and institutional communities of users of ocean dynamics data. With the user requirements as a basis, the feasibility studies examined the Seasat mission from an overall systems viewpoint, including a review of instrumentation and possible spacecraft (bus) approaches to accommodate the instrumentation.

Subsequent to the submission of the Phase A studies in July 1973, a joint NASA/User Study Task Team was formed to review the Phase A studies, integrate the results, and provide technical and programmatic guidance for more in-depth Definition Phase studies.

As a result of this review, the Task Team recommended a Baseline Mission which included a complement of the five sensor types that actually ended up flying on Seasat.

Based upon cost estimates prepared by the Phase A study participants, the Task Team recommended a target cost of $58.2 million for the Baseline Mission. This included the cost of the spacecraft bus and instruments, the launch vehicles, and tracking and data acquisition. An Alternate Payload Mission of reduced capability, excluding the synthetic aperture radar, was also recommended for further study with a target cost of $43.2 million.

There was some discussion in the Seasat Study Study Task Team Report (October 1973) of the use of an existing bus to minimize cost. The idea, however, was addressed with some skepticism. While it was believed that the use of subsystems with a high degree of inheritance from existing programs was desirable and possible, it was not clear at that time that an existing bus could be adapted economically.

Definition Studies and Preliminary Design (Phase B) - Definition Phase Studies of the Baseline and Alternate Payload Missions recommended by the Seasat Study Task Team were conducted from November 1973 to the summer of 1974. The Wallops Flight Center managed the Definition Phase Study of the Baseline Mission which was conducted by the Applied Physics Laboratory. The JPL, assisted by various aerospace companies familiar with Earth satellite design, conducted the Definition Phase Study of the Alternate Mission.

In December 1973, NASA management adopted the $58.2 million figure recommended by the Task Team as a *not to exceed ceiling* for the Seasat Baseline Mission. The efforts of the Definition Phase Study participants were accordingly intensified to develop the most economical satellite system possible that would best suit the user requirements within the cost ceiling.

GSFC declined to participate in the Definition Phase activity as they had serious doubts as to their ability to structure a full Baseline Mission within the design-to-cost ceiling.

With the stimulus of the design-to-cost ceiling, and management emphasis on the maximum use of existing subsystem hardware, the JPL Definition Phase Group proposed the of idea building a spacecraft system comprising two major elements: a sensor module designed specifically for Seasat, and a spacecraft bus based on an existing, flight proven bus devloped for other Air Force or NASA programs. The JPL viewed the results of the Phase A studies as indicating that the requirements of the sensors could be satisfied by standard support subsystems for attitude control, power, structures, thermal control, etc. On the other hand, the area of greatest uncertainty was seen to be the definition of the sensor's operating capabilities, data requirements and sensor system integration. It was therefore proposed that if a suitable spacecraft bus were available, the design and development effort could be concentrated on the sensors and their integration with a sensor module that could then be mated to the bus via a mechanical/electrical interface.

The JPL entered into four $15,000 study contracts with aerospace companies (Boeing, General Electric, Lockheed, and TRW) that had existing spacecraft designs with capabilities in the range of Seasat requirements to evaluate the concepts that: (1) there are existing buses that could be used, without modification, to supply the necessary support functions for the sensor payload, and (2) new design functions could be incorporated in a separate module along with the sensors and thereby reduce the systems development task to a *sensor system* development task. The studies were conducted from November 15, 1973 to March 30, 1974. The sensors were described to the study contractors as they were developed on December 15, 1973, with updates as appropriate until the end of these studies.

It was concluded as a result of these studies that basic sensor support requirements could be satisfied by the existing spacecraft bus designs studied with "no major changes," although "minor modifications" were acknowledged to be required. It was contemplated, for example, that minor modifications would be required of the attitude control, power, and temperature control subsystems. Telemetry, tracking and command subsystems were reported to be off-the-shelf designs, but required significant modification. It should be noted that the contractor bus studies were concerned almost solely with mission performance requirements. The reports did not sufficiently define the subsystem design or component selections to provide a basis for an adequate penetration of heritage. The JPL Definition Phase Final Report nevertheless concluded that the existing bus approach had significant cost, schedule and risk advantages, and permitted a concentration of development efforts on the sensor system.

Midterm reports in May 1974 of the JPL and the Wallops Flight Center and Applied Physics Laboratory Definition Phase study groups demonstrated that neither the Baseline nor Alternate Payload Mission was achievable within the $58.2 million ceiling. The Wallops Flight Center and Applied Physics Laboratory's estimate for the Baseline Mission, which included an in-house designed spacecraft, was $85.2 million. At this point in time the Wallops Flight Center and the Applied Physics Laboratory adopted the sensor module/existing bus concept that JPL was pursuing. JPL's midterm estimate for the Alternate Payload Mission using the existing bus concept was $65.9 million.

The JPL and the Wallops Flight Center and Applied Physics Laboratory searched for ways to descope the project in order to stay within the cost ceiling. Each group performed a number of iterations wherein sensor performance and sensor combinations were varied in order to decrease the cost and yet meet the basic user requirements.

A final presentation of the JPL and Wallops Flight Center and Applied Physics Laboratory's Definition Phase studies to NASA Headquarters management in August 1974 resulted in a reduced baseline payload at the $58.2 million ceiling which eliminated the microwave radiometer and combined the altimeter and scatterometer into a single instrument, but which retained the synthetic aperture radar, as well as the visual and infrared radiometer.

SPACECRAFT REQUIREMENTS AND DOCUMENTATION

The two primary contractual documents on Seasat were the Satellite Vehicle Specification (Part I and Part II) and the Satellite Vehicle System Test Plan. There were 13 other documents which required JPL approval, but these were primarily implementation and operations type plans; i.e., Data Management Plan, Quality Assurance Plan, etc. One of these plans, the Reliability Assurance Plan, is relevant to this chapter and will be discussed herein.

Part I of the Satellite Vehicle Specification established the performance, design, development, and qualification requirements for the Seasat mission. Part II of the specification established the product configuration and system test acceptance requirements. This specification is similar to a typical Part I, Part II Contract End Item specification used for most NASA programs.

The Satellite Vehicle Systems Test Plan established the test program for assembling, testing, monitoring and operating the Seasat spacecraft from manufacturing through launch. The Satellite Vehicle Systems included all Lockheed and government furnished hardware installed in the Agena bus assembly and the sensor module. The test plan was the controlling test document and subordinate only to the Satellite Vehicle Specification. An evaluation was made regarding this flow of requirements and the interrelationships of Lockheed and JPL relative to control and the visibility of requirements.

Compliance with Requirements – During the Board's review, it was determined that a significant test required by the JPL approved test plan was not conducted. The Satellite Vehicle Test Plan required electronic assemblies to be subjected to eight cycles in thermal environment of which, as a minimum, two cycles should be in a vacuum chamber (acceptance test). The Slip Ring Assembly Component Specification, however, did not require a thermal vacuum test. This noncompliance was not recognized by JPL or Lockheed systems engineering until the present failure investigation was begun. Discussions with Lockheed and JPL personnel revealed that there was not a closed loop system to assure compliance with contractual requirements identified in the test plan.

The fact that a component specification that violated a contractual requirement could be issued is indicative of a lack of checks and balances in the system. Another indication of this lack surfaced in reviewing the qualification requirements. In at least two cases, to be discussed below, qualification requirements noncompliance was not documented. In fact, in the areas where the Board performed an in-depth evaluation, inconsistencies in requirements were noted in many cases. Most inconsistencies were minor; however, the impression left was that both compliance with requirements by Lockheed and the check and balance system at Lockheed and JPL were deficient.

Engineering Memoranda – Environmental derivations, test criteria and detailed test requirements were documented in engineering memoranda (EMs). Lockheed stated that EMs were used to allow early generation of requirements while the spacecraft design was being finalized. A considerable number of EMs were developed during the course of the Seasat program, and it accordingly became very difficult to establish a documentation trail as to how test requirements were established, modified, and satisfied. In fact, two particular incidents were uncovered during detailed evaluation into the qualification status of the electrical power subsystem components that point out the weakness of the EM system.

In one case, the Seasat environmental requirements specified a five minute per axis random vibration level but several components were qualified by similarity to a program that required only a three minute per axis vibration. This five minute per axis requirement was also specified in Part I of the Satellite Vehicle Specification. There was no documented evidence that this noncompliance was acceptable. In the second incident, pyro shock levels for Seasat were not enveloped by the program to which the Seasat slip ring assemblies were "qualified by similarity." While an EM stated that the slip ring assemblies are "not highly sensitive to pyro shock," there was no documentation or analysis to support the stated conclusion.

Because Seasat was a one-of-a-kind vehicle, Lockheed did not summarize the requirements contained in the various EMs into a single baseline document. A baseline document, with change control, would have been a systematic approach to assuring requirements were satisfied and would have provided a feedback mechanism to all parties. The large number of EMs produced in the Seasat program made it very difficult for Lockheed to use the EMs to manage the program and to assure continuity in requirements, as exemplified above, and equally difficult for JPL to effectively penetrate the system.

The Failure Modes, Effects and Criticality Analysis (FMECA) – The FMECA prepared for Seasat utilized the Fault Tree Analysis Technique. In effect, this was a method for studying the factors that could cause an undesired event to occur and inputting these factors into a computer model to which probability data could be applied to determine the most critical and probable sequence of events that could produce the undesirable event.

The Reliability Assurance Program Plan required that a FMECA be performed at the system level. Further evaluation revealed that "critical/new equipment" would also be subjected to an FMECA. Out of the 74 critical items identified on Seasat, only three were judged to require component level FMECAs. These were the command timing unit (CTU), the telemetry sensor unit (TSU) and the synthetic aperture radar (SAR) antenna (supplier performed).

The FMECA for the electrical power subsystem stated that there were "no single point failures" and listed a number of redundancies, including main bus power supply channels, batteries, charge controllers, and others. Electrical shorts were, however, *not* included as possible failure modes; almost all of the effort was directed toward consideration of failure modes that would result in loss of solar array power, and the only slip ring assembly failure mode considered was "slip ring contact failure." The lack of consideration of electrical shorts in effect prevented the FMECA from serving as a tool for directing attention to those portions of the system where electrical shorts could occur and led to the erroneous conclusions that there were no single point failure modes in the electrical power subsystem.

Component Specifications – Component specifications were used on Seasat to define the design, performance, acceptance, and qualification requirements of the major hardware items and subassemblies. Because the program intent was to utilize as much off-the-shelf hardware as possible, many existing specifications were redlined and updated for the Seasat Agena bus. These redlined specifications were then converted into component specifications by the responsible equipment engineers. After April 1976, a program directive established that all component specifications on Seasat required the signature approval of reliability engineering, of space technology, and of the chief systems engineer in addition to the responsible equipment engineer and the program engineer. Two specifications were released prior to April 1976 and never received the full complement of signature approvals. These two specifications were for the Slip Ring Assemblies and the Solar Array Drive Motors. Had the other three engineering organizations reviewed the specifications, quite possibly the Slip Ring Assembly thermal vacuum test deletion may have been prevented and inconsistencies in the qualification requirements may have been avoided. The component specifications were not reviewed and approved by JPL.

Qualification for Flight – The Seasat program used the classical methods of qualifying hardware for flight. These were:

a) Qualification by test to demonstrate the capability of an item to meet specification requirements.
b) Qualification by design similarity whereby an unqualified item is compared with an item qualified by test to determine whether the requirements for both items and their configurations are sufficiently similar to justify not testing the unqualified item.
c) Qualification by engineering analysis, independently or in conjunction with test and/or similarity, to meet a specific qualification in the specifications. The use of engineering analysis alone could not be used to satisfy all qualification requirements.

In September 1976, the Lockheed Seasat project issued a directive creating an Equipment Qualification Review Board for the purpose of reviewing and approving all qualification and design similarity certificates. The primary membership of the board included the program engineering managers, the chief systems engineer, the program reliability engineer, the quality assurance manager, and the applicable space technology manager. This Board met every two weeks to review the status of the qualification program and to determine what additional tasks were required to qualify a given item. Status reports were issued by program reliability engineering which tracked the qualification progress and documented open items.

The qualification cycle concluded with a meeting to review all test data, design similarity statements, engineering analyses, and individual component pedigree packages. Individual Certificates of Qualification were issued stating that the specific component had been qualified to the intended environment and was acceptable for flight. A JPL engineering representative attended these qualification review meetings but was not required to approve the qualification certificate. A JPL reliability representative attended approximately 25 percent of the review meetings.

Review of Build Paper – An evaluation of the Seasat "build" paper was made with primary attention focused on the electrical power subsystem. The review encompassed the electrical harness fabrication and installation, the "pedigree packages" on electrical components and assemblies, nonconformance reports on anomalies encountered in assembly and test, vehicle log books, and the vehicle acceptance summary.

Because the Board's failure analysis eventually identified the slip ring assembly as the component responsible for the Seasat failure, the detailed build paper associated with only this component will be discussed in the next section. However, some brief observations are presented below that deal with other findings made during the course of the investigation.

The nonconformance reports are used by Lockheed to document nonconforming conditions and resultant dispositions and correction actions. In general, the nonconformance report system at Lockheed was found to be acceptable. At the Board's request, Lockheed reviewed, cataloged, and summarized all electrical power subsystem nonconformance reports and made a conscious decision as to the possible effect of the anomaly in contributing to the Seasat failure. None of the nonconformances were judged to be contributory to the failure.

Evaluation of the spacecraft build paper of the electrical power subsystem indicated that the Air Force Plant Representative Office involvement, operating under delegation from JPL, was shallow. Inspection coverage was concentrated at the system level with few in-process mandatory inspection points.

Early negotiations surfaced the fact that the Air Force Plant Representative Office could provide neither the number of personnel nor the required skill levels to perform electronic inspections. As a result of these negotiations, JPL elected to send three JPL inspectors on extended temporary duty to perform 100 percent of the solder joint inspections and electronic component acceptance testing. While it cannot be stated that a more in-depth involvement by the government would have prevented the failure, it is the opinion of the Board that the depth of penetration was inappropriate and a more selective penetration would have been in order rather than a nearly total reliance on system level audits and shakedown inspections for the bus assembly operations.

SLIP RING HERITAGE

Consistent with the basic philosophy of the Seasat program to use, to the maximum extent possible, standard flight-proven equipment, the solar array drive motors and slip ring assemblies for Seasat were adapted from another Lockheed program. At the time of initial contract negotiations, this other Lockheed program had just developed a slip ring assembly and was in the process of performing qualification testing. This slip ring was also being considered for still other Lockheed programs and it was anticipated that the assembly would be a qualified and flight-proven design by the time Seasat was flown. As it turns out, however, the program for which the design was originally developed was canceled after completion of slip ring qualification but prior to flight; however, one other Lockheed program did fly a slip ring assembly of this design shortly before Seasat was launched. While the designs of the slip ring assembly for Seasat and this "previously flown" program were identical, the wiring sequence of the individual rings and brushes was different in the two programs. As noted earlier, the Seasat slip rings were wired such that most of the adjacent power brushes were of opposite DC polarity while the other Lockheed program was wired such that the adjacent power brushes had the same polarity. This difference in how the slip ring assemblies were connected into the electrical power subsystem thus became crucial to the heritage of the Seasat slip ring assembly; when the Seasat slip ring assembly became, in its application, connected in a manner that was different from its sole predecessor it became a unique, first of a kind component.

Two significant problems were noted as a result of random vibration testing of the slip ring assemblies used for the other Lockheed flight program. An isolation failure was found after vibration testing in two adjacent brush/ring circuits. The corrective action was to separate the brushes. Also, when the assembly was opened for this operation, a crack was noted in the brush mounting block at a mounting hole. This block was replaced on the failed unit and a "T" strengthener was added to all identical slip ring assemblies, including the Seasat units, to distribute the mounting loads away from the mounting point.

Failure History – Slip ring assemblies of the design flown by Seasat experienced two nonconformances that provide evidence of two separate failure mode possibilities. One of these was the isolation failure noted above on the other Lockheed flight program that was indicative of a possible failure mode due to contact between adjacent brushes of opposite polarity. Another failure mode identified on one of the Seasat assemblies was caused by shorting of a wire to ground due to cold flow of the Teflon insulation in the region where high stresses were imposed on the wire. This incident will be described later.

Considerable evidence exists in published reports that the sliding friction between brushes and rings will generate debris particles that can accumulate and produce electrical noise or, in some cases, short circuits between adjacent rings and brushes. Lockheed experienced a shorting failure in a slip assembly used in ground tests of a control moment gyro prior to June 1977, which was attributed to accumulation of brush-generated debris and subsequent arcing between adjacent power brushes. Discussion with engineering personnel from TRW, Ball Corporation, and Sperry Flight Systems have indicated that other aerospace contractors have experienced similar slip ring shorts in ground tests. As a result of their experience with slip rings, Sperry initiated an experimental study of the possible effects of debris. While the Board recognizes that there are significant differences between the design and application of the Seasat slip ring assembly and these other units, experience illustrates a third possible failure mode due to shorting caused by contaminants or debris within the assembly.

Seasat Slip Ring History – A portion of the build history of components is assembled by Lockheed into pedigree packages. These packages contain component drawings, a component specification including acceptance and qualification test requirements, nonconformance reports, and some vendor documentation including specified testing and plans test records. Component selection for pedigree packages was determined by the Seasat Program Office and the quality assurance organization at Lockheed. The Seasat slip ring assemblies are documented by such pedigree packages. Relevant component history not contained in the slip ring pedigree packages include vendor assembly and test nonconformance reports (including failure reports), assembly test procedures and records (including brush alignments and pressure checks and brush "run-in" procedures), and relevant vendor and customer correspondence.

The timing of the Seasat contract was such that Lockheed was able to acquire two partially assembled slip ring assemblies when another Lockheed program referred to herein as Program A, was canceled. Program A had initially contracted for 10 assemblies and, at the time of termination, had accepted delivery of one qualification unit, one development unit, and two production units leaving six partially assembled units at the vendor. The Seasat program picked up two of these units and Lockheed Program B picked up the additional units. Reference will be made to Program B in other portions of this report relative to test experience and use of Program B qualification testing as a basis for qualifying the Seasat slip rings by similarity.

Program A personnel were informed by Poly-Scientific in late 1973 that the constraints placed upon the length of the assembly were found to be restrictive and that relief of the specifications would enhance reliability. Program A, however, could not relax the specification. Although the Seasat application was not constrained by length, the program desire to use available off-the-shelf hardware precluded the development of a new unit having increased dimensional tolerances between the rings and brush assemblies with possibly enhanced inherent reliability.

Seasat personnel initiated discussions with Poly-Scientific in late 1975 using the Lockheed Program A specification as a baseline. On February 3, 1976, Poly-Scientific submitted its first written quote for two assemblies to be fabricated and tested per the Program A specification. This initial quote was not acceptable to Lockheed, and the responsible equipment engineer and buyer responded on March 5, 1976, with a Seasat redlined version of the Program A specification. It was in this March 5, 1976, specification that the Program A requirement for 10 cycles of thermal vacuum acceptance testing was deleted. This deletion occurred even though: (1) the majority of the Seasat electronic assemblies and electromechanical assemblies were subjected to a thermal vacuum acceptance test; (2) Seasat reliability and systems engineering personnel, and JPL personnel were unaware of this deletion until the present failure investigation; and (3) the thermal vacuum test was contractually required and a waiver of the requirement was never issued.

Upon pursuing the thermal vacuum deletion further, it was determined from interviews with involved personnel that the test was deleted during verbal negotiations between both the responsible equipment engineer and the buyer at Lockheed, and the vendor in order to reduce unit cost of the slip ring assemblies. The responsible Lockheed program engineer approved the deletion but, at that time, there was no requirement to coordinate specifications with the Seasat program reliability engineer or the chief systems engineer. The fact that a waiver was not issued on this and other contract noncompliances is indicative of a weak compliance system between Lockheed and JPL.

On March 25, 1976, Lockheed issued a formal Request for Quote to Poly-Scientific for two Seasat slip ring assemblies built to the March 5, 1976 specification with a requested delivery date of one year. On May 26, 1976, Lockheed authorized contract go ahead for two slip ring assemblies at a unit price of $8,953.50.

Researching the manufacturing history and fabrication and test anomalies at Poly-Scientific resulted in the following:

a) There were four anomalies noted on slip ring unit 1001. Three were minor and appear to have had no real impact on assembly reliability. The fourth anomaly was a Teflon wire short to an adjacent ground lug. The repair action, approved by Lockheed engineering, was to insulate the ground terminal and repot with ES 222-2 cement. The damaged insulation on the wire was not repaired. This discrepancy report was not included in the vendor's data package and consequently this failure was not contained in the Lockheed pedigree package.

b) Slip Ring Unit 1002 (-Y solar array) had the more significant anomalies noted during fabrication and test. These anomalies are summarized as follows:
   1) 9/20/76 - 80 minute run-in of brushes to rings at 100± 10 rpm. Run-in time should have been for 100 to 115 minutes. This discrepancy was missed and not documented.
   2) 9/23/76 - discrepancy No. 146522 - discolored rings noted after above run-in test. Unit had to be completely disassembled, brushes and rings recleaned, unit reassembled and another run-in performed. The exact run-in time was not recorded nor entered into the log book.
   3) 11/12/76 - discrepancy No. 151887 - excessive noise noted caused by moisture pick-up in the brush material. Corrective action was to run the unit in vacuum at 14.4 rpm for 1½ hours. No vacuum cleanup was performed after this 14.4 rpm run-in test. This run time was not entered into the log book.

c) Review of vendor documentation and subsequent teleconferences with Poly-Scientific personnel revealed the following assembly technique and procedures:
   1) The assembly planning documentation specified that the brushes were to be aligned "in center of the rings." This requirement was verified visually by the inspector, but no dimensional checks were made. Proper alignment of the brushes is dependent, therefore, on the inspector's judgment.
   2) Poly-Scientific stated that the tolerances within the slip ring assembly could allow adjacent brushes to touch. It is noted here that an identical slip ring assembly experienced an isolation failure during acceptance testing which was probably caused by adjacent brushes touching. (Program B hardware).

Both Seasat slip ring assemblies were shipped from Poly-Scientific on February 22, 1977. These units were received and accepted at Lockheed on March 11, 1977, where they remained in storage until required for installation on their respective solar array modules.

In approximately July 1977, Lockheed Program B, which utilized identical slip ring assemblies, made a wiring change external to the slip rings that separated the polarity arrangement of adjacent slip rings. By changing connector pin functions, the power applied to individual rings was changed from a configuration in which adjacent rings were of opposite polarity to one having positive contacts on one end of the slip ring assembly and negative contacts on the opposite end. This wiring change significantly reduced the possibility of internal shorts within the slip ring assembly.

The Seasat chief system engineer was contacted by a system engineer from Program B about this change in wiring in August 1977. The explanation given for the wiring change was a concern that the ascent vibration environment could cause adjacent brushes to make contact and thus produce an electrical short because Program B slip rings had power applied during launch. The chief system engineer discussed this change with the Seasat program engineer and they decided not to make a similar wiring change because Seasat did not see the same launch vibration levels and because Seasat slip rings were not planned to be powered during launch. It is noted that in April 1978, a change in launch relay configuration was made which did apply power to the slip ring assemblies. In retrospect, the decision not to change the wiring sequence for Seasat was a crucial one. When the other program changed its wiring and Seasat did not, Seasat became the first program to fly a 52-brush slip ring assembly with adjacent brushes of opposite polarity. Had there been better visibility to the problems experienced with slip rings by both the vendor and by other organizations within Lockheed, the Seasat engineering managers may have been more sensitive to the failure prone nature of this complicated device and to the importance of the electrical polarity of adjacent brushes. Unfortunately, such visibility, which may only have needed to have been slight to have been effective, was lacking.

Slip Ring Assembly serial number 1002 was installed on the -Y solar array module on August 17, 1977. On August 30, 1977, a nonconformance report was written because the mechanic "lost" an undetermined number of shim washers.

Review of the installation drawing revealed that four number 10 washers were required between the solar array mounting structure and the slip ring assembly. The cover of the assembly is made of thin sheet metal and is prone to bow up during installation operations. Because the mounting bolts go through the cover plate into the threaded holes in the slip ring body, the mechanic had to place the round washers over the bolts between the structure and the cover plate. It was during this operation that the mechanic lost the washers. The S/N 1002 slip ring assembly was removed from the solar array module, the cover plate removed and three washers were found. Because some areas were still obscured, an x-ray of the slip ring was taken. No additional washers were located. A nonconformance report was then written against Slip Ring Assembly 1001 and no washers were found by either visual or x-ray inspection. It is interesting to note two things: (1) there were no downstream electrical functional checks after installation of the slip ring assembly which could have detected missing washers in the slip rings, and (2) it was never conclusively determined if all lost washers were found.

The solar array modules, including the slip ring assemblies, were shipped to the launch site in April 1978. The last reported anomaly on the slip rings was high contact resistance on unit 1002 during interface tests performed when the solar array modules were mated to the vehicle. The resistance reading recorded was 2.38 ohms; the specification value was 2.00 ohms maximum. The engineering disposition in the nonconformance report was "use-as-is" because inflight operation would decrease the contact resistance.

SIGNIFICANT FINDINGS

1) The spacecraft failure that occurred on October 9, 1978, was due to a loss of electrical power in the Agena bus as a result of a massive and progressive electrical short within the slip ring assembly of the -Y solar array.
2) The electrical short was most probably initiated by an arc between adjacent components in the slip ring assembly. Possible triggering mechanisms for this arc are momentary shorts caused by wire-to-brush assembly contact, brush-to-brush contact, or by a contaminant.
3) The congested nature of the slip ring design, coupled with a wiring arrangement for connecting the slip rings into the power subsystem that resulted in most of the adjacent brush assemblies being of opposite polarity, made the Seasat slip ring assembly particularly prone to shorting.
4) The combination of design and wiring sequence used for the Seasat slip ring assemblies made these unique, first-of-a-kind components.
5) The possibility of slip ring failures resulting from placing opposite electrical polarities on adjacent brush assemblies was known at least as early as the summer

1977 to other projects within the prime contractor's organization. That the Seasat organization was not fully aware of these potential failure modes was due to a breakdown in communications within the contractor's organization.

6) The failure to recognize the potential failure modes of the slip ring assembly and to give this critical component the attention it deserved was due, in part, to the underlying program policy and pervasive view that it was an existing component of a well-proven and extensively used standard Agena bus. This program policy further led to a concentration by project management on the sensors and sensor module of the spacecraft to the near exclusion of the bus subsystems. In actuality, many of these subsystems, including the power subsystem, contained components that were neither flight proven nor truly qualified by similarity.
7) Lack of proper attention by both Lockheed and JPL Seasat program engineering to the new and unproven components on the Agena bus resulted in several instances of both noncompliance with contractual, qualification and acceptance requirements and failure to document such noncompliances.
8) The Failure Modes, Effects, and Criticality Analysis that was conducted for the electrical power subsystem did not consider shorts as a failure mode and thus did not reveal the presence of single point failure modes in the subsystem nor provide a basis for the development of a full complement of safing command sequences that could be used by the flight controllers in responding to anomalies.
9) The strong desire on the part of all concerned to initiate the project as soon as possible resulted in inadequate time for an effective Phase B study. As a result, the project office did not have the opportunity to plan the activity thoughtfully and establish the preliminary designs, component evaluations, test plans, and other Phase B project plans before becoming engaged in the actual spacecraft development.

Although unrelated to the failure of the Seasat, certain deficiencies in flight control procedures were present that are worthy of note as a lesson for the future. The flight controllers were not provided with an adequate set of safing command sequences to use in response to anomalies, were not sufficiently familiar with the system they were controlling, received insufficient anomaly training and, during the failure event itself, failed to follow the prescribed procedures in response to the flight data available to them. Compounding these difficulties were the frequent breakdowns of the ground data acquisition and processing system throughout the mission.

It is ironic, and yet typical, of spacecraft failures that the termination of the Seasat flight was caused not by a malfunction of a new or sophisticated device, but by a failure in a very common component of a type that has flown in many spacecraft for many years. It is also ironic, and instructive, that the smallest of events or the slightest of communications could have prevented the failure. Better clarity in an oral communication, a brief memorandum of the right kind at the right time, a failure report coming to the right person, or an alert engineer could have made all the difference.

Basic to the Seasat mission was the concept of using an existing, flight-proven spacecraft bus for the services and housekeeping functions required by the sensors in order to minimize program costs and to permit a concentration of effort on the sensors and their integration into the spacecraft. Thus the use of a "standard Agena bus" as part of the Seasat spacecraft became an enduring tenet of the program. So firmly rooted was this principle in program philosophy that, even after the engineering staffs of both the government and the contractor were well aware of the final uniqueness of their Agena bus, the words, and the associated way of doing business, persisted. They became deceived by their own words.

Consistent with the concept of the "standard Agena bus" was the policy decision to minimize testing and documentation, to qualify components by similarity wherever possible and to minimize the penetration into the Agena bus by the government. As a result, a test was waived without proper approval, important component failures were not reported to project management, compliance with specifications was weak, and flight controllers were inadequately prepared for their task. Significantly, the Seasat slip ring assembly had no applicable flight history at the time of its launch and, in its application to the spacecraft, was a new device.

There can, of course, be no quarrel with the policy of using existing and well proven equipment. The use of such equipment has certainly reduced the costs and contributed to the success of many space missions. But the world of space flight is an unforgiving one and words like "standard," "existing," and "similar to" can be traps for the unwary. The technical risks of using standard equipment can be as high as those present in a new or untried piece of equipment, but the approach, both technical and managerial, must be different. For new equipment, one designs carefully, reviews thoroughly, and tests completely — and that we know how to do. For standard equipment, one should diligently and thoroughly probe the heritage that justifies the classification and identify, component by component and piece by piece, those that are truly standard and those that are not. One should assume that each space vehicle is unique until proven otherwise. Then, for those parts that are standard or well proven, and that are applied in the same way, one can forego design, reviews, testing and extensive documentation. Conversely, components that are different should be treated as new. The policy of limited penetration into Seasat's Agena bus by the government was appropriate, but a limited penetration must be a selective penetration and not a reduced effort everywhere.

This identification of the heritage of previously used equipment, in both design and application, need not require a large staff or a lot of money. But it does take time, both at the start of the project and at the time of the Critical Design Review. And here, responding to strong desires by all concerned to get the project on contract and underway, the Seasat project was denied the advantage of an effective Phase B study. Had there been an effective Phase B study period, preliminary designs would have been completed, component selections better understood, test plans and qualification requirements better established, and possibly, the critical role and inherent complexities of the slip ring assembly might have been more apparent to the Seasat engineering staffs. Whether such a Phase B study period would have precluded the Seasat failure is, of course, uncertain for history does not reveal its alternatives. But such a carefully conducted planning and study period would have minimized the chances for the type of failure that did occur.

The policy of using existing, flight-proven equipment can be both valid and cost effective. But it is the main lesson of Seasat that an uncritical acceptance of such classifications as "standard" can submerge important differences from previously used equipment in both design and in application. It is important, therefore, that thorough planning be conducted at the start of a project to fully evaluate the heritage of such equipment, to identify those that are standard and those that are not, and to establish project plans and procedures that enable the system to be penetrated in a selective manner.