AN EARLY STUDY OF DISPOSAL OPTIONS FOR THE HUBBLE SPACE TELESCOPE

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ABSTRACT

Since its launch in 1990, the Hubble Space Telescope has been one of the most productive scientific endeavors in history. Nonetheless, all good things must eventually come to an end, including the useful life of this spacecraft. Since Hubble has no on-board propulsion system, its orbit is currently decaying, and recent models predict that without any intervention the telescope will reenter the atmosphere, no earlier than 2031. Due to the very large size of the spacecraft and the extensive use of materials that are expected to survive reentry heating, an uncontrolled reentry would pose an unacceptable risk of injury to the general public. The original designs called for the telescope to be retrieved by the Space Shuttle at the end of its mission, but that is no longer an option. An early study has been conducted to examine options for disposing of Hubble in a way that would drastically reduce the risk, or eliminate it entirely. In order to lay the foundation for an eventual decision several years from now, four basic options for disposal were studied, each based on three possible telescope hardware status conditions. The study included an examination of the feasibility, reliability, end-to-end risk, cost, and schedule for each potential approach. A summary of the findings of the feasibility, reliability, and risk assessments from that study will be presented.

1 INTRODUCTION

There is an international effort to limit the generation of, and risks from, orbital debris. This international effort has produced the IADC Space Debris Mitigation Guidelines and the United Nations Space Debris Mitigation Guidelines. The U.S. Government Orbital Debris Mitigation Standard Practices (USGODMSP) formally adopts these practices for all United States government-sponsored missions. Within NASA, the detailed policy and technical implementation of orbital debris limitation are documented in NPR 8715.6, presenting policy and programmatic requirements, and NASA-STD 8719.14, presenting technical requirements for NASA missions. While there are a total of fifteen NASA orbital debris limitation requirements, for the purposes of the end of the HST mission, two technical requirements clearly dominate the concerns: those regarding the disposal method and the reentry risk.

This paper will present a background on the Hubble Space Telescope (HST), providing detail on its extraordinary 20+ year mission life and information on how NASA has proactively taken the initiative to apply the above mentioned guidelines and Standard Practices to HST. These details are presented through a discussion of the results of a NASA initiative study to assess compliance methodology and basic mission architecture. Also presented are implications and options available to NASA to maximize compliance with the guidelines while minimizing mission risk.

2 BACKGROUND

The baseline assumption at this time is that the HST will remain an active and vital asset for at least another decade, in parallel with the James Webb Space Telescope for at least five years. If still operational, it would be desirable to continue collecting science until the orbit decays to 500 km before beginning any disposal maneuvers. Current predictions indicate that HST will remain above 500 km until at least 2024, so that the selection of a disposal approach does not need to be made for about another five years.

The HST Project is an international partnership with ESA and NASA. It is considered one of NASA's most successful international partnerships, forging a consolidated team of dedicated scientists and engineers to execute six extremely complicated and successful space shuttle missions. This relationship is ever evolving as ESA and NASA scientists continue to expand our knowledge of the Universe. As we approach the eventual disposal of the HST observatory, ESA and NASA engineers are committed to work together to complete this important mission with same cooperation and excellence leadership as has been demonstrated over the past 30-plus years.

Hubble is a Ritchey-Chretien design Cassegrain telescope with a 2.4 meter mirror. It is 15.9 meters long and has a diameter of 4.2 meters. The original observatory (including the spacecraft bus as well as the instruments) weight was approximately 11,000 kg. It was originally launched with five scientific instruments.

On April 25, 1990, HST was deployed into its low earth orbit, (nominal orbit 590 km or 320 nmi, inclined at 28.5 degrees from the equator), by the crew of the Space

Transportation System (STS) mission, STS-61. In the subsequent 23 years of on-orbit operations, the observatory has been visited five times by shuttle astronauts to upgrade, replace and/or repair spacecraft systems and science instruments.

One characteristic that makes HST unique among science satellites is its capability to be serviced by astronauts during dedicated Space Shuttle flights, also known as HST Servicing Missions (HST SM). Five HST SMs were successfully conducted between 1994 and 2009. These five missions had specific objectives, and each mission left the vehicle in better shape than before. For example, the new Wide Field Planetary Camera -2 and the Corrective Optics Space Telescope Axial Replacement (COSTAR), installed in the first servicing mission, HST SM-1, enabled the HST Program to successfully achieve its Level 1 requirements. The final mission, HST SM-4, upgraded the observatory to full operational redundancy of the spacecraft systems and restored operational capability of two science instruments. The mission also expanded the resolution of science observations through the installation of Wide Field Camera -3 and the Cosmic Origins Spectrograph (COS).

NASA proactively prepared the spacecraft for disposal by installing the Soft Capture Mechanism (SCM). The SCM is intended to provide docking compatibility with robotic and human spaceflight missions, including various international ISS resupply vehicles and manned vehicles (e.g., Orion). Photography of HST, using video cameras that were candidates for future servicing vehicles, recorded imagery of HST's final flight configuration during release.

3 SUMMARY OF REQUIREMENTS

It is important to note that while the current requirements in NASA-STD 8719.14A are applied to existing operational missions, they were not in existence at the time of the launch of HST. In some cases, therefore, the mission was not designed with them in mind, and it may be impossible to meet them with the existing operational hardware and plans.

Disposal methods and timing for NASA's LEO missions are specified in NASA-STD 8719.14A, Requirement 4.6-1. There are three basic options specified for the disposal: atmospheric reentry, maneuvering to a storage orbit, or direct retrieval. Atmospheric reentry can be achieved either through natural decay that results in reentry within 25 years after the completion of the mission (but no more than 30 years after launch), or by controlled reentry soon after the mission is complete. The requirement defines a storage orbit between 2000 km altitude and 500 km below GEO, excluding the commonly used region of 19,200 km to 20,700 km. Direct retrieval refers to capturing the spacecraft and returning it to the ground intact. This last approach is not currently a practical option for NASA missions since the conclusion of the Space Shuttle program.

This requirement presents both restrictions on the disposal of HST and options for alternative approaches. The primary purpose of limiting the time in operational orbit regions is to mitigate the risk of large object collisions which could generate a generous quantity of secondary debris objects. As implied by the requirement, this can be achieved either by raising or lowering the orbit to outside of the protected operational regions.

It is interesting to note that the USGODMSP and the international guidelines on removal from operational orbit regions refer only to removal within 25 years after the end of the mission. As a result, HST can probably meet those guidelines even without any intervention, but will likely violate the more stringent NASA disposal requirement (30 years since launch) even while the mission is still operational. In the case of such a valuable and productive mission, however, the extended orbital lifetime is considered reasonable and acceptable.

The risk to the general public from reentering NASA space vehicles is controlled by NASA-STD 8719.14A, Requirement 4.7-1. An overall end-to-end risk (including any active disposal) of a human casualty from surviving debris of 0.0001 (1 part in 10,000) is defined as the acceptable risk threshold. The requirement further defines a threshold of 15 Joules as the minimum impact energy for an object to be capable of inflicting a casualty. The 'buffer zone' around land masses for controlled reentry into the open ocean is also defined by Requirement 4.7-1.

Detailed modeling of the spacecraft has shown that an uncontrolled reentry would result in a reentry risk of approximately 0.004, or 1 in 250 odds of a single significant injury. One way to envision this risk is that even if 250 spacecraft like HST were to reenter uncontrolled, you would expect only one significant injury to occur. Clearly, though, the risk exceeds the level that is considered acceptable by a factor of 40, so it is prudent to study options to reduce the risk.

Any sort of active disposal of HST becomes complicated, though, by the lack of an existing propulsion system on-board the spacecraft. Several basic methods of orbit change were studied, including propulsion systems, tethers, sails, and others, and most involved a need for rendezvous and capture of the HST spacecraft. The need for significant control authority for targeted reentry precluded non-contact de-orbit options, so these were not studied in detail. Because an active disposal of HST can therefore only be brought about through the launch and rendezvous of an additional disposal vehicle, it is necessary to include the reliability of the launch and rendezvous in the end-to-end risk estimate.

Another complication in early planning for HST disposal is the inability to accurately predict what condition the spacecraft might be in at the time of disposal. Ideally, at least the attitude control system would be functional, so that the vehicle could be oriented and steadied during rendezvous. Because that can not be relied upon in a vehicle that will have by then been on-orbit for 35 years or more, it is necessary to plan for the worst-case scenario of a non-cooperative 'dead bird' during rendezvous. It is still desirable, though, for the disposal vehicle design to retain the capability of continued science operations, if the HST hardware supports that goal.

4 STUDY GOALS/ CHARTER/ OBJECTIVES

Prior to this study, engineering judgment within NASA was that in order to achieve the desired risk reductions, it would be necessary to plan for a redundant mission. The first mission would have a certain probability of success, but in the case of a launch vehicle failure or other mission failure, a second system would need to be built and launched. Based on this, NASA was going to need to start building the first system early enough that, should it fail, a second could be built and launched before HST naturally reenters. This meant budget planning to allocate funding in relatively early years, a potential disposal while HST was still operational, and other unattractive measures. The primary goal of this study was to inform NASA as to whether its original scenario was necessary, or whether there were reduced cost options that would have lower, and later, impact on the NASA budget.

The study would also ensure that all assets needed to prepare for a future mission were captured, and that all prior study on HST disposal was taken into account. In 2003, after the Shuttle Columbia was destroyed during reentry, NASA decided that return of HST via the Shuttle payload bay was no longer an option, as it was too risky to the crew. Plans began for including hardware in the final servicing mission that would enable a controlled reentry. This effort centered on a propulsion module to be carried to space in the Shuttle, and installed onto HST during the mission, and lay dormant until needed years later. In 2004 the Constellation Program was started, and with an earlier planned end to the Shuttle program and other safety concerns, the final servicing mission was cancelled by the Agency. Work began on a mission that could rendezvous and capture/berth or dock with HST, attach a propulsion module, and either deorbit right away or wait until HST ceased operations. Within a short time, Congress authorized a study of a more ambitious HST Robotic Servicing and Deorbit Mission. During one year, the study team designed the deorbit propulsion module, plus a servicing robot, special tools, and replacement parts to both extend the life of HST and prepare for disposal. In 2006, new NASA Administrator Mike Griffin developed a plan to conduct a final Shuttle-based servicing mission, and outfit HST with a docking fixture that would make HST compatible with the Constellation Program. This mission occurred in May 2009.

This latest HST De-orbit Study began with a combined NASA Headquarters and Cosmic Origins Program Office tactics meeting in June 2011. The key study objective was to identify a mission concept capable of autonomously achieving a safe disposal of HST and minimizing the overall mission cost to Science Mission Directorate. The study was to look at existing vehicles as well as fresh designs and emerging technologies. By January 2012, an Aerospace Corporation study team completed a 6 month study effort and delivered a task report containing high level architecture and costing information. The Aerospace report served as reference material for the subsequent, 3-month HST Disposal Architecture Design Laboratory (ADL) study. The agency intention was to enable the effort to enter a "Hold Phase" at minimal cost, monitoring further developments, until work needed to resume. The objective of the study was to provide recommendations for enabling a Pre-Phase A project at a later time.

The ADL is the newest expansion of the Integrated Design Center (IDC) at NASA's Goddard Space Flight Center. As with the other IDC laboratories, which focus on specific mission and instrument designs, the ADL brings together subject matter experts from a number of disciplines for a focused short-term study. In the case of the ADL, a wide variety of options is studied, to identify the most practical approach to solving new and unique challenges. The HST Disposal Study was the first to be conducted by the ADL.

5 STUDY METHODOLOGY AND RESULTS

5.1 Orbit Predictions

The minimum timing until performing any active disposal of HST (and thus the timing for a decision on the disposal approach) is driven strongly by orbital decay from the current 554 km x 559 km x 28.55° orbit. That orbital decay process is in turn driven strongly by atmospheric drag, which is a function of solar flux. The solar flux varies during an approximately eleven-year cycle. Natural variations in the sun cause the solar flux to be relatively predictable over about one cycle, but less so beyond that point. This variability in the solar flux predictions is one reason to delay the decision until the orbital decay can be more clearly estimated.

Figure 1 illustrates the predicted decay in mean altitude over time, assuming the current starting altitude, a ballistic coefficient of 82 kg/m^2, and current Schatten solar flux predictions. The plot also shows projected mean altitude for both the earliest and latest credible solar flux cases (Schatten +2σ early and -2σ late, respectively). The nominal expected reentry date is in 2040, but for planning purposes the earliest date will be considered. It is believed that 500 km represents the best compromise between continued collection of science data and the stability needed for a potentially non-cooperative capture by a disposal vehicle. Thus, baseline planning at this time is for disposal to commence in about 2024.

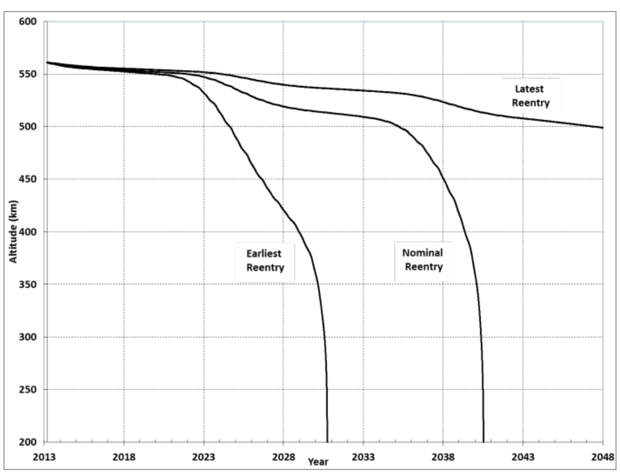

Figure 1. Orbital Decay Profile Predictions for HST.

It is desirable to delay the decision process regarding HST disposal as long as possible for several reasons. Just during the duration of the study, the reentry date predictions for HST varied by greater than one year, demonstrating the value of actual data in the planning phase. Technology development also advances at an unpredictable pace, so that new technologies may become practical at a faster or slower pace than is currently expected, including advances in launch vehicle reliability. While it is hoped that the HST spacecraft bus systems and instruments will be functional for a long time, short-term failures may affect the disposal complexity or timing. By delaying the final decision until roughly 2018, each of these factors will be more definite, enabling a better data-driven decision than could be made today.

5.2 Disposal Options Examined

As described above, NASA-prescribed basic disposal options for reducing the reentry risk for HST are limited to controlled reentry or raising the spacecraft into a storage orbit. The feasibility of both of these options was studied, as well as various methods to achieve these goals. It quickly became clear that some options were highly impractical, and they were not studied further for HST disposal.

Controlled reentry requires a precise change in velocity applied to the vehicle at exactly the right time, to ensure that reentry occurs in a targeted location. It is beneficial to use a series of phases to refine the trajectory, with the final phase intended to produce a perigee of 50 km or less. Various methods for delivering that change were examined, including chemical propulsion, drag enhancement, electrodynamic tethers, and laser nudging. Some of these large categories include several detailed options.

Orbit raising requires the application of thrust to increase both apogee and perigee, circularizing the final orbit for long-term stability. Methods studied for delivering that thrust included chemical propulsion, solar electric propulsion, electrodynamic tethers, and solar sails.

Most of the disposal methods studied include a need for rendezvous and capture of the target vehicle. The existing hardware configuration of HST was examined, to determine the practicality and remaining development necessary for docking. While a docking ring was installed onto HST during the final manned servicing mission, the development of a mating ring for the docking vehicle was not completed. Other attach points were considered, but provide less capability to deliver the necessary thrust through the Center of Gravity.

On-orbit demolition of the spacecraft was also briefly studied, but quickly dismissed as an option. Examining just the main mirror (representing about 2 percent of the total risk), it was determined that the 1000 kg mirror would need to be reliably broken pieces smaller than 67 grams in order to reduce the risk to the public. This is because each piece of surviving debris can endanger any person within an area approximately 0.3 m around it. Increasing the number of surviving pieces rapidly increases the risk, analogous to a shotgun pattern versus a rifle bullet. Until those pieces are so small that their impact energy is less than 15 Joules, they are considered dangerous. If the mirror could be broken perfectly into 67 gram particles, it would create about 15,000 pieces, though of course in actuality there would need to be even more breakup to account for size variation. Any more than 14 chunks larger than 67 grams would increase the risk from the mirror, relative to intact reentry. Given the extent of demolition needed to make even this one piece of the spacecraft safer, complete destruction to reduce the risk is obviously not feasible.

5.3 Basic Feasibility

Non-contact disposal options offer the advantage of lower operations complexity, and potentially lower cost. In the case of laser orbit modification, the lack of a launch vehicle is also attractive. Frozen mist has been proposed for orbit modification through deceleration, by distributing droplets of liquid or tungsten dust in the path of the target vehicle, without the need for docking. Unfortunately, these methods can cause only gradual orbit decay, and are therefore insufficient to result in a positively targeted reentry point necessary to reduce reentry risk. These methods have no application for orbit raising on the scale needed to reach a storage orbit. Moreover, some non-contact methods have the potential to increase the drag on other active spacecraft in the area of influence, which the affected satellite operators would consider unacceptable.

Drag enhancement techniques were studied, including the ballute (inflatable decelerator), solar sail, and drag enhancement tethers. Again, these approaches provide insufficient control authority to accomplish a targeted controlled reentry. While they could hasten the reentry date, the ground footprint could not be assured to occur in an area with practically zero population density. The solar sail is considered impractical for boosting HST into a storage orbit due to likely conflicts with the large solar arrays on the spacecraft. Clearly, drag enhancement methods have no application for orbit raising.

Electrodynamic boost tethers and solar electric propulsion both have the capability to impart low thrust over a long period of time, with minimal monitoring effort. While this would not support controlled reentry, these approaches may have potential for boosting HST into a storage orbit, since that can occur over a longer time consistent with their lower thrust. These techniques are considered worthy of further study, particularly as the technology matures.

Chemical propulsion is by far the most conventional and well-understood of the orbit modification approaches. A wide variety of propellants can be considered, from hydrazine to the newer ‘green’ propellants currently under development. As broad categories, monopropellant and bipropellant technologies were studied separately for feasibility. While either approach could provide the necessary control authority for a targeted reentry, it was found that bipropellant designs are likely the better choice in terms of delivering higher thrust per unit mass, thus reducing launch mass. It was, however, determined that the amount of propellant needed, even with a bipropellant design, was impractical to achieve the 2000 km defined storage orbit region.

5.4 Option Refinement – 1200 km storage

Since raising the orbit of a spacecraft as large as HST to greater than 2000 km by traditional propulsion requires an impractical amount of propellant, other potential storage orbit options were studied as well. Figure 2 shows that there is a region between 1200 km and 1350 km where the orbital debris density is very low (about the same as that of the current HST orbit), which is within the reach of standard chemical propulsion systems. The low existing debris density results in a relatively low collision probability for any objects left in that orbit thus lower long-term debris generation potential. Such an orbit would be stable for centuries, essentially eliminating any concerns over reentry risk. This approach, however, would require a very significant deviation from NASA and US Government policies, as well as the international guidelines described above. Nonetheless, for the purposes of this early study, it has been retained as an option to be studied further.

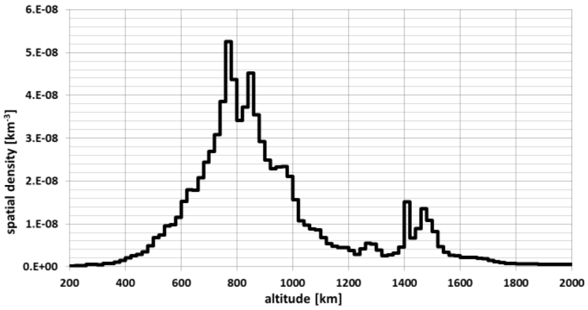

Figure 2. Spatial Density of Orbital Debris across the LEO Region (data supplied by ODPO)

5.5 Reliability

The reliability of a successful disposal of the HST spacecraft is a major driver in the disposal method selection, as well as the design choices in the hardware to carry out that design. An early study such as this requires that several simplifying assumptions be made in order to estimate the probability of success. These assumptions include the expected launch vehicle reliability (0.98), the availability of an exact replica of the docking fixture now on HST, and the ability to make four attempts at the docking to HST, learning from each successive attempt if necessary (0.9999 after four attempts). Hardware reliability estimates were based on time-related failure rates as well as estimated hardware complexity, so that the reliability depends heavily on disposal mission duration. Early estimates indicated that solar electric or electrodynamic tether propulsion to 2000 km was impractical without redundancy in portions of the systems, so redundancy was assumed for the reliability of those approaches. This study found that reliability of up to 0.9749 could be achieved if conservative design guidelines are followed. The acceptable risk requirement can be met with an end-to-end reliability of 0.976, so it is believed that a single mission will be sufficient, in terms of the disposal hardware.

5.6 End-to-End Reentry Risk

One of the main drivers for even discussing the intentional disposal of HST is the result of a previous assessment of the HST reentry risk. In 2004, the Orbital Debris Program Office (ODPO) at NASA/JSC used the Object Reentry Survival Analysis Tool (ORSAT), version 5.8, to simulate the reentry of HST. Through a detailed study of the construction of the spacecraft, it was estimated that approximately 195 m^2 of the Earth surface would be at risk from parts of HST that survive an uncontrolled atmospheric reentry (referred to as the Debris Casualty Area, or DCA). That DCA results in a risk of about 0.004, or 1 in 250 odds of a single significant injury, if HST were to reenter in a random location (within the 28.5°N to 28.5°S latitude region). There are plans to update this baseline DCA to account for hardware changes during the final HST servicing mission, which occurred in 2009.

Reentry risk is generally calculated using Equation 1.

$$Risk_{uncontrolled} = \rho_{pop} \times DCA \qquad (1)$$

Where ρ_{pop} is the average population density over the latitude band bounded by the orbit inclination. Population density values, extrapolated to the estimated year of reentry, were supplied by the ODPO, and consider the time spent at various latitudes within the band. In the specific case of controlled reentry disposal, the end-to-end reliability of the disposal is incorporated into the risk estimate as in Equation 2.

$$Risk_{controlled} = \rho_{pop} \times DCA \times (1 - P_{success}) \qquad (2)$$

When estimating the end-to-end risk for various HST disposal scenarios, it is necessary to consider each phase of the disposal mission and the probability of success for that phase. For example, the launch vehicle could potentially fail, leaving HST on orbit, with no improvement over the original uncontrolled reentry scenario (a launch vehicle failure here is assumed to occur prior to achieving orbit, so any disposal vehicle debris would reenter harmlessly over water). Equation 2 above was used to estimate the risk for each possible outcome: launch vehicle failure, unsuccessful disposal, and successful disposal – and the results were totaled for each disposal scenario. The probability of success, DCA, and reentry year vary from scenario to scenario, so that the total end-to-end risks varied by more than a factor of ten.

The DCA was estimated for all possible outcomes of the HST disposal options under study. In the case of an uncontrolled reentry of HST (through inaction or launch vehicle failure), the baseline ORSAT result of 195 m^2 was used. For the controlled reentry scenarios, a propulsion system was assumed that included demiseable COPV pressurant tanks, and four large titanium alloy propellant tanks, as well as about 13 m^2 DCA contribution from other components, for a total DCA of 25 m^2 for the disposal vehicle, and 220 m^2 for the mated pair. The scenarios that include boosting to 1200 km use very similar basic hardware designs, and result in the same DCA estimates for reentry. Finally, the scenarios that use electric propulsion to raise HST to 2000 km require only one propellant tank, which was assumed in this case to be titanium. The remaining components in these scenarios are assumed to contribute about 7 m^2, for a total DCA for the disposal vehicle of 10 m^2, and 205 m^2 for the mated pair.

6 RESULTS

After an initial wide range of options was studied, four basic disposal approaches were selected for detailed consideration: 0) do nothing (baseline), 1) controlled reentry, 2) boost to 1200 km, and 3) boost to 2000 km. These options are represented graphically in Figure 3. The reliability, total risk, schedule, and cost of each was examined in order to form some early baseline comparisons. The estimated reliabilities, and their effect on the end-to-end reentry risk, are shown in Table 1.

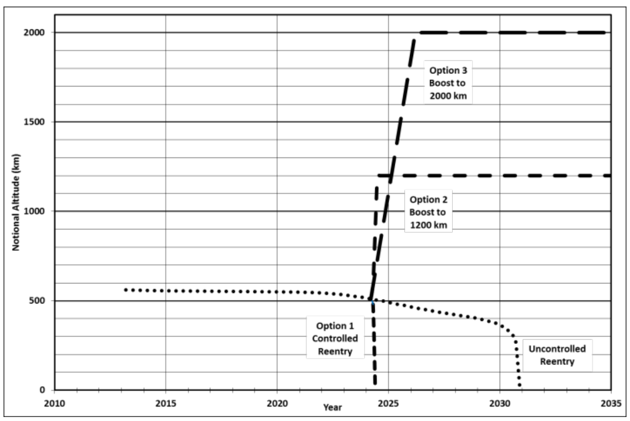

Figure 3. Altitude Profiles for Disposal Options Studied

It is important to discuss the role of the mission operations timeline in these results. While controlled reentry or 1200 km storage might be achieved within a month after launch, solar-electric propulsion or electrodynamic tether to the 2000 km storage orbit is estimated to take nearly two years to complete. As described above, time is a major contributor to the reliability estimates, so that those disposal options that take longer to accomplish will carry a relatively lower reliability estimate, resulting in a higher overall reentry risk.

As shown in Table 1, the overall reentry risk to the public is estimated to decrease dramatically through any of the intentional disposal options studied. Using either a controlled reentry or raising the orbit to 1200 km, it is possible to reduce the risk by a factor of 39 times, to nearly 1 part in 9000. Raising HST to the sanctioned storage orbit altitude of 2000 km reduces the reentry risk by a factor of almost 12, to better than 1 part in 2600. Launch vehicle reliability is the major driver preventing the NASA design requirement of 1 in 10,000 from being met in this preliminary study. Updated reliability values for the specific launch vehicle chosen may very well demonstrate that the NASA requirement is achievable. In any case, it is feasible to greatly reduce the reentry risk by a number of approaches.

Outcome - LV Failure	Option 0	Option 1	Option 2	Option 3
DCA (m^2)	195	195	195	195
Probability	1	0.02	0.02	0.02
Reentry Year	2030	2030	2030	2030
Population Density	22.17	22.17	22.17	22.17
Risk	0.004323	0.000086	0.000086	0.000086
Outcome - Unsuccessful Disposal				
DCA (m^2)		220	220	205
Probability		0.0051	0.0051	0.0638
Reentry Year		2030	2030	2030
Population Density		22.17	22.17	22.17
Risk		0.000025	0.000025	0.000290
Outcome - Successful Disposal				
DCA (m^2)		220	0	0
Probability		0.975	0.975	0.7087
Reentry Year		2024	N/A	N/A
Population Density		0.00	0	0
Risk		0.000000	0.000000	0.000000
Total Risk	**0.004323**	**0.000111**	**0.000111**	**0.000376**
Odds of an injury (1:	**231**	**8995**	**8995**	**2658**

Table 1. Total Reentry Risk for the Main Disposal Options Studied

Due to the slower passage through altitudes with relatively higher spatial density, an additional risk was studied for the 2000 km storage orbit disposal options. The risk of collision with objects larger than 10 cm was estimated using recent ODPO debris flux predictions for the worst-case almost two year path from 500 km to the 2000 km storage orbit altitude. It was found that the probability of such a collision randomly occurring is on the order of 0.04 %, less than half of the NASA design requirement allowance. In addition, any impending collision predicted thorough conjunction assessment activities could be mitigated by discontinuing the thrust for several days, until the threat passes, altering the disposal orbit slightly. It was concluded, then, that while a risk of large object collision during orbit raising does exist, that risk is small and can be mitigated.

The cost of each disposal option was also examined, using an estimation model drawn from actual cost data collected from over 130 space missions. The model is driven primary by the expected complexity, dry mass, and operational mission time, to produce a rough estimate for the purpose of comparing several architectures. Estimates ranged from $440 M for controlled reentry through $620M for 2000 km storage orbit disposal, including launch services, for a conventional single-flight mission implementation. Adaptation of existing vehicles appears feasible, with added cost for necessary modifications. Cost estimates at this time on such vehicles would likely be obsolete by the time a disposal mission is initiated. Emerging vehicles dedicated to active orbital debris mitigation or satellite servicing might also be adapted, at unknown cost.

Table 2 summarizes the benefits and challenges inherent in each of the disposal options for HST.

Disposal Option	Advantages	Disadvantages
0) Uncontrolled Reentry	Zero cost	Unacceptable public risk
1) Controlled Reentry	Lowest cost Short time Mature technology Accepted approach	Sensitive to errors High visibility
2) Boost to 1200 km	Short time Low cost Insensitive to errors	Violates NASA requirements and International agreements
3) Boost to 2000 km	Meets all disposal requirements Insensitive to errors	Longest time Highest cost Technology maturity

Table 2. Advantages and Disadvantages of each of the Main Options Identified

7 CONCLUSIONS

One of the primary goals of this study was to determine whether HST disposal could be achieved with a single mission. It was demonstrated that not only is disposal feasible, but depending on launch vehicle reliability the NASA requirement may be achieved in a single attempt. At least three options have been identified for disposal of the spacecraft, each carrying both advantages and disadvantages. Destruction and drag enhancement were studied, and found to not be feasible for disposal of HST. Finally, it was shown that not only is it possible to delay the final decision on a disposal approach, but it is advantageous to do so, for better knowledge of the key factors in the decision.

8 ACKNOWLEDGEMENTS

The authors would like to thank everyone who contributed to the information contained in this paper, which is based upon the results from prior studies. We especially appreciate the efforts of all those who participated in the most recent HST Disposal study and those who served as advisors.

HST-D Study Customer Team (GSFC): Tupper Hyde, Steve Benner, Ruth Carter, Jacqueline Townsend, Arthur Whipple, Beth Keer

Study Advisors (GSFC): Gabe Karpati, Aron Brall, Steve Queen, Rich Burns, Jaime Esper, Rud Moe, Terry Smith, Bo Naasz, Mike Moreau, Matthew Strube, John Vaneepoel, Tom Hanyok, Tom Walsh, Brian Roberts, Bruce Campbell

Study Advisors (MSFC): Les Johnson, Ricky Howard, Shayne Swint, Mary Hovater, Jack Mulqueen, Tom Bryan

Additional Study Advisors: Chris White (SpaceX), Dustin Doud (SpaceX), James Lewis (JSC), Allan Cohen (Aerospace Corp.)