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Planning and Scheduling the Hubble Space Telescope: Practical Application of Advanced Techniques

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INTRODUCTION

NASA's Hubble Space Telescope (HST) is a major astronomical facility that was launched in April, 1990. In late 1993, the first of several planned servicing missions refurbished the telescope, including corrections for a manufacturing flaw in the primary mirror. Orbiting above the distorting effects of the Earth's atmosphere, the HST provides an unrivaled combination of sensitivity, spectral coverage and angular resolution.

The HST is arguably the most complex scientific observatory ever constructed and effective use of this valuable resource required novel approaches to astronomical observation and the development of advanced software systems including techniques to represent scheduling preferences and constraints, a constraint satisfaction problem (CSP) based scheduler and a rule-based planning system. This paper presents a discussion of these systems and the lessons learned from operational experience.

PLANNING

An astronomer wishing to observe with the HST competes for time in a peer-review process. If a proposal is selected, the astronomer submits a detailed observing program which gives specific exposures, instrument configurations and constraints on exposures. There are a variety of scientific reasons why an astronomer might place constraints on exposures: they may be constrained to be executed in a certain order or within a designated time interval. In the case of time-variable phenomena (e.g. variable stars), the proposer may require repeated observations at specific time intervals.

In addition to the constraints imposed by the proposer's scientific program, there are a large number of other constraints which must be considered. Many orbital factors exert a strong influence on scheduling: targets are occulted (blocked) by the Earth for up to 40 minutes each 95 minute orbit. The telescope cannot point too closely to the Sun, Moon or bright Earth limb. The roll orientation of the spacecraft is constrained in order to maintain correct power and thermal balance.

HST observing proposals are prepared using the Remote Proposal Submission System (RPSS) [2]. The astronomer prepares a proposal file, which is a text file in keyword-value format. The entries in this file specify the astronomical targets, exposures, instrument parameters and scientific constraints. The proposer then runs the RPSS *Validation* program which detects problems with the proposal file such as syntax errors, typographical errors, improper values on parameters and missing information. Validation can be performed by logging into a computer at the STScI or downloading the program via Internet and running locally. To our knowledge, RPSS was the first system of its kind for a major scientific installation (it has been in use since early 1986).

The RPSS format proposal describes the observations at a high level. The actual activities which are planned and scheduled by the downstream systems are called *scheduling units* and are specific realizations of the observations including details relating to spacecraft and orbital parameters and instrumental operational scenarios. The process of creating scheduling units from the proposal is called *transformation* and is a planning process. The STScI developed a rule-based expert system to implement transformation. When first proposed in 1984, the concept of an automated transformation of scientific proposals to implementation parameters was quite novel. Since that time, the system has demonstrated the capability to routinely perform this task and allows STScI staff to focus more attention on innovative and difficult observations. Additionally, as improved implementation strategies are devised, Transformation is quickly modified and allows us to re-transform proposals in order to benefit from these improvements. Transformation was originally implemented as a production rule-based system in OPS5, but was rewritten in Lisp as a procedural planning system [1].

Once a proposal is transformed to scheduling units, STScI staff members examine the scheduling opportunities for the proposal using the Spike system (discussed in the next section). Problems found at this stage are fixed by modifying the proposal, e.g. relaxation of observing constraints or choosing an alternate implementation strategy.

We are currently developing a second-generation RPS system which provides two major improvements over the existing system: greater insight into the planning and scheduling process and support for changes to proposals after execution has begun.

Greater insight into the planning and scheduling process is accomplished by providing the proposers with essentially the same tools as used by STScI staff, including Transformation and Spike. Graphical output will show proposers the layout of exposures and telescope activities during each orbital viewing period and the scheduling opportunities during the year, allowing them to see the implications of their choices of observing constraints, instrument parameters, etc. Proposers will also be given explicit control over the assignment of exposures to scheduling units. Previously this was determined by Transformation on the basis of a set of rules. However this was not visible to the proposer and often required several iterations with the STScI to achieve the desired groupings. Transformation will still be used to determine the detailed implementation of activities within a scheduling unit.

In addition, the proposal syntax has been enriched to allow the proposer to specify how observations should be expanded or contracted to make best use of the actual observation time (which cannot be accurately predicted more than a few months in advance).

A severe shortcoming of the current system is that once execution has begun, change to a proposal is a labor-intensive, manual process. The original ground systems were built with the assumption that most proposals would not change after submission. This has turned out to be a very poor assumption - scientific observations often require adjustment based on the results of other observations or to adjust for changes in instrument or telescope performance. Change responsiveness is being addressed in several ways. First, the overall time from proposal preparation to execution is being shortened (by about a factor of two). Second, proposal data and tools are being redesigned to be more modular so that a change to one scheduling unit or target can be processed independently of others.

SCHEDULING

Scheduling the HST is a challenging problem for several reasons: A year's observing pool consists of tens of thousands of exposures for a few thousand astronomical targets. There are a large number of interacting constraints with timescales covering several orders of magnitude (minutes to years). Scheduling is many months in advance of execution and many constraints cannot be predicted in detail in advance. There is no one overriding factor which determines the schedule so that complex trade-offs between competing factors is necessary. Continuous modification of the schedule is necessary as observations are executed and proposals are changed.

A two-level, hierarchical approach has been used for HST science scheduling by dividing the problem in to long- and short-term scheduling. Long-term scheduling allocates observations over a 1-2 year interval, while short-term scheduling covers a one-week period and creates a detailed timeline of activities. Feedback from the weekly plans is used to update the long-term plan and to reschedule as needed. Long-term scheduling is performed with Spike [3] (developed at the STScI), while detailed short-term scheduling is performed with the Science Planning and Scheduling System (SPSS) which was developed by TRW and extensively modified by the STScI. Important features of Spike include:

- A constraint representation and propagation mechanism (suitability functions) which includes the ability to express human value judgements as well as strict constraints that can never be violated.
- Proposal evaluation tools that allow planners to display and manipulate observations and constraints on workstations.
- Automated and manual scheduling tools based on constraint satisfaction problem (CSP) techniques and a high-level scheduler that combines evidence from competing factors [3,4].
- Automated tools to track the status of the planning and scheduling process at all stages.

Spike is used in two ways. First as an analysis tool for individual proposals and second as a scheduling tool to produce a multi-year plan for an HST observing cycle. As an analysis tool, Spike shows the user (via a graphical interface, postscript plots or alphanumeric reports) the effects of scheduling constraints. It also has an explanation facility which can help a user understand why an observation is unschedulable so constraints can be modified.

As a scheduling tool, Spike is used to create and maintain the long-term plan. As observations are executed and proposals are created or modified, automated and manual tools in Spike are used to update the plan.

Spike was designed with generality in mind and has been adapted to about a dozen other satellite or ground-based observatories. Several of these were feasibility prototypes, but two are in flight operations: the Extreme Ultraviolet Explorer (EUVE) and the X-ray observatory ASCA. Observations with EUVE are sufficiently long (2-3 days) that a division into long- and short-term scheduling is not needed. ASCA uses a two-level hierarchy with Spike performing the long-term scheduling.

Adaptation of Spike to a new system is straightforward and largely consists of defining methods which describe mission-specific elements such as constraints. The core system which includes the constraint representation, propagation, scheduler and user interface are largely unchanged.

The adaptability of Spike was shown in another way as well - prototype short-term schedulers have been implemented for HST, ASCA and the X-ray Timing Explorer satellite. The major changes required to implement short-term scheduling included: the development of a new task which has a variable duration depending on when it is scheduled and that can be preempted (e.g. by Earth occultation or radiation belt passage); more accurate implementation of short-term constraints; a post-scheduler which adjusts task durations to utilize small gaps remaining in the schedule.

For initial HST operations, long-term scheduling allocated each scheduling unit to a particular week. However this approach was sensitive to perturbations in the short-term schedule: If a scheduling unit could not be executed in the chosen week, this would leave a gap in the schedule which required additional effort to fill. These disruptions were sometimes caused by the fact that short-term scheduling has more information available to it and therefore can uncover problems which cannot be seen at a higher level. Another, more important, factor contributing to this was the large degree of change to HST proposals after submission - for a variety of reasons most proposals where changed after long-range planning began. The first response to this problem was to "oversubscribe" the long-range plan, that is, allocate an excess of observations to each week. In practice an oversubscription level of ~100% was necessary to ensure well-filled weekly schedules, and this made it impossible to predict with reliability when an observation would occur and required a large amount of rescheduling. We have recently developed an alternate long-term strategy which solves this problem. The long-term plan allocated each scheduling unit to a range of weeks (called a plan window). This range provides for each week an implicit oversubscription to maintain short-term efficiency, yet there is a high degree of certainty that the observation will be executed within the plan window. Our initial studies indicate that with plan windows as small as 4 weeks over 95% of the observations are executed within the plan window.

SUMMARY

HST science operations introduced several novel concepts for astronomical observation, including distributed proposal preparation tools, abstraction of the scientific program from the specifics of the implementation, and fully interleaved scheduling. To support this, a number of advanced planning and scheduling systems were developed and have supported HST throughout four years of operations. Current major enhancements to these systems include making more tools available to proposers and re-engineering the systems to better support proposal changes. Several tools have been adapted to other space- and ground-based observatories.

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