Paper Session I-A - Development of Modular Replacement Instruments to Maximize the Science Return of Hubble Space Telescope (HST)

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The Hubble Space Telescope science return has been and will continue to be improved through regular shuttle servicing missions which replace first generation science instruments with advanced design second and third generation instruments. Orders of magnitude improvement in science return per dollar comes primarily from incorporation of state of the art 1/100 wave optics such as were used on Corrective Optics Space Telescope Axial Replacement (COSTAR) to fix Hubble's vision and from large area Charge Coupled Device (CCD) and Multi Anode Microchannel Array (MAMA) detectors that enable hundreds of times more spectral and/or spatial coverage of the sky with approximately the same sensitivity.

The Hubble Space Telescope (HST) science has been improved and will continue to be improved by regular shuttle servicing missions. History has shown that regular servicing provides a much higher science return per invested dollar than has ever been possible for expendable spacecraft. HST was built with servicing in mind both through the use of orbital replaceable components and by providing standardized electrical, optical and mechanical interfaces. NASA had the foresight to build standard interface hardware. This allows a ground comparison/verification before service missions launch. Servicing missions also require practice. This is done by practicing on the flight hardware where possible, doing underwater (neutral buoyancy) testing at JSC and by installation in the High Fidelity Simulator at GSFC.

The rewards of regular servicing are great. The first servicing mission concentrated on fixing Hubble's vision, replacing several pieces of hardware which had deteriorated and replacing items that improved performance (pointing accuracy and science throughput). Instruments currently being built at Ball for the 1997 & 99 servicing missions will significantly improve science capability. It's these servicing missions that have the highest science return on invested capital.

HST is Built to be Serviced

Figure 1 show how the science instrument modules fit into the rear of the Optical Telescope Assembly structure. Each science instrument is replaceable on orbit by disengaging the four standard electrical connectors and three standard mechanical interface fittings. Figure 2 shows the "A" fitting near the bottom

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which is opened and closed by the astronauts during servicing and the "C" fittings near the top right which snaps into the front of the replacement Science Instrument (SI). Figure 3 shows the "B" fitting which has a spring loaded plunger which engages into the rear of the SI as the astronaut turns the spleen with his/her power tool. This forces the SI into the "A" and "C" fitting on the front of the SI. After the "B" fitting is tight, the astronaut tightens the "A" fitting with the power tool to lock the SI into alignment with the telescope.

The "A", "B", and "C" fittings are very precisely located so that the SI is co-alignment to the telescope axis to within 30 seconds of arc and the mechanical position is known to within 150µm. For example the COSTAR alignment was only two or three mechanism steps from nominal out of thousands of adjustment steps provided after being installed during the first servicing mission.

HST Interface Standards

As noted above COSTAR instrument alignment was only two or three steps from the nominal position selected on the ground. This would not have been possible if NASA had not had the foresight to maintain several standards that were calibrated from the flight HST hardware. Figure 4 shows the SI Axial Bay Simulator (ABS) (commonly called the Iron Pipe) which has all the physical dimension for the "A", "B" and "C" fitting referenced to an optical cube at the focal plane. This standard was placed in all four axial payload bays of the HST telescope assembly during Integration and Test to verify the position of all of the "ABC" fitting and has been used since to transfer this standard to other simulators. During the HST fabrication phase NASA also built a heavy structure which simulates one quarter of the HST Optical Telescope Assembly instrument bay. Figure 5 shows the COSTAR Instrument being checked in this "quarter panel". This standard is used to verify all
Fig. 3. "B" Science Instrument attach point

mechanical interfaces and has an optical reference to check focus and angular alignment.

Since the COSTAR instrument needed to correct the apertures in three instruments at once Ball built the HST Optical Mechanical Simulator (HOMS) to mechanically simulate two bays and optically simulate all four bays. Figure 6 shows the COSTAR instrument in HOMS as it was being tested alongside the engineering model Faint Object Camera (FOC) which is not visible. Ball was able to demonstrate COSTAR operations by first taking a picture of an aberrated beam from the optical simulator with the FOC, compare the images with flight data to verify the fidelity of the simulated image, and then take a second image with COSTAR deployed to verify COSTAR fixes the problem. The COSTAR settings...
derived from this test were so good that literally no adjustments were needed in flight. The HOMS has now become another HST optical standard to be used on the Space Telescope Imaging Spectrograph (STIS) Instrument and the Near Infrared Camera & Multi-Object Spectrometer (NICMOS) Instrument due to launch in 1997 and the Advanced Camera for Exploration (ACE) to be launched in 1999.

Test, Test, Test, Practice, Practice, Practice.

The success of the HST Mission can be attributed to not assuming anything to be a "by God". Every piece of flight hardware installed on the 1993 refurbishment mission was tested many times. One of our greatest fears was that the flight hardware would work fine during ground test but not work in orbit due to the mechanical, electrical or optical interfaces being slightly in error. Figure 7 shows a typical axial bay instrument ready to be installed in HST. The "A", "B", and "C" fitting must all be in the correct configurations, they must be located in the correct place relative to each other and, the guide rails and blocks must be located correctly relative to the "ABC" fittings. Most importantly all the optics inside must be aligned relative to the "ABC" so that they will be aligned to the HST focal plane when installed. Electrically the two power connectors and the two signal connectors must be wired properly. Astronauts trained in the water tanks at JSC making sure in the early years of HST that the proposed designs were compatible with servicing. In the later years they developed and practiced in orbit servicing procedures. Figure 8 shows two astronauts in the tank installing the Wide Field and Planetary Camera radial science instrument in preparation for the 1993 servicing mission. Frogmen assist the process and document the procedure. The water tank provides the feeling of weightlessness and exemplifies the problems of handling large items. Detailed mechanisms are hard to simulate so in order to get "hands-on" experience with the flight hardware the astronauts spend significant time in the clean rooms watching fit checks, touching the hardware, exercising power tools on latches etc.

Fig. 7. Science Instrument ready for Installation in HST

Fig. 8. Underwater practice for Orbital Installation
Figure 9 shows COSTAR installed in the High Fidelity Simulation of HST at GSFC. Astronauts watched the process, witnessed the indicator light changes as the instrument hit the limit switches and felt the pressures required to push the instrument into its latches.

Practice makes Perfect. Figure 10 shows the COSTAR instrument being installed in HST during the December 1993 servicing mission. An unprecedented five space walks all were completed as scheduled. Some things took a little longer and some shorter but on average mission planning was amazingly accurate. There were very few problems that were not anticipated. The worst problem was solved by Story Musgrave when he used a "come along" to get the doors closed on mission day 1.

The Science Payback from Servicing

HST was proposed, designed and built largely to address some of the "big questions" in astronomy relating to the universe as a whole (cosmology). Issues such as size, age and content of the universe were to be answered. The aberration found in the HST during its initial checkout in orbit made the fulfillment of this goal nearly impossible but thanks to the 1993 Service Mission HST has performed beyond most astronomers' wildest dreams. In the past year HST has re-written the Astronomy text books.

1. The Hubble Constant

The linear relation between distance to a galaxy and velocity (red shift) of that galaxy is known as the Hubble constant. Without worrying about units, the numbers ranged from 45 to 110 before HST launch. Current analysis suggests a number of 80 ± 17 which relates to an age of the universe of 10 ± 2 billion years rather than the 16-18 billion years previously believed. These numerical values will be refined as more distant galaxies are measured but all indications are
that HST will fulfill its promise. There is a slight problem with the age of the universe data because the oldest stars in our own Milky Way galaxy appear to be older than the Universe itself.

2. Central Regions of Active Galaxies and Super Massive black holes.
For years astronomers suspected that black holes existed as centers of very bright but relatively far away galaxies. The red shifts of quasis-stellar objects (quasars) combined with the "then believed to be" Hubble constant indicated these galaxies to be very far away but with brightness thousands of times brighter than what seemed possible at that distance. In 1994 the COSTAR corrected FOS and GHRS Spectrographs were used to measure the velocity of the gas spiraling into a famous galaxy called M87. They measured speeds of over one million miles per hour and an implied central mass of over two billion solar masses. Again HST delivered on its promise but only after in orbit servicing was able to fix its vision.

3. Proto-Planetary Systems
The theories of how stars form from the gas and dust of space suggest that the formation of planets, asteroids, comets, etc. should be fairly normal/common process, and many (or most, or all) stars should have their own "solar systems". That's the theory. Unfortunately planets are very small and very faint compared to the stars they orbit, and are extremely difficult to detect. There are only one or two stars other than our sun for which we have any real evidence of objects of planet size accompanying them. The service mission corrected HST was used last year to photograph a group of very young stars in the Orion nebula which are still in the process of forming. They discovered that over half of these stars are surrounded by disks of material that appear to be orbiting around them. None of these are claimed to be planets now, but they may be the raw material out of which planetary systems will form as the stars evolve. These disks are small and faint, and just about impossible to see without HST. Since they are known to be bright infrared emitters, they will be prime targets for NICMOS (planned launch in 1997 servicing mission) which can take images in wavelengths that will show them more clearly than at visible wavelengths. This is a major discovery of a new class of objects in the sky just waiting to be studied by the next generation of instrumentation and scientists.

General Technology Improvements expected from Servicing Missions.

Regular servicing provides the opportunity to upgrade the HST to the latest technology. The three primary improvements come from (1) better detectors, (2) better computers and (3) better optics.

Detector technology changes at a fast pace. NICMOS was originally proposed using a 32x32 individual diode/amplifier detector (1024 channels) but will be flown in 1997 with three each 256x256 HgCdTe detectors with built in multiplexers that cut the number of amplifiers/electronic channels to four per detector. That's almost two orders of magnitude capability enhancement over the development time of one instrument. Figure 11 tells a similar story for the various cameras flown/proposed for HST. The original WF/PC I instrument had four each 800^2 CCD compared to the ACE Instrument plans to use two each existing technology 2k x 4k detectors. Larger arrays exist but do not have flight heritage and/or do not provide the same low dark noise and/or high quantum efficiency expected from the selected option. These larger pixel format arrays can be used either to increase Field of View or improve Resolution.
Figure 11. Resolution Elements vs Mission

Figure 12 shows the expected improvement in field of view versus each mission and Figure 13 shows the trade space between a larger field of view and spatial resolution. Note that NICMOS (1997 launch) is on the 256\(^2\) pixel line, STIS (1997 launch) on the 1024\(^2\) pixel line, WF2 (1993 launch) is above the 1024\(^2\) line, the ACE High Resolution Channel (HRC) and the Solar Blind Channel (SBC) use the STIS 1024\(^2\) detectors and the ACE Wide Field Channel (WFC) jumps to the 4096\(^2\) pixel line. Each of these detectors is at a different wavelength and therefore has a different critical sampling pixel width in arc seconds. There is no need to go below a 20 millisecond pixel width because there is very little additional information; given the current HST configuration and wavelength coverage. Another measure of technology improvement versus mission is shown in Figure 14. The ACE Instrument will provide a significant improvement in overall sensitivity because of better and more simplified optics and in improved detector optical coatings.

More Science Return per Invested Capital for Serviceable Missions

Several methods have been used to get a handle on the amount of science for the buck. Figure 15 compares several well known missions by dividing the Instrument/Science and Operations cost...
by the total costs. You will note that the return on invested capital is much higher for the SMM mission because of in orbit servicing (44% vs 25%). If you look at the plans for HST in Figure 16 servicing becomes even more dramatic (70% vs 15%) for an overall average of 52%. When missions are ranked by the number of "Important" science stories we see a similar trend (Figure 17).

If you've read the paper or any science journal over the past year you will already know that HST has made the news and was ranked number one in significant science breakthroughs for the year. Without servicing in 1993 none of this would have been possible.