RE-ENGINEERING UEVE TELEMETRY MONITORING OPERATIONS: A MANAGEMENT PERSPECTIVE AND LESSONS LEARNED FROM A SUCCESSFUL REAL-WORLD IMPLEMENTATION

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ABSTRACT

The Extreme Ultraviolet Explorer (EUVE) Science Operations Center at UC Berkeley was recently successful in implementing an automated monitoring system that allowed reduced operations staffing from 24 hours per day to 9 hours per day. The payload safety is monitored exclusively by artificial intelligence (AI) telemetry-processing systems for 16 hours per day. At launch, the EUVE Science Operations Center was staffed and operated as a typical satellite control center, receiving real-time and tape recorder data 24 hours per day. From September 1993 through February 1995, EUVE science operations were redesigned in a phased, low-cost approach. A key factor in the implementation was to utilize existing personnel in new roles through additional training and reorganization. Through- out this period, EUVE guest observers and science data collection were unaffected by the transition in science operations. This paper describes the original and actual implementation plan, staffing phases, and cost savings for this project. We present the lessons learned in the successful transition from three-shift to one-shift operations.

KEY WORDS

Telemetry Monitoring, Mission Operations Management, Artificial Intelligence

INTRODUCTION

EUVE launched on June 7, 1992, with a mission to explore the extreme ultraviolet (EUV) region of the electromagnetic spectrum from approximately 100 to 700 . EUVE operates in a 28.5 degree inclination, low-earth orbit and uses NASA's Tracking and Data Relay Satellite System (TDRSS) for all normal uplink and downlink communications. EUVE is managed and operated jointly by Goddard Space Flight Center (GSFC), Greenbelt, MD and the Center for EUV Astrophysics (CEA) at the University of California, Berkeley. The Flight Operations Team (FOT), staffed by Loral Aerosys at GSFC, controls satellite operations and communications scheduling.

The EUVE Science Operations Center (ESOC) team at CEA is responsible for all payload operations and long term archiving of the complete science data set.

In the fall of 1993, CEA faced the prospect that EUVE might be turned off after its primary mission because of budget cuts. Although cost saving measures were examined and implemented throughout CEA, the project was forced to consider radical, new, low-cost approaches for operating the observatory. A three part strategy was developed which included: (1) converting operations from around-the-clock monitoring to day-shift only monitoring; (2) attempting to reduce the large NASA institutional costs (e.g., TDRSS) of operating EUVE; and (3) operating EUVE as a mission operations testbed to introduce new technology in a systematic and disciplined manner (Malina 1994). The last strategy recognized the need to prototype new technology for reduced cost operations while increasing the value of the mission to NASA as a technology testbed. A concurrent study for Dr. Guenter Reigler of NASA Headquarters Code SZ headed by Dr. Ron Polidan (GSFC Code 681) recommended a transition to one-shift operations for both spacecraft and payload operations to reduce costs on the project.

In order to cut costs to the required level for an extended mission, the Principal Investigator, Dr. Roger F. Malina, was willing to accept an increased level of risk in a slower response time to problems and the potential loss of some science data. Two key factors in accepting this risk were that the primary objectives of the mission had been accomplished and the inherent safety of the EUVE spacecraft and payload had been demonstrated. Both the spacecraft and the instrument contained on-board safing mechanisms that had performed remarkably well. The payload safing mechanisms had been activated over a dozen times with no recovery problems. As of the date of this paper (April 1995), both spacecraft and payload continue to perform very well. Two partial failures in the tape recorders and one redundant transmitter failure occurred in 1994, none of which has prevented or restricted science operations. Over 99% of the science data continues to be returned as originally scheduled. No major failures in any payload component have occurred.

The risk associated with one-shift operations was mitigated by the introduction of artificial intelligence (AI) software into the EUVE Science Operations Center (ESOC) to monitor the health of the payload during the unstaffed shifts. Our strategy was to evaluate the potential of several commercial and government developed systems before making a full commitment to implement one-shift operations. Since we intended to introduce an AI system to replace entire shifts, not augment existing operator functions, the system had to work in a fully automated fashion, integrated with our existing software. Some of the key criteria were compatibility with our existing software environment (UNIX, distributed network), extensibility to add our own functions, and good technical support and documentation. User interface capabilities, while important, were not a strong factor in the selection since the software would act in the absence of people. A more detailed discussion of the criteria and packages evaluated can be found at our world wide web (WWW) internet site, http://www.cea.berkeley.edu. The product that best met our criteria was a commercial product, RTworks, by Talarian Corporation of Sunnyvale, CA.

Dr. Mel Montemerlo from NASA Code X and Dr. Dave Korsmeyer from Ames Research Center (ARC) assisted us in establishing collaborations with the Jet Propulsion Laboratory (JPL) and ARC to utilize their expertise in the development of AI software for mission operations. These centers were instrumental in providing technical and programming assistance, recommending techniques and advising us on effective ways to capture the console operators' knowledge and encode the knowledge into a rule base. Both ARC and JPL provided copies of AI software packages developed at those institutions for our evaluation.

In January 1994, after identifying a suitable AI package for implementation, an internal precommitment review of the proposed transition to one-shift operations was held at CEA for an invited review panel of scientists, engineers, and GSFC personnel. The review placed the transition to one-shift operations within a long term concept for lowcost EUVE operations that included controlled introduction of new technology, more autonomous ground systems hardware, and automated telemetry monitoring. CEA management presented an implementation schedule, cost analysis, payback timetable, and post-transition operations concept as well as planned support roles from CEA departments, such as the Guest Observer Center, software development, hardware systems, engineering, and outside collaborator support from ARC. Payload scientists presented an analysis of the impact on payload health, safety, and science quality of the observations. Based on the recommendation of the panel, the principal investigator (PI) decided to proceed with the implementation.

IMPLEMENTATION

The implementation schedule (Figure 1) was divided into three tracks: software development, operational changes, and personnel reorganization. Software developers were redirected from enhancing existing software to developing the AI software. Only essential software maintenance was performed on existing systems. CEA has two separate networks, a physically secure network (SOCnet) for receiving satellite data from GSFC and the other (SDAFnet) for science and other processing, e-mail, internet connections, etc. New software releases are developed and tested on SDAFnet before being installed on SOCnet. All software releases and system patches are configuration con- trolled through signed-off "engineering change orders." The AI software was

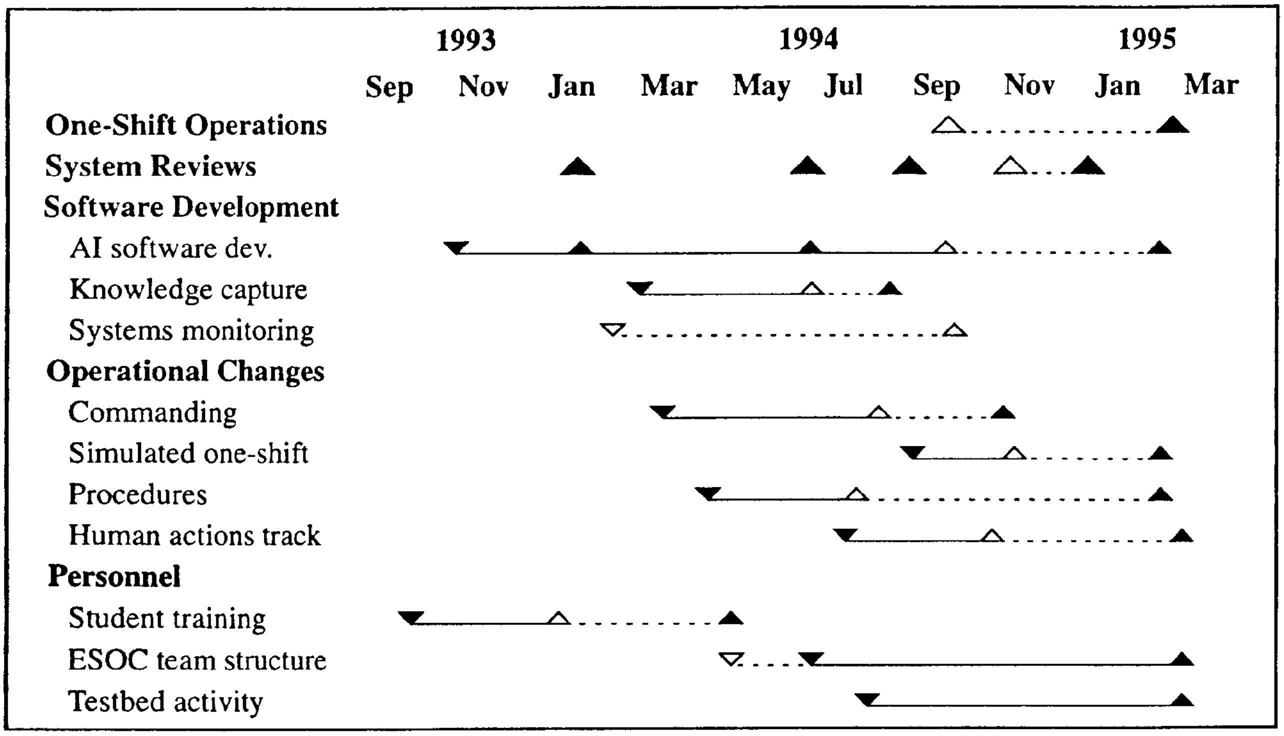

Figure 1.—Implementation Schedule: planned start (▽), actual start (▼), planned finish (△), and actual finish (▲). The final switch to one-shift operations occurred on February 14, 1995.

similarly developed and tested on the SDAFnet first. Each release was tested on three types of data before being released: previous telemetry anomalies, specially prepared data sets to test specific logic rules, and normal data. On the SOCnet a semi-isolated machine that could only receive telemetry was set up to parallel test the AI software in a working operational environment. Operators compared operational anomalies as they occurred with the AI software responses and wrote data discrepancy logs (DDLs) on differences. DDLs were either resolved within 24 hours or converted into an EUVE problem report (EPR). An automated tracking system followed EPRs from assignment and analysis to resolution. Only software successfully tested on the semi-isolated machine was released on the SOCnet for operations.

A systems monitoring task was established to monitor the complete communication path between CEA and GSFC under the assumption that if data were not received we could not monitor the health of the instrument. Because we had difficulty obtaining the resources and expertise for this task, the PI forced a reexamination of our assumptions about network monitoring. The results indicated that the issue was not whether the network was operating, but rather whether the CEA software was active and receiving enough data to detect safety problems. If the network failed, the software would notice it wasn't receiving data. This example of re-examining our assumptions during the course of the implementation illustrates a significant lesson learned.

On an operations shift, many human actions are not formally recognized. In order to eliminate the evening and night shifts, we had to become aware of all activities that occurred on those shifts. We established a metric tracking all human action in the ESOC during the hours from 5 pm to 8 am (Figure 2), including all voice communications with GSFC (August jump in metric). Systematically, we eliminated all actions that required a person's presence in the ESOC over the following months. Tasks that could not be eliminated were shifted to the day shift or automated. Throughout the one-shift transition period, as new software capabilities were introduced, new operational procedures were implemented and tasks were shifted from nighttime to daytime operations. Our work in automating procedures produced innovative techniques for document handling that are applicable to any operations environment (Kronberg 1995).

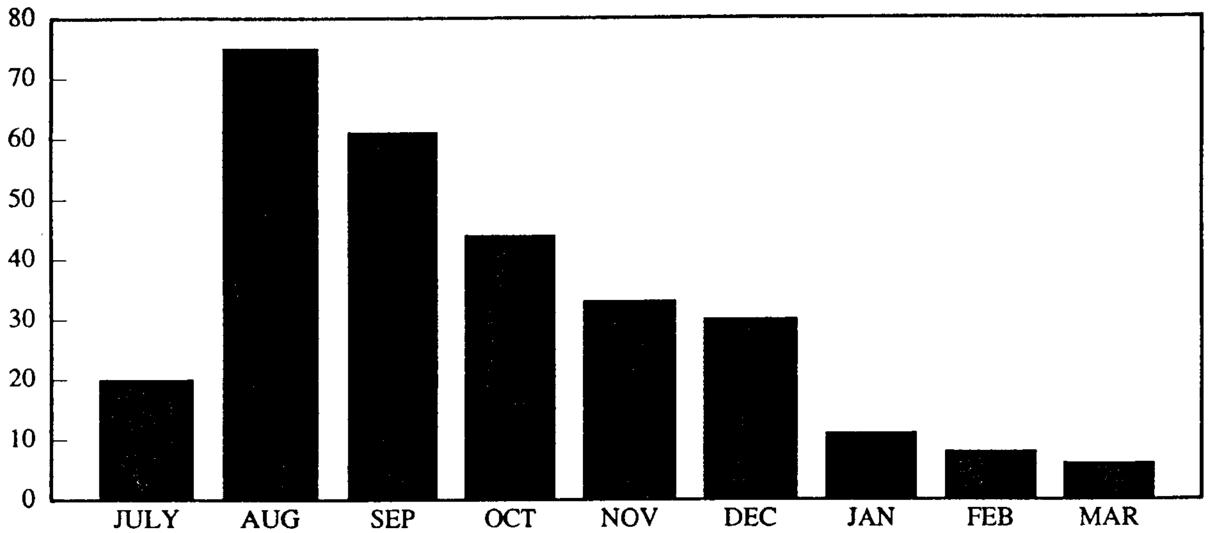

Figure 2.—Human Interaction Metric. The chart tracked all actions requiring a human response between 5 pm and 8\x11am. Examples of human actions are: voice communications or telephone contact with GSFC, pages from the telephone messaging center or the autonomous monitoring software (EWORKS), real-time commanding at night, and ESOC hardware and software problems.

With a one-shift operations scenario, continuity and coordination of problem resolution that occurs with personnel on-shift 24 hours per day is more difficult. To resolve the problem, we established a system of on-call anomaly coordinators for EUVE (ACE) who provide the first response to pages by the autonomous monitoring software. The ACEs are responsible for initial investigation of a problem, coordination with GSFC, initial involvement of appropriate support personnel, and follow-up of the problem to a resolution. We continued our standard problem reporting system where all problems are recorded as DDLs and EPRs. We continued the system of on-call hardware, software, and scientist support, adding the ACEs for prime response and problem coordination.

Under ESOC personnel changes, students were trained to assume a greater role in monitoring the payload health. The student training required more time than originally planned because half the students had just been hired into operations in September 1993 and were not experienced in basic operations. However, the additional training for students was significant in reducing costs by freeing the console operators to participate in the knowledge capture process and to use their knowledge to focus the AI implementation.

Both students and console operators were organized into teams, each of which assumed responsibility for a major function within the one-shift implementation schedule. The team concept emerged as a solution to the problem of directing shift-oriented console personnel to priority-driven, non-console tasks associated with the transition to one shift. When personnel on shift are assigned non-console tasks, these tasks are often interrupted by console priorities and suffer delays when the personnel assigned are off shift. Under the team concept, the whole team was responsible for meeting deadlines, conveying information among members and achieving results. Each team concentrated on separate aspects of the transition: telemetry focused on the Eworks validation, commanding on the changes to pay- load commanding, operations on the changes to procedures, and scheduling on maintaining the current science scheduling activities. As the ESOC progressed into the simulation phase of the transition, the teams began to focus more on non-ESOC activities associated with CEA's innovation technology program, becoming involved in projects on automated heuristic scheduling, advanced payload diagnostic software, and thermal modeling visualization tools. The team approach proved successful in focusing console personnel on one-shift tasks and then refocusing those personnel on tasks beyond console operations.

Our original schedule called for a final software release by September 1994, followed by a two month simulation period. The actual implementation required five additional months, primarily to overcome problems associated with handling poor data quality (Lewis 1995). With the start of the simulation phase in September, resources became less constrained as monitoring operations steadily diminished. Before the transition to one-shift operations was made, a final review was held and GSFC EUVE project approval obtained. The final switch to one-shift operations occurred on February 14, 1995.

RESULTS

Additional costs were incurred when the implementation took five months longer than originally planned. We also needed additional copies of the RTworks software to allow us to operate, test, and develop on two networks simultaneously. However, we originally projected that we would need a controller and student assistant on the console for nine hours per day. The chart in Figure 3 shows the actual reduction in staffing during the transition to one-shift operations. The total ESOC staff graph only includes staff dedicated to operations and does not include the support from software engineers, hardware engineers, and scientists, which did not change during the implementation. We are currently operating with only one person on the console, either a student or a controller, and corresponding with the fewer console positions, fewer management personnel. The goal of one shift operations was to reduce payload monitoring costs by 70% and we have achieved an actual cost saving of 75%. The actual implementation costs were 50% over our original estimate, but the payback period for the transition to one-shift operations will still be only 11 months.

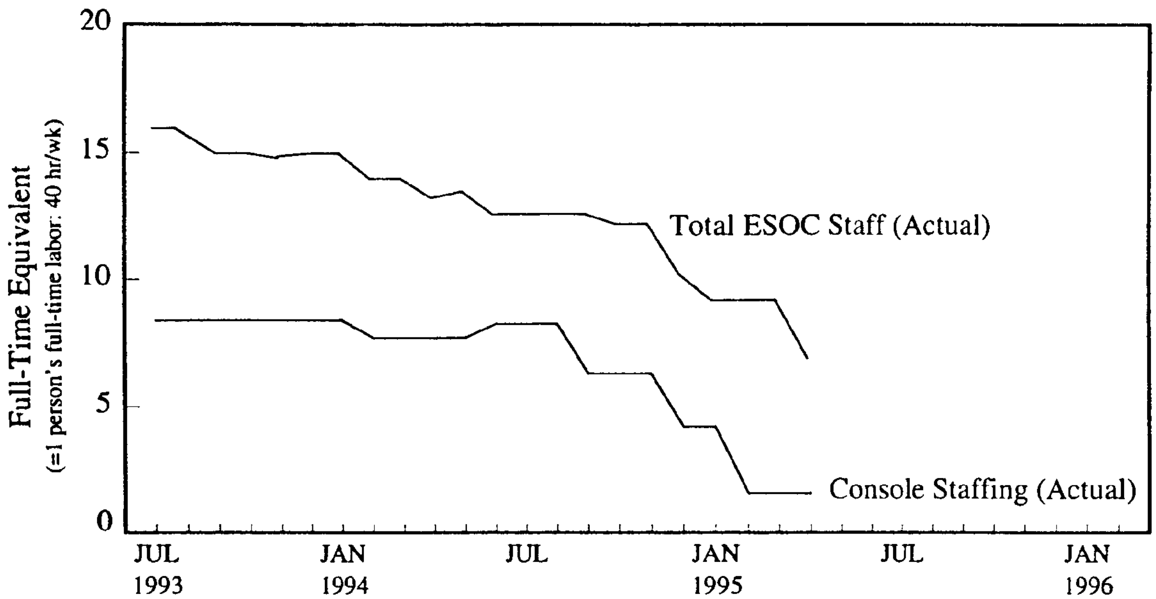

Figure 3.-ESOC Staffing. Both total staffing and console staffing have been reduced significantly since the beginning of the simulation period in September 1994. Throughout the transition period, staffing was reduced through attrition and reassignment to areas outside of operations.

LESSONS LEARNED

Cost and Schedule: Re-examining our assumptions based on risk and response time at each technical decision point provided major cost and schedule savings, particularly in the case of the system monitoring task described earlier. Two correct decisions also affected cost and schedule: enlisting the collaboration of ARC researchers in initially assisting us; and redirecting existing resources for the implementation. The ARC collaboration gave our personnel immediate access to expertise until we gained experience implementing AI software. Redirecting our own resources allowed us to use our own software and operations experience much more effectively and reduced costs. Both costs and schedule were 50% over the initial projections, but the schedule delays (and subsequent costs) were associated with solving software problems associated with handling poor data quality near the end of the implementation. We were unable to obtain quality information on real-time data from GSFC and failed to realize the impact immediately because we tried several solutions to the poor real-time data problem.

Focused AI Implementation: Our goal was cost reduction through personnel reduction and not a "state-of-the-art" AI implementation. AI systems are often constructed around challenging problems associated with problem diagnosis. However, satellite operations expenses relate more to maintaining crews for the day-to-day problem detection process. The required response time determines whether automated diagnosis is cost effective. For EUVE, both the instrument and the spacecraft have on-board safing mechanisms that have been proven very effective in orbit. These safing mechanisms allowed us to relax our required problem response time from minutes to several hours. Considerable effort was put into accurate problem detection and making the AI anomaly detection logic robust. We decided to rely on human experts to diagnose and correct problems.

User Interface: Significant resources are typically expended on the user interface during AI implementation. Only a basic user interface was implemented because of the resources required and the philosophy of replacing human activity, not just augmenting it.

AI Telemetry Monitoring: Rule-based AI systems need a consistent telemetry picture to reason from. Some of the problems we solved were poor data quality, normal on-board transitions temporarily inconsistent in the telemetry, normal science instrument reconfiguration, and benign instrument transients that telemeter non-normal states. Some of these were solved by waiting a known time to achieve a consistent state. Others were solved with a page screening system that records, but does not page, for specific problems. The screening must be very specific or effective monitoring could be compromised.

Terminals at Home: It is technically possible to page people at night and allow them to respond to the problem from their homes. Security considerations for this type of access can also be overcome. The PI made a correct decision not to allow this type of access to our system believing such access would inevitably lead to an elaborate on-line remote response system. We were forced to review our assumptions about paging, limiting pages to those requiring action and eliminating nonessential pages. For the last three months, we have been successfully operating on one-shift operations with no remote access to the system.

Review of Assumptions and Clear Definition of Response Times: Because of the self-imposed time constraints to save costs for the project, we were forced to repeatedly focus on the minimum requirements essential to complete the project. This approach caused us to review and revise our basic assumptions almost continually, usually with good results. One of the most important assumptions to be reviewed was our response time to various situations (e.g., if we normally have only one pass per 90 minute orbit, does our response time need to be less than 90 minutes?). In this analysis, the on-board safing mechanisms, which have proved extremely effective, allowed us to safely extend our response time to several orbits. We repeatedly reexamined our assumptions regarding the response time necessary for payload safety. Another clear example of reviewing assumptions was the reexamination of net- work monitoring as described previously.

Phased Simulations: From the start of the project, we planned a phased implementation approach. While this approach is quite common, the simulations were also phased in very gradual, short stages of six weeks over a period of five months. The simulations allowed time to work out software and procedural bugs and allowed the few external interface changes to become "normal" to all GSFC shifts. The actual transition to one-shift operations was experienced as a minor transition from the previous simulation phase.

Resistance to Change: The transition to one-shift operations involves accepting higher levels of risk, changing job roles and responsibilities, and dealing with new uncertainty. In many cases, we experienced considerable resistance to change when personnel did not fully understand or accept the changes to operations. The PI and the operations manager provided strong leadership in maintaining deadlines and questioning assumptions based on previous or risk-adverse operations methods. Accepting a longer response time and loss of some science data affected nearly all technical decisions in the one-shift transition. The risk and response time assertions were repeated throughout the transition period, not just at the beginning, since they affected software development, hardware systems monitoring, operational procedures, and one-shift simulations.

The Team Approach: Organizing ESOC personnel into teams proved successful in involving console personnel in the transition from the beginning, utilizing their experience to keep the AI implementation focused. Later, teams were instrumental in redirecting personnel away from console operations toward new technology applications. The teams successfully defined group goals important to the transition and then helped define new roles for console personnel.

CONCLUSIONS

At CEA, we have accepted the challenge of re-engineering our science operations, introducing commercial-off-the- shelf (COTS) technology and dramatically reducing our operations costs. In our implementation, we took a very practical, low cost approach driven by a tight timetable. We continually reviewed our basic assumptions to achieve our goals and limited the scope of the AI software to what was necessary. We reorganized our console personnel to help with the implementation and to refocus on non-console tasks as the transition took place. Our results indicate a savings of 75% over the traditional 24 hour per day monitoring schedule. Currently, we are reviewing our daytime operations tasks with the goal of achieving a zero-shift operation. Zero shift means no time-specific tasks, such as pass monitoring, exist that require a person's presence at a console. Off-line tasks, such as trending and analysis, may still be required.

In the future, we plan to integrate our science operations, science data analysis, and data archive functions to create an integrated/intelligent science operation. Under this concept, we plan to maximize the automation for three types of user requests: public archive data, science data processing, and new observations. EUVE users may be scientists submitting peer reviewed proposals, guest investigators seeking to mine the EUVE public archive, amateur astronomers, educators, or the general public seeking access to EUVE data. For most users, we are automating the request and delivery of data sets through an internet WWW interface. Information on CEA technology innovation and educational outreach is available on the CEA WWW site at http://www.cea.berkeley.edu. The EUVE mission has now been extended through the fall of 1997. A "Flight Test Bed-Innovative Mission Operations" (FTB-IMO) program has been established for EUVE whereby up to 25% of the spacecraft time is available for flight testing or testing of new mission operations concepts. The program is managed by Mr. Peter Hughes, GSFC, Code 522.

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