HUBBLE SPACE TELESCOPE OBSERVATORY: STATUS, FUTURE PLANS, AND OPTIONS

HST Project Input to the NASA HST-JWST Transition Plan Review Panel

1. EXECUTIVE SUMMARY

Since launch in 1990 the Hubble Space Telescope (HST) has proven to be an extraordinarily powerful and productive astronomical observatory, expanding knowledge of the Universe and providing imagery that captivates the public. The crown jewel of astronomy has energized the professional community and inspired an international audience of millions, especially youth, with a revitalized interest in exploring the mysteries of the universe. Two qualities unique to Hubble are responsible for its success: it has a superior vantage point -- in space -- and it is designed to be upgraded on orbit every three to four years through shuttle-based astronaut servicing. The cost of each servicing mission is comparable to other medium-large space science missions (e.g., New Frontiers, Discovery, Einstein Probes), but the result of each mission is the renewal of a Great Observatory, a unique, strategic resource for astronomy.

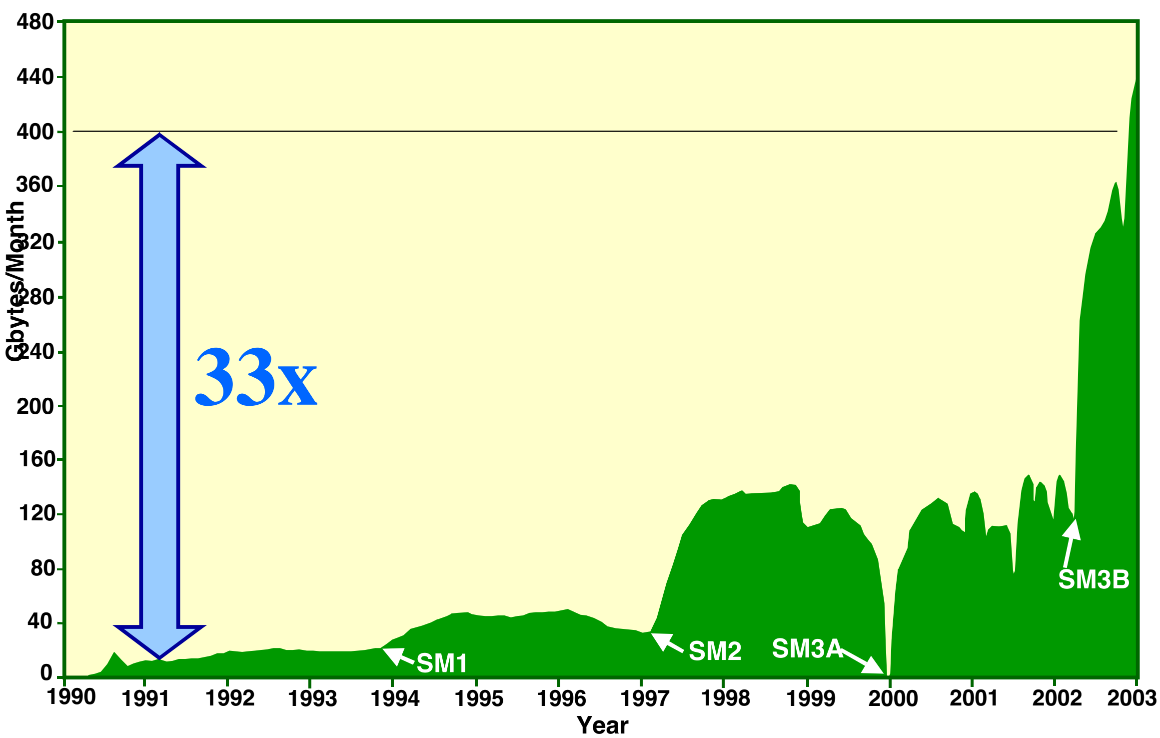
NASA now faces the challenge of developing the endgame for the mission. Since HST can be maintained and upgraded almost indefinitely, the decision to terminate the mission must be based on scientific return instead of hardware obsolescence or failure. Furthermore, end of mission planning must include safe disposal of the vehicle after the science mission has been terminated.

This document provides a brief synopsis of several key topics that influence the future plans and strategy for the Hubble Space Telescope. Specifically, the paper discusses: 1) the current status of HST, 2) the role that on-orbit servicing has played in the evolution of HST, and by simple extrapolation can play in the future, 3) the plans and supporting rationale for Servicing Mission 4 (SM4), the final planned maintenance mission to Hubble, 4) the expected orbital altitude of Hubble with and without various reboost options, 5) the reliability of the telescope in terms of expected lifetime for science operations, and 6) a description of the end of mission options and the significant aspects of each option.

Currently, the telescope is performing extremely well. All subsystems, which have been turned on since launch, have full redundancy except the gyroscopes and the Space Telescope Imaging Spectrograph (STIS). Three gyroscopes are required for normal science operations, and two of the six gyroscopes have failed. All six gyroscopes will be replaced on the next maintenance mission. STIS is the only spectrograph on Hubble, and is a very powerful multi-purpose instrument with a wide range of capability. STIS sustained an electronics failure in the year 2001, and the critical control electronics for the entire instrument are now single string. Thermal insulation on the telescope, and Fine Guidance Sensor 3 are degraded but not failed. Thermal insulation on the exterior of the telescope has degraded over time and will be repaired during Servicing Mission 4 (SM4). The only Fine Guidance Sensor that was never replaced since launch has degraded and will also be replaced in SM4. The original set of spacecraft batteries, installed prior to launch in 1990, are aging gracefully, and will be replaced during SM4 to ensure safe and productive operations through end of mission.

The generally excellent condition of the telescope is due to four servicing missions conducted over the past 10 years. Periodic servicing calls by astronauts have enabled the telescope to stay healthy and technologically fresh. The first visit in 1993 restored the full resolution of the primary mirror. Successive visits added new instruments to increase observing capabilities by between one and two orders of magnitude across the entire spectrum. Supporting subsystems have been maintained and upgraded to modernize the technology of the spacecraft and add capability such as additional electrical power, reliability, computing power, and data capacity. Four servicing missions have demonstrated that virtually everything on the telescope can be repaired through astronaut intervention, except for possibly the primary and secondary mirrors, which are in excellent condition. The ability to upgrade science instruments and data systems with new technology has increased the science data volume by a factor of 33 since the early 1990s.

Science Data Production
HST Monthly Calibrated Science Data Volume



Successive instruments have been built for substantially less cost than the previous set. This achievement results from reusing designs and components from one instrument to the next supplemented with the judicious application of new technology in high payoff areas. Building instruments for Hubble entails relatively low risk with high scientific gain.

Servicing Mission 4 scheduled for mid-2005 is the last planned servicing mission. Two new instruments will be installed on the telescope, the Cosmic Origins Spectrograph (COS) and the Wide Field Camera 3 (WFC3). The COS has very high throughput in the ultraviolet, an important performance niche not addressed by the more all purpose STIS. The Wide Field Camera 3 is a multi-purpose imaging instrument that covers a wide spectral range (200 - 1700 nm). Other hardware to be installed on SM4 includes six new gyroscopes, a new set of spacecraft batteries, a replacement Fine Guidance Sensor, an Aft Shroud Cooling System that will permit cooling of instrument detectors to the design specification and permit parallel instrument operations as the instrument surroundings warm up, insulation repair, and a Data System Cross strap kit to improve reliability of the science data path. The above tasks will require 5 full days of spacewalks, the maximum number permitted. The inclusion of additional items on Servicing Mission 4 will necessitate removal of one or more of the items mentioned above.

The telescope is located in low earth orbit (circular orbit at an altitude of ~575 km), and left unto itself will eventually fall to earth. Additional reboosts by the space shuttle are not required to achieve the currently planned mission end date in 2010. Using worst-case solar cycle assumptions, the telescope is expected to reenter in 2013 with no additional reboosts. A four nautical mile reboost in SM4 (2005) would delay Hubble's reentry by about 2 years, from 2013 from 2015. Likewise a ten nautical mile reboost in 2009 would delay reentry until 2020. It should be noted that as the altitude decreases the atmospheric density increases. Approximately one year prior to the reentry date the telescope will begin to encounter longer slew times and degraded science due to the higher atmospheric density overwhelming the precision control ability of the guidance control system. Also note that solar cycles have proven to be notoriously unpredictable. As a result, the *worst case solar cycle* should be used for purposes of developing end of mission or extended mission strategies.

The HST reliability model is used to predict expected science lifetime. The Aerospace Corporation developed and maintains the HST reliability model for the HST Program. It encompasses all spacecraft subsystems, with the exception of the scientific instruments, and considers hardware redundancies, component failure rates, and HST on-orbit experience. The reliability predictions are recalculated based upon the successful completion of a servicing mission. For predictions of expected science lifetime following the final maintenance mission, the model is updated with the assumption that full redundancy will be restored to the HST spacecraft hardware during Servicing Mission 4, e.g., six functional gyroscopes are restored. The model forecasts that the probability of science operations through May 2010 is approximately 30 percent, assuming a May 2005 launch date for Servicing Mission 4. Similarly, a space shuttle visit to Hubble in the 2009-2010 timeframe to correct failed hardware and restore redundancy would enable another three to four years of science operations and potentially extend operations to 2015 or longer.

The gyroscopes have proven, over the years, to be wear out items that require close attention. As a result, the Hubble Program is taking steps to enhance the life of the gyros and is proposing a new operations mode that would allow science to be performed using only two gyros if necessary. This mode would allow the execution of most science programs although some observations may not be schedulable due to the manner in which the two gyro mode functions. Additionally, jitter will be increased 3 to 4 times (total jitter of ~20-30 milli-arcseconds) above what is experienced today. The effect from this will be small for most observations, although small instrument apertures (e.g. STIS 0.025" and 0.034" wide slits) will not likely be usable. If the two-gyro mode is enabled after the fourth gyro failure, an additional 12 to 15 months of science operations can be expected excluding failures in other subsystems.

Several end of mission options have been considered, and the two most attractive are summarized below. As previously described, if Servicing Mission 4 were to be conducted in 2005 as currently planned, the odds are against continued science operation in the 2010 timeframe.

The first end of mission scenario, a post-SM4 space shuttle mission which addresses both HST disposal and science longevity, is a relatively straightforward extension of the HST Program's series of highly successful servicing missions – four missions to date consisting of 18 consecutive fully successful space walks to maintain and upgrade the HST. For this option the telescope could be serviced to increase life expectancy. However, the major new aspect of such a mission would be procuring a propulsion system that would permit controlled reentry and be compatible with HST requirements for maintaining performance and operational efficiency. The propulsion module would be installed on HST in one spacewalk. Maintenance could be performed on the telescope to enable continued science operations to approximately 2014. The propulsion module would provide the capability for controlled reentry into the ocean at any desired time in the future. This end of mission approach provides minimal uncertainty regarding schedule and cost. The major technological issue to be resolved in future studies is the compatibility of a propulsion module with HST science operations.

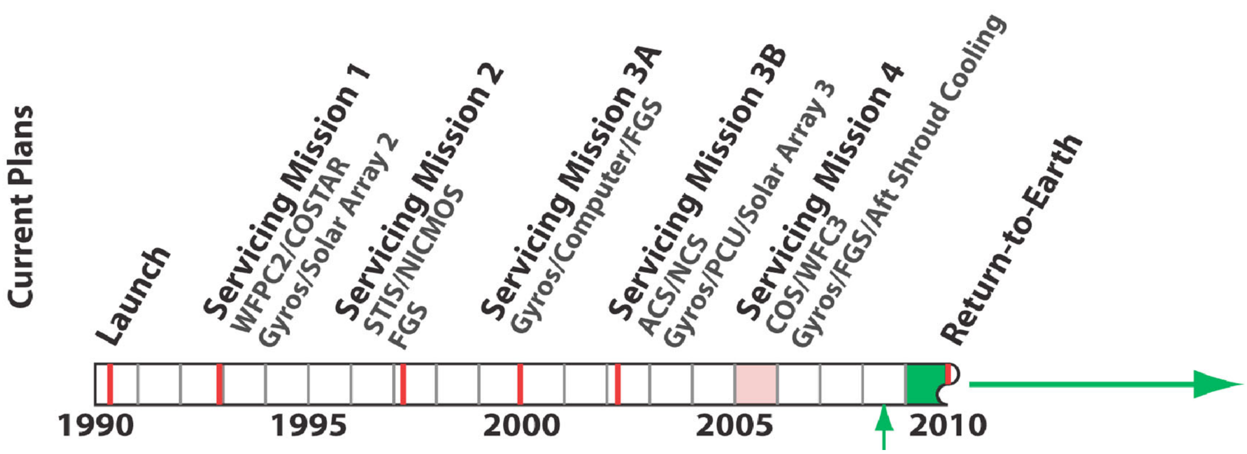
The other potentially attractive option involves robotic installation of a propulsion module after HST's operational life is over. This approach could be carried out independently of the Human Space Flight program. Some aspects of the module's design would be simplified because it would not have to be compatible with HST scientific performance requirements. The major drawback of this option is that the technology for autonomous rendezvous and capture is currently immature. It is not clear how much time or money will be required for the development of such a system. Reboosting Hubble, via the space shuttle, to a higher orbital altitude would delay its re-entry and give this technology more time to naturally mature. As previously described, a 4 nautical mile re-boost in SM4 would delay Hubble's reentry by about 2 years, from 2013 from 2015, although science operations would almost certainly have ceased long before then, without additional servicing beyond SM4. A shuttle provided reboost closer to the solar maximum in 2009-2010 would extend Hubble's orbital life by a decade or more.

If it were decided to extend the scientific lifetime of Hubble with an additional servicing mission in 2009 or 2010, in lieu of the currently baselined shuttle retrieval and return mission, either the astronauts could install a prop module at that time, or a reboost of up to 10 nautical miles could be executed to forestall re-entry for many years, allowing more time to develop the robotic system.

2. ROLE OF SERVICING IN MAINTAINING HST'S HEALTH AND TECHNOLOGY

2.1 HST SERVICING HISTORY

Shortly after the 1990 launch of HST, NASA discovered the primary mirror's spherical aberration. The installation of corrective optics and instruments in 1993 enabled HST to rapidly recover from its initial handicap, and to fully meet or exceed original expectations. Since this historic mission, three additional missions—in 1997, 1999 and 2002—added more capable scientific instruments and maintained vehicle systems in peak condition. NASA plans currently call for another HST upgrade and servicing mission in 2005 (SM4) and a retrieval mission in 2010. The following chart summarizes the maintenance of the telescope over the mission as well



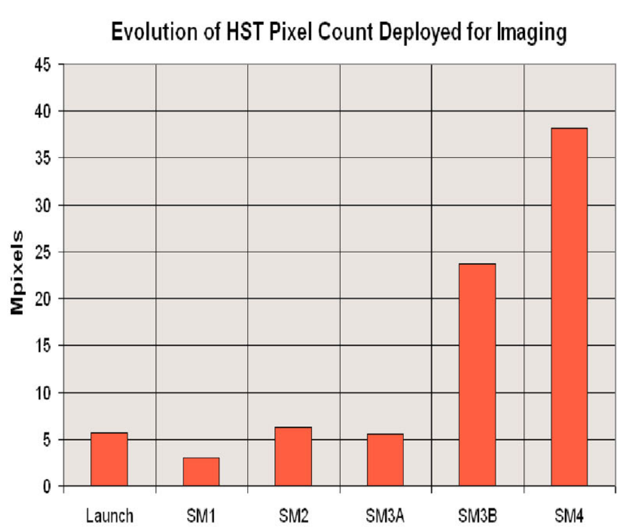
as options under consideration.

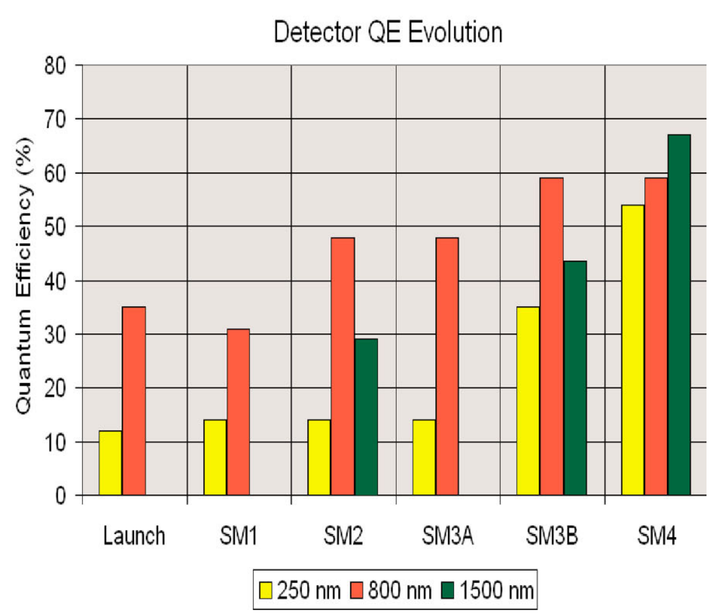
The HST scientific instruments are refreshed at three to four year intervals, which enable the observatory's capabilities to be tailored to address the most current and pressing scientific investigations. These instruments draw upon the latest technological advances, particularly in the area of detectors. Because detector systems are frequently the most demanding hardware aspect, techniques have been developed to allow for installing the most capable detectors shortly before deployment. As a result, HST has broken the constraining paradigm of more traditional, large space mission architectures, where long development, integration, and testing phases can prevent fielding the most capable and modern technologies.

On-orbit servicing also affords the opportunity to maintain HST vehicle systems, both to repair failures and upgrade capabilities to support more capable instruments. Furthermore the continuity of the HST program has enabled the HST mission to exploit the efficiency of using standard designs and procedures. For example, the instrument computers are common to five previous instruments, and the two that will be installed in 2005.

2.2 SCIENTIFIC INSTRUMENT EVOLUTION

This section summarizes the improvements in HST's scientific instrumentation through the servicing missions. The trend has clearly been to substantially increase the scientific capability with each mission. Two parameters, detector pixel counts and quantum efficiency (QE), are the improvements most directly responsible for the order of magnitude gains in scientific power which each new instrument possesses over the previous generation. The improvement trends are shown in the figure below. The following discussion concentrates on the detectors, since advances in this area are especially rapid (and the challenges they present are often the most severe).





During the _First Servicing Mission_, the key instrumentation improvements were the Corrective Optics Space Telescope Axial Replacement (COSTAR) and the Wide Field and Planetary Camera 2 (WFPC2). COSTAR used state-of-the-art mirror fabrication technology, originally developed for the semiconductor fabrication industry, to correct the spherical aberration in the primary mirror for three of the instruments. This was the first major demonstration of the flexibility provided by satellite servicing.

The new radial instrument, WFPC2, was internally corrected using the same mirror technology. WFPC2 deployed a new generation of charge-coupled device (CCD) detectors that provided improved performance in the ultraviolet while eliminating the quantum efficiency hysteresis in the original WF/PC instrument that required periodic solar flooding. The result was a far more stable instrument in the UV and a far more efficient camera that did not require solar flooding to stabilize the CCDs.

On _Servicing Mission 2_ (SM2), the Near-Infrared Camera and Multi-Object Spectrometer (NICMOS) enabled near-infrared astronomical observations with HST. Its 256x256 Mercury-Cadmium-Telluride (HgCdTe) detectors on a silicon Complementary Metal Oxide Structure (CMOS) multiplexer provided exceptional performance from 800 nm through 2500 nm. These were among the first detectors of this kind and performance level to be used for astronomy. (A thermo-mechanical problem led to early cryogen depletion, which terminated NICMOS operation 22 months after deployment. Operation was restored with the NICMOS Cooling System installed during SM3B.)

The Space Telescope Imaging Spectrograph (STIS), also installed during SM2, provided the observatory with a broad band imaging spectrograph. Compared to the 512 element linear arrays in HST's first generation spectrographs, STIS's dual photon-counters (1024x1024 pixel Multi-Anode Multichannel Array detectors) for the ultraviolet and a CCD (1024x1024 pixel) for the visible provide a tremendous increase in qualitative and quantitative capability. These advances in detector format enabled STIS to cover hundreds of independent spatial elements simultaneously in imaging spectroscopy, while improving the efficiency of high-resolution echelle spectroscopy by factors of 20 to 35 via simultaneous coverage of many echelle orders and the inter-order background. STIS also brought a solar-blind imaging capability to HST.

Servicing Mission 3B delivered the Advanced Camera for Surveys (ACS) and the NICMOS Cooling System (NCS). ACS provides over a factor of ten increase, relative to WFPC2, in discovery efficiency (twice the field of view and 5X the through-put) for imaging surveys using new large-format CCDs (two 2048 x 4096 butted CCDs). A red-sensitive coating further optimized these CCDs to improve ACS's ability to observe the distant Universe. On-orbit servicing enabled astronauts to retrofit NICMOS with a new, non-depletable cooling system, the NCS, restoring its scientific capabilities and improving its quantum efficiency at short wavelengths (a selectable temperature setting capability provided the ideal temperature for the detectors).

<u>Servicing Mission 4</u> will deploy the Cosmic Origins Spectrograph (COS) and the Wide Field Camera 3 (WFC3) instruments. By using an innovative design and large format, crossed delay line microchannel plate detector, COS will provide an order of magnitude improvement in the efficiency of high-resolution ultraviolet spectroscopy. WFC3 will extend HST's wide-field imaging capability into the near-UV by using a new, UV-optimized CCD technology. It will also increase the discovery efficiency (product of field of view and throughput) for near-IR observations by a factor of 11 through its wide field 1K x 1K HgCdTe array, which is optimized for operation between 800 nm and 1700 nm. This new IR detector provides electro-optical performance improvements over the NICMOS devices, while tailoring the spectral band allows for background-limited performance using only thermoelectric cooling (no cryogens).

2.3 POTENTIAL INSTRUMENT ADVANCES WITH AN ADDITIONAL SERVICING MISSION

The instrument upgrades through SM4 do not constitute fundamental limits to HST's potential capabilities. New technology becomes available continuously, leading to corresponding new opportunities for improving the observatory. Two instrument concepts illustrating the potential for continuing HST's scientific contributions into the next decade have been studied. These concepts are not meant to imply they are the only viable or desirable areas to pursue, but are illustrative of potential.

An instrument development time of four years has been assumed based on previous instrument development efforts. Coupled with an additional one year for the Announcement of Opportunity and selection process to complete, the top-level schedule would require that the acquisition process start five years before launch. Given that any additional servicing mission would not occur until the 2009 time frame, there would be sufficient time if the process were begun in FY2004.

High Contrast Imaging. A new optimized coronagraph[(1)(2)] for extra-solar planet detection would take advantage of either a deformable mirror or a high-fidelity inverse to the primary mirror using the optical fabrication technology used for the spherical aberration correction. This inverse has sufficient fidelity to minimize the mid spatial frequency (~50 cycles/diameter) imperfections in the primary mirror to provide the optical quality required for high contrast imaging. Both of these approaches build upon detailed understanding of the HST optical system to provide coronagraphic capabilities that would not have been possible earlier in the HST mission.

Wide-Field Imaging. A new wide-field imager[(1)(2)] using CCD or CMOS detector technology could provide a large-format (~100 square arc min) visible and near-IR imaging capability. It would take advantage of improvements in readout multiplexers and detector materials developed for the JWST and ground-based astronomy applications over the past few years to provide a greatly expanded capability for large area surveys of the high redshift Universe. The intrinsically radiation-hard CMOS infrared detectors, coupled with a simplified version of the

NICMOS Cooling System cryocooler (to achieve an operating temperature of ~ 140K), would provide this capability for any credible remaining lifetime of the observatory. Both CCD and CMOS technologies have now matured to a point that enables such an instrument to be built at relatively low risk and cost. Such an imager could be used to open up new discovery space in wide-field imaging in the near-UV through near-IR, and in particular, could be designed to be complementary to JWST capabilities.

Other Scientific Instruments. The examples above are drawn from readily accessible studies of potential new instruments that could address the important scientific questions of the next decade. Other options exist, including spectrographs and integral field spectrographs from the ultraviolet through the near-IR. An Announcement of Opportunity would undoubtedly reveal additional innovative ideas, and provide the process for selecting among these ideas.

2.4 OBSERVATORY SUBSYSTEM IMPROVEMENTS AND REPAIRS

The table below summarizes the trend of improvement in key observatory performance parameters.

Improvement in Key Observatory Performance Parameters

Parameter	Launch 4/1990	SM1 12/1993	SM2 2/1997	SM3A 12/1999	SM3B 4/2002	SM4 2005
Total Available Power (W)	2495	2495	2270	2150	2835	2770 (est.)
Power Available to SIs (W)	1080	1190	1035	1000	1760	1640 (est.)
Power Required by SIs	500	465	690	655	1260	1505 (est.)
Peak Science Jitter (mas, 60-second rms) due to all disturbances	39	23	No Change	No Change	14	No Change Predicted
Peak Science Jitter (mas, 60-second rms) due to disturbances occurring at least once per orbit	36	21	No Change	No Change	6	No Change Predicted
Quiescent Science Jitter (mas, 60-second rms)	3 30% of orbit time	3 35% of orbit time	No Change	No Change	3 95% of orbit time	No Change Predicted
Data Storage Capacity (G Bits)	3	No Change	12	21	No Change	No Change
Computer Processing Power (MIPS)	0.4	4.6	No Change	91	No Change	No Change

3. SERVICING MISSION 4 CONTENT AND RATIONALE

Servicing Mission 4 scheduled for mid 2005 is the last planned servicing mission. Two new instruments will be installed on the telescope, the Cosmic Origins Spectrograph (COS) and the Wide Field Camera 3. The design of COS is centered around a very important performance niche not addressed by the more all-purpose STIS spectrograph -- optimized throughput in the FUV. With this advantage, COS will be scientifically potent in several areas including: 1) the origins of large-scale structure in the universe and the intergalactic medium; 2) the formation, evolution, and ages of galaxies; and 3) the origins of stellar and planetary systems. The COS provides limited backup to STIS. It does not replicate STIS' capabilities for long-slit imaging spectroscopy, spectral coverage from 300 to 1000 nm, nor very high-resolution (R ~100,000) spectroscopy. The Wide Field Camera 3 is a multi-purpose imaging instrument that enables panchromatic imaging over a wide spectral range (200 - 1700 nm). The detector optimized to operate in the ultraviolet and visible (UVIS) wavelengths utilizes a CCD with advanced coatings that provide greater than 50% quantum efficiency at 250 nm. Combining the high quantum efficiency with its field of view results in a ~35x improvement over the rate at which the Advanced Camera for Surveys High Resolution Channel can tile an area of sky to a given photometric depth. The near IR channel in WFC3 also has high quantum efficiency and a large field of view, so it will supplant most of the NICMOS science capabilities, and serve as an important pathfinder for JWST. Other hardware to be installed on Servicing Mission 4 includes 6 new gyroscopes, a new set of spacecraft batteries, a replacement Fine Guidance Sensor, an Aft Shroud Cooling System, and a Data System Cross strap kit to improve reliability of the science data path. The Aft Shroud Cooling System will enable lower operating temperatures for the instrument detectors, thereby improving detector performance, and will also allow for increased science efficiency by providing more flexibility in the parallel use of instruments. Accomplishment of the above tasks will require 5 full days of spacewalks, the maximum number permitted. The inclusion of additional items on Servicing Mission 4 will necessitate removal of one or more of the items mentioned above, with a corresponding impact on performance or reliability.

4. OBSERVATORY ORBITAL LIFETIME

The telescope is located in low earth orbit (circular orbit at an altitude of ~575 km), and left unto itself will gradually fall back to earth. Orbit decay predictions for HST are performed on a continuous basis. Daily orbit altitude determinations and short-term decay predictions are used to support day-to-day science operations. Long-term decay predictions are utilized for servicing mission and lifetime strategy planning. Orbit decay predictions are made with the Goddard Trajectory Determinations System that uses the Jacchia-Roberts atmospheric model and the Schatten solar flux predictions. The table below summarizes HST altitude decay with and without various space shuttle reboost options.

	Reentry Date	
	Worst Case Solar Cycle	Nominal Case Solar Cycle
No Additional Reboosts	Dec 2013	Dec 2022
4 mile reboost in 2005 (SM4)	Dec 2015	April 2024
10 mile reboost in 2009 (no reboost in 2005)	June 2020	>2028

Additional reboosts are not required to achieve the currently planned mission end date in 2010. It should be noted that as the altitude decreases the atmospheric density increases, and approximately one year prior to the reentry date the telescope will begin to encounter longer slew times and degraded science due to the higher atmospheric density overwhelming the precision control ability of the guidance control system. Also note that solar cycles have proven to be notoriously unpredictable, as a result, the *worst case solar cycle* should be used for purposes of developing end of mission or extended mission strategies.

5. RELIABILITY

The HST end of mission is currently baselined for the year 2010, and the final HST maintenance action will occur in Servicing Mission 4 (SM4), which is expected to be launched sometime in 2005. The principal factors that affect the lifetime of HST and the duration of its science capabilities are addressed in this section. These four factors are:

- Degradation of the telescope's optics
- Likelihood of scientific instrument failures
- Health of spacecraft systems and their failure probabilities
- Decay of HST's orbit (previously discussed)

The first three items are discussed below.

5.1 OPTICAL TELESCOPE ASSEMBLY

Based on instrument performance histories there has been no detectable degradation of the Optical Telescope Assembly (primary and secondary mirrors). Two types of degradation are of concern: thin deposits of molecular contamination and physical degradation of the mirror surfaces. Thin deposits of molecular contaminants would be made evident by loss of sensitivity at ultraviolet wavelengths, particularly below 200nm. Physical degradation of the mirror surfaces, e.g. pitting or deposits of dust would be evident in changes over time in the properties of the images of stars or other point sources. It is not possible to measure independently the properties of the in-orbit primary optics. Instead measurements are taken with the onboard scientific instruments. Consequently, it is not possible to disentangle variations in reflectivity of the telescope optics from changes in the throughput of the instruments. However, measurements with the instruments place an upper bound on changes in the telescope. Based on these measurements, there is no evidence of degradation of the performance of the HST optics in the far ultraviolet at the 2-5% level over 13 years and across four servicing missions. As to the surface roughness of the primary optics, subtractions of point-source images taken years apart with WFPC2 for purposes of high-contrast imaging science (e.g., studies of circumstellar disks) would be sensitive to changes in the large-angle scattering pattern. These images have not revealed any evidence of problems.

5.2 INSTRUMENTS

Hubble's scientific instruments are each designed for a five-year operational lifetime in orbit. Historically, they have lasted considerably longer than that. Only one instrument, the Goddard High Resolution Spectrograph (GHRS), has suffered an electrical or mechanical failure that left it completely inoperable. That failure occurred in 1997, just a few weeks before the GHRS was to be removed from Hubble during the second servicing mission. The GHRS was one of the original five instruments launched on Hubble in April 1990. After about two years of operation, GHRS lost a portion of its observing capabilities, but a simple repair by the astronauts restored these during Servicing Mission 1 (SM1) in 1993. The Near Infrared Camera and Multi-Object Spectrometer (NICMOS) were originally designed to be cooled by a block of solid nitrogen ice, with an expected lifetime of about four years. A thermal short in the instrument reduced its “first life” to about 22 months. However, during Servicing Mission 3B (SM3B) in March 2002, astronauts installed a newly designed mechanical cooling system and the instrument’s science operations were resumed (with a 30-50% improvement in sensitivity).

At the conclusion of SM4, Hubble’s complement of scientific instruments will consist of two spectrographs and three cameras (as well as a Fine Guidance Sensor useful for astrometry). Key lifetime aspects for each are discussed below.

Space Telescope Imaging Spectrograph (installed 1997). Some loss of limiting sensitivity in the CCD detector is seen because of charge transfer efficiency degradation, though this is not performance limiting. UV performance is degrading by ~three percent/year at Lyman alpha, and less at longer wavelengths. This instrument is currently not redundant because one of the two electronics sets has failed. On an absolute scale, the risk associated with loss of redundancy is expected to be small, since infant mortality has passed, and there are no known threats to functioning electronics. The addition of the Aft Shroud Cooling System (ASCS) during SM4 will improve UV detector background performance by lowering the temperatures of the detectors.

NICMOS/NCS (installed 1997/2002). There are no specific concerns about scientific performance degradation. The experimental NICMOS Cooling System (NCS) has performed flawlessly during its first year of operation. The life-limiting element is likely to be the Power Conversion Electronics in the NCS that provides the power to drive the micro-turbines. This element is expected to have a nine percent failure probability after five years of operation. Current science plans are considering “campaign-mode” operations for this instrument after SM4, since Wide Field Camera 3 will be the dominant instrument for IR science.

Advanced Camera for Surveys (installed 2002). Charge-transfer efficiency degradation presents the most serious performance degradation, though some improvement may be achievable through the use of an internal lamp “post-flash” background, at the cost of increased shot noise. A six percent loss of useful detector area is expected by 2010 due to hot pixels.

Cosmic Origins Spectrograph (to be installed in 2005). There are no specific concerns about scientific performance degradation. COS will provide a limited degree of backup scientific capability for the more all purpose STIS in the UV and near-UV.

Wide Field Camera 3 (to be installed in 2005). CCD charge-transfer efficiency degradation will affect the UV-visible (UVIS) channel over time. The Marconi CCDs in the UVIS channel will perform better than previous generations in this respect, but they will not eliminate the concern entirely. While it is difficult to accurately translate ground radiation test results to on-orbit projections, the data indicates that up to a factor of two improvement over the ACS experience is possible. In addition, a novel charge-injection technique mitigates charge-transfer efficiency degradation through the electronic injection of a trap-filling background signal with much lower noise than the shot noise of a corresponding lamp flat. There are no specific concerns on degradation in the IR channel.

In summary, the lifetimes of WFC3 and COS should extend to 2010. Thus, in 2010 one could expect Hubble to have powerful instrumentation both for ultraviolet spectroscopy to very deep levels of sensitivity and for high-resolution, wide-field imaging spanning the range 200 – 1700 nm. The ACS will be about two years beyond its design lifetime in 2010, but can reasonably be expected still to be in operation. Its CCD detectors will have suffered significant levels of degradation in both charge-transfer efficiency and growth of the population of unusable "hot pixels" to about 6%. However, these signs of "aging" potentially affect only a sub-set of ACS science and there likely will be operational approaches to mitigating them. Mechanical cooling systems such as the one now cooling NICMOS have demonstrated lifetimes of over a decade in ground testing. The life-limiting element for NICMOS is likely to be the Power Conversion Electronics, and to have a 9% probability of failure after five years of operation. The near-infrared channel of WFC3 will supplant most of NICMOS' science capabilities. There is no accurate way of predicting STIS' longevity, as it operates on its remaining redundant electronics.

5.3 Expected Science Lifetime

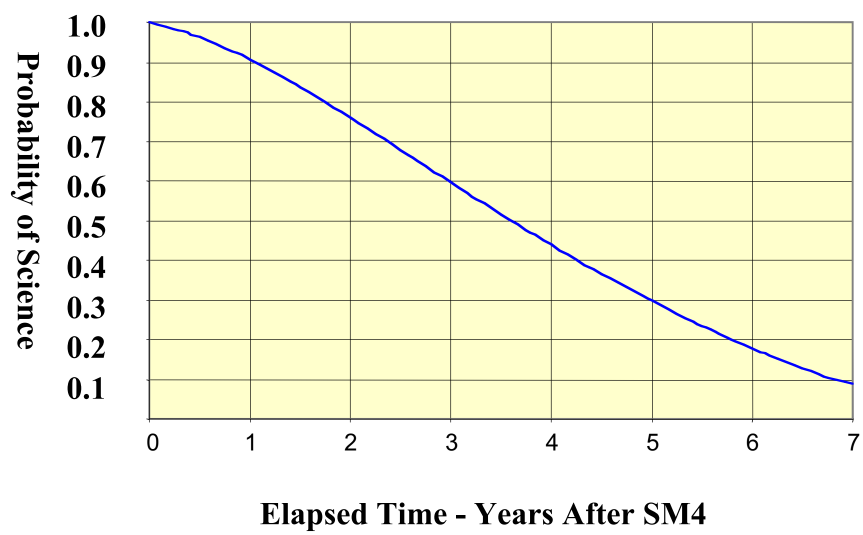
The HST science operations depend upon a healthy, reliable and efficient spacecraft. HST hardware subsystems have significant redundancy. However, hardware failures may reduce or eliminate redundancy to the point where additional failure can lead to the loss of function and ultimately to the loss of the science mission.

Maintaining HST spacecraft health and safety is the highest priority task for the HST Program. Spacecraft subsystem performance is continually monitored. In an effort to further extend the observatory's life, the HST program performs and updates reliability analyses to identify the lowest reliability items and to mitigate the identified risks. One example is the addition of the Data System Cross-strap kit on SM4 that will increase the fault tolerance of the science data path.

Beyond this, several other life-limiting mechanisms on HST are of concern and are not readily modeled for wear out. A number of steps have been taken to extend the life of these mechanisms. For example, flight planning minimizes solar array slews to ameliorate wear on the slew mechanism. Reaction Wheel Assemblies (RWA) are a wear item where a flight spare currently exists which could be installed if needed on a future servicing mission.

The HST reliability model is used to predict expected science lifetime. The Aerospace Corporation developed and maintains the HST reliability model for the HST Program. The model has been reviewed and validated by the HST Independent Review Team. It encompasses all spacecraft subsystems, with the exception of the scientific instruments, and considers hardware redundancies, component failure rates, and HST on-orbit experience. The HST Program models overall spacecraft subsystem reliability as a function of time. The reliability predictions are recalculated based upon the successful completion of a servicing mission. For predictions of expected science lifetime following the final maintenance mission, the model is updated with the assumption that full redundancy will be restored to the HST spacecraft hardware during Servicing Mission 4, e.g., six functional gyroscopes are restored. The projections of expected science lifetime are a function of time elapsed following a servicing mission. The reliability curve below is constructed from the product of the values of reliability versus time of the individual spacecraft subsystems. The model forecasts that the probability of science operations through May 2010 is 30 percent, assuming a May 2005 launch date for Servicing Mission 4. Similarly, a space shuttle visit to Hubble in the 2009-2010 timeframe to correct failed hardware, and restore redundancy, would enable another three to four years of science operations and potentially could extend operations to 2015 or longer.

Overall, the model tends to be conservative in two ways. First, an individual part failure is assumed to cause loss of function for the hardware component modeled. It is not inconceivable that components may still function at some level in spite of a single part failure. Secondly, loss of hardware functionality may be mitigated by workarounds, e.g., added flight software functionality, to overcome the hardware problem. It is simply not possible in advance of a failure to evaluate how pessimistic the model predictions might be.



The gyroscopes have proven, over the years, to be wear out items that require close attention. As a result, the Hubble Program is taking steps to enhance the life of the gyros and is proposing a new operations mode that would allow science to be performed using only two gyros if necessary. This mode would allow the execution of most science programs although some observations may not be schedulable due to the manner in which the two gyro mode functions. Additionally, jitter will be increased 3 to 4 times (total jitter of ~20-30 milli-arcseconds) above what is experienced today. The effect from this will be small for most observations, although small instrument apertures (e.g. STIS 0.025" and 0.034" wide slits) will not likely be usable. If the two gyro mode is enabled after the fourth gyro failure, an additional 12 to 15 months of science operations can be expected excluding failures in other subsystems.

It is important to note that the probability that the HST will be recoverable after an extended period is significantly higher than the predicted probabilities for continued scientific operation. Six years after the last servicing mission, there is a 70-80 percent probability that HST can be retrieved and serviced by the Shuttle.

6. END OF MISSION OPTIONS

The following discussion lists all EOM options that have been or are currently being considered, together with the salient aspects of each.

Uncontrolled Re-entry: Without intervention the HST orbit will eventually decay and the vehicle will re-enter and breakup in an uncontrolled manner. The time of re-entry is highly dependent on the timing and level of solar activity and whether re-boosts have been performed during the final servicing missions. In the case of no further re-boosts and a $+2\sigma$ peak level of solar cycle 24, re-entry is predicted in 2013. A re-boost of 4 nautical miles in SM4 (assumed mid-2005) is plausible, and this would extend the date of re-entry by approximately 24 months to 2015. Note that, approximately one year prior to re-entry, HST will start to encounter longer slew times and degraded science due to the increase in atmospheric density, which will overwhelm the precision control ability of the pointing control system. Although portions of HST will burn up in the atmosphere during re-entry, a significant debris field is expected to hit the surface of the earth. In particular the massive primary mirror and its surrounding titanium main ring – the structural backbone of HST – will almost certainly impact the earth. Calculations with the Johnson Space Center's ORSAT (orbital re-entry spacecraft analysis tool) program, which includes projections of human population densities versus time, predict a 1/700 probability of human casualty resulting from an uncontrolled HST re-entry. The current NASA requirement is a probability of less than 1/10,000. The present official policy of the NASA Office of Space Science is that the HST will not be allowed to reenter in an uncontrolled manner.

Return to Earth Via the Space Shuttle: This is the currently planned baseline option to which the HST Program Office is working. The technical implementation of a return to earth mission has been studied in detail by the HST Program. In summary, the execution of the mission is similar in scope to a typical servicing mission of the kind successfully executed by the HST

Program and its partners at JSC and KSC four times in the past. Because the HST must be stable and safe for shuttle retrieval, this option must be executed while the HST is functional and possesses sufficient redundancy in key systems to ensure it remains so during mission execution – e.g. thermal control, pointing stability sufficient for grappling, communications, commanding and telemetry. With complete loss of pointing control, HST would be semi-stable in a "gravity gradient" mode and still could be grappled with the Shuttle's remote arm. However, extended periods of gravity gradient operation could lead to HST structures becoming too cold, and possibly unsound, so that they would no longer be safe for landing within the Shuttle payload bay. Thus, the loss of redundancy in key systems, or the threat of irrecoverable entry into gravity gradient mode, would require an early "call-up" mission to assure that HST can be safely retrieved and returned to earth by the astronauts. There is a small but non-negligible chance (of order 10%) that a retrieval mission would be unsuccessful, and that the HST would subsequently undergo an uncontrolled re-entry. Taking this into account, the overall probability of human

casualty resulting from the return-to-earth option is about 1/7000, still somewhat worse than the NASA standard 1/10,000 (this does not include probabilities associated with loss of the shuttle itself).

The current HST Program budget for the execution of a retrieval and return-to-earth mission totals approximately $137M, with detailed mission planning commencing in 2007 for a 2010 mission. It is assumed that the costs of the Human Space Flight elements of the mission are covered outside the HST budget, as they have been for all other servicing missions. Although no official policy has been promulgated to the HST Program by NASA Headquarters, informally it is expected that the retrieval and return to Earth of the HST by Shuttle astronauts will be judged of insufficient value in relation to the risks to crew and shuttle vehicle, and that other EOM options must be identified.

Boost to a High Altitude Disposal Orbit: The feasibility of raising the HST orbit to an acceptable disposal altitude (2500 km) has been examined. This is far beyond the capability of the space shuttle and would require the addition of a large (22,000 lbs) propulsion system to the HST. This option is no longer under study, as the propulsion system required has been deemed impractically large and expensive.

Space Shuttle-Installed Propulsion Module Followed by Continuing Science Operations: The installation of a propulsion module carried to orbit on the space shuttle, potentially on a future servicing mission, would enable a controlled, safe re-entry when it is decided to terminate the HST mission. The HST Program completed a preliminary study of this option in 2001. It is currently the subject of an ongoing NASA feasibility study led by Marshall Space Flight Center. In this option it is essential that the installed propulsion module not unduly interfere with ongoing HST science operations – e.g. liquid propellant "slosh" should not impart unacceptable "jitter" to HST pointing control, nor should the module add so much mass to the HST as to yield unacceptably slow slewing rates. The module needs to be an autonomous, self-contained system requiring no external or HST-provided guidance, navigation and control services. It should require minimal (if any) connection to HST spacecraft systems (e.g., for electrical power).

In the preliminary (2001) study, five propulsion systems were considered: solid rocket motors, monopropellant, bipropellant and dual-mode systems, and ion engines. Of these only the electric ion engine was eliminated from further study (because of inadequate power). A field survey of existing systems and technologies was conducted in the preliminary study. Numerous potential vendors were identified that had prior experience with moderately priced, low-risk, low-development options for propulsion stages as utilized in prior NASA robotic missions (e.g., Mars Global Surveyor, Orbital Star-2, Triana, Deep Space-1, Chandra, COMSAT). The study concluded that only minor HST interface changes would be necessary and that these should be straightforward. Installation would require only one space walk. However, further study is warranted to provide independent verification of the technical soundness of the proposed approach. . Once installed, such a propulsion module would give considerable flexibility to HST operations, allowing re-boost if needed for continuing operations and de-orbit when needed without further reliance on the shuttle. Its principal drawback is that if it does not work properly when commanded, another shuttle mission would be required to repair or replace it. Otherwise uncontrolled re-entry is inevitable. Of course the shuttle mission to install the propulsion module could also do other maintenance and upgrades of HST, thus extending its scientific lifetime.

Recently Lockheed Space Systems has provided to the Marshall-led study team a description and cost estimate for a propulsion module that would meet the requirements of this option. The estimated cost is approximately $60M. It must be noted that the more detailed feasibility studies of this option currently in progress may or may not reach the same conclusions, as did the 2001 preliminary study.

Space Shuttle-Installed Propulsion Module After Science Operations Have Ceased: This is a variation of the prior option. In this case the performance characteristics of the propulsion module would not be constrained by issues of non-interference with continuing HST science operations. The module would presumably be simpler, and the interfaces with the HST would be very simple. Even if HST had spent considerable time in gravity gradient mode prior to the installation mission, and had become very cold and structurally unsound, this would not be a safety issue as it is in the case of shuttle retrieval and return to earth. The module still must operate reliably when commanded; otherwise uncontrolled re-entry or a follow-up shuttle mission would be the consequence. In this option there is no possibility of servicing HST to extend its scientific lifetime. One must consider if the objective of such a mission – to facilitate the controlled re-entry of a dead HST – is commensurate in value with the corresponding risks to the shuttle crew and vehicle.

Robotically Installed Propulsion Module Followed by Continuing Science Operations: A propulsion module launched on an expendable rocket could dock with the HST and provide the capability for a controlled re-entry at the appropriate time in the same manner as the shuttle-launched propulsion module described above. Currently there exists no capability within NASA for passive, unmanned rendezvous and docking with robotic spacecraft. This lack of technical maturity presents significant challenges in the near term, including feasibility, cost and schedule compatibility with an HST end of mission in 2010. Possible contamination of HST during rendezvous and capture is also a concern. This propulsion module would need to satisfy all the same constraints on compatibility with continuing HST science operations, as its counterpart in the shuttle-installed option described above. However, given that HST science operations would be on-going at the time of this mission, HST would be guaranteed to be stable and controllable – a cooperative partner for rendezvous and docking. A virtue of the robotic approach is that if the mission failed or if the propulsion module failed to function properly, further attempts could be made – additional expendable rocket missions could be undertaken – without reliance on the availability of the shuttle. If this option, or the next one, were selected, it is possible that space walk time on SM4 would have to be set aside for the installation of targets or other docking aids onto HST. Since the current payload slated for SM4 already fully subscribes the available space walk time, this means that other important items might have to be removed from the manifest. With no servicing mission planned subsequent to SM4, no further opportunity would be available to install such items on HST.

Robotically-Installed Propulsion Module After Science Operations Have Ceased: Analogous to the shuttle-installed propulsion module options described above, this is a variation on the prior robotic installation option. The propulsion module would be launched and docked to HST "on need" when it is decided that science operations are no longer viable. This approach significantly relaxes the design requirements for the propulsion module, because the science mission will have been terminated. It potentially offers a somewhat longer time to develop the required unmanned rendezvous and docking technology. At worst HST would be in a semi-stable gravity gradient attitude state, so that rendezvous and capture should be feasible. Once again, should the first robotic mission fail for any reason, presumably further attempts could be made at the cost of additional expendable rocket launches and the cost of replicating the propulsion module, without having to invoke a follow-up shuttle mission with its attendant risks. This option is also under active study by Marshall. Its cost is roughly estimated to be around $230M.

Conclusions:
None of the available options described above can be considered "ideal". Each has significant elements of risk or issues of feasibility or both. However, two of the options stand out as being more attractive than the others – a shuttle mission to install a propulsion module, followed by continuing science operations, or a robotically-installed propulsion module after science operations have ceased. To reiterate, further integrated systems-level studies are required to determine the feasibility, reliability, and engineering details of these or any other propulsion module option.

The attractive shuttle mission option is a relatively straightforward extension of the HST Program's series of highly successful servicing missions – 4 missions to date consisting of 18 consecutive fully successful space walks to maintain and upgrade the HST. The major new aspect of such a mission would be procuring a suitable propulsion system that would be compatible with HST requirements for maintaining its performance and operational efficiency.

The other potentially attractive option, robotic installation of a propulsion module after HST's operational life is over, could be carried out independently of the Human Space Flight program. Some aspects of the module's design would be simplified because it would not have to be compatible with HST scientific performance requirements. The major drawback of this option is that the technology is currently immature. It is not clear how much time or money will ultimately be required for the development of such a system. Re-boosting Hubble to a somewhat higher orbital altitude would delay its re-entry and give this technology more time to mature. For example, a 4 nautical mile re-boost in SM4 would delay Hubble's re-entry by about 2 years, from 2013 to 2015, although science operations would almost certainly have ceased long before then, without additional servicing beyond SM4.

If it were decided to extend the scientific lifetime of Hubble by means of an additional servicing mission in 2009 or 2010, in lieu of the currently base-lined shuttle retrieval and return mission, either the astronauts could install a prop module at that time, or a re-boost of up to 10 nautical miles could be executed, which would extend Hubble's orbital life by a decade or more, allowing more time for NASA to develop a suitable robotic system.

In summary, if SM4 is executed in 2005 as currently planned, the odds are against continued HST science operations much beyond 2009-2010. A small re-boost of HST in SM4 would forestall its re-entry by about two years, allowing more time for a robotic retrieval mission and controlled re-entry. A shuttle-based servicing mission in the 2009-2010 timeframe would enable science operations to continue to approximately 2014-2015 or potentially longer. A prop module installed by the astronauts in 2009 or 2010 would provide the capability for controlled de-orbit and re-entry at any desired time in the future. A re-boost during such a mission could extend Hubble's orbital lifetime for a decade or more, and provide significant additional time in the development of a robotically installed propulsion module.

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