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An updated re-entry analysis of the Hubble Space Telescope

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ABSTRACT

The Hubble Space Telescope (HST), launched in 1990, has without question given us a better understanding of the Universe [1]. The storied spacecraft has far exceeded its design life and, in spite of four repair missions, is nearing the end of its useful lifespan. Originally designed to be returned by the Space Shuttle, the HST has no on-board propulsion system. A 2012 study estimated that without intervention, the HST will re-enter the atmosphere in approximately 2027 with a 1:240 risk of fatality [2]. This study updates that analysis with more recent de-orbit technologies and updated trajectory information. We propose a design solution to safely perform a targeted de-orbit, assuming a worst-case scenario (a non-functional, tumbling spacecraft). Multiple de-orbit options are assessed to actively capture the satellite. Results frame an approach that could be accomplished with proven technologies at reasonable cost to improve the fatality risk as required by US Government regulation [3]. Moreover, delayed action would significantly increase mission cost and complexity so we recommend a project start in the near future.

1 INTRODUCTION AND BACKGROUND

The Hubble Space Telescope (HST), one of the most iconic satellites in history, is still in use but has lost altitude due to atmospheric drag and deteriorated mechanically due to system degradation over its nearly thirty years on-orbit. The original deorbit plan for HST was to use the space shuttle to retrieve it at end of its life; however, no one foresaw that it would outlive the Space Shuttle Program [1]. A previous study [2] investigated three de-orbit proposals: uncontrolled re-entry, which was deemed unacceptable due to the risk; a storage orbit beyond HST's current orbit, which delayed but did not solve the problem; and lastly, a controlled de-orbit using an additional 'capture' spacecraft, which was examined and deemed to be the most feasible solution. NASA recommended a project start date of 2019; however, low solar activity in the intervening years has effectively extended a projected start date.

1.1 HST current status and configuration

HST is 13.2m long, has a max diameter of 4.2 m, and had a final mass of 12,218 kg after all servicing missions, resulting in an estimated (tumbling) ballistic coefficient of 82 kg/m^2 [4,6]. As of mid-2019, the HST orbit perigee is 534.4 km, and the attitude control system consists of one fully mission-capable gyroscope, one partially mission-capable gyroscope, and one non-mission capable gyroscope [4]. In anticipation of a capture mission, the Low Impact Docking System (LIDS) soft-capture mechanism was attached to HST during the last servicing mission. The HST also has multiple trunnion pins and hand rails as depicted in Figures 1.

1.2 Study objectives

This study was conducted by students at the Naval Postgraduate School as a capstone design project, with the objective of improving the casualty risk by designing a method to safely de-orbit HST before its natural, uncontrolled re-entry. Seven years have passed since NASA's 2012 deorbit study. Since then HST's orbit has decayed while launch, rendezvous, and de-orbit technologies have advanced. This report updates that study with new orbital parameters, technologies, and a proposed spacecraft design that would de-orbit HST. The spacecraft proposed is "Capture Hubble and Safe Re-entry" (CHASER).

CHASER has two configurations. The first, and recommended configuration, is a spacecraft that captures and deorbits HST using the LIDS docking mechanism (hereafter called the 'LIDS-only mission'). This is the most straight-forward solution found. However, LIDS has a maximum rotation rate that could be exceeded as HST's orbit decays (more on this later), so a 'worst-case' mission using a robotic arm to capture HST prior to LIDS docking, that can accommodate higher tumble rates, was also assessed. We call this the 'robotic arm + LIDS mission'. While not recommended due to cost and complexity, it is important to characterize this alternative potential mission as a consequence of delay. Comparison of the two possibilities bounds the tradeoffs necessary to decide *when* to mount a deorbit mission for HST.

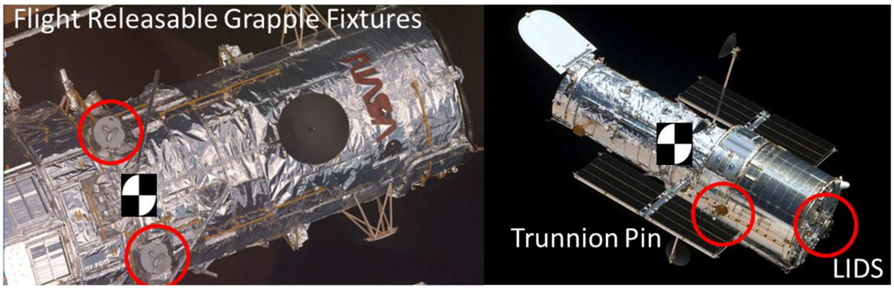

Fig. 1. (Left) HST, highlighting placement of two Flight Releasable Grapple Fixtures (FRGF). (Right) Placement of payload bay trunnion pins and LIDS docking system.

2 PROJECT OVERVIEW

2.1 Ground rules and assumptions

The goal was to make technically sound assumptions and establish applicable ground rules and constraints. Two primary assumptions drove the design. First, in the 2012 study, NASA determined that HST's maximum allowable rotation rate was 0.22 °/sec per axis. This is expected to occur as the spacecraft approaches a 500-km perigee (due to expected atmospheric effects at that altitude). Capture beyond this rotation rate was deemed unmanageable; therefore, we use this as the limiting rate in our analyses. This narrowed the trade space, put an upper limit on de-tumble torque calculations, and focused mission timeline and scope. Second, we based the CHASER concept upon heritage from the NASA *Restore-L* on-orbit satellite servicing mission planned for 2020 or later; including the *SSL-1300* bus architecture and *RAVEN* sensor suite [5]. Reliance upon heritage enabled us to baseline proven technologies that could potentially lower cost and schedule risk as well as accomplish the design within the classroom constraints. We further assumed Tracking and Data Relay Satellites (TDRS) systems would be preferred for space-based communications [7]. Lastly, the Falcon 9 [16] was assumed to be the launch vehicle, and CHASER was assumed to be the primary payload so that Classical Orbital Elements (COEs) could be selected to minimize required rendezvous operations.

2.2 High Level Requirements

Requirements were identified to capture the major decision drivers of CHASER's design. They were broken up into four mission phases: grappling, de-tumbling, berthing, and deorbiting. Functionally, they were attributed to CHASER's control system, robotic arm, and propulsion system. Of note, the key requirements that levied performance thresholds were for the robotic arm accuracy, end-effector type, control system de-tumble rates, and re-entry splashdown location. An important bounding requirement regards the LIDS maximum capture limit. LIDS is capable of maximum 0.15 °/sec roll rate and 0.15 °/sec combined pitch and yaw rate [9]. These roll rates are reasonable if HST is still under active control when captured, and even shortly after loss of control at sufficient altitudes. As the HST orbit decays, however, these rates could be exceeded, and it is difficult to predict when and at what altitude this could occur. This requirement drove the consideration of the two mission types described in Section 1.2.

2.3 Trade Space

A trade space analysis was conducted using two trade trees: first, for methods to capture and deorbit HST; second, for methods to grapple HST. The former addressed the uncertainty in HST's operational status due to system degradation and failures, but required an assumption that HST could be tumbling outside of the LIDS capture limit. This could result in deorbit forces exceeding the capability of de-orbiting with only a robotic arm, yielding a decision to develop a spacecraft with both a robotic arm and docking system (the 'robotic arm + LIDS mission').

The latter trade tree addressed the location of CHASER's connection to HST to efficiently reduce the roll, pitch, and yaw rates to 0 °/sec. Multiple dedicated and undedicated grapple points and end-effectors were analyzed (Fig. 1), along with whether CHASER would release its connection to HST upon completion of de-tumbling or maintain connection for berthing. Down-selection was based on the ability to support expected de-tumble forces, the complexity of grapple operations, and the risk of imparting forces to HST upon arm detachment. Based on these factors and advisement from subject matter experts, maintaining a robotic-arm connection while berthing with LIDS was chosen as the baseline operational scenario.

2.4 Robotic Arms

Multiple existing and planned robotic arms were evaluated to meet requirements. We examined the Canadarm, Canadarm2 (SSRMS), and Canadarm3; the Special Purpose Dexterous Manipulator; Space Station Remote Manipulator System (SSRMS); the Japanese Experiment Module Remote Manipulator System (JEMRMS); and the European Robotic Arm (ERA). Except Canadarm3, and ERA, all these robotic arms have been operated onboard or in proximity to, the International Space Station (ISS). Two arms not involved with ISS operations were also considered: The Restore-L arm and Orbital Express. Of these, Canadarm2 is the only candidate capable of handling the large HST mass [8]. While oversized, with a capacity exceeding 100,000 kg, we used Canadarm2 as the baseline for meeting all known requirements.

3 CONCEPT OF OPERATION (CONOPS)

Figure 2 depicts the CONOPS for 'robotic arm + LIDS mission' CHASER de-orbit mission. The mission was broken up into nine phases, from launch until splashdown in a remote area.

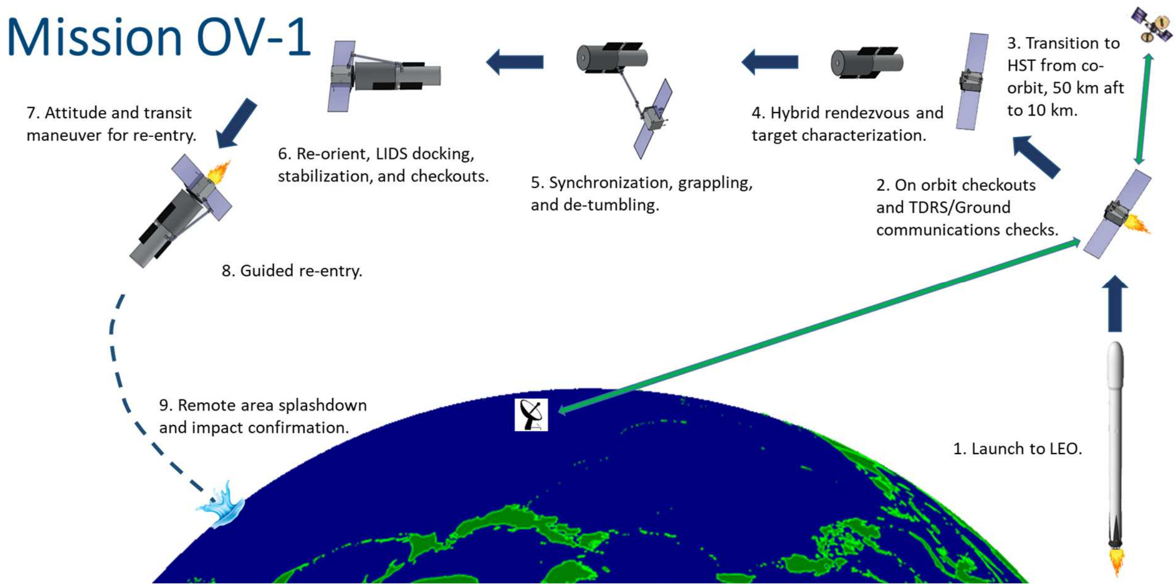

Fig. 2: CHASER mission concept of operations (Not to scale).

4 DESIGN

The following section details the overall design of the 'robotic arm + LIDS mission' CHASER, focusing on the satellite bus, systems engineering practices, and highest priority subsystems. We note that the subsystems addressed are not all-inclusive, but focused on those most critical to the mission to assess the adequacy of the selected bus. For instance, we did not assess the thermal subsystem because we did not identify any design drivers beyond the SSL-1300 bus capabilities.

4.1 Spacecraft Bus

CHASER utilizes the SSL-1300 bus as noted in Section 2.1. Over 100 SSL-1300 buses have been launched to GEO orbit, increasing its maturity, compatibility, and mission heritage. While nominally a communications satellite bus, it was selected for the Restore-L mission, and we opted to utilize this heritage. Table 1 lists the specific capabilities required by CHASER as compared to the heritage systems adopted in our design, showing that all requirements can be met.

Table 1. CHASER design requirements compared to that available from selected heritage systems.

CATEGORY	CAPABILITY	HERITAGE SYSTEM	REQUIRED	LEVEL PROVIDED
Power	Power	SSL-1300	~5kW	5-9kW
	Battery Capacity	SSL-1300	3970 W-hr	4060 W-hrs
Robotic Arm	Translational Arm Speed	CANADARM2	0.016 m/s	0.36 m/s
	Rotational Arm Speed	CANADARM2	0.22 deg/s	4 deg/s
	DOF	CANADARM2	6	7
	Joint Torsional Moment	CANADARM2	250 Nm	3000 Nm
Communications	Uplink/Downlink	SSL-1300	S, Ka Bands	L, X, Ka, Ku, S, C Bands
	Data Storage	SSL-1300	81 Mb	5.8 Tb
Propulsion	Delta V	SSL-1300	180 m/s	4073 m/s
	Propellant	SSL-1300	916.5 kg	2272 kg
	Spacecraft Torque	SSL-1300	67.5 Nm	68.2 Nm
ADCS	4-wheel, 3 axis control	SSL-1300	3 axis control	3 axis control
	Gyro control	SSL-1300	1 laser ring gyro	2 laser ring gyros
Sensor Package	Visual Range	RAVEN	100 m	~16 km
	Visual Resolution	RAVEN	1000 x 1000 pixels	1000 x 1000 pixels
	IR Range	RAVEN	100 m	~16 km
	IR Resolution	RAVEN	640 x 480 pixels	640 x 480 pixels
	LIDAR Range	RAVEN	100 m	~16 km
	LIDAR Resolution	RAVEN	256 x 256 pixels	256 x 256 pixels

4.2 Robotic Arm

The Canadarm2 is the baseline for CHASER's Robotic Arm (CHARM) because no other current space rated robotic arm can match Canadarm2's capabilities. This capability is needed because with a mass of 12,128 kg and length of 13.1 m, HST has a high moment of inertia. Canadarm2 uses Joint Motor Modules (JMM) that feature harmonic drives in its seven Degrees of Freedom (DOF) design. Although its specifications are restricted, early NASA design documents show these components enable a high torsional stiffness sustaining a minimum torque of 1630 N-m while stationary, a torque ability of 1022 N-m while moving, and positional capacity to move payloads up to 116,000 kg [14]. We assume capability available from a harmonic drive of equivalent size [15]. Because this exceeds some of CHARM's requirements, the design was scaled down. For example, the joint, latching end-effector (LEE), and camera on one end of CHARM were not needed and removed. Conversely, CHARM uses the same construction material, JMMs, and LEE as Canadarm2, but the links were shortened to both fit within the Falcon 9 launch vehicle fairing and meet mission requirements for grapple and docking with LIDS.

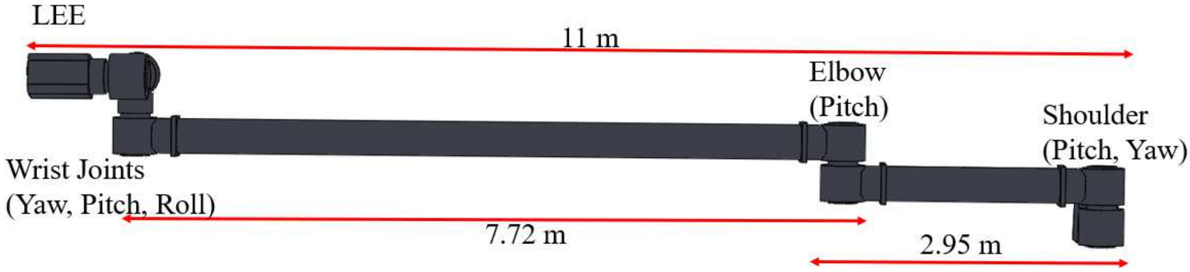

Fig. 3. CHASER robotic arm concept.

Capturing and de-tumbling HST is the primary mission challenge. The 'worst-case' 0.22 °/sec tumble rate was used in our analysis to determine the expected torques applied to the joints and the requisite counteracting torque for the CHASER propulsion system while maintaining the arm in a straight and stiff condition. The Spacecraft Robotics Toolkit was used in MATLAB for the analysis [17]. It uses kinematic and dynamic properties to analyze positions, velocities, forces, and torques for each joint in the robotic arm and the CHASER. Preliminary results showed that the joints sustained the torques required to de-tumble HST with large margins. The highest torque felt in the joints was 222 N-m for a 7-minute HST de-tumble operation, well below the joint torque limit of 1630 N-m. Further analysis will be required to understand how to configure the attitude control with respect to HST as well as to determine the best positioning options to de-tumble HST.

A structural analysis for CHARM was completed using Solidworks® showing a margin of safety of 3.4 for the arm. Preliminary analysis shows CHARM is a very robust system that can handle much more than its mission requirements, indicating it can be further down-sized to save cost and complexity if desired.

4.3 Propulsion

The propulsion system onboard CHASER has four main tasks to conduct: Rendezvous and Proximity Operations (RPO), grapple, de-tumble, and de-orbit. The SSL-1300 bus provides enough technical capability to accomplish each of these tasks. It comes equipped with a bi-propellant, hydrazine, and nitrogen-tetroxide system with a propellant capacity of 2,272 kg that can be increased up to 3,800 kg [18]. The thrusters native to the 1300 bus include a 445 N liquid apogee thruster and multiple thrusters with 1,222 N capacity as part of the Attitude and Orbital Control System (AOCS) [19]. The heritage system is designed for the main thruster to boost a spacecraft into geostationary orbit with an isolation valve that activates to shift the fuel to a hydrazine-only monopropellant for AOCS operations.

The amount of propellant necessary for RPO, grapple, and de-orbit is determined by the ΔV necessary to change CHASER's orbit. During RPO, the assumption is that CHASER will be placed into the same orbit as HST with a 50-km separation. For orbit phasing, it was estimated $\Delta V = 0.003\ km/s$ to decrease the separation between HST and CHASER from 50 km to one km, and $\Delta V = 0.001\ km/s$ for each grapple attempt. Consistent with [2], CHASER will have more than enough propellant to allow for four grapple attempts. The propellant necessary for the de-tumbling portion of the propulsion system is based on the length of time it will take to bring the tumbling of the HST from 0.22 °/sec to zero °/sec. The mass of propellant can be calculated with an assumed time of 250 seconds and a known flow rate of 7.71 g/sec. Using two of the 22 N AOCS thrusters, a total of 3.9 kg was calculated to generate enough torque to de-tumble HST. To deorbit HST, it was estimated $\Delta V = 0.145\ km/s$ to decrease altitude from 500 km to 100 km. From there, the final burn to deorbit the CHASER-HST results in $\Delta V = 0.031\ km/s$ and a final burn time of 17.4 minutes.

Including margin, the propellant needed is approximately 1000kg, and is well within the capacity of the SSL-1300 capacity (Table 1). In addition, the heritage thrusters available provide enough capability to complete all aspects of CHASER's mission within reasonable time frames. Therefore, the heritage SSL-1300 bus propulsion system is robust enough to satisfy all of CHASER's requirements. Further study would be needed to validate the sizing and positioning of the thrusters on the spacecraft.

4.4 Communications and command and data handling (C&DH)

The TDRS constellation in Geosynchronous Orbit (GEO) would serve as a link between CHASER and ground control stations. TDRS is capable of transmitting S-Band and Ka-Band communications with a downlink data rate of 7 Mbps with S-band and up to 350 Mbps with Ka-band [7]. Via this analysis, it was determined that the CHASER mission communications would not be power limited nor bandwidth limited, as expected of a SSL-1300 communication bus.

CHASER's C&DH architecture would be in accordance with the Consultative Committee of Space Data systems, which provides a communication standard in support of space communication systems. The data bus architecture for the CHASER will be in accordance with the MIL-STD-1553D. CHASER will employ semi-autonomous control throughout the de-orbit mission. NASA's assessment in [20] of Autonomous Decision Making and Robot Software is Technology Readiness Levels of 2 and 5, respectively. Therefore, semi-autonomous control would enable hitting range gates and having human-in-the-loop commanding during CHASER's approach to HST to administer proceed authority to move past designated waypoints. CHASER would use TLE data to maneuver within ranges of 5 km, 1 km, and then 500 m. When CHASER is within 500 m of HST, ranging/characterization data would come from *Raven* and include range waypoints requiring proceed authority of 100 m, 50 m, 25 m, 10 m, then 1 m by 1 m until CHASER has grappled with HST [20–21].

4.5 Power

CHASER's peak power requirements would occur during capture and are influenced by the bus, sensor package, robotic arm, and docking device loads. An estimate for nominal operational of the SSL-1300 Bus and RAVEN Sensor Suite is derived from *Restore-L*'s rendezvous phase of operation [5]. The CHARM power requirements are assumed to be roughly the same order of magnitude as the power required for CANADARM 2 operation [10]. Lastly, LIDS power loading is derived from its successor, the NASA Docking System [9]. This results in an expected peak power requirement of 5.5 kW for CHASER. Loral's SSL product line is highly modular and could scale up to provide from 5 kW of power (near *Restore-L* levels) to a maximum of about 20 kW, easily supporting CHASER power needs on their smallest model [17]. When a 30% power margin is considered, the required battery capacity is between 3,000 and 4,000 Watt-hours with a solar array size of 38 to 48 m^2.

4.6 Sensor package

In order to rendezvous with HST, CHASER would use the self-contained *Raven* sensor package to find, fix, and track the satellite. This package would provide imagery of the area in vicinity of CHASER, determine distances to objects within its field of view, and provide that information to the semi-autonomous rendezvous software. *Raven*, developed by NASA Goddard Space Flight Center, is heritage equipment, having been flight-tested aboard the ISS, and is planned for the *Restore-L* on-orbit servicing mission that includes similar mission tasks like grappling [11]. The system is composed of three visual sensors: LIDAR, IR, and EO Visual. Lastly, the resolution of the three cameras on the sensor are estimated at 1000 x 1000 pixels each, with a max combined data rate of 1 Hz. During operation, the camera would capture imagery, determine the distance to the target, and then use spacecraft gimbals to maintain track of the target [11]. Therefore, *Raven* satisfies CHASER's mission requirements.

4.7 Failure modes and effects analysis (FMEA)

A high-level FMEA was conducted for CHASER using the Ishikawa styled fishbone diagram in Figure 4 [31]. Each of the mission phases have at least one failure mode that would prevent mission completion. The "sync, grab, de-tumble" and "re-orient, LIDS dock, stabilize" phases each have two failure modes due to their potential impact. The diagram highlights areas that require mitigation strategies such as redundancy, design margin, and procedural attention in the CONOPS. For this study, each of the causes of failure below were captured in a risk analysis with mitigation strategies determined and applied (not include due to page constraints).

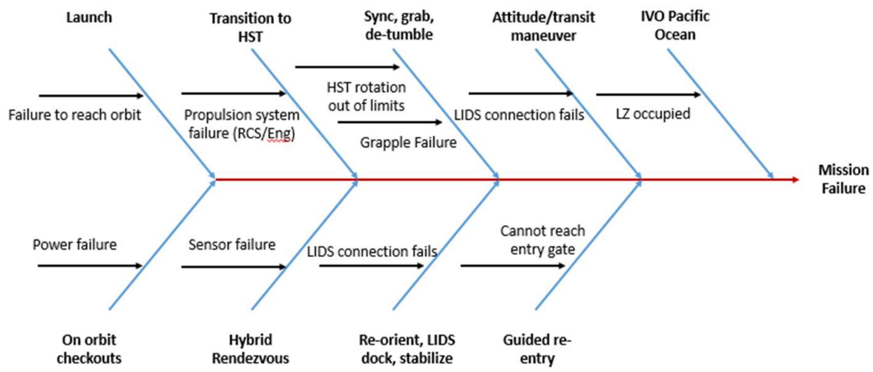

Fig. 4. Primary FMEA for CHASER's mission to de-orbit HST through all the phases of the mission.

4.8 Mass estimates

CHASER's mass budget was determined using the known and assumed masses of the major components and is depicted in Table 2. The masses were known for the bus, LIDS, and RAVEN. The mass value for the CHASER Hubble Arm (CHARM) is based on Canadarm2, but modified to account for the scaled down dimensions and only one end-effector [10]. The wet mass for CHASER accounted for rendezvous and proximity operations, grapple, de-tumble, and deorbit while [12, 13] were used to determine the propellant mass margins. The mass calculations presented are for a scenario in which a single burn is enough to accomplish each of the propulsion mission phases. In actual operation, additional propellant will be required for station keeping and course corrections, however, the planned tank size and 50% propellant reserves account for the additional fuel to support these events.

Table 2. Mass budget for CHASER mission including both dry and wet mass values.

SYSTEM	COMPONENTS	MASS
STRUCTURES:	Bus	916 kg
	CHARM	1000 kg
	LIDS	340 kg
	Sensor Package	60 kg
CHASER Dry Mass		**2316 kg**
PROPELLANT:	RPO (10%)	2 kg
	Grapple (10%)	3 kg
	De-tumble	4 kg
	Deorbit	578 kg
	Reserves (50%)	295 kg
	Trapped Propellant (3%)	27 kg
	Loading Uncertainty (0.5%)	4 kg
Subtotal		914 kg
CHASER Wet Mass		**3229 kg**

5 PROGRAM METRICS

5.1 Schedule

The developmental schedule for CHASER was adapted from the Department of Defense's acquisitions pipeline as described in DoD instruction 5000.02 [23], and updated using timelines from *Restore-L*'s schedule, as described in the Government Accountability Office's (GAO) Assessments of Major Projects for NASA [24]. The schedule is a four-year development timeline. The main takeaway from the schedule is that the development is heavily dependent upon the integration of heritage components, which would be a primary focus for the development team.

5.2 Cost

As noted earlier, CHASER has two configurations: the 'LIDS-only mission' and the 'robotic arm + LIDS mission'. Both were costed to provide clarity on when the mission should begin. We performed both parametric cost estimates (based on available *Restore-L* cost history) and using NASA's Project Cost Estimating Capability (PCEC) [25]. The tool took in various programmatic and technical inputs including known costs, work breakdown structure, estimated schedule, component masses, lines of code, thrust, materials, part heritage and quality, orbital parameters, and more [26–28]. When part quality and heritage are varied, the expected cost range in FY2020 dollars ranges from $668M to 792M. Most notably, when the robotic arm and its associated costs are not included, reflecting the 'LIDS-only mission, the project can save upwards of $200M. *This reinforces the conclusion that a mission should be launched early in order to perform a direct dock with HST in support of its eventual deorbit.*

5.4 Reliability

Overall reliability was calculated for CHASER in aggregate, based upon the Mean Time Between Failures (MTBF) and reliability of each subsystem. The primary CHASER subsystems for analysis were the (AOCS), Power, CDH, TTC, and structures and mechanism system (Mech/Payload). The breakdown in Table 3 was adapted from [29], which analysed 156 failures on 129 satellites from a pool of over 4,000 satellites over the past few decades. Several assumptions were made in this adapted analysis. First, the average lifetime of a satellite was 10 years, accumulating to 350,640,000 total hours in the study, adapted from the lower bound found in [30]. Second, not every satellite in the study attempted a docking maneuver; a conservative 100 attempts were used for the reliability calculations. Third, CHASER's mission length was prolonged to one year. Lastly, SpaceX's reliability of the Falcon 9 launch vehicle was based upon 75 of 77 successful launches up to August 2019 [16].

The results show the mission reliability without the launch vehicle is over 99% and the reliability with the launch vehicle included is 97%. Note that the launch vehicle reliability alone is 97% -- the driving factor for CHASER's overall reliability. This result is to be expected and moreover confirms other analyses that have shown that the 1:10,000 re-entry risk threshold cannot be met when launch vehicle reliability is included.

Table 3. Reliability calculations for CHASER primary subsystems and launch vehicle.

Subsystem Name	Component Percentage	MTBF (years)	Reliability
AOCS	100%	801	0.9988
Power	100%	949	0.9989
C&DH/TTC	100%	1709	0.9994
Mech/Payload	100%	2136	0.9995
Docking	5%	1068	0.9991
Payload	55%	3885	0.9997
Other	100%	1831	0.9995
Falcon Launch[3]	100%		**0.9740**
CHASER Reliability	(no L.V)		**0.9961**
Overall Reliability			**0.9702**

6 RECOMMENDATIONS AND FUTURE WORK

According to a new data by NASA Goddard Space Flight Center (GSFC), HST will reach an altitude of 500 km in approximately eight years, around 2027 (personal communication with Scott Hull). Given the difficulties of developing, testing, and launching a new space system, eight years is a relatively small amount of time to find a way to either deorbit HST or prolong its lifespan. In addition, while this study has provided two options—a LIDS-only mission and a LIDS+robotic arm mission, there is still much work to be done.

Figure 5 is a pictorial summary of the HST deorbit cost and complexity analysis. As HST gradually decreases in altitude, remaining attitude control functionality is expected to further degrade. The rate of this is unknown; however, at some point, HST may be declared a 'dead bird'. Taking action to mount the simpler LIDS-only mission is the best option, saving somewhere near $200M over the more complex LIDS+robotic arm mission. The robotic arm poses design and developmental challenges, being both technically and operationally complex compared to a docking mission.

There are other options to prolonging HST's orbital lifetime. CHASER could be designed to remain attached to HST and extend its life. This would present significant attitude control system challenges due to HST's very stringent pointing requirements. Alternatively, CHASER could loiter-in-place proximate to HST until the final reaction wheel fails or the orbit decays below acceptable limits. This would extend the science mission as long as possible and provide a safe de-orbit. We showed earlier that the fuel capacity of CHASER could accommodate this.

Our recommendation is to start the planning for the simpler LIDS docking mission, and evaluate whether this could prolong the HST science return. We recommend that a loiter-in-place option be assessed for CHASER so that science can be accomplished for as long as possible.

7 ACKNOWLEDGEMENTS

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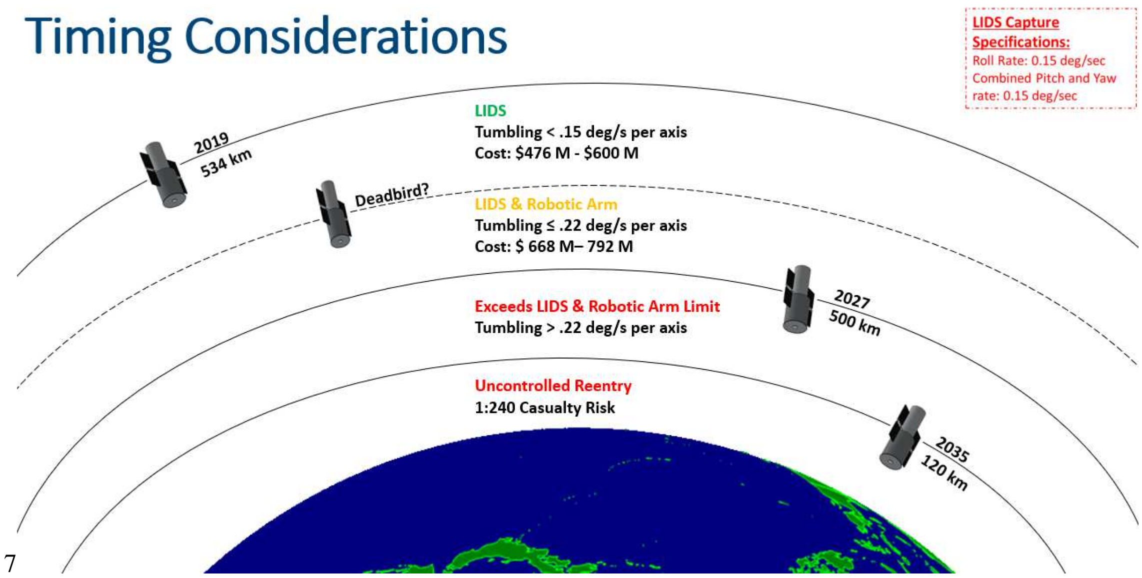

Fig. 5. Timing Considerations for HST deorbit approaches.

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