Flexible Scheduling of Automatic Telescopes over the Internet

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Abstract. This paper outlines a new telescope operations paradigm that is intended to achieve low operating costs with high operating efficiency and high scientific productivity. The paradigm is based on the existing *Principal Astronomer* approach used in conjunction with ATIS, a language for commanding remotely located automatic telescopes. This paper describes a telescope management system called the *Associate Principal Astronomer*, or APA. At the heart of the APA is automatic observation loading and scheduling software, and it is this software that is expected to help achieve efficient and productive telescope operations. The purpose of the APA is to make it possible for many astronomers to submit observation requests to, and obtain resulting astronomical data from, a remotely located automatic telescope. All communication is conducted via the Internet in a highly-automated way that minimizes day-to-day human management of the system and that maximizes the scientific return from observing time.

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1. Introduction

This paper presents an instance of a new paradigm for telescope operations. The general paradigm is based on the idea of specifying an observing request in a programming-language-like fashion and sending this specification to a telescope that is able to automatically execute it. The instance of this paradigm discussed in this paper is based on one particular language for specifying observing requests: the Automatic Telescope Instruction Set, or ATIS(Boyd, *et al.*, 1993). ATIS has recently undergone formalization by the International Astronomical Union, and the result is ATIS93, a language well-suited for specifying both observing requests, and, interestingly, the order in which those requests should be executed. This paper discusses ATIS-based telescope operations and presents a general design for a system that works with ATIS telescopes. The system is called the *Associate Principal Astronomer*, and it is designed to support multiple astronomers accessing a remotely located, fully automatic telescope, over the Internet.

2. Background

Research-quality telescopes located at prime observing sites have always been a scarce resource, and astronomers have typically had to work with extremely limited access. With manual observations, observing time is allocated to an individual astronomer a few times per year in short contiguous blocks of a few nights each. Furthermore, an astronomer has needed to be physically present at a given telescope in order to operate his or her instrumentation for data acquisition. Limited access, block allocation, and local operation have restricted both the amount of data that can be gathered and the type of observational campaigns that can be accomplished. In recent years, two new observing paradigms have been developed to overcome the problems associated with this traditional telescope operations model.

2.1. Teleoperation

Electronic network and communication technologies have enabled a new observing paradigm where astronomers may participate in an observation program from a remote location. Various approaches have been considered, from remote verbal communications with the on-site telescope operations staff, to actual remote control of a telescope with real time video feedback (see Emerson and Clowes, 1993). Such approaches to remote observation provide flexibility by allowing the observer to be physically distant from the telescope yet to remain in direct control. However, even with this remote observing paradigm, an astronomer must still be involved during the execution of an observing program, and human presence at the observatory is often still required. We refer to this paradigm of remote observation as *teleoperation*, since an astronomer is in direct control of the telescope while his or her observational campaign is performed.

There are a number of problems with teleoperation as a telescope operations paradigm. Primarily, a telescope is not used *efficiently*, and this is a result of a number of factors. First, while teleoperating a telescope, an astronomer repeatedly decides which object to observe next. When making such a decision, the telescope is often idle, waiting for a command from the astronomer.

A second inefficiency in teleoperation results from *block allocation* of observing time. Block allocation typically means that an astronomer is given a number of consecutive nights of observing time on a given telescope. With fine-grain block allocation, an astronomer is given a number of consecutive hours of observing time on some particular night. Allocating a block of time is the only way that teleoperation can work effectively, since it is unrealistic to expect each astronomer to establish a long-distance connection to the telescope, make a single observation, and then disconnect. The overhead of such single-observation teleoperation sessions is simply too great.

Whether allocation of time is in terms of blocks of nights or blocks of hours, the result is similar: during the time that a given astronomer has control of the telescope, no other astronomer's observations can be made. This decreases the operating efficiency of the telescope, since the particular block of time assigned to a given astronomer might not provide observing conditions suitable for that astronomer's campaign. For instance, if the astronomer is planning on doing high precision photometry, and if the hours for which the astronomer is given the telescope have extremely thin cirrus cloud cover, then those hours are wasted, since high precision photometry is impossible. However, to a spectroscopist, those hours are not without merit. Thin cirrus clouds simply result in longer integration times for spectroscopic observations.

Finally, another problem with teleoperation as a paradigm for remote observing is that it can be extraordinarily tedious for an astronomer to carry out repetitive observing sequences. Repetition can occur within a single night, as it is often necessary to observe the same star under a number of different conditions (at different airmasses and at different times of the night). Repetition can also occur over a number of nights, as it is often necessary to observe a star for months, or years, in order to obtain a meaningful account of the star's long-term behavior. For such observational campaigns, teleoperation is an inappropriate and inefficient way to use an astronomer's valuable time.

Rather than require an astronomer to be in remote control of the telescope whenever data is acquired, it is possible to allow the astronomer to specify his or her observing campaign in a domain-specific programming language. This idea gives rise to a rather different remote observing paradigm, that of fully automatic execution.

2.2. Fully automatic execution

Fully automatic telescopes represent an alternative to teleoperation, allowing an astronomer to be removed from the telescope in both space and in time. For example, Fairborn Observatory (Mt. Hopkins, Arizona) has designed and built software and hardware systems for the control of modest-aperture telescopes equipped with photoelectric photometers. These systems make it possible for a remotely located telescope to operate unattended for significant periods (up to a number of months). These telescopes execute commands provided by an astronomer in such a way that the astronomer is not required to participate in the execution of the observing program. It is in this sense that these telescopes are *fully automatic*. (Genet and Hayes, 1989, describe automatic photoelectric telescopes in some detail.) While the majority of existing ground-based automatic telescopes are used for aperture photometry, automation support for spectroscopy and imaging has been increasing (primarily due to the efforts of R. Kent Honeycutt and Don Epand; see Boyd, *et al.*, 1993).

This paper is concerned only with the fully automatic telescope operations paradigm; however, before we continue, it seems reasonable to consider the conditions under which teleoperation is more appropriate than automatic execution. Suppose, for instance, that an astronomer's observing campaign cannot be algorithmically expressed, that is, written down as a program. Clearly, this astronomer must be in direct control of the telescope at the time of observing. Additionally, if observations to be made depend heavily on what has just been observed, and if there is significant human judgment required to determine the particular observations to make, then teleoperation is a reasonable mode of operation. However, when the observing program *can* be algorithmically expressed, and when the sequence of observations is not decided on-the-fly by human judgment, then fully automatic telescope operation is more appropriate and significantly more efficient than teleoperation.

3. An example of fully automatic execution

In this section we first introduce the Automatic Telescope Instruction Set and then discuss the sort of fully automatic telescope operations that it supports. We also briefly evaluate the performance of some telescopes that use this language in order to better define the problems that our software system is intended to solve.

3.1. The Automatic Telescope Instruction Set, ATIS

For the automatic telescopes we are considering, the language used to define observation requests is the Automatic Telescope Instruction Set, or ATIS (Boyd, *et al.*, 1993). In ATIS, a *group* is the primitive unit to be scheduled and executed. A group contains commands to move the telescope, to control the filters, and to gather data in a defined sequence. In the initial version, ATIS89, the only instruments accommodated were photometers, but the most recent version, ATIS93, also includes commands to obtain CCD camera images.

In addition to specifying the syntax and semantics for observation requests and results, the ATIS standard provides a set of *group selection rules* that are used to determine the execution order of groups during the night (see Genet and Hayes, 1989). The group selection rules provided by ATIS essentially implement a first-to-set-in-the-west policy: at any given point in time the telescope observes the star that will set next. Other group selection rules provided by the ATIS standard deal with factors such as priority and execution count, but the first-to-set-in-the-west rule typically dominates group selection.

3.2. How ATIS-based telescopes work

The left half of figure 1 shows the overall flow of requests and results in an ATIS-based telescope operations system.

First, an astronomer forms a set of groups to achieve the scientific goals of his or her observation campaign. For any given automatic telescope, there is

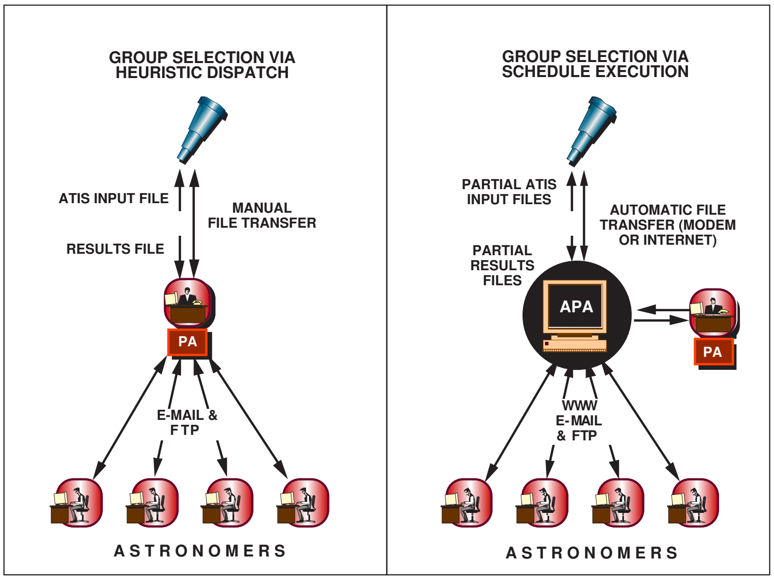

Figure 1. Life, before (left) and after (right) the APA.

a single *Principal Astronomer* or PA. The PA manages the set of requests that are loaded onto the telescope. Thus, once an astronomer has assembled a set of ATIS groups, these are sent to the appropriate PA, typically via electronic mail (e-mail) or by the Internet's File Transfer Protocol (FTP).

The PA collects together requests from participating astronomers and attempts to ensure that the total set of groups is reasonable – that the telescope load makes good utilization of observing time and is fair to all participating astronomers, that there are appropriate groups for quality control and data reduction, and so on. Then the complete set of groups is sent to the computer that controls the telescope. Communication between the PA and the telescope control computer is typically carried out using personal computers connected via the Internet or over modems and phone lines. The important aspect of this communication is that the PA can be located anywhere on the planet (in principle) and need only have access to some sort of communication link.

The telescope controller uses its built-in ATIS group selection rules to implement a form of heuristic dispatch scheduling (see Genet and Hayes, 1989). At any point in time, the rules recommend a single group to execute next. The groups are executed by the telescope controller for some number of nights (often months); eventually, the PA requests from the controller the results that have been collected thus far. The collected data are returned to the PA as an ATIS results file (the format of which is also specified by the ATIS standard). The results include the raw data obtained from the observations, as well as a chronological record of the groups that were executed and relevant observing parameters to help with data reduction. The PA edits this results file and sends each astronomer the pieces corresponding to his or her requested observations (again, typically via e-mail or FTP). In some cases the PA provides a basic data-reduction service, returning reduced results, not just raw data.

3.3. ATIS-based telescopes can work extremely well

One of us (GWH) has been working as a PA for a number of years with automatic telescopes. Together with Louis Boyd (of Fairborn Observatory) acting as principal telescope engineer, several telescopes have been operated automatically on Mt. Hopkins in southern Arizona to accomplish a wide variety of different scientific programs.

The efficiency of operations for these telescopes has been estimated to achieve a dollar-cost-per-observation that is 30 to 40 times cheaper than previously possible using traditional manual telescope operations (see Henry, "The Fairborn/TSU Robotic Telescope Operations Model", this volume). There has also been an enormous increase in observational efficiency: the combined *yearly* output of the automatic telescopes managed by GWH would require a *lifetime* of effort to obtain by previous manual methods of operation.

Cost and efficiency are not the whole story, of course. Of paramount importance is the precision with which measurements can be made. Henry (see "The Development of Precision Robotic Photometry", this volume) has demonstrated an order of magnitude improvement in automatic telescope photometry, and measurements of millimagitude precision are now routine. This is a dramatic improvement when compared to previous manual photometric observations.

Another benefit of the ATIS operations paradigm is the ability to pursue extremely long-term observing campaigns. Some of the Fairborn telescopes, mentioned above, have been used in support of campaigns lasting many years. In differential photometry, it is common to attempt to measure the light curve for a given variable star. When a variable star has very long periodicities, obtaining sufficient data can be very difficult. ATIS-based fully automatic telescopes directly address this long-term data acquisition problem. For instance, Fairborn telescopes have been used to obtain data on chromospherically active stars like λ Andromedae for the last 12 years (see Henry, "The Development of Precision Robotic Photometry", this volume, figure 13).

3.4. But there are problems with ATIS operations

There *are* some problems with the current operation of ATIS-based telescopes. Most of these problems relate to the way in which the ATIS group selection rules order astronomers' groups for execution at the telescope.

First and probably most important, the group selection rules can easily give rise to a horizon-to-horizon "thrashing" behavior. The ATIS group selection rules start observing stars in the west. The rules specify that the star that is about to set next be observed next (all other things being equal). Under the guidance of these rules, the telescope tends to work its way through the given set of groups, moving from the telescope's western observing limit towards the meridian. The telescope then proceeds towards its eastern observing limit, making measurements of stars as they move towards the meridian. If the telescope reaches the eastern limit before dawn and if the PA has requested multiple observations of groups in anticipation that the telescope might be underloaded, then the ATIS group selection rules instruct the telescope to return to the western observing limit to make another observation of the next star to set. During this observation, however, new stars can have risen in the east, some of which are defined as targets by existing ATIS groups. The group selection rules instruct the telescope to move to the east in order to observe these newly risen stars. Once they have been observed, however, the group selection rules instruct the telescope to return again to the western observing limit to observe the next star to set. This limit-to-limit thrashing behavior can continue for the remainder of the night.

This thrashing behavior has the unfortunate result of making observations through very high airmass. Ideally, and all other things being equal, observations would be made only near the meridian, as it is there that the airmass is minimal for a star of a given declination. Of course, all other things are rarely equal, and it is often necessary to make observations well off the meridian. However, with better scheduling, it is possible to prevent this sort of limit-to-limit thrashing behavior (Drummond, Bresina, and Swanson, 1994).

The thrashing is essentially a result of under-loading the telescope with respect to the default ATIS group selection rules. The entire concept of under-loading is only defined with respect to a particular scheduling policy, in this case, the default ATIS rules. It is also possible to overload a telescope. Using the ATIS group selection rules, an overloaded telescope starts at the western observing limit, but never makes it all the way across the sky to the eastern limit; indeed, with sufficient overloading, the telescope might never make it as far as the meridian. It is important to realize that these sorts of under-loading and overloading behaviors are defined only with respect to a given scheduling policy. The behavior of the telescope is a function of the groups that it is given *and* the policy by which those groups are scheduled for execution. With a different scheduling policy, but with the same set of groups, entirely different execution behavior can be obtained.

Unfortunately, with ATIS89, there is no way to change the scheduling policy "on the fly". The rules by which the scheduling policy are implemented are fixed in ATIS89, so the only variable that can be controlled by a PA is the set of groups sent to the telescope. Thus, to correctly load an ATIS89 telescope, a PA must carefully judge the number of groups that he or she sends to it. Too many groups, and the telescope will be overloaded. Too few, and it will be under-loaded (and will probably thrash). Thus, with improper loading, observations will either not be accomplished at all or will be accomplished at a greater airmass than is strictly necessary.

To date, each of GWH's automatic telescopes has been dedicated to a specific, long-term observing program. The operating schedule for each telescope has been extensively tuned by GWH to achieve excellent loading and, thus, good overall telescope performance. However, even small changes to the observing program make it very difficult to optimize the loading and scheduling. For multi-user telescopes, and for varied observing campaigns, this sort of extensive manual tuning is impractical.

Another problem with the ATIS operations paradigm is that there is no provision for multi-night loading of observations onto the telescope. Any given ATIS telescope has a set of groups, and this set is active on any given night during the year. The definition of an ATIS group does provide a range of dates on which it can be executed, but within this range, the group will be executed without regard to what has happened in the past (or, indeed, with regard to what might happen in the future). In essence, there is no "memory" between successive observing nights. For example, there is no way in ATIS to express the requirement that a particular group should receive a higher priority on some given night if that group has not been observed as desired on a previous night. To accomplish this, the PA would have to manually tune the priorities of all groups from night to night. Thus, it is clearly impractical to provide any long-term loading capability for astronomers if that capability has to be manually implemented by the PA.

4. Problems solved by the APA

It is possible to improve upon the default ATIS group selection rules by using more sophisticated scheduling techniques (Drummond, Bresina, and Swanson, 1994). Specifically, it is possible to improve the quality of observing data by more precisely scheduling groups so that observations are taken at lower airmass (on average), and so that observations are obtained at astrophysically interesting times. Additionally, for a multi-user telescope, better scheduling can result in a fairer allocation of telescope time to requesting astronomers. By implementing a database of observing requests and some historical information regarding their execution history, it is also possible to more effectively load the observations over multiple nights according to astronomer-defined constraints and preferences.

We are building a system to achieve these goals. Our system is called the Associate Principal Astronomer, or APA. It is an "associate" to the PA in the sense that it is responsible for handling the low level day-to-day details of ATIS group management. It is responsible for collecting observing requests (expressed in ATIS), for loading those requests over multiple nights, for scheduling the requests within each night, for monitoring their execution throughout each night (and for rescheduling when things go wrong), and for returning the resulting data to astronomers as soon as it is available. The goal of our project is to have the APA provide automation support for all aspects of the management of ATIS-compatible telescopes. Our focus is on providing software tools to help a PA who represents a community of participating astronomers.

The APA is based on ATIS93 (Boyd, *et al.*, 1993), which represents a significant extension over ATIS89 in a number of ways. We were invited to be part of the International Astronomical Union ATIS93 standardization committee to assist with ATIS extensions in support of advanced scheduling. In collaboration with other committee members, we designed a new group selection advice statement (see Bresina, *et al.*, 1994). This new statement is used to override the default ATIS group selection rules. The committee also agreed on a mechanism for communication with an ATIS-based telescope controller in terms of partial input and partial output files. Together, these new features make it possible to implement a non-native (*i.e.*, external) scheduler that can effectively drive an ATIS93 telescope controller to better serve the scientific objectives of participating astronomers. Using the new capabilities of ATIS93, the APA is able to effectively schedule for and communicate with remotely located automatic telescopes.

5. A day and a night in the life of the APA

In essence, the APA is a three-way moderator, moving information between the telescope, the PA, and the telescope's users. The right half of figure 1 and the following scenario illustrates "a day and night in the life of the APA" to help explain the nature of the APA's role.

5.1. From an astronomer's perspective

There are basically two ways that an astronomer can submit an observing request to the APA. First, an astronomer can use the world-wide web ("the web") to create and submit a request.[1] The APA provides a web "form" that an astronomer fills out; this form allows the astronomer to define his or her groups and to then submit them to the APA's database. We are using a version of George McCook's *create* program (McCook, 1991) as a back-end for these forms. Our system captures the user's form-based specification and converts it into input that is appropriate for *create*, which in turn converts the specification into pure ATIS instructions.

The form-based interface allows each astronomer to list the requests that he or she has in the APA's database, to access the data generated by the execution of any given group, and to delete (or edit) any given group that he or she owns. Alternately, an astronomer can use basic Internet e-mail to send a message to the APA. Such messages can contain requests to add a group to the database, to list the groups that are contained in it, to delete a group contained in it (which must be owned by that astronomer, of course), or to access the data produced by the execution of any given group. For simplicity, our discussion assumes the electronic mail method of group submission, since it is the more common of the two.[2]

Suppose that an astronomer creates an ATIS93 observation request file and sends it via e-mail to the APA. The mailed file is automatically received and parsed to check for syntax errors. If the file adheres to the ATIS93 specification, then the APA e-mails a message back to the astronomer acknowledging successful receipt of the request; otherwise, a message is e-mailed back identifying the request's syntactic errors. Once the request has been accepted, the astronomer is free to go about his or her day-to-day business, while the APA and the telescope take care of the newly submitted requests. At the end of each observing night, the APA e-mails the astronomer a message containing pointers[3] to the data files

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[1] The web is to documents as the Internet is to computers. While the Internet provides a mechanism for connecting a number of computers together through a common protocol, the web provides a means of linking together hypertext documents that reside on different computers located throughout the Internet.

[2] Access to the web requires a direct connection to the Internet via TCP/IP; e-mail access requires only a gateway of some sort.

[3] Each file pointer is actually a Universal Resource Locator, or URL. A URL is a compact way of naming a protocol, a computer, and a file that resides in the directory system of the given computer. FTP is one possible protocol, but the protocol used by the web is known as HTTP, which stands for HyperText Transfer Protocol.

that were generated by the execution of his or her requests, along with the results necessary for data reduction and data quality assessment.

5.2. From the PA's perspective

The PA is responsible for scientific aspects of telescope use, while the APA is responsible for telescope administration. The PA's real expertise is in ensuring that the telescope is performing useful scientific observations, and in setting the general policy by which the APA schedules observations. The APA provides a number of displays and analyses to help the PA determine whether or not the telescope is performing useful science. The APA does not, however, attempt to offer any advice in this area, since such judgments are based on intuition and many years of scientific experience. In addition to scheduling, the APA takes care of ATIS bookkeeping, syntax checking, accounting, and distribution of observing results.

The APA divides the overall problem of group scheduling into two subproblems: first, it assigns a group to execute on a specific set of dates; second, for any group that has been selected for execution on the current date, it assigns specific times throughout the night at which that group should be executed. The first process is called *telescope loading*, and the scope of time that it covers includes many months. The second process is called *night scheduling*, and the scope of time that it covers includes the hours, minutes, and seconds that occupy a given night. After performing group loading and night scheduling, a new combined ATIS93 file is automatically assembled by the APA and sent to the telescope.

The PA can check how the telescope controller will execute the new request file by displaying a prediction of telescope behavior for the night. This prediction is based on the best schedule found by the night scheduler. The APA's predictions regarding how this schedule will be executed assume that nothing will go wrong during the night. Of course, errors in execution do occur: a cloud obscuring a star can make a group abort, for instance, and an abort causes an execution failure for the current schedule. (Dynamic rescheduling deals with this problem, and is discussed below.) If the PA is satisfied with the nominal schedule, then nothing more needs to be done. If the PA is not satisfied with the nominal schedule, then the APA's scheduling policy can be modified and the scheduler re-run. (Various interface controls are available to the PA that define the APA's scheduling policy.)

The next morning, the results from that night's observations are already stored at the APA, and astronomers who have obtained new data have already been notified via e-mail. If the PA wants to assess the quality of the night's observation schedule and results, the actual telescope behavior can be displayed. Once the PA has tuned the APA to consistently produce high quality schedules, the APA takes care of routine observation loading and scheduling with only occasional supervision. The PA must remain vigilant with respect to scientific quality, however. The APA makes no attempt to ensure that the observing results are serving the needs of the telescope's users. Such scientific and engineering judgment is left firmly in the hands of the PA.

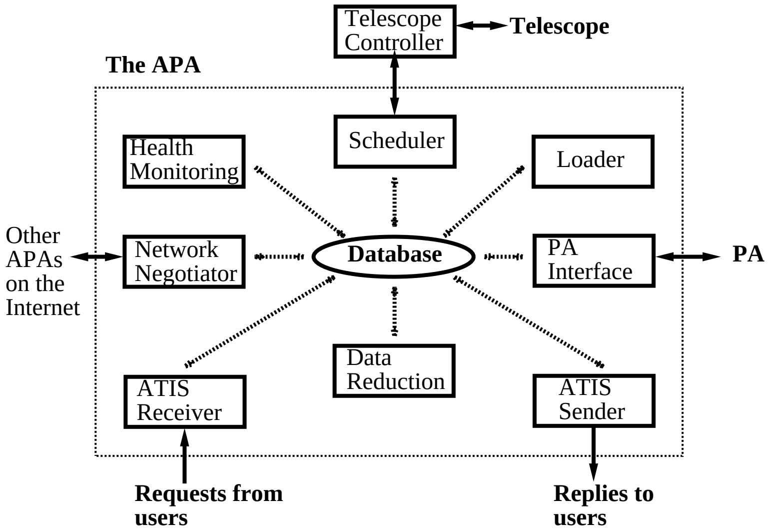

Figure 2. Block diagram architecture of the APA.

5.3. From the telescope controller's perspective

Just before nightfall, the ATIS93 input file is automatically transferred to the telescope controller along with the observation schedule. The controller executes the schedule and, at the end of the night, transfers the ATIS93 output file back to the APA. Such an interaction is ideal but rarely realized, since the schedule can break during execution. Schedule breakage is a result of unpredicted (sometimes, unpredictable) events occuring during execution, such as a cloud obscuring a star during automatic acquisition. The ATIS93 specification was designed with this in mind, however. ATIS93 allows for partial input and partial output files to be transmitted between the APA and telescope controller during the night. The partial output files enable the telescope behavior and status to be monitored during the night – either by a person (for example, to check the status of the telescope mechanics and optics) or automatically by the APA. Partial input files enable the APA to transmit new schedules and new groups during the night as necessary.

6. The architecture of the APA

This section provides an overview of the architecture of the APA. It covers the basic mechanisms by which the APA connects together the community of astronomers, the PA, and the telescope.

6.1. Architecture components

Figure 2 shows a block diagram for the architecture of the APA. Central to the APA is the database of ATIS requests, shown in the middle of the figure. This database contains all users' ATIS requests, together with the data that these requests have generated. It also contains information regarding the telescope itself: filter set, observing window, latitude, longitude, elevation, PA scheduling preferences, and other relevant parameters to allow for effective telescope management.

The figure also shows a number of components that extract data from, and enter data into, the database. Included among these components are the scheduler, loader, PA interface, ATIS sender, data reduction, ATIS receiver, network negotiator, and health monitoring.

Briefly, the eventual goal for the network negotiator is to have the APA be able to work with other copies of itself on the Internet, handing off and accepting observing requests as conditions warrant.[4] In terms of health monitoring, the goal is to have the APA able to spot long-term trends in telescope behavior and to make recommendations regarding possible mechanical, optical, and electrical faults, together with suggestions for their correction. It should be possible to integrate existing work on automated telescope monitoring (for instance, see Monahan, Patterson-Hine, and Iverson, "Automated Telescope Monitoring and Health Diagnosis", this volume). Such integration is an interesting area for future work.

For now, the network negotiator and health monitor functions are simply place holders and are discussed no further. We also do not say much about the data reduction function shown at the bottom of the figure; for now, we are using algorithms written by one of us (GWH) that are specific to a particular telescope and observing program. These algorithms have been ported by Don Epand (of Fairborn Observatory) to run under Unix, and we have simply incorporated his work into the APA. Don Epand is working on a more general version of GWH's data reduction system, and we hope to incorporate it into the APA as and when appropriate. Thus, the focus of this discussion is on the ATIS receiver, scheduler, loader, PA interface, ATIS sender, and on the database that binds them together.

6.2. Activation, loading and scheduling

The basic process within the APA is a clocked loop that counts down to sunset at the telescope site. We refer to this clocked loop as the *activator*, since it is responsible for activating various parts of the APA at appropriate times of the day and night. At a fixed time before sunset at the telescope, the activator "freezes" the database. During the day, requests are received from the telescope's community of users by the ATIS receiver, parsed to ensure validity, acknowledged, and then incorporated into the database. Freezing the database means that any request received after this time will not be considered for execution during the coming night. When the database is frozen, users are still able to submit requests, of course; requests received after the database is frozen for the current night are simply not considered for execution until after the database is unfrozen just after dawn.

Once the database is frozen, the activator starts the loader in order to determine the nights on which each group should be considered for execution. The loading process is sketched graphically in figure 3. The loader examines the telescope's execution history (contained in the database) to see when each group ran last. It also examines execution constraints that have been imposed

[4] Using multiple copies the APA distributed over a network, it should be possible to implement a globally coherent observing system of the sort outlined by Crawford (1992).

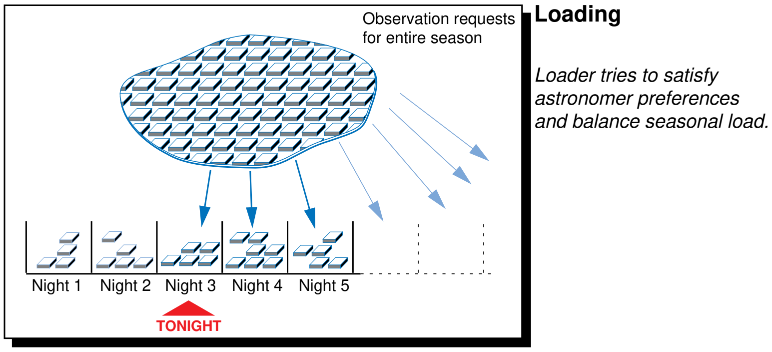

Figure 3. Assignments made by the loader.

by each astronomer on his or her ATIS groups. These constraints take the form of metric temporal expressions on the execution count and inter-execution gap length. For instance, an astronomer might specify that she is interested in no fewer than 10 observations, that she requires no more than 20, and that each observation in the sequence should be scheduled every other night. The loader takes into account all such execution constraints, posed by all astronomers, and attempts to find an assignment of groups to nights that satisfies all constraints and astronomer preferences as much as possible. The details of this process are beyond the scope of this discussion; see Bresina (1994) for more information.

The result of the loading process is an assignment of groups to nights, stretching for months into the future. The coming night is, of course, the first night in this sequence. The activator process next starts the night scheduler in order to find a good sequence in which to execute the coming night's groups. The scheduler searches over various possible execution sequences, eventually selecting one that scores well according to various PA-defined attributes. This process is shown graphically in figure 4. The scheduler is given a mathematical statement of what constitutes a good schedule. This mathematical statement is called an *objective function*, and is a weighted sum of various schedule attributes. The scheduler uses the objective function to search a space of possible schedules. The objective function is used as a heuristic to guide the search – it allows the scheduler to make informed tradeoffs about which particular group to execute at which particular time.

It is important to note that the interaction between the loader and the scheduler involves some feedback, since the loader evaluates the potential performance of the scheduler on any given potential load. This feedback allows the loader to form a set of groups for each night that the scheduler can effectively sequence. However, the details of this process are beyond the scope of this discussion; see Bresina (1994).

The result of scheduling is a set of ATIS93 instructions that tell the telescope controller the order in which to execute the given set of groups (these ATIS93 instructions encode the schedule). The APA assembles a file that contains the selected groups for the coming night, together with a schedule that dictates how they should be executed. More detail on these ATIS93 instructions and how they are generated by the scheduler is available elsewhere (Bresina, *et al.*, 1994).

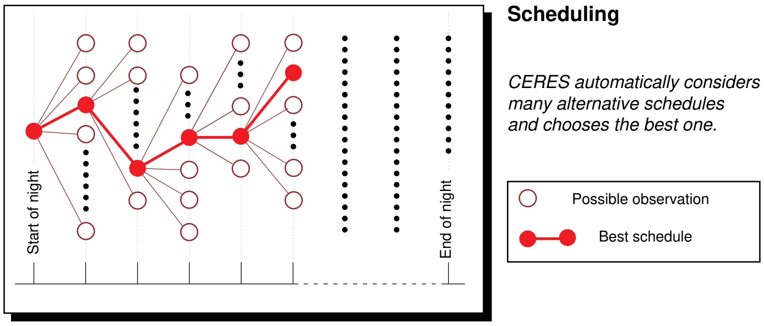

Figure 4. The scheduler's search space.

6.3. Schedule execution and dynamic rescheduling

At a pre-specified time, the telescope controller takes the schedule file from the APA via FTP.[5] The semantics of the schedule is defined in the ATIS93 standard. Thus, any telescope controller that understands ATIS93 is able to execute an APA-produced schedule. At the appropriate time, the telescope controller rolls off the observatory roof (or opens the dome) and starts executing groups as specified by the schedule.

The telescope controller is able to send partial ATIS93 output files to the APA throughout the night. The presence of a partial output file is detected by the APA, and, in general, is taken to mean one of two things. Either, the partial output file just represents a report on the telescope controller's current status; in this case, the APA simply updates any active tracking displays and continues watching for files, since no particular response is required by the controller. Alternatively, the partial output file can represent a schedule break, in which case the telescope controller is expecting the APA to produce a new schedule. The APA can easily distinguish between the two cases by examining the contents of the partial output file. If the presence of the partial output file represents a schedule break, then the waiting scheduler is given the break information and is asked for a new schedule that covers the remainder of the night (the scheduler takes into account what has already been executed up to the break). The APA and the telescope controller continue through the night in this manner, passing ATIS93 partial input and output files back and forth, communicating current status and new schedules as required.

While this dynamic rescheduling can handle execution errors, the APA goes one step further, attempting to avoid such errors when possible. The APA uses a technique called Just-In-Case scheduling to form robust schedules. A robust schedule is one that is less likely to break during execution. The Just-In-Case technique forms contingent schedules to cover likely schedule breaks; for more information on Just-In-Case scheduling, see Drummond, Bresina, and Swanson (1994).

If, for some reason, the communication link expires, then the telescope controller "falls back" on its native ATIS group selection rules. This scheme allows the telescope controller to continue executing the given set of ATIS groups, even

[5]This transfer can be accomplished via other protocols and communications mechanisms such as Kermit, if necessary or desired.

without the benefit of the APA's scheduling advice. We call this the "principle of independent competence", since the telescope controller is able to schedule and execute groups with or without the help of the APA. Of course, schedules produced by the APA are typically much better than those produced by the ATIS group selection rules. However, we feel that it is better for the controller to go ahead and execute some groups, rather than sitting idle, waiting for a better solution that might never arrive.

In the morning, the APA examines the database to see which astronomers have obtained new data. An e-mail message is composed for each such astronomer, informing him or her of how to obtain the data. The message is composed and sent by the ATIS sender component of the APA architecture (shown in the lower right hand part of figure 2). The activator process then queues itself to run again the next evening, at which time the entire procedure starts again.

6.4. Displays and controls for the PA

The APA provides a number of interface tools so that the PA can examine and customize the process described above. These interface tools provide a means for the PA to track down execution problems, to examine the contents of the ATIS database, to watch the telescope's behavior in real-time, and to tune the scheduler's search engine.

The execution analysis tool provides a set of routines for examining ATIS output files in order to find patterns of successful executions and aborts. These tools extract data from ATIS output files over a range of dates and plot that data in a manner specified by the PA. For instance, the PA can request a plot of abort types in terms of star magnitude versus star color index; such a plot shows the correlations that exist between abort type (the reason for a failed execution) and the characteristics of the star being studied. (See the APA project web page for some example displays.)

The APA also provides graphical displays of the contents of the ATIS database, allowing the PA to see the users' requests in a variety of different formats. There are also a couple of tracking displays that are updated automatically during schedule execution through the night. One school of thought suggests that these tracking displays represent a tremendous retrograde step, since one of the goals of ATIS-based operations is to let all astronomers (including the PA) sleep at night while the telescope is busy collecting data. However, we feel that such tracking displays should be useful for detecting problems in real-time, and hopefully, will be used only every now and then.

Finally, we have plans for a class of interface tools that allow the PA to tune the APA's scheduling search engine. These tools are not yet implemented, but our plan is to make it possible for the PA to set the weights on all terms within the scheduler's objective function. Adjusting the weights of terms within the objective function is a way of expressing relative preference over the different attributes of a good observing schedule. It is still too early to say how successful this sort of tuning mechanism will be, but we eagerly look forward to completing our first implementation and subsequent testing.

6.5. Tools used to construct the APA

Our approach in constructing the APA has been to use high performance, free, off-the-net software. We have done this to ensure that the APA can be freely distributed and modified by others. The ATIS parser has been implemented using variants of Lex and Yacc, Unix tools for building lexical analyzers and compilers. As a result, it should be easy to modify the parser to work with a new version of the ATIS language (whenever a new version is defined), or to work with another telescope control language altogether. The ATIS database has been built on top of the Gnu database management (GDBM) system.[6] The interface is written entirely in Tk, a library of graphical tools that works with the X11 windowing system. The framework that holds all the APA utilities together is written in Tcl, the tool command language, designed to work well with Tk.[7] (See Ousterhout (1994) for more information on Tk and Tcl.) The core of the scheduler is written in "C", with surrounding support routines written in Perl (Wall and Schwartz, 1994) and Tcl.

7. Implementation and testing status

In the spring of 1994, we first implemented and tested a LISP-based version of the APA's scheduler. Testing of this system was carried out on a telescope simulator, and on a 10" telescope located in Ft. Collins, Colorado. These early tests demonstrated that it is possible to improve upon the scheduling offered by the default ATIS group selection rules. Various astronomers (including one of us, GWH), also made it quite clear that scheduling was only part of the overall story, and that if our goal was to produce a useful telescope management tool, we would have to address the entire life cycle of an ATIS request, from first submission to final release of the data. We also realized that LISP, powerful as it is for prototyping, is not the language of choice among astronomers. Thus, we made the commitment to redesign the entire system in the more commonly accepted "C" language.

The complete system is still undergoing construction, but most parts of it now exist. We have implemented the ATIS parser and database and have built a graphical tool that allows a user to employ the parser to construct a database from raw ATIS files. We have built a suite of execution analysis tools and are currently evaluating them on live data obtained from the automatic photoelectric telescopes located on Mt. Hopkins (the telescopes are managed by Louis Boyd of Fairborn Observatory). The new C-based version of the scheduler is almost complete. Preliminary tests suggest that it is able to generate a schedule for an entire night in about 60 seconds. This performance is perfectly acceptable for deployment on a real telescope, but we must exercise the scheduler in a closed-loop dynamic rescheduling context before making any specific performance claims. To this end, we are collaborating with Fairborn Observatory on

[6] GDBM is available from the Free Software Foundation. A place to look on the web is `http://csugrad.cs.vt.edu/manuals/gdbm/gdbm_toc.html` .

[7] Tk and Tcl are available from various FTP sites around the Internet, primarily from the University of California at Berkeley. On the Internet, see `ftp://ftp.cs.berkeley.edu/ucb/tcl/` .

a new ATIS93-based telescope. This telescope will be located at Fairborn, and its controller will implement enough of the ATIS93 command set to allow it to execute APA-produced schedules and to allow the APA and telescope controller to communicate throughout the night (as discussed in the previous section). The loader currently exists in prototype form only, written in LISP.

We have also developed a set of prototype web forms that allow an astronomer to specify observing campaigns. These forms are based on a proposal by Louis Boyd (Boyd, *et al.*, 1993) for a goal-directed observation specification language. These forms are also connected to a version of McCook's *create* program (McCook, 1991), in order to allow an astronomer to specify the groups that are part of any given campaign.

8. Discussion

The overall goal of our project is to provide automation support for the management and use of remotely located, automatic telescopes. So far, we have focused on building the core of an Associate Principal Astronomer, or APA. This core consists of an ATIS parser and database, automatic group loading and scheduling mechanisms, together with a means for executing schedules automatically and dynamically rescheduling as necessary. Experience gained with simulation tests and preliminary runs on a single automatic telescope have been very encouraging.

It is clear that there are other instances of the fully automatic execution paradigm. Others have built APA-like systems (Richmond, Treffers, and Filippenko, 1993). The primary advantage of the APA is that it uses advanced loading and scheduling techniques and that it operates with any telescope that adheres to the ATIS93 standard.

Of course, NASA has a number of orbital telescopes that are operated remotely. The Hubble Space Telescope (HST), for instance, is operated in a way that is somewhat similar to our APA paradigm. However, there is a significant amount of human infrastructure associated with the management of HST. Such infrastructure is expensive, and it cannot be replicated for every single telescope that is to be run automatically. Clearly, the human infrastructure surrounding HST performs useful tasks that our APA paradigm ignores: for instance, helping users formulate their telescope requests and helping users make sense of the data they obtain. Our APA paradigm leaves all such tasks firmly in the hands of the telescope users (and their scientific community).

Additionally, since HST is an orbiting telescope, and since it costs many millions of dollars, the human infrastructure is well-justified: nothing can be allowed to go wrong with the telescope, or a lot of money and time will be wasted. The telescopes for which the APA paradigm has been developed are rather different: they tend to be cheap (on the order of hundreds of thousands of dollars, not millions), and they are bolted to a platform with essentially infinite inertia (the Earth). Thus, many of the delicate operations issues that arise for HST simply do not come up for our telescopes. A human infrastructure the size of that required for HST is clearly unreasonable for one of our target telescopes. Our APA operations paradigm requires one workstation (or a high-end personal computer), one experienced astronomer to act as the telescope PA, and an engineer to fix the telescope and observatory control systems when things go wrong.

The goal of this paper has been to provide an overview of the APA operations paradigm, and to explain, in general terms, how it is being built. We hope to soon report on specific results obtained by using the APA to manage a number of remotely located, fully automatic telescopes.

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