National Aeronautics and Space Administration

Hubble Space Telescope Disposal Study

Closeout Report

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Signature Page

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EXECUTIVE SUMMARY

The natural orbital degradation of the Hubble Space Telescope (HST) will cause it to reenter the Earth's atmosphere eventually, an event that is currently anticipated to occur no earlier than 2027. With its present 1 in 240 risk of human casualty by uncontrolled reentry, HST does not meet the requirement of 1 in 10,000 risk of human casualty at end of mission as required per NASA Procedural Requirement (NPR) 8715.6A for Limiting Orbital Debris, or NASA-Standard (NASA-STD) 8719.14A, Process for Limiting Orbital Debris. Without a propulsion system and no planned servicing missions, the National Academy of Sciences National Research Council's 2010 "New Worlds, New Horizons in Astronomy and Astrophysics" (NWNH) decadal survey report[1] endorses NASA's plan to "…deorbit the HST robotically at the end of the decade."[2]

The HST De-orbit Study began with a combined NASA Headquarters (HQ) and Cosmic Origins (COR) Program Office (PO) 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 Science Mission Directorate's (SMD) overall mission cost. The architecture design portion of the study examined both the controlled reentry and disposal orbit storage options. The study was later renamed the "HST Disposal Study" as a means of including both disposal methods until a single disposal method is selected. The overall HST Disposal (HST-D) Study identified the activities necessary to define mission architecture concepts, develop a Design Reference Mission (DRM), conduct a study "Hold" during which mission-enabling technologies and potential partnerships are monitored, and provide recommendations for enabling a 2019 Pre-Phase A project. This document includes the overall study results, potential risks and their mitigations, and recommendations for enabling a 2019 Pre-Phase A project start based upon taking action prior to HST reaching 500 km altitude, which is currently predicted to occur in mid-2024. HST is now near the 565 km altitude assumed for HRSDM. The experts who had produced one of the analyses predicting tumble rates confirmed that that analysis should remain valid down to about 500 km, below which atmospheric drag might have a variety of effects on rates, which have never been analyzed. Based on this, any action to capture HST should occur by the time HST drops to 500 km.

The activities completed during this Fiscal Year (FY), FY11/12, the HST-D Study consisted primarily of two parts: 1) an Aerospace Task; and 2) an HST-D Architecture Design Lab (ADL) session. By January 2012, the Aerospace Corporation study team completed a 6-month study effort and delivered a task report. The Aerospace task report contained high-level architecture and costing information. The report identified adaptation of existing vehicles, especially the Progress and Dragon, as potentially the most economical option. Aerospace also evaluated an option for implementing two HST-D missions as a means of mitigating a potential first attempt launch failure. Due to limited benefits and high costs, Aerospace eliminated this option and anticipated the future availability of highly reliable launch vehicles. The Aerospace report served as reference material for the subsequent 3-month HST-D ADL study.

The ADL focused particular attention on meeting the orbital debris requirement of a less than 1 in 10,000 chance of a casualty, including the effect of reliability and probability of mission success. The ADL completed an engineering and cost trade of several mission architecture concepts to launch a deorbit vehicle to safely and autonomously place the HST into either a storage orbit or perform a controlled reentry prior to HST's orbit decaying to an altitude of

500 km. The mission architecture is based on the need to capture HST while its tumbling rate is still low enough to allow capture using current technology. The study team created a trade tree of five mission elements: HST's functional state, disposal location, capture method, disposal method, and main propulsion system. Twenty-seven architectures were considered and dispositioned, each with a rationale.

The ADL eliminated a very inexpensive option considered by Aerospace, the breakup by a hyper-kinetic weapon, as increasing the probability of casualty because of the unique composition of HST (large Pyrex mirror and a large amount of titanium). The ADL further studied the Aerospace finding that the most economical mission option may be an adaptation of an existing vehicle, such as the Russian Progress or the SpaceX Dragon.

A significant finding of the study is that several mission architectures exist that come very close to meeting the 1 in 10,000 requirement for risk of human casualty. Key factors are the net reliability from successfully docking within four docking attempts, the existence of an exact replica of the Soft Capture Mechanism (SCM) fixture that is currently on the aft end of HST, and the high reliability of a brief mission. Essentially, the docking reliability drives the mission architecture. As the docking reliabilities degrade for a specific architecture option, the Total Mission Reliability (TMR) also degrades.

The SCM, which was added to HST during Servicing Mission 4 (SM4) in 2009, was intended to enable reuse of human spaceflight items, such as the Low Impact Docking System (LIDS), to lower the development cost of a disposal mission. This study also found that use of a LIDS variant would be effective. The standard version used on the International Space Station (ISS), the International Low Impact Docking System (iLIDS) (also known as the NASA Docking System, or NDS) is not mechanically compatible with HST's SCM. Due to differences in diameter and hard-dock mechanisms, developing an HST-compatible LIDs version requires a customized design. Just prior to the completion of this report, NASA retired and terminated development of the standard iLIDS. In response to this announcement, the COR Program Office is documenting the location of both the Soft Capture Mechanism (SCM) and LID-related diagrams, drawings, and GFE for future availability and development. A decision to design and manufacture the HST-compatible version of LIDS should be reevaluated prior to a Phase A mission start.

The study included discussions with one of the commercial cargo and crew developers, SpaceX, which provided reinforcement of initial speculation that at least one of these providers had the potential to dispose of HST at a very competitive price. During the ADL, SpaceX provided a Rough Order of Magnitude (ROM) estimate that supported considering Dragon as a low cost option. Also on the horizon are commercial providers of satellite servicing and active orbital debris mitigation. The deployment of a flight system in either of these emerging industries could provide a very competitive, low-cost option for HST-D. It remains to be seen if either of these come to fruition, but a 2012 workshop on satellite servicing of geostationary satellites, progress on the design of NASA's Restore mission to provide servicing of geostationary satellites, demonstration of an Autonomous Rendezvous and Docking (AR&D) sensor and algorithms in NASA's Satellite Servicing Capabilities Office laboratory, and the Robotic Refueling Mission on-orbit testing are all promising steps toward having this capability.

The ADL results recommend developing a DRM based on boosting a non-functional HST up to 1200 km. This option envelops the capabilities required for the other cost-effective options, including a controlled reentry, while meeting the mission reliability and risk of human casualty requirements.

Another interesting study result arose when brainstorming different types of mission implementations that would support potential partnerships and cost-sharing opportunities. The HST Disposal Vehicle (HDV) could feasibly serve multiple purposes, such as disposing of the HST and hosting either a science instrument or a technology demonstration. Various mission partnering concepts are documented in the Partnership Survey (Appendix B). At the time of this report, the Ultraviolet/Visible (UV/Vis) study determined that a mission to capture and dispose of HST immediately followed by boosting a new telescope into its operational orbit would be a feasible, cost-effective mission.

The HST-D study activities completed during Fiscal Year (FY) 2011/2012 consisted primarily of two parts: 1) an Aerospace Task; and 2) an HST-D Architecture Design Lab (ADL) session.. This document includes overall study findings, results, potential risks and their mitigations, and recommendations for enabling a 2019 Pre-Phase A project start and taking action prior to HST reaching 500 km, which is currently predicted to occur in mid-2024.

1.0 STUDY OVERVIEW

1.1 Introduction

The future mission portfolio of NASA's Astrophysics Division is constrained by budgetary resources. Assuming that the NASA science budget is a zero-sum proposition, every dollar spent on the disposal of HST is subtracted from the resources available to perform science inquiry. The Division is making a concerted effort to control the cost growth of future strategic missions through a combination of improved early cost estimation, a more conservative posture of cost reserves, a reinvigorated technology development program, and by taking advantage of economical commercial systems or cost-sharing partnership opportunities which would reduce NASA's SMD-related HST-D mission costs.

The COR PO will work with the astrophysics science community via the Study Scientist to keep the science community informed of plans for safely disposing of HST, including determining opportunities for enabling science through strategic, multipurpose use of the HDV.

This document describes the study plan approach and estimated resources required to develop HST-D mission architecture concepts.

Potential new mission architecture concepts were developed during the Aerospace Corporation study and 3-month ADL. These concepts were evaluated for their ability to meet the human casualty requirement and their cost, which ranged from $400M to more than $1B (FY2012$; refer to Section 3.7) using a Goddard Space Flight Center (GSFC) costing tool. A cost estimate was obtained from a commercial vendor, SpaceX, to use a Falcon 9 plus Dragon, which was significantly lower than $400M, but could not be independently validated.

Due to the expectation that significant new capabilities will be fielded during the next three to five years, it is highly recommended that the Astrophysics Division (APD)/COR PO conduct a Request for Information (RFI) near the end of the "Hold" time and identify the latest, most recent mission concepts and developments from system integrators using mission-enabling technologies that may also include total mission solutions (e.g., spacecraft, autonomous rendezvous and capture/docking (AR&C/D), launch vehicle, mission operations, etc.

Major Study Elements

The following describe the major elements of the study:

a) Notional Mission: Conduct a trade study and recommend 1–2 mission architectural concepts at different cost points—use fundamentally different approaches or technology.

b) Design Labs: Study team develops concept(s) through mission design lab runs. Lab focus is on identifying the technical and cost drivers of each concept.

c) Final Report: The Final Report is due to NASA HQ APD on November 30, 2012.

1.2 HST Disposal Study Objectives

1. Minimizing SMD's mission cost for a disposal of HST;
2. Providing engineering analysis to establish a Phase A mission start date, rather than relying upon the currently estimated 2019 Phase A start date;
3. Identifying mission-enabling technologies and relying on external, non-SMD funding for these technologies to reach a Technology Readiness Level (TRL) of 6 prior to an estimated 2019 Phase A mission start date;
4. Identifying potential cost-sharing partners;
5. Completion of the remaining study objectives, which were not completed prior to the start of the study's directed "Hold" period, is recommended to support a Phase A start;
6. Developing a DRM and updating it with higher-fidelity cost and schedule estimates after the "Hold" period;
7. Documenting the technology readiness levels for mission-enabling technologies, such as for AR&C/D, which must be developed and reach TRL 6 prior to Phase A start.

1.2.1 Study Interim Results Presentations

The HST-D ADL study results were presented to NASA's APD at HQ on June 7, 2012. The AR&C/D Survey was completed in March 2012, and the Partnership Survey was developed in May 2012, immediately after the ADL. The HST-D Study Report was prioritized for completion prior to the Partnership Survey Outbrief to the COR PO.

1.3 Study Approach

The study began with an exploration of architectural options by the Aerospace Corporation. This was followed by the HST-D ADL session. In parallel, the AR&C/D survey was updated and partnership opportunities were explored. The overall study objective was to assess various mission architecture concepts and recommend 1–2 concepts for future mission design lab runs where higher-fidelity cost and schedule estimates would be developed. It is anticipated that technologies relevant to a future HST-D mission will be developed by industry during the study's "Hold." Therefore, it is recommended that an industry RFI be conducted during the latter part of the "Hold" to assess HST-D-relevant technology readiness levels prior to a Phase A start and conducting a future Mission Design Lab (MDL) session.

1.3.1 Aerospace Study Task

An Aerospace task report provided high-level architecture and costing information that served as reference information for the subsequent ADL. The Aerospace team was led by Allan Cohen and Greg Richardson, and included 11 other members covering architecture, vehicle design, Guidance, Navigation and Control (GN&C), orbital mechanics, propulsion, reliability, cost, and mechanisms. The briefing to the COR PO took place on January 26, 2012. It examined background assumptions, the HST state at the time of disposal, the technology trade space with a focus on rendezvous and docking, architecture options, and architecture summary, other analyses, and conclusions.

1.3.2 Architecture Design Lab (ADL)

The HST-D ADL utilized analyses completed during previous HST Deorbit Studies [e.g., the Hubble Robotic Servicing and Deorbit Mission (HRSDM), HST End of Life (Marshall Space Flight Center, or MSFC), and SM4], relevant engineering expertise (e.g., GSFC, MSFC, industry), and

GSFC's Integrated Design Center's ADL staff and facilities. GSFC's ADL is a new GSFC capability for architecting and evaluating mission concepts.

1.4 Organization of this Report

This report is organized into the following sections:

EXECUTIVE SUMMARY. The executive summary provides a high-level synopsis of the overall study, including the methodology, results, and recommendations.

SECTION 1.0, STUDY OVERVIEW. This section presents some background about the need for a mission to dispose of the HST at end of life, study objectives, study results, and the organization of this document.

SECTION 2.0, AEROSPACE STUDY TASK. This section describes the methods and results of the study performed by the Aerospace Corporation on the various options, implementation risk, and cost.

SECTION 3.0, ARCHITECTURE DESIGN LAB. This section describes the study performed by NASA GSFC's Architecture Design Lab to study design options, probability of casualty, and mission cost.

SECTION 4.0, STUDY "HOLD" RECOMMENDATIONS: MONITORING TECHNOLOGIES AND PARTNERSHIPS. This section describes the activities that will take place during the study's "Hold" period and prior to reactivation into pre-Phase A.

SECTION 5.0, STUDY DELIVERABLES. This section provides the main conclusions reached during the study, and provides recommendations for future study of how best to dispose of HST at end of life.

SECTION 6.0, STUDY BASELINE. This section summarized the Automated Rendezvous and Capture/Docking Survey and Partnering Possibilities Survey.

SECTION 7.0, STUDY MANAGEMENT. This section describes how the study was managed.

SECTION 8.0, APPENDICES. The remainder of the report consists of appendices. Appendix A is Acronyms. Appendix B is the Study Team Organization, Roles and Responsibilities. Appendix C is the Study Team Relationship to the Cosmic Origins Program Office and NASA HQ APD. Appendix D is Presentations and Surveys, including the final study plan, ADL outbrief, the AR&C survey, and partnership survey. Appendix E is References.

2.0 AEROSPACE STUDY TASKS

A study task was performed by the Aerospace Corp., which looked at a large variety of architecture options for implementing HST's disposal. Factors considered in developing the list of options included disposal method (storage orbit, controlled deorbit, or uncontrolled deorbit), disposal agent (modify an existing vehicle, a new vehicle, or hypervelocity impact), which specific existing vehicle, direct dock versus grapple and berth, main propulsion (chemical, electric propulsion, or exotic propellantless), new vehicle configuration, and grapple/docking mechanism. Figure 1 illustrates the Architecture Tradespace (Final).

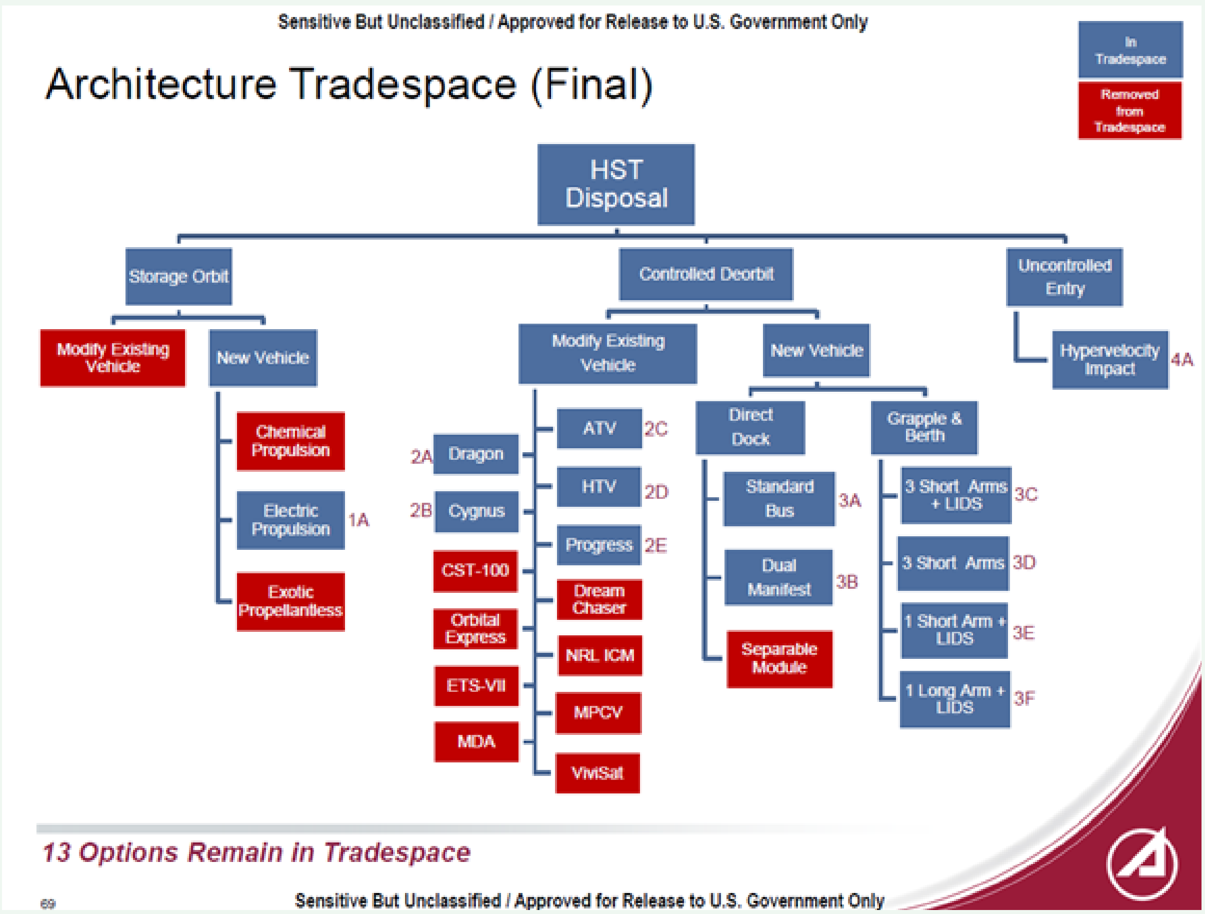


Figure 1. *Architecture Tradespace Final*

The Aerospace study evaluated the feasibility of each option in the trade space, and eliminated those found to be not feasible for one reason or another, which are shown in red. The primary outcome of that study, shown in Figure 1, was that several ISS visiting vehicles should be able to be adapted to the HST-D task, with varying amounts of modification. The Aerospace study also looked at options, including several variations in the number of robotic arms, as an alternative to relying on LIDS. This study kept several options in the trade space (shown in blue) while eliminating others (shown in red).

Their major finding is that adaptation of the Progress or Dragon ISS resupply vehicles offer good opportunities for a lower-cost mission. The possibility of using a hypervelocity impact weapon to break up HST was later elimited by the ADL as greatly increasing the debris casualty area by creating a multitude of glass and titanium pieces that would impact separately with high enough energy to cause casualties.

The Aerospace study went on to estimate the costs of each of the design options that were not eliminated earlier. Each cost estimate included a base cost estimate for development and operation of the flight system, cost reserves estimate, and launch cost estimate. The resulting data are displayed in Figure 2.

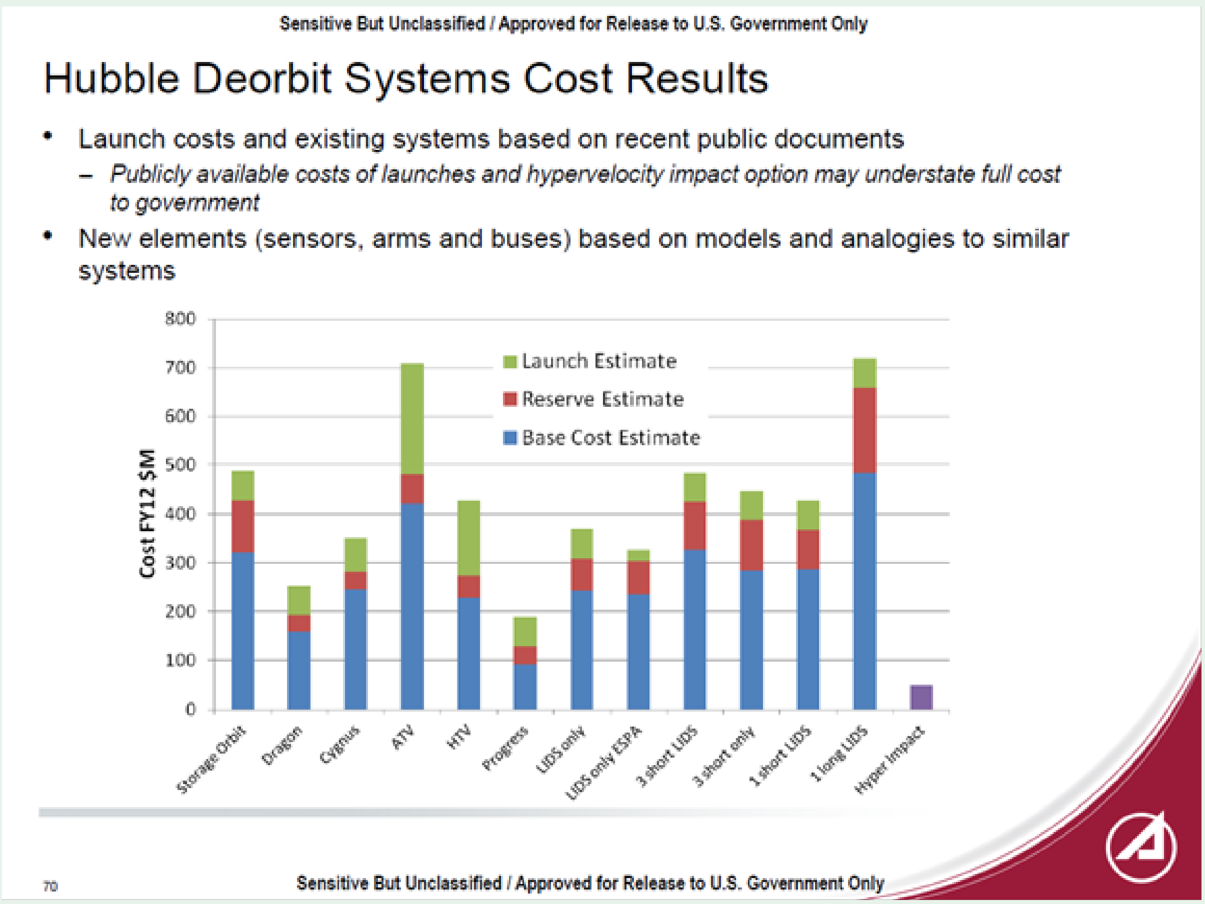


Figure 2. *HST Deorbit Systems Cost Results*

The major finding is that adaptation of the Progress or Dragon ISS resupply vehicles offer good opportunities for a lower-cost mission. The possibility of using a hypervelocity impact weapon to break up HST offers a much lower cost, but is not confirmed to be applicable because the effect on debris casualty error was not evaluated.

3.0 ARCHITECTURE DESIGN LAB (ADL)

GSFC's ADL is a capability for architecting and evaluating mission concepts. The HST-D ADL Study Team and Customer Team are listed in Appendix B.

The ADL study methodology included several sessions which were dedicated to a particular topic, and for which expert advisors were invited to make a presentation and/or discuss the topic. Some presentations included past work, while others performed new design work (e.g., spacecraft sizing) and presented their work products. A list of the workshop topics follows:

Workshop Topics (in chronological order):

- HST Hardware
- HST Drift Rates
- SCM, iLIDS
- Robotic Arm
- Spacecraft sizing
- Solar Sail, Space Debris
- Dragon / Falcon 9
- Electrodynamic Tether (EDT)
- Trade Space, Partnering
- AR&D
- Probability of Success or Casualty
- An additional workshop topic on partnering opportunities was also completed.

3.1 Background: Architecture Design Lab

The 3-month Architecture Design Lab began its study based upon the assumption that the natural orbit decay of the HST will result in its uncontrolled reentry no earliar than (NET) ~2025, modeled using 3-sigma predictions of solar cycle and atmospheric effects. HST's Debris-Casualty Assessment (DCA), completed prior to SM4, also predicts a 1 in 240 chance of harm from an uncontrolled reentry.

The ADL's objective was to identify cost-effective architecture concepts that would meet or approach a 1 in 10,000 chance of casualty. During the ADL, the study team created a trade tree of five mission elements: HST's functional state, disposal location, capture method, disposal method, and main propulsion system. Twenty-seven architectures were considered and dispositioned with a rationale (see Trade Tree in Appendix B—ADL Outbrief):

- o Cat 1: Confirmed realistic/feasible
- o Cat 2: Potentially feasible, requires further analysis
- o Cat 3: Unattainable/unfeasible/absurd

After mapping a trade tree, nine Cat 1 architectures and uncontrolled reentry were developed and assessed for risk and cost.

Of the trades completed, the notion of replicating the shoot-down of the National Reconnaissance Office Launch 21 (NROL-21) satellite by a Standard Missile 3 (SM-3) launched from the USS Lake

Erie warship in February 2008 was found to not apply to HST. Due to HST's large Pyrex glass mirror and large titanium structural pieces, this approach would only increase the risk of human casualty. Another potential game changer, the EDT, upon closer inspection was mostly a variant on electric propulsion without an obvious advantage over existing systems.

The Soft Capture Mechanism, which was added to HST during SM4 in 2009, was intended to enable reuse of human spaceflight items, such as LIDS, and lower development cost of a disposal mission. This study also found that use of a LIDS variant would be effective. Due to differences in diameter and hard-dock mechanisms, the standard version used on ISS, the iLIDS (aka NDS), is not mechanically compatible with HST's SCM. Therefore, obtaining a flight qualified HST version of LIDs requires customized design, development, and manufacture.

ADL Findings

The ADL findings for the Architecture Options (AO) included the following:

Finding #1: HST's natural orbit degradation will cause its uncontrolled reentry NET ~2027. Action is required as HST reaches an altitude of 500 km. Uncontrolled reentry is predicted to occur 3 to 5 years later. Future orbit degradation profiles may change HST's estimated uncontrolled reentry date.

Finding #2: Uncontrolled HST attitude rates modeled for HRSDM are 0.22 degrees per second per axis. Analyses from HRSDM were examined and judged to be reliable. Proper consideration of the magnetic damping in the torque bars is the key to the relatively low rates predicted. HST would be in a slow, chaotic tumble. Action is required as HST reaches altitude of 500 km. Below that altitude, the current models for HST's expected uncontrolled attitude rates become unreliable—rates are likely higher, and capture becomes more difficult.

Finding #3: The preferred baseline HST docking hardware is the HST's SCM that was installed during SM4. A passive, direct docking interface based on LIDS—in development in 2006–2007 for Constellation and ISS resupply—is required for all architectures. This would enable a larger 'capture box' of relative distance, angles, and rates than the grapple arm, with the benefit of easier access and one set of hardware for capture and docking.

Finding #4: The preferred baseline disposal vehicle docking hardware is HST-LIDS for all architectures. **HST-LIDS requires customized flight design, development, and hardware.** After the study was mostly completed, a decision was made to not complete the HST-LIDS design at that time. This decision can be reevaluated during system formulation. Other options considered in the Aerospace study, such as a short robotic arm plus docking mechanism, might prove to be less costly. Other systems which may be developed for on-orbit servicing or active orbital debris removal, such as a system for docking to a launch vehicle separation ring, may be in production and flight qualified.

Finding #5: HST-D should be the primary mission. In order to achieve high reliability and low probability of casualty, the HST-D must be prioritized.

Finding #6: The preferred solution is the autonomous rendezvous and docking sensor package proposed for NASA's Restore mission[3].

Finding #7: All architecture options require at least one waiver to orbital debris mitigation standards NASA-Standard (NASA-STD) 8719.14A. None achieves a 1 in 10,000 chance of casualty.

Finding #8: The most recent Debris-Casualty Assessment (DCA) analysis, prior to SM4, predicts a 1 in 240 chance of harm from an uncontrolled reentry. An update to this to evaluate the post-SM4 configuration of HST was considered as part of this study, but deemed unnecessary and not in scope.

Finding #9: The probability of Mission Success (P_S) is factored into the DCA, so the disposal mission approach must balance the mission cost and mission risk. The FY11/12 HST-D study activities included: a) performing high-level trades of risk versus cost for multiple mission architectures; b) considering architectures for HST-D via controlled reentry into the Pacific Ocean, boost to an off-nominal disposal orbit at 1200 km, and boost to a 2000-km disposal orbit, which is in accordance with international agreement; c) surveying AR&D capabilities and monitoring industry system integrators during the study's "hold" and until project formulation; d) identifying potential partnership options to offset or leverage SMD's cost for this mission. Study activity "a" would include an Aerospace task (cost and development risk) and an Architecture Design Lab (ADL) task (cost and mission risk).

Prior to starting Phase A and to obtain higher-fidelity cost and schedule estimates, consideration should also be given to: 1) conducting an industry RFI; and 2) selecting and further developing an architecture into a design reference mission via an MDL session.

3.2 Summary: Approach and Results

Approach

The ADL team studied three different AO and created a Trade Tree: 1) Dead bird; 2) No Science; and 3) HST Working. Each AO has three different disposal methods: A) Deorbit (Bi-prop); B) 1200 km storage orbit (Bi-prop); and C) 2000 km storage orbit (Solar Electric Propulsion, or SEP). One Exception: C.5 is for Option 1, and is higher reliability. These architecture options are described in Table 1 and are further explained in Section 3.3.

Table 1*—ADL Architecture Options*

0	Uncontrolled Reentry	
1A	Biprop deorbit	Dead bird
1B	Biprop to 1200 km	
1C	SEP to 2000 km	
1C.5	SEP to 2000 km (High Rel)	
2A	Biprop deorbit	No science, ACS working
2B	Biprop to 1200 km	
2C	SEP to 2000 km	
3A	Biprop boost and deorbit	HST working
3B	Biprop boost to 1200 km	

Study Results

Docking Reliability Dominates Mission Reliability

As the docking reliability degrades for a specific option, the Total Mission Reliability (TMR) degrades. The options were analyzed by parameterizing (unknown) docking reliability (e.g., based on docking reliability values of 1, .99, .9, .85) and residual dependency of multiple docking attempts. Similar TMR degradation exists for all architecture options. The Reliability is explained further in Section 3.5.

Probability of Injury

There is a low probability of injury for Architecture Options 1A, 1B, 2A, and 2B. The odds of an injury (1 in "*n*") for AO 1A/B and 2A/B are approximately 1:9 and 152, respectively. The requirement (1 in "*n*") is 1:10,000. All other AO exceed the requirement. Refer to Section 3.6 for more information.

Estimated Life Cycle Cost (Over Design Life)

The Life Cycle Costs (LCC) were estimated at or below $500M for AO 1A, 2A, and 2B. The LCC were estimated greater than $500M for Options 1C, 1C.5, 3A, and 3B. For more details on the cost estimation, refer to Section 3.7.

Table 2—*Cost-Mass-P_S-Casualty Summary*

Architecture Options:	AO-0	AO-1A	AO-1B	AO-1C	AO-1C.5	AO-2A	AO-2B	AO-2C	AO-3A	AO-3B
Life Cycle Cost (Over Design Life) [$M]	0	440	515	622	625	415	482	579	1090	1264
Total Wet Launch Mass [kg]	0	2549	4494	2046	2398	2496	4417	2026	3183	5052
Mission Reliability (Pdock =.9 ea try, no residual dependence)	1	0.9749	0.9749	0.7458	0.9174	0.9749	0.9749	0.7458	0.9481	0.9481
E-E Probability of Casualty	0.00424	0.00011	0.00011	0.00115	0.00037	0.00011	0.00011	0.00115	0.00102	0.00102
Odds of an Injury—1 in "*n*"	236	9,152	9,152	868	2,704	9,152	9,152	868	981	981

Recommendations for a Design Reference Mission

Based on the ADL, developing a DRM based on boosting a non-functional HST up to 1200 km, Option 1B, is recommended. Option 1B envelops the capabilities required for the other cost-effective options, including a controlled reentry (Option 1A), while meeting the mission reliability and risk of human casualty requirements. Disposing of HST at 1200km requires a waiver and is not the internationally agreed upon disposal altitude. However, all options require some type of waiver. In prior studies, the 1200 km storage disposal case was not examined closely. This case now shows promise for its potential of leaving a highly capable debris removal asset available after the HST Disposal mission concludes. This asset could enable science, technology demonstrations, or orbital debris mitigation missions and serve as a multipurpose, on-orbit platform.

3.3 Architecture Options

After the Aerospace study wascompleted, the study by NASA GSFC's ADL began. The ADL approached the matter from a different direction, with more consideration of timing and an alternate disposal orbit. A summary of the disposal options considered is shown in Figure 3.

HST has no propulsion on board, and its orbit naturally decays due to atmospheric drag. During the various servicing missions, its orbit has been boosted at discrete intervals. As the plot's dark blue line shows in Figure 3, it will take several years to drop from the current 565 km altitude to about 500 km, then more quickly drop to about 380 km, and finally deorbit within another year in an uncontrolled manner.

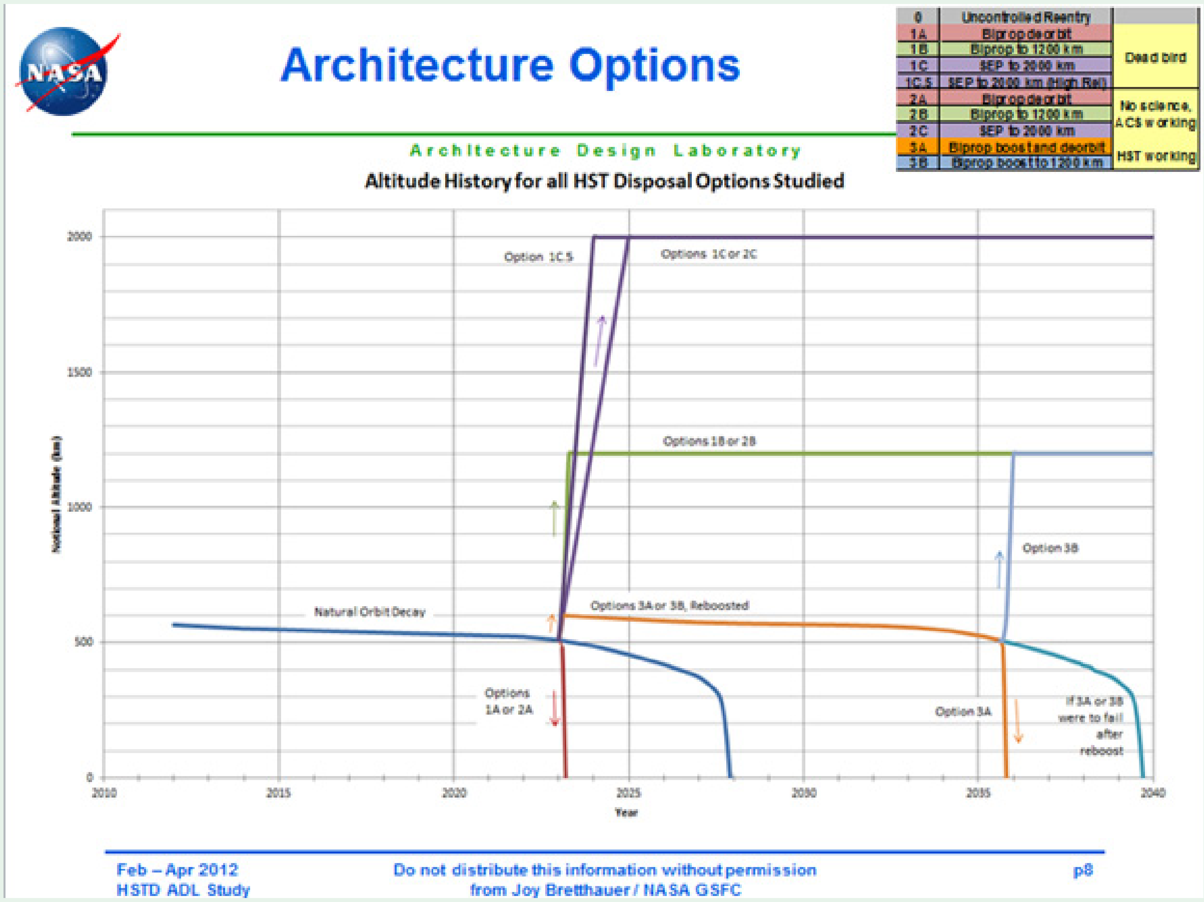


Figure 3. *Architecture Options—Altitude History for All HST-D Options Studied*

The ADL researched prior work on predictions of the attitude that HST will take on if its control system has failed (the 'dead bird' scenario). The most comprehensive study of this was done as part of the HRSDM study in 2004, which led to a Preliminary Design Review in 2004. Teams from Lockheed Martin and GSFC independently agreed that a combination of initial conditions, disturbance torques, and electromagnetic damping within the torque rods would lead to a random tumbling at rates of up to .25 degrees per second per axis. This value was used as the design requirement for the HRSDM mission.

Since then, the STS-125 / SM4 was performed, adding the SCM to HST to make it compatible (or nearly so) with the Constellation Program and the ISS (and associated resupply craft), and HST's orbit was boosted. HST is now near the 565 km altitude assumed for HRSDM. The experts who had produced one of the analyses predicting tumble rates conferred with the ADL team, and confirmed that that analysis should remain valid down to about 500 km, below which atmospheric drag might have a variety of effects on rates, which have never been analyzed. Based on this, any action to capture HST should occur by the time HST drops to 500 km.

At that time, a vehicle would be sent to autonomously rendezvous and dock with HST. Based on inputs from experts on HRSDM, SCM, and LIDS, plus the ADL's own analysis, the best choice from the standpoint of cost, mass, and performance would be to use a docking interface based on LIDS to dock directly to HST's SCM interface that was added during SM4. This was fully capable of handling the anticipated tumbling rates of an uncontrolled HST, or a controlled HST.

Table 3*—ADL Architecture Options*

0	Uncontrolled Reentry	
1A	Biprop deorbit	Dead bird
1B	Biprop to 1200 km	
1C	SEP to 2000 km	
1C.5	SEP to 2000 km (High Rel)	
2A	Biprop deorbit	No science, ACS working
2B	Biprop to 1200 km	
2C	SEP to 2000 km	
3A	Biprop boost and deorbit	HST working
3B	Biprop boost to 1200 km	

The ADL distinguished between group 1, in which HST is a 'dead bird' and in an uncontrolled tumble, group 2, in which HSTis no longer doing science but the attitude control system (ACS) is still working (not fine control for science, but the various safe modes and zero-gyro modes), and group 3, in which HST is still doing science. In addition, a direct deorbit using bipropellant was case A, a boost using biprop to 1200 km was case B, SEP to 2000 km was case C, and SEP to 2000 km using more thrusters and power in half the time was case C.5. These cases are sumarized above in Table 3.

While the Aerospace study had eliminated the option of a chemical rocket to boost HST to 2000 km, the ADL added a new option to boost with chemical rockets to a lower disposal orbit, at 1200 km. At this altitude there is relatively little debris or active satellites, and the ADL team thought that it might be feasible to get a waiver against the standard requirements to allow a reasonably sized booster to perform that maneuver. The ADL confirmed the Aerospace conclusion that chemical boosters to 2000 km was not feasible. It was also thought that there was no point in a SEP booster stopping at 1200 km because it took relatively modest additional fuel to continue on to a proper 2000 km orbit. If the disposal vehicle had additional mission objectives, such as active removal of other debris items, then SEP to 1200 km coud be reconsidered. This rationale lead to including cases B and C in the trade space.

For HST still conducting science, the rationale is that HST should be captured by the time it reaches 500 km and before it uncontrollably reenters Earth's atmosphere. Case 3A would immediately boost HST to about 600 km, where HST would continue operations with the deorbit vehicle attached, much like the HRSDM post-servicing case. This was case 3A. For case 3B, the same scenario would end in a boost to 1200 km instead of controlled deorbit. The use of SEP attached to HST during science operations was not considered because the large solar arrays would likely interfere with HST operations.

3.4 Cost-Mass-P_S-Casualty Summary Table

***Table 4**—Cost-Mass-P_S-Casualty Summary*

Architecture Options:	AO-0	AO-1A	AO-1B	AO-1C	AO-1C.5	AO-2A	AO-2B	AO-2C	AO-3A	AO-3B
Life Cycle Cost (Over Design Life) [$M]	**0**	**440**	**515**	**622**	**625**	**415**	**482**	**579**	**1090**	**1264**
Life Cycle Cost Normalized	0.00	0.35	0.41	0.49	0.49	0.33	0.38	0.46	0.86	1.00
Life Cycle cost per kg Dry Launch Mass [$k/kg]	0	241	191	321	273	232	182	298	501	420
Life cycle Cost per kg Wet Launch Mass [$k/kg]	0	173	115	304	261	166	109	266	342	250
Chemical S/C Dry Mass [kg]	0	1236	1662	1105	1157	1211	1628	1093	1442	1847
Chemical Propellant Mass [kg]	0	725	1795	106	109	708	1769	86	1007	2038
SEP Stage Mass [kg]				469	688			466		
Total Wet Launch Mass [kg]	0	2549	4494	2046	2398	2496	4417	2026	3183	5052
Total Wet Launch Mass [kg]—Normalized	0.00	0.50	0.89	0.40	0.47	0.49	0.87	0.40	0.63	1.00
Mission Reliability (Pdock =.9 ea try, no res. Dependence)	1.0000	0.9749	0.9749	0.7458	0.9174	0.9749	0.9749	0.7458	0.9481	0.9481
E-E Probability of Casualty	0.00424	0.00011	0.00011	0.00115	0.00037	0.00011	0.00011	0.00115	0.00102	0.00102
Odds of an Injury—1 in "*n*"	236	9152	9152	868	2704	9152	9152	868	981	981

The LCC of each mission was estimated, as is fully described in Section 3.7. Note that these costs are for a full development effort and do not include potentially less costly options such as the use of an existing vehicle.

The total wet launch mass affects the choice of launch vehicle and is provided for each case. The launch vehicle cost is included in the estimate and the effect of the flight system mass is included in the cost model. Each architecture case has a nearly identical set of AR&D sensors (80–90 kg) and a low-impact docking system (340 kg). Several other subsystems were essentially common to the different options. The differences come in the structure and mechanism mass (253–615 kg), power system mass (200–260 kg), the chemical propulsion hardware (15–365 kg), SEP hardware (0–688 kg), and the chemical fuel mass (86–2038 kg). Note that the SEP mass is estimated for conventional SEP, not for the EDT option. All SEP-based systems also need to have a chemical rocket system capable of performing the AR&D sequence.

The reliability of the system is fully described in Section 3.5. The same basic information is shown three ways in Table 4, as Mission Reliability, Probability of Casualty, or Odds of an Injury. The last can be compared directly to the policy requirement of the odds of an injury (or casualty) to be less than 1 in 10,000. Note that four of the Options, AO-1A, AO-1B, AO-2A, and AO-2B, all come quite close to meeting the requirement. These are the two options for deorbit, and the two options for raising the orbit to 1200 km using chemical propulsion (biprop). One other Option, AO-1C.5, outperforms the rest by a factor of three, and a factor of more than 10 over doing nothing, by quickly raising the orbit via SEP to 2000 km. The remaining active options provide relatively little improvement over taking no action, although the two versions of option 3 could potentially extend HST's science life, in the unlikely scenario of HST still being capable of science by that late date.

3.5 HST-D Architecture Reliability Summary

The reliability engineering effort for this architecture development study was to assess the reliability of the various proposed mission options for meeting the designated reliability requirements.

The following reliability requirements were used for determining the adequacy of each option and for characterizing each option as to mission length and complexity.

Mission Parameters

The HST-D mission was determined to be a Class B mission with a target requirement of 1 in 10,000 risk of human casualty on disposal from its present 1 in 240 risk of human casualty. Mathematically, this requires a mission reliability of 0.976 or better.

The mission duration required was 2 weeks for Options 1A, 1B, 2A, and 2B; 719 days for Options 1C and 2C; 367 days for Options 1C.5, 2C.5; and 10 years for Options 3A and 3B.

With the exception of redundant thermostatic heaters and extrasolar array strings, the initial design of the spacecraft is a single string design. Redundancy variations were also addressed, as detailed later, for several of the options.

Reliability Assurance

The reliability analysis was based on the designs being validated with the appropriate reliability analyses Fault Tree Analysis (FTA), Failure Mode and Effects Analysis (FMEA), Parts Stress Analysis, Worst Case Analysis, and Probabilistic Risk Analysis (PRA); Parts and Equivalent Source Control Drawings being Level 2 or better; and designs meeting NASA and GSFC specifications, including: EEE-INST-002; General Environmental Verification Standard (GEVS) (GSFC-STD-7000)); GSFC Rules for the Design, Development, Verification, and Operation of Flight Systems, also known as the Goddard Open Learning Design (GOLD) Rules (GSFC-STD-1000); Safety and Mission Assurance (SMA) requirements (NPR-8705.4); and NASA Procedural Requirements for Limiting Orbital Debris (NPR-8719.14).

Reliability Methodology

The reliability approach and methodology are presented to provide an explanation of what the probabilities derived represent. There are two assumed sources of mission failure. The first source is controllable failure and error modes. These are primarily design, manufacturing, and operational errors. It is the general assumption that these errors will be removed through preventive and corrective actions during the design, manufacturing, and test phases of the project through detailed design reviews, design analyses including stress analysis, FMEA, parts stress analysis, PRA, simulation, inspection, and test. Waivers to not perform analyses and/

or implement recommended actions increase the risk of mission failure. The probability of occurrence of these failures is directly related to the actions taken to avoid, detect, and remove the errors. For HST-D, if all preventive, evaluation, and corrective actions are completed, there will be an extremely low probability of this type of failure occurrence. The second source is random failures. These failures are primarily inherent in piece-part design and manufacture and are the most predictable part of reliability analysis. For a 2-week mission (Options 1A, 1B, 2A, 2B), there is a very low probability of occurrence, and therefore a small contribution to total mission reliability. For longer missions, these failures become a finite part of total mission reliability.

Reliability Calculation

The various blocks in the Reliability Block Diagrams (RBD) are each evaluated for reliability (probability of success). The product of the reliability of the blocks shown in a series diagram produces the final reliability value for that diagram. The order of the blocks in the diagram is for convenience and is unrelated to importance, time of occurrence, or physical location. The reliability of each block is assumed to be independent of all of the other blocks in the diagram. Figures 4 and 5 show the RBDs for the HST-D spacecraft and mission.

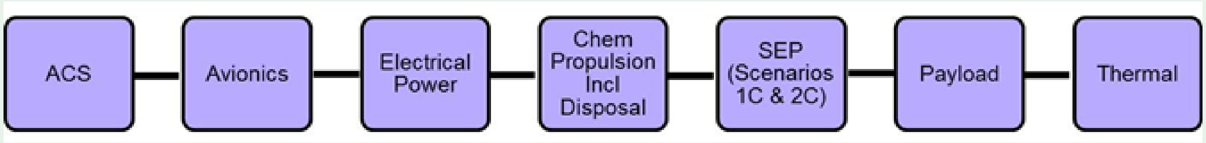


Figure 4. *Spacecraft Reliability Block Diagram*

Figure 5. *Mission Reliability Block Diagram*

Failure Rate Sources

Failure rates used in making the reliability assessment are based upon previous NASA projects, heritage, vendor's data based on similar hardware, and estimations based on engineering judgment, when other acceptable data is unavailable. Failure rates of most of the electrical components are based on the reliability prediction of electronic equipment contained in the Military Handbook[4] (MIL-HDBK-217F), Notice 2 with manufacturer's predictions, or on-orbit performance data used, where available.

Component Life Distribution

Exponential component models are used for electronics and non-wear related items. Weibull component models are used for items subject to wear or aging—pressure gauges, motor and mechanism bearings, and SEP thrusters.

Mathematical Models

Exact models were used to determine subsystem reliabilities. Series models are used for single string subsystems, and cold or hot standby models are for redundant subsystems. Binomial models are used for k of n subsystems; i.e., 45 of 46 solar array strings in the power subsystem.

Reliability Risk Discussion

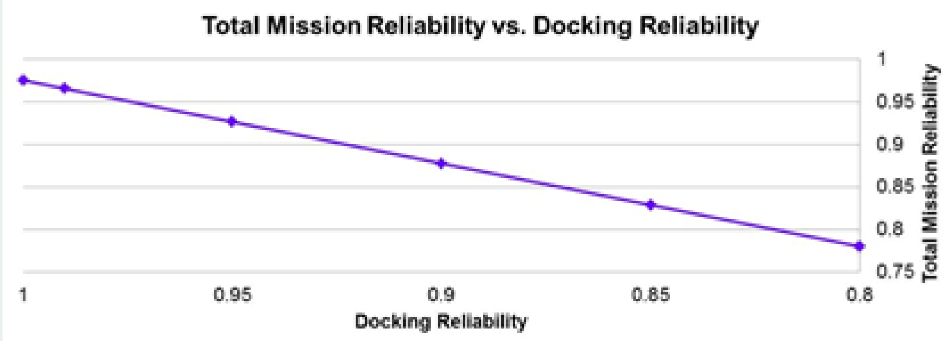
The key to mission success was determined to be the reliability of the LIDS docking maneuver. Even with a successful launch and deployment, and no hardware failures, a failure of the docking maneuver would cause the mission to fail. The docking maneuver is a combination of hardware, software, and process design. A failure of any aspect of this design—i.e., the process conceived is problematic in execution—will cause the docking maneuver to fail. It was defined that there would be a maximum of four docking attempts. Assuming the reliability for each docking attempt is 90 percent and each attempt is independent of any other attempt yields a 99.99 percent probability of docking success for four attempts. This assumption is dependent on addressing all risks before commitment to a design, detailed simulation of docking, and a thorough integration and test program to address potential infant mortality.

Table 5 details the results for 90 percent, 80 percent, and 70 percent docking attempt reliability, with no residual dependency as well as residual dependencies up to 50 percent. If the probability of docking success falls below 99 percent, docking becomes the key driver for mission reliability and risk of human casualty.

Table 5. *Determination of Docking Reliability*

Docking Attempt Reliability	0.9	0.9	0.9	0.9	0.9	0.9	0.8	0.8	0.8	0.8	0.8	0.8	0.7	0.7	0.7	0.7	0.7	0.7
Probability of Zero Residual Dependence	1	0.9	0.8	0.7	0.6	0.5	1	0.9	0.8	0.7	0.6	0.5	1	0.9	0.8	0.7	0.6	0.5
Reliability of 1st Attempt	0.9	0.9	0.9	0.9	0.9	0.9	0.8	0.8	0.8	0.8	0.8	0.8	0.7	0.7	0.7	0.7	0.7	0.7
Reliability of 2nd Attempt	0.9	0.81	0.72	0.63	0.54	0.45	0.8	0.72	0.64	0.56	0.48	0.4	0.7	0.63	0.56	0.49	0.42	0.18
Reliability of 3rd Attempt	0.9	0.73	0.58	0.44	0.32	0.23	0.8	0.65	0.51	0.39	0.29	0.2	0.7	0.57	0.45	0.34	0.25	0.18
Reliability of 4th Attempt	0.9	0.66	0.46	0.309	0.19	0.11	0.8	0.58	0.41	0.27	0.17	0.1	0.7	0.51	0.36	0.24	0.15	0.088
Total Docking Reliability	0.9999	0.998	0.994	0.986	0.975	0.962	0.998	0.992	0.98	0.96	0.94	0.91	0.992	0.98	0.95	0.92	0.89	0.85

A curve detailing LIDS docking reliability versus the total mission reliability for Options 1A, 1B, 2A, and 2B, as well as the impact on human casualty risk, is provided in Figure 6.



Docking Reliability	0.9999	0.99	0.95	0.9	0.85	0.8
Total Mission Reliability	0.9749	0.9653	0.9263	0.8775	0.8288	0.7800
Risk of Human Casualty	1 in 9413	1 in 6797	1 in 3201	1 in 1927	1 in 1378	1 in 1073

Figure 6. *Total Mission Reliability versus Docking Reliability*

Table 6*—Color-Coded Probabilities of Docking Success*

Probability of First Docking Success	Probability of Zero Residual Dependency: 1	.9	.8	.7	.6	.5
.9	.9999	.998	.994	.986	.975	.962
.8	.998	.992	.98	.96	.94	.91
.7	.992	.98	.95	.92	.89	.85

Table 6 provides a color-coded risk type chart for the various docking reliabilities, where green is acceptable, yellow is marginal, and red is unacceptable. Mission planning, docking maneuver design, and simulation both computerized and model-based are necessary to providing an adequate probability of docking success. The mission should not be launched until the docking maneuver has been completely modeled, assessed, and validated for an acceptable probability of success. Also note that if each docking attempt is truly independent, there is a significant margin in docking reliability for successful docking. Also note that dependency can significantly deteriorate docking reliability. Positive dependency—learning from failed attempts to improve subsequent attempts—was not addressed because it has no negative, only positive, influences on reliability at this time; however, it should be addressed in determining suitability of the mission moving forward.

Figure 7 provides the reliabilities for all of the options, variations, and range of reliability from 90 percent to 99.99 percent for the docking maneuver.

	Options							
	1A, 2A	1B, 2B	1C, 2C	1C.5	3A Var 1	3B Var 1	3A Var 2	3B Var 2
Spacecraft Reliability	0.9949	0.9949	0.7611	0.9362	0.8225	0.8225	0.9675	0.9675
LIDS Docking Reliability	0.9999	0.9999	0.9999	0.9999	0.9999	0.9999	0.9999	0.9999
Launch Reliability	0.98	0.98	0.98	0.98	0.98	0.98	0.98	0.98
Total Mission Reliability	**0.9749**	**0.9749**	**0.7458**	**0.9174**	**0.8060**	**0.8060**	**0.9481**	**0.9481**

	Options							
	1A, 2A	1B, 2B	1C, 2C	1C.5	3A Var 1	3B Var 1	3A Var 2	3B Var 2
Spacecraft Reliability	0.9949	0.9949	0.7611	0.9362	0.8225	0.8225	0.9675	0.9675
LIDS Docking Reliability	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99
Launch Reliability	0.98	0.98	0.98	0.98	0.98	0.98	0.98	0.98
Total Mission Reliability	**0.9653**	**0.9653**	**0.7384**	**0.9083**	**0.7980**	**0.7980**	**0.9387**	**0.9387**

	Options							
	1A, 2A	1B, 2B	1C, 2C	1C.5, 2C.5	3A Var 1	3B Var 1	3A Var 2	3B Var 2
Spacecraft Reliability	0.9949	0.9949	0.7611	0.9362	0.8225	0.8225	0.9675	0.9675
LIDS Docking Reliability	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95
Launch Reliability	0.98	0.98	0.98	0.98	0.98	0.98	0.98	0.98
Total Mission Reliability	**0.9262**	**0.9262**	**0.7086**	**0.8716**	**0.7657**	**0.7657**	**0.9007**	**0.9007**

	Options							
	1A, 2A	1B, 2B	1C, 2C	1C.5, 2C.5	3A Var 1	3B Var 1	3A Var 2	3B Var 2
Spacecraft Reliability	0.9949	0.9949	0.7611	0.9362	0.8225	0.8225	0.9675	0.9675
LIDS Docking Reliability	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90
Launch Reliability	0.98	0.98	0.98	0.98	0.98	0.98	0.98	0.98
Total Mission Reliability	**0.8775**	**0.8775**	**0.6713**	**0.8257**	**0.7254**	**0.7254**	**0.8533**	**0.8533**

Figure 7. *Reliability Summary for HST-D*

Reliability Assumptions

The following assumptions were made to determine the mission reliability. The reliability of the payload (including light detection and ranging, or LIDAR, cameras, and LIDS) assumed that the LIDAR and cameras have 1 week of operation in all options; LIDS reliability is estimated as one success in four attempts with a 90 percent probability of success on any attempt (prior discussion on docking was used to define the uncertainty and importance of proper simulation and docking process design); and LIDS attachment on HST is fully functional. Software reliability is assumed to be equal to 1 (except for the impact of software reliability on docking, which is included in the docking reliability estimate). Pre-launch reliability is assumed to be equal to 1. A 0.98 launch reliability was used, based on historical data and assumes known problematic launch vehicles were not selected.

Note: While 6 significant digits are used for reliability numbers in calculations, the accuracy of these numbers is actually 1-½ to 2-½ significant digits, due to the early stage of the design and the 60 percent confidence level for many of the basic predictive numbers. The added precision is used to identify differences between subsystems and provide the required calculations for risk. The confidence limits chart is provided to identify the uncertainty limits of the calculations.

Non-credible single point failures (SPF) include structural and non-moving mechanical components, short or open on power bus, propulsion fuel tank, and plumbing rupture.

The following duty cycles (relative to mission duration) were used:

- Thrusters (Attitude Control)—1 percent;
- Thrusters (Disposal)—<1 percent (22-min. demise, 53-min. raise orbit);
- SEP—35 percent for a 705-day mission, 70 percent for a 353-day mission;
- Payload—50 percent for a 2-week mission (1 week oper.);
- Ka Band Comm.—50 percent for a 2-week mission (1 week oper.);
- Operational Heaters—70 percent; Survival Heaters—10 percent;
- HGA Gimbals—25 percent for a 2-week mission (1 week oper.);
- Solar Array Gimbals—25 percent;
- And all other items assumed to have 100 percent duty cycle.

The following redundancy scheme options were assumed: for Option 1C.5 (SEP to 2000 km orbit), cold redundancy for two sets of two gimbaled electric thrusters, double thrust, half mission time, redundant gyro, redundant avionics; for Options 3A and 3B (orbit boost to enable 10 years of additional HST operation before disposal), Variation 1—Single String, Variation 2—all long-term electronics cold redundant.

The following spacecraft configuration was assumed:

Payload (All Options)

Docking Mechanism—two motors with mechanisms,
AR&D—five circuit card assembly equivalent electronics,
LIDAR (9 of 10 laser detector pairs required)—10 laser diodes, 10 photodiode detectors
Three cameras, one megapixel sensor per camera (96 percent of detector columns require

Spacecraft (All Options, except as noted)

ACS (all Options)—Star Tracker (DTU) with two heads and one processor, six coarse sun trackers (Adcole), gyro (NG IMU)

Avionics (all Options)—nine circuit card assemblies

Electrical Power System—Solar Array (all Options) 46 - 28V strings (45 of 46 required), Second Solar Array (Options 1C, 2C) 40 - 28V Strings (36 of 40 required), battery (all Options) eight cell lithium ion (seven of eight cells required)

PSE—four PSE Boards, four power distribution boards

Propulsion—16 attitude control thrusters (all Options), four main thrusters (Options 1A, 1B, 2A, 2B, 3A, 3B), SEP (Options 1C, 2C), two gimbaled SEP thrusters (two pairs for Options 1C.5), SEP control system, plumbing, filters, pressure detectors, pyrovalves, and latch valves

Communications (all Options)—Ka band transponder, 10 Watt TWTA, S-band transponder, global positioning system (GPS), two diplexers, hybrid, two gimbaled HGA

Thermal (all Options)—30 redundant operational heater circuits, 30 redundant survival heater circuits, 150 thermistors, six heat pipe assemblies

Conclusions

The highest modeled reliability of 0.9749 obtained for mission scenarios 1A, 2A, 1B, 2B (assuming a 90% independent probability of LIDS docking per attempt—99.99 percent for four attempts) falls slightly short of the required 0.976 reliability. The high reliability is due to the brevity of the mission; 2 weeks. The lowest modeled reliability obtained for Scenarios 1A, 2A, 1B, and 2B, with an acceptable docking probability (95 percent for four attempts), is 0.9262. The use of SEP without significant redundancy falls substantially below the required reliability (0.7384) due to the increased mission time (~2 years). Adding redundancy and shortening mission time can increase this to 0.9174. Docking with HST and continuing science for 10 years falls substantially below the required reliability (0.8060) and requires significant redundancy due to the extended mission time. Adding redundancy can increase this to 0.9481.

Reliability risk mitigation is required. This includes: performing a PRA early in the program to address high-risk items and events, such as LIDS docking; no waivers of reliability or risk assessments and analyses; implementing recommended corrective actions from the analyses and assessments. Because it is the linchpin to this mission, the docking process has to be fully defined, simulated, and error proofed to assure that the probability of successful docking is at the highest levels practicable.

If SEP or a 10-year mission are to be selected, significant redundancy is required and docking has to be at the highest reliability levels.

Use high reliability components on potential single point failures. Assure that all parts meet at least Level 2 requirements per NPR 8705-4 and EEE-INST-002. Assure that all assemblies (in- and out-of-house) have Parts Stress Analysis (PSA) and FMEA performed to assure compliance with derating and fault tolerance requirements.

"Non-credible" single point failures should be addressed with PRA, FMEA, or detailed failure modeling to assure they are truly "non-credible."

3.6 Orbital Debris Risk Considerations Related to HST-D

There is an international effort to limit the generation of, and risks from, orbital debris. This international effort is reflected within NASA in NPR 8715.6A, presenting policy and programmatic requirements, and NASA-STD 8719.14A, presenting technical requirements for NASA missions. In addition, there are a number of handbooks, tools, and detailed procedures which support the technical requirement assessments. 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. In both cases, the NASA requirements are based on the U.S. Government Orbital Debris Mitigation Standard Practices, and non-compliances must therefore be reported to the U.S. Secretary of State.

Disposal methods and timing are specified in NASA-STD 8719.14A, Requirement 4.6-1:

> *"Requirement 4.6-1. Disposal for space structures in or passing through (Low Earth Orbit) LEO:* A spacecraft or orbital stage with a perigee altitude below 2,000 km shall be disposed of by one of the following three methods: (Requirement 56557)
>
> a. Atmospheric reentry option:
>
> • Leave the space structure in an orbit in which natural forces will lead to atmospheric reentry within 25 years after the completion of mission but no more than 30 years after launch; or
>
> • Maneuver the space structure into a controlled de-orbit trajectory as soon as practical after completion of mission.
>
> b. Storage orbit option: Maneuver the space structure into an orbit with perigee altitude greater than 2000 km and apogee less than geosynchronous orbit (GEO)—500 km.
>
> c. Direct retrieval: Retrieve the space structure and remove it from orbit within 10 years after completion of mission."

Because raising the orbit of a spacecraft as large as HST to greater than 2000 km by traditional propulsion requires such a large amount of propellant, other storage orbit options were studied as well. There is a region between 1200 km and 1350 km where the orbital debris density is very low (about the same as 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, there is a lower long-term debris generation potential. Such an orbit would be stable for centuries, greatly postponing any concerns over reentry risk. This approach, however, would require a very significant deviation from NASA and U.S. Government policies, and international agreements.

The risk to the public from reentering space vehicles is controlled by NASA-STD 8719.14A, Requirement 4.7-1:

> *"Requirement 4.7-1. Limit the risk of human casualty:* The potential for human casualty is assumed for any object with an impacting kinetic energy in excess of 15 joules:
>
> a. For uncontrolled reentry, the risk of human casualty from surviving debris shall not exceed 0.0001 (1:10,000) (Requirement 56626).
>
> b. For controlled reentry, the selected trajectory shall ensure that no surviving debris impact with a kinetic energy greater than 15 joules is closer than 370 km from foreign landmasses, or is within 50 km from the continental U.S., territories of the U.S., and the permanent ice pack of Antarctica (Requirement 56627).
>
> c. For controlled reentries, the product of the probability of failure of the reentry burn (from Requirement 4.6-4.b) and the risk of human casualty assuming uncontrolled reentry shall not exceed 0.0001 (1:10,000) (Requirement 56628)."

Note that in addition to limiting the overall risk from reentry events to no more than 0.0001 (1 in 10000 odds of a significant injury), the requirement also defines the limit for a potentially lethal object as having 15 Joules (J) of impact energy. In practice, most objects with mass of more than about 50 grams, made of a high survivability material, will usually just meet this criterion.

There are also two specific requirements applied to controlled reentry: the first defines the minimum distances that must be allowed as a buffer to land areas, and the second incorporates disposal reliability to arrive at a total end to end risk to the public.

Reentry risk is generally calculated as follows:

$$\text{Risk}_{\text{uncontrolled}} = \rho_{\text{pop}} \times \text{DCA} \quad \text{(OD1)}$$

Where ρ pop is the average population density over the latitude band bounded by the orbit inclination, and DCA is the Debris Casualty Area associated with the reentry event. The DCA is the portion of the Earth's surface that is at risk due to surviving debris objects. It is determined by examining the vehicle construction and simulating the breakup, aerodynamics, and heating of objects as they reenter the atmosphere. If objects are predicted to survive reentry to impact the Earth's surface, a 0.3 m border is drawn around each object, to account for the size of an average person (averaged over a wide range of body sizes and positions). The sum of these individual DCA results is the total DCA for the reentry event. In the specific case of controlled reentry disposal, the reliability of the disposal is incorporated into the risk estimate as:

$$\text{Risk}_{\text{controlled}} = \rho_{\text{pop}} \times \text{DCA} \times (1 - \text{P}_{\text{success}}) \quad \text{(OD2)}$$

One of the main drivers for discussing the 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 Johnson Space Center (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, a total of 75 percent of the mass of the vehicle was identified in sufficient detail to perform the simulation. The result was that at least 98 different objects were predicted to survive reentry, with a total DCA of 146 m^2. This result was extrapolated to 195 m^2, in order to account for the 25 percent of the mass which could not be completely detailed. 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 2020. (It is recommended that the HST DCA estimate should be updated to reflect the hardware changes from the final HST servicing mission, the newest updates to ORSAT, and the updated reentry year.)

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, and resulting in the original case of an uncontrolled reentry (a launch vehicle failure here is assumed to be prior to achieving orbit, so any debris would reenter harmlessly over water). Equation OD2 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 10.

For the purposes of reentry risk estimation, the scenarios can be grouped into four groups. Scenario 0 is simply the baseline case of an uncontrolled reentry, updated only to reflect the slightly higher population density for a reentry in 2028. For the controlled reentry scenarios (1A, 2A, and 3A), a propulsion system was assumed that included demisable composite overwrapped pressure vessels (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 m2 for the disposal vehicle, and 220 m^2 for the mated pair. The scenarios that include boosting to 1200 km (1B, 2B, and 3B) 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 (1C, 1C.5, and 2C) 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.

Table 7 presents the details of the reentry risk estimates for each possible outcome, using each studied disposal scenario. It incorporates results from the reliability study performed by another team member. The population densities are from a table assembled by the ODPO, and compensate for the longer time spent near the northern and southern portions of the 28.5-degree orbital inclination. As can be seen in Table 7, the resulting totals fall into five groups.

Table 7*—Reentry Risk Estimates for Each Possible Outcome*

Scenario	0	1A	1B	1C	1C.5	2A	2B	2C	3A	3B
Outcome—LV Failure										
DCA (m^2)	**195**	**195**	**195**	**195**	**195**	**195**	**195**	**195**	**195**	**195**
Probability	1	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Reentry Year	2028	2028	2028	2028	2028	2028	2028	2028	2028	2028
Population Density (people/km^2)	21.7865	21.7865	21.7865	21.7865	21.7865	21.7865	21.7865	21.7865	21.7865	21.7865
Risk	4.24E-03	8.48E-05	8.48E-05	8.48E-05	8.48E-05	8.48E-05	8.48E-05	8.48E-05	8.48E-05	8.48E-05
Outcome—Unsuccessful Disposal										
DCA (m^2)		220	220	205	220	220	220	205	220	220
Probability		0.0051	0.0051	0.2389	0.0638	0.0051	0.0051	0.2389	0.1775	0.1775
Reentry Year		2028	2028	2028	2028	2028	2028	2028	2040	2040
Population Density (people/km^2)		21.7865	21.7865	21.7865	21.7865	21.7865	21.7865	21.7865	23.9226	23.9226
Risk		2.44E-05	2.44E-05	1.07E-03	2.85E-04	2.44E-05	2.44E-05	1.07E-03	9.34E-04	9.34E-04
Outcome—Successful Disposal										
DCA (m^2)		0	0	0	0	0	0	0	0	0
Probability		0.9749	0.9749	0.7458	0.9174	0.9749	0.9749	0.7458	0.806	0.806
Reentry Year		2023	N/A	N/A	N/A	2023	N/A	N/A	2036	N/A
Population Density (people/km^2)		20.7904	0	0	0	20.7904	0	0	23.2511	0
Risk		0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Total Risk	**4.24E-03**	**1.09E-04**	**1.09E-04**	**1.15E-03**	**3.70E-04**	**1.09E-04**	**1.09E-04**	**1.15E-03**	**1.02E-03**	**1.02E-03**
Odds of an Injury (1: XXXX)	**1:236**	**1:9152**	**1:9152**	**1:868**	**1:2704**	**1:9152**	**1:9152**	**1:868**	**1:981**	**1:981**

The results will be discussed here using the odds of a significant injury, because they are generally easier to conceptualize. As expected, the risk of doing nothing is slightly worse than the original estimate of 1 in 250, because of the slightly higher population density during the later reentry. Boosting HST to 2000 km with single string hardware improves those odds by only about a factor of 3.7×, partly because the longer time to reach the disposal orbit reduces the reliability. Performing the same disposal using dual string redundant hardware improves the original risk by a factor of 11×. Disposal after extended science operations results in an improvement over the baseline case of only 4.2×, again due to the reduced reliability resulting from a longer mission lifetime. The reentry risk estimates show that if disposal is performed almost immediately after capture (either raising to 1200 km or controlled reentry), then the end-to-end risk can be improved by a factor of about 39× over the baseline case.

Each of the disposal scenarios studied (including the uncontrolled reentry baseline case) violates one or more of the NASA requirements quoted above. Table 8 summarizes which requirements are violated by each approach, and would therefore need to be addressed through a waiver request to examine and accept the associated risks. The controlled reentry options nearly meet the 1 in 10,000 reentry risk requirement, but not quite. As described previously, the disposal location requirement violation (for using a storage orbit of 1200 km) is non-trivial, and this approach has not been proposed previously for NASA missions. Note also that there is an additional column concerning the 0.90 minimum disposal reliability requirement (4.6-4) for all missions, which had not been discussed previously.

Table 8*—ADL Options—Recommended Waivers for Specific Requirements*

	Scenario	Req. 4.6-1 Orbital Lifetime	Req. 4.6-1 Disposal Location	Req. 4.6-4 Disposal Reliability	Req. 4.7-1 Reentry Risk
0	Do Nothing	Waiver	√	√	Waiver
1A	Cont. Reentry, Dead HST	Waiver	√	√	Waiver
1B	Up to 1200 km, Dead HST	√	Waiver	Waiver	Waiver
1C	Up to 2000 km, Dead HST	√	√	Waiver	Waiver
1C.5	Hi-rel up to 2000 km, Dead	√	√	√	Waiver
2A	Cont. Reentry, Live ACS	Waiver	√	√	Waiver
2B	Up to 1200 km, Live ACS	√	Waiver	√	Waiver
2C	Up to 2000 km, Live ACS	√	√	Waiver	Waiver
3A	Cont. Reentry, HST Science	Waiver	√	Waiver	Waiver
3B	Up to 1200 km, HST Science	√	Waiver	Waiver	Waiver

3.7 Cost Estimation for HST-D

One of the major objectives of this study was to obtain a relative cost for each of the options. Because a detailed MDL had not been done and a Master Equipment List (MEL) was not available, only a rough estimate could be made of the cost, but one that would provide at least a relative comparison of the LCC for each HST-D mission. The model chosen was Quick Cost, a cost-estimating tool for missions developed by Dr. Joe Hamaker for NASA HQ. The most current version (5.0, released in February 2011) was used for the calculations. The model is based on a database of 131 missions ranging from Flagship to SMEX missions. The database is included with the model, so direct comparisons with previous missions are possible. There are nine independent variables that need to be input. They are:

- Type of orbit
- Authorization to Proceed date
- Operational life
- Instrument complexity
- Expected total mass with margin
- Expected total power with margin
- Bus heritage
- Instrument heritage
- Confidence level

The only subjective inputs are the instrument complexity and heritage and the bus heritage, all of which range from 20 to 100 percent. Examples from the database were consulted to determine an approximate estimation for these. A confidence level of 70 percent was used for all of the options. For the various options, the total power changed only slightly but the weight did range from 1400 to 2400 kg depending on the option. The final results are shown in Figure 8. The least expensive option is 2A (deorbit using a bipropellant, ACS working) with 1A (deorbit using biprop, totally dead satellite) in second place. Even though the LCC ranges from $400M to $1200M, these are only relative costs; more accurate estimates will come from a detailed MDL and are subject to changes in the technology and the industry.

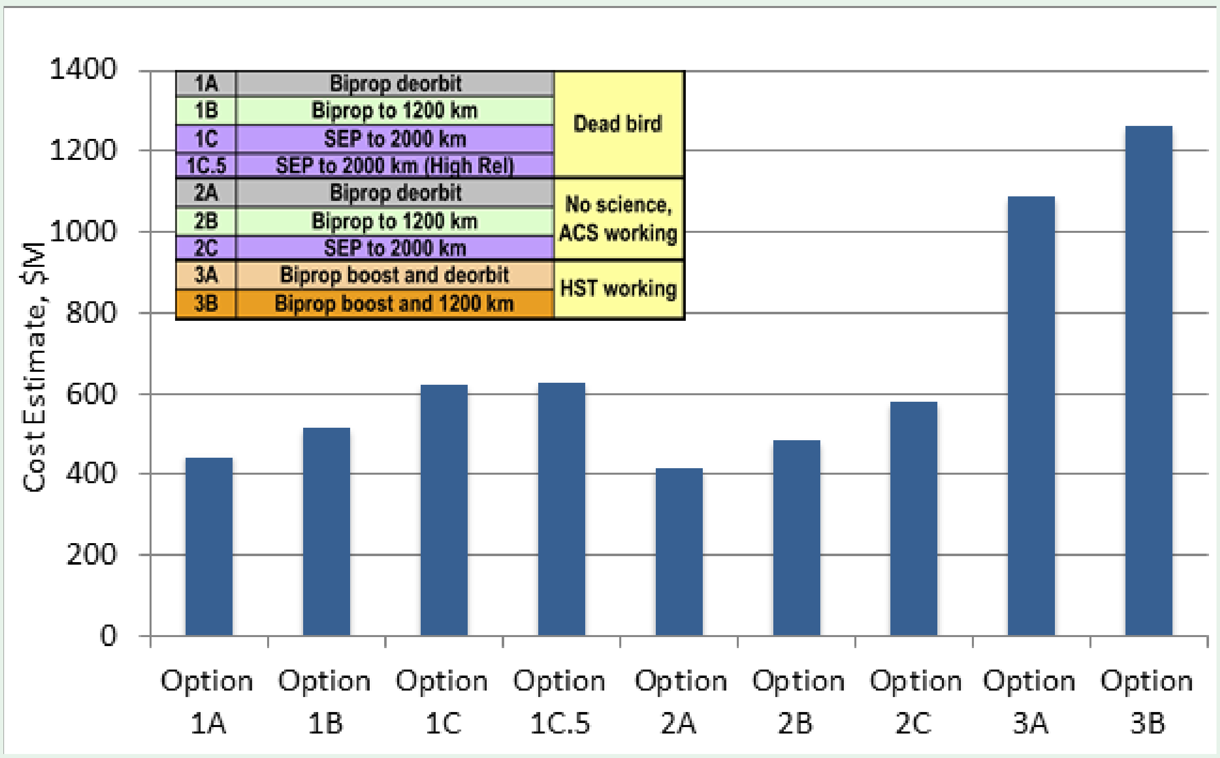


Figure 8. *Relative LCC for HST-D Mission Options*

3.8 Partnering Possibilities

The ADL supported Partnering Possibilities "brainstorming" sessions after the HST-D study activities were completed. The ADL team served as a valuable resource for assessing the technical feasibility of the various partnering concepts. The main objective of these sessions was to identify alternative mission implementations and concepts for performing the HST-D that would also provide a benefit opportunity for a potential cost-sharing partner. The team developed and began populating a draft Partnering Possibilities template for the Partnership Survey deliverable. Refer to Section 5.2 for information on the partnering possibilities.

4.0 STUDY "HOLD" RECOMMENDATIONS: MONITORING TECHNOLOGIES AND PARTNERSHIPS

4.1 Overview

Starting in FY2013, the HST-D Study will become mostly inactive. The exception is that the COR Program Office plans to monitor the technologies that may be needed for the mission when it is reactivated. This "hold" period will last for at least 3 years and may extend beyond that, depending on the altitude of the HST. The project will be reactivated when HST is about 5 years from reaching an altitude of 500 km. HST is currently predicted to reach 500 km in 2023, so the project would be reactivated in 2018. This 5-year reactivation date for the project is only an estimate and would benefit from both a DRM and/or an RFI to better establish this timeframe. During this inactive period, a five-pronged approach requiring 0.2 full-time equivalent (FTE) is recommended to keep abreast of changes in the technologies needed for the HST-D mission: 1) checking suppliers twice a year, 2) soliciting inputs from the AR&C community, 3) attending trade shows and conferences, 4) providing timely notification if difficulties arise that prevent technologies from reaching a TRL 6 prior to a Phase A start; and 5) issuing an RFI prior to reactivation. The updated supplier and AR&C/D databases will be reissued on a semi-annual basis. The MSFC team will be tasked with the bulk of the monitoring effort, and the availability and funding of their workforce is essential to the success of this effort. The continued monitoring is planned so the latest AR&C companies, products, and technology information will be available when the "hold" period is over.

Monitoring technology tasks include providing timely notification if technology demonstrations, commercial systems, and/or partnering opportunities arise. Any of these situations may trigger a decision for a faster HST-D mission start and capture the potential benefits from participating in low-cost or cost sharing opportunities.

4.2 HST Orbit Altitude Decay Profile

It is critical that the HST altitude data be incorporated as part of the monitoring effort on the same semi-annual basis as the technology. Once the earliest date the HST will reach an altitude of 500 km has been determined, the HST-D mission needs to start 5 years prior to that date.

4.3 Monitoring Technologies

The MSFC team compiled a comprehensive survey of past and current AR&C missions and companies into a database that will serve as the basis for the monitoring effort. As mentioned in Section 4.1, a five-pronged approach is planned to keep abreast of changes in the required AR&C technologies. The first prong is that twice a year, or more frequently, someone would either check the websites or call the suppliers in the database to verify that they are still in business and that they are still making the desired product. If not, they should be removed from the list with the appropriate explanation and a red flag should be raised to alert the COR Program Office if there is a possible loss of the technology or of the maturation of the technology. The second is to keep in communication with the AR&C community and to periodically solicit them for inputs to the database.

The third is to attend annual trade shows and technological conferences to obtain the current status of the technology, both to confirm that known suppliers are active and to add additional suppliers as they come into the market. For example, the American Institute of Aeronautics and Astronautics (AIAA) Space 2012 conference had several sessions with presentations that had technologies relevant to the HST-D mission. There were talks given by employees of some of the major players in AR&C as well as talks given by universities and small businesses doing research that could support a future HST-D mission. The Boeing Company gave a good presentation and paper about progress it has made on the design of its Commercial Crew Transportation System (CCDev) spacecraft. That system will use AR&C, and the capture will be done with the NASA Docking System, which is a variant of the Low Impact Docking System which was attached to HST during the last servicing mission. Lockheed Martin presented a low-cost launch concept for smaller payloads, which could keep costs down if a low-mass method for HST-D were used. The Aerospace Corporation presented an electric propulsion tug concept and modeling for its use, while the U.S. Naval Research Laboratory presented on the testing of robotic arms on the ISS for future use on satellite servicing. York University in Toronto, Canada, presented their work with a vision-based robotic arm control for on-orbit servicing, and several groups (Tethers Unlimited, York University, and Pennsylvania State University) presented on the use of EDTs for propulsion in low-Earth orbit. Any of the systems or technologies from these presentations (and their accompanying papers) could mature over the next 5 years to something that will be used in the HST-D mission.

The fourth is providing timely notification if difficulties arise that prevent technologies from reaching a TRL 6 prior to a Phase A start. If technologies are not maturing at an adequate pace to support a 2019 Phase A start, then the COR Program Office will notify HQ and recommend mitigations.

The last prong is to issue an RFI, which will be discussed in Section 4.5, prior to coming out of the "hold" period. It is envisioned that the database would become a tool for the AR&C community during the "hold" period and after. This effort is anticipated to be minimal at about 0.1 FTE a year.

In addition to the AR&C database, the MSFC team compiled an AR&D sensor database from the AR&D Community of Practice. It is still being updated and converted to a more usable database format. After it has completed this initial phase, it will become part of the technology monitoring outlined in the previous paragraph.

Due to its association with the human exploration program, MSFC will not only benefit from knowledge gained from monitoring the database but also will be a source of new information from AR&D activities on the human flight projects. It is also recommended that industry, DoD, and other NASA activities are monitored for other relevant capabilities, such as propulsion, AR&C/D, orbital debris mitigation, EDTs, etc.

4.4 Monitoring Potential Partnerships

During this part of the study, a database of potential partners was created jointly by GSFC and MSFC, including a subset of companies responding to a highly relevant Defense Advanced Research Projects Agency (DARPA) RFI. Monitoring possible partnerships during the inactive period will be essentially the same as that used for the technology monitoring and would include: periodically checking potential partners' websites and, if needed, a telephone confirmation; communicating with the AR&D community; making contact at trade shows and conferences;

and issuing an RFI (this is in combination with the technology RFI, not a separate RFI). This effort would also be on the order of 0.1 FTE per year.

4.5 RFI: Potential AR&C/D System Integrators and Partners

About 18 months prior to the reactivation of the HST-D project, an RFI will be issued for inputs pertaining to this mission, such as determining the interest, capabilities, and potential HST-D mission integrators. This will provide enough time to receive and review the inputs and then to hold a workshop to cover the best responses. The results of this workshop will provide updates for the databases and input for the MDL planned soon after coming out of the "hold" period.

4.6 Pre-Phase A Study Recommendations

Soon after reactivation, the HST-D project should go through the MDL to provide higher-fidelity designs (for AR&C/D hardware, spacecraft bus, launch vehicle, etc.), cost, and schedule estimates for long-term planning. The data from the technology and the partnership databases, combined with the RFI and workshop results, will be important inputs to that activity. It is possible that, due to circumstances such as solar activity, time-sensitive partnering opportunities, or loss of available technologies, HST-D may require a fast start and, by monitoring the technologies and partners, it is possible to have the HST-D mission up and running in a minimum amount of time.

4.6.1 Free Body Drift Rates

When the HST-D project enters Phase A, designing reliability into the system, as described in Section 3.5, is highly recommended. Performing additional analyses to characterize HST's free-body drift rates below 565 km is also highly recommended. The ADL relied upon analyses completed in previous HST De-Orbit studies and the engineering judgment of the GN&C engineers who completed those analyses.

4.6.2 Updating Debris Casualty Area and Human Casualty Risk

The ADL team also recommends updating the DCA and human casualty risk analyses to include the components changed during the HST SM4. Monitoring HST's altitude data is critical to determining the earliest date HST will reach an altitude of 500 km and more credibly establishing a Phase A start date.

4.6.3 Design Reference Mission

The ADL team recommends developing a DRM based on Option 1B, boosting a non-functional HST up to 1200 km. Option 1B was studied as a Class B mission with mission reliability of .976 or better and a target requirement of 1 in 10,000 risk of human casualty. This option envelops other cost-effective options, meets the required mission reliability, and minimizes the risk of human casualties. The most cost-effective possible mission concept, purchasing a total HST-D mission service, will become feasible when technologies and commercial capabilities evolve and support procuring HST's Disposal as a commercial service. The MDL should also include a higher-fidelity Phase A project start date and better define the HDV's mission-specific requirements.

4.6.4 HST Low Impact Docking System (LIDS)

The baseline docking hardware for all ADL architecture options is the HST-LIDS. Therefore, during system formulation we recommended reevaluating the decision as to if and when the HST-LIDS design should be completed. Customized flight design, development, and hardware are required to produce HST-LIDS flight hardware. The HST-specific version of

LIDS is different than the IDSS and is not compatible with the iLIDS version used for human spaceflight and the ISS. The iLIDS version also includes additional, more costly hardware required for human spaceflight (e.g., pressure seals) that is not necessary for interfacing with the HST's soft capture mechanism.

The HST-specific LIDS hardware could be provided as Government-Furnished Equipment (GFE) to a future systems integrator for the HDV. To mitigate the risk of incorrectly designing the flight HST-LIDs, developing the engineering design with Johnson Space Center's LIDS-knowledgeable engineering team should be reevaluated. There may also be an industry-developed solution using sensors and actuators from LIDS, but customized mechanical components. Other options that may evolve during the "hold" period may also prove to be a better value.

4.6.5 HST Mission-Specific Requirements

At the release of this document, HST-specific requirements for enabling technologies were not defined. Defining HST-specific requirements for enabling technologies early in the study "hold" will facilitate more focused technology monitoring efforts.

5.0 STUDY DELIVERABLES

5.1 HST Automated Rendezvous and Capture or Docking (AR&C/D) Survey

In order to move HST to a safe location, the mission requires a rendezvous with HST, grappling or capturing HST, and then maneuvering HST. Because AR&C will be responsible for those phases of the mission, it is one of the elements most critical to the success of the HST-D mission. AR&C consists of parts of a spacecraft system that work together to achieve those portions of the mission, and the AR&C components must be integrated in from the beginning. AR&C is not only vital for the HST-D mission, but also it is vital to a number of future NASA missions that are laid out in various roadmaps and plans.

AR&C is sometimes also referred to as Automated Rendezvous and Docking (AR&D), but the more general AR&C term will be used in this section. AR&C consists of several main technology areas: algorithms and software, sensors, mechanisms, Fault Detection, Isolation, and Recovery (FDIR), and system design and integration. The algorithms and software are the heart of an AR&C system in that they control the spacecraft motion, whether in the area of rendezvous, proximity operations, or capture, as well as make higher-level decisions about which phase of the mission is next. The sensors are the eyes of the system, providing information about the relative positions and attitudes of the chase vehicle and the target vehicle (HST, in this case.) The mechanisms are the hands of the system, allowing the chase vehicle to dock with or grab the target vehicle and, in the case of HST, hold it in a rigid fashion such that the combined pair of vehicles can be maneuvered into a safe location. FDIR is not unique to AR&C systems, but, due to the automated and constantly maneuvering or manipulating that occurs, FDIR takes on a new level of importance. The high level of automation calls for good system design and integration as well as considerable testing.

NASA has had different groups look at areas in which NASA should be going or missions NASA should be doing. The Human Space Flight Architecture Team (HAT) as well as the Office of Chief Technologist (OCT) created various roadmaps and mission plans. Some of the OCT Space Technology Roadmaps will require AR&C technologies in order to be carried out. Those roadmaps include the "In-Space Propulsion Systems Roadmap: Technology Area 02,"[5] the "Robotics, Tele-Robotics and Autonomous Systems Roadmap: Technology Area 04,"[6] the "Human Exploration Destination Systems Roadmap: Technology Area 07,"[7] and the "Entry, Descent, and Landing Roadmap: Technology Area 09."[8] Some of the potential NASA missions that will require AR&C in order to be realized include the HST-D mission, unmanned and manned visits to near-Earth objects, infrastructure and utilization of the L2 Gateway, lunar and planetary sample return missions, the manned Mars DRM, a cryogenic propulsion, storage, and resupply mission or system, any kind of orbital debris mitigation, and maintenance and servicing of spacecraft. AR&C is vital to a number of future missions being considered by NASA.

There are people who will ask why NASA should invest at all in AR&C for the HST-D mission, given that different aspects of AR&C have been demonstrated on orbit several times over the last few years. The short answer is that there is not an AR&C system available for HST-D. There are some components of it that are available—some image processing algorithms and software, a couple of space-qualified sensors, and some GN&C algorithms that could be used. But while those are available at present, they may not be available in 5 or 10 years, when the HST-D mission will take place. Additionally, there are no docking/capture/grapple mechanisms currently available that could capture the HST and allow it to be propelled to a safe location. There are targets and fixtures on HST that are designed to be used with sensors and mechanical systems, but those systems do not currently exist. Since the available AR&C capabilities will be changing over the next few years, and given the unique requirements of HST-D, continued investment should be made both in keeping up with available technologies, sensors, algorithms, software, and mechanisms and in considering the unique portions of this mission so that when the HST-D mission is started, the requirements and current capabilities will be well known.

Due to the importance of AR&C to the HST-D mission, several things were done during the course of the HST-D study. A comprehensive survey of past and current AR&C missions and companies was compiled. In addition, a list of companies responding to a DARPA RFI in the area of satellite servicing was also compiled. Both lists of missions and companies can be used to keep track of past, current, and potential future vendors or system integrators. Another task that was accomplished was the updating of the AR&D Community of Practice's AR&D Sensor database. The database, a list of past and current sensors for use in AR&D in space, was updated to include more sensors. It was converted from a spreadsheet to an actual database (Microsoft Access) that allowed easier searching, listing, and comparing of the sensors in the database.

AR&C is a vital part of the HST-D mission, but there is not a complete set of hardware or technologies currently available. The HST-D mission will require custom development in addition to any off-the-shelf components that could be purchased. The technologies and available components will be changing over the next 5 years, and they will need to be monitored for relevance and capability. HST-D will obviously benefit from this monitoring and the NASA AR&D community as a whole will benefit. the AR&C is important to many future NASA missions. The companies involved in AR&C work will also be changing over the next 5 years, and they will also need to be monitored for their suitability to carry out the HST-D mission. The information from this continued monitoring of sensors, technologies, and companies will feed into a future MDL effort to create a point design for this mission, or the information will feed directly into the HST-D mission.

5.2 Partnering Possibilities Survey

The ADL supported Partnering Possibilities "brainstorming" sessions after the HST-D study activities were completed. The team developed and began populating a draft Partnering Possibilities template for the Partnership Survey study deliverable. The monitoring activities during the study "hold" and timely notification to the COR Program Office will be a critical part of whether or not the HST-D mission may take advantage of potential cost-sharing opportunities. The objectives of the brainstorming sessions were to: 1) identify alternative HST-D implementations with benefits/opportunities that may attract partners; and 2) focus on types of partnerships that may reduce SMD's cost for the HST-D mission. Partnerships of interest include those which would provide the government with a financial benefit, hardware, or service.

The information for each idea/concept was organized to make it useful for person(s): 1) monitoring the technologies, vendors, and potential partnerships during the study's "hold" period; 2) assessing risk to the disposal mission, increasing the cost of the mission; or 3) determining political/education/outreach benefit, science benefit, technology demonstration, standalone payload.

Alternative Disposal Implementations (ADI) for executing a partnership mission with the HDV were identified for various phases of the HST-D mission, inclusive of the following:

A. Pre-rendezvous, on the way up to HST;

B. While attached to HST; and

C. **After HST's disposal:** This significantly new disposal implementation includes reusing the HDV after HST's disposal. This implementation would provide mission opportunities for potential, cost-sharing partners. This implementation requires reboosting the HDV after HST's disposal is complete (via reentry or storage orbit) as a means of reusing the HDV and enabling other types of missions (e.g., science, technology demonstration, orbital debris disposal, and commercial).

A Partnership Survey Spreadsheet was developed, located in Appendix D, and documents the ideas, concepts, and rationale obtained during the Partnering Possibilities brainstorming sessions. Some examples of the ideas captured for each ADI are provided below.

A. On the way up (pre-rendezvous)

- Co-manifest payloads (e.g., commercial, Hubble replacement, etc.)
- Technology demonstration
- New propellants (high-performance green propellant, hydroxyl ammonium nitrate (HAN), green propellants, sub-cooling)
  - New propulsion technologies (e.g., ED tether)
  - Guidance technologies
  - New communication systems
- Science data collection
- Operations test bed

B. While attached to HST (Option 3A or 3B)

- Science data collection
- Technology demonstration

C. After HST's disposal

Examples of missions that would interest potential partners and require reboosting the HDV include: 1) deorbiting other large debris; 2) collecting science data; or 3) performing a technology demonstration or a commercial mission.

Reusing the HDV could create new opportunities and benefits for potential partners that may include the following:

- **Solar sail demonstration** (only after Architecture Options 1C or 2C)
- **Slow boat to a storage orbit:** e.g., via EDT. Although EDTs are not currently feasible, if the technology matures, the HST-D mission could be used to demonstrate the EDT's capability to support active debris removal
- **Operations test bed**

- **Earth-cam from 2000 km.** The primary HST-D mission may become the secondary mission with a secondary payload. This is currently not feasible. Using an altitude of 2000 km for an optical instrument is not recommended due to the high flux of charged particles which interfere with the detectors, making them noisy and limiting their life.
- **Replace HST with another optical telescope and use the same mission to do both the deorbit module and a Hubble replacement;** drop off, deorbit separates, and place the new telescope.

6.0 STUDY BASELINE

6.1 Study Team Schedule and Deliverables

Figure 9 shows the study schedule of activities and deliverables prior to receiving direction to cancel the FY2012 Baseline DRM. As a result, the Baseline DRM, the Draft Technology Plan, and Summary Report are no longer FY2012 and FY2013 required deliverables. This HST Study Plan and Closeout Report is a new deliverable and serves to document the pre-"hold" HST-D Study Plan, activities, results, recommendations, and post-"hold" activities necessary for a Pre-Phase A start.

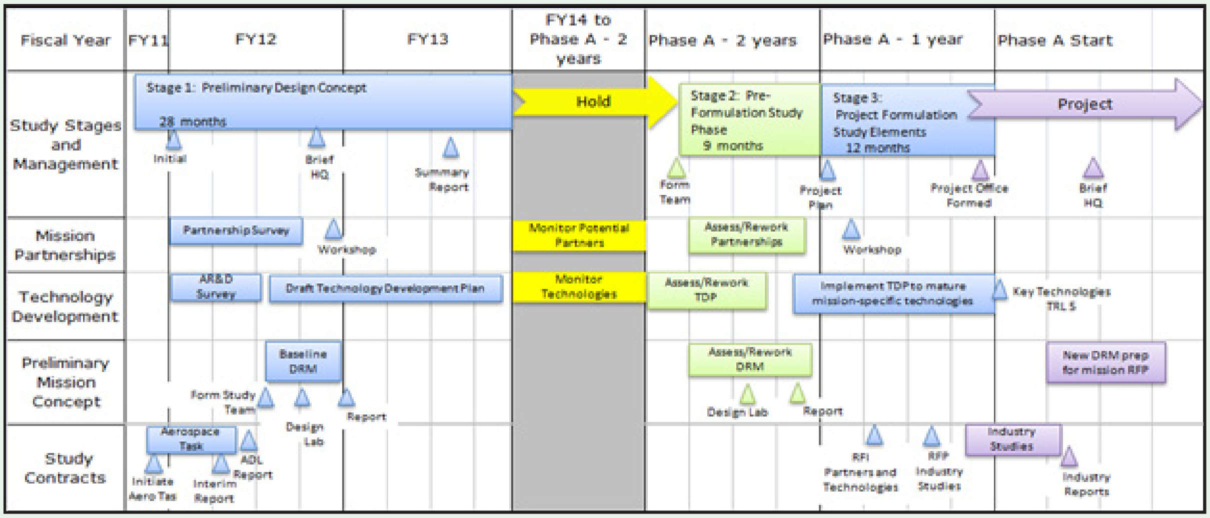


Figure 9. Study Schedule and Deliverables—Before Direction to Cancel FY2012 MDL

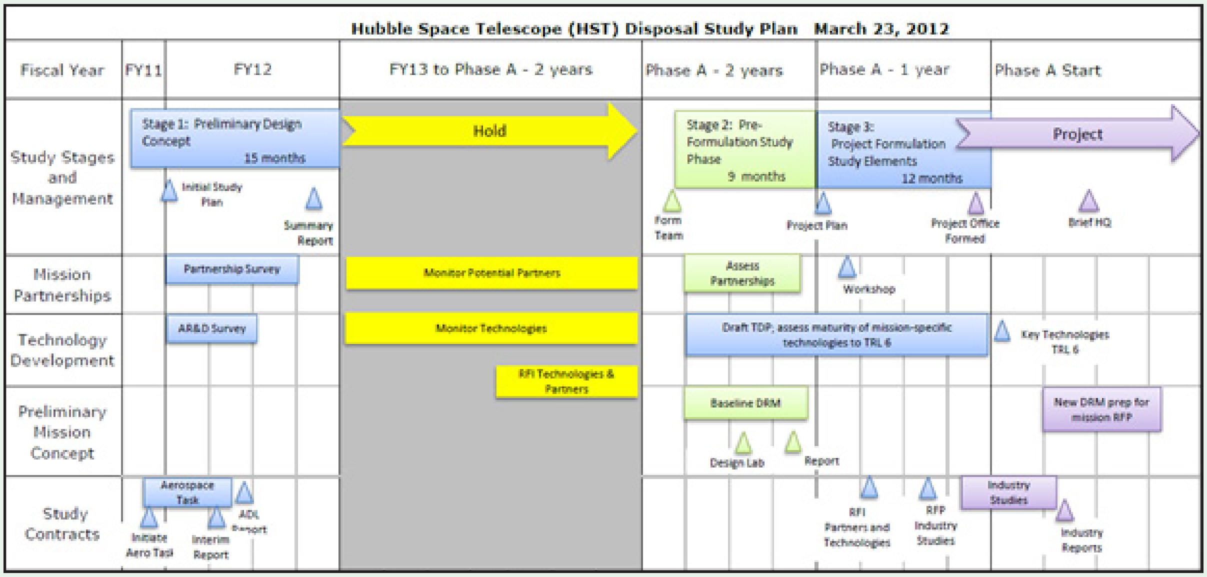


Figure 10. Study Schedule and Deliverables—After Direction to Cancel FY2012 MDL

7.0 STUDY BASELINE

7.1 Cost, Schedule, and Technical Data Management Approach

The study team Financial Manager will provide monthly financial data, obtained via standard Goddard Business Warehouse tools and reports, to the Study Manager, in order to assess the cost actual versus the cost plan. The cost actual data will be compared to the expected schedule progress to ensure resource expenditures progress the schedule activities per both the cost and schedule plans.

The Study Manager and Study Team Leads—Scientist, Mission Systems Engineer (MSE), and Financial Manager—will all provide schedule updates to the Study Team Scheduler; this will occur on a monthly basis to coincide with the release of the study team monthly financial reports.

Assessments of progress against cost and schedule will be made at a monthly status meeting, attended by the Study Team Leads. Adjustments will be made to future cost and schedule plans in the event the integrated cost and schedule plan is not progressing as expected in order to stay with allocated resources.

All technical data will be housed on the COR Program Office website; this will include, but is not limited to: the RFI responses; presentations; science or engineering analyses, design lab presentations, and summary reports; and the final HST-D Study Plan and Closeout Report.

The configuration change control of the missions that will be studied in the MDL will be controlled by the Study MSE with approval by the Study Manager. There will be no formal configuration management (CM) plan or configuration control boards.

7.2 Risk Assessment and Mitigation Approach

The study team performed high-level risk assessment against those mission architectural concepts recommended from the ADL for further development into the MDL, including determining risk mitigation approaches. Due to the cancellation of the August 2012 MDL, the risk assessments planned to be made against any technology development efforts, cost and/or schedule estimates, programmatic realities, etc., could not be completed. Future risk assessment and mitigations will be approved by the Study Manager in consultation with the Study Team leads. If a future MDL is conducted, the final report should include discussion of these risk assessments and mitigations.

During the pre-“hold” study activities, the Core Study Team provided on-time deliverables and maintained its regular status meetings.

7.3 Team Communications Approach

The study team held a weekly status meeting involving all core engineering science team members. The COR PO and ACTO managers were invited to attend all meetings. These meetings assessed study status and reported progress against the study plan. Members of the team who were not physically at GSFC were allowed to dial into the status meetings.

NASA HQ PCOS Program Executive and Program Scientists were invited to meetings with the COR Program Office, where status and deliverables were provided.

7.4 Study Team Reporting and Review Approach

The Study Manager reports monthly cost, schedule, and technical performance progress to NASA HQ APD COR Program Executive and Program Scientist through the PCOS ACTO Manager. The Study Manager provides a final HST-D Closeout report to the COR Program Office.

The Study Manager provides monthly status through the COR Program Office to the GSFC Center Management Council.

There are no formal reviews involved in the study; however, the Study Manager does meet weekly with the COR ACTO Manager to review and assess study progress.

7.5 Knowledge Capture and Lessons Learned

Most likely, the GSFC Astrophysics Projects Division and the PCOS and COR Program Offices will be undertaking similar studies as the decade unfolds. However, due to prematurely entering the pre-“Hold” period for this HST-D study, limited resources, and reduced staffing, any significant lessons and knowledge learned from this study are documented only in this report and will reside in the COR Program Office. The COR PO and Study Manager will not engage the services of the GSFC Chief Knowledge Officer to perform an ‘after action review’ of the study effort to insure future studies are informed of the lessons learned throughout this HST-D mission architecture concepts study.

8.0 APPENDICES

Appendix A—Acronyms

AoA	Analysis of Alternatives
ACS	Attitude Control System
ACTO	Advanced Concepts and Technology Office
ADL	Architecture Design Lab
AIAA	American Institute of Aeronautics and Astronautics
AO	Architecture Options
APD	Astrophysics Division
AR&C	Autonomous Rendezvous and Capture
AR&C/D	Autonomous Rendezvous and Capture/Docking
AR&D	Autonomous Rendezvous and Docking
CAA	Committee on Astrophysics and Astronomy
CCDev	Commercial Crew Transportation System
CET	Core Engineering Team
CM	Configuration Management
CST	Community Science Team
COPV	Composite Overwrapped Pressure Vessels
COR	Cosmic Origins
DARPA	Defense Advanced Research Projects Agency
DCA	Debris-Casualty Assessment
DoD	Department of Defense
DRM	Design Reference Mission
EDT	Electrodynamic Tether
FDIR	Fault Detection, Isolation, and Recovery
FTE	Full-time Equivalent
GEO	Geosynchronous Orbit
GEVS	General Environmental Verification Standard
GFE	Government-Furnished Equipment
GN&C	Guidance, Navigation, and Control
GPS	Global Positioning System
GSFC	Goddard Space Flight Center
HAN	Hydroxyl Ammonium Nitrate
HAT	Human Space Flight Architecture Team
HDV	HST Disposal Vehicle
HQ	Headquarters
HRSDM	Hubble Robotic Servicing and Deorbit Mission
HST	Hubble Space Telescope
HST-D	Hubble Space Telescopy Disposal
HST-LIDS	HST-Low Impact Docking System
JSC	Johnson Space Center
LEO	Low Earth Orbit
LIDS	Low Impact Docking System

iLIDS	international Low Impact Docking System
IDSS	International Docking System Standard
IMDC	Integrated Mission Design Lab
ISS	International Space Station
LCC	Life Cycle Costs
LIDAR	Light Detection and Ranging
LIDS	Low Impact Docking System
MDL	Mission Design Lab
MEL	Master Equipment List
MSE	Mission Systems Engineer
MSFC	Marshall Space Flight Center
NASA-STD	NASA-Standard
NDS	NASA Docking System
NET	No Earlier Than
NPR	NASA Procedural Requirement
NWNH	"New Worlds, New Horizons in Astronomy and Astrophysics" report
OCT	Office of Chief Technologist
ODPO	Orbital Debris Program Office
ORSAT	Object Reentry Survival Analysis Tool
PCOS	Physics of the Cosmos
PO	Program Office
PRA	Probabilistic Risk Analysis
Ps	Probability of Mission Success
PSA	Parts Stress Analysis
RBD	Reliability Block Diagrams
RFI	Request For Information
ROM	Rough Order of Magnitude
SCM	Soft Capture Mechanism
SEP	Solar Electric Propulsion
SM4	Servicing Mission 4
SMD	Science Mission Directorate
SMEX	Small Explore
SPF	Single Point Failures
TMR	Total Mission Reliability
TRL	Technology Readiness Level
UV/Vis	Ultraviolet/Visible

Appendix B—Study Team Organization, Roles, and Responsibilities

The Study Team organizational structure is show below in Figure 1. Key team members are the Study Manager, the Study Scientist, the Lead Mission Systems Engineer, and the Study Financial Manager. Their roles are described below. Additionally, a list of the ADL Study Team members and Advisors are located in Appendix B.6.

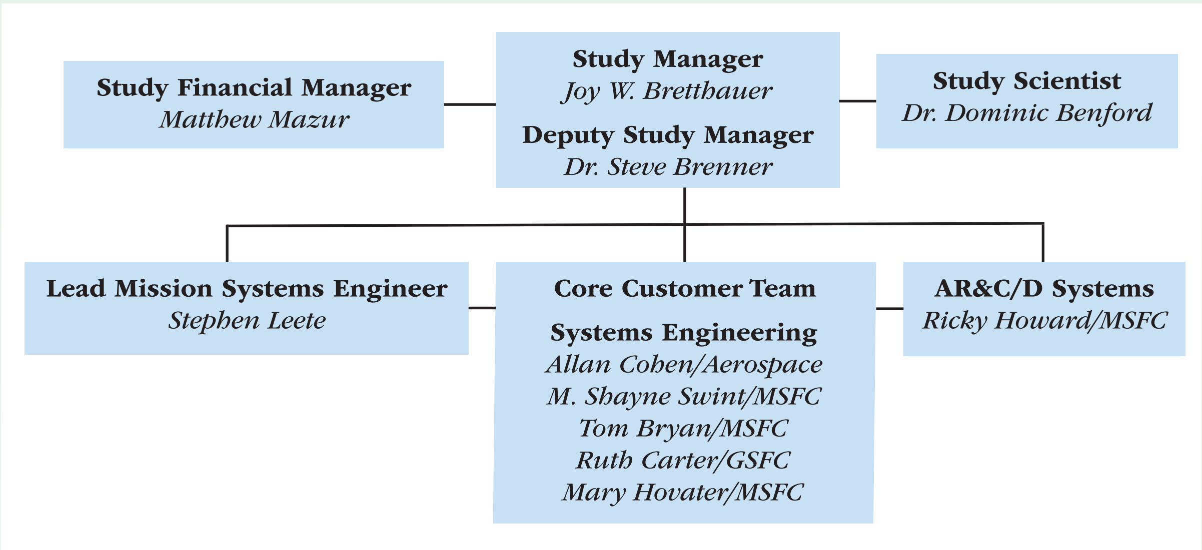


Figure B1. *Study Team Organization*

B.1 Study Manager

The Study Manager has overall responsibility for the execution of the study and is accountable to the ACTO Manager for ensuring study programmatic requirements, objectives, and deliverables, as delineated in Section 1.2, are successfully met.

The Study Manager, working with COR Program Office staff, is responsible for: managing the study and presenting study deliverables to the APD PO and HQ, handling all of the logistics for the outbrief presentations; providing support as requested by the Core Team to facilitate their travel, meetings, and team communications. The Study Team Manager is supported by a Deputy Manager.

B.2 Study Scientist

The Study Scientist is responsible for all science aspects of the study and provides the science leadership role for the science community. As the HST-D mission does not currently include science, this study does not have a Core Science Team or a Community Science Team. The Study Scientist is the primary point of contact for the broader HST community and works to ensure that all voices and concerns within that community have been heard and considered as the study unfolds.

The Study Team Scientist is accountable to the Study Manager.

B.3 Lead Mission Systems Engineer

The lead MSE provides leadership over the technical engineering aspects of the study effort. The lead MSE leads the Core Team in assessing the technical viability, TRL, and the degree to which technologies meet the HST-D study objectives. The lead MSE also is responsible for the technical synthesis of the mission concepts for further study in the GSFC MDL; preparing the data packages required by the MDL at the start of each of these new mission concept design labs, and the final study closeout report.

The lead MSE supports the Study Manager.

B.4 Study Financial Manager (FM)

The study FM is responsible for planning and tracking the budget necessary for performance of the studies. This includes both the budget for the core engineering team necessary to support studies, as well as the budget for specific study activities. The study Financial Manager is responsible for tracking, monitoring, and reporting on the status and expenditure of all study resources. In addition, the study team FM will be involved in the creation and validation of the total cost estimate for each of the studied concepts, as part of the overall cost estimate team utilized in performance of the study.

The FM is accountable to the Study Manager.

B.5 Core Engineering Team (CET)

The CET is responsible for evaluating and assessing the technical merits and plausibility of the various HST-D architecture concepts. The CET also ensures that the engineering approach will meet the key study objectives. The CET is responsible, from an engineering perspective, for recommending a candidate mission architectural concept for further study in an MDL, performing any engineering analysis required during any phase of the study, for reviewing and verifying engineering content and assessments in the final report, and for preparing the required engineering inputs for the MDL runs. The CET is responsible for synthesizing the ADL and MDL products such that they can be used in the final study report for submission to NASA HQ.

B.6 The HST-D ADL Study Team, Customer Team, and Advisors are listed below:

ADL Study Team

- ADL Study Lead: Gabriel Karpati (GSFC-592)
- ADL Deputy Study Lead: Scott Hull (GSFC-592)
- ADL MSE: Stephen Leete (GSFC-599)
- ADL Reliability / Mission Success: Aron Brall (GSFC-300 / SRS Technologies)
- ADL Flight Dynamics: Brent Barbee (GSFC-595)

ADL Customer Team

- HST-D Study Customer Lead: Tupper Hyde (GSFC-590)
- HST-D Manager: Joy Bretthauer (GSFC-440)
- HST-D Deputy: Steve Benner (GSFC-401)
- COR Program Office: Ruth Carter (GSFC-440)
- COR Program Office: Jacqueline Townsend (GSFC-440)
- HST: Arthur Whipple (GSFC-599)

Study Advisors

- HST Drift Rates: Steve Queen (GSFC-595) and Rich Burns (GSFC-595)
- S/C sizing, Mission Design: Jaime Esper (GSFC-592)
- HST Hardware: Rud Moe (GSFC-592)
- Avionics: Terry Smith (GSFC-565)
- AR&D: Bo Naasz (GSFC-595), Mike Moreau (GSFC-595), Matthew Strube (GSFC-596), John Vaneepoel (GSFC-591)
- SCM, iLIDS: Tom Griffin (GSFC-440), Tom Hanyok (GSFC-408), Tom Walsh (GSFC 408), James Lewis (JSC)
- Robotic Arm: Brian Roberts (GSFC-408 / J&T)
- Solar Sail, Space Debris: Bruce Campbell (GSFC-500)
- Electrodynamic Tether: Les Johnson (MSFC)
- Dragon / Falcon 9: Chris White (SpaceX), Dustin Doud (SpaceX)
- Trade Space, Partnering: Allan Cohen (Aerospace Corp.)Partnering: Ricky Howard (MSFC), Shayne Swint (MSFC), Mary Hovater (MSFC), Jack Mulqueen (MSFC), Tom Bryan (MSFC)

Appendix C—Study Team Relationship to the COR Program Office and NASA HQ APD

The organization chart in Figure C1 illustrates the lines of accountability (both programmatic and supervisory), during the study, between the Study Team and the COR Program Office and NASA HQ APD. At the release of this report, the following positions are as follows: Deputy Director Astrophysics Division - Andrea Razzaghi; the COR Program Office Deputy Program Manager - Mark Brumfield; and the COR Advanced Concepts and Technology Head position - Vacant.

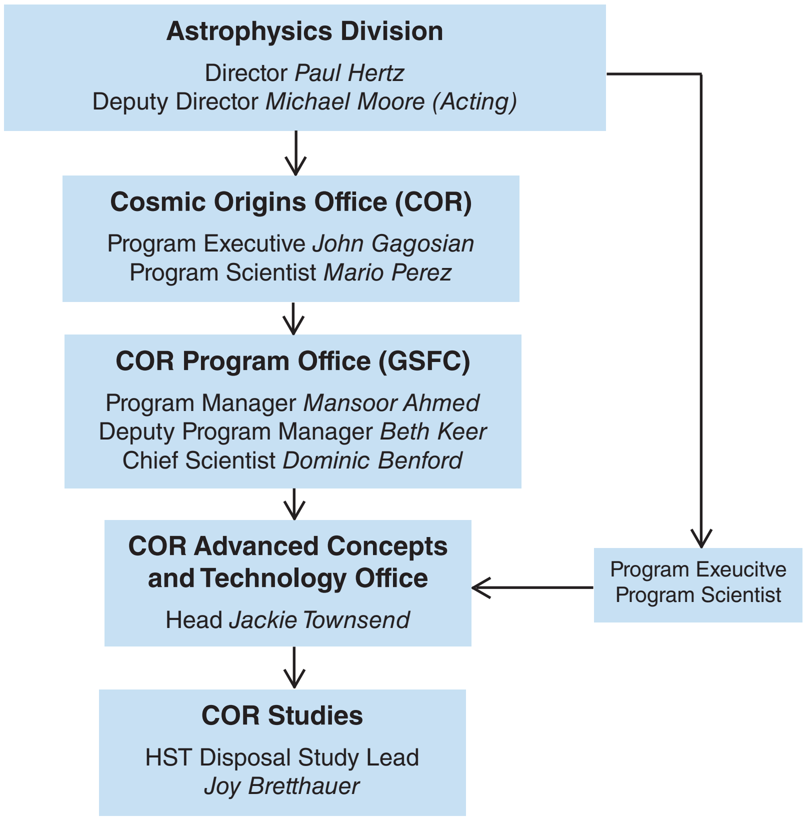


Figure C.1 *Organizational Relationship: NASA HQ and Study Team*

Appendix D—Presentations and Surveys

D.1 Final Study Plan Presentation to HQ

To view the Final Study Plan Presentation to HQ, go to https://apdmis.gsfc.nasa.gov/. Click on the "SHARED FILES" located in the lefthand menu.Follow the links to this location:

"Current location: SHARED FILES\Advanced Concepts and Technology Development\HST Disposal Closeout Report Appendices"

NOTE: Prior approval must be requested by contacting Kay Deere (kay.m.deere@nasa.gov) or Mandy Tatum (mandora.l.tatum@nasa.gov) in the APD Office..

D.2 ADL Outbrief

To view the ADL Outbrief, go to https://apdmis.gsfc.nasa.gov/. Click on the "SHARED FILES" located in the lefthand menu. Follow the links to this location:

"Current location: SHARED FILES\Advanced Concepts and Technology Development\HST Disposal Closeout Report Appendices"

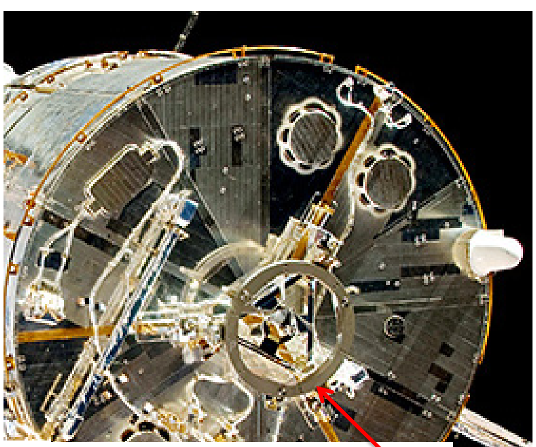
NOTE: Prior approval must be requested by contacting Kay Deere (kay.m.deere@nasa.gov) or Mandy Tatum (mandora.l.tatum@nasa.gov) in the APD Office..

D.3 AR&C Survey

PCOS
Physics of the Cosmos Program
Cosmic Origins Program

HST Disposal Study

Automated Rendezvous and Docking or Capture (AR&C) for
Hubble Space Telescope Disposal (HST-D)



Hubble Space Telescope Aft Bulkhead
with Soft Capture Mechanism (SCM)
installed during SM4

Cosmic Origins Program Office Brief
to HQ

Ricky Howard

August 1, 2012

Outline

- **Background**
- **What isn't Autonomous Rendezvous & Capture (AR&C)?**
- **What are the Elements of AR&C?**
- **NASA Plans/Roadmaps Requiring AR&C**
- **Potential NASA MISSIONS Needing AR&C**
- **Why Invest at all in AR&C?**
- **What work is HST-D doing in AR&C?**
- **AR&C Survey Snapshot**
- **Conclusion**

2

What are the elements of AR&C?

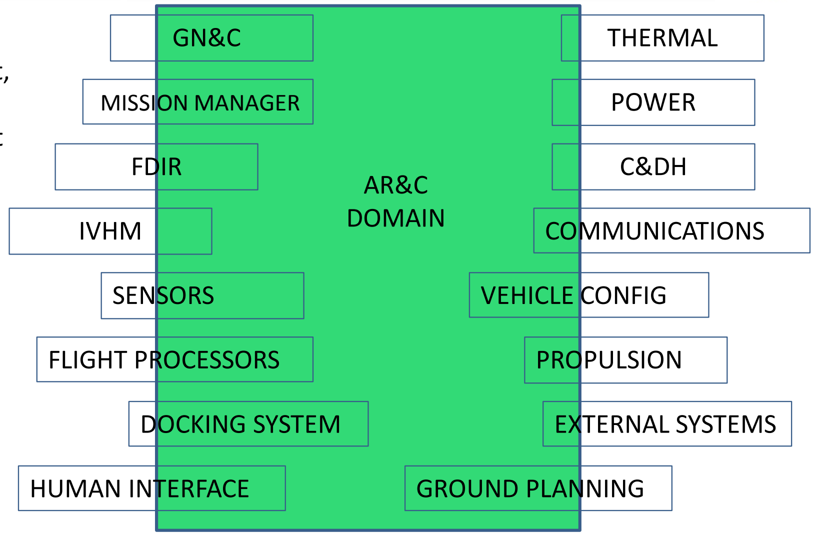
- **AR&C Consists of several technology areas**
  - Algorithms and software for rendezvous, proximity operations, GN&C, and mission management
  - Sensors for rendezvous, proximity operations, and docking
  - Mechanisms for docking and/or capture
  - Fault detection and recovery systems
  - System design and integration

NASA is already doing work in these areas, but not specifically for this mission

5

Pictorial Representation of AR&C Domain

External systems include spacecraft, ground systems, and other support systems (TDRSS, GPS, etc.)



Some elements are less developed or more important to the HST-D mission

6

NASA Plans/Roadmaps Requiring AR&C

- **Human exploration Architecture Team (HAT)**
  - Lunar
  - L2 Gateway
  - Near Earth Asteroids/Objects
  - Mars (Design Reference Mission 4)
- **Office of Chief Technologist (OCT) Roadmaps**
  - TA02: In-Space Propulsion
  - TA04: Robotics, Tele-robotics and Autonomous Systems
  - TA05: Communications and Navigation
  - TA07: Human Exploration Destination Systems
  - TA09: Entry, Descent, and Landing Systems
- **Orbital Debris Mitigation**
  - Hazard to current & future satellites, ISS, and spacecraft
  - Some space transportation concepts (low-thrust drives) will be limited by orbital debris

AR&C Plays a part in much of NASA's future

7

Potential NASA MISSIONS Needing AR&C

- **HST De-orbit**
- **Near Earth Object (NEO) DRM**
- **L2 Way Point**
- **Sample-return**
- **Mars DRM**
- **Cryogenic Propulsion Storage/Resupply**
- **Orbital Debris Mitigation**
- **Robotic Landers**
- **Maintenance & Servicing of Spacecraft**

Monitoring future NASA missions that involve AR&C is important in order to assess their relevance to the upcoming HST-D mission and whether any of their technologies could be utilized.

AR&C is vital to numerous future missions

8

Why Invest at all in AR&C?

- **AR&C demonstrably works: DART, Orbital Express, Soyuz, ATV, HTV, and Dragon**
- **<u>But</u> there isn't an "AR&C system" available for HST-DO**
  - Almost every AR&C mission is a custom mission
  - HST has a unique target and unique grapple fixtures
  - Some sensors and algorithms exist, but not many
- **Since the actual HST-D mission will not even get started for at least 5 more years, AR&C companies and technologies need to be monitored (new products, discontinued items, new players, etc.)**

Available AR&C capabilities will change over the next five years

9

What work is HST-D doing in AR&C?

- A comprehensive survey of past and current AR&C missions and companies was compiled
- A list of companies responding to a highly relevant DARPA RFI was also compiled (potential future players)
- The AR&D sensor database (from the AR&D Community of Practice) was updated and is being converted to a more usable format (database instead of spreadsheet)
- Continued monitoring is planned so the latest AR&C company, product, and technology information will be available when the "hold" period is over

Available AR&C capabilities will change over the next five years

10

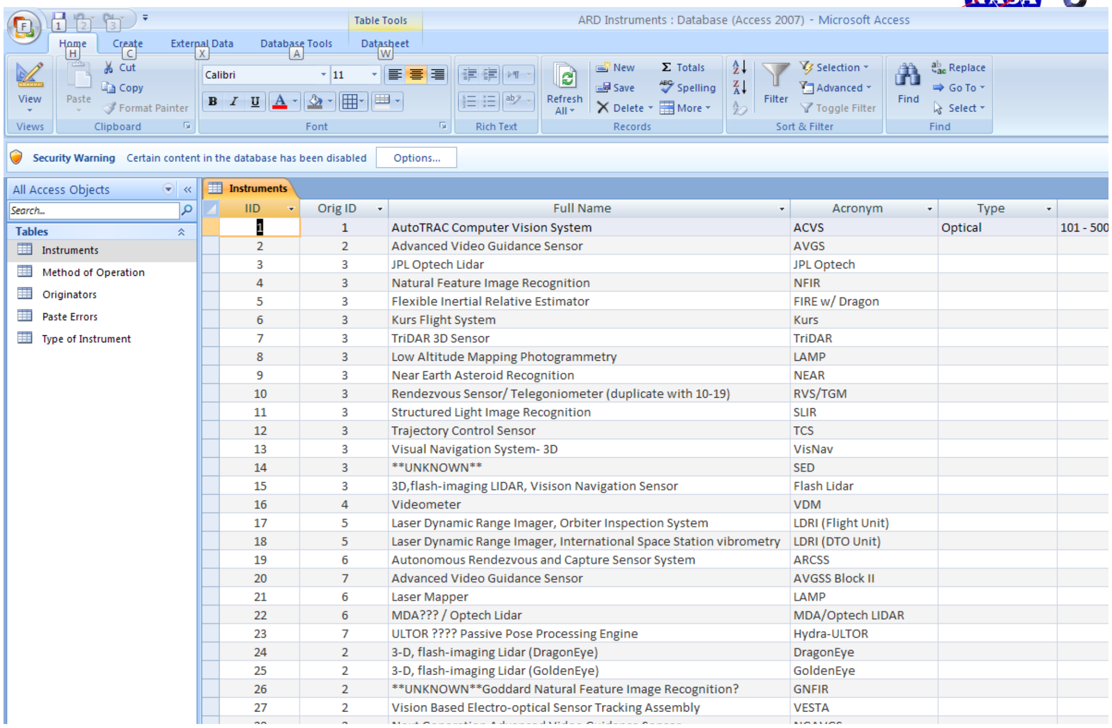
AR&C Survey Snapshot

E7

	A	B	C	D
1	29-Mar-12	HST Disposal: Autonomous Rendezvous & Capture/Docking Survey		
2	Name	When	What They Did/What They Will do	URL
3	SSCO	2009-2010	***NASA On-Orbit Satellite Servicing Study***	http://ssco.gsfc.nasa.gov/servicing_study.html
4	SSCO	Ongoing	***Robotic Refueling Mission***	http://ssco.gsfc.nasa.gov/robotic_refueling_mission.html
5	SSCO	September 6-7, 2011	+Launch Lock Removal and Vision	http://www.edcheung.com/job/iss/iss6.html
6	SSCO	March 5-7, TBD June 2012	+Gas Fittings Removal	
7	SSCO	July 2012 - end of 2013	+Refueling	
8	SSCO	July 2012 - end of 2013	+Thermal Blanket Manipulation	
9	SSCO	July 2012 - end of 2013	+Bolt (Fastener) Removal	
10	SSCO	July 2012 - end of 2013	+Electrical Cap Removal	
11	SSCO	March 6 2012	NASA's Robotic Refueling Mission, a space station-based demonstration effort caught up in a cascading series of delays following the last summer's crash of a Russian cargo module, will finally begin its first on-orbit satellite servicing tests in March	http://www.spacenews.com/civil/120123-nasa-robotic-satellite-servicing-demonstration-delayed-until-march.html
12	SSCO	The future	***Notional Robotic Servicing Mission***	http://ssco.gsfc.nasa.gov/robotic_servicing_mission.html
13	SSCO	06.12.2008	Lunar Robotic Manipulator Passes Early Test	http://www.nasa.gov/centers/langley/news/researchernews/rn_lsms.html
14	SSCO	2011	In 2011, personnel from the West Virginia facility worked with researchers from NASA's Langley Research Center to start to develop procedures to construct a large rod and joint simulated space structure that could be used as a telescope mirror platform.	
15	SSCO	Jul-11	Goddard tests robot that refuels satellites	http://www.wjla.com/articles/2011/07/goddard-tests-robot-that-refuels-satellites-63400.html
16	SSCO		More info at http://ssco.gsfc.nasa.gov/newsroom.html	
17	SSCO	2011-2012	Autonomous rendezvous and docking ground demonstrations: research and technology development	
18	DARPA	20-Oct-11	INNOVATORS SOUGHT FOR DARPA SATELLITE SERVICING TECHNOLOGY PROGRAM. DARPA met with interested parties in Nov 2011. See Pheonix Contractors Tab for a list of the Interested Contractors	http://www.darpa.mil/NewsEvents/Releases/2011/10/20.aspx
19	ESA	Future Proposal	GSV is currently in a conceptual state	http://www.on-orbit-servicing.com/pdf/GSV_1.PDF http://www.esa.int/TEC/Robotics/SEM9TIKKKSE_0.html
20	Intelsat		Satellite Servicing of In-Orbit Satellites	http://www.intelsatgeneral.com/service-offerings/satellite-servicing
			Space Infrastructure Servicing Update Richmond, B.C. - MacDonald, Dettwiler and Associates Ltd. (TSX: MDA), a provider of essential information solutions, announced today that as previously reported, MDA has not yet made a decision to proceed with its commercial Space	

Organization-Activity | Phoenix Contractors | Launch Schedule 2012

AR&D Sensor Database Screen Shot



IID	Orig ID	Full Name	Acronym	Type	
1	1	AutoTRAC Computer Vision System	ACVS	Optical	101 - 500
2	2	Advanced Video Guidance Sensor	AVGS		
3	3	JPL Optech Lidar	JPL Optech		
4	3	Natural Feature Image Recognition	NFIR		
5	3	Flexible Inertial Relative Estimator	FIRE w/ Dragon		
6	3	Kurs Flight System	Kurs		
7	3	TriDAR 3D Sensor	TriDAR		
8	3	Low Altitude Mapping Photogrammetry	LAMP		
9	3	Near Earth Asteroid Recognition	NEAR		
10	3	Rendezvous Sensor/ Telegoniometer (duplicate with 10-19)	RVS/TGM		
11	3	Structured Light Image Recognition	SLIR		
12	3	Trajectory Control Sensor	TCS		
13	3	Visual Navigation System- 3D	VisNav		
14	3	**UNKNOWN**	SED		
15	3	3D,flash-imaging LIDAR, Visison Navigation Sensor	Flash Lidar		
16	4	Videometer	VDM		
17	5	Laser Dynamic Range Imager, Orbiter Inspection System	LDRI (Flight Unit)		
18	5	Laser Dynamic Range Imager, International Space Station vibrometry	LDRI (DTO Unit)		
19	6	Autonomous Rendezvous and Capture Sensor System	ARCSS		
20	7	Advanced Video Guidance Sensor	AVGSS Block II		
21	6	Laser Mapper	LAMP		
22	6	MDA??? / Optech Lidar	MDA/Optech LIDAR		
23	7	ULTOR ???? Passive Pose Processing Engine	Hydra-ULTOR		
24	2	3-D, flash-imaging Lidar (DragonEye)	DragonEye		
25	2	3-D, flash-imaging Lidar (GoldenEye)	GoldenEye		
26	2	**UNKNOWN**Goddard Natural Feature Image Recognition?	GNFIR		
27	2	Vision Based Electro-optical Sensor Tracking Assembly	VESTA		

Conclusions

- **HST-D requires AR&C**
- **AR&C will require custom development – HST has unique attachment point & target**
- **There are few AR&C components available**
- **Technologies and availability will change over the next 5 years**
- **AR&C players, technologies, and off-the-shelf availabilities will be monitored so data will be available to future Mission Design Lab efforts**

NASA will benefit, not just HST-D

13

D.4 Partnership Survey

For electronic viewing purposes only. For a printable version, go to https://apdmis.gsfc.nasa.gov/. Click on the “SHARED FILES” located in the lefthand menu. Follow the links to this location: “Current location: SHARED FILES\Advanced Concepts and Technology Development\HST Disposal Closeout Report Appendices”

NOTE: Prior approval must be requested by contacting Kay Deere (kay.m.deere@nasa.gov) or Mandy Tatum (mandora.l.tatum@nasa.gov) in the APD Office..

5/17/2012 HST Disposal Mission Partnering Possibilities	SMD	HEOMD	OCT	DoD	International	Civil (e.g., NOAA)	Commercial	Academia	Science	Technology	Commercial	Debris Cleanup	Other	Pre-disposal	During Disposal	Post-disposal	1200 km	2000 km	Co-manifested Launch	Secondary Payload	Integral with Disposal	Launch Vehicle	Likelihood	Potential Gain to NASA	Potential Gain to Partner	Potential Cost Impact	Potential Value	Requirements Impact	Risk to Disposal Impact	Potential Cost Impact	Potential Value	Other Considerations	Technology and Missions Watchlist
	Partner: Nasa			Partner: Non-Nasa				Application						Mission Phase					Partner Type				L × C			Impacts to HST Disposal				Impacts to Partner			* Filter template based on % necessary to be a significant partner; place percentage in the Potential Cost column.
Co-Manifested Payloads																																	
Cubesats	x	x	x	x		x	x	x	x	x				x		x	x	x	x							Outreach				Need a launch, at or below market cost;			
De-Orbit Monitor				$					x	x	x	x			x					x	x		high			understand physics of re-entry							
Larger Spacecraft	x	x		x	x	x	x		x	x	x	x	x	x		x			x	x													highly unlikely to use for public space tourism; this mission is used to reduce risk to human life and a de-orbit of HST is for a space tourism opportunity
Xprize-like - NASA funded	x											x			x							low	cost savings; negative publicity	profit/technology/ publicity		cheaper, generates excitement & interest				negative publicity stunt for NASA;			Safe disposal of HST is the target for the Prize;
Xprize-like - jointly funded							x					x			x							zero-low	cost savings	publicity;		cheaper, generates excitement & interest							Safe disposal of HST is the target for the Prize. Unrealistic to get partner strictly to deorbit HST.
Technology Demonstrations																																	
Science Data Collection/ Instruments	$$	$	$											x		x	x	x															"IDC has well known Astrophysics Pis asking for this orbit & comparable spacecraft. NOAA may not desire to have a payload on a disposal mission. HEO: interested in radiation hard, cryogenic, & a few others"
New Propellants (HPGV, HAN, green propellants)			$							x	x			x	x	x	x				x	high	new propellants; proof of concept	proof of concept									presently looks like this will already be demonstrated
New propulsion technologies (ED tether, for example)	x		x	x						x	x	x				x			x		x												
Electrodynamic tethers			$$							x						x	x	x		x	x	low	high	high	total mission cost increase; each org's part could be less	adds risk (negative)	medium	low - medium	$-$$	high			up and coming technology; may change the inclination; good to ~ 30,000 km
Solar sail demonstration										x						x	x	x			x												not a viable solution due to low-level thrust, difficult controlling LEO, size of the sail, and the drag forces at LEO
Slow boat to the moon																x																	not viable due to burden on lunar vehicle, schedule; check w/ Tupper
Operations testbed																x																	
Planet Finder Sunshade	$		x													x						very low	demonstration of exoplanet sunshade		$$			increases risk, complicates the mission		valuable demonstration			put out RFI to do science, etc. at this altitude; not viable if HST is dead-need 2 s/c in formation w/ line of sight; works for Option 3A and 3B (put on before HST dies, stay dormant, combine 3A & 3B w/sunshade demo; chase vehicle needs sunshade occulter
Autonomous Rendezvous & Capture/Docking				$	$					x	x			x							x	med-high	mutual benefit from partner's technolgy	flight opportunity for the technology	$-$$			low	$$$	partner gains knowledge, may contribute to get proof of concept & demonstration of technology			AR&D as a potential contribution to the primary mission.
Earth-cam from 2000 km	x								x					x			x	x		x		low	publicity; outreach	publicity	$								not likely to bring in additional funding for NASA
Reuseable S/C Service			x	x			x			x	x	x				x	x	x	x	x	x				x								If fidelity/reliability increases, risk to primary mission may also inrease
HST Disposal Vehicle reboost/reuse (custom)												x	x																				Satellite servicing; could serve as a cost-sharing opportunity for anyone interested in satellite servicing ; could do multiple de-orbit missions with refueiing from satellite servicing
Reuse SpaceX's DragonLab (cargo)		$$$$$					x				x			x	x	x	x	x	x	x	x	high	lower cost; negative as there would be less control in oversight due to buying a service		$$$$$; lowers cost, risk (if qlready qualified & proven for a similar type mission)								most viable option available as of 5/2012; must resolve insight/oversight & QA with SpaceX; could be an opportunity for satellite servicing
Replace HST w/other telescope																																	de-orbit module and a Hubble replacement; drop off, de-orbit separates, and place the new telescope;
UV/optical	$$$$								x					x																			
Dark Energy	$$$$																																
																																	star shade needs a demonstration
Exozodiacal Dust																																	If small telescope can't see exoplanet, maybe it sees exozodiacal dust
Reboost HST for extended ops or piggy back payload																																	more $$, politically could generate some interest; sadness over loss of Hubble is mitigated over having the “son of Hubble”

$ is 0 value;
$$$$ = free launch

$$ < 100M

D.5 Soft Capture Mechanism and LIDs-related Documentation

For electronic viewing purposes only. For a printable version, go to https://apdmis.gsfc.nasa.gov/. Click on the "SHARED FILES" located in the lefthand menu.

Follow the links to this location:

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NOTE: Prior approval must be requested by contacting Kay Deere (kay.m.deere@nasa.gov) or Mandy Tatum (mandora.l.tatum@nasa.gov) in the APD Office..

Appendix E—References

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