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Lessons Learned from Hubble Space Telescope ExtraVehicular Activity Servicing Missions

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ABSTRACT

NASA's Hubble Space Telescope was designed for periodic servicing by Space Shuttle astronauts performing extravehicular activities (EVAs), to service, maintain, repair, and upgrade the telescope. Through three successful servicing missions to date, EVA processes have been developed by applying a series of important lessons learned. These lessons learned are also applicable to many other future human spaceflight and robotic missions, such as International Space Station, satellite retrieval and servicing, and long-duration spaceflight. HST has become NASA's pathfinder for observatories, EVA development, and EVA mission execution.

INTRODUCTION

NASA's Hubble Space Telescope (HST) was deployed from the Space Shuttle in April 1990. It was designed for periodic servicing visits through ExtraVehicular Activities (EVAs), spacewalks by Shuttle astronaut crews, to support its systems. This support is planned in three areas: maintenance, repair, and enhancement. The servicing crews remove and replace electronic components and scientific instruments after normal degradations, after failures, or incorporate state-of-the-art advancements in technology. Since its launch, there have been three very successful EVA-intensive servicing missions: STS-61 in December 1993, STS-82 in February 1997, and STS-103 in December 1999. All three missions returned the telescope back into orbit to continue its task of collecting superb scientific data. Each new scientific instrument installed by the EVA astronauts has increased Hubble's scientific power by an order of magnitude (Goddard, 2000). The next servicing mission is planned for early 2002 and is designated STS-109. The telescope originally had a planned life of 15 years, but servicing by EVA has already extended the expected life of the observatory to 20 years.

In each of the three servicing missions, the tasks performed by the EVA crewmembers have ranged from the change-out of small data recorders to large telephone booth-sized scientific instruments, and from simple electrical harness connections to complex solar array panel change-outs. They have ranged from nominal, well-practiced upgrades of a computer to the unplanned contingency IntraVehicular Activity (IVA) fabrication and EVA installation of thermal insulation blankets. The three missions have included more than 93 hours of EVA over 13 days installing 45 items on the telescope, making it a pathfinder for NASA observatories, as well as for EVA development, training, verification, and mission timeline execution.

The key to the servicing of Hubble is the original risk-management philosophy of designing for "EVA friendliness" – the pre-planned capability to easily remove and replace many components through astronaut team servicing. The designers of the telescope planned ahead and provided for subsystems known as Orbital Replacement Units (ORUs) and Orbital Replacement Instruments (ORIs) with standardized and EVA-compatible interfaces (Marshall, 1987). In addition, the telescope itself was designed with built-in astronaut crew aids, such as handrails and tether points for translation paths, sockets for attaching portable foot restraint platforms to provide secure worksites, standardized access doors, electrical connector maps, and instruction labels.

HST is an 11 metric ton Cassegrainian telescope with a 2.4-meter diameter primary mirror. The telescope is nominally 4.2 meters in diameter by 15.9 meters high, with two 12-meter solar array panels (Lockheed, 1993). It is in Low Earth Orbit at an altitude of approximately 500 kilometers, always looking into outer space. For servicing, it is grappled by the Space Shuttle's Remote Manipulator System (RMS) and then placed on and latched to a special carrier platform in the Shuttle Payload Bay. This platform allows HST to be rotated and/or pivoted to a proper servicing orientation. Servicing is accomplished by two alternating teams of two EVA astronauts each, with each EVA day planned for 6.5 hours.

The primary reason for the successes of the three HST servicing mission EVAs has been the application of a proven process that serves as a model for the two remaining Hubble missions planned for 2002 and 2004 – as well as for International Space Station (ISS) missions for assembly, logistics, and maintenance. The ISS Program plans to conduct more than 160 EVAs by 2006 (Golightly, 2000). In comparison, the sixth spacewalk for

ISS, conducted on STS-106 in September 2000, was the 50th EVA in Shuttle Program history. The HST methodology also applies to future large space structure deployments, satellite refueling (Sullivan, 2000) and servicing, satellite retrieval, ExtraVehicular Robotics (EVR) missions, and long-duration spaceflights such as missions to a libration point, the moon, or Mars. EVR includes robotics, telerobotics and astronaut-robot “partnerships”.

Ten primary lessons learned have been collected as the basis for the successful HST EVA development process. The first, and arguably the most important, is…

…build a team of experts.

The extensive teamwork throughout formal and informal operations is the prime reason for the success of Hubble servicing missions. HST instruments and hardware come together from manufacturers all over the United States and Europe. They are integrated and tested at the Goddard Space Flight Center (GSFC) in Greenbelt, Maryland in a class 10,000 laminar flow clean room, the largest of its type in the world. It is there that the astronaut crewmembers get their familiarization and training with the Hubble flight hardware. In addition, the crew is trained by a team of Johnson Space Center (JSC) and Goddard engineers at the Neutral Buoyancy Laboratory (NBL) in Houston, Texas. The NBL facility is a 12-meter deep pool containing 24 million liters of water for simulated zero-gravity testing and training. Testing and training with the combined team continues at Kennedy Space Center for final integration and Shuttle launch. The on-orbit servicing mission of EVAs is controlled from JSC by the joint team. In preparing for each servicing mission, the team members communicate and make decisions through Integrated Project Teams.

The extravehicular activity portion of the HST Project team is organized by designating an expert with "ownership" for each planned change-out who interfaces with the corresponding Project hardware design engineers. In order to provide for proper plans and designs for EVA enhancements and procedures, the EVA expert must become involved very early in the design process. This is analogous to the basic requirement for robotic interfaces when designing hardware for robotic applications. The EVA expert is an important team member because the requirements and standards for EVA operations are often unique. The EVA engineer must consider the HST subsystem along with the astronaut in a pressurized space suit which is actually a spacecraft itself. One specialized EVA engineer is the astronaut tool designer who must design, test, integrate, and provide training for the use of unique, special-purpose space tools.

In order to provide continuity, the Astronaut Office at JSC has established a significant transition between servicing missions. An EVA astronaut from a previous servicing mission has carried over as an HST EVA expert liaison until the next servicing mission crew has been named. This crewmember then became the Payload Commander for the next mission. In addition, IVA crewmembers have been assigned to follow-on HST servicing missions in order to provide continuity from in-cabin HST mission experts.

A significant part of our lessons learned with respect to teamwork was the importance of "building" our own experts working in the astronaut suit. Because the EVA human factors aspects of Hubble servicing mission designs and operations are so unique, the EVA team has received substantial benefits from getting Project design engineers trained as suited subjects for the Neutral Buoyancy Laboratory testing. This means that the designers can apply their own experiences for moving with and operating tools and performing change-outs of ORUs and ORIs. Their understanding of mobility, visibility, and pressurized suit and glove operations were able to be applied daily throughout the design process. This resulted in a more efficient process with quicker, better tool and hardware designs.

As the EVA team members begin this development process, it is essential that they…

…start by establishing requirements.

With the original objective – and challenge – of making Hubble serviceable by Shuttle astronauts, it has always been critical to plan ahead to include requirements for features that would permit future EVA servicing. Likewise, the HST servicing mission EVA tool and hardware design process always starts with the establishment of requirements (Sheffield, 1992). The basis for all follow-on testing, evaluation, training, and verification activities for HST servicing is this set of requirements. These requirements are formulated by the experts at each level of management, flowing down from the highest level:

- Overall mission
- Mission change-out hardware
- EVA portion of the mission
- EVA change-out support hardware
- EVA tools to accomplish change-outs
- EVA interface requirements from existing NASA standards

EVA procedures and hardware designs start with the rationale for each requirement and allow the flexibility to add derived requirements. They often include classic brainstorming sessions to provide and evaluate alternate concepts for the design. The basic design philosophy is to design for success, but to always prepare for contingencies. Therefore, the design alternatives address anticipated contingency features or future requirements. An example of this was a lubricant applicator that was designed to preclude problems with the latches securing HST instrument bay doors. Another example is a power tool that is currently being considered to aid in removing electrical connectors that will replace manual connector tools in order to reduce fatigue and to save valuable EVA time.

Regular briefings after HST EVA tests, including those with the astronaut crew, are often brainstorming sessions. The EVA design engineers, the astronauts, and other Project engineers discuss requirements and solutions to problems that have occurred during the tests. Another example of classic brainstorming also occurred during the first HST servicing mission. When the EVA astronauts unexpectedly discovered a loose cover on a magnetometer on HST, a real-time decision had to be made on how to fix the problem. The mission support ground crew personnel at JSC and GSFC formed a team to assess the problem, set requirements, and arrive at a solution. The team considered all possible hardware resources that were available and two alternatives were considered: cutting off either a flat sheet of insulation or a contoured cover from an instrument carrier in the Shuttle's payload bay. The first option would require the forming of a cover to fit the magnetometer. After consulting with the contamination expert and conducting fit-checks on mock-up hardware, the contoured cover option was selected. Complete procedures and drawings were sent to the Shuttle crew and the magnetometer cover fabrication (by IVA) and repair (by EVA) was successfully carried out. A result of this problem and its solution was to establish a new requirement for subsequent missions to manifest a contingency insulation repair kit. This kit contains insulation sheets, wires, and fittings. It was used on the second servicing mission to fabricate insulation patches when unexpected tears were found on several pieces of the telescope's exterior insulation.

With firm requirements established, the HST EVA team's basic design objective is then to…

…keep the designs simple.

A key consideration in designing for HST that is different from most other engineering design considerations is that one side of the engineering interface is not physically available; it is on the telescope in orbit. Because of this, and because a major HST objective is to save valuable EVA time, the hierarchy of design goals and considerations for EVA tools and interfaces to meet the initial and derived requirements are:

- Wherever possible, don't require a tool interface; use the gloved hand.
- If a tool is determined to be required, use an existing standard tool or interface, such as a 7/16-inch hex head bolt.
- If necessary, design a general-purpose manual or power tool.
- If necessary to meet the specific objective, design a unique tool.
- Is the task to be performed by the crewmember on the Remote Manipulator System arm platform or by the "free-floater", the crewmember away from the arm who is tethered to the Shuttle?
- Is the task to be performed single-handedly?

The basic considerations for EVA design also apply to robotic system design:

- How would a person do the same or similar task in 1-g?
- What standard interfaces can be used?
- How do hardware or tool stowage, staging, transportation to the worksite, and tool interchangeability affect the design?

For EVA applications, special considerations must also be given to safety of the astronauts, the payload, and the Shuttle; tethering requirements; thermal conditions; pressurized EVA suit operations; astronaut capabilities, limitations, and fatigue; and the saving of EVA time.

There are typically 150 types of tools manifested for a Hubble servicing mission. Examples of EVA designs developed by the Hubble Space Telescope EVA team include adjustable-length extensions, articulating crew aids for use in translation or as platforms at work sites, tools to capture removed hardware, electrical harness retention devices, unique manual tools for small low-torque coaxial cable connectors, and computer-controlled power tools to save EVA time.

The HST Project's philosophy for design solutions is typified by the surprisingly simple solution to the aspherical aberration of the primary mirror that was discovered soon after Hubble's deployment in 1990. The outer edge of the mirror had been ground too flat during fabrication – by only 2.2 microns – and this caused degradation of some of the initial images. The simple, but elegant, solution was to design a series of small, trainable corrective mirrors attached to the replacement axial scientific instrument that was already planned for installation during the scheduled first servicing mission in 1993.

In order to ensure the best design possible in the process of evolving into mature designs, the HST EVA development team must then…

…get feedback from users.

An important Hubble Space Telescope lesson learned is the value of establishing a process that asks for, records, evaluates, and then responds to feedback from users. In our case, the "users" are the EVA astronauts that carry out the Hubble servicing mission. They are the experts who have experienced hands-on EVA operations on orbit.

The HST engineering development process – for flight hardware and for on-orbit procedures – is built around iteration based on extensive feedback. The process starts with the development of initial concepts based on the requirements established for each change-out. The first evaluations from testing at NBL are made by the Project engineers as surrogate EVA astronauts. Their feedback allows improvements to the hardware and procedures before the Johnson Space Center astronauts conduct their evaluations.

Then, crews of JSC astronauts who are potential candidates for HST servicing mission EVA positions evaluate the hardware and procedures. Their feedback leads to further design enhancements. This feedback process has been critical in the design of effective tools and operations for Hubble servicing.

The astronaut feedback has been effective because it is provided in four standardized rating categories:

ACCEPTABLE: No design changes are required and the astronauts can accomplish the task with little or no difficulty. Recommendations may be included to improve hardware operations.

UNACCEPTABLE-1: Minor design changes are required.

UNACCEPTABLE-2: Major design changes are required. Retesting is required to verify the adequacy of the design changes.

INCONCLUSIVE: The hardware or task cannot be fully evaluated because of improper test conditions or environment, inadequate hardware fidelity, or insufficient number of test subjects used. Retesting is required.

In tests where multiple test subjects participate, an astronaut summary Crew Consensus Report is submitted to the HST Project in order to document itemized test results, design recommendations, and overall ratings. This standardized, orderly feedback process leads to specific responses by the Project as to what modifications can be made. Many Hubble tools, ranging from manual connector tools to computerized power wrenches, have evolved through many significant improvements based on this astronaut crew feedback process.

A primary example where major changes have been incorporated is the Cross Aft Shroud Tool (CAST) that was designed to meet a requirement to pass a harness from one side of the interior of the telescope to the other. Because the tool was at the limit of the astronaut's reach, it was suggested by the crewmembers that the tool be eliminated and that additional stiffness be added to the harness in order to accomplish the pass-through task and to save EVA time. Based on this feedback, the tool evolved from a separate tool to an integrated tool-harness combination, and then to a tool-less harness.

Asking the astronaut-users for feedback needs to be followed up with another question from the design team members as they…

…continually ask "What if…?"

One of the key lessons learned that is applicable to hardware design – and ultimately to mission readiness – recognizes the importance of constantly considering "What if this component does not operate properly?"

In parallel with the development of nominal procedures and hardware there are activities for contingency procedures and documentation, fault-tolerant tools, and contingency training. All hardware and procedures are required to be single-fault tolerant to support the servicing mission.

Several levels of important questions that the HST EVA designers have learned to continually ask are:

- "What if this mechanism fails?" (This leads to collecting and verifying engineering data for torque requirements and mechanical failure modes.)
- "Is there a method of trouble shooting?" (This leads to a documented procedure in the EVA Contingency Document (Goddard, 1999) for the servicing mission.)
- "Can this component be overridden, removed, or jettisoned?" (This leads to additional design features for use in case an anomaly occurs.)
- "Are there back-up tools?" (This leads to a logistics policy for manifesting spares or alternate tools in accessible stowage locations in case they are needed in a contingency.)

Answering each of these questions leads to the incorporation of contingency planning, documentation (Goddard, 1993), and training in order to cover potential anomalies.

The ground and astronaut crews undergo extensive simulations to train for possible failures. This practice helps in developing and validating procedures and hardware. During mission simulation sessions, anomalies are injected to test the overall team readiness. Typically, the most extensive contingency planning is for the loss of the Shuttle's Remote Manipulator System (RMS), or robot arm. This requires the addition of new crew aids on the orbital replacement hardware or on the HST carriers in the payload bay in order to accomplish a contingency change-out without the RMS.

In some cases, special hardware training devices are built specifically to provide – and expand – training by allowing practice for nominal and contingency procedures. An example is the Power Control Unit (PCU) Trainer, which is a full-scale, high-fidelity mock-up of an equipment bay with the PCU and its connectors with difficult access.

In supporting a servicing mission, the HST EVA team is actually divided into three teams in order to address nominal and contingency situations:

- The EVA Orbit Team, on duty during the scheduled 6.5-hour on-orbit EVAs, responds to real-time anomalies.
- The EVA Replanning Team revises mission plans and projects the activities and timelines for any changes.
- The EVA Transition Team spans the other two teams' duty times in order to increase situational awareness, improve communications, and provide continuity, especially when anomalies occur.

Each of these EVA teams and the astronaut crewmember team benefits because we…

…use a variety of training methods.

It is essential for Hubble servicing mission success that the astronaut crew is trained using various methods and hardware trainers. The challenges of preparing for a remote mission in space demand that these training methods supplement each other.

The astronauts receive extensive training on the actual flight hardware or on high-fidelity, flight-like hardware at the Goddard Space Flight Center. The primary advantage of this training is that it involves flight instruments and flight tools interfacing with high-fidelity mock-ups built to flight drawings. The disadvantages are the presence of gravity, the mechanical limitations on cycling of flight mechanisms, and the absence of a pressurized astronaut suit capability.

These disadvantages are mostly overcome by the extensive underwater testing that is conducted at the Johnson Space Center, where full-scale mock-ups are used in testing at the Neutral Buoyancy Laboratory. The advantages of these tests are that the entire task can be choreographed in pressurized suits with buoyancy removing most of the negative effects of gravity. The key to effective neutral buoyancy training is the quality and neutralization of the mock-ups. The primary limitations of neutral buoyancy testing are the lower fidelity and lower mass of the hardware mock-ups, and the drag of the water. In addition, even though the astronaut suits and much of the hardware are neutrally buoyant, the astronauts themselves and some of the operational tools are not.

The high-fidelity mock-ups for Hubble include:

- The High Fidelity Mechanical Simulator (HFMS), a mock-up of the HST Focal Plane Assembly bays for large axial and radial scientific instruments.
- The Vehicle Electrical System Test (VEST) facility, a mock-up of the electrical support system equipment sections which contain the smaller orbital replacement units such as the computer, electronics boxes, and tape recorders.
- The Exterior Simulator Facility (ESF), a mock-up of the forward exterior shell of the telescope for training for external components and insulation.
- The Aft Shroud Door Trainer (ASDT), a mock-up to provide training for door latches, door opening and closing, and contingency operations after the difficulties on the first servicing mission in December 1993. Six years later, this special-purpose trainer proved its usefulness during the third servicing mission.

All of these trainers, built to HST flight drawings, have been very effective in providing training for the servicing missions. After returning from a servicing mission, the astronauts have provided feedback that their initial work with these high-fidelity trainers provided them with the correct images and operations of what they found on orbit.

For the next servicing mission scheduled for early 2002, we have built another special-purpose, high-fidelity trainer for the critical Power Control Unit replacement task. The worksite for this electronic box has very tight access to 36 electrical connectors and therefore requires a special trainer.

To complement these facilities, thermal vacuum testing, which can include astronaut suited subjects in a space thermal and vacuum environment, is used to simulate flight hardware operations under space conditions. Astronaut training at JSC also includes computer-generated virtual reality simulations using "digital mock-ups" for maneuvering large-mass scientific instruments and solar array panels. Because HST is on orbit, a great portion of the crew's training – as well as the auditing of the mock-ups and trainers – comes from referring to an extensive library containing over 65,000 photographs of flight hardware before it was launched, during crew testing and training, and on orbit during the servicing missions.

The high fidelity training facilities are supplemented by the lower fidelity of neutral buoyancy simulations, which use mock-ups that emphasize the form, fit, and function of interfaces critical to the astronauts' operations. The facilities and mock-ups are audited by the EVA and equipment engineers who are the experts for that equipment. The experts ensure that all of these features of the underwater test hardware are in a fidelity as close as possible to the flight hardware. In all cases, the possibility for negative crew training is minimized.

The complementary nature of all of these HST EVA training facilities and methods emphasizes the need for elements of each phase of the development process to…

…evolve.

Many HST lessons learned are based on the importance of establishing processes that allow natural evolution. Recognizing that the following evolutions are a normal and beneficial part of the development process has been an important lesson learned in itself:

- Initial EVA hardware procedures and concepts evolve into mature designs after testing, evaluation, and feedback from the astronaut crew.
- Frequently, EVA tools that were originally initiated as concepts for nominal tasks evolve into designs for tools for contingency use.
- Part-task testing in the neutral buoyancy simulations evolves into final end-to-end task choreographies.
- Engineering development of EVA tools and procedures by GSFC evolves into formal astronaut crew training by JSC and documentation into flight data files.
- Rough timeline estimates by the planners for EVA tasks are refined as they evolve into the final EVA task times that are expected on orbit. As this evolution begins, typically a 20-percent time adjustment factor is added to allow for future efficiencies, historical expansion of times on orbit, and improvements that are achieved through repetition in training.

In order to reduce risk and to plan for mission success, as each phase of the EVA development process evolves, we have learned that it is critical to…

…train, train, and retrain.

A lesson learned that has been critical to the success of each Hubble Space Telescope servicing mission has been the importance of extensive training. This applies to training for nominal tasks and possible contingencies for both the ground team and the on-orbit EVA astronaut team. A basic HST EVA principle is that there must be training for each item of hardware that is manifested on a Hubble servicing mission.

The neutral buoyancy testing at NBL is the primary method for practicing end-to-end operations. It starts with part-task training for a particular task, such as the Rate Sensor Unit (RSU) change-out. It is supplemented by practicing with near flight-like RSU mass mock-ups in the High Fidelity Mechanical Simulator at GSFC. Then it concludes with formal NBL crew training by JSC for end-to-end operations by both of the EVA crewmembers assigned to perform the RSU change-out task and cross-training for the other two crewmembers.

An important part of this lesson learned is that the end-to-end practicing must consider all aspects and details of the change-out such as:

- Relative positions of the two EVA crewmembers (one on the Remote Manipulator System, the other “free-floating”).
- The transportation of the old and new RSUs between their stowage location and HST, and the tools required for the task.
- All tethering protocols and transfer operations for the crewmembers, RSUs, and tools.
- The time and motion efficiencies of the RSU change-out and any parallel tasks during the change-out.

The extensive astronaut crew training in NBL simulations follows these proven guidelines:

- Start with 1-g familiarization and training using the mock-ups out of the water and using any special-purpose trainers.
- Conduct training for contingency as well as nominal tasks, supplemented by briefings and very effective “tabletop” scale models.
- Include other astronaut crewmembers, such as the IntraVehicular Activity Remote Manipulator System arm operator inside the Shuttle.
- Conduct cross-training so that each EVA crewmember can perform any task during the mission.
- Practice enough to achieve at least 10 hours of NBL training for every hour of EVA time planned on orbit. This 10:1 ratio is the minimum level for Shuttle EVA missions.

Training and practicing continues in mission team simulations with the entire ground-based team on console with all flight nominal and contingency documentation, and often with the EVA astronauts conducting their exercises in the NBL facility during the simulation. This provides extensive, realistic practice for nominal and contingency operations for each planned EVA day.

In parallel with many HST EVA opportunities for training, there are also opportunities to…

…verify flight hardware and procedures.

One reason that historically there have been no problems with components or tools interfacing with HST on orbit is that there has always been an extensive verification program to fit-check as much hardware as possible. Because the real “payload” for HST servicing missions – HST itself – has been on orbit since 1990, some fit-checks naturally are impossible. In these cases, the fit-checks are performed with respect to engineering units, flight spares, or high-fidelity simulators built to flight drawings.

For EVA procedures, neutral buoyancy testing and high fidelity simulator verifications are conducted for:

- Translation paths
- Task sequences
- Stowage locations.
- Task worksites and working volume
- EVA astronaut visibility and gloved hand access
- Form, fit, and function

For all nominal and contingency tools, it is has been significant that 100-percent verifications are conducted for:

- Tool-to-tool fit-checks for all serial numbers of all nominal and possible back-up tools, such as an adjustable-extension socket fitting on a wrench.
- Tool-to-equipment fit-checks, such as the tool socket fitting on a Fine Guidance Sensor (FGS) latch bolt.
- Equipment-to-equipment fit-checks such as the flight FGS fitting into its flight stowage container on a payload bay carrier and into the flight-like mock-up of its Aft Shroud position in HST.

For a typical servicing mission, more than 3,500 flight tool fit-checks are conducted, giving confidence that there should be very little risk of fit problems on orbit.

As new scientific instruments and orbital replacement units are scheduled for installation, fit-checks with nominal and contingency tools are conducted and recorded. For example, before the Near Infrared Camera and Multi-Object Spectrometer (NICMOS) scientific instrument was launched for the February 1997 second servicing mission, two sets of special, large sized sockets were fit-checked with valves on NICMOS because of their potential need on a future mission. During the December 1999 third servicing mission, the same sockets were successfully used to open the valves on orbit.

All of the fit-check data is entered into an extensive verification matrix database for formal documentation and archiving (Goddard, 1995).

This and other lessons learned have contributed to Hubble EVA mission success because the HST Project has continually met its objective to…

…apply lessons learned.

The Hubble Space Telescope EVA development and mission support processes have been successful for three servicing missions because attention has been paid to identifying – and then applying – lessons learned. EVA lessons learned, along with those of other branches of the Hubble Project, are collected on many levels:

- Lessons learned that are applicable internally within the EVA Team.
- EVA Team lessons learned with respect to other HST Project teams (Goddard, 1994).
- Project lessons learned applicable to other NASA Centers, such as Johnson Space Center and Kennedy Space Center.
- Lessons learned from other EVA missions (Fullerton, 1994).

CONCLUSION

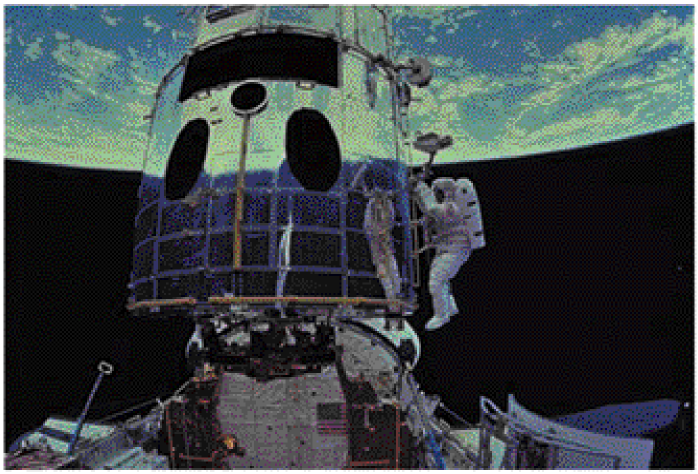
Significant lessons learned have been collected, reviewed, reported, and incorporated wherever process improvements can be made to the Hubble Space Telescope ExtraVehicular Activity development process. These HST EVA lessons learned also have been applied to other projects, such as International Space Station, for flight tool development and the neutral buoyancy simulation process.

In the future, many aspects of these lesson learned will be applicable to large space structure deployment, satellite servicing (including refueling), satellite retrieval, extravehicular robotics missions (including robotics, telerobotics, and astronaut-robot “partnerships”), and long-duration spaceflights.

The HST EVA lessons learned that have been identified are in the areas of:

- Team building
- Requirements definition
- Hardware and procedures design
- Astronaut crew feedback
- Contingency planning
- Training methods and facilities
- Extensive training
- Evolution
- Verification
- Application of lessons learned

These lessons learned are currently being applied to the next HST servicing mission planned for January 2002 as the Hubble EVA development cycle continues.



EVA astronaut on Hubble Space Telescope servicing mission.

Astronaut providing feedback while verifying flight power tool interface in clean room.

Neutral buoyancy training with astronaut using power tool mock-up.

Use of power tool on orbit during a servicing mission.

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