KNOWLEDGE BASED AUTOMATED SCHEDULING AND PLANNING TOOLS FOR IUE

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Abstract. The International Ultraviolet Explorer has been successfully operated as a real time user-interactive space observatory for twelve years. It is expected to continue operation for up to five additional years, but under increasing constraints. The option to operate IUE in a more automated, non user-interactive mode is under consideration. A sophisticated software system to support such an operation is a clear requirement. The conceptual framework of such a system is described. Results of a preliminary tests are presented for which a hypothetical four day schedule of space-craft activities at a time resolutions as low as ten minutes was generated.

1. Introduction

The International Ultraviolet Explorer (IUE) has been arguably the most successful of all satellite observatories to date. Part of its legacy of success is a result of the mode in which it has been operated: a real time, user-interactive observatory. Guest observers have been assigned telescope time in units of eight hour blocks, and are given full flexibility for planning their observing strategies within that time (a basic familiarity of IUE operations on the part of the reader is assumed; for a description see (4; 4)).

It is now recognized however, that in view of increasing pointing constraints, or in the event of a major S/C subsystem failure, that it might become necessary to operate IUE in more automated manner, incorporating an *integrated* mode of planning and scheduling. Observations would be preplanned, with a detailed timeline derived from all guest observer programs, and little realtime capability. Careful preplanning could in principle offset the decrease in efficiency imposed by stricter constraints and possible onboard hardware failures.

The complexity of the problem would clearly necessitate a high degree of automation in the form of an off-line software system. (see e.g. (4; 4)). Efforts within the IUE project have been made to develop such a system. This effort has benefited by drawing conceptually from several existing systems, most notably the powerful STScI Scheduling and Planning Interactive Knowledge Environment SPIKE (e.g. (4)). Other systems which have been studied are the JPL PLANIT (4) system which supports Voyager activity scheduling, also see (4). I will describe my conceptual approach, and later present some test results.

2. Conceptual Background

The similarity between the methods proposed here, and the HST SPIKE system is use of a "suitability function" (SF) framework, as the primary means of constraint

Y. Kondo (ed.), Observatories in Earth Orbit and Beyond, 525–530.

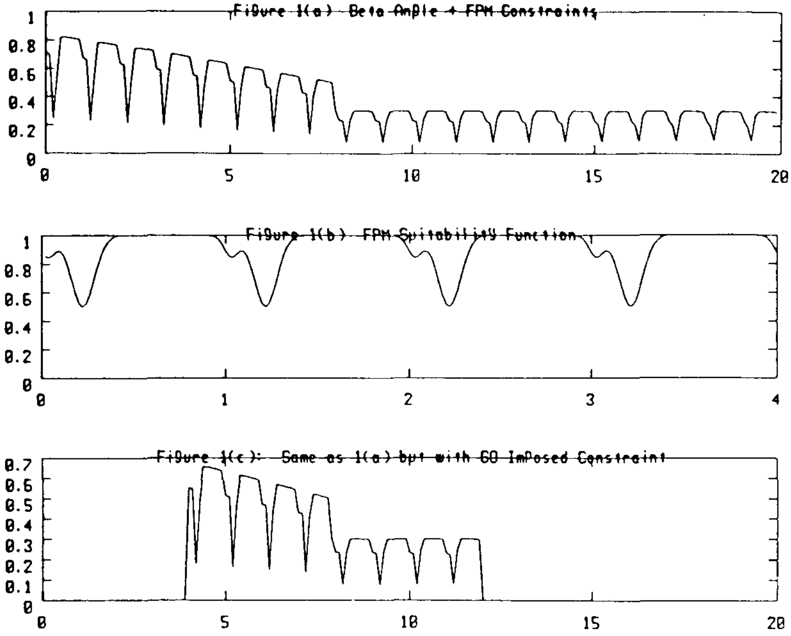

Fig. 1.

representation (4). This is an elegant and powerful technique, as should become evident. The SF for a given S/C event $S(t)$, has a probabilistic interpretation and is a function of time. The resolution of the time axis is determined by the minimum size, τ, of an activity cell to be considered. Values of $S(t)$ of order unity represent optimal scheduling situations and values tending towards zero represent undesirable or unallowed scheduling situations. Some examples are depicted in Figure 1; in Figure 1(a) only β-angles and charged particle (FPM) restrictions are considered. In Figure 1(b) the event is unconstrained with respect to β-angle; the FPM constraint is depicted at higher resolution than in (a); (c) is the same as (a) but with an additional observer imposed constraint, i.e. a window.

In addition to the SF methodology, a *Rule Based* mechanism is applied for interrelating the constraints of separate, but 'linked' events. This is where an object oriented programming language such as LISP is well suited (e.g. (4)), but out of necessity, development was done with existing resources and no LISP compiler was available. The code was written in C under VAX/VMS and run on a micro-VAX II with 5 Mb memory.

3. Detailed Description

It will now be necessary to treat consider individual **observations** rather than **observing programs**. A timeline can be represented as a series of events each consisting of a series of activities. For example, an FES image, target acquisition, followed by one or more exposures are an event in this context. Generally, one event occurs between each major spacecraft (S/C) slew. The IUE Resident Astronomers (RAs), as a part of the technical proposal review, will make entries into a knowledge base (KB) which will be used in assessing program scheduling priority and to drive a rule based inference engine for constraint handling. The RA will also estimate time and resource requirements.

The (subtle) difference between a knowledge base and a data base is that the former attempts to capture the **educated intuitive response of the human expert**, in this case in of a simple parameterization of constraints. These parameters are then combined algebraically to quantify the level of scheduling constraint for the event. This is then combined with a priority ranking based on scientific merit; the result determines the overall scheduling priority . The integrated SF over the balance of the scheduling period can also be folded into this calculation. If this is small, one should increase the priority, ie. this could be the last window of the scheduling period. The KB will also be used to treat linked event constraints, as will be described subsequently.

The SF for each event is computed and represented as a discrete vector. The vector dimension N, is the length of the scheduling interval divided by the size of an activity cell. M such vectors are used to construct an $N \times M$ matrix [S]. M is then the number of events to be considered for scheduling in the interval $N\tau$. Each column of [S] is the scheduling suitability vector for an event. Associated with each column are KB parameters as described above, including the time requirements of the event. The overall scheduling priority decreases from left to right. This is the order in which events will be scheduled, or at least be considered for scheduling. As is the case with a human scheduler, a schedule is typically derived from a pool of events larger than what can actually be scheduled. The following quantity is then optimized:

$$\chi(i_1, i_2) = \sum_{i_1}^{i_2} \left\{ S_{ij} - \sum_{k=j+1}^{M} \alpha_j S_{ik} \right\} \tag{1}$$

where α_j is a monotonically decreasing function of j of order $1/M$. The summation interval (i_1, i_2) is over the required time allocation for the j-th event; ie. $(i_2 - i_1)\tau$. The first term, $\sum S_{ij}$ is thus the integrated SF for event j. The second term, $\sum\sum \alpha S$ represents the net impact to all unscheduled events resulting from scheduling event j in (i_1, i_2). That α is monotonically decreasing reflects the hierarchal nature of the scheduling strategy; events of lower priority will contribute less to the net impact term than those of higher priority. χ is then optimized over all allowed intervals (i_1, i_2). An interval is allowed only if **every** suitability vector element on (i_1, i_2) is greater than a prespecified threshold. If no intervals are found to satisfy this condition, the event is flagged as unschedulable and the event of next highest priority is tried. After an event j is scheduled on (i_1, i_2), the elements S_{ik} in (i_1, i_2) and $k > j$ are set to zero (ie. no other event can be scheduled in this interval). The overall quality of the schedule is reflected in the parameter $E = \sum \chi(\Delta i)$ where the summation is over all scheduled events.

If all S/C activities were mutually independent, it would suffice to simply apply the above algorithm until all or most cells were occupied. However, the actual IUE scheduling problem is not so simple; events generally impact or are dependent on other events. For example:

1. Heavy saturation of a detector precludes long integrations on that detector for a subsequent period.
2. Certain types of events require phased or periodic scheduling. In such a case scheduling of one event predetermines the scheduling of subsequent ones. These are referred to as linked events.
3. It is undesirable to sequentially schedule observations of targets widely separated on the sky.

I will now describe my approach to handling linked-constraints of this nature.

Since S/C events are treated sequentially by decreasing priority, upon scheduling the j-th event, one needs to consider potential implications on only the subsequent (unscheduled) $M - j$ events, thus the size of the computational problem decreases with each step. Handling of linked-constraints is accomplished by applying a set of if-then type rules. A logical premise is evaluated on the basis of information in the KB. The consequence is a biasing of the appropriate suitability vector, e.g. consider the following piece of pseudo code:

```
Schedule event $j$ in cells $(i_1, i_2)$ For $k = j + 1$ to $M$

    If {event $j$ involves heavy saturation of the SWP}
        And event $k$ needs quiet SWP then
            Bias $S_{ik}$ on the interval $(i_2, i_2 di)$
```

The bias applied to S_{ik} is such that its elements now tend to zero for values of i in $(i_2, i_2 + di)$, where di is the length of time required for the SWP to recover. This is an example of an inhibitory bias. The quantity di can have a fixed canonical value or it can be weighted using the KB parameters. This type of inhibitory biasing can be applied for various types of linked-constraints; I have thus far considered: maneuver distances, heavy overexposures, thermal control, efficiency of instrument overhead and phased or periodic observations.

Spacecraft maneuvers are a special type of linked-constraint. Long maneuvers are undesireable, although it is unlikely that they can be eliminated entirely as thermal control and maneuvering efficiency tend to work against each other. Here, we represent each target in terms of its celestial, unit-position vector. Consider the following pseudo code:

```
Schedule { event $j$ in the interval $(i_1, i_2)$ } For { $k > j$ and $k \leq M$ }

    If { $\mathbf{R}_j$ $\mathbf{R}_k$ ¡ threshold value }
     Then { Bias { $S_{ik}$ in $(i_1 - di, i_1)$ and in $(i_2, i_2 + di)$ } }
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An inhibitory bias is applied for to activity cells preceding and succeeding event j. This discourages maneuvers longer than some prespcified threshold.

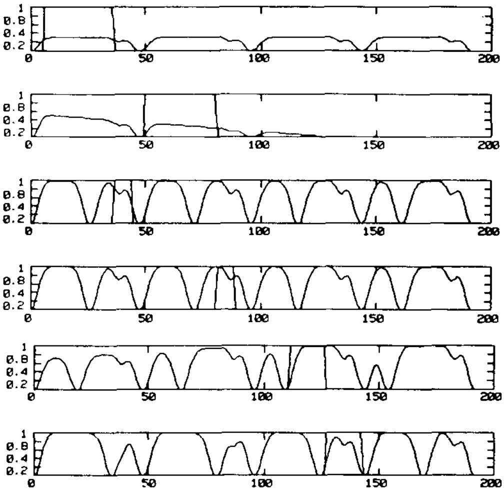

Fig. 2.

4. Test Results

I have conducted a zeroth order test employing the scheduling strategy described above, for which the following simplifications were made:

1. The smallest activity cell considered was 30 minutes.
2. Events were assumed to be mutually independent.
3. Programs were arbitrarily prioritized, except that the longest exposures were given highest priority.

Four days of hypothetical S/C events were scheduled. Events were constructed using target and exposure data from four days of actual S/C operations. The types of constraints considered were β-angles, earth occultation and FPM. Some results are depicted graphically in Figure 2. Vertical lines depict scheduled event boundaries superimposed on SF curves. Some notable features are:

1. Long exposures were set into the schedule with endpoints overlapping the wings of FPM troughs, but never centered about these troughs. Thus, FPM avoidance for long exposures was accomplished.
2. Centers of deep earth occultation troughs were avoided, e.g. Figure 2(c) and (d).
3. 95% of the activity cells were scheduled. The balance of unscheduled cells were distributed more or less uniformly over the scheduling period. Some of this could be filled by extending long integrations.
4. In cases of high scheduling priority, some situations of marginal suitability were scheduled. 18 out of the 20 highest priority events were scheduled.

A follow up, first order test, also for 4 days of S/C activities was made, this time using a more realistic 10 minute time granularity. In addition to a finer time resolution, several linked-constraints were applied. A series of periodic observations was scheduled successfully, and a heavy saturation of both primary instruments was fixed in the schedule. The SW successfully avoided following the latter by a long integration.

These initial results are encouraging and warrant further investigation.

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