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John L. Goodman
United Space Alliance, LLC

Stephen R. Walker
NASA Johnson Space Center

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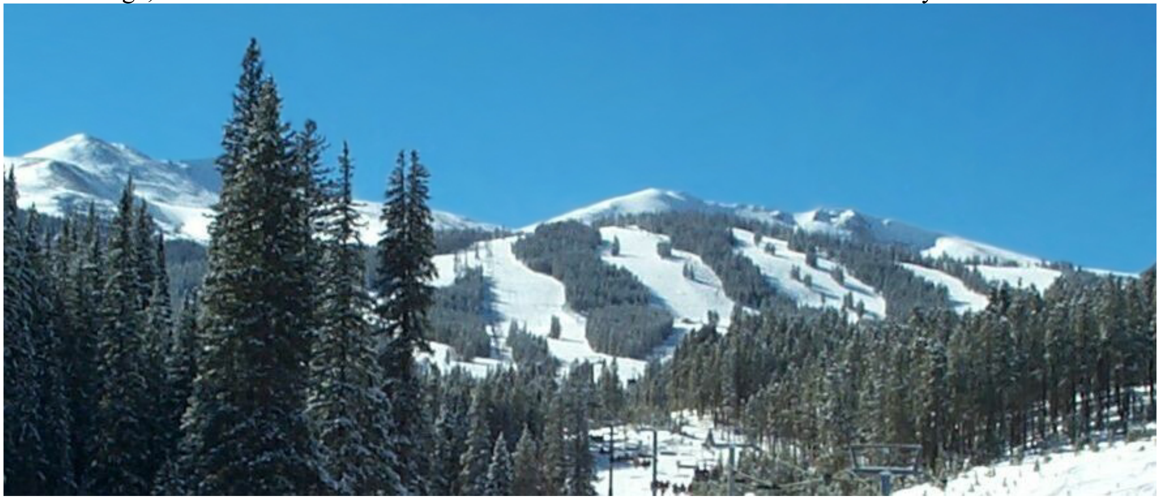

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HUBBLE SERVICING CHALLENGES DRIVE INNOVATION OF SHUTTLE RENDEZVOUS TECHNIQUES*

John L. Goodman[†]
Stephen R. Walker[‡]

Hubble Space Telescope (HST) servicing, performed by Space Shuttle crews, has contributed to what is arguably one of the most successful astronomy missions ever flown. Both nominal and contingency proximity operations techniques were developed to enable successful servicing, while lowering the risk of damage to HST systems, and improve crew safety. Influencing the development of these techniques were the challenges presented by plume impingement and HST performance anomalies. The design of both the HST and the Space Shuttle was completed before the potential of HST contamination and structural damage by shuttle RCS jet plume impingement was fully understood. Relative navigation during proximity operations has been challenging, as HST was not equipped with relative navigation aids. Since HST reached orbit in 1990, proximity operations design for servicing missions has evolved as insight into plume contamination and dynamic pressure has improved and new relative navigation tools have become available. Servicing missions have provided NASA with opportunities to gain insight into servicing mission design and development of nominal and contingency procedures. The HST servicing experiences and lessons learned are applicable to other programs that perform on-orbit servicing and rendezvous, both human and robotic.

INTRODUCTION

Hubble Space Telescope (HST) servicing performed by Space Shuttle crews has contributed to what is arguably one of the most successful astronomy missions ever flown. On-orbit servicing performed by four Space Shuttle servicing missions between 1993 and 2002 has increased the science return and extended the life of the telescope by correcting performance problems, replacing malfunctioning hardware, and equipping it with more advanced astronomy sensors.[1] A fifth servicing mission is planned for 2009. Servicing missions involve extensive coordination between specialists in multiple disciplines in both the Shuttle and HST Programs to develop new or adapt existing techniques for HST servicing. These disciplines include trajectory design, robotics, flight control, thermal control, power generation, structures, orbital debris, and Extra-Vehicular Activity (EVA).[2]

HST servicing missions have provided NASA with opportunities to gain insight into servicing mission design and to develop nominal and contingency procedures. HST performance issues have driven new and unanticipated servicing and proximity operations techniques development. Both nominal and contingency procedures and mission plans for rendezvous, proximity operations, jettison, deployment, and tool capture have evolved since HST was deployed on STS-31 in 1990. Although Space Shuttle missions to HST

[†] Senior Navigation and Rendezvous Specialist, Mail Code USH-806A, United Space Alliance, LLC, 600 Gemini Ave., Houston, TX 77058.

[‡] NASA Group Lead, Rendezvous Guidance and Procedures Office, Mail Code DM34, NASA Johnson Space Center, 2101 NASA Parkway, Houston, TX 77058.

involve human-in-the-loop rendezvous, capture, and servicing, the HST servicing experiences and lessons learned are also applicable to current and future robotic flight programs that involve on-orbit servicing and rendezvous.[3-8] The recent and highly successful Orbital Express robotic servicing demonstration mission illustrated the importance of pre-mission development of contingency procedures to address postulated anomalies, as well as real-time development of contingency procedures in response to unanticipated anomalies.[9] Although HST EVA and robotic activities are outside the scope of this paper, those disciplines have likewise developed and evolved extensive nominal and contingency procedures.

Servicing missions succeeded in part due to the efforts of experienced HST and Shuttle Program personnel (NASA and contractor) from multiple disciplines that had extensive experience planning and flying servicing and assembly missions to a variety of spacecraft. This facilitated application of best practices and lessons learned. These personnel were responsive to unanticipated satellite performance issues that drove late and significant changes in servicing mission plans. These events drove changes to existing proximity operations, robotic operation, and servicing procedures or required the creation of new procedures and mission plans. HST and Shuttle Program personnel continually learned about emerging HST and shuttle orbiter constraints. Unforeseen constraints and performance limitations drove development of new or changes to existing nominal and contingency plans and procedures. Rendezvous, proximity operations, and other mission techniques from other Space Shuttle missions were successfully applied to mitigate risk to HST servicing mission success.

This paper provides an overview of HST servicing missions. This is followed by a description of HST design and operations that are pertinent to Space Shuttle rendezvous and proximity operations. Next, relative navigation and shuttle plume impingement challenges are discussed. For the deploy mission and the servicing missions an overview is given of the rendezvous, proximity operations, and deploy procedures that were flown, along with mission results. In addition, contingency procedures to address the HST aperture door failed closed or failed open cases are described. Other contingency proximity operations and hardware jettison procedures are then outlined. Finally, Table 1 is an overview of HST servicing mission objectives. Table 2 is a list of nominal and contingency procedures for each mission that address relative motion. The table lists procedures for rendezvous, proximity operations (approach and grapple), jettison, and deploy and separation.

Finally, a rescue mission has been planned if a thermal protection system problem prevented the safe return of the STS-125 crew during the last HST servicing mission in 2009. Since the rescue mission is different in many respects from the HST deployment and servicing missions, nominal and contingency procedures are discussed in a separate section at the end of the paper.

OVERVIEW OF HST SERVICING MISSIONS

Planning for all HST missions has involved trade studies, simulations, and extensive technical discussions covering both nominal and contingency mission plans and procedures. Mission preparation includes timeline and crew activity planning, procedure development, and trajectory design covering all aspects of the mission. This includes ascent, launch aborts, rendezvous, proximity operations, entry and landing, EVA, robotics, etc. Contingency procedures are also developed or adapted to addresses systems anomalies that may occur in the rendezvous, proximity operations, servicing, and deploy phases.

Shuttle rendezvous with HST and grapple, by the Remote Manipulator System (RMS) robotic arm, is normally scheduled for flight day three.[**] On the morning of flight day three, the shuttle relative navigation sensors (radar and star tracker) obtain relative measurements that are used to improve the estimate of the relative navigation state in the shuttle flight computers. Rendezvous maneuvers are also computed by the shuttle flight computers.

[**] Flight day one begins with crew wakeup at the Kennedy Space Center on the day of launch. Subsequent flight days on-orbit begin when the crew wakes up.

Once the orbiter is within approximately 2000 feet of HST the proximity operations phase begins. The relative motion trajectory is designed to accommodate orbiter and HST constraints such as orbiter Reaction Control System (RCS) jet plume impingent, power generation, and thermal control. The crew grapples HST with the RMS and berths it in the shuttle payload bay. After several days of servicing by EVA crew members, HST is deployed and resumes the astronomy mission. Deploy procedures are designed to ensure safe separation of the orbiter from HST while also concurrently protecting HST from plume impingement. Deploy procedures may also have to meet additional constraints for thermal, lighting, and communications.

TABLE 1
SPACE SHUTTLE MISSIONS CONCERNING THE HUBBLE SPACE TELESCOPE

Mission	Orbiter	HST Mission Objectives	Launch Date, Pad Landing Date, Runway	Remarks
STS-61J	*Atlantis* OV-104	Deploy HST	Mission planned for August, 1986.	Canceled after *Challenger* accident.
STS-31	*Discovery* OV-103	Deploy HST	4/24/90, 39B 4/29/90, EDW 22	HST successfully deployed. Contingency rendezvous with HST planned but not required.
STS-42	*Discovery* OV-103	Proposed HST photo inspection.	01/22/92, 39A 01/30/92, EDW 22	Proposed inspection was to document solar array tip deflections that could lead to array failure and negatively impact astronomy. Inspection proposal rejected in August 1991. Primary mission objective International Microgravity Laboratory-1.
STS-61	*Endeavour* OV-105	Servicing Mission 1 (SM1)	12/02/93, 39B 12/13/93, KSC 33	Installation of corrective optics. Solar arrays replaced and one old array jettisoned by EVA crew.
STS-82	*Discovery* OV-103	Servicing Mission 2 (SM2)	2/11/97, 39A 2/21/97, KSC 15	MECO under-speed. During rendezvous star tracker broke lock on HST, then tracked a star and orbital debris. SEP2 maneuver under-burn. Re-planning and crew procedures executed in response to these issues ensured successful rendezvous and separation.
STS-103	*Discovery* OV-103	Servicing Mission 3A (SM3A)	12/19/99, 39B 12/27/99, KSC 33	Flown in response to HST gyro failures. HST in Hardware Sun Point safe mode at the time of rendezvous due to fourth gyro failure. *Discovery* yaw maneuver due to off nominal HST attitude at the time of grapple.
STS-109	*Columbia* OV-102	Servicing Mission 3B (SM3B)	3/01/02, 39A 3/12/02, KSC 33	Rendezvous altitude decayed below insertion altitude, forcing one rendezvous maneuver to be retrograde.
STS-125	*Atlantis* OV-104	Servicing Mission 4 (SM4)	Mission planned for 2009.	Mount passive LIDS docking hardware and laser retro-reflectors on HST for possible missions by future human or robotic spacecraft.
STS-40x	?	Rescue 125 crew if required.	Mission planned for 2009, if required.	Rescue orbiter grapples *Atlantis* with RMS. EVA transfer of *Atlantis* crew to rescue orbiter. TCS retro-reflector mounted in *Atlantis* payload bay for use by rescue orbiter TCS.

EDW – Edwards Air Force Base
EVA – Extra Vehicular Activity
HST – Hubble Space Telescope
KSC – Kennedy Space Center
LIDS – Low Impact Docking System
MECO – Main Engine Cut-Off
OV – Orbiter Vehicle
RMS – Remote Manipulator System
SM – Servicing Mission
STS – Space Transportation System
TCS – Trajectory Control Sensor

TABLE 2
NOMINAL AND CONTINGENCY PROCEDURES FOR HST SERVICING MISSIONS

Mission	Rendezvous	Proximity Operations	Jettison	Deploy/Separation
STS-31				
Nominal				• Deploy with RMS
Contingency	• Stable Orbit (2 rev) • Radar Fail • Rndz Breakout • Ti Delay	• Inertial Approach • Fast Flyaround • STS Roll to Align • Prox Ops Breakout • EVA Rescue • Loss of VRCS		• Emergency RMS Deploy • No RMS Backaway Deploy
STS-61				
Nominal	• Stable Orbit (2 rev)	• Inertial Approach		• Deploy with RMS
Contingency	• Radar Fail • Rndz Breakout • Ti Delay	• Manual Inertial Flyaround Alignment Trim • AUTO Inertial Flyaround • Prox Ops Backoff • Prox Ops Breakout • Tool chasing • EVA Rescue • Loss of VRCS	• HST Jettison • SAC Jettison • ORUC Jettison • SA Jettison Using Jettison Handle (performed) • SA Jettison Using Portable GF	• RMS Quick Deploy • No RMS Backaway Deploy • Low Propellant Sep (performed)
STS-82				
Nominal	• Stable Orbit (2 rev)	• +R Bar Approach/Inertial Grapple		• Deploy with RMS
Contingency	• Radar Fail • Rndz Breakout • Ti Delay	• Inertial Approach • RBAR Yaw Alignment • Manual Inertial Flyaround Alignment Trim • AUTO Inertial Flyaround • Prox Ops Backoff • Prox Ops Breakout • Loss of Low Z Braking • Loss of Low Z Breakout • Loss of VRCS • Tool chasing • EVA Rescue	• HST Jettison • EVA Hardware Jettison	• RMS Quick Deploy • No RMS Backaway Deploy • No FRCS Sep
STS-103				
Nominal	• ORBT (2 rev)	• +R Bar Approach/Inertial Grapple		• Deploy with RMS
Contingency	• Stable Orbit (2 rev) • Radar Fail • Rndz Breakout • Ti Delay	• Inertial Approach • RBAR Yaw Alignment • Manual Inertial Flyaround Alignment Trim • AUTO Inertial Flyaround • Prox Ops Backoff • HST R Bar Breakout • HST Flyaround/Loss of LOW Z Breakout • Loss of VRCS • Loss of Low Z Braking • Tool Chasing • EVA Rescue	• HST Jettison for Rapid Safing • ORUC Jettison • EVA Hardware Jettison	• RMS Quick Deploy • No RMS Backaway Deploy
STS-109				
Nominal	• ORBT (1 rev)	• +R Bar Approach/Inertial Grapple		• Deploy with RMS
Contingency	• Stable Orbit (1 rev) • Radar Fail • Rndz Breakout • Ti Delay	• Inertial Approach • RBAR Yaw Alignment • Manual Inertial Flyaround Alignment Trim • AUTO Inertial Flyaround • Prox Ops Backoff • HST R Bar Breakout • HST Flyaround/Loss of LOW Z Breakout • Loss of VRCS • Loss of Low Z Braking • Tool Chasing • EVA Rescue	• HST Solar Array Jettison • HST Jettison for Rapid Safing • SAC Jettison • RAC Jettison • EVA Hardware/Solar Array Jettison	• RMS Quick Deploy • No RMS Backaway Deploy
STS-125				
Nominal	• ORBT (1 rev)	• +R Bar Approach/Inertial Grapple		• Deploy with RMS
Contingency	• Stable Orbit (1 rev) • Radar Fail • Rndz Breakout • Ti Delay	• Inertial Approach • RBAR Yaw Alignment • Manual Inertial Flyaround Alignment Trim • AUTO Inertial Flyaround • Prox Ops Backoff • HST R Bar Breakout • HST Flyaround/Loss of Low Z Breakout • Loss of VRCS • Loss of Low Z Braking • Tool Chasing • EVA Rescue	• HST Jettison for Rapid Safing • SLIC Jettison • ORUC Jettison • EVA Hardware Jettison	• RMS Quick Deploy • No RMS Backaway Deploy
STS-40x				
Nominal	• ORBT (1 rev)	• +R Bar Approach		• Separation
Contingency	• Radar Fail • Rndz Breakout • Ti Delay	• Prox Ops Backoff • HST R Bar Breakout • Loss of VRCS		

EVA – Extra Vehicular Activity
FRCS – Forward Reaction Control System
GF – Grapple Fixture
HST – Hubble Space Telescope
ORBT – Optimized R Bar Targeted Rendezvous
ORUC – Orbital Replacement Unit Carrier
RAC – Rigid Array Carrier
RMS – Remote Manipulator System
Rndz – Rendezvous
SA – Solar Array
SAC – Solar Array Carrier
SLIC – Super Lightweight Interchangeable Carrier
STS – Space Transportation System
Ti – Transition Initiation
VRCS – Vernier Reaction Control System

THE HUBBLE SPACE TELESCOPE

Figure 1 is an illustration of the HST as it appears on-orbit while conducting the astronomy mission. Two solar arrays provide electrical power. HST attitude and solar array orientation must be carefully managed to ensure that sufficient power is available to recharge HST batteries. In addition, the HST solar arrays, solar array support structure, and rotational mechanisms are sensitive to shuttle RCS jet plume contamination and over-pressure. Significant analysis is required to develop nominal and contingency proximity operations procedures (approach, grapple, deploy) that do not violate HST plume constraints. Furthermore, HST attitude during shuttle proximity operations must be carefully managed to ensure that the HST solar arrays can generate sufficient power, even in the presence of degraded HST attitude control system performance. HST optics are sensitive to plume contamination as well. However, the optics are protected by closing the aperture door during the approach by the shuttle.

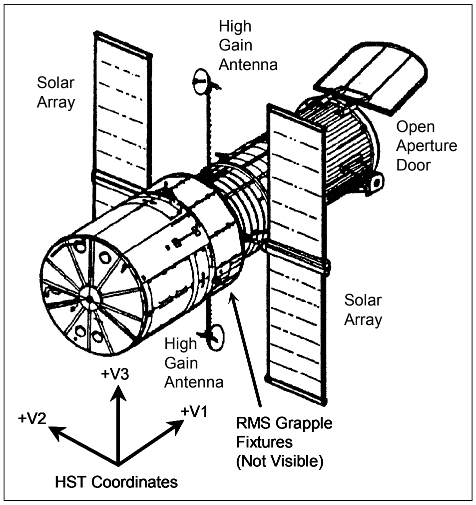

Figure 1 Hubble Space Telescope

HST relies on four Reaction Wheel Assemblies (RWAs) for attitude control, rather than using RCS jets. Six Rate Gyro Assemblies (RGAs) provide redundant measurements for attitude control. However, only three RGAs are required for attitude control. The Retrieval Mode Gyro Assembly (RMGA) is a non-redundant set of back-up gyros that are independent of the RGAs. The RMGA can provide course attitude data for limited periods to support shuttle proximity operations and grapple.

In the event of performance anomalies HST has two attitude control safe modes to maintain HST in a power positive configuration. A HST systems anomaly that forces use of one of the safe modes has implications for proximity operations and shuttle robotics procedures. The Hardware Sunpoint (HWSP) safe mode uses RMGA data and points the +V3 axis to the Sun, maintains an inertial attitude hold, aligns the solar arrays with the V1 axis, and closes the aperture door. The Zero Gyro Sun Point (ZGSP) safe mode points the +V3 axis in the general direction of the Sun, maintains a slow spin about the V3 axis, aligns the solar arrays with the V1 axis, and closes the aperture door. Coarse rate and Sun position data is obtained from the Coarse Sun Sensor. No RGA data is used by the ZGSP safe mode.

Before the shuttle begins the final approach to grapple HST with the RMS, the HST is placed in a proper systems configuration and attitude. The –V3 High Gain Antenna (HGA) (Figure 1) is stowed and latched, and the solar arrays rotated to be parallel with the V1 axis. HST performs a roll maneuver to place the RMS grapple fixture on the north side of the orbital plane. HST continues to maintain an inertial attitude hold during rendezvous and final approach. Two RMS grapple fixtures are mounted on the HST along the –V3 axis (Figure 1). The fixtures can be removed and installed by EVA crew, if required. The nominal grapple attitude of HST is not optimal for power generation by the solar arrays. When the roll maneuver completes, a 180 minute Sun pointing timer is started. If HST is not grappled by the orbiter after 180 minutes, HST performs a low rate attitude maneuver to a power optimal attitude. However, this maneuver has not been required on the missions flown.

PROPULSION, ATTITUDE CONTROL, AND PLUME IMPINGEMENT CHALLENGES

The early operational concepts for HST defined in the 1970s included on-orbit servicing by astronauts. HST hardware and systems layout was designed to support servicing. However, the design of both the HST and the Space Shuttle was completed before the potential of HST contamination or structural damage, resulting from over-pressure by shuttle RCS jet plume impingement, was fully understood. As a result, proximity operations design for servicing missions has evolved as insight into plume effects on HST has improved. To minimize risk of plume contamination and over-pressure the shuttle Low Z flight control mode is used for HST and other proximity operations missions, such as Mir and ISS, rather than normal Z-axis firings (Figure 2). The Low Z mode provides some RCS braking capability while minimizing RCS plume impingement. The Low Z mode uses X body axis jets that have a small thrust component along the Z-axis, rather than Z-axis jets that direct plumes at the target spacecraft. The X-axis thrust components of the forward and aft-firing jets sum to near-zero, leaving a small Z-axis component that can be used for braking. Propellant consumption for braking is increased dramatically in the Low Z mode. The Z-axis thrust component of the X-axis jets was not an original Space Shuttle design requirement for proximity operations. The Low Z mode was developed in the 1977-1978 time period, after the shuttle design was finalized and hardware was already under construction. However, use of the Low Z mode increases propellant consumption on missions that are already propellant limited as the HST orbital altitude is much higher than the orbital altitude of other shuttle missions.

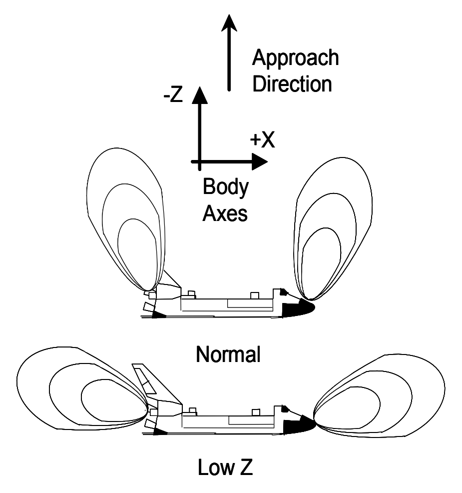

Figure 2 Normal and Low Z Primary RCS jet plumes.

HST does not have a propulsion system for orbit maintenance or attitude control. Consequently it is dependent on the shuttle for orbit raising maneuvers to counteract orbital decay due to atmospheric drag. While the HST is in the shuttle payload bay the shuttle performs a re-boost maneuver to increase the HST orbital altitude. Since years separate servicing missions, HST is placed and maintained at as high an altitude as can be reached by the shuttle. The orbital altitude coupled with the previously mentioned extensive use of the Low Z flight control mode reduces available propellant margins.

STS-31 – HST DEPLOY

After a four year delay due to the loss of the Space Shuttle *Challenger*, HST was deployed from the orbiter *Discovery* on April 25, 1990 (flight day two), during the STS-31 mission (Table 1).

STS-31 Deploy

After HST was unberthed from the payload bay with the RMS, solar array #2 did not unfurl. Concurrent with crew and ground troubleshooting, preparations began for an unscheduled EVA in the event that a manual unfurl was required. Two EVA crewmembers conducted the in-suit pre-breath activity (required to flush nitrogen from the bloodstream before being exposed to the reduced pressure environment of a spacewalk), and then entered the shuttle airlock. The airlock was then depressurized to 5 psi. However, another pre-planned contingency procedure successfully unfurled the array on the third attempt and the EVA was not required. Solar array #1 and the two HGAs were deployed without incident before HST was released from the RMS on revolution 20 (Figure 3).

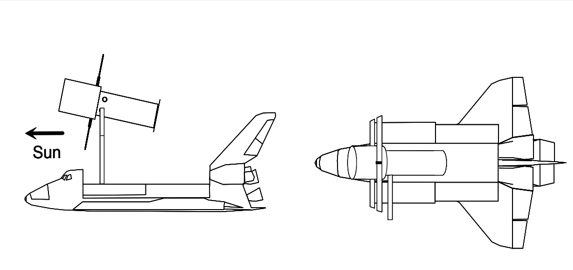

Figure 3 STS-31 HST Deployment

The shuttle rendezvous radar tracked HST from a range of 96 feet to 38,000 feet, when the Ku antenna was taken to the communications mode. Rendezvous radar data was incorporated into on-board navigation during the separation to improve crew and Mission Control knowledge of relative motion (Figure 4). Use of the rendezvous radar provided a more accurate relative state solution than could have been obtained with ground radar and Tracking and Data Relay Satellite System (TDRSS) tracking.

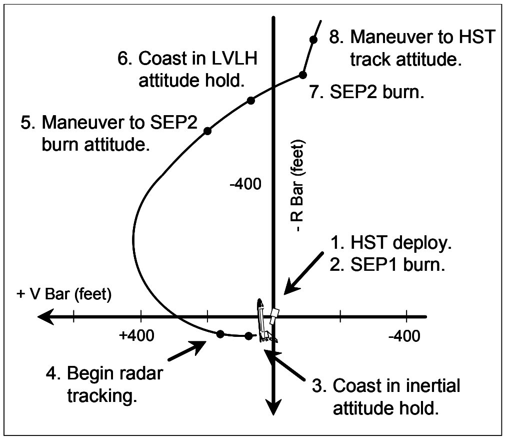

Figure 4 STS-31 HST Deploy Profile

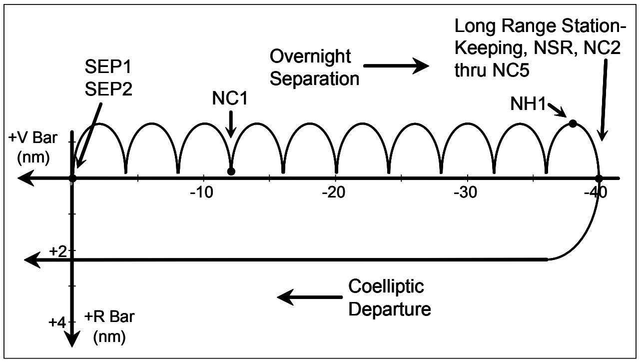

Figure 5 STS-31 separation, long range station-keeping, and coelliptic departure profile.

The Separation 1 (SEP1) maneuver was performed with the RCS in the Low Z mode to minimize HST contamination by RCS plumes. Separation maneuvers performed by *Discovery* were required to prevent recontact with HST and ensure that the safe separation continued during the crew sleep period following HST deployment (Figure 5). The HST inertial deployment was designed to ensure that HST sun sensors would lock onto the Sun after release from the RMS. The time required for HST to acquire and track the Sun to minimize battery discharge and recovery time was also considered.

Continuous communications with *Discovery* was required for pre-defined periods before and after deployment. Once HST was released and *Discovery* separated to a safe distance, HST mission responsibility was transferred to the HST Director of Orbit Verification at the Space Telescope Operations Control Center (STOCC) at the Goddard Space Flight Center. After HST deploy, *Discovery* separated overnight and conducted long-range station-keeping in the general vicinity of a position 40 nm behind HST on the –V Bar (Figure 5). The Shuttle Program was required to maintain a capability to rendezvous with HST for up to 45 hours or until the STOCC verified that the aperture door was open. Long range station-keeping was conducted until HST activation was complete and the aperture door successfully opened by the STOCC. At approximately 1 day and 19 hours after deployment *Discovery* was released from HST operations. A contingency rendezvous was not required. *Discovery* left the long-range station-keeping trajectory using an orbit coelliptic to HST to ensure safe separation (Figure 5).

STS-31 Contingency Rendezvous and Inertial Approach

While rendezvous was part of the nominal mission plan for future servicing missions, it was a contingency procedure for STS-31. The only driver, for a contingency rendezvous following deploy, was to open a failed closed HST aperture door (Figure 1). The contingency rendezvous timeline was written for a flight day 5 rendezvous and EVA by the crew to open the door, with an additional flight day added to the mission (Figure 6). However, HST would have been released even if it was known that an existing orbiter systems problem would prevent a contingency rendezvous from being performed. An orbiter systems problem could require the orbiter to return to Earth sooner than planned. In this case a Minimum Duration Flight (MDF) could be declared, with the orbiter returning to Earth as soon as 72 hours after launch. The MDF mission timeline could not have supported a contingency rendezvous and EVA to open the failed closed aperture door.

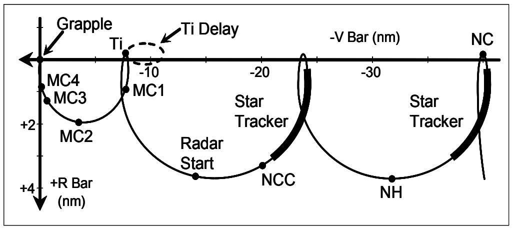

Figure 6 Stable orbit rendezvous profile for STS-31 (contingency) and STS-61 and STS-82 (both nominal).

The contingency rendezvous profile was the standard stable orbit profile (Figure 6) with an inertial approach (Figure 7).[10] If a rendezvous and grapple were required, mission responsibility would revert from the STOCC to the Mission Control flight director in Houston. At sunrise, on the grapple orbit, HST would be maneuvered so that the –V1 axis would be pointed into the velocity vector at orbital noon. At this time the –V1 axis would also be pointed at the payload bay of the approaching *Discovery* when it arrived on the +V Bar. At orbital noon HST would then roll about the V1 axis so that the –V3 RMS grapple fixture would be pointed in a specified direction out-of-plane and on the north side of the orbit (Figure 8). After the roll maneuver was complete *Discovery* would approach to within 200 feet and the RCS system would be placed in the Low Z mode (Figure 2). This HST maneuver sequence was designed to align the HST for capture with the RMS of *Discovery* and to reduce or eliminate the need for *Discovery* to perform additional maneuvers to prepare for capture.

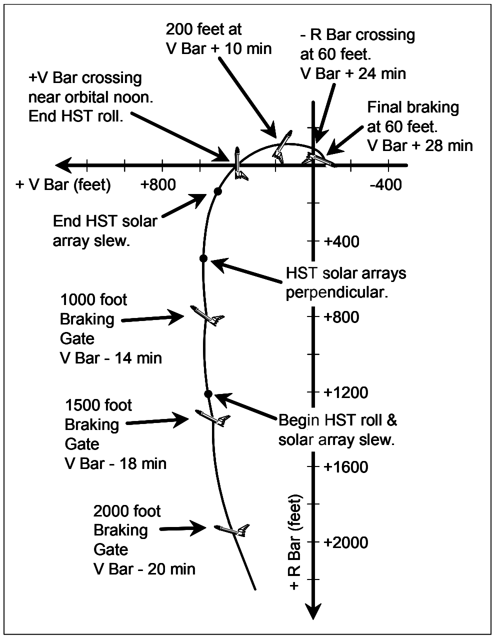

Figure 7 Inertial proximity operations approach for STS-31 (contingency) and STS-61 (nominal).

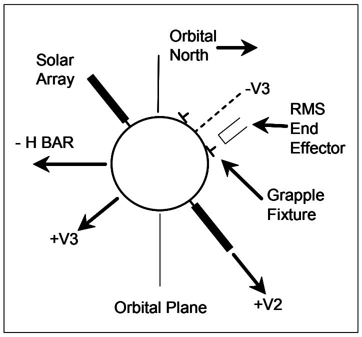

Figure 8 Nominal HST attitude as seen from the orbiter at grapple. Aperture door end of HST is pointed away from the orbiter.

STS-61 – SERVICING MISSION 1 (SM1)

On June 25, 1990, two months to the day after deployment from *Discovery*, a spherical aberration was discovered in Hubble's primary mirror, significantly reducing the quality of astronomical observations. A major objective of the first servicing mission was to install the Corrective Optics Space Telescope Axial Replacement, or COSTAR. Five corrective mirrors in COSTAR corrected the optical effects of the flawed mirror. Additional upgrades made by the EVA crew included the Wide Field Planetary Camera 2 (WFPC2) to replace WFPC1, new solar arrays and solar array drive electronics, new magnetometers, new coprocessors for the flight computer, two new Rate Sensor Units, two new Gyroscope Electronic Control Units, and a Goddard High Resolution Spectrometer redundancy kit. The new solar arrays reduced the vibration caused by array motion as HST moved from orbital night to day.

STS-61 Rendezvous and Proximity Operations

HST was successfully maneuvered to the rendezvous attitude and the aperture door closed on flight day 2. The nominal rendezvous was designed with HST grapple on flight day 3. The on-board targeted phase profile on the day of rendezvous was the standard stable orbit profile (Figure 6) that was also carried as a contingency for STS-31. The crew sighted HST near the start of the first star tracker pass (Figure 6). Two star tracker passes were performed before the first on-board targeted maneuver, Corrective Combination (NCC).[††] Radar data was incorporated after NCC. The Transition Initiation (Ti) maneuver targeted the orbiter for a HST intercept. Following Mid-course Correction 4 (MC4) the crew began the proximity operations phase and near-continuous manual trajectory control.

After the orbiter Ti maneuver, HST was configured by the STOCC to reduce the electrical power required, in order to accommodate the HST roll to grapple attitude during proximity operations. At the start of the terminal phase (post MC4), the HST +V3 axis pointed at the sun. The solar arrays were aligned with the V1 axis and the –V3 HGA was stowed to maximize clearance for the RMS grapple. However, HST could have been grappled and berthed with the HGA deployed, if required. Approximately 20 minutes before the orbiter reached the +V Bar, HST began a roll maneuver to place the RMS grapple fixture on the north side of the orbital plane (Figure 8).

At a range of 400 feet the crew transitioned the flight control system to the Low Z mode to avoid plume over-pressure on the HST solar arrays (Figures 2 and 7). Increased fidelity plume impingement analysis resulted in a procedural change to place the flight control system in the Low Z mode at a range of 400 feet, rather than 200 feet as had been called out in the STS-31 contingency rendezvous procedures. This change was made to avoid structural damage to the HST solar array bi-stems.

The HST roll maneuver was completed by the time the orbiter arrived on the +V Bar, at orbital noon, at a range of approximately 350 feet (Figure 7). At this time the HST –V1 axis (end of HST opposite the aperture door) was aligned with the +V Bar and pointing at the orbiter (Figure 8). The crew continued the inertial approach until reaching the station-keeping range of 35 feet. The grapple was successful, and was scheduled to occur 10 minutes after orbital sunset to minimize shuttle camera blooming and permit completion of photography of solar array deflection during sunset.

During the flight, considerable work was done on possible changes to the solar array jettison procedure to account for the possibility of having to jettison one jammed solar array while the other fragile array was also stuck in a deployed state (Table 2). One of the original solar arrays did not retract when commanded, and was subsequently jettisoned by an EVA crew member attached to the end of the RMS. The other array was returned to Earth**.** After jettison, rotational and translational motion imparted to the solar array by shuttle RCS jet plume impingement was clearly visible to the crew and Mission Control personnel. Some personnel commented that the flapping motion of the array appeared to be like a prehistoric pterodactyl. It was estimated that 3 feet/second of delta-velocity was imparted to the array by RCS jet firings based on radar ground tracking and on-board laser measurements. Solar array motion heightened concerns about plume impingement on HST. The new solar arrays were installed and unfurled successfully. However, the new arrays had a noticeable twist that contributed to increased plume impingement concerns on later missions. Additional work during the flight focused on changes to the tool chasing procedure, and a separation procedure that used the normal Z RCS jets (Figure 2).

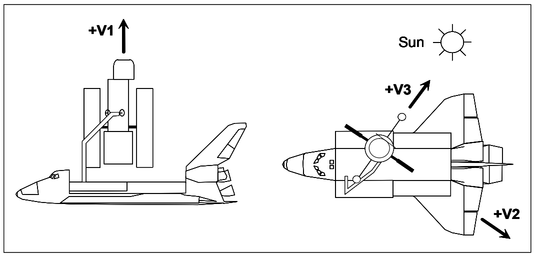

Figure 9 HST deployment for STS-61 and subsequent missions. Note open door.

STS-61 Deploy

Before HST deploy the shuttle performed a re-boost, circularizing the HST orbit at 321 nm. Starting with STS-61, the aperture door was opened before HST was deployed from the shuttle (Figure 9). If the door failed to open, the crew could perform an EVA with HST

[††] “N” originally (pre-1965) was the number of the crossing of the chaser line of apsides where the maneuver was performed (as in 1 for first apogee, 1.5 for first perigee, 5 for fifth apogee, etc.). The number is no longer assigned to the burn names NC (Catch-up or phasing), NH (Height), NPC (Plane Change), NSR (Slow Rate or coelliptic), and NCC (Corrective Combination).

berthed in the payload bay to manually open the door. Unlike STS-31, no contingency re-rendezvous for the crew to manually open the aperture door during an EVA was planned for STS-61 or subsequent servicing missions. However, this did not preclude one from being performed, if required. The HST deploy and separation sequence was designed to be flexible to preserve a re-rendezvous capability.

The nominal separation sequence provided safe post-deploy relative motion and minimized plume impingement, contamination, and propellant consumption (Figure 10). Nominal HST deploy was designed to occur at least 20 minutes before sunset. Ground communications with HST was required from before the opening of the deploy window to after deploy. Both HGAs were deployed before HST release from the RMS, with the solar arrays aligned with the V1 axis and the +V3 axis pointed at the sun. This deploy attitude was optimal for power generation. An alternate separation sequence was developed late in the mission planning process that required less propellant, but it had a shorter deploy window. HST was successfully re-deployed and the alternate separation sequence was flown.

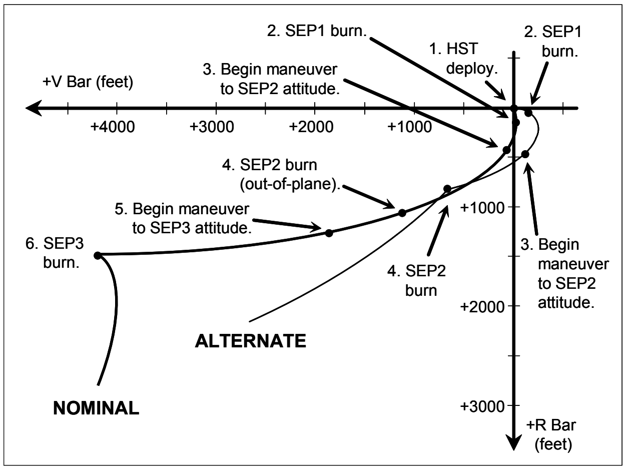

Figure 10 Nominal and Alternate STS-61 HST Deploy Profiles.

STS-82 – SERVICING MISSION 2 (SM2)

Two new science instruments were added to HST during the second servicing mission (Table 1). These were the Space Telescope Imaging Spectrograph and the Near Infrared Camera and Multi-Object Spectrometer. Hardware replacements included a refurbished Fine Guidance Sensor, a new Solid State Recorder, one new Reaction Wheel Assembly to replace one of the four original units, and the addition of an Optical Control Electronics Enhancement kit. Other maintenance items included replacement of one of the four Data Interface Units and replacement of one of the two Solar Array Drive Electronics units.

STS-82 Rendezvous and Proximity Operations

At the end of powered ascent, a 6.1 ft/sec Main Engine Cut-Off (MECO) under-speed occurred. This resulted in the re-planning by Mission Control of two burns on the day of rendezvous, before on-board sensor tracking started (Figure 6). Similar MECO under-speeds were seen on other HST servicing missions as well. While the under-speeds were within the design margins of the shuttle, mission planning for the later STS-125 and *Atlantis* rescue mission was performed to minimize MECO under-speed and subsequent rendezvous burn impacts.

The rendezvous profile flown by STS-82 was the same stable orbit profile flown by STS-61 (Figure 6). During the first star tracker pass, the star tracker lost lock on a dim HST and began tracking what was later determined to be the star Saiph. The relative navigation filter in the shuttle computer rejected two star tracker measurements and then momentarily re-established lock on a slightly brighter HST. Lock on HST was lost again and the star tracker acquired what was apparently nearby orbital debris. The navigation state was corrupted by three navigation updates during the debris tracking period. A crew command to inhibit navigation processing was not accepted by the shuttle computer due to a known timing issue. The star tracker re-acquired HST and subsequent measurements corrected the error introduced by the spurious measurements. The crew replaced the state vector that had received spurious updates with a backup vector. The star tracker pass continued without incident. Post flight analysis indicated that the HST solar arrays were parallel to the star tracker's line-of-sight and pointed to the Sun. The end of the HST (the V1 axis,

Figure 1) was pointed to the orbiter. This combination of HST attitude with the sun 90 degrees from the star tracker line-of-sight resulted in a dim target, causing the star tracker to lose lock on HST.

After the first star tracker pass, an additional unplanned out-of-plane correction maneuver was performed based on ground radar tracking data and the results of the first star tracker pass (Figure 6). Out-of-plane corrections during the rest of the rendezvous were minor. The remaining rendezvous and grapple activities were nominal.

While the rendezvous profiles for STS-61 and STS-82 were the same, STS-82 flew a different final approach during proximity operations. Just after MC4 the crew transitioned from the inertial approach to a lower energy +R Bar approach (Figure 11). The +R Bar approach (Figure 12) was developed for the shuttle missions to Mir and the ISS in 1994. It was first flown on STS-66 (November 1994) during the rendezvous with and retrieval of the CRISTA-SPAS deployed payload.[10]

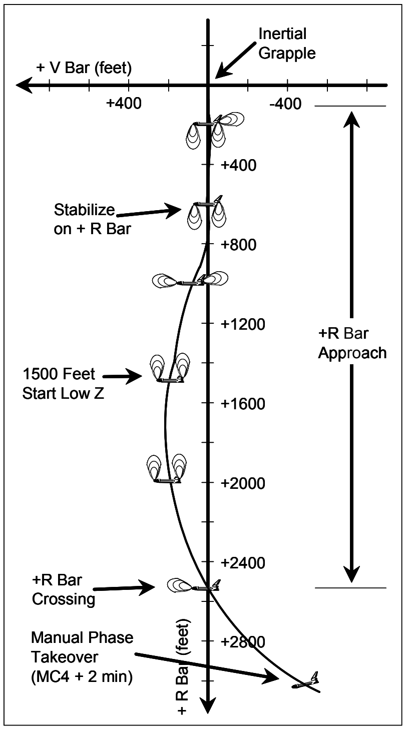

Figure 11 STS-82 +R Bar approach from stable orbit profile.

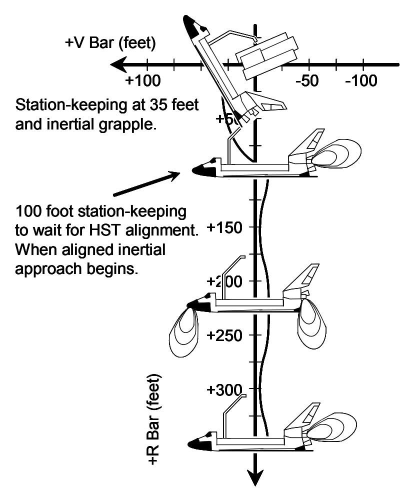

Figure 12 Final +R Bar approach and inertial grapple.

The primary advantage of the new approach was natural orbital mechanics braking. This reduced the risk of plume impingement as fewer RCS jet firings were required. The natural orbital mechanics braking allowed the HST Low Z range constraint to be increased to 1500 ft to provide additional plume protection as the HST slowly rotated above the approaching shuttle. A +R Bar approach also provided a hands-off separation, that required no RCS jet firings due to orbital mechanics. Once the range to HST was less than 150 feet, the crew would station-keep on the +R Bar and wait for the HST –V1 axis to align with the orbiter –Z axis (Figures 12 and 13). Once the axes were aligned, the crew would establish an inertial attitude hold and perform an inertial approach to the 35 foot station-keeping range for RMS grapple of HST.

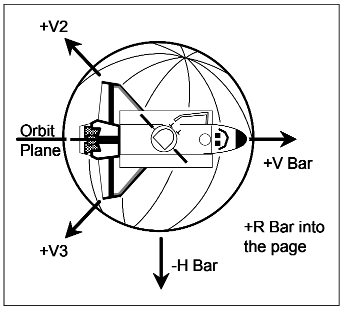

Figure 13 Bird's eye view of HST in nominal grapple attitude for the +R Bar approach.

STS-82 Contingency Inertial Approach

If the aperture door failed to close before rendezvous, the unprotected HST optics could be pointed at an orbiter performing a +R Bar approach (Figure 12). This would result in unacceptable contamination of the HST optical system. To protect for the aperture door failed open case an inertial proximity operations approach, like that flown on STS-61, would have been performed (Figure 7). During an inertial approach the open aperture door would be pointed away from the approaching orbiter during proximity operations. The inertial approach, however, meant increased propellant consumption. For STS-82, the inertial approach procedures were not part of the rendezvous procedures book flown on the orbiter, but they would have been uplinked to the crew, if required.

STS-82 Nominal Deploy

STS-82 included a new deploy requirement as ultraviolet light reflected off of the Earth might enter the telescope when the aperture door was open. The ultraviolet light could cause any contamination that might accumulate on the mirror during the servicing mission to permanently adhere to the mirror. The STS-82 deploy procedure had the same RMS position as on STS-61, but a new orbiter attitude. The new requirement was to point the HST +V1 axis away from the bright Earth limb. HST was to be released in daylight before sunset to allow adequate HST sun sensor acquisition time. The release attitude pointed the +V3 axis at the sun. Both HGAs were deployed. The overall deploy procedures minimized plume impingement, contamination, and propellant use. Deploy design also ensured shuttle crew and ground communication with HST before and after release.

Two deploy and separation profiles were prepared for the mission (Figures 14 and 15). The appropriate profile was chosen based on the side of the orbital plane where the Sun was located. The initial HST separation burn was changed based on experience from procedures developed for deployments of spacecraft equipped with a solid rocket motor, such as the Inertial Upper Stage. The first separation burn was performed with two forward firing –X RCS jets while the flight control system was in free drift. As this burn moved the orbiter away from the HST, the +Z thrust component of the forward jets caused the orbiter to pitch nose-down until commanded to stop a short while later. This rotation provided adequate clearance to the cabin while keeping HST visible to the crew over the payload bay. The –X jet separation also used less propellant and had a lower risk of plume impingement than a Low Z separation.

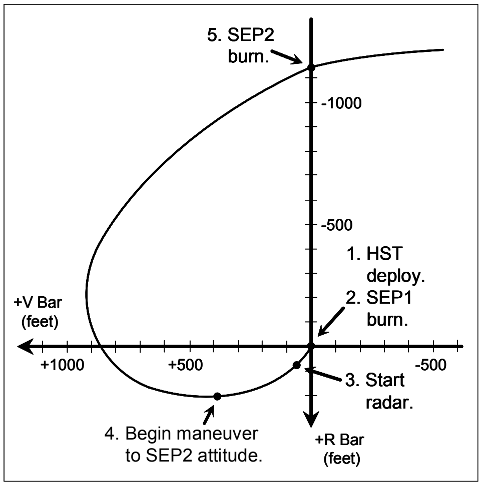

Figure 14 Nominal HST deploy profile for Sun north of the orbital plane, missions 82, 103, 109, and 125.

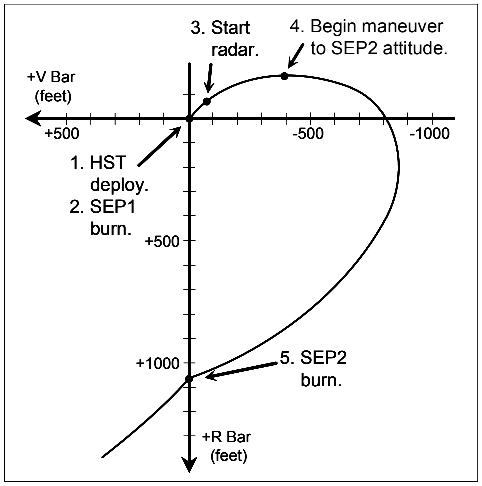

Figure 15 Nominal HST deploy profile for Sun south of the orbital plane, missions 82, 103, 109, and 125.

HST re-deploy was nominal. However, the second burn in the two burn separation sequence was under-burned (Figure 14). While the post-burn relative motion placed *Discovery* on a safe departure trajectory, the separation rate was less than desired. In addition, cross-coupling, of RCS attitude control firings into translational motion, threatened to further decrease the separation rate of *Discovery*. A third separation burn was computed by Mission Control. Burn data was voiced to the crew and the burn was executed. Post-flight analysis indicated that the under-burn was due to the high rate of Translational Hand Controller (THC) deflection. A restriction on the THC deflection rate was known at one time, but the constraint had not been included in the crew procedure. The procedure was later modified for later flights to replace large numbers of pulses with a single continuous THC deflection, and crew training was improved to increase awareness of the deflection rate limit.

STS-103 – SERVICING MISSION 3A (SM3A)

The third servicing mission (SM3) was originally planned for June of 2000. However, in February of 1999 a third gyroscope failure occurred. While HST was capable of supporting science activities with no fewer than three gyroscopes, NASA decided to re-schedule the third repair mission to fly before the end of 1999 and replace the failed gyroscopes. Some hardware originally scheduled for the original SM3 mission in 2000 was not ready to support a flight in 1999. As a result, SM3 was split into two missions, SM3A (STS-103) and SM3B (STS-109). Replacement hardware, not available to support the 1999 SM3A mission, was redirected to the newly defined SM3B (STS-109) mission that was later flown in March of 2002.

SM3A servicing objectives included replacement of all six gyroscopes, a new computer, replacement of one of three Fine Guidance Sensors, an aft shroud latches repair, installation of handrail covers, a new outer blanket layer, a new S-Band Single Access Transmitter, shell/shield replacement fabric, and voltage/temperature improvement kits for the batteries. SM3A did not install any new scientific instruments. The failure of a fourth gyroscope on November 19, 1999, a month before the SM3A launch, resulted in HST entering a safe mode. Astronomical observations could not be performed while in safe mode. Significant crew training resources were expended to develop and refine manual piloting techniques to approach and grapple HST in the HWSP and ZGSP safe mode configurations. SM3A mission planning ensured that the deorbit and landing would occur in 1999 to avoid any potential year 2000 rollover computer issues.

STS-103 Rendezvous and Proximity Operations

The previous mission, STS-82, flew a stable orbit profile with a +R Bar final approach (Figures 6 and 11). However, the stable orbit profile baselined for the shuttle in April of 1983 was originally designed to support inertial approaches with lower energy than inertial approaches from the Apollo legacy coelliptic profile.[10] While the stable orbit/+R Bar combination was successfully flown on a number of missions, starting with STS-66 in November of 1994, stable orbit was not a propellant optimal profile to support a +R Bar approach. A new version of stable orbit rendezvous, Optimized R Bar Targeted (ORBT) rendezvous, was specifically designed to support the +R Bar technique (Figures 16 and 17). ORBT required fewer jet firings for +R Bar trajectory stabilization and braking than stable orbit. ORBT was first flown on the STS-86 mission to Mir in September-October 1997. STS-103 was the first HST servicing mission to fly the ORBT/+R Bar combination. The change from the stable orbit to the ORBT profile resulted in some differences in STS-82 and STS-103 +R Bar approach procedures.

On the day of rendezvous, during the first star tracker pass, the Moon approached the star tracker line-of-sight to the HST. Anticipating that the bright Moon would cause an automatic closure of the star tracker shutter, flight controllers prepared for the event by providing the crew with times to inhibit star tracker measurements as the Moon passed through the star tracker field of view. However, the star tracker Bright Object Sensor did not close the shutter in response to the Moon until the Moon was well inside the field of view. In response the crew inhibited star tracker measurements for approximately seven and a half minutes during the first pass and for approximately eight minutes during the second pass (Figure 16). Sufficient navigation data was collected during the two passes. Some noise in the radar angle measurements was noted after the MC4 burn. This was normal and the noise seen on HST missions is much less than that observed on ISS missions.

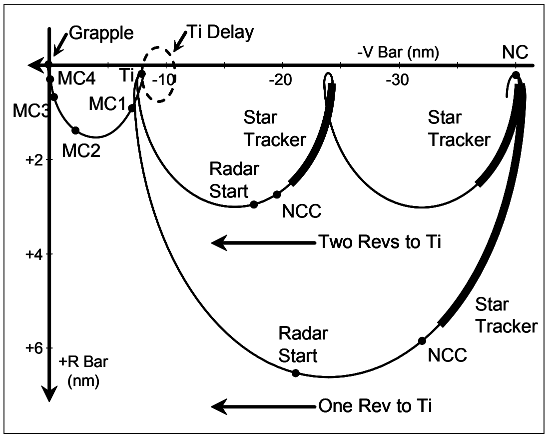

Figure 16 Two revs (STS-103) and one rev (STS-109 & -125) to Ti Optimized R Bar Targeted (ORBT) rendezvous profiles.

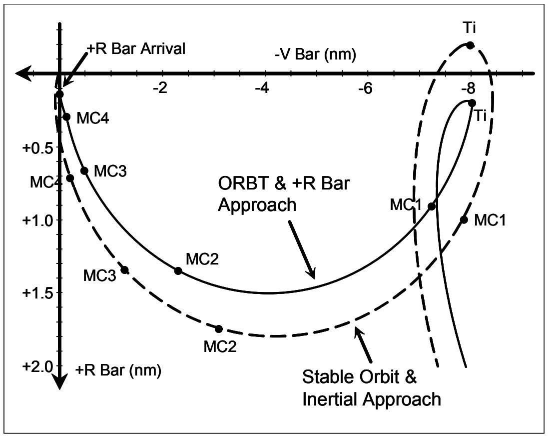

Figure 17 Comparison of ORBT and contingency stable orbit rendezvous profiles for STS-103, STS-109, and STS-125.

Due to the fourth gyro failure on November 19, 1999, the HST Program chose to maintain attitude using the Hardware Sunpoint mode and back-up gyros (RMGA). Fortunately, HST entered the Hardware Sunpoint mode with the V1 axis very close to the orbital plane. The crew was able to confirm the Hardware Sunpoint attitude using binoculars about an hour before the grapple. After a nominal +R bar approach the crew executed a 90 degree yaw maneuver on the +R Bar to achieve the grapple attitude. HST was grappled with *Discovery* on the +V1 aperture door end of HST (Figure 1). Propellant consumption during proximity operations was higher than expected. Possible causes included noisy radar range rate measurements, and RCS jet cross coupling during the yaw maneuver. Low Z braking starting at 1500 feet also increased propellant consumption. Had the V1 axis not been close to the orbital plane, the grapple alignment maneuver would have been more complicated than a simple yaw and cost even more propellant. In addition, the Sun was close to the orbital plane and above HST, complicating observation of HST and washing out displays in the shuttle cockpit.

STS-103 Contingency Stable Orbit and Inertial Approach

Starting with STS-103, the nominal rendezvous profile was ORBT, supporting a +R Bar approach (Figures 12, 16, and 17). However, should the aperture door fail to close before rendezvous, a +R Bar approach could expose the HST optics to RCS jet plume contamination. Like STS-82, in the event that the HST aperture door failed to close before rendezvous, the orbiter would perform an inertial approach. However, this inertial approach would be flown from a legacy stable orbit profile (Figures 6, 17, and 18), instead of the nominal ORBT profile (Figures 16, 17, and 18).

With the proper timing, the failed open HST aperture door could be pointed away from the approaching orbiter throughout an inertial approach, to minimize risk of optics contamination. Execution of a contingency stable orbit would have required re-planning of the last ground targeted maneuver by

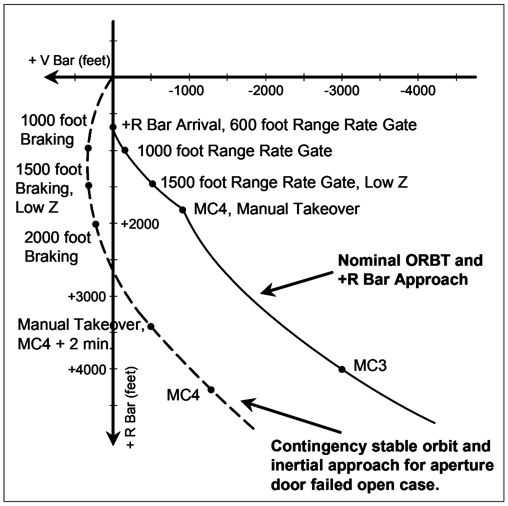

Figure 18 Comparison of nominal and contingency approaches to HST for STS-103, STS-109, and STS-125.

Mission Control (NC in Figures 6 and 16). HST attitude would be managed so that the –V1 axis would be pointed at the orbiter at the MC4 + 2 minute point, where the crew took manual control and placed the orbiter in an inertial attitude hold (Figure 18). At +V Bar arrival the –V1 axis would be pointed at the orbiter payload bay. This combination of HST attitude and inertial approach ensured that the failed open aperture door would always be pointed away from the approaching orbiter during proximity operations, minimizing the risk of plume contamination of HST optics. However, as the aperture door had closed at the time of the fourth gyro failure on November 19, there was no need to protect for this contingency.

STS-103 Deploy

STS-103 mission planning included the same nominal deploy sequence options as STS-82 (Figures 14 and 15). Re-deployment of HST and separation by *Discovery* were nominal (Figure 15).

STS-109 – SERVICING MISSION 3B (SM3B)

Servicing mission SM3B (March 2002) placed new hardware on HST that was not ready in time to support the SM3A mission flown in December of 1999 (Table 1). Maintenance activities included an Advanced Camera for Surveys to replace the Faint Object Camera, replacement of a power control unit, one of four reaction wheel assemblies, and a new cooling system for the Near Infrared Camera and Multi-Object Spectrometer. With the replacement of the Faint Object Camera, none of the optical sensors required the corrective optics installed in HST with COSTAR on STS-61 in December of 1993. In addition, new solar arrays were installed that had more rigidity, produced more power, and were smaller than the arrays installed during STS-61.

STS-109 Rendezvous and Proximity Operations

The rate of orbital decay of HST resulted in a rendezvous altitude that was lower than the orbital insertion altitude. To compensate, the normally posigrade catch-up maneuver (NC in Figure 16) before the first star tracker pass on the day of rendezvous was retrograde.

The ORBT rendezvous profile for STS-109 was modified from two revolutions to Ti to one revolution to Ti (Figure 16), taking advantage of experience gained in numerous shortened rendezvous profiles flown on missions to the Mir space station and ISS. This eliminated one star tracker pass that had mainly served as a backup relative navigation opportunity, but provided extra time in the crew day in the timeline after HST grapple. Other aspects of the STS-109 ORBT profile were the same as STS-103. STS-109 also carried the same +R Bar approach procedure as STS-103 (Figures 12, 13, 16, and 17).

The +R Bar approach proceeded more slowly than in ground simulations. This was consistent with previous missions and likely due to noisy range rate measurements and the difficulty of viewing HST against the Sun. Welding goggles were used by the crew to view HST, but the goggles made it difficult to observe displays in the cockpit. Proximity operations propellant consumption was higher than predicted, but within acceptable margins. HST was successfully grappled.

STS-109 Contingency Stable Orbit and Inertial Approach

STS-109 carried the same contingency stable orbit and inertial approach procedures as STS-103 (Figures 17 and 18). Unlike the stable orbit profile in Figure 6, the STS-109 stable orbit profile would have been one revolution between NC and Ti. However, these procedures were not performed as the HST aperture door was successfully closed before rendezvous.

STS-109 Deploy

STS-109 mission planning included the same nominal deploy procedures as STS-82 and STS-103 (Figures 14 and 15). HST was successfully deployed (Figure 14).

STS-125 – SERVICING MISSION 4 (SM4)

The primary objective of SM4, scheduled to be flown in 2009, is the installation of two new scientific instruments, the Wide Field Camera 3 (WFC3) and the Cosmic Origins Spectrograph (COS). The COSTAR, installed during STS-61 to correct the spherical aberration of the primary mirror, will be removed to make room for the COS and returned to Earth. New scientific instruments installed since STS-61 in 1993 have corrective optics installed and COSTAR is no longer needed. WFC2 will be removed from HST as well. The Advanced Camera for Surveys partially failed in 2007 due to an electrical short and it will be repaired. The Space Telescope Imaging Spectrograph suffered a power failure in 2004 and will also be repaired. In addition, all six gyroscopes and batteries will be replaced. One of three Fine Guidance Sensors will be replaced and new Outer Blanket Layer insulation will be installed. The crew will also replace the Science Instrument Control & Data Handling (SIC&DH) unit. Side A of the HST Control Unit/Science Data Formatter within the SIC&DH failed on September 27, 2008. Side B supported astronomy activities after the failure.

SM4 will also mount a Low Impact Docking System (LIDS) passive interface on the Hubble aft bulkhead. LIDS was developed as the docking hardware for the Constellation Program. LIDS will enable future human or robotic vehicles to dock with HST for servicing or HST deorbit. The Hubble soft capture mechanism, including the LIDS passive interface, will be attached to the HST berthing pins that are used to berth Hubble to the Flight Support System (FSS) in the shuttle payload bay. Four retro-reflectors will also be mounted on the assembly to support relative navigation sensors of future human or robotic vehicles.[11] The retro-reflectors are designed to work with the lidar sensors that were commercially available at the time of the Hubble Robotic Servicing and Deorbit Mission design effort.[5] Painted patterns on the target assembly are designed to work with future optical recognition algorithms.

STS-125 Propellant, Deorbit, and Landing Challenges

The high HST orbital altitude increases the risk of a collision with orbital debris as the lower atmospheric density does not cause the debris to decay as rapidly as debris at lower orbital altitudes. Increased concern about orbital debris at the HST orbital altitude led the Shuttle Program to reduce the amount of time the orbiter is at that altitude between HST deployment and the deorbit burn. In addition, it is necessary that any maneuvers performed by the orbiter after HST deploy contribute to deorbit. Placing the orbiter in an elliptical orbit before the deorbit burn limits the landing opportunities since deorbit burns near perigee are far more costly in propellant. This is true even for landing sites that are within the orbiter's entry cross-range capability. The post deorbit burn perigee has to be placed at an appropriate latitude for a landing at the Kennedy Space Center or Edwards Air Force Base.

STS-125 Nominal and Contingency Procedures for Rendezvous, Proximity Operations, and Deploy

STS-125 will carry the same ORBT rendezvous profile and +R Bar approach procedures as STS-109 (Figures 12, 13, 16, and 17). In the event that the HST aperture door fails to close before final approach, STS-125 will perform the same contingency stable orbit and inertial approach that was prepared for STS-103 and STS-109. The nominal STS-125 deploy sequence is the same as that flown on STS-82, STS-103, and STS-109 (Figures 14 and 15).

OTHER CONTINGENCY RENDEZVOUS PROCEDURES

There are three contingency rendezvous procedures that have been flown on all HST missions (Table 2). These are Ti Delay, Radar Fail, and Rendezvous Breakout.

Ti Delay permits the orbiter to fly a relative motion football (Figures 6 and 16) at the 8 nm Ti point. This delay could provide the crew, Mission Control, and the HST STOCC at the Goddard Space Flight Center with time to resolve a problem before proceeding with the rendezvous. Alternatively, if the problem could not be resolved in time to permit the rendezvous and grapple on that crew day, the orbiter could separate and phase away from the HST overnight. Ti Delay has not been performed on a HST mission. The only Ti Delay flown by the shuttle was on STS-49 (May 1992), in response to a Lambert maneuver targeting anomaly.[10,12]

The Radar Fail procedure would be used by the crew after the Mid-course Correction (MC2) maneuver, if radar data were not available for relative navigation and proximity operations (Figures 6, 16, and 17). A radar failure has not occurred on HST missions. However, the rendezvous radar did fail before the STS-92 rendezvous with the ISS in October of 2000. The Radar Fail contingency procedure was successfully executed on that mission.[10]

If a shuttle or HST problem prevented the rendezvous and grapple from being completed, the Rendezvous Breakout procedure would enable the orbiter to establish a safe relative motion trajectory that would not come close to the HST. A breakout during the rendezvous phase (Figures 6 and 16) has not been performed on a HST servicing mission, or on any other shuttle mission.

OTHER CONTINGENCY PROXIMITY OPERATIONS PROCEDURES

Like nominal proximity operations procedures, the contingency procedures are heavily influenced by HST and shuttle hardware design. Contingency proximity operations procedures have evolved, but the number of procedures stabilized by the third servicing mission, STS-103 (Table 2).

Some contingency procedures are designed to enable the orbiter to safely leave the vicinity of the HST if a problem prevents grapple. The orbiter may station-keep in the vicinity of the HST while Mission Control, the STOCC, and the crew work to resolve the problem. If the problem cannot be resolved in a timely manner, a breakout is performed so the orbiter safely leaves the vicinity of the HST. Prox Ops Backoff allows the orbiter to back away from HST to a safe station-keeping distance. The HST +R Bar Breakout (Table 2) was designed for execution starting at a range of 500 feet until the crew initiates the final inertial grapple (Figure 12). A backout along the +R Bar may be required to at least 75 feet before the orbiter can leave the +R Bar via a breakout to avoid undesirable contact with HST. Prox Ops Breakout permits the orbiter to safely leave the vicinity of the HST and exit the proximity operations phase.

The EVA Rescue procedure is used to retrieve an EVA crew member that is no longer tethered to the orbiter or EVA tools that are no longer tethered to the crew member. It is desirable for any EVA tools that are lost overboard to be retrieved as they present a collision hazard. The procedures ensure that structural loads imparted by translational RCS jet activity will not cause failure of the connection between the HST and the FSS in the shuttle payload bay.

Some contingency procedures permit grapple to be accomplished or a breakout to be performed in the event of vernier or Low Z RCS jet failures. The Loss of Vernier RCS procedure permits proximity operations to continue if the orbiter 25 pound thrust vernier RCS jets are no longer available for fine attitude control. The Loss of Low Z Braking procedure provides options to use for any loss of or degradation of Low Z capability during the approach. The approach could be continued or a Loss of Low Z breakout performed. The HST Flyaround/Loss of Low Z Breakout is performed between initiation of inertial attitude hold by the crew and grapple. By the time of STS-103, the number of breakout scenarios had increased and a new flow chart was implemented on a cue card to help the crew navigate through the many options.

Other contingency proximity operations procedures listed in Table 2 are performed if HST is not in the correct attitude for grapple when the shuttle arrives. These include the STS Roll to Align, Manual Inertial Fly-Around, Auto Inertial Fly-Around, Yaw/Pitch/Yaw Fly-Around, and the R Bar Yaw Alignment.

CONTINGENCY DEPLOY

Contingency deploy procedures have also been carried on all HST missions (Table 2). These procedures permit HST deployment if the RMS is not available or if a faster than normal deployment must be accomplished in response to a systems performance anomaly. These anomalies could require the orbiter to perform an emergency deorbit or a perigee adjust.

Contingency procedures were developed to cover partial or complete failures of the RMS (Table 2). For a total RMS failure a backaway deployment would have been performed. This procedure has been prepared for all HST missions. The procedure for the STS-31 deploy mission involved releasing HST retaining latches in the payload bay and performing a +Z translation burn (Figure 2) by the orbiter to slowly back away from the HST. The procedure for all subsequent flights was designed to allow the HST berthing pins to clear the FSS latches, while avoiding attitude jet firings that could cause the pins to re-contact. The deploy attitude avoids shadowing of the HST solar arrays by orbiter structure.

All HST missions have been equipped with an Emergency RMS Deploy (STS-31) or a RMS Quick Deploy (STS-61, STS-82, STS-103, STS-109, and STS-125) procedure. The RMS Quick Deploy could be performed if a faster than normal release of HST is required in response to an orbiter systems problem. The quick deploy has essentially the same sequence as the nominal deploy, but certain non-mandatory HST crew commanding and orbiter relative navigation procedures are omitted to save time.

JETTISON

Jettison procedures are carried to permit the release of payload bay hardware from the orbiter if it cannot be secured in the payload bay or it is stuck in an unsafe configuration (Table 2). Jettison procedures are designed to permit the orbiter to safely leave the jettisoned hardware while minimizing risk of re-contact. Some jettison procedures can be executed by the crew from the cockpit, while other procedures may require crew action during EVA. Jettison procedures are not considered nominal, are often payload and payload support hardware specific, and will vary from flight to flight. Jettison procedures for servicing hardware include the Orbiter Replacement Unit Carrier (ORUC), Rigid Array Carrier (RAC), Solar Array Carrier (SAC), and the Super Lightweight Interchangeable Carrier (SLIC). These procedures require that HST be jettisoned first. The ORUC, SAC, and SLIC jettison procedures require action by EVA crew members.

A HST Jettison would be performed if the orbiter were required to perform a time critical de-orbit in response to problems such as loss of crew cabin pressure or a propellant leak. The jettison procedure can be performed in any attitude. Low Z RCS jet firings are used to back the orbiter away from HST after the FSS latches are opened.

The orbiter payload bay doors must be closed for the orbiter to safely return to Earth. If the RMS or the rendezvous radar cannot be stowed for entry, then they would be jettisoned to enable the payload bay doors to be closed. A generic hardware jettison procedure is available on all flights if the crew has to jettison generic hardware, including EVA hardware.

A solar array jettison procedure was developed for STS-61 and STS-109 in case an array could not be fully retracted and stowed for return to Earth. The power generation side of the array must face away from the Sun when the array electrical lines between HST and the array are disconnected by the EVA crew. The array would be released by an EVA crew member mounted on the RMS with a foot restraint, using either a jettison handle or a portable grapple fixture. One solar array was jettisoned on STS-61. This is the only jettison that has been performed on a HST servicing mission.

ATLANTIS RESCUE

Since the loss of *Columbia* in 2003, each shuttle mission has performed inspection of the Thermal Protection System (TPS) to determine if the TPS sustained damage during ascent from External Tank foam shedding. The primary means of inspection is the Orbiter Boom Sensor System (OBSS) that is mounted on the end of the RMS. On ISS missions, a R Bar Pitch Maneuver (RPM) is performed ~600 foot below the ISS to permit ISS crew to photograph the orbiter TPS.[13] Photographs provide an additional source of data on TPS integrity. If TPS damage is detected and is considered to be a safety risk and cannot be repaired on-orbit during an EVA, plans were developed to permit a Space Shuttle crew to use the ISS as a safe haven. The next Space Shuttle in the launch preparation flow for an ISS mission would be launched to retrieve the crew from the ISS and return them to Earth.

Like ISS missions, the STS-125 crew will perform a TPS inspection using the OBSS. However, the STS-125 *Atlantis* crew could not use the ISS as a safe haven in the event the *Atlantis* TPS was compromised, as the shuttle does not have sufficient propellant to reach the ISS from the HST orbit. To provide a rescue capability, a Launch On Need (LON) *Atlantis* rescue mission was prepared (Table 1). A rescue shuttle flown by the four flight deck crew members from the STS-123 (March 2008) mission to the ISS would fly the rescue mission, if it were required. The rescue concept requires the pre-launch parallel processing of both *Atlantis* and the rescue orbiter at the Kennedy Space Center. The rescue Space Shuttle would be on one of the Complex 39 launch pads while *Atlantis* would be launched from the other pad. This would be a first for the Shuttle Program. Although maximum crew awake time is limited to 18 hours to avoid fatigue, this limit could be waved in a rescue scenario to ensure the safe retrieval and return of the *Atlantis* crew.

Atlantis Rescue Rendezvous Design

The nominal rendezvous mission plan for the rescue was a flight day 2 grapple of *Atlantis* by the rescue orbiter, with the possibility of a flight day 3 or 4 grapple, if permitted by ample propellant margins. A flight day 2 grapple is preferred so that the rescue orbiter could reach *Atlantis* as quickly as possible and provide maximum on-orbit time for the crew transfer to be completed. This is the first nominally planned flight day 2 rendezvous and grapple in the Shuttle Program and would be the first rendezvous of one shuttle with another. Ground-up shuttle rendezvous missions to the ISS normally conduct docking/grapple on flight day 3, with a flight day 2 or flight day 4 docking/grapple as a possible contingency. Rendezvous trajectory dispersions are expected to be higher than normal due to the limited amount of time to track out dispersions on flight day 1 in support of rendezvous orbital adjustment burns. The crew rendezvous checklists for both the STS-125 and the rescue mission have been combined into one document.

The ORBT rendezvous on flight day 2 (the star tracker pass through the MC4 burn) is similar to that of ISS and HST servicing missions (Figure 17 and the one revolution to Ti profile in Figure 16). For all shuttle rendezvous missions, in the event of a rendezvous radar failure, a correction burn is performed after the third mid-course correction burn. If *Atlantis* has sufficient propellant and power, contingency night star tracker measurements could be obtained by the rescue orbiter if the payload bay lights of *Atlantis* were turned on and the payload bay pointed in the direction of the approaching rescue orbiter. However, if *Atlantis* is not able to perform the procedure, the rendezvous profile timing was adjusted pre-mission to insure *Atlantis* would be lit by the sun to support crew procedures for the radar fail correction burn.

Atlantis Rescue Contingency Rendezvous Procedures

In the nominal rendezvous plan the rescue orbiter performs all maneuvering. Contingency rendezvous recovery plans were also developed in case the rescue orbiter could not execute the nominal rendezvous profile due to an ascent under-speed at MECO or a propellant failure. The rendezvous recovery profile would preserve the flight day 2 grapple, if possible. While it is preferred to fly a rendezvous with the rescue orbiter approaching from behind and below, off-nominal cases could require a rendezvous with the rescue orbiter ahead and above *Atlantis* for much of the rendezvous. In these contingency cases *Atlantis* might also be required to perform orbit adjustments of relative altitude and phasing to enable the rescue orbiter to complete the rendezvous. Propellant margins on both vehicles would be carefully managed to ensure that the rescue orbiter had sufficient propellant for a safe deorbit.

This technique is known as control box rendezvous, and was performed on STS-49 (INTELSAT VI/F-3 rendezvous, May 1992) and STS-72 (Space Flyer Unit rendezvous, January 1996).[10] The target spacecraft executes a series of maneuvers after the chaser spacecraft is launched. The maneuvers are designed so that the target enters a volume in space, called a control box, at a designated time. This technique reduces chaser vehicle (in this case, the rescue orbiter) propellant consumption. Once the target enters the box, it no longer maneuvers. Rendezvous recovery would be planned so that *Atlantis* would not perform orbit adjustments on the day of rendezvous.

The final rendezvous orbit for the rendezvous recovery case impacts landing opportunities for the rescue orbiter. The final orbit must preserve at least one continental United States landing opportunity for the rescue shuttle per day, with two opportunities preferred. If required, a landing could also have been performed at sites outside the continental United States. In addition, achievement of acceptable disposal areas for *Atlantis* would also be factored into rendezvous recovery planning and determination of the final rendezvous orbit. However, protecting the rescue orbiter deorbit propellant margins has a higher priority than *Atlantis* propellant margins for achieving a safe *Atlantis* disposal footprint.

For the on-board targeted phase on the day of rendezvous, the rescue orbiter will fly three contingency rendezvous procedures flown by other HST servicing and ISS missions. These are Radar Fail, Rendezvous Breakout, and Ti Delay (Table 2).

Atlantis Rescue Nominal Proximity Operations

Atlantis will maneuver to the grapple attitude just before the rescue orbiter executes the MC4 burn (Figure 17). The grapple attitude places the nose of *Atlantis* out-of-plane toward orbital south and the payload bay pointed at the Earth (Figure 19). The flight control system would maintain this attitude using the 25 pound thrust vernier RCS jets.

The proximity operations profile (starting at manual crew take-over after MC4) is a +R Bar approach. However, unlike ISS missions, the R Bar Pitch Maneuver would not be performed.[13] The rescue orbiter flight control system would be placed in the Low Z mode from a range of 1000 feet through grapple. This range was chosen as the crews from ISS missions are familiar with Low Z operation starting at this range. *Atlantis* and the rescue orbiter would be at 90 degree angle to each other (*Atlantis* nose toward orbital south, the rescue orbiter nose pointed along the velocity vector) to minimize plume impingement effects during the Low Z +R Bar approach by the rescue orbiter (Figure 19). The rescue orbiter would carry both Trajectory Control Sensor (TCS) and Hand Held Lidar (HHL) for use during proximity operations.

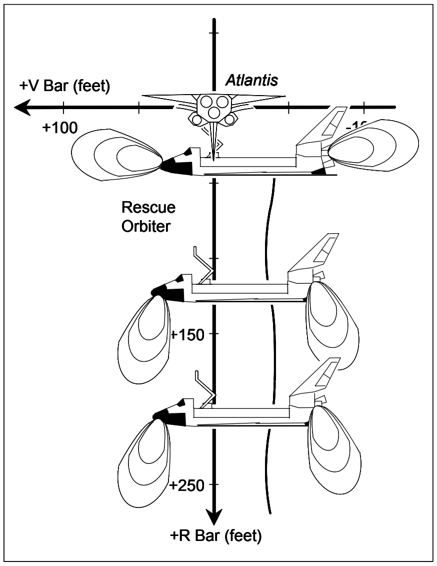

Figure 19 Rescue orbiter approach to *Atlantis*.

Capture would be performed with the RMS of the rescue orbiter grappling the forward grapple fixture on *Atlantis'* berthed OBSS. After grapple the OBSS would roll out and the RMS of the rescue orbiter would be used to maneuver *Atlantis* so that both orbiters were nose-to-nose for effective mated attitude control. The rescue orbiter would then maneuver the mated stack to a gravity gradient attitude. The RMS of *Atlantis* is not used.

Atlantis Rescue Contingency Proximity Operations Procedures

Three contingency proximity operations procedures have been prepared for the rescue mission (Table 2). These procedures, Prox Ops Backoff, HST R Bar Breakout, and Loss of Vernier RCS are the same as those flown on HST servicing missions.

EVA Crew Transfer, Separation, and Deorbit

The rescue involves the transfer by EVA of the seven member *Atlantis* crew to the rescue orbiter on flight days 3 and 4. A total of three EVA transfers from *Atlantis* to the rescue orbiter would be performed using the white Extra-vehicular Mobility Unit (EMU) suits. Only *Atlantis* crew members would participate in the EVAs. The four members of the rescue orbiter crew (Table 1) would remain inside the rescue orbiter. At the start of the first EVA participating crew members would install a translation rope along the RMS of the rescue orbiter. Astronauts McArthur, Feustel, and Grunsfeld would transfer to the rescue orbiter during the first EVA. Johnson would transfer during the second EVA, along with all of the thermal protection system repair hardware.

The third and final EVA would transfer Altman, Massimino, and Good. Before the last EVA, the remaining crew members on *Atlantis* would configure the cockpit for the separation and ground commanded deorbit burn. *Atlantis* disposal procedures are based on those developed for damaged orbiter disposal on ISS missions.[14] This includes opening allowable attitude error and rate limits so that automatic flight control firings of the RCS jets would not be performed with the rescue orbiter in close proximity to *Atlantis*. *Atlantis* would be released by the rescue orbiter on flight day 4 (Figure 20). TPS inspection using the OBSS would be performed on flight day 5, and flight days 6 and 7 would be used for entry preparation. Rescue orbiter entry and landing is planned for flight day 8.

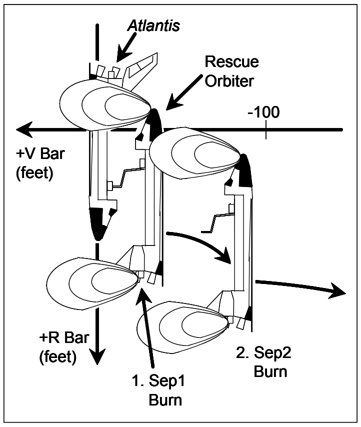

Figure 20 Rescue orbiter separation from *Atlantis*.

OBSERVATIONS AND LESSONS LEARNED

HST missions succeeded in part due to the efforts of personnel from multiple disciplines that had extensive experience planning and flying servicing missions to a variety of spacecraft. This facilitated application of best practices and lessons learned.[3-8] These personnel are experienced at working in a multi-discipline environment involving multiple NASA organizations and supporting contractors that requires lateral communication. Shuttle Program personnel are experienced in development of contingency procedures, both pre-mission and during a flight, and with interacting with development and operations personnel representing a variety of target spacecraft.

A flight program must be responsive to unanticipated satellite performance issues that may drive late and significant changes in servicing mission plans. These events can drive changes to existing proximity operations, robotic operation, and servicing procedures, or require the creation of new procedures and mission plans. The availability of additional qualified personnel to develop new procedures and operational work-arounds enables a flight program to effectively respond to off-nominal events during real-time operations.

Development and operations personnel continually learn about vehicle systems performance and limitations even after a spacecraft has been built and is in orbit. Unforeseen constraints and performance limitations will emerge that drive development of new or changes to existing nominal and contingency plans and procedures. Over the life of a flight program improvements in analysis and simulation fidelity may reveal additional operational constraints. An example of this was the gradual discovery of HST sensitivity to plume impingement that resulted in the increasing range of Low Z mode initiation from 200 feet out to 1500 feet.

Servicing mission personnel should consider applying rendezvous, proximity operations, and other techniques from other spaceflight missions and flight programs to mitigate risk to mission success. High value missions may drive significant investment in low-probability of occurrence contingency procedures to ensure mission success in the presence of failures and degraded systems performance. However, this may result in an increase in the number of procedures that program personnel must maintain and be prepared to execute over the life of a flight program.

Many nominal and contingency HST procedures were driven by RCS plume impingement overpressure and contamination concerns. Consideration should be given to building spacecraft structures and systems that are not as sensitive to servicing vehicle characteristics such as RCS jet plumes. Furthermore, servicing spacecraft should be designed with RCS and other systems that do not pose a potential hazard to satellites that could be serviced.

The highly reflective surface of HST makes it a poor target for the HHL and causes shuttle payload bay camera blooming, complicating proximity operations piloting. Experience has shown that the RMS grapple fixtures on HST are good targets for the HHL. Proximity operations contingency procedure development for the ZGSP and HWSP HST attitude control safe modes was complicated by a lack of HST retro-reflectors to support the shuttle TCS and HHL. In addition, Mission Control and crew insight into HST attitude during these safe modes was limited, and based primarily on crew observations. Comprehensive telemetry, sensor aids on the vehicle to be serviced, and relative sensors capable of performing relative attitude determination can simplify proximity operations piloting.

In spite of the previously mentioned challenges, ground personnel (HST STOCC, Space Shuttle Mission Control) and shuttle crew members possessed the flexibility, creativity, and situational awareness to analyze unforeseen issues and develop new procedures in a timely manner. Spacecraft and ground support organizations in future robotic or human flight programs should be flexible enough to accommodate late changes in mission requirements. Such responsiveness significantly enhances the probability of mission success.

SUMMARY

The Space Shuttle Program has successfully flown servicing missions that have repaired and upgraded the Hubble Space Telescope. These repair missions increased the science return and extended the life of the telescope by correcting performance problems, replacing malfunctioning hardware, and equipping it with more advanced astronomy sensors. Conducting these missions required the development, adaption, and evolution of numerous crew procedures and flight techniques for performing rendezvous, proximity operations, and deployment. Nominal and contingency procedure development required the efforts of both Shuttle and HST Program personnel in disciplines including trajectory design, robotics, flight control, thermal control, power generation, structures, orbital debris, and extra-vehicular activity. Space Shuttle and HST hardware design and limitations placed requirements and constraints on these nominal and contingency techniques. Some constraints were known early in the development of mission techniques in the 1980s, others emerged after HST was placed in orbit in 1990. Particular care was taken to "do no harm" to HST and not impede the ability of HST to perform the science mission. The HST servicing experience and lessons learned are applicable to other programs that perform on-orbit servicing and rendezvous, both human and robotic.

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