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THE HUBBLE SPACE TELESCOPE SERVICING MISSION PLANNING AND REPLANNING SYSTEM

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ABSTRACT

The Hubble Space Telescope (HST), NASA's renowned astronomical observatory, has been orbiting the earth for eight years. Launched and deployed in 1990, HST was successfully serviced on-orbit in 1993 and 1997 by NASA Space Shuttle Orbiter crews. The HST mission is planned to continue at least until the year 2010. Two additional servicing missions are planned to upgrade and maintain the observatory. Future HST discoveries will no doubt continue to make news headlines, but behind the scenes a sophisticated operation planning system has evolved to ensure the past and future success of the Hubble's ambitious servicing missions.

Each HST servicing mission is a complex and integrated sequence of ground control spacecraft command activities and on-orbit repair and maintenance activities. A computer-based planning system, the "Servicing Mission Planning and Replanning Tool" (SMPART) is used to schedule and constrain these activities. Each activity can be constrained (restricted to when it can occur) by as many as ten different time or orbital parameters. With servicing missions of more than 600 potentially dynamic activities containing over 50,000 spacecraft commands, SMPART schedules and reschedules all activities in less than a minute to meet the exacting demands of on-orbit spacecraft maintenance. Without such a responsive flexible system, these servicing missions could encounter critical delays effecting overall servicing mission objectives and success.

Herein we will review the history and evolution of the HST operations mission planning system. We will also provide an overview of the SMPART system and discuss how servicing mission activities are planned, integrated and scheduled. We will detail the replanning aspects that occur during a mission, which are necessary to insure that all activities and personnel achieve the mission objectives as laid out in the two major SMPART products. With the HST mission nearing its planned mid-way point we will speculate on the future applications of SMPART to HST and other missions.

1. INTRODUCTION

The Hubble Space Telescope is orbiting the earth at an altitude of 320 nautical miles. The HST control center is located at the NASA Goddard Space Flight Center in Greenbelt, Maryland, USA. More than one thousand people work on the HST program. The majority of these people are involved in the planning for HST servicing missions. The extensive in depth planning effort for each servicing mission takes at least 2 1/2 years and is documented using the SMPART system. Servicing missions are planned to occur approximately every three years.

A servicing mission begins with the launch of the NASA Space Transportation System Shuttle Orbiter vehicle. It ensues with the HST rendezvous and a subsequent 4 to 6 days of on-orbit servicing by space-walking astronauts and culminates with the Orbiter redeployment of the HST.

SMPART is a planning and scheduling system tool that is designed to build HST integrated timelines and command plans. Each servicing mission is planned by developing a Servicing Mission Integrated Timeline (SMIT) and a Servicing Mission Command Plan (CP). Alternate Command Plans (ACPs) are also created by SMPART to be invoked in the event of any anticipated anomalies that may occur.

The SMIT (see Figure 1) acts as the servicing mission bible of activities. It is a time ordered schedule of all HST commanding activities integrated with the Shuttle Orbiter and Orbiter crew activities.

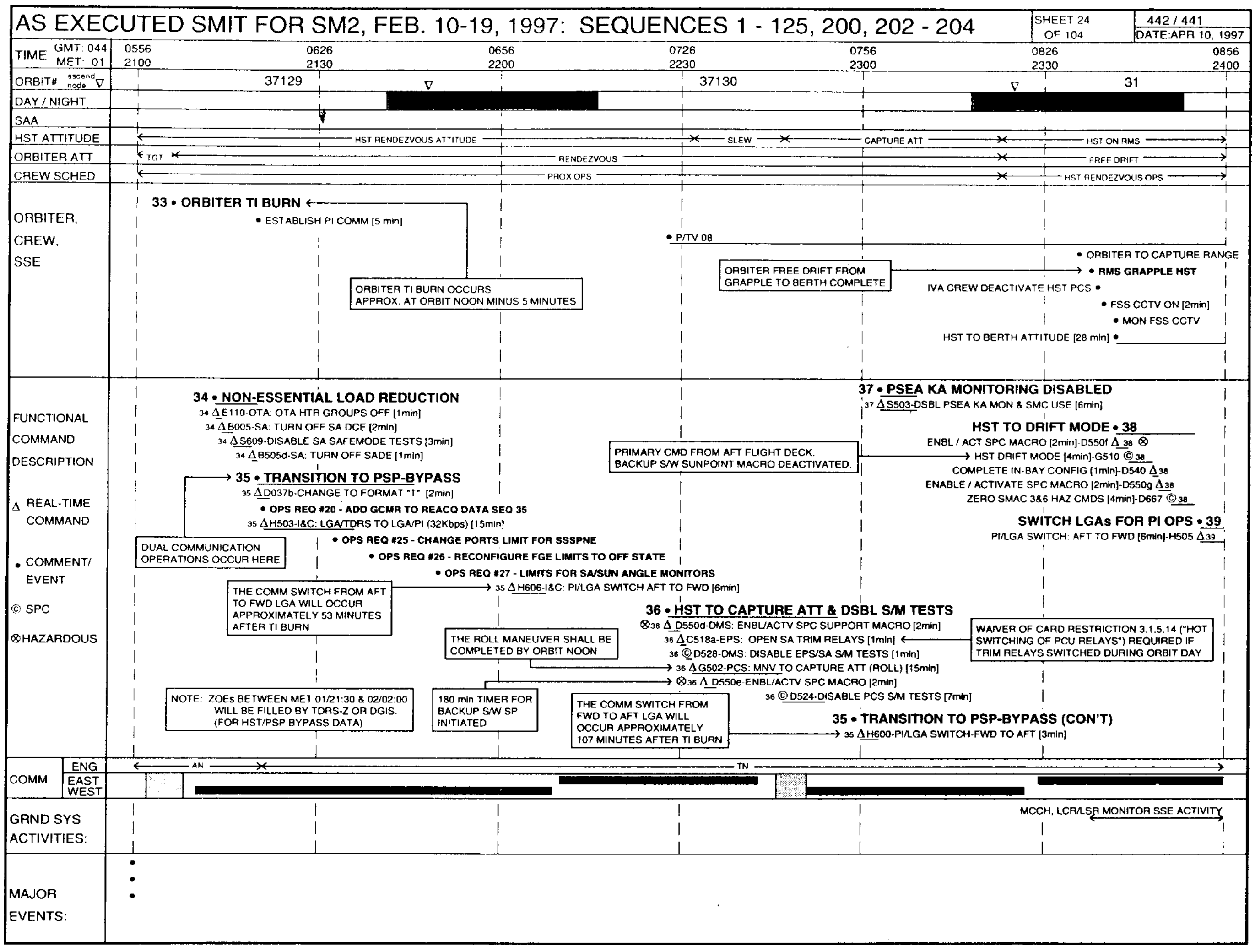

Figure 1: Servicing Mission Integrated Timeline (SMIT)

The above SMIT in Figure 1, illustrates HST and Orbiter activities from 2 1/2 hours prior to initial rendezvous thru the actual grapple of HST by the Orbiter. The leftmost column lists the major headings, for each respective graphic field to the right. The “Functional Command Description” field - the largest field in the middle of the figure - contains all command activities for the HST. Also note at Mission Elapsed Time (MET) 01:2345 (Day/Hour/Minute) that the HST ephemeris is now replaced by the Orbiter ephemeris. This can be noticed by the change in Orbit # from 37130 (HST’s #) to 31 (Orbiter’s #). At this transition, the night and day and other orbital elements match since both spacecraft are now together in the same orbit.

The Command Plan (see Figure 2) is the detailed implementation of the SMIT. It breaks down every activity (e.g. Sequence #36 - “HST to Capture Attitude ...”) into the associated HST commands necessary to complete the activity. The Command Plan also lists all “voice protocols” between ground personnel, all major Go/No-Go calls between the ground control and the Orbiter crew, and all “hazardous commanding” activity.

HST SECOND SERVICING MISSION CP
FEB 11, 1997 LAUNCH
(RELEASED 2/3/97)
Revised 02/03/97

SEQUENCE # 36
MET: 01:22:24
DURATION: 32min
SEQUENCE TITLE: HST TO CAPTURE ATT & DSBL S/M TESTS
SEQUENCE DESCRIPTION: SA/EPS S/M TESTS DISABLED VIA R/T ACTIVATION OF TIMED PROCESSOR. ROLL MAN TO CAPTURE ATT PERFORMED BY R/T PRT SLEW. TSPC EXECUTION ALSO DISABLES PCS AND DMS S/M TESTS AND ALL S/M & HLD MACROS. DISCONNECT +/- SPA TRIM RELAYS. AT COMPLETION OF ACTIVITY, SSPC IS ACTIVATED BY TSPC FOR BACKUP S/W SUNPT SPC MACRO.
INITIAL CONDITIONS: 32 KBPS TN FORMAT ACTIVE WITH PSP-BYPASS MODE OPERATIONS.

TIME COMPLETE	STEP#	PROC	ACTION	TLM	ΔTIME (min)	AD	DESCRIPTION
	36-1	--	* STOCC CONTROL TO HOUSTON DATA: * ENABLE HAZARDOUS COMMAND GROUP 6 FOR UPLINK				
	36-2	SERMSPC(6) *** HAZ CMD GRP 6 ***	DMS: VERIFY TIMED PROCESSOR ACTIVE AND SAFEMODE TESTS ARE DISABLED. P DF1: DCNXT1 = NOT EQUAL TO 0 DTIMSPCL = ACTV DTIMSPCR = NO WAIT	TN	2	D550d	TIMED PROCESSOR SPC MACRO USED TO DISABLE EPS AND SA SAFEMODE TESTS. ALL SAFEMODE TESTS THAT COULD RESULT IN SOLAR ARRAY OR VEHICLE MOTION MUST BE DISABLED WHEN ORBITER IN CLOSE PROXIMITY TO HST. TOTAL MACRO EXECUTION TIME = 20sec
			* NOTE: WAIVER OF CARD 3.1.5.14 ("HOT SWITCHING OF PCU RELAYS") REQUIRED IF TRIM RELAYS SWITCHED DURING ORBIT DAY *				
	36-3	SPAX(3,0)	EPS: VERIFY +WING SPA TRIM RELAYS DISCONNECTED. P EPWR1: C%ASPA = DISCONN C%BSPA = DISCONN C%CSPA = DISCONN C%DSPA = DISCONN C%ESPA = DISCONN C%AASPA = DISCONN C%BBSPA = DISCONN C%CCSPA = DISCONN C%DDSPA = DISCONN C%EESPA = DISCONN	TN	2	C518a	DISCONNECT +WING SPA TRIM RELAYS.

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Figure 2: Servicing Mission Command Plan (CP)

The above Command Plan in Figure 2, details the first two activities in Sequence #36 (reference Fig 1). Step 36-1 is a voice protocol between control centers and the next two steps are actual command activities for HST. The whole sequence #36 consists of 17 steps.

Twelve months prior to each mission, personnel including the mission astronauts, are familiarized via simulations with all aspects of the SMIT and CP. When each mission commences, all flight operations ground personnel are guided by the SMIT and Command Plan in order to perform their respective tasks. In this manner all personnel work together to achieve the mission objectives as detailed in the SMIT.

The next (third) HST servicing mission, the most ambitious to date, is scheduled for May 2000. The mission manifest includes the installation of, one new science instrument to further expand the observatory's science capabilities, new rigid solar arrays, a new spacecraft main computer, and a cooling system designed to return the existing infrared instrument to useful operations following expected loss of cryogen late in 1998. There will also be replacement and repair of other critical components, such as the Fine Guidance Sensor, Solid State Recorder and Multi Layer Insulation blankets.

2. THE DEPLOYMENT MISSION PLANNING SYSTEM

Since the mid 1980's, the operations planning, for the HST deployment and subsequent servicing missions, has undergone an evolution from using a rudimentary Computer Aided Design (CAD) system to a sophisticated computer-based scheduling system called the "Servicing Mission Planning and Replanning Tool."

For the 1990 Deployment mission of HST, the CAD planning system created a Mission Activity Timeline that was updated semi annually prior to launch of HST. To process to update the timeline took nearly one month. This timeline also could not be replanned in real time during the mission. A Command Plan, which was the spacecraft commanding implementation of the CAD generated mission timeline, was created by a separate word processor application. If any anomaly occurred during the deployment mission affecting the scheduled commanding, the Timeline and Command Plan could be reworked (replanned) only in real time via paper and pencil redlining. This performance-limited system was not well matched to the HST integrated commanding activities for a successful time critical deployment. Since the future servicing missions would also make use of space-walking astronauts performing time critical activities, a more robust planning/replanning system became a priority.

3.0 THE PLANNING AND REPLANNING SYSTEM

3.1 REQUIREMENTS AND SOFTWARE

A lesson learned from the 1990 deployment mission was that the generation and update of the mission timeline and command plan for servicing missions, had to be automated. The dynamics of pre-mission planning and mission replanning necessitated a quick response planning system. SMPART was developed as just such a system.

The main specifications for the new computerized planning system were as follows:

1. To create a graphic timeline (SMIT) that could be revised and or replanned in less than 30 minutes.
2. To automatically generate a command plan from the nominal or replanned timeline.
3. The capability to link all timeline activities to any other scheduled timeline activity or event.
4. The capability to constrain all activities to orbital and communications events.
5. The capability to automatically reschedule activities when constraint violations are detected.
6. The capability to import Orbiter and HST orbital ephemerides data into the graphic timeline display.
7. The capability to import Orbiter and HST communications data into the graphic timeline display.

All of the above requirements were developed, tested and implemented, and SMPART was successfully used to plan and support the first servicing mission in 1993. SMPART was such an efficient scheduling tool, that for the first time ever, the NASA Houston Shuttle operations personnel used a payload's timeline (the SMIT) for their mission planning. Previously all Shuttle payloads (e.g., HST) had to distill their timelines into a Houston defined timeline called an, "Ops Support Timeline."

After each mission SMPART requirements and specifications are reviewed and refined and the system is upgraded to enhance capabilities. The requirement to replan the SMIT in less than 30 minutes is now implemented in less than one minute.

SMPART is currently hosted on an IBM RISC 6000 computer workstation using a UNIX based operating system. There are 70,000 lines of executable code. The HST dedicated system software cannot currently be transported between different platforms.

3.2 PLANNING PHASE

The planning phase begins soon after the end of each servicing mission. During the 2 1/2 year planning phase, the SMIT and Command Plan are developed and updated three to four times a year. All of the HST servicing mission operations activities are defined and integrated by a series of multi-disciplinary engineering and management working groups. After activities are defined an operator enters the data to generate the Servicing Mission Integrated Timeline (SMIT). The majority of activities are spacecraft commands to prepare the HST for the Shuttle Orbiter rendezvous (positioning solar arrays, retracting high gain antennas, powering down subsystems, disabling safemode tests, etc.), configuring hardware for changeout during Extra Vehicular Activities (EVAs) (space-walks to replace HST hardware), testing of new and replaced hardware, and for configuring HST for redeployment and post deployment.

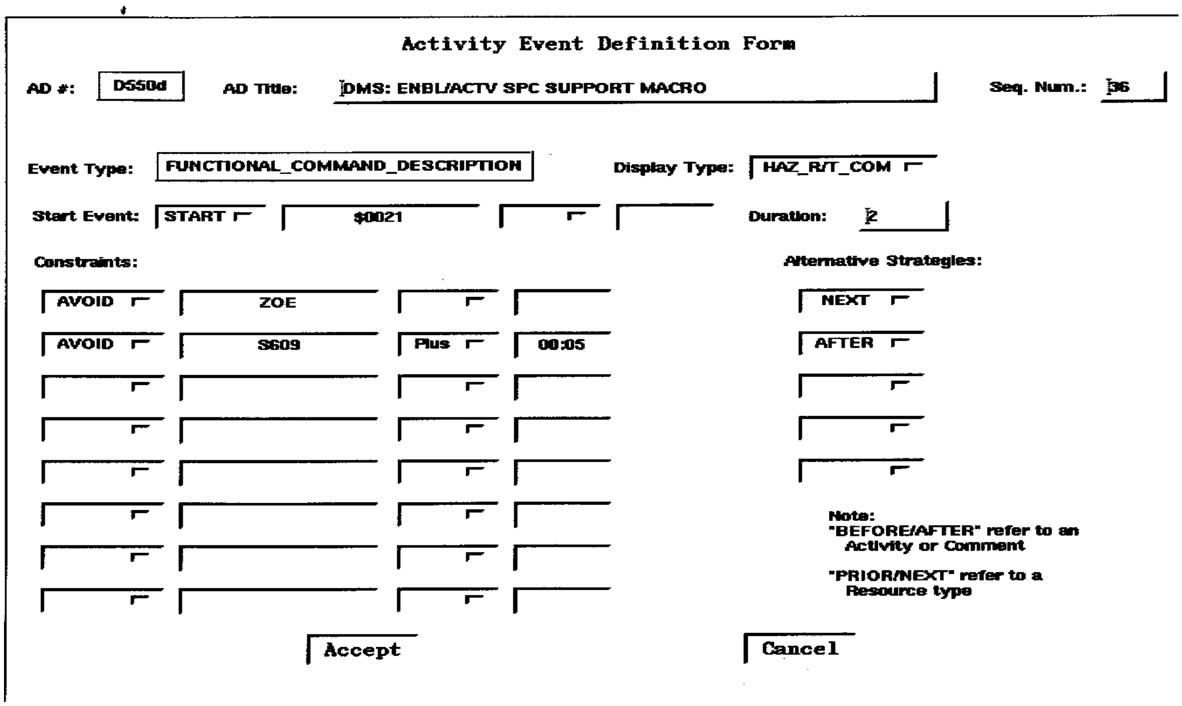
All of these commanding activities are chronologically ordered (scheduled) with respect to Mission Elapsed Time and Greenwich time. The command activities can further be constrained by one or more of the following parameters (see Figure 3)

Activity	Constraining Event	Constraint	Reschedule
HST activity	Orbit Number	Prior/Next	Prior/Next
HST activity	Day/Night	Avoid/During	Prior/Next
HST activity	South Atlantic Anomaly	Avoid/During	Prior/Next
HST activity	Zone of Exclusion (Comm)	Avoid/During	Prior/Next
HST activity	TDRS S or Ku Band (Comm)	Avoid/During	Prior/Next
HST activity	Orbiter activity	Prior/Next	Before/After
HST activity	Orbiter crew activity	Prior/Next	Before/After
HST activity	Other HST activity	Prior/After	Before/After
HST activity	Major Event	Prior/After	Before/After
HST activity	Ground system activity	Prior/After	Before/After

Figure 3: Activity Constraint Table

In figure 3 above, an example of an HST activity scheduled with constraints would be sequence #36 step 2, “D550d - DMS:Enable/Activate SPC Support Macro (see Figs. 1 & 2). The activity is constrained to “avoid” any Zone Of Exclusion (ZOE). It is also constrained to start “after” sequence #34 activity, S609 - “Disable SA Safemode Tests”. The Command Plan steps 36-1 and 36-2 further identify D550d as a “hazardous command”.

All of these constraints can also have a +/- delta time offset associated with the avoid/during/prior/after parameters. Furthermore if any one constraint is violated the scheduling system can automatically reschedule the associated activity based on the next or previous opportunity as defined by the activity constraints (see Figure 4). The violated constraint may also be flagged and not rescheduled.


Activity Event Definition Form

AD #: D550d AD Title: DMS: ENBL/ACTV SPC SUPPORT MACRO Seq. Num.: 36

Event Type: FUNCTIONAL_COMMAND_DESCRIPTION Display Type: HAZ_R/T_COM

Start Event: START $0021 Duration: 2

Constraints:

AVOID ZOE

AVOID S609 Plus 00:05

Alternative Strategies:

NEXT

AFTER

Note:
"BEFORE/AFTER" refer to an Activity or Comment
"PRIOR/NEXT" refer to a Resource type

Accept

Cancel

Figure 4: Activity event definition form (Automatic constraint checking and rescheduling).

The above figure is the actual SMPART operator generated data base file record for the identified activity. In this example, the command activity is constrained to avoid a ZOE and another HST activity identified as “S609”. If either activity constraint is violated the software automatically will try to reschedule the activity based on the “Alternative Strategies identified in the file record.

3.3 REPLANNING PHASE

The replanning phase occurs during the servicing mission. The baseline servicing mission SMIT and CP are invoked 24 hours prior to launch of the Space Shuttle Orbiter. After launch, the SMIT and Command Plan will be replanned near the end of each Orbiter crew flight day to account for any changes to the nominal timeline. The SMPART is easily capable of scheduling and replanning a 10 to 12 day servicing mission, consisting of over 600 command activities containing over 50,000 spacecraft commands. For each servicing mission, personnel work either of two shifts, the “Replan” or “Orbit” shift.

The 12 hour Replan shift begins four hours prior to Orbiter crew sleep. Replans performed prior to the Orbiter rendezvous with HST, account for launch delays and any failure to configure HST as nominally planned. Replans after Orbiter rendezvous with HST, account for failed hardware change-outs or replaced hardware Aliveness/Functional tests that were not successful. For all replans, after all the revised data has been entered by the operator, the SMPART software regenerates the entire SMIT in less than one minute. The resulting replan is then thoroughly reviewed and approved by the HST community during the 12 hour Replan Shift. A replanned CP is also generated, reviewed and approved.

The 12 hour Orbit shift begins with the wake up of the Orbiter crew. After wake up, the entire supporting ground team and the astronauts are briefed about the coming day’s replanned activities. Three hours into the shift two crew members egress from the Orbiter airlock to perform a scheduled 6 hour EVA. This is a critical time period filled with precisely choreographed hardware replacement and spacecraft command activities. It is not uncommon for anomalies to occur and to disrupt the timeline. When anomalies occur and subsequently impact the EVA, SMPART is often called upon to quickly reschedule the remaining activities. Based on how the replanned activities lay out against the remainder of the 6 hour EVA day, management may make decisions on whether or not to schedule, replace or postpone activities. It should be noted that many EVA activities are constrained to occur only during orbit night or while the Orbiter attitude control system is deactivated or while in a specific Orbiter attitude. The importance of SMPART automatic constraint checking and rescheduling, is that it allows for quick replan assessment during the EVA.

The capability for the timeline to be replanned and the information disseminated to all participants in a timely manner, is essential to achieving the goals of a successful mission. In addition there are safeguards built into the command plan that are meant to protect the crew and the HST from hazardous situations brought on by inappropriate spacecraft commanding (e.g., commanding an HST solar array to move). When situations arise where a deviation from the nominal plan occurs, automated safety features in SMPART can help maintain a level of safety assurance that may otherwise be compromised.

If a major anomaly occurs (e.g., “Rapid Deployment of HST”) an SMPART Alternate Command Plan (ACP) may be invoked. This ACP is a preplanned command and activity response to the predicted anomaly. Based on a credibility/criticality assessment, twenty-two ACPs were created for servicing mission #2, but none were invoked.

4. **THE FUTURE OF SMPART**

As the third and most complex servicing mission approaches, the SMPART has and continues to evolve to meet the scheduling needs of a complex spacecraft and the array of professional engineers and scientists who must determine how to successfully service and maintain the HST on-orbit.

The HST operations ground system is currently being re-engineered. This project, called Vision 2000, has redesigned the HST ground system and these changes will for the first time allow semi-autonomous commanding during the servicing mission. Instead of an operator typing in each HST command from a keyboard, the new ground system will extract commands directly from the Command Plan file in SMPART. An operator will then transmit the command at the touch of a button.

SMPART is currently being used as the planning system for another major NASA mission, the Earth Observing System (EOS). The timeline for this mission is expected to be a least 90 days in duration. By the time this mission is launched, it is planned to host the SMPART system on a Personal Computer (PC). For this to happen a major software modification will have to be made. This will allow for portability and in the future, SMPART will be easily customizable to meet each new missions specific scheduling requirements.