Distribution of a Generic Mission Planning and Scheduling Toolkit for Astronomical Spacecraft

Contract NAS5-32800

Progress Report Nos. 2 and 3

For the period 19 October 1995 through 18 October 1997

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Distribution of a Generic Mission Planning and Scheduling Toolkit
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I. Summary

- We have continued our development of scheduling algorithms and user interfaces while awaiting launch of our spacecraft.
- We have developed a simple, fast and robust scheduling algorithm.
- We have built a novel graphical user interface implementing this algorithm.
- We are building a flight system which will be distributed as per this contract.
- We have demonstrated the success of a 'low road' approach exploiting the natural intelligence of the scheduler.

II. Outline

This contract was awarded in October 1994 to package and distribute the planning and scheduling toolkit developed for the SWAS astronomical spacecraft. At that time SWAS was scheduled to be launched on a Pegasus XL vehicle in Fall 95. The contract was to conclude in Oct. 96. Since that time, however, three separate failures in the Pegasus XL launch vehicle have delayed the SWAS launch. We have used this time to continue developing scheduling algorithms and GUI design. We can report success in both of these endeavors.

We describe a scheduling algorithm which builds robust schedules. We break the schedule into two parts, an abstract plan and a concrete schedule. We define a scheduling function that maps a plan into a schedule. We do not try to modify schedules – instead we modify the plan, which is more tolerant of change, and then quickly build a new schedule. We describe a user interface consisting of a mixer and a schedule display. The mixer allows the planner to adjust the composition of the schedule while the schedule display allows the planner to select targets and activities to go on the schedule.

SWAS is expected to be launched this year and we are now building a flight version. This is the version we will distribute to complete the contractual work.

Sections III through V below describe the new algorithm and the user interface. Section VI and VII review the scope and extent of the scheduling system developed for SWAS. Section VIII describes the plan for completing the contract. Section IX contains our conclusions.

III. Background

Planning and scheduling for spacecraft is a small but active research field. JPL, NASA/Ames, NASA/MSFC, NASA/GSFC, Carnegie-Mellon Robotics Institute and Space Telescope Science Institute all support planning and scheduling research. Most of these groups, however, derive from academic AI rather than spacecraft ops backgrounds.

The SWAS Planning and Scheduling system, by contrast, has been driven by practical considerations – it must provide a functioning scheduling system by the time the spacecraft is launched. The SWAS system also reflects eight years of experience scheduling the Hubble Space Telescope.

The main lesson that experience has taught us is that spacecraft schedules always change. The ability to modify or replan schedules quickly is just as important as the ability to produce good schedules in the first place. In real life we have often seen highly efficient schedules which had to be discarded in favor of relatively poor schedules because of changes that had to be made at the last minute. Schedules may need to be revised because of engineering tests, late-breaking scientific developments, human error or sudden inspiration but one may be assured that they will need to change. And when schedules need to change, they usually need to be changed quickly. In the case of spacecraft or receiver anomalies schedules may need to be replanned and regenerated on the time scale of one or two hours.

The need to accommodate re-planning adds new requirements on schedules. In addition to being efficient schedules should be:

- robust – changes do not disturb the rest of the schedule,
- predictable – changes are accommodated in a straightforward manner,
- conservative – changes do not undo the scheduling decisions made previously.

These criteria have driven the development of the scheduling algorithm described below.

IV. SCHEDULING ALGORITHM

Scheduling systems have always focused on the schedules themselves. Schedules, however, are difficult to modify once built. We have taken a step back and divided a schedule into two parts. The first is an abstract 'plan' that describes the activities to go on the schedule and their scheduling requirements. The second part is the schedule proper, the concrete timeline which is a realization of the plan. We can liken the plan to a blueprint of a house and the schedule to the actual construction of bricks and mortar. If we are designing houses, it is more efficient to revise the blueprints than to build and rebuild actual houses.

We start with a detailed plan or specification for the schedule. We then define a scheduling function which builds a straightforward schedule from the plan. We improve the schedule by changing the plan, not by changing the schedule. We always a build a fresh schedule each time we change the plan. We have found that this process is well behaved and we rapidly arrive at a good schedule. We have built a graphical user interface that implements this strategy. We have found this algorithm/interface combination to be a simple yet powerful scheduling tool.

Our algorithm requires a plan and a scheduling function. In the case of SWAS we are doing astronomical observations with a radio telescope. The plan consists of a list of 'activities' each of which expands into one or more observations. Each activity consists of a target, a pointing offset from the central position and an observing mode. A grid size and spacing are also defined and are used for mapping modes. The scheduling requirements for each activity are set by a sequence number or scheduling rank, the total number of orbits requested and the maximum number of orbits per day to schedule.

We have built two scheduling functions, a first-available-place and a best-available-place scheduler. A place is simply a spot on the scheduler where an activity can be scheduled. The first scheduler simply places each candidate in the first available place in the schedule. The other function searches the schedule for the most efficient place to schedule the activity. We have found that even the first available place scheduler works suitably well. For this function the time required to schedule N activities remains linear in N which leads to very fast scheduling. We can build a week's schedule on a fast workstation with minimal (~1 sec) delay. This leads to a very smooth and natural user interface.

V. GRAPHICAL USER INTERFACE

The figures described below are also available in color at

http://cfa-www.harvard.edu/~xps

We have developed two planning and scheduling desktops, one for scheduling and one for guide star selection. Figure 1 shows the scheduling desktop consisting of four parts. The visibility display is at lower right and is shown in detail as Figure 2. This planning tool displays target rise and set times as seen from the spacecraft. The scale across the top is time in minutes from the ascending node crossing. The SWAS orbital period is about 97 minutes.

The toolbar, at bottom center, manages the schedules. The system provides two copies of the schedule at any time, a baseline version and a scratch copy. The scheduler can experiment on the scratch copy and then save it as the next baseline version when it meets his satisfaction.

The scheduling mixer, at top right and Figure 3, adjusts the scheduling requirements carried in the plan. It functions like a mixer in a recording studio, changing the mix of the activities which go into the final schedule. If we see that one activity is underrepresented on the schedule, we can change its sequence number to raise its priority. If another activity is over-scheduled, we can lower its priority or reduce the number of orbits per day allowed for it.

The schedule window, at top left and Figure 4, is the main display. It shows the SWAS schedule for one week, two orbits per row. Orbital time in minutes is displayed across the top. The time in the left column is the UT time of the ascending node crossing of the first orbit in the row. The format is DOY:HH:MM, where DOY is the day of the year from Jan 1. Day 032, for example, represents Feb. 1. Scheduled activities are shown by the boxes labeled with the target name. This is a 'live' display linked to the mixer display. Clicking on a scheduled activity refreshes the mixer display to show all the activities corresponding to that target and only those activities. Clicking on a gap selects those activities which overlap that gap and could be scheduled there. This selection mechanism makes it very easy to relate the schedule to the activities on the order form. The schedule is then modified by adjusting the mix of the activities on the order form. A new schedule is automatically created whenever the plan has been changed.

Figure 5 shows the guide star selection desktop. At left is an all-sky map showing the location of the targets as the guide stars are selected. The window at right shows the field of view of the Ball CT601 star tracker used onboard SWAS. The target selector at bottom left lets us sort and select targets based on criteria such as the target right ascension, target name, quality of guide stars, the target class (e.g. giant cloud core, dark cloud core, star, and so on) and scientific interest, and visibility start time and duration.

VI. Scheduling Internals

The scheduling internals refer to the geometrical calculations such as determination of rise and set times that we need to do in support of the scheduling. We have managed to shape all of our geometrical calculations into one consistent form. We use one or more coordinate transformation as defined by the classical Euler angles to find a reference coordinate frame which simplifies or eliminates the spherical trigonometry otherwise required. To find target rise and set times during an orbit we transform to the orbital plane. To find target availability with respect to Sun avoidance constraints we transform to the ecliptic plane. To calculate spacecraft nominal roll and pointing offsets we transform to target-centered coordinate frame. The same Euler angle description also gives us the spacecraft pointing quaternion required by the onboard computer.

The SWAS planning and scheduling system must calculate the following items:

- Annual target availability. We must determine when each target satisfies the Sun constraints during the course of the year;
- Target rise and set during each spacecraft orbit;
- Spacecraft nominal roll and pointing offsets. There is no single spacecraft pointing that can be used throughout the code. We need to calculate and follow the axes of the Winston Cone thermal radiators, the star tracker active axis and the radio telescope beam axis all of which have their own offsets and rotations from the spacecraft axes;
- Waypoint positions. These are safe parking positions in the orbital plane where the spacecraft can pause briefly before the next science target becomes visible;
- Gyro calibration targets. These are spaced 90D apart but still satisfy all of the pointing constraints and have adequate guide stars. We are forced to use Earth shadow in order to satisfy all of the pointing constraints;
- Guide stars. These are selected after transforming into the star tracker reference frame.

In addition to these trigonometric calculations the planning and scheduling system is also required to:

- Calculate Doppler corrections for the Earth motion and calculate the local oscillator settings for radio telescope receiver;
- Manage 'generic' activities for targets which do not have specific activities defined in the plan. These generic activities are needed to fill gaps left in the schedule after the primary science targets have been scheduled;
- Process the binary ephemeris received from NASA/GSFC Flight Dynamics Facility. The ephemeris consists of the Cartesian position and velocity vectors. The system converts these state vectors to the classical Keplerian elements used in the orbital calculations described above.

VII. Scheduling Flow and Timeline Generation

Planning and scheduling will be done in three stages. We will receive a predictive ephemerides four weeks in advance. The first stage is a preparation stage. The ephemeris is processed, guide stars are checked and target visibilities are calculated. The second stage is the scheduling stage in which schedules are built and evaluated. A final schedule is selected and a timeline is generated in the third stage. A timeline is the detailed schedule containing all of the information needed to generate a binary command load for the spacecraft computer. The first and third stages are 'closed' in the sense that they generally will only need to be done once and will be done offline by the planner. The middle or scheduling phase is intended to be 'open' in the sense that the scheduling tool can be made available to the science group to do hands-on schedule building.

A set of observations is defined by an activity on the plan. Generally an activity will require several orbits of observing time. During scheduling each activity is mapped to different orbits as determined by the scheduling parameters assigned to each activity. Each piece of activity on a different orbit is denoted as an observing segment. The science timeline which is the end product of the planning and scheduling process at the Science Operations Center is an ASCII file consisting of a header and a list of segments. The science timeline is transmitted to the Flight Operations Team at GSFC where it is merged with engineering commanding and converted to a binary load and uplinked to the spacecraft.

Figure 6 displays the header and the first segment from a science timeline. Each timeline is nominally 24 hours long and will contain about 64 segments. The first three lines are the timeline header and contain a timeline id, starting, ending and generation times, a version number and other descriptive fields. Commanding for the first segment follows. It includes:

- Descriptive comments identifying the target, observing mode and duration;
- A pointing mode command with a command execution time. The pointing command contains the on position quaternion, the off position quaternion and unit vectors and magnitudes for five guide stars;
- A receiver tuning command which points to entries in receiver setting tables for receiver channel 1 and 2;
- An instrument configuration command containing target and segment ids and observing mode configuration information. This information includes for example the number of on position scans and off position scans for beamswitching and the number and frequency of calibration scans.

VIII. Concluding the Contractual Work

The flight version of the SWAS planning and scheduling software is essentially complete. This is the version that will be packaged for general distribution under this contract. We have started to build a world wide web site to describe the SWAS scheduler and we anticipate using this site to distribute the scheduling package.

We have used contract money to purchase a Linux graphics workstation. We have used this workstation to great advantage for developing the scheduling system. It has been a delight to do software development under Linux and we can only assert our conviction that this has been money well spent. (We are hearing rumors that even some mainstream manufacturers such as HP are using Linux PCs to do software development and then porting the code back to their main machines!)

Now that we have a working software system, we have been thinking of ways to demonstrate and publicize it. The code is lean enough that it will run quite handily on a laptop. We think it would be a most impressive demonstration to walk into a conference room and show off a fully featured spacecraft planning and scheduling system running on a conventional laptop! The planning and scheduling system we have developed with the support of this contract is a noteworthy achievement worth showing off. We plan to submit a purchase order for a laptop for your review.

IX. CONCLUSIONS

- We have developed a full soup-to-nuts planning and scheduling system for the SWAS astronomical spacecraft. This system starts with the ingestion of the binary ephemeris from GSFC, proceeds through interactive scheduling and finishes with the generation of a detailed timeline ready for command load generation.

- The system is very small (~40K lines of C code) and fast. A week's schedule can be generated in a few minutes.

- We have developed novel coordinate transformation algorithms to simplify the complex geometrical calculations required for planning and scheduling.

- We have developed a new scheduling approach, based in large part on long experience in Hubble Space Telescope scheduling, which produces robust and efficient schedules.

- We have developed an unusual graphical user interface to implement our scheduling algorithm.

- We have demonstrated the strength of a low road approach. We have not tried to pose and solve a generalized constraint satisfaction problem. We have stayed focused on the spacecraft scheduling problem at hand and have tried to exploit the natural intelligence of the scheduler. People are very good at scheduling – it is keeping track of the details that makes the task difficult. Machines, however, are very good at the bookkeeping. The design of the SWAS system exploits these complementary strengths.

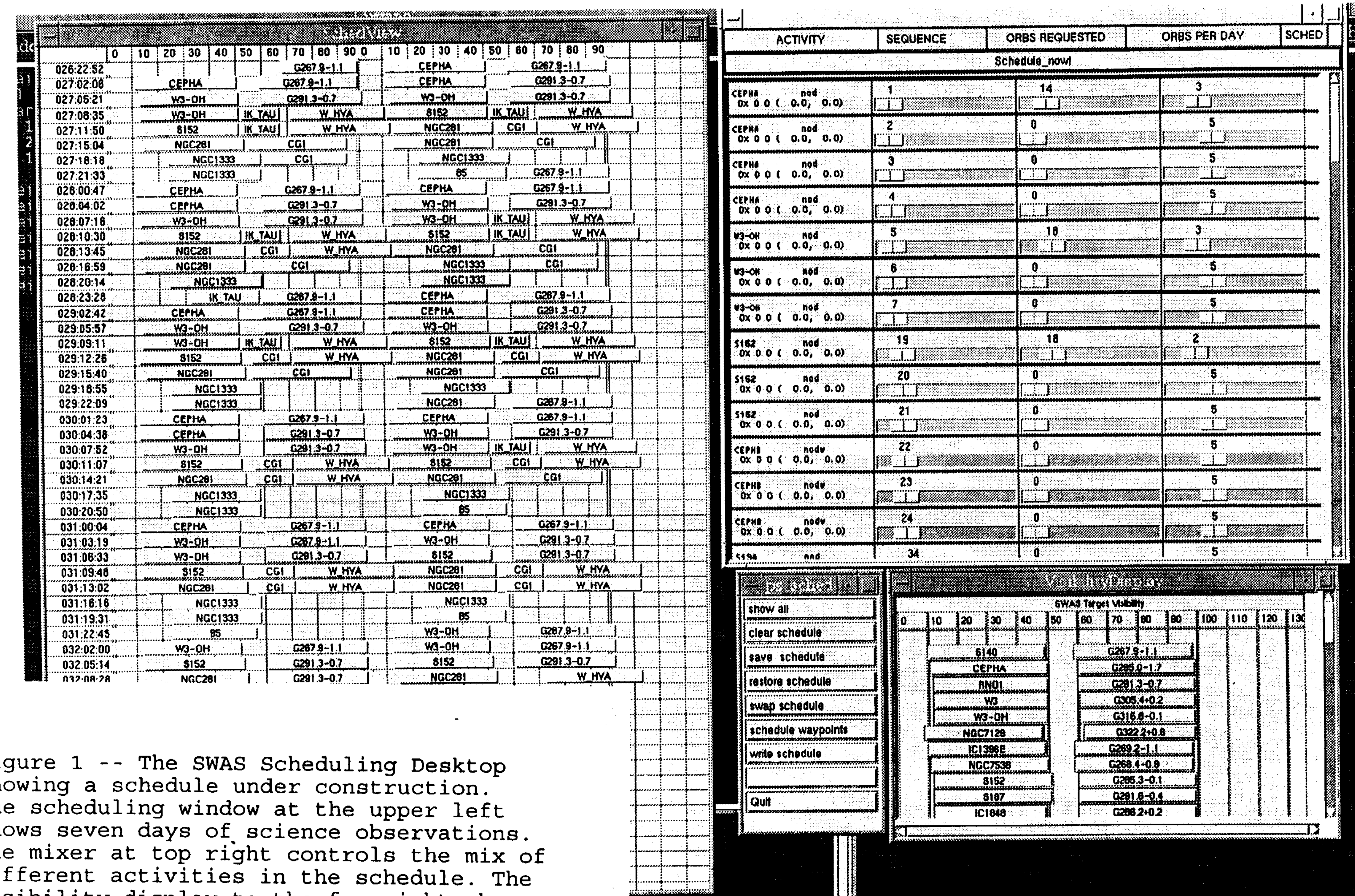

Figure 1 -- The SWAS Scheduling Desktop showing a schedule under construction. The scheduling window at the upper left shows seven days of science observations. The mixer at top right controls the mix of different activities in the schedule. The visibility display to the far right shows target rise and set times during a spacecraft orbit. The pushbuttons at right control scheduling functions.

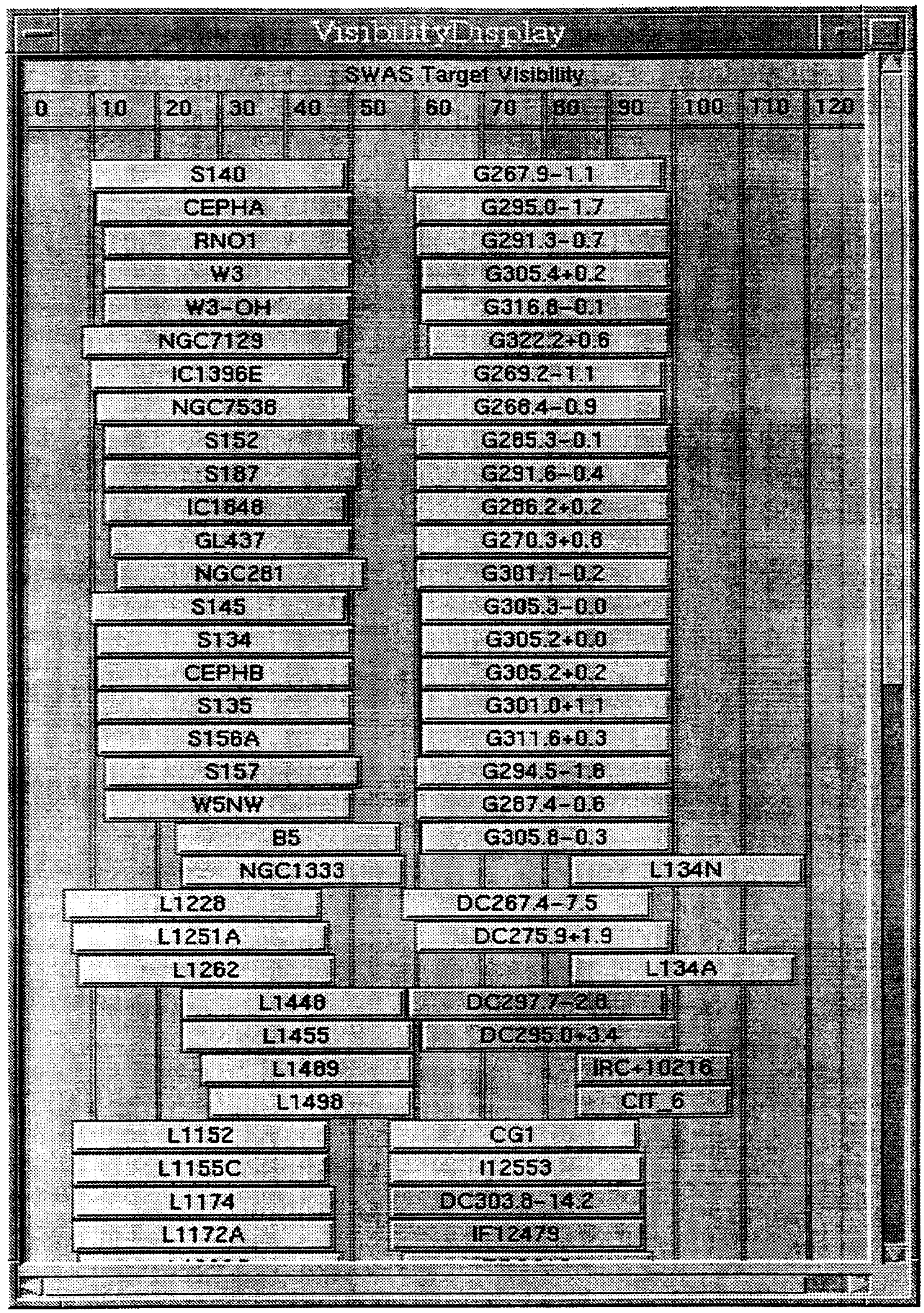

Figure 2 -- SWAS Target Visibility Display shows how each target rises and sets as seen by the space craft. The horizontal scale is in minutes from ascending node crossing. The SWAS orbital period is ~ 97 minutes. Some targets are seen to rise near the end of one orbit and set in the next orbit.

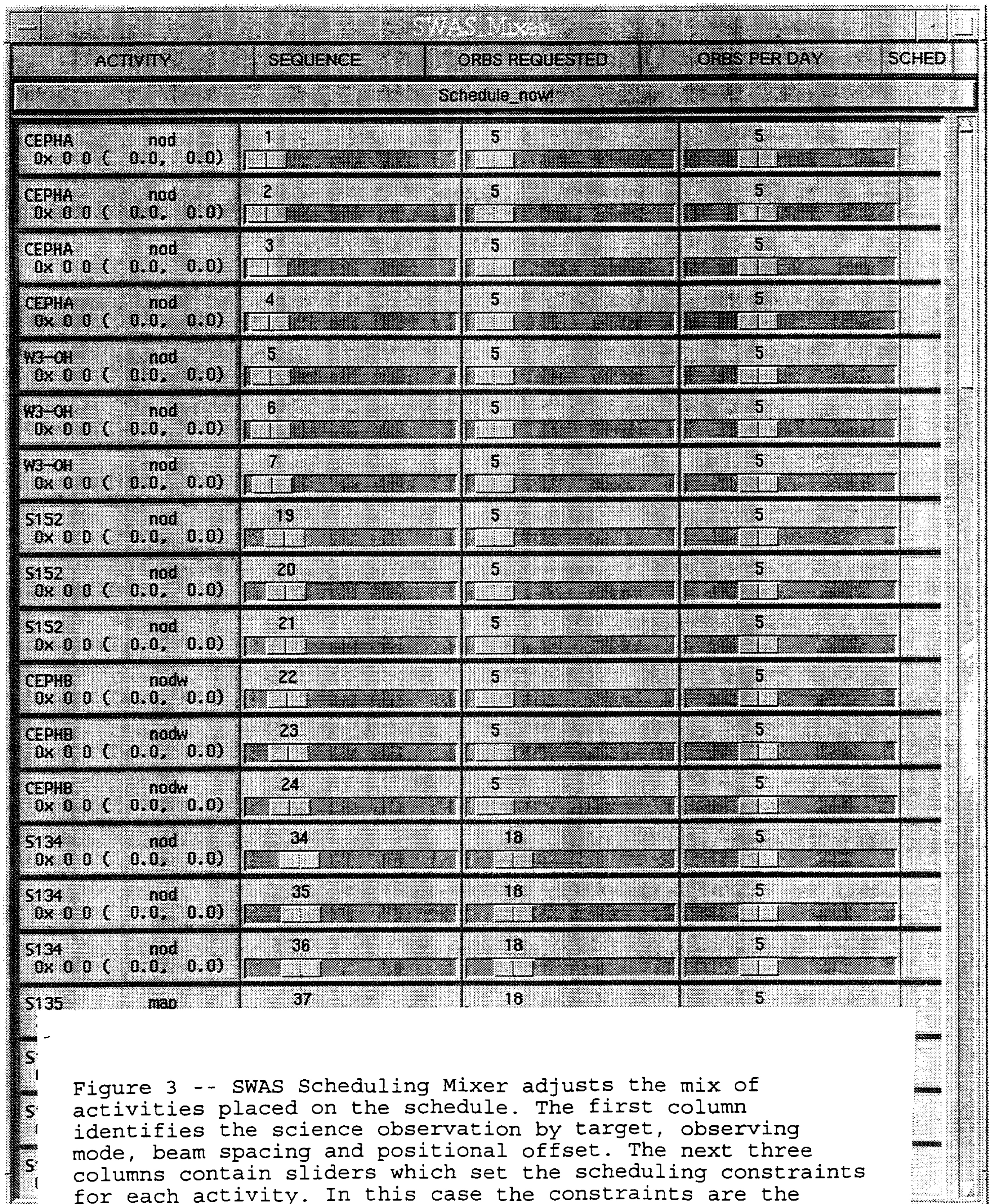

Figure 3 -- SWAS Scheduling Mixer adjusts the mix of activities placed on the schedule. The first column identifies the science observation by target, observing mode, beam spacing and positional offset. The next three columns contain sliders which set the scheduling constraints for each activity. In this case the constraints are the sequence number or rank, the total number of orbits to schedule and the maximum number of orbits allowed to be scheduled per day.

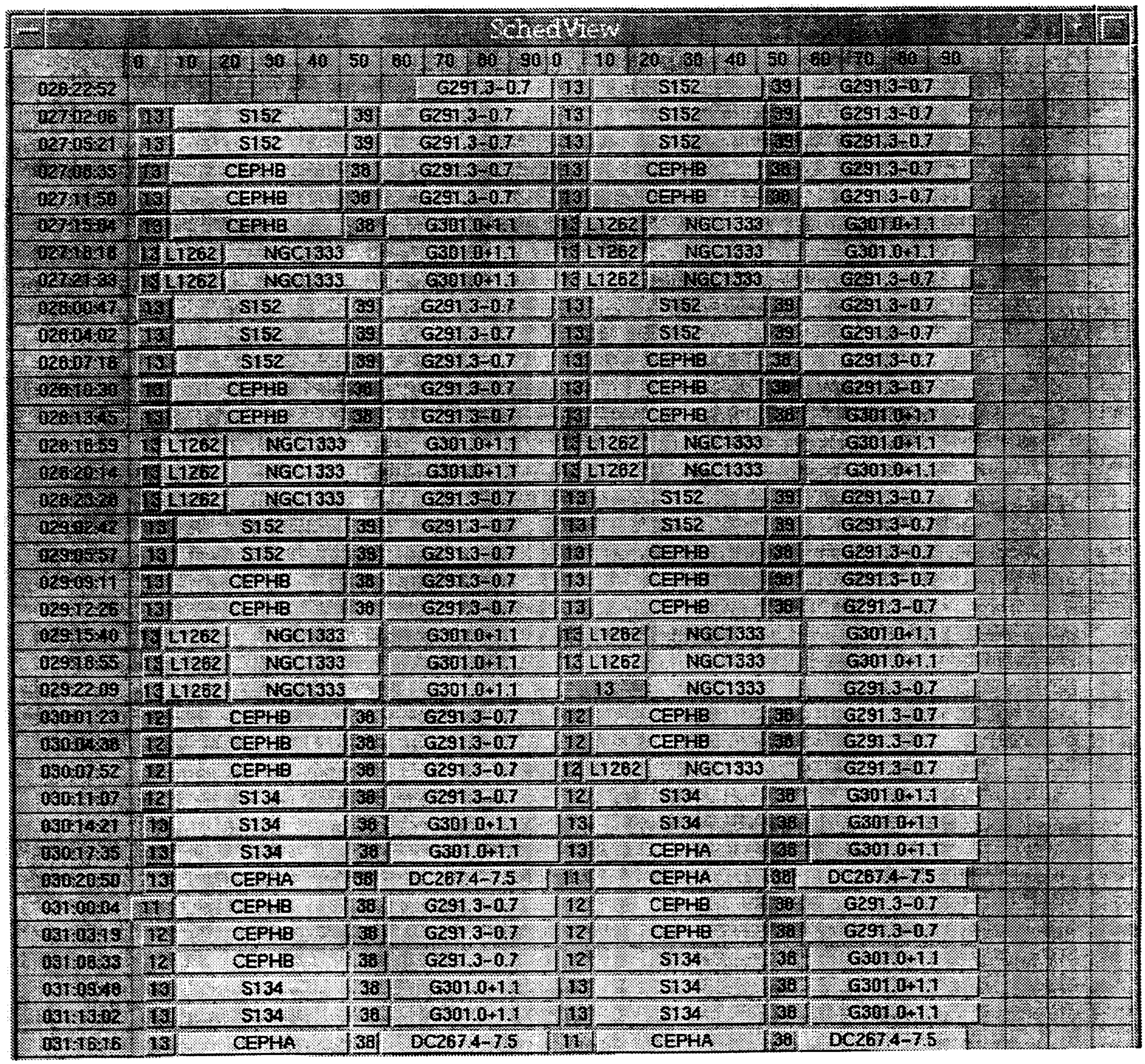

Figure 4 -- SWAS Scheduling Display shows a full week's schedule, two orbits per row. The time across the top is orbital minutes from the ascending node crossing. At left is the ascending node crossing time as DOY:HH:MM.

The larger blocks are science observations labeled with the name of the target. The smaller blocks labeled only with a numeral represent waypoint targets. The spacecraft is parked here briefly between science targets. (Waypoints are generated automatically after science scheduling is completed.)

This is an interactive display. Clicking on a science observation displays all the observations scheduled for that particular target. Clicking on a gap between science observations identifies all the observations which can be scheduled in the gap. After a few moments this interface becomes very natural and schedules can be built and modified with surprising speed.

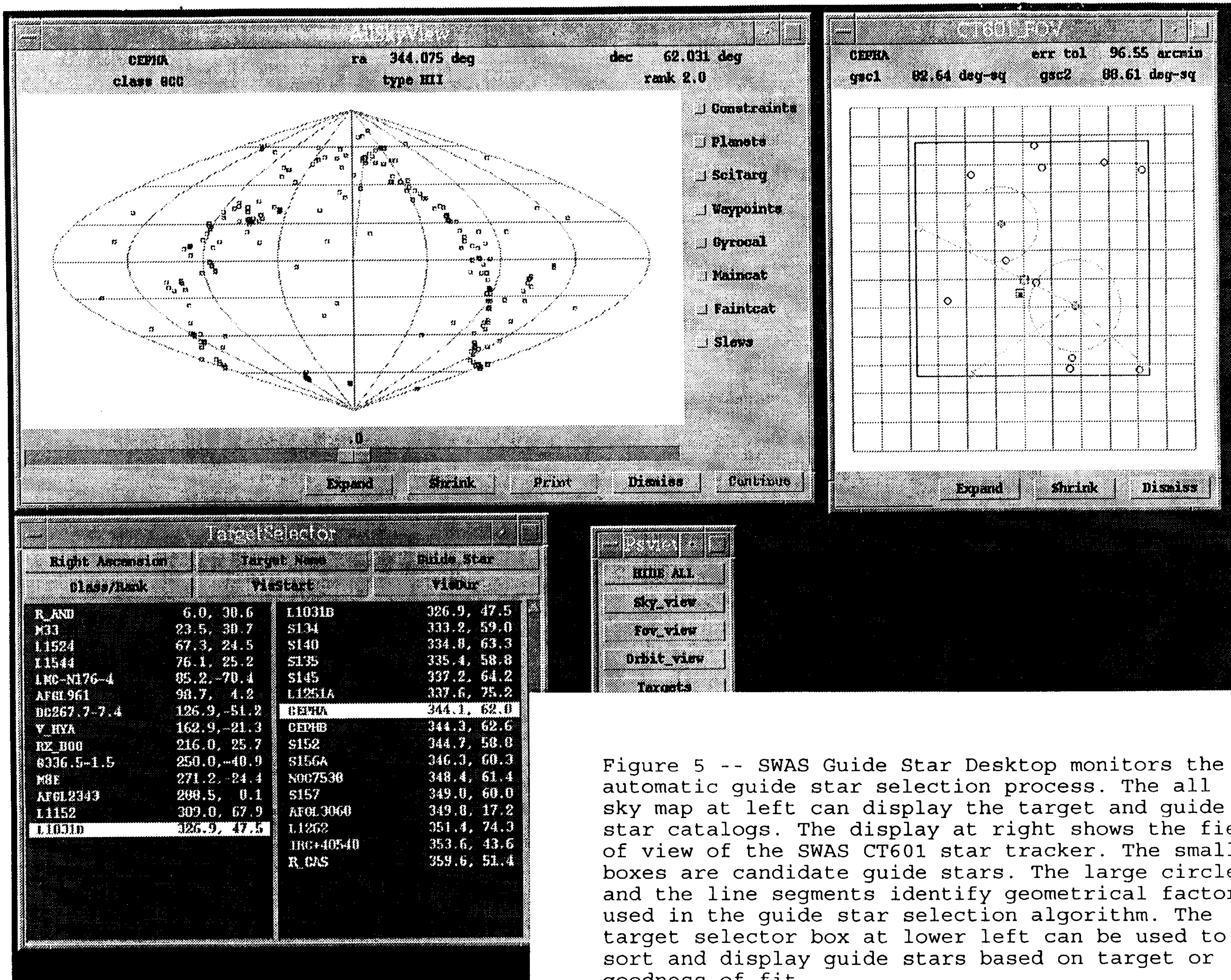

Figure 5 -- SWAS Guide Star Desktop monitors the automatic guide star selection process. The all sky map at left can display the target and guide star catalogs. The display at right shows the field of view of the SWAS CT601 star tracker. The small boxes are candidate guide stars. The large circles and the line segments identify geometrical factors used in the guide star selection algorithm. The target selector box at lower left can be used to sort and display guide stars based on target or goodness-of-fit.

```
W97029REGOTL.01,    1996:306:23:00:40, SWAS, SAOSOC,  1.00, SCS,
                    1997:029:00:00:00, 1997:030:00:00:00, YES,
                    REGULAR, 01, NONE, LAUNCH AND EARLY ORBIT;

//----------------------------------------------------------------------
//
//  W3-OH              nod                  dur: 19.79 min
//  ra 36.7617   degrees     dec 61.8725   degrees
//
1997:029:00:00:00   CMD   AMNNOD(
        RFOVWIN     =              30,       NORS,
        ONQ1        =      0.23790394,       ONQ2        =   0.04951129,
        ONQ3        =      0.87910349,       ONQ4        =  -0.41003341,
        OFFQ1       =      0.24495487,       OFFQ2       =   0.05380933,
        OFFQ3       =      0.87272868,       OFFQ4       =  -0.41886312,
        S1X         =      0.38942440,       S1Y         =   0.21230980,
        S1Z         =      0.89625510,       S1M         =           58,
        S2X         =      0.31743010,       S2Y         =   0.26074290,
        S2Z         =      0.91172980,       S2M         =           81,
        S3X         =      0.44324610,       S3Y         =   0.27879130,
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        S4X         =      0.34308230,       S4Y         =   0.33115820,
        S4Z         =      0.87899310,       S4M         =           90,
        S5X         =      0.39287330,       S5Y         =   0.19962340,
        S5Z         =      0.89766420,       S5M         =          88);
1997:029:00:00:01   CMD   CLOTBLSET(
        CHAN1       =              28,       CHAN2       =          76);
1997:029:00:00:02   CMD   CICCONFG(
        SEGMNTIDX   =        759000,      TARGETID    =          124,
        SEGMNTNUM   =             0,      SEGMNTREP   =            0,
        OBSMODE     =             2,      CHOPPER     =            1,
        NUMONS      =            20,      NUMOFFS     =           20,
        ONSPEROFF   =             1,      CYCPERCAL   =            8,
        CYCPERCOMB  =             4,      CYCPERZERO  =            0,
        NUMCALS     =             1,      NUMCALSCAN  =            2,
        NUMCOMBS    =             1,      NUMZEROS    =           0);
```

Figure 6 -- Start of SWAS Science Timeline, the end product of the SWAS Planning and Scheduling System. The header at top identifies the timeline. The first segment describes a position switching or 'nodding' science observation of the molecular line source W3-OH. The pointing command at 00:00:00 slews the spacecraft and provides on and off quaternions and guide star data. The Local Oscillator Table Setting command tunes the spectral line receiver. The Instrument Controller Configuration Command identifies the observation and supplies observing parameters. There will be about sixty-four segments in each twenty-four hour timeline.

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15. Supplementary Notes

16. Abstract

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