Coarse-grained scheduling for astronomy satellites

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ABSTRACT

For the past fifteen years, the International Ultraviolet Explorer (IUE) astronomical satellite has been successfully scheduled by "coarse-graining" the time into large discrete blocks. The success is due in part to the flexibility of coarse-graining which allows real-time modifications to the observing plan by the guest investigators. Such flexibility is desirable whenever an astronomical object is observed for the first time by a particular mission, since new data sometimes contain scientific surprises, and because several important types of astronomical objects are characteristically unpredictable and variable (e.g. supernovas, X-ray transients, etc.). Software which can incorporate this approach has the potential of significantly improving the efficiency and scientific return of future satellite missions.

We give an overview of the IUE satellite and its scheduling requirements and describe our approach to satellite scheduling using constraint logic programming. We describe some of the constraints which are useful for satellite scheduling and show how the constraints can be used for efficient coarse-grained scheduling. We also discuss advantages of this approach for other satellite telescopes.

1 INTRODUCTION

For the past fifteen years, the International Ultraviolet Explorer (IUE) astronomical satellite has been successfully scheduled by "coarse-graining" the time into large discrete blocks. The IUE has established a reputation for high quality science and high observing efficiency (60% of its time is spent collecting data). This success is due in part to its highly flexible approach in planning and executing its science programs. It is also partly due to the system of allowing real-time modifications to the observing plan by the guest investigators, who base the changes on a quick first-look analysis of the data as it is taken, in order to maximize the quality of science. This real-time flexibility is desirable because several important types of astronomical objects are characteristically unpredictable and variable (e.g. supernovas, X-ray transients, etc.). Such flexibility is also desirable whenever an astronomical object is observed for the first time by a particular mission, since new data sometimes contain scientific surprises.

We report on our initial attempt to incorporate the IUE's flexible scheduling approach, in to software which is adequate for a more complex mission, while retaining the IUE's high flexibility and efficiency. This has the potential of significantly improving the efficiency and scientific return of future satellite missions.

The IUE is scheduled by dividing observer time into 8-hour time periods which are scheduled as discrete blocks ("coarse-graining"). In the past, the IUE's scheduling has been performed by a human scheduler, with minimal software support. No attempt is made by the satellite scheduler to specify details of operations within each time block. It is the Guest Observer, whose science program is being done in that block, who plans the observing in the block, with the help of IUE staff, and also supervises, in real time, gathering the data.

Our first step is to develop a representation for the constraints sufficient for scheduling relatively simple satellites and implement a constraint logic program which accesses the representation and discovers a set of coarse-grained schedules. We demonstrate this approach by representing the information needed to schedule observations for the IUE satellite. Our coarse-grained scheduler can find a collection of schedules which satisfy the overarching spacecraft, instrument, target, and scientific program constraints, where the program constraints refer to restrictions on the collection of observations requested by a Guest Observer. A human scheduler can then choose an optimal schedule from the set which maximizes the quality of science after consulting with the Guest Observer about priorities and trade-offs which may be necessary.

We set up a representation for the programs, targets, instruments, and instrument exposures and a representation for general constraints on them, including constraints on the spacecraft operation. We have developed a simple constraint logic programming language for program (observation) specific constraints embedded in the programming language LIFE. Our satellite scheduling language can then be used to represent constraints specific to particular programs, such as various types of temporal constraints, target observation constraints, and instrument exposures. We then show how a simple, priority-based scheduler can create a collection of useful schedules which satisfy these requirements.

The advantages of this approach are that it makes use of existing human expertise (i.e., qualitative scientific judgements and decisions by the investigators) which can not be readily represented but which significantly affect the quality of science return, and that it allows flexible schedules to be created which can be rapidly modified when unplanned observations must be scheduled.

2 THE IUE SPACECRAFT AND ITS SCIENCE PROGRAMS

Launched in 1978, the IUE consists of one telescope presently having two usable spectrographic detectors, each covering a different wavelength region in the ultraviolet. The two detectors cannot be used simultaneously with the same target. There is no scientific imaging capability. There are two different apertures, but one of these is used so rarely that it can be ignored for the purpose of this project. Each detector has two gratings, one giving high spectral resolution and one for low resolution. Ignoring the different apertures, there are 4 mutually exclusive modes of taking data (two per detector).

The satellite is operated jointly by NASA and the European Space Agency (ESA). For 16 hours of each day, the IUE is controlled from a site in the US, and carries out US science programs. ESA controls the spacecraft for the other 8 hours a day from a location in Europe, carrying out ESA science programs. Usually NASA and ESA science programs can be scheduled independently. The IUE is in a geosynchronous orbit (40,000 km), which is far enough that most targets are not occulted by the Earth. The orbit is eccentric enough that for about 8 hours each day, the spacecraft passes through the Van Allen belts, causing a large increase in background radiation, which is seen by the detectors during that time as increased background noise. The noise is cumulative, limiting the useful time of exposure during the radiation period. The satellite is physically capable of remaining pointed at the same target for weeks at a time without interruption. However, it can continue the same exposure for no more than approximately 20 hours before background radiation accumulates to where even exposures of bright targets become degraded. Usually, however, several different targets are observed in a 24-hour period, with an average of approximately 12 exposures taken per day.

The overarching operational constraint is that the instrument is restricted in the range of pointing angles relative to the sun. This angle, which we shall call the "sun angle", must fall between 28 and 108 degrees (0 degrees is defined to be an orientation toward the Sun) at all times. The satellite can never be oriented outside of this range, due to the fact that the solar power arrays must be kept oriented roughly perpendicular to the sun in order to generate enough power for the spacecraft. A particular target usually falls within permitted sun angles during part of the year, or at several periods throughout the year. Some targets happen to be positioned in the sky where they are at permitted sun angles year round.

Guest observers are awarded time on the IUE in blocks of 8 hours, called "shifts". There are two types of shifts: "US1" and "US2". US1 shifts, always and by definition, occur during the time when the background radiation is negligible. US2 shifts always are placed so as to cover the period when the background radiation is high. Because the high background radiation shows up as noise in the data, with the amount of radiation received roughly proportional to the exposure time, a detector may only be exposed at most about 1 hour during a US2 shift before the background radiation accumulates to where the data are not usable.

The exposure times needed for useful data with the IUE vary from 1 second to 16 hours, depending on the brightness of the target. The high background radiation during US2 forms a scheduling constraint by limiting the exposure times possible. However, this constraint is usually dealt with formally at the time of the science peer review in the following way: Astronomers are required to specifically request a certain number of US1 or US2 shifts when they submit their proposals to the science peer review, according to whether they will need long or short exposures. Science programs needing only short exposures are granted only US2 shifts. Programs needing exposures longer than one hour are granted only US1 shifts. Sometimes a program is granted both US1 and US2 shifts in order to obtain round-the-clock monitoring of some target, or, less often, if the program has both bright and faint targets. A science program is required to use exactly the number of US1 and US2 shifts it was awarded, so usually the operations staff is not required to determine whether a program should be scheduled for US1 or US2 time on a given day, since the the program has only US1 or US2 time available. This helps to reduce the need for the scheduler or a scheduling program to take into account exposure times when constructing the schedule.

During each 8-hour shift, the Guest Observer who was awarded the shift is responsible for planning which targets are observed and in which observation data mode. This is done with the assistance of IUE staff members. Thus problems such as how long to expose on a particular object, which data mode to use, how many targets to observe in a shift, and which combinations of targets may be observed in a shift, are not dealt with by the IUE science scheduler, but by the Guest Observer. Scheduling details which are relevant only to time scales smaller than large ("coarse") time blocks are ignored by the scheduler. In effect, this treats the scheduling problem as a set of "coarse" time blocks rather than small ("fine") time blocks, thus a "coarse-grained" approach to scheduling.

The coarse-grained approach greatly simplifies the scheduling problem. In planning what to observe within a single time block, the Guest Observer must take into account various forms of unavoidable "overhead" which is time during which no data can be taken. For example, each detector must be prepared for several minutes before taking a new exposure, with the length of preparation depending somewhat on the nature of the exposure taken previously. It takes several minutes to read the data down at the end of each exposure before a new exposure can be taken. The time required to re-point the telescope to a new target typically ranges from a few minutes to nearly an hour, depending on how far apart in the sky the two targets are, and depending on the brightness of the new target. In addition, the exposure time required for each target can vary by about a factor of five, depending on the quality of data needed by the Guest Observer. Since IUE science programs often have 5 to 10 different targets (sometimes more), the Guest Observer must decide on tradeoffs between observing more targets with lower quality data or fewer targets with higher quality data. All of these details and judgements are left to the Guest Observer to plan after the shift has been scheduled for a certain day. This approach is overall very similar to how observing time at ground-based telescopes is scheduled and planned. It requires some work on the part of the Guest Observer, but it has been popular with the astronomical community because it permits maximum control and flexibility in the actual gathering of data, and allows the Guest Observer to determine what constitutes an optimal program of observations.

3 OUR IMPLEMENTATION

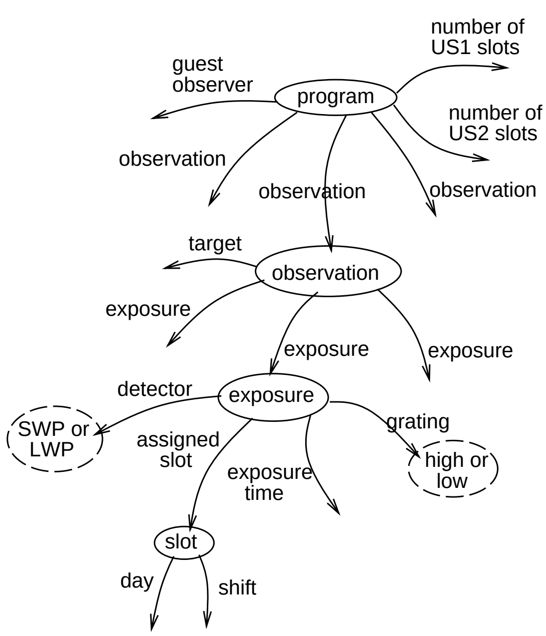
To demonstrate the effectiveness of coarse-grained scheduling, we have developed a constraint logic program for scheduling programs on the IUE satellite. The overarching spacecraft, instrument, target, and scientific program constraints are used by our coarse-grained scheduler to find a collection of schedules which meet the constraints.

We set up a representation for the scientific programs, targets, instruments, and instrument exposures and a representation for general constraints on them, including constraints on the spacecraft operation. We have developed a simple constraint logic programming language for program (observation) specific constraints embedded in the programming language LIFE. LIFE is a fusion of functional, logic, and object-oriented programming paradigms being developed at Digital Equipment Corporation.[1,2] We have chosen to use LIFE because it has useful facilities for handling constraints in a declarative manner.

Our satellite scheduler can represent constraints specific to particular programs, such as various types of temporal constraints, target observation constraints, and instrument exposures. To set up the constraints, we first delineate the domain and describe its representation. We then look at how constraints can be placed on the objects in the domain to restrict the possible schedules. Finally, we look at how these constraints can help serve as a heuristic to reduce the number of possible schedules which must be examined.

The satellite scheduling domain consists of a collection of scheduling programs, where each program consists of many observations. Each observation of a target can have multiple exposures. The detector, grating, target, and exposure time must be defined, and temporal constraints can be placed on the observation date. There are constraints on the observation based on the angle of the target with respect to the sun, and each program is assigned a fixed number of US1 shifts and US2 shifts which cannot be exceeded.

The domain can be described in graphical form as:



The constraints which must be represented fall generally into two classes: the spacecraft and instrument constraints which are always in effect and the target and program constraints which vary depending upon the observations requested.

The spacecraft and instrument constraints include:

1. There are 2 cameras (spectrographic detectors) available, but only one of them can be used at a time.
2. Each detector has two different dispersion gratings, but only one of them can be used at a time.
3. The spacecraft is restricted in the angle it can take in orientation to the sun, because of location of the camera and solar panels. This restricts the time of year that a target can be observed.
4. During several months of the year, there is a range of angles to the sun which will cause on-board equipment to overheat. These are called the "hot" angles. During these months the satellite can only stay within the "hot" range for less than about 4 hours.
5. Exposures during US2 shifts are limited to approximately 1 hour.

The target and program constraints include:

1. Each Guest Observer is allocated a specific number of US1 shifts and US2 shifts which cannot be exceeded.
2. The detector, grating, target and exposure time which are to be used for each observation are specified by the Guest Observer.
3. For scientific reasons, some targets must be observed on a particular day of the year or within some narrow range of days.
4. Some programs involve multiple exposures of the same target at regular intervals for an extended period of time.
5. Other programs observe the same target several times within a few days, for example, repeating exposures continuously for 5 days.

Constraints like these can be embedded in a typed, constraint logic programming by placing information on the values that aspects of the representation can take, such as observation date, exposure time, and number of assigned slots. Because most of the constraints are on the observation date, we will look at that aspect of the representation here. To set up constraints using constraint logic programming requires a different mode of programming than traditional, procedural languages: Instead of iterating through the days to check that the angle of the target to the sun is valid, a constraint can be placed on the observation that its assigned shift fit within the appropriate range of days. Another constraint which can be placed on an observation is that the Guest Observer's request for specific days also be taken into account. These constraints can be combined using the unification operation which restricts the observation to the appropriate dates without having to completely specify the actual dates.

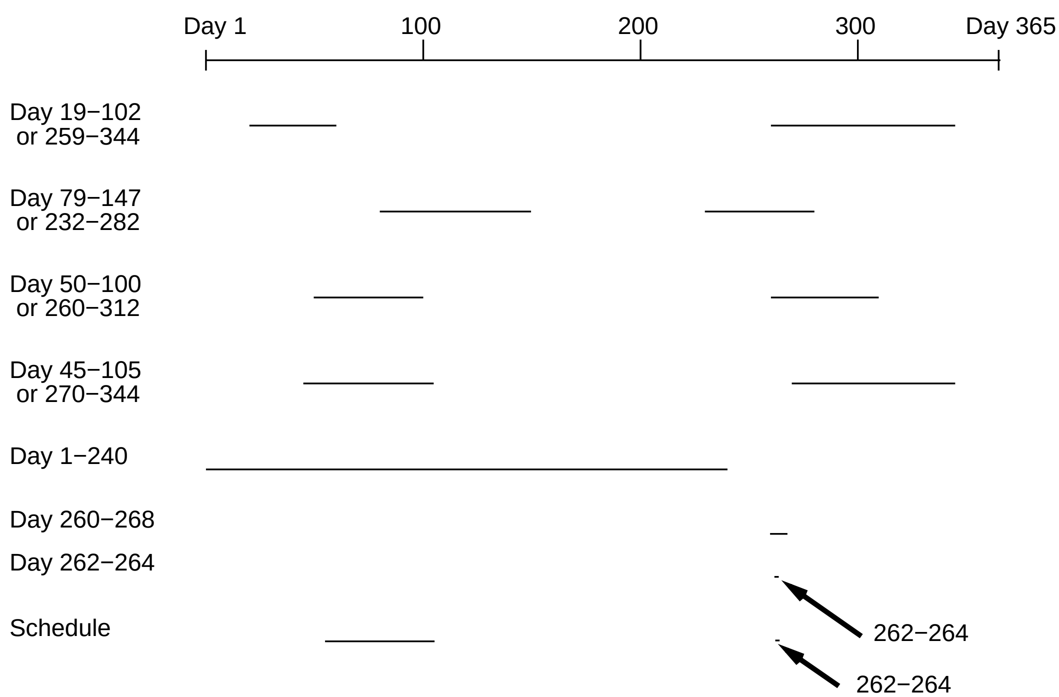
For example, if the Guest Observer requests that an observation occur between Day 55 and Day 59 of the observing year and the target is constrained to be observed either between Days 50-90 or 300-340, then the observation is constrained to be in the range Day 55-59. Mathematically, the unification of constraints which range over finite sets may be modeled as the intersection of those sets, and this can lead to efficient, straightforward implementation for simple scientific programs. However, a more realistic example is to consider a program of multiple targets with various exposure times whose schedule must be coordinated with an additional satellite.

Thus, it is useful to have a declarative representation for complex constraints. For this reason, we are using a constraint logic programming language for representing the constraints.

Consider an example program with five targets and which was assigned two US1 shifts. The restrictions to the date based on the angle to the sun are calculated from the celestial position of the target and the location of the sun on a particular day. For the five targets, the days must be in the ranges:

1. Day 19 – 102 or 259 – 344
2. Day 79 – 147 or 232 – 282
3. Day 50 – 100 or 260 – 312
4. Day 45 – 105 or 270 – 344
5. Day 1 – 240

Three of these targets must be coordinated with two additional satellites. Target one must be observed between Day 260 and Day 268. Targets two and three must be observed between Day 262 and Day 264. Based on these constraints, one shift must be assigned between Day 262 and 264, while the other shift must be between Day 45 and Day 105. This can be illustrated by the constraint diagram:



Constraints placed on the observation date restrict the schedules which will be considered, and this reduces the space of search to be considered. After the constraints reduce the search space, a simple logic program with backtracking can be used to find the possible schedules and present them to a human scheduler. Because backtracking is allowed it not essential that the observations be considered by the scheduler in any particular order. However, for efficiency it is useful to consider the observations in order of the severity of constraints on possible observation days. This heuristic helps reduce the search.

To make scheduling the observations more efficient, we would like have the most specific observations scheduled first. If one observation requires a specific date, it is scheduled for that day. Then, other observations with many temporal constraints are scheduled, such as those with many observations repeated over a period of time. Finally, the remaining observations are scheduled. But, because the most important constraint is the angle the target has with the sun, this should also be included in the scheduling. To prioritize the scheduling while including the sun angle constraint, we take the restrictions it places on the possible observation days into account while ordering the observations.

The Guest Observer's requests and the target's angle with the sun are both used as constraints on the day of the year in which the observation can be scheduled. The algorithm uses these constraints to estimate the number of days on which an observation might be scheduled. This number serves as the priority of the observation within the scheduling algorithm. The observations which are restricted to one day out of the year are scheduled first while those that have no restrictions are scheduled last.

The observations are scheduled by the priority scheduler, and then other constraints are taken into account, such as, verifying that the number of shifts assigned to a Guest Observer is not exceeded and that long exposures do not occur at "hot" angles. If a violation of these constraints occur, backtracking is performed to have the scheduling algorithm assign different dates to the observations. After a successful schedule is obtained, the human scheduler can also specify that alternative schedules be generated.

Other scheduling programs have also been written which make use of constraints for satellite scheduling, but none make use of the coarse-grained approach. Some systems, such as SPIKE,[3] use constraint satisfaction to create fine-grained schedules. One advantage of constraint logic programming over constraint satisfaction is that constraint logic programming deals with constraints in the declarative framework of a logic programming language. This allows the implementation to be directed by the variety of constraints and not the problem of satisfying them.

We note that our implementation in its present form would have to be modified to work for other satellite telescopes. However, because details of filter, exposure time, resolution or detector are mainly left to the Guest Observer to plan within assigned time blocks, our implementation should contain many elements which would be applicable to other satellite scheduling problems. Furthermore, the overarching sun-angle pointing constraint is a general characteristic of all astronomy satellites, only the range of acceptable angles varies.

4 ADVANTAGES TO "COARSE-GRAINED" SCHEDULING AND POTENTIAL APPLICABILITY TO OTHER SATELLITE TELESCOPES

There are several significant advantages inherent in a "coarse-grained" scheduling approach, which we expect would apply to some degree to all astronomy satellites.

First, it makes changing the schedule relatively easy and fast, because most shifts can be scheduled independently of one another. The schedule of science is effectively broken into interchangeable parts. For example, the science program scheduled for the US1 shift on May 1 can be switched with the US1 science program on June 20 without affecting the rest of the science programs merely because a change has occurred. A scheduling change is a mere formality as far as science operations is concerned, and does not cause a "ripple" through the following weeks of observations. This flexibility is important in maximizing the science return of the satellite because it is not unusual for astronomy science programs to have to change dates unexpectedly in order to achieve their science goals. Such changes occur for two types of reasons: 1) some important types of astronomical objects, such as supernovas, novas, and some stars which exhibit sudden "flares", always occur unpredictably and are often short-lived, so that in order to obtain useful data, the data must be obtained on short notice (hours or a few days); and 2) many science programs require that data be collected simultaneously with more than one satellite instrument, which means that a change in the schedule of one satellite may affect the schedule of another satellite. All satellite telescopes have been subject to unforeseen hardware problems from time to time which usually have required temporarily suspending data-taking, and sometimes required changing overarching observing constraints either temporarily or permanently. However, it has become not uncommon for changes in the timeline of one astronomy satellite to affect the science of another satellite because both satellites may be needed to observe the same target at the same time. In the 1990's there has become available an unprecedented array of long-lived astronomy satellites (HST, EUVE, ROSAT, ASCA, Compton GRO, and others due to be launched later in the decade) which study objects at different wavelength regions (X-ray, ultraviolet, etc.). Large multisatellite astronomy projects which require synchronized scheduling present significant new research opportunities, and have become increasingly popular, resulting in a greater need than ever for flexibility in the scheduling of astronomy satellites.

Another important advantage inherent in "coarse-graining" is that having the Guest Observer present while the observations are taken allows a rapid and efficient response to unforeseen characteristics of the target being observed. Several types of astronomical objects change in brightness or spectral characteristics unpredictably over time. Furthermore, many targets have never before been observed by a particular satellite, so a scientifically important characteristics of the data cannot be known in advance. For some variable objects or targets which are being observed for the first time, it is not practical for the Guest Observer to specify months in advance the exact exposure times needed. Instead, the Guest Observer may need to change both the exposure times and the gratings, filters, etc. used based on the physical state of the target at the time of the first exposure. The best scientific return can be obtained if the Guest Observer has a time block wherein several exposures may be taken and the freedom to alter the observing plan within that time block based on unforeseen changes, while data are being taken. Sometimes the most important information about a target comes from some feature in the data that was not foreseen. If the Guest Observer can have a quick look at the data during the time block, then later exposures can be modified to best study any significant but unforeseen characteristics. The ability to make such real-time changes in the observing plan can make the difference between a successful program and a wasted one. This approach has worked successfully for the IUE for 16 years.

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6 REFERENCES

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