Hubble Space Telescope (HST) Servicing Analyses of Alternatives (AoA)

Final Delivery Executive Summary

August 3, 2004

Outline

- Introduction
- Description of Alternatives
- Measures of Effectiveness
- Summary of Results
- Key Findings

Acknowledgements

- Vicky Hwa - NASA Study Lead
- Matt Schaffer - Office of Exploration Systems
- Mike Moore - HST Program Executive
- Jennifer Wiseman - Office of Space Science
- Mike Weiss - NASA/GSFC HST Program Office
- Joe Fragola - SAIC Advisor on Risk Assessment
- JC Duh - Office of the Chief Engineer

Study Overview

- Non-advocate assessment of HST servicing alternatives
  - Alternatives that encompass a range of options from safe disposal to re-hosting capability on other spacecraft
  - For each alternative assess: (a) cost and schedule; (b) risk and safety, and (c) capability relative to HST post-SM4 state
- Study Scope
  - Nine week study: ATP June 1, briefing presentation Aug 3
  - Level-of-detail scaled according to available data and schedule
  - Written report to be provided in September
- Include HST science and technical communities
  - Status to and feedback from stakeholders on alternative concepts and Measures of Effectiveness (MOEs)
  - Implications of capability impact on science
  - Access to accurate data on HST technical baseline/constraints, operational state

Schedule

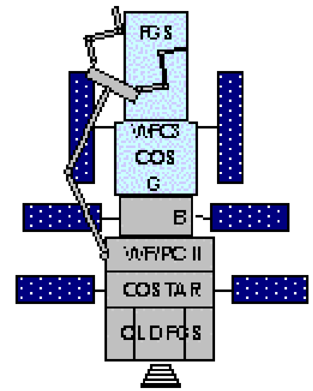
✓	ATP	June 1
✓	Study Plan Due	June 8
✓	Kickoff Meeting w/NASA	June 14
✓	Draft Alternatives to NASA	June 15
✓	GSFC PO Fact Finding	June 21-23
✓	GSFC TIM (Mike Weiss)	June 28
✓	"Final" MOEs to NASA	July 2
✓	Mid-term Update	July 9
✓	Cost/Schedule Estimate Calibration	July 14
✓	Analysis Complete	July 25
✓	Preview with NASA	July 27
o	Final Presentation to NASA	August 3
o	Final Report	Sept 17

Approach

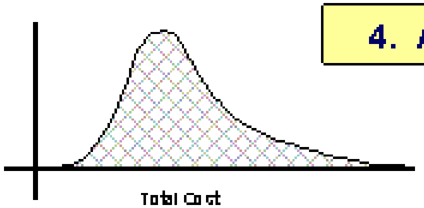
1. Identify Alternatives

2. Define Measures of Effectiveness

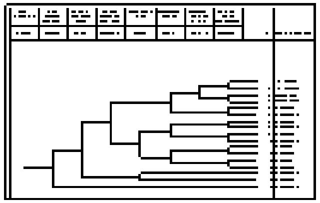
3. Assess Cost & Schedule

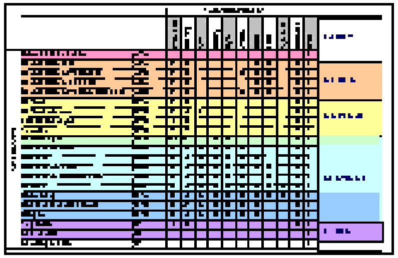


4. Assess Risk and Safety



5. Assess Capability Impact





6. Integrate Findings

7. Deliver Final Report

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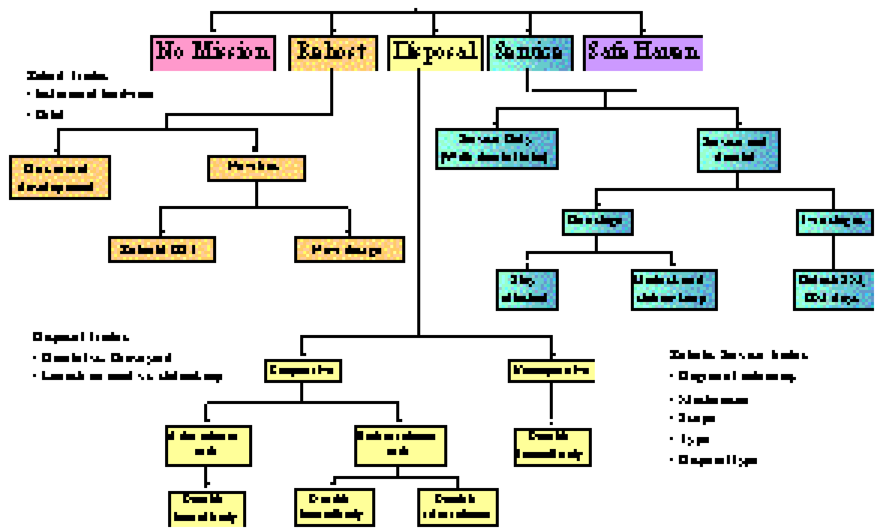
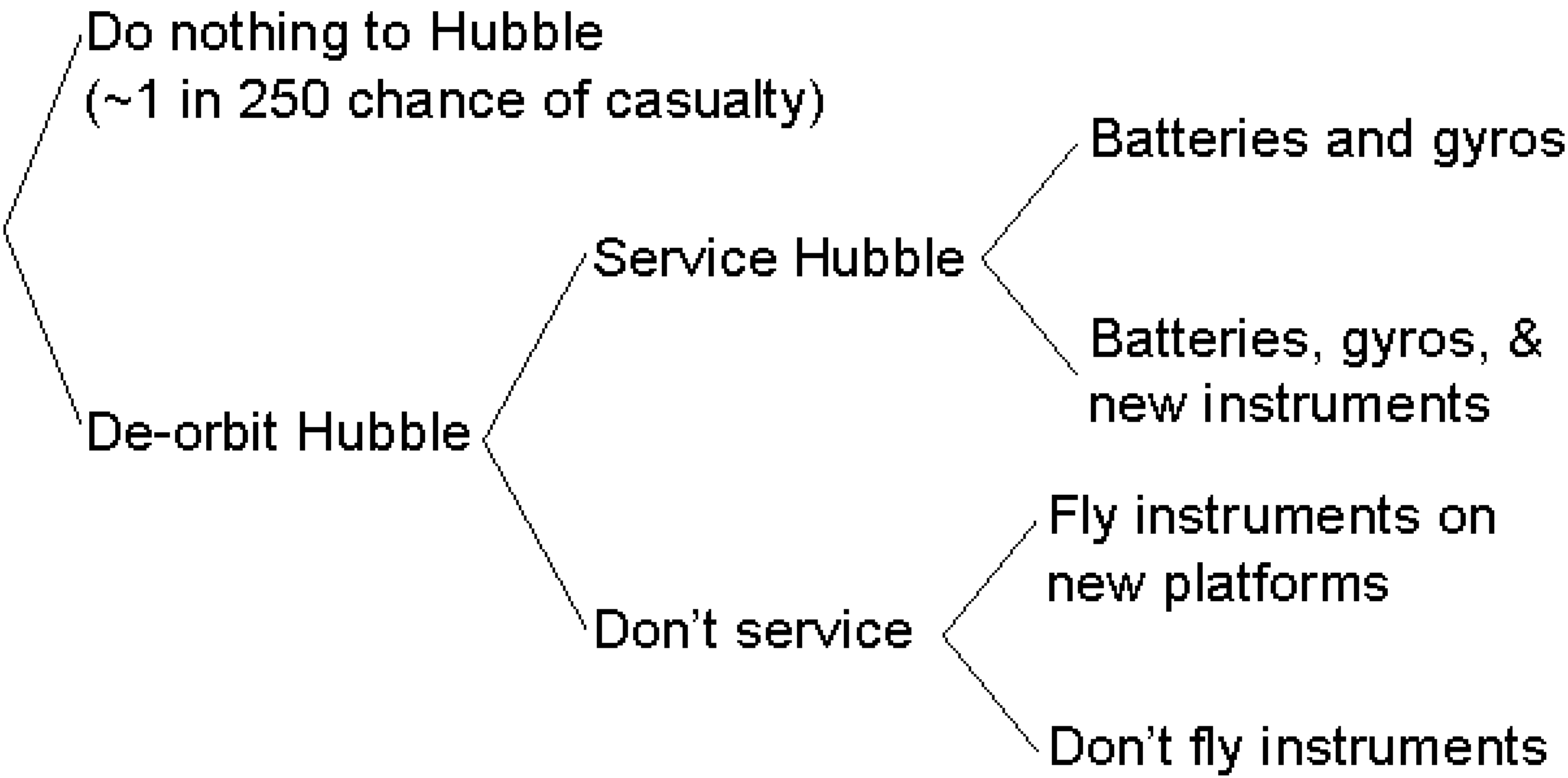
Alternatives Development

- **Goal**
  - Represent range of variation in cost, schedule and risk
  - Sufficiently broad to 'cover' most concepts 'out there'
  - Emphasize robotic concepts
- **Methodology**
  - Identify spectrum of alternatives (brainstorming and methodically)
  - Down-select to a handful of representative concepts
  - Define selected alternatives (concept design, CONOPS, timeline)
- **Down-select Criteria**
  - Reasonable coverage of trade space including: lowest cost, least impact to HST, most complex, etc.
  - Not an exhaustive coverage of every variation - bounding cases
  - Inclusion of a concept does not imply feasibility or endorsement

Option Tree Analyses



Robotic Servicing Decision Tree



Alternatives Families

- Extension of HST science through non-servicing means
  - A1: Existing HST configuration
  - A2: Rehost in LEO
  - A3: Rehost outside LEO
- Robotic Missions
  - B1: Disposal
  - B2: Servicing (Life Extension Only) with Separate Disposal Mission
  - B3: Combined Servicing (Instruments and Life Extension)
  - B4: Servicing (Instruments and Life Extension) and Attach Later for Disposal
- Other Missions
  - C1: Tug to ISS
  - C2: Safe Haven
  - D1: SM4

All Alternatives Include a De-orbit Mission

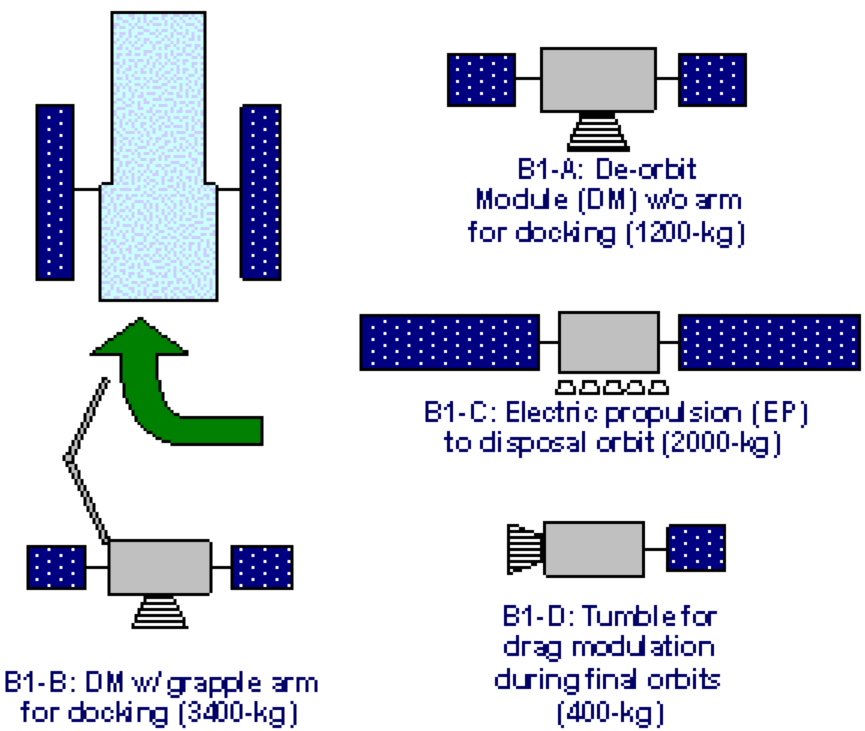
Summary of 21 Alternatives

M = Monoprop, B = Biprop, E = ElectricProp
U = Untargeted docking, T = Targeted docking, A = Grapple arm assisted
D = Dexterous arm, G = Grapple arm
L = LEO, O = Outside LEO
X = Includes task/component

ALTERNATIVE		TASK/COMPONENT											
		Propulsion	Docking	Arm	Battery	Gyro	WFC3	COS	FGS	A, N & D	Disposal	Orbit	FAMILY
Ground Life Extension	A1-A											L	
Rehost COS LEO	A2-A	B	U					X	X		X	L	REHOST
Rehost COS & WFC3 LEO	A2-B	B	U				X	X	X		X	L	REHOST
Rehost COS outside LEO	A3-A	B	U					X	X		X	O	REHOST
Rehost COS & WFC3 outside LEO	A3-B	B	U				X	X	X		X	O	REHOST
De-orbit	B1-A	B	U								X	L	DISPOSAL
De-orbit with Arm	B1-B	B	A	G							X	L	DISPOSAL
Electric Graveyard	B1-C	E	U								X	L	DISPOSAL
Tumbler	B1-D	M	U								X	L	DISPOSAL
Servicer Light	B2-A	M/B	U/T		X	X					X	L	
Baseline no COS	B3-A	M	A	D	X	X	X				X	L	SERVICE
Baseline	B3-B	M	A	D	X	X	X	X			X	L	SERVICE
Baseline with FGS	B3-C	M	A	D	X	X	X	X	X		X	L	SERVICE
Baseline no COS with FGS	B3-D	M	A	D	X	X	X		X		X	L	SERVICE
Cadillac	B3-E	M	A	D	X	X	X	X	X	X	X	L	SERVICE
Boomerang	B4-A	M	A	D	X	X	X	X	X	X	X	L	
Baseline separate deorbit	B4-B	M	A/T	D	X	X	X	X			X	L	
Cling-on	B4-C	M	A	D	X	X	X	X			X	L	
Tug to ISS	C1	E	U								X	L	ASTRONAUT
Safe habitat	C2											L	ASTRONAUT
Servicing Mission 4	D1											L	

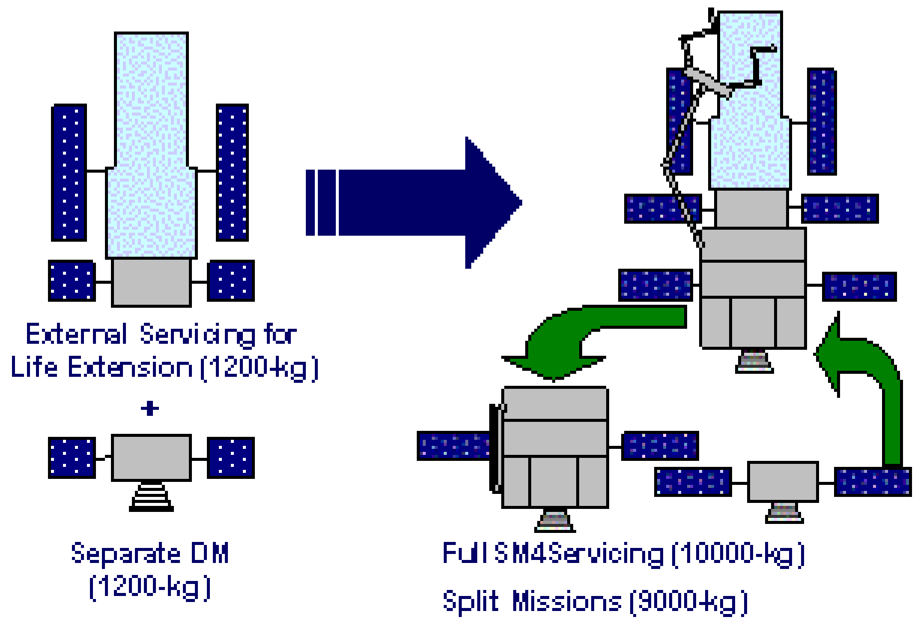
Disposal, Servicing Alternative Configurations

B1: Disposal Only, No Servicing



- Electric propulsion tug to disposal orbit (2500-km)
- Small mono-prop "Tumbler"
- De-orbit before 450 km altitude
- Pegasus to Delta-II-class

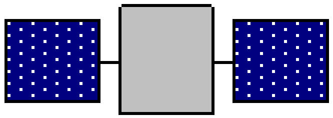
B2-B4: Robotic Servicing



- Minimal servicing (batteries and gyros only) to instruments to full SM4 servicing
- Includes combinations of FGS, COS, WFC3
- Separate de-orbit missions, and options with re-rendezvous for de-orbit
- Minimum and maximum residual mass permanently attached to HST
- No arm and dexterous arm
- Delta-II to Delta IV/Atlas V- class

Rehost, Other Alternative Configurations

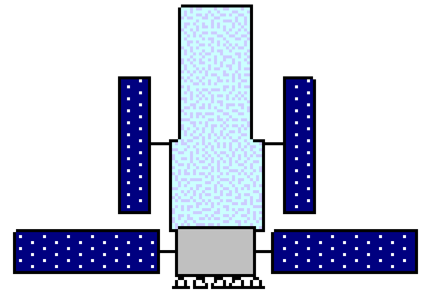
A: COS and WFC3 on Separate Platforms

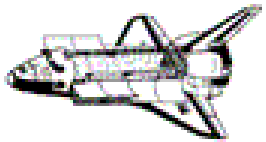


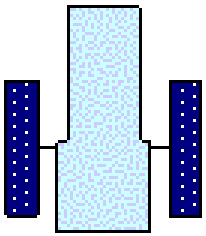
Re-host WFC3 & COS Instrument Capability in LEO or beyond LEO (5500-7500 kg)

- Feasibility not constrained by HST life expectancy
- Includes separate de-orbit mission for HST
- Science gap after HST EOM
- Improved scheduling efficiency beyond LEO
- New program start
- 2.4m aperture
- HST spare primary mirror for LEO, light weight optics beyond LEO
- Duplicate FGS pointing & HST fine-balance reaction wheel capability
- Limited instrument component re-use for environments beyond LEO
- EELV Medium to Heavy

C: Servicing With Shuttle and Safe Haven

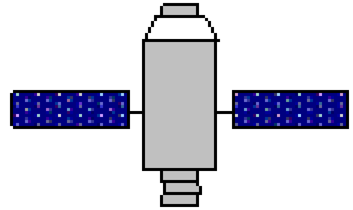


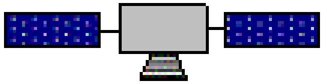




EP tug to transfer HST to ISS (9500-kg)

OR





Launch Safe Haven to Rendezvous with HST, EOL de-orbit mission (19000-kg)

- Shuttle servicing with astronaut safe haven (based on Russian FGB)
- Full SM4 servicing
- Disposal or de-orbit via EP or separate disposal mission
- EELV Medium to Heavy & Shuttle

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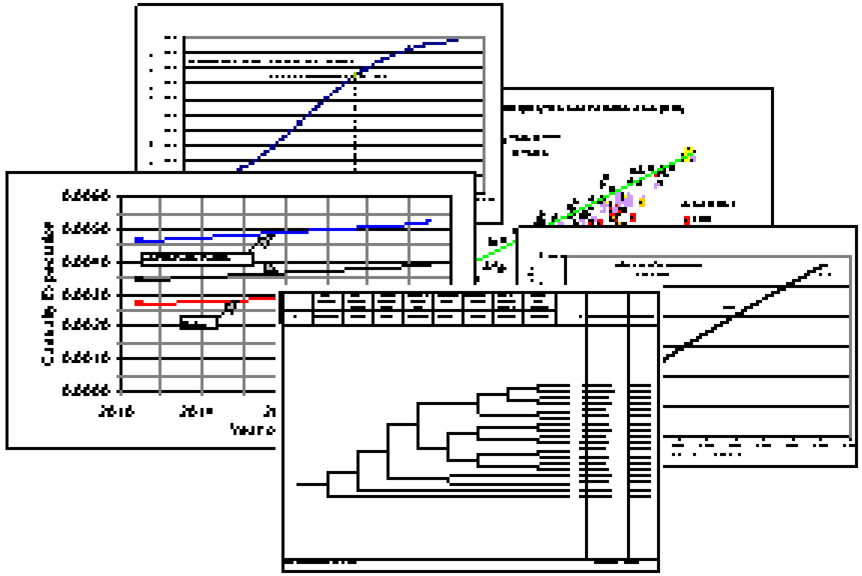
Measures of Effectiveness (MOEs)

- Analyses Categories
  - Cost and Schedule
  - Risk and Safety
  - Capability



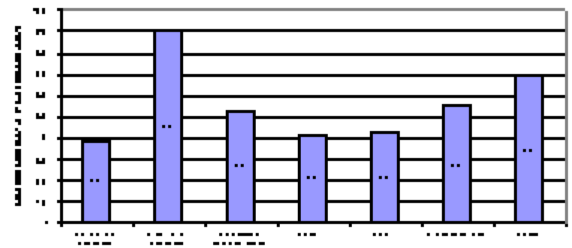
- MOEs

Cost	Life Cycle Cost (FY04$B)
Schedule	Nominal Development Time (Months)
Development Risk	Probability of HST in Required State (%)
Mission Risk	Probability of Full Mission Success (%)
Capability	Capability Relative to Post-SM4 HST

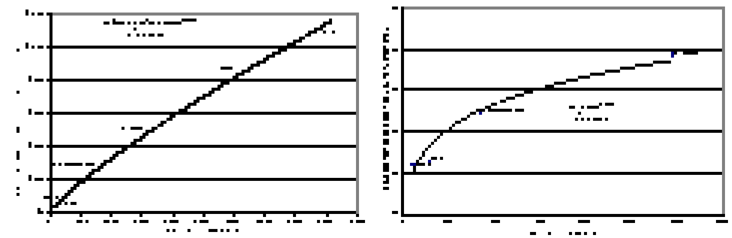
Cost & Schedule Methodology

1. Life Cycle Cost ($FY04B)
   - Program Management, Systems Engineering & Mission Assurance
   - Vehicles
   - Robotics
   - Ground System Development
   - Mission Operations & Data Analysis (3 years)
   - De-orbit (if separate)
   - Launch Vehicle
   - Reserves
2. Nominal mission development time (months)
   - Time from contract start (or authority to proceed, ATP) to launch

1. Select a set of analogous missions for analyzing alternatives



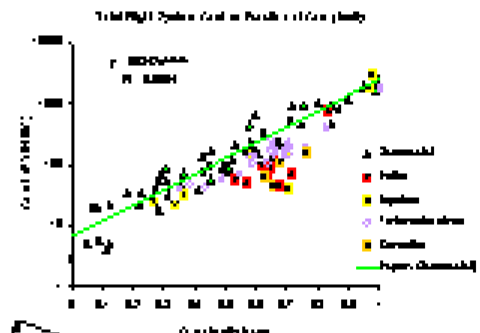
2. Develop cost and schedule estimating relationships based on actual/projected data

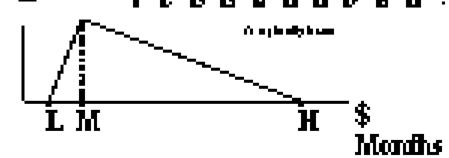


3. Develop cost and schedule estimates using average of viable estimates/models:

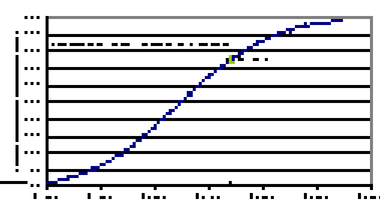
CER and SER, NAFCOM

Complexity Based Estimate





4. Determine cost and schedule triangular risk distributions and develop S-curve

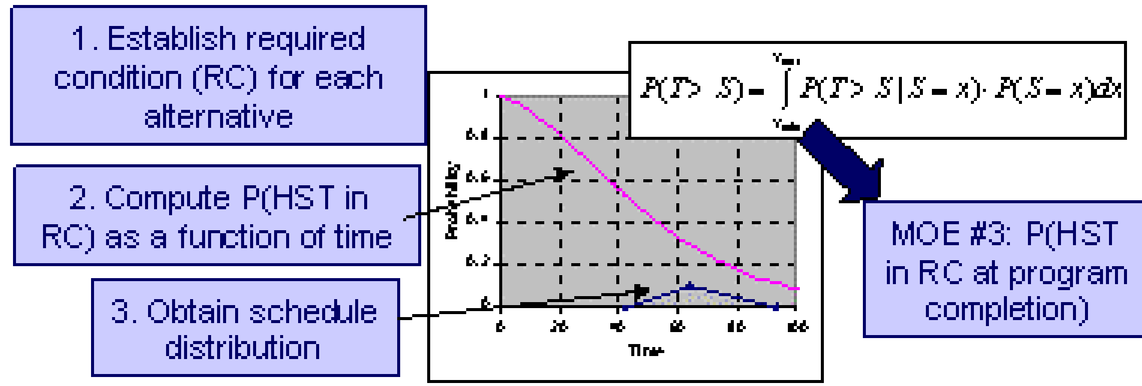


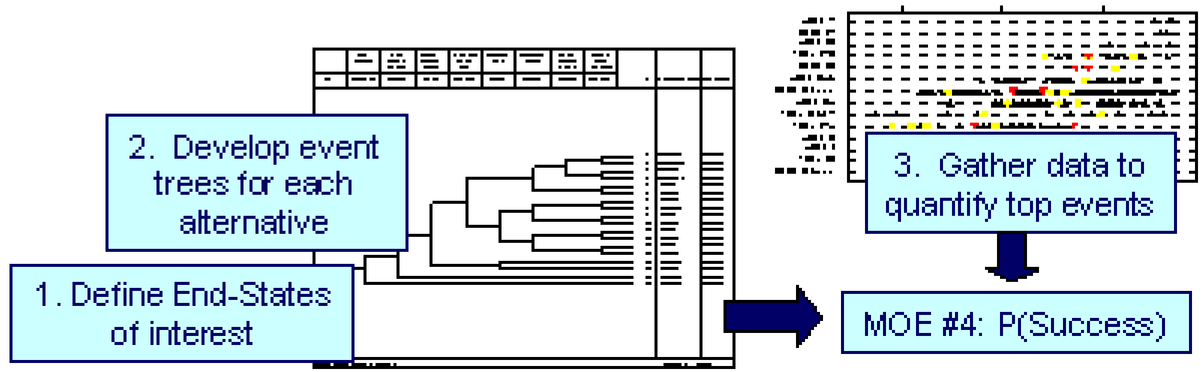
MOE #1 and #2

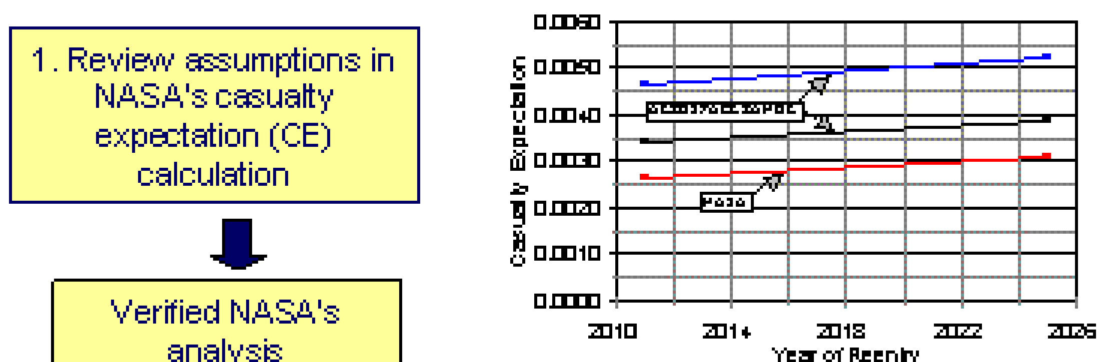
Risk & Safety Methodology

3. Development Risk
   - Risk related to the ability to execute the program on a schedule compatible with the degradation of the HST

4. Mission Risk
   - Risk related to the ability to successfully and safely execute the defined mission, including
     - 3 years of science operations
     - Disposal





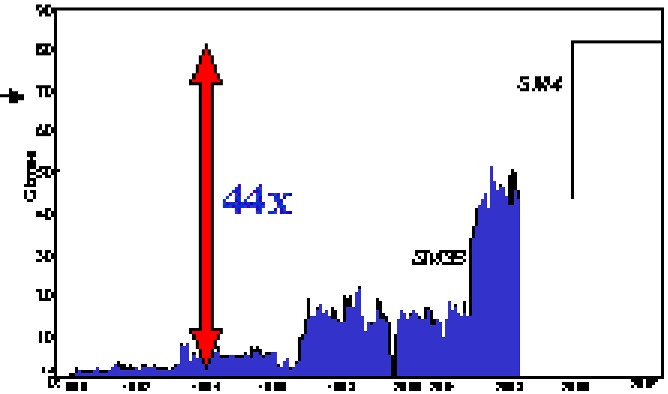


Capability Assessment Methodology

5. Capability Relative To Post-SM4 HST (%)
   - Instrument performance after servicing, relative to post-SM4 baseline (%)

Quantitative Approach

1. Examine historical data for instrument usage patterns when new instruments are installed



2. Develop conversion factor based on historical data volume

3. Define instrument suite for each alternative

4. Predict instrument usage for HST after servicing mission

Instrument Usage Allocation Predictions

Instrument	Pre-SM4 actuals	B2 predicted	B3-A predicted	B3-B predicted	B3-C predicted
ACS	48%	61%	23%	11%	11%
NICMOS	21%	-	10%	5%	9%
STIS	23%	29%	11%	5%	9%
WFPC2	6%	7%	-	-	-
FGS	3%	3%	3%	3%	3%
WFC3	-	-	53%	38%	38%
COS	-	-	-	38%	38%

5. Compare instrument usage for each alternative to post-SM4 configuration

→ MOE #5

Qualitative Approach

1. Estimated mass properties for each alternative
2. Considered induced dynamic disturbances (e.g. slosh, mechanisms)
3. Considered alternative-unique performance drivers such as ACS

↓

Qualitative comments on jitter performance, control authority, etc.

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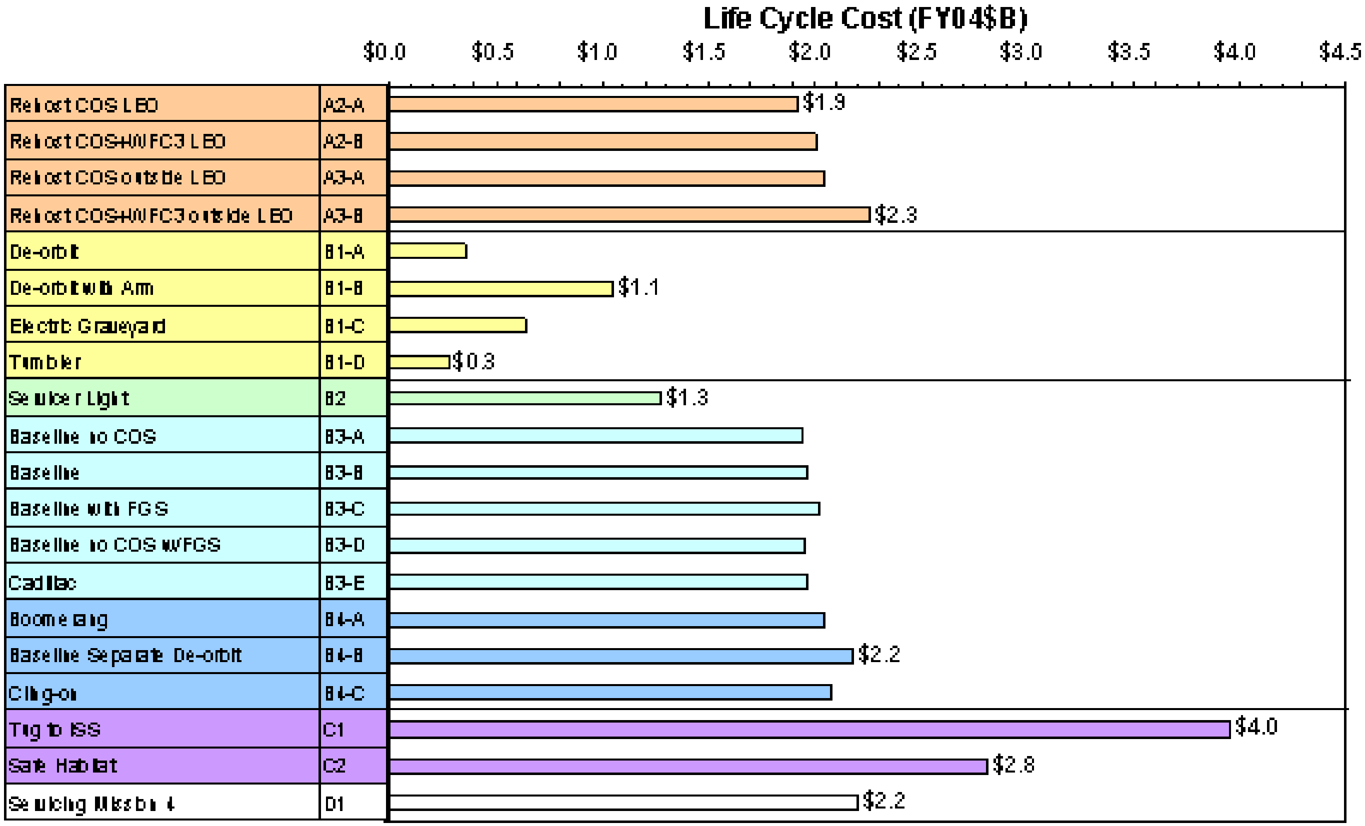
MOE 1: Life Cycle Cost

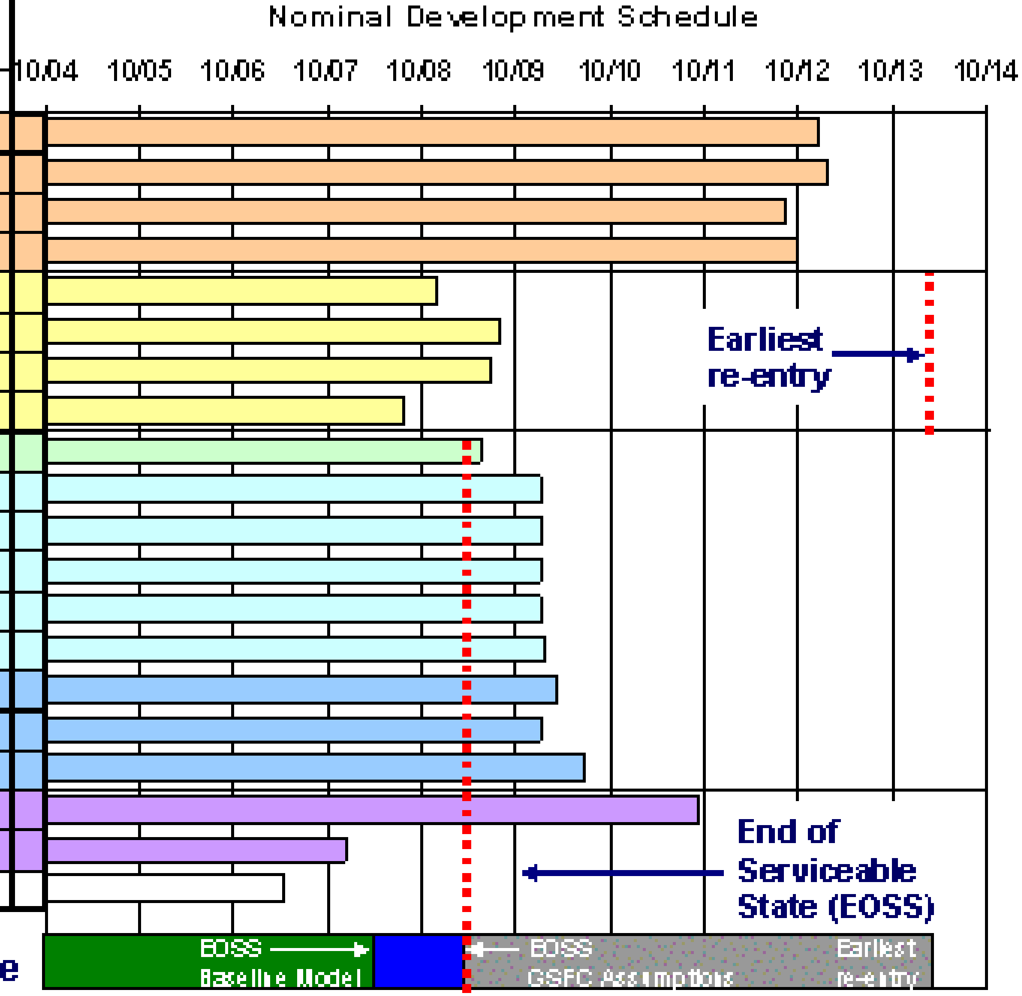


LCC Estimates Show Little Cost Difference Between Rehost & Servicing Missions

MOE 2 & 3: Schedule & Development Risk

Serviceable state = HST will be able to be restored to full operations using only the replacement parts associated with the current design of the servicing alternative

Alternative		ATP to Launch (months) Nominal	Prob HST in Serviceable State P(Success)
Rehost COS LEO	A2-A	100	N/A
Rehost SM4 LEO	A2-B	101	N/A
Rehost COS outside LEO	A3-A	96	N/A
Rehost SM4 outside LEO	A3-B	97	N/A
De-orbit	B1-A	51	1.00
De-orbit with Arm	B1-B	59	1.00
Electric Graveyard	B1-C	58	1.00
Tumbler	B1-D	47	1.00
Servicer Light	B2	57	0.40
Baseline no COS	B3-A	64	0.38
Baseline	B3-B	64	0.38
Baseline with FGS	B3-C	64	0.38
Baseline no COS w/FGS	B3-D	64	0.38
Cadillac	B3-E	65	0.38
Boomerang	B4-A	66	0.38
Baseline Separate Deorbit	B4-B	64	0.38
Cling-on	B4-C	70	0.37
Tug to ISS	C1	85	0.26
Safe Habitat	C2	39	0.59
Servicing Mission 4	D1	31	0.74

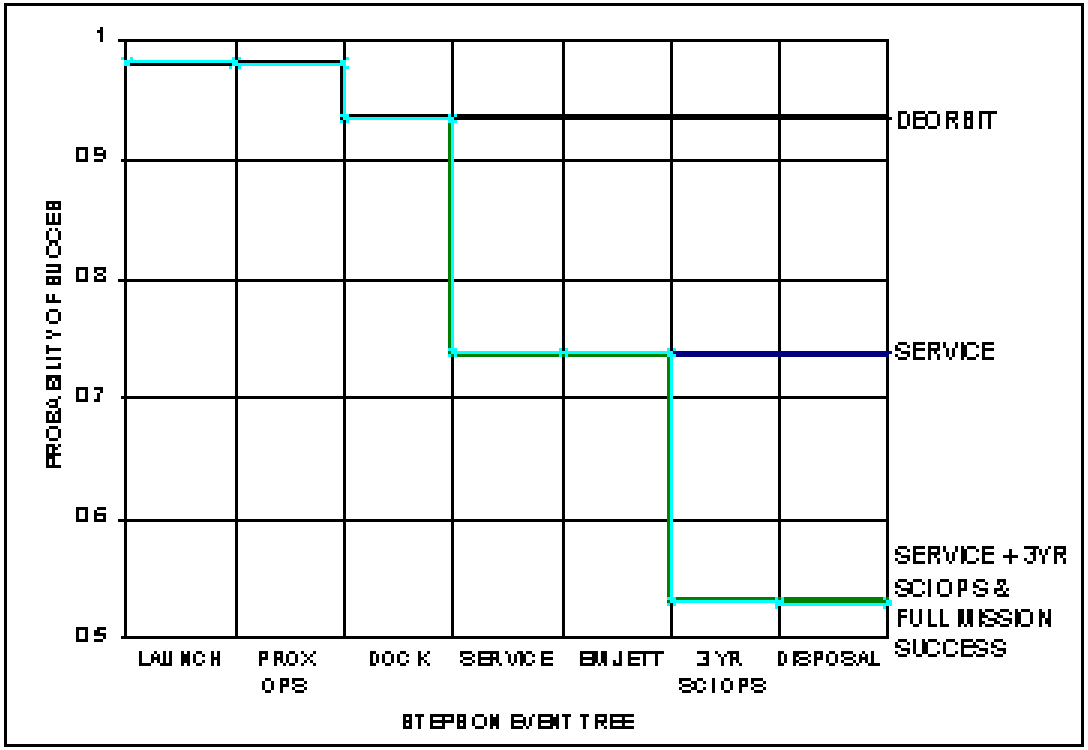


HST Predicted Lifetime

MOE 4: Mission Success

		Mission (Serv, Sci, Dispose)
		P(Success)
Rehost COS LEO	A2-A	0.87
Rehost SM4 LEO	A2-B	0.87
Rehost COS outside LEO	A3-A	0.84
Rehost SM4 outside LEO	A3-B	0.84
De-orbit	B1-A	0.89
De-orbit with Arm	B1-B	0.93
Electric Graveyard	B1-C	0.88
Tumbler	B1-D	0.87
Servicer Light	B2	0.58
Baseline no COS	B3-A	0.58
Baseline	B3-B	0.52
Baseline with FGS	B3-C	0.48
Baseline no COS w/FGS	B3-D	0.54
Cadillac	B3-E	0.32
Boomerang	B4-A	0.26
Baseline Separate Deorbit	B4-B	0.47
Cling-on	B4-C	0.52
Tug to ISS	C1	0.43
Safe Habitat	C2	0.63
Servicing Mission 4	D1	0.63

Example Calculation: Baseline Alternative



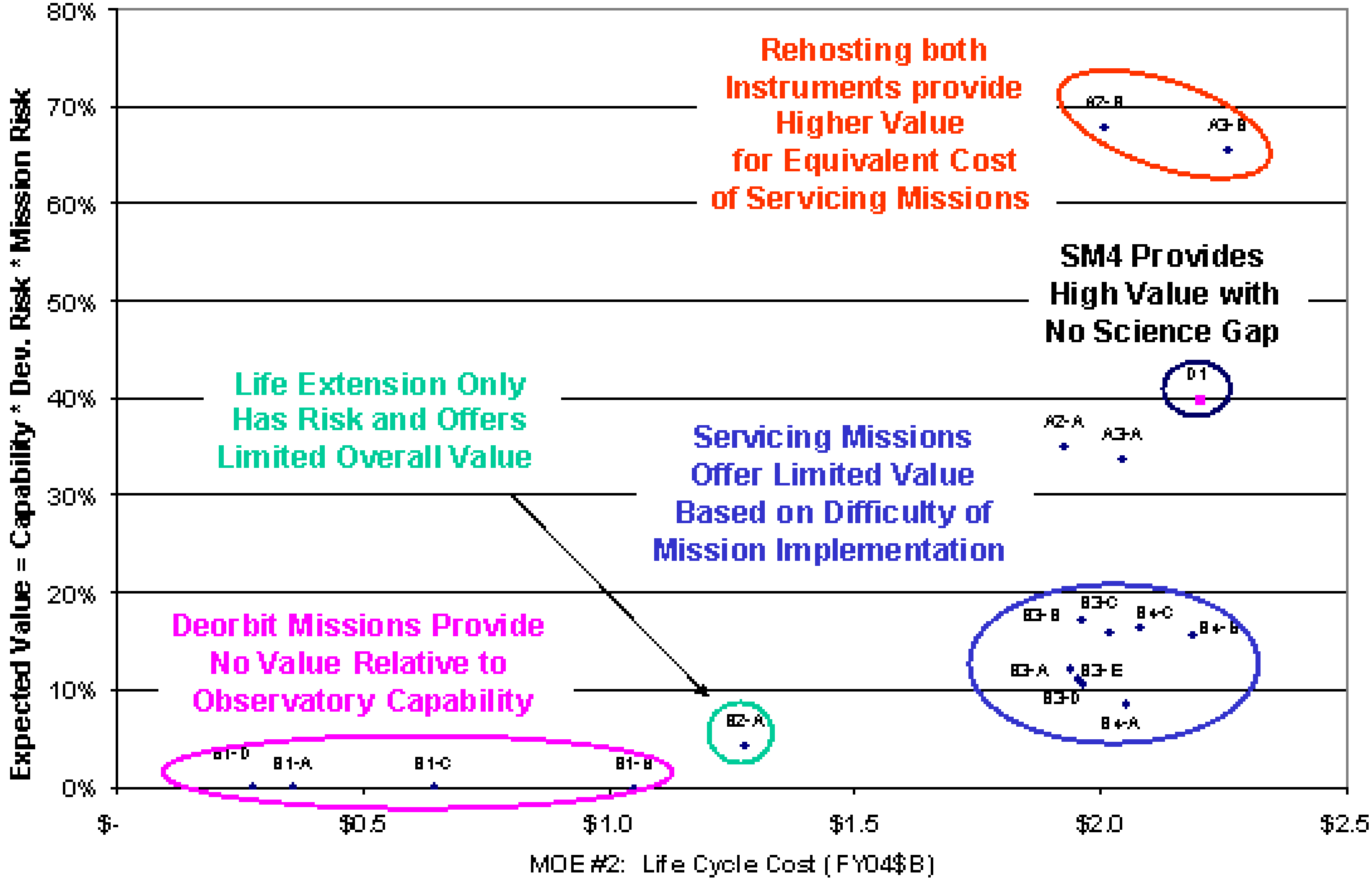
MOE 5: Capability Relative to Post-SM4 HST

			Instruments						
		Capability Relative to Post-SM4 HST	WFPC2	STIS	ACS	NICMOS	WFC3	COS	Family
Rehost COS LEO	A2-A	40%						X	REHOST
Rehost SM4 LEO	A2-B	78%					X	X	
Rehost COS outside LEO	A3-A	40%						X	
Rehost SM4 outside LEO	A3-B	78%					X	X	
De-orbit	B1-A	0%	No value						DISPOSAL
De-orbit with Arm	B1-B	0%							
Electric Graveyard	B1-C	0%							
Tumbler	B1-D	0%							
Servicer Light	B2	21%	X	X	X				
Baseline no COS	B3-A	62%		X	X	X	X		SERVICING
Baseline	B3-B	100%		X	X	X	X	X	
Baseline with FGS	B3-C	100%		X	X	X	X	X	
Baseline no COS w/FGS	B3-D	62%		X	X	X	X		
Cadillac	B3-E	100%		X	X	X	X	X	
Boomerang	B4-A	100%		X	X	X	X	X	
Baseline Separate Deorb	B4-B	100%		X	X	X	X	X	
Cling-on	B4-C	100%		X	X	X	X	X	
Tug to ISS	C1	100%		X	X	X	X	X	OTHER
Safe Habitat	C2	100%		X	X	X	X	X	
SM4	D1	100%		X	X	X	X	X	

HST Servicing Summary

Alternatives		Cost & Schedule		Risk & Safety		Capability						Family
		Life Cycle Cost (FY04$B)	Nominal Development Time (Years)	Development Risk	Mission Risk	WFPC2	STIS	ACS	NICMOS	WFC3	COS	
Ground Life Extension	A1					X	X	X	X			
Rehost COS LEO	A2-A	$1.9	8.4	Science Gap	Low						X	REHOST
Rehost SM4 LEO	A2-B	$2.0	8.4							X	X	
Rehost COS outside LEO	A3-A	$2.0	8.0								X	
Rehost SM4 outside LEO	A3-B	$2.3	8.1							X	X	
De-orbit	B1-A	$0.4	4.2	Low	Low	No value						DISPOSAL
De-orbit with Arm	B1-B	$1.1	4.9									
Electric Graveyard	B1-C	$0.6	4.8									
Tumbler	B1-D	$0.3	3.9									
Servicer Light	B2	$1.3	4.7	High	High	X	X	X				
Baseline no COS	B3-A	$1.9	5.4	High	High		X	X	X	X		SERVICING
Baseline	B3-B	$2.0	5.4				X	X	X	X	X	
Baseline with FGS	B3-C	$2.0	5.4				X	X	X	X	X	
Baseline no COS w/FGS	B3-D	$2.0	5.4				X	X	X	X		
Cadillac	B3-E	$2.0	5.4				X	X	X	X	X	
Boomerang	B4-A	$2.1	5.5	High	High		X	X	X	X	X	
Baseline Separate Deorb	B4-B	$2.2	5.4				X	X	X	X	X	
Cling-on	B4-C	$2.1	5.8				X	X	X	X	X	
Tug to ISS	C1	$4.0	7.1	High	High		X	X	X	X	X	OTHER
Safe Habitat	C2	$2.8	3.3		Medium		X	X	X	X	X	
SM4	D1	$2.2	2.6	Medium	Medium		X	X	X	X	X	

Expected Value vs. Life Cycle Cost



Analysis Points to Rehost Options as Highest Value for Given Cost

Outline

- Introduction
- Measures of Effectiveness
- Description of Alternatives
- Summary of Results
- ➡ Key Findings

Findings (1 of 3)

- **Without servicing, HST will begin degrading, likely expiring in 2008-2009**
  - Failure estimates are based on NASA studies and recently updated Aerospace HST reliability models and battery studies
  - Gyros likely to fail first, though early failures of other subsystems (fine guidance sensors, data management unit, etc.) are possible
- **With uncontrolled HST re-entry, the casualty risk (~1 in 250) is about 100X greater than U.S. gov't standard (1 in 10,000)**
  - Independent Aerospace simulations confirm NASA's casualty estimates
- **A de-orbit mission ($0.3 B to $1.1 B life-cycle cost) is technically and programmatically feasible**
  - HST lapses into stable gravity-gradient attitude with earliest re-entry 2014
  - Suitable robotic docking technologies demonstrated in other programs
  - All propulsive re-entry options, except Tumbler, reduce casualty expectation to zero, if successful

Findings (2 of 3)

- **A combined servicing and de-orbit mission using one expendable launch vehicle (approx. $2B) is high risk**
  - 5 years of development likely required
  - HST will likely fall into an unserviceable state in ~4 years, before robotic service mission could arrive
  - High failure risk due to unprecedented mission and unproven technologies (~ 50% probability of failure, rough estimate)
- **Separate servicing and de-orbit missions provide flexibility**
  - Push de-orbit portion into out-years and decouple from servicer failure
  - However, even a minimal servicing mission ($1.3B) has high programmatic risk (~40% probability of arrival while HST is in a serviceable state)
  - The minimal servicing option would externally replace only the gyros and batteries providing about 4 years life extension of current instruments

Findings (3 of 3)

- **Re-host options ($1.9 B to $2.3 B) are technically and programmatically feasible**
  - However, there will be a 2-7 year gap in science return, between when HST ceases science operations and a new program can come on line
  - New observatory program will be subject to requirements creep, cost and schedule growth, and will likely compete with ongoing and future observatories for funding
- **Some areas that warrant further study include:**
  - HST reliability predictions in light of up-to-date degradation/failure information and changes in the way HST is operated
  - Lifetime-extension only mission detailed assessment of impact of gyros located on servicer vehicle