THE HUBBLE SPACE TELESCOPE SERVICING MISSIONS: PAST, PRESENT, AND FUTURE OPERATIONAL CHALLENGES

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ABSTRACT

The Hubble Space Telescope (HST) is a complex spacecraft designed to conduct leading edge scientific observations over a planned fifteen year mission lifetime. It was designed for servicing by the Space Shuttle to upgrade systems, replace failed components, and boost into a higher orbit. There are many operational challenges that must be addressed in preparing for and executing a Servicing Mission (SM) which range from both technical to managerial issues. This paper will be exploring the operational challenges faced by the HST Operations and Ground System Project in supporting the First Servicing Mission (FSM) and future Servicing Missions. We give special emphasis to those areas that helped ensure mission success. These areas include training, testing, and contingency planning.

SERVICING MISSION OVERVIEW

The HST Project, which is responsible for overall management of the HST at Goddard Space Flight Center (GSFC), has two suborganizations: Operations & Ground Systems (O&GS) and Flight Systems & Servicing (FS&S). The O&GS is responsible for on-going spacecraft operations, flight software and ground systems maintenance and development, servicing mission operational preparations and execution, and science operations. Science operations are conducted by the Space Telescope Science Institute (STScI), located in Baltimore, Maryland. FS&S is responsible for the planning and execution of servicing missions, as well as the development of new scientific instruments and replacement hardware.

The HST was originally designed to be serviced by the Space Shuttle Program every 2-1/2 to 3 years. The purpose of servicing is threefold. The first is to install new science instruments to fully utilize and explore the broad range of HST's capabilities. Secondly, servicing restores redundancy to subsystems that have experienced failures. Finally, servicing upgrades HST hardware to ensure its 15 year minimum life and further expand its capabilities. Figure 1 identifies each of the Servicing Missions and defines their associated activities. Note that currently a SM in 2005 is being studied to replace failed components to extend HST's lifetime beyond 15 years.

O&GS has numerous and varied responsibilities for planning and executing SMs. These responsibilities include the integration of new hardware into the operational environment and implementation of ground system and on-board flight software requirements. Other responsibilities include mission planning, extensive contingency planning, mission simulations, and the development and execution of tests that integrate ground system, flight software, databases, and new flight hardware.

SERVICING MISSIONS	PLANNED ACTIVITIES	UNPLANNED ACTIVITIES
SM-1 (Dec. 1993)	• Gyros (2) • Gyro Electronics (2) • Fuses • Solar Arrays • Wide Field/ Planetary Camera-II • Magnetometers • Corrective Optics Space Telescope Axial Replacement • Coprocessor • Solar Array Electronics • Goddard High Resolution Spectrometer Repair Kit • Reboost	• Aft Shroud Door Closure • Solar Array Jettison • Magnetometer MLI Covers • Solar Array boom manual deploy
SM-2 (Feb. 1997)	• Space Telescope Imaging Spectrometer • Near Infrared Camera and Multi-Object Spectrometer • Fine Guidance Sensor • Tape Recorder • Digital Interface Unit • Solid State Recorder • Solar Array Electronics • Magnetometer Covers • Reboost	• Not Applicable
SM-3 (Nov. 1999)	• Advance Camera Survey • Solar Arrays • 486 Flight Computer • Batteries • Fine Guidance Sensor • Reboost	• Not Applicable
SM-4 (Nov. 2002)	• Science Instruments (2) • Fine Guidance Sensor	• Not Applicable

Figure 1 - Servicing Mission Activities

OPERATIONAL CHALLENGES

There were many challenges that faced the O&GS in preparing for the FSM. First and foremost was the problem of how to maintain nominal HST operations and still prepare for the FSM, while maintaining schedules and not increasing budgets. The challenge was met by dedicating only a small group, approximately five to ten percent of the organization, of individuals to SM preparations. Another small group of engineers was dedicated to on-going HST operations. Senior engineers were then matrixed to support both servicing and on-going operations. This allowed for support to problems that arose on the spacecraft while minimizing impacts to SM preparations. This same successful approach is being used for future SMs.

Another challenge for the FSM was the rapid generation of operational products. Prior to preparations for the FSM, a manual process involving a Computer Aided Design system was used to produce mission timelines and scripts. For the HST Deploy Mission, timelines and scripts were only produced two or three times a year. Additionally, once the Deploy Mission began there was no way to rapidly replan activities. For the FSM, we determined that there must be a tool that can rapidly and efficiently create and replan mission timelines and scripts in response to anomalies and changes in mission objectives. O&GS developed the Servicing Mission/Planning and Replanning Tool (SM/PART). SM/PART applies artificial intelligence techniques to the mission planning process. SM/PART used the software engine of another planning system in use at GSFC. Using rapid prototyping, O&GS developed a basic operating SM/PART system in six months. Once fully operational, SM/PART saved thousands of staff hours in mission development.

One of the more difficult challenges is the integration of new scientific instruments and other hardware components into an existing operational environment. This is particularly true for the Second Servicing Mission with the installation of two totally new instruments and a Solid State Recorder. To help ensure a smooth transition from the hardware test environment to the operations environment, a number of initiatives were undertaken. First, a Science Instrument Test System (SITS) was developed to emulate the ground system and delivered to the science instrument manufacture. SITS allows the instrument developer to test and integrate the instrument with a functional ground system. Secondly, operations personnel were located at the instrument manufacturer and integrated into the development team. These personnel provide operations experience and expertise in the areas of procedure development, database population, etc. In return, they bring back to operations a greater knowledge of the instrument and the ability to train other operations personnel. Finally, operations and hardware personnel work on hardware test teams. These teams define the Integration and Test program at GSFC as well as the initial on-orbit testing of each new component.

For SMs in 1999 and beyond, one of the more significant challenges will be continually decreasing budgets coupled with increasing technical goals. Future SMs will each present their own unique technical challenges with the replacement of flight computers, new solar array designs, and more advanced scientific instruments. The O&GS budget has already been cut more than 20% since the FSM and further reductions are anticipated. One way O&GS is meeting this challenge is to re-engineer the operational environment and develop a highly automated system requiring fewer people. This will allow the O&GS to reduce its budget , but still provide the required resources to support servicing mission activities. This effort is known as "Vision 2000" and its major goals are summarized in Figure 2.

CURRENT OPERATION	VISION 2000
Manual telemetry monitoring	Automated telemetry monitoring
Manual ground system configuration	Automated ground system configuration
Multiple iterations to produce command loads	Single, error-free pass to produce loads
Complex decision-making authority	Localized decision-making
HST proposers require help to generate valid proposals	Proposers have HST-provided tools to produce accurate, constraint-free proposals.
Change process long, complex, frustrating	Minor changes in days, major in months

Figure 2 - Vision 2000 Reengineering Effort

MISSION TRAINING

Comprehensive training in unique requirements and goals for all levels of supporting personnel is an essential part of HST Servicing Mission preparation activities. These activities must include a full range of training sessions and exercises designed to expose all personnel to new flight and ground systems hardware and software performance characteristics in both nominal and contingency operations.

To achieve the goal of keeping the training exercises as realistic and as close to real operations as possible, a portion of the core group of SM personnel is dedicated to the preparation and execution of training exercises. To allow the four flight operations teams to support the training exercises in the same facilities to be used during an actual Servicing Missions, a fifth flight operations team was formed. They relieve the scheduled real-time flight operations team during the training exercises. During the training exercises, real-time spacecraft operations are moved to a duplicate control center. Refer to Figure 3 for the ground system configuration used to support simulations.

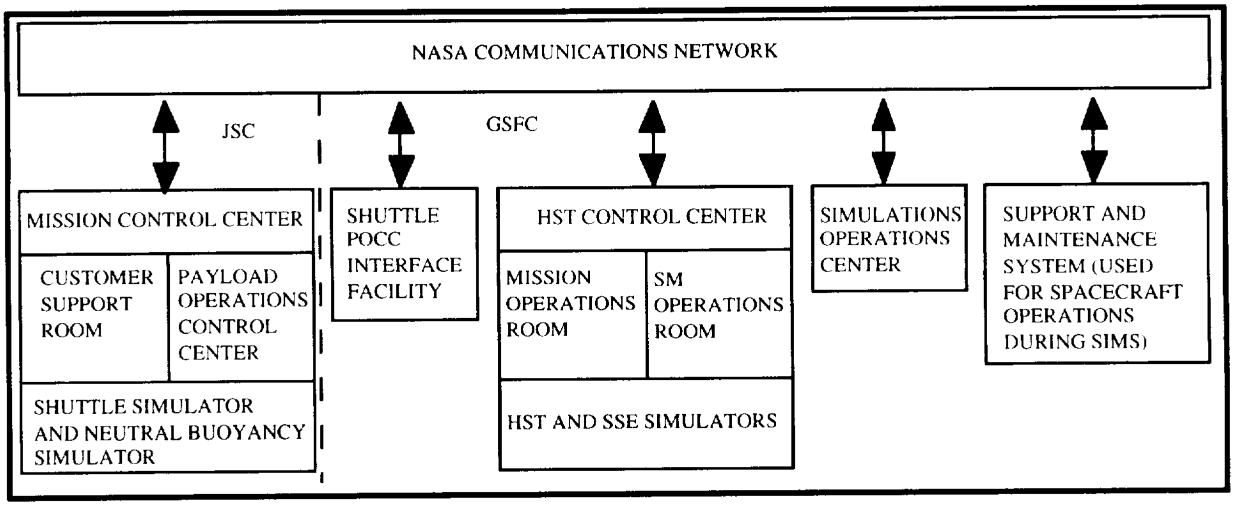

Figure 3 - HST Simulation/JIS Configuration

The primary means of providing the necessary training is through the use of an extensive series of GSFC Internal Simulations and Joint Integrated Simulations (JISs). All members of the Flight Operations Teams, NASA Headquarters, the Space Telescope Science Institute, and Johnson Space Center (JSC) are involved.

The purpose of the Internal Simulations is to train the SM operations, engineering, and management teams to support both nominal and contingency operations. In addition they verify the execution of the Servicing Mission Integrated Timeline (SMIT) and Command Plan, and refine operational concepts. Each mission segment is simulated at least twice and all members of the Project teams are exposed to at least one iteration of each simulation type or mission segment. JSC personnel are invited to participate in the preparation and execution of the internal simulations to cover key JSC operational interfaces. The simulation team creates a repertoire of anomalies and inserts them into each simulation exercise. This tests the Project team's reactions to anomalous conditions and exercises contingency documentation and procedures. HST, Space Support Equipment (SSE), and Space Shuttle data for the simulations are provided by a combination of software models and interface facilities. These include the HST Simulator, the SSE Simulator, the Shuttle Payload Operations Control Center Interface Facility, and the Simulations Operations Center.

The purpose of the JISs are to ensure the operational readiness and effectiveness of the entire GSFC/JSC operations team and flight crew. In addition, the JISs aid in the further refinement of the SMIT and Command Plan during joint mission activities. JSC support includes personnel located in the Mission Control Center, Customer Support Room, the Payload Operations Control Center, and Simulation Control Area. The flight crew supports the JIS from the Shuttle Mission Simulator and from the Weightless Environment Training Facility.

The GSFC Internal Simulations and the JISs are the principal method for certifying support teams at the conclusion of the Servicing Mission training exercises. All HST personnel must support a minimum of 40 hours during four or more Internal Simulations or JISs.

TESTING

To prepare for a SM a very intensive test program is conducted by both the HST O&GS and FS&S Projects. The overall test program for each component to be replaced consists of

Interface Compatibility, Functional, System Level, and Servicing Mission Ground Tests. To support this testing the FS&S Project constructed the Vehicle Electrical System Test (VEST) facility. The VEST is an electrical replica of the HST consisting of flight spares, engineering models, and simulators of the HST subsystems. The VEST has its own control center and can also be commanded from the Space Telescope Operations Control Center. Additionally, the FS&S project has built a High Fidelity Mechanical Simulator (HFMS). The HFMS is a replica of the HST focal plane structure and aft shroud area. It contains all the applicable interfaces and locations of the in-orbit hardware. The HFMS also interfaces to the VEST via an electrical harness. It is used in both electrical testing and mechanical fit checks of new hardware.

Interface Compatibility testing consists of both electrical and mechanical testing. Electrical testing includes power, data, and grounding, while the mechanical tests consist of fit checks in both the HFMS and in associated protective enclosures. Also, the tools and aids used by the astronauts are tested. Functional testing consists of basic component aliveness, mission critical functions, flight software, and system safing. System Level testing consists of compatibility tests in which each new component is fully integrated into the VEST and HFMS and tested as part of an operational spacecraft environment.

O&GS is responsible for the Servicing Mission Ground Tests (SMGTs). The SMGTs are part of an overall O&GS test program that verifies the Project's readiness to support the preparation and execution of the SM and post-SM operations. The test programs verify existing and new ground system and flight software functions, timelines and operational procedures, contingency procedures, and all Ground/Space Network operational interfaces (both data and voice communications) between NASA facilities and centers supporting the SMs.

The SMGTs provide the mechanism for integrating the O&GS and FS&S projects verification activities together. They integrate flight hardware, ground system, flight software, timeline, and mission script activities together. They also provide the tool for demonstrating end-to-end capabilities. The SMGTs fall into three basic categories as defined in Figure 4.

SMGT TYPE	TEST OBJECTIVES
Ground System String Tests	• Verify ground system requirements • Verify ability to support training program • Verify ability to support hardware testing • Verify ability to support SM Observatory Verification • Verify ability to support routine operations
Flight Hardware Tests	• Verify commanding required to support hardware installation on-orbit • Verify subset of commanding required to support SM Observatory Verification and routine operations
Command Plan Tests	• All commanding required to execute the SM is verified (approximately 54,000 commands sent to spacecraft during FSM)

Figure 4: Servicing Mission Ground Tests

Ground System/Space Network testing is conducted with Kennedy Space Center (KSC) and Johnson Space Center (JSC). Testing at both centers includes Shuttle communications and other interfaces. Figure 5 below describes the testing performed in conjunction with each center.

NASA CENTER	TESTING PERFORMED
Kennedy Space Center	• On-orbit communication paths with the Shuttle
Johnson Space Center	• GSFC/JSC telemetry interfaces • GSFC/JSC electronic documentation interfaces • Hazardous command checkout • Shuttle aft flight deck displays • Shuttle communication interfaces not checked at KSC

Figure 5: NASA Intercenter Testing

Finally, O&GS is responsible for the development and execution of the Servicing Mission Observatory Verification (SMOV) program. The SMOV phase of the mission starts when the release of HST by the Space Shuttle is completed. The purpose of SMOV is to re-commission the observatory after servicing by verifying its overall performance. Additionally, initial alignments and calibrations for the new hardware and early release observations are obtained to demonstrate the capabilities of new science instruments. Depending on the activities defined, SMOV can last anywhere from 4 to 6 months. It executes in parallel with the resumption of nominal science operations.

CONTINGENCY PLANNING

A key element in preparation for servicing missions is contingency planning. In preparation for the FSM, the HST Project developed an ambitious contingency management plan. This was necessitated by the complexity of the mission and the potential for anomalies in either the HST, astronaut EVA, or SSE areas. For the FSM over 700 contingency procedures were developed. An important aspect of the plan is modularity and therefore a significant number of these procedures are reusable for SM-2 and future missions as well.

The process used for developing contingency products is shown in Figure 6. The first step is to prepare a list of potential anomalies that may need to be addressed. This is done using a bottom-up approach. The Servicing Mission Command Plan is broken down into a series of activities. Anomalies associated with each activity are added to the list. For the FSM, a top-down fault tree was also produced to double check the anomaly list. Since very few discrepancies were found, this effort was not repeated for SM-2. Once the list is developed, a review is then held to assess both the credibility and criticality of each anomaly. From this review, a prioritized list of anomalies is produced. Anomalies that are considered to be very credible (e.g. solar array retraction from the FSM) or very critical (e.g. anomalies that threaten crew safety) are given a high priority and are worked first. Items deemed to be non-credible or have a low level of impact to the mission are dropped from the list. Once the prioritized list is agreed to development begins. Each anomaly is decomposed into the procedures required to diagnose and correct the problem. The list of procedures is compared with the current library of procedures (from day to day operations or the previous servicing mission) to determine which can be used as is, revised, or must be created. For SM-2 approximately 68% of the procedures could be reused or required minor revision.

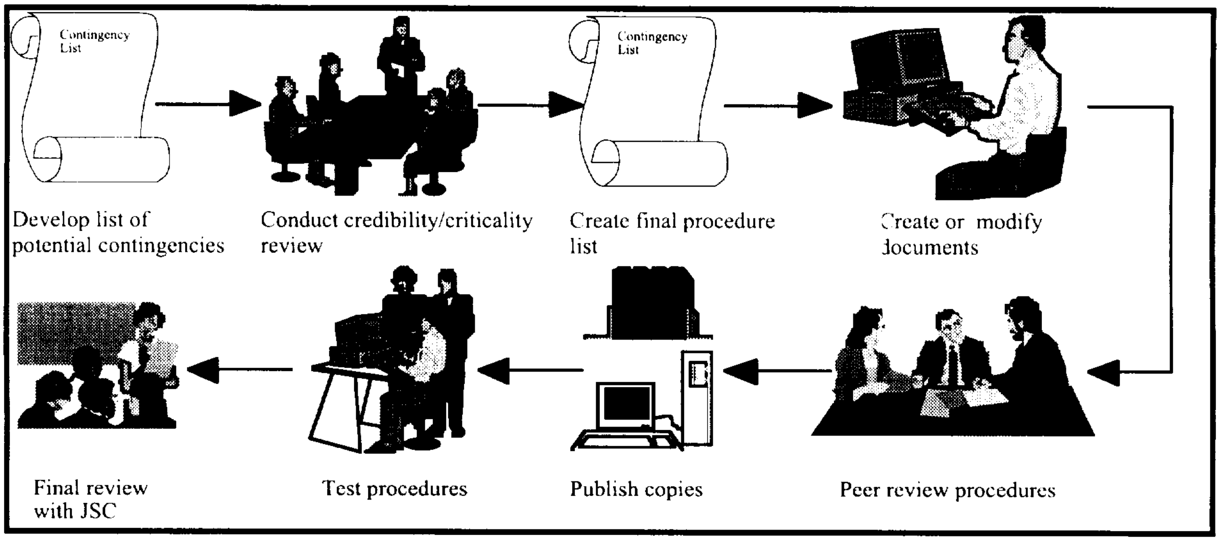

Figure 6: Contingency Development Process

Once the procedures are developed, they are peer reviewed by a team composed of system engineers, subsystem operations engineers, hardware experts, and JSC Space Shuttle operations personnel. The draft procedures are then posted on the electronic documentation system where they are available to all members of the HST organization as well JSC. Non-executable procedures (e.g. Fault Isolation Procedures) are considered validated at this point. Executable procedures are validated by testing against the appropriate hardware or simulators. Once the baseline set of procedures is generated, a review of the entire document set is held at JSC to familiarize and get final buy-in from Space Shuttle operations personnel.

Figure 7 is a simplified flow diagram depicting the contingency resolution process used for conducting HST servicing missions. Anomalies are divided into two major categories, anticipated and unanticipated. Solar array retraction and high gain antenna boom retraction are examples of anticipated problems that occurred during the FSM. Despite the best efforts at anticipating and prioritizing anomalies there are still lower credibility problems that can occur or some that are totally unexpected. The loss of Data Interface Unit 2A due to a short in the solar array is an unanticipated problem that happened during the FSM. Some anomalies can significantly impact the entire mission. An example might be the loss of the Shuttle's Remote Manipulator System (RMS) following HST berthing on the FSS. Since the nominal plan is to use the RMS to grapple the HST and position it for deployment, if the RMS fails the HST must be deployed using a backaway technique. In addition, the EVA activities must be replanned since the RMS is used as a maneuverable platform for the astronauts.

The Contingency Roadmap is a top-level document that defines the contingency plan for the mission. It summarizes the anticipated anomalies and their impact on the mission. It provides flow diagrams and listings of procedures for all identified anomalies for each Command Plan sequence. The Roadmap directs the team to the appropriate procedures in each of three major disciplines covered by the plan: HST, SSE, and EVA. Each of these areas has non-executable procedures to isolate the cause of the anomaly and provide the recommended course of action, and executable procedures used to enact the required changes. Alternate Command Plans (ACP) are overlays to the nominal Command Plan that are used to implement recoveries from anomalies with big mission impacts or where contingency EVAs are required.

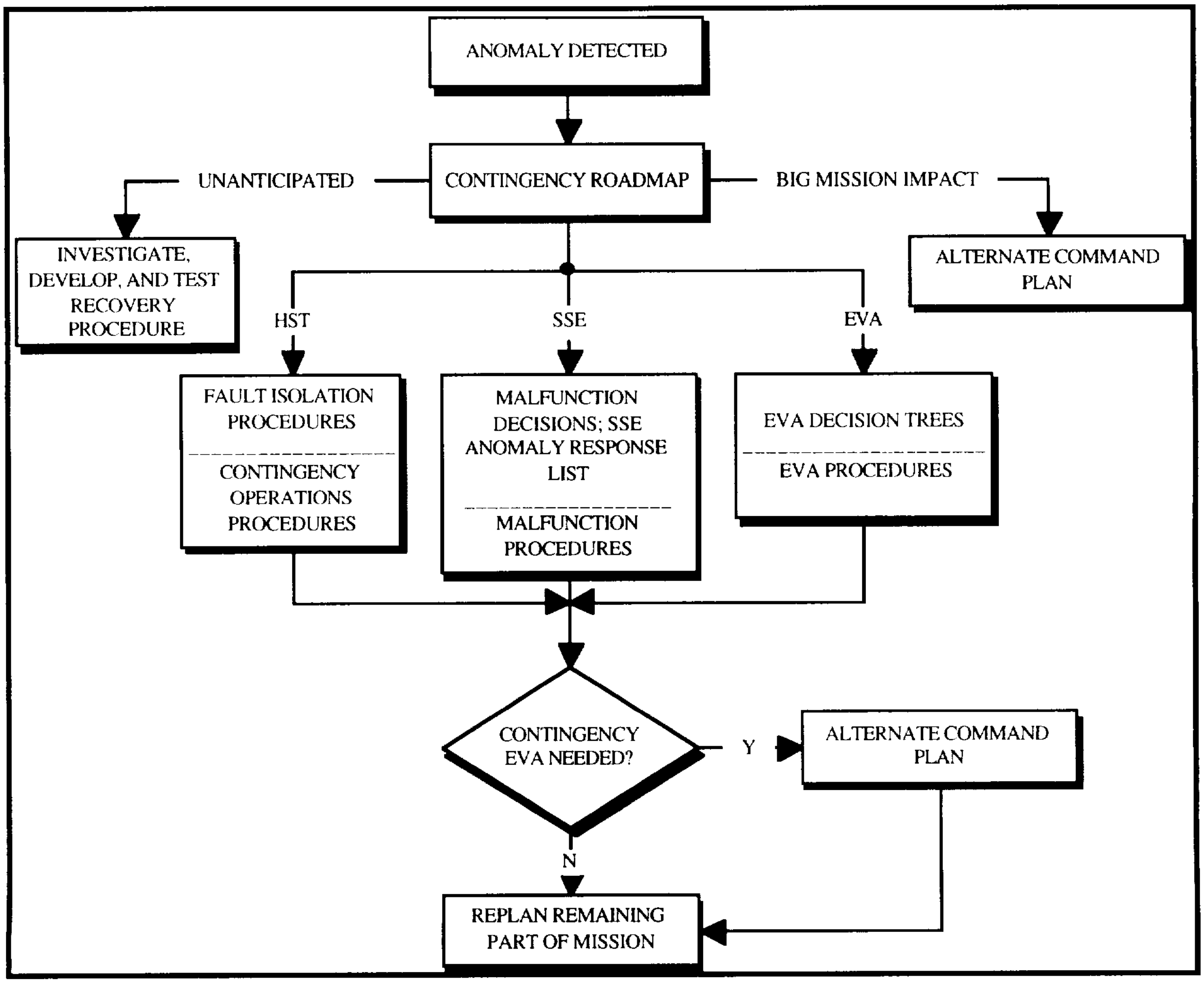

Figure 7: Contingency Resolution Process

SUMMARY

The requirement to prepare for and execute complex periodic servicing missions, while continuing to operate the HST has led to the development of some valuable technical and management techniques. The processes developed for the first two missions should allow the O&GS to execute future missions despite decreasing budgets. These techniques may be applicable to other missions with servicing requirements.