Leveraging Planning Tools to Demonstrate the Feasibility of the OpTIIX Public Outreach Mission

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Abstract

OpTIIX is a proposed NASA technology mission that will demonstrate the ability to build and deploy a telescope on the International Space Station (ISS). The primary goal of the mission is to demonstrate the robotic assembly of a telescope in space, and the use of wavefront sensing technology to adjust multiple segment mirrors to achieve diffraction limited observing. In addition to the technology demonstration, the mission has a goal of supporting public outreach to school children and interested amateur astronomers. This paper describes how existing planning tools were used to provide a proof of concept for the OpTIIX mission.

Introduction

When proposing the construction of a new astronomical observatory, in space or otherwise, the primary concern is whether or not an observatory can be built that meets the primary science and technology goals of the mission within the desired costs and schedule. Much of verifying mission goals involves hardware concerns such as mirror size, stability, and detector sensitivity. Examining these concerns can tell us whether individual observations or observing modes are possible. However, the ability to plan and schedule a set of observations that achieve the entire observing program is critical to showing that a mission is feasible. Often the desire to show scheduling feasibility is required early in the mission planning process before the mission is approved and limits on hardware capability have been determined. In addition, planning feasibility studies are often required to be produced quickly and at low cost. This paper shows how tools developed at STScI for HST and JWST operations were used to determine the feasibility of scheduling public outreach observations for the OpTIIX mission.

The rest of the paper reads as follows. We first overview the goals of the OpTIIX mission and then present OpTIIX scheduling constraints and observation requirements. We next describe the OpTIIX ground system architecture and a proof of concept system. Experimental results are then presented showing how OpTIIX observing requirements can be met.

The OpTIIX Mission

OpTIIX (**Op**tical **T**estbed and **I**ntegration on **I**SS e**X**periment) is a testbed for technologies for future large optical space telescopes. One such technology is the robotic assembly of telescope components in space. OpTIIX will be packaged and launched in separate parts, and then robotically assembled on ISS. Another technology is laser metrology and wavefront sensing and control. The optical system of OpTIIX will be controlled and adjusted on a daily basis with the goal of achieving diffraction-limited performance. The telescope will have a 1.5-meter primary mirror consisting of 3 actuated segments, wavefront sensing instruments and an imaging camera.

An additional component to the OpTIIX mission is public outreach. OpTIIX will have an imager capable of producing high quality asotronomical images. The mission includes an education and public outreach aspect where students can obtain images and learn about astronomy. In addition, amateur astronomers will have the chance to propose their own observations. The main focus of this paper is to present a proof of concept system that shows that the public outreach component of the mission is feasible.

OpTIIX Scheduling Constraints

The telescope module of OpTIIX will be mounted on a 3-axis gimbal. As the whole OpTIIX unit will be fixed to ISS (Figure 1), the area of sky the telescope can observe at any time is limited by the flexibility of the gimbal, which is currently designed to have +/- 90 degree azimuth, +20/-45 degree elevation and +/- 20 degree field of rotation. In addition, the following scheduling constraints need to be satisfied:

- Sun occultation. No target can be observed unless the Earth occults the sun from ISS's point of

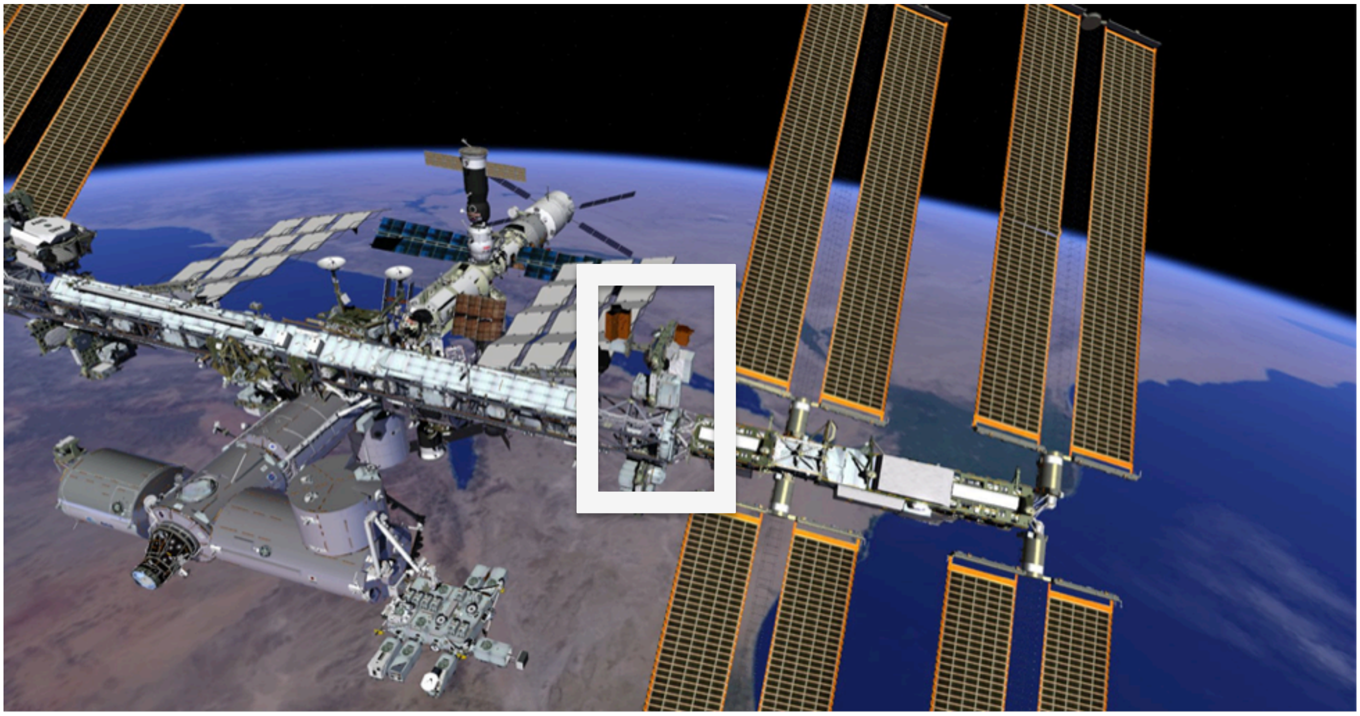

Figure 1: OpTIIX as mounted on ISS

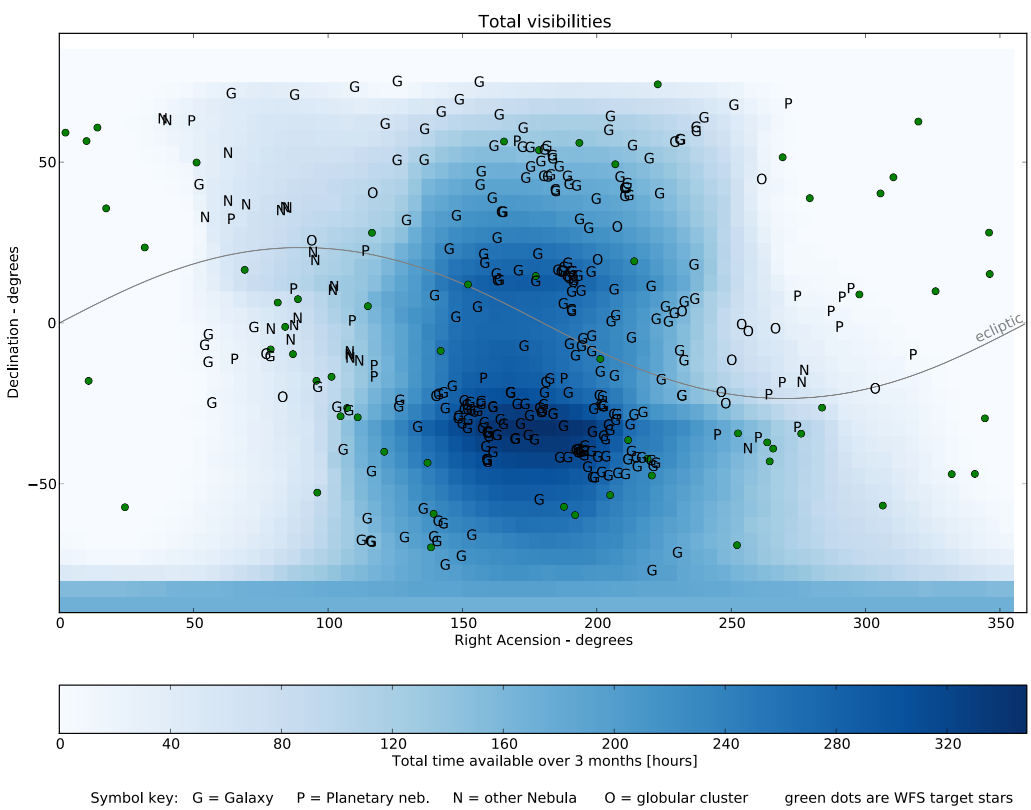

Figure 2: Total OpTIIX target visibility time in hours over the 3 month period with potential outreach targets in overlay.

position during the sunny portion of the ISS orbit.

- Moon avoidance. The target has to be separated from the moon by a to be decided amount.
- South Atlantic Anomaly (SAA) avoidance. No observation can be performed while ISS crosses over the high radiation region near South America.
- Guide star availability. A guide star has to be available on a fine guidance sensor to track the target.
- ISS exclusion. OpTIIX cannot be used during certain ISS activities (e.g. Soyuz dockings).

The sun occultation constraint makes more than half of ISS's 95-minute orbit unusable for observations. However, it simplifies the scheduling as the constraint makes the start and end of target viewing time the same for most of the targets that are observable in an orbit.

Figure 2 shows the amount of visibility per region of the sky over a three month planning period. The visibility was calculated for a 5-degree x 5-degree grid of the entire sky. Potential outreach targets are shown on the plot with a letter coding.

OpTIIX Outreach Requirements

Currently the lanuch of OpTIIX is scheduled in the spring of 2015. The mission will have three phases, the first to launch and install the telescope, the second to do wavefront sensing and control activities to adjust the mirror segments. In the third phase, public and education outreach observations will be conducted. Our primary role at STScI for the mission is the operation of the public and education outreach activities, including:

- Creating observations for public outreach
- Presenting these observations to the public and schools
- Scheduling selected observations
- Processing the downloaded data and distributing the the images.

For web-based interface with schools, we are teaming up with Micro-Observatory at Harvard (http://mo-www.cfa.harvard.edu/) (Sadler *et al.* 2001).

Every day, ISS orbits around the Earth about 15 times. Of those, 1 or 2 orbits will be used for wavefront calibration activities. ISS exclusion is estimated to make about 5-10% of time unusable. A bright target like a planet requires very short total exposure time, easily fitting within one orbit, while a faint galaxy or nebula would require multiple orbits. The mission requirement specifies OpTIIX will perform at least 50 observations of planets, stars, nebulae and galaxies at visible wavelengths during the 3 month outreach observation phase. The challenge is to have a variety of interesting targets (a planet, two galaxies and a nebula, for example) available for observation in any given week, in order to appeal to students.

OpTIIX Ground System Operations Concept and Architecture

Figure 3 shows the core components and actors in the proposed OpTIIX ground system. The telescope supports amateur users in the general public as well as public outreach users in kindergarten through high school. In-house scheduling staff provides support for both these use cases. Both amateur users and the in-house scheduling staff will use a proposal entry system to enter observation specifications such as targets, filters, total exposing duration per filter, and min/max durations for individual

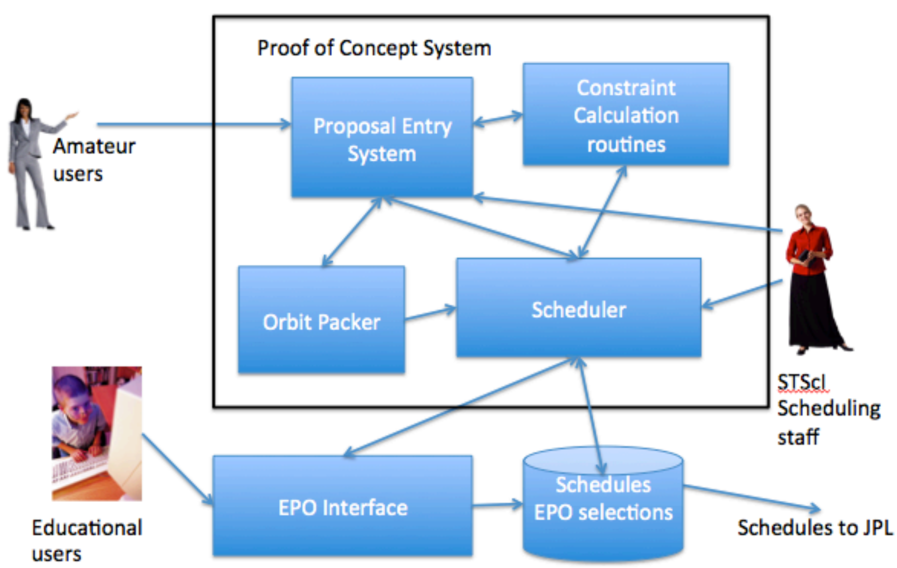

Figure 3: OpTIIX ground system architecture

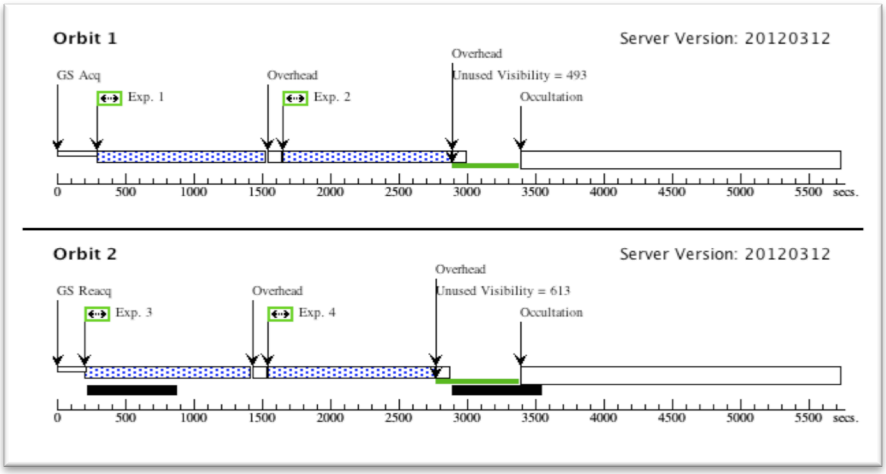

Figure 4: Orbit layout sample (from the Hubble Space Telescope)

exposures. In-house users create candidate observations for outreach users while amateurs create their own observations. Given a total exposing duration and min/max values for individual exposures, the orbit packer will break the overall exposing duration into individual exposures, determine overheads for filter moves, and fit groups of exposures into orbits. For example, an observation may require 100 minutes of total observing time in 5 minute exposures. Given 20 minutes of visibility per orbit, the orbit packer would create 5 orbits each with four 5 minute exposures (5 x 4 x 5 = 100). An example orbit layout from a Hubble Space Telescope observation is given in figure 4. The figure shows a two orbit observation where each orbit contains two exposures. The figure shows how overheads such as time to acquire the target (GS acq), exposure transition overheads (slews and/or instrument configurations), and data dumps (shown as black bars underneath the exposures in orbit 2). The constraint calculation routines determine times when the orbit structure for an observation can be observed given the constraints on the OpTIIX system.

The challenge for outreach observations is to give students some control of what gets executed while staying within a realistic time frame for scheduling, executing, and post-processing observations. In order to integrate with existing teaching methods and lesson plans, the time between a student selecting an observation and receiving the data needs to be a week or less. Having students select the actual observations that get scheduled would require at least three uploads a week and would require the time between knowing the observing pool and uploading to the telescope to be a day or less. Also, this would require data download and calibration to be done in a day or less. Compressing schedules to this extent was not thought to be realistic, as preparing and uploading schedules would require effort by staff at STScI, JPL, and Johnson Flight Center. Yet the desire is to give students an active role in selecting observations and not just be selecting data from an existing archive. A solution that gives students some control over the observing program is outlined below.

OpTIIX observing cycles would be done in a short cadence of a month or two. At the start of each cycle STScI staff would:

- Determine which proposals by amateur users to accept
- Determine targets and observations that are schedulable during the cycle and that would be good for educational public outreach.
- Create and publish a schedule of these observations.

The observations specified by STScI scheduling staff would contain a superset of the filters and observing times that an educational user might select. The idea is that educational users will be presented with a web interface that allows them to select from targets that will be observed by OpTIIX in the next few days. Educational users will also select filters and exposure durations out of those available in the superset observations. OpTIIX will then execute the schedule produced by STScI. As observation data comes back from OpTIIX, images will be calibrated, pipelined and archived for each observation specified by an educational or amateur user. This approach allows some control and active participation in selecting observations for educational users while not requiring an unrealistic schedule preparation timeline. The potential danger of this approach is that OpTIIX will execute observations that no one wants.

Proof of Concept System

The system architecture in figure 3 shows that the proposal entry, orbit packer, constraint calculation, and scheduler routines of the components were approximated by a single proof of concept system. This system was put together using existing SPIKE scheduling components over a matter of a month in the summer of 2012.

The first part of the system coded was the core constraint calculation routines that calculate how much target visibility is available per orbit. Existing SPIKE orbital event calculation and SAA modeling routines were leveraged to make these calculations. The routines sample at one-minute intervals finding transitions between visible and non-visible times. A binary search is then used to find the transition to the granularity of a second.

In an operational system, the proposal entry system would allow users to enter observations and to then visualize whether or not the observations are schedulable over some interval. In the proof of concept system, the visibility routines were used to produce plots over a desired planning interval showing which areas of the sky had sufficient visibility. The OpTIIX science representative on the team then used the plots to select valid targets.

As described in the operations concept section, observers will describe observations in terms of a target, a total exposure duration, a set of filters, and a desired duration for each exposure. The ground system then needs to determine how many exposures are needed and how these exposures plus their overheads can be fit into visibility orbits. In some cases a single observation may require many orbits (in our tests described below, observations require 1 to 10 orbits). To allow flexibility in scheduling, observations are broken down into entities called visits. Each visit is a sequence of one or more orbits that cannot be interrupted by other visits. So a 10 orbit observation could be constructed as a single 10 orbit visit or 10 one orbit visits. Having multiple visits for an observation allows for the visit to be interrupted (e.g. by a calibration) but complicates scheduling. All visits in an observation are linked via a timing constraint so that they complete within 24 hours. A simple orbit packer was coded for the proof of concept system that allows users to specify the total exposure overhead, the slew overhead per orbit, the maximum number of orbits per visit, and the maximum possible orbits per observation. The system queries the constraint system to determine a representative visibility duration and creates a set of visits implementing the observation. A target visibility cache was coded for the proof of concept system. Computing target visibility is relatively expensive requiring three hours for our experimental set. Caching raw target visibility allows different visit structures to be explored in just a few minutes. To determine if a visit is schedulable starting in an orbit, the constraint calculation system checks the visibility required for each orbit in the visit, as determined by the orbit packer, with the visibility determined by the target calculation routines.

The proof of concept system handles calibration observations in a different manner. Calibration requires observing a target from a predefined list of calibration targets. OpTIIX is required to observe a one orbit calibration every day and a six orbit calibration once a week. Each orbit in a calibration observation requires 20 minutes of visibility. The proof of concept system allows the specification of observations that expand into multiple visits where each visit has a fixed duration and is scheduled to occur at a fixed cadence (in this case the visits from an observation are not linked via a timing constraint). Two calibration observations were defined for OpTIIX. The first will create one visit per day in the planning interval and will constrain each visit to occur within a specific day (i.e. the n-th visit is constrained to schedule in the n-th day). The second calibration observation creates a six orbit visit per each week. In either case, to schedule the visit the system searches through the calibration targets and selects the first target that meets the visibility requirements for the given cadence.

The scheduler was coded using the SPIKE Constraint Satisfaction Problem (CSP) scheduling module. This module is an object oriented design pattern that allows the construction of scheduling engines by extending a set of classes with domain specific scheduling functionality. The system has built-in modules for handling many scheduling features such as overheads between observations, variable duration observations, resource accounting, preferences, and links between observations. The scheduler has a large collection of existing scheduling algorithms and supports the construction of new algorithms through a collection of software macros.

OpTIIX scheduling constraints have properties that simplified the coding within the CSP design pattern. In particular, OpTIIX can only observe a target if the ISS is in the Earth's shadow. While the ISS is not in the Earth's shadow, OpTIIX has to be at a safe position. Thus, every OpTIIX orbit will have the same structure:

- Start slewing from the safe position to the target as ISS enters the earth shadow
- Observe the desired target
- Slew to the safe position before leaving the Earth's shadow
- Stay at the safe position until the next orbit

The simplifying factor is that the ISS being in or out of the Earth's shadow is independent of the target in consideration. These properties allow the SPIKE CSP to model time as integer ISS orbits. Schedulability can be determined per orbit and the system does not need to consider where within the orbit scheduling starts. Also, from preliminary designs OpTIIX would be able to slew to any viewable target and back from the safe position with 12 minutes of slew overhead. As a result, the system does not need to worry about slewing between different targets as there is always the slew to the safe position.

The scheduler supports ISS exclusion days by removing domain values from CSP visits that correspond to days where the ISS will be used for activities that would prevent OpTIIX from observing targets.

Experimental Results

A Science Operational Design Reference Mission (aka SODRM) was defined containing a mix of observations that would be typical for a 90 day OpTIIX planning cycle. The contents of the SODRM are summarized in the table below.

Type	Number of observations	Duration per observation (in seconds)
Planet	2	600
Galaxy	257	12000
Globular Cluster	14	1000
Planetary Nebulae	23	8000
Other Nebulae	24	5000

The two planets to be observed, Mars and Jupiter, are expected to be popular options for educational outreach and were set up to be repeated once a week. Out of the 320 observations listed in the table, two were unschedulable during the desired planning interval leaving 318 observations for scheduling. An eighty-nine day planning interval was defined starting on February 1st 2016. There are 1383 physical orbits in the 89 days. Twelve days were removed from the planning interval to account for ISS exclusions (e.g. docking activities) resulting in 77 schedulable days with 1203 usable orbits. The 318 observations in the design reference mission need the total of 56700 minutes of visibility. Scheduling these observations in orbits with 20 minutes of visibility would require 2835 orbits. In other words, the observations in the reference mission are oversubscribed, and the scheduler needs to consider which observations it schedules.

A set of plan optimization criteria was defined to evaluate the schedules produced by the system. Equivalent minimization criteria are given for maximization criteria as the current system only support minimization criteria:

- Maximize the time on target.
  - Minimize time spent in overheads or not observing.
- Maximize the number of science observations that are fully scheduled.
  - Minimize the number of science observations not executed.
- Maximize the number of wavefront calibration observations scheduled.
  - Minimize the number of wavefront calibration observations not executed.
- Minimize the number of orbits scheduled from partially scheduled observations
- Maximize the number of orbits scheduled from fully scheduled observations.
  - Minimize the number of observations that are not fully scheduled.
- Minimize the schedule gap time

Existing SPIKE scheduling utilities and tools were combined to make an OpTIIX scheduling algorithm that:

- Gives highest priority to scheduling wavefront observations.
- Gives high priority to completing observations as opposed to scheduling parts of each observation
- Gives high priority to having schedules with no gaps
- Gives secondary priority to scheduling partial observations
  - Fills gaps with partial observations where it can schedule over a given threshold of the orbits in the observation
- The algorithm has significant random components.

Given that target constraints have been calculated and cached, the system takes about 2 minutes to load a planning scenario and a minute to run the scheduling algorithm. The system supports a multi-objective scheduling approach where individual planning criteria are independently tracked. Using the multi-objective component the system was instrumented to run overnight and to produce a Pareto-surface of scheduling solutions (i.e. no solution is strictly dominated by another solution on the surface) (Giuliano and Johnston 2010). Results of the scheduler run are shown in Figure 5. Each line in the chart represents a complete schedule and shows the value of each criteria. The colors are there to help distinguish the different solutions while the bold blue line represents the selected solution. Some statistics from the solution set:

- All schedules but one completed all of the wavefront calibration activities.

- Wavefront calibration activities were not completed for the ISS exclusion days.
- The solutions completely schedule from 129 to 139 outreach observations
  - The mission requirements are to complete 50 outreach observations
  - All moving targets were scheduled once a week.
- Partially scheduled observations fill gaps but are not the main contributor to achieving efficient schedules.
- Schedule gaps ranged from 2-5%.

A final figure shows the status of the observing pool for a selected schedule on the Pareto-surface. The X axis gives the declination in degrees and the Y axis the right ascension in degrees. A point is plotted for each observation specification minus the moving targets and wavefront calibrations. The color of each dot gives the scheduling status where green means fully scheduled, yellow means partially scheduled, and red means not scheduled. The shape indicates the type of science where a diamond means a globular cluster, a circle means a galaxy, a plus sign means a planetary nebula, and a square means other nebulae. This schedule was selected as it has no gaps.

The results of the experimentation show that the OpTIIX mission can achieve its goal of 50 outreach targets in a three month interval with significant margin.

Related Work

Other planning systems have been used for feasibility analysis during the mission design phase. For example, the CLASP planning system was used to simulate different mission scenarios for the DESDynI Earth surface deformation observation mission. (Knight *et al.* 2012).

A similar mission in terms of education outreach is EarthKAM (www.earthkam.uscd.edu) on ISS. EarthKAM is an educational outreach program allowing middle school students to take images of the Earth from a digital camera on board ISS. The EarthKAM camera is pointed straight down at the Earth. The mission's web based interface allows students to find the ISS's path in upcoming orbits. Up until as little as 2 hours in advance, students can specify coordinates directly below the path of ISS and send a request. After the image is captured, it can be viewed by students in as little as 5 to 10 minutes after the observation was made (Hurwicz, 2002). The initial concept of the OpTIIX outreach program was similar to EathKAM's; allowing students to pick targets and observation specification, and then create observation schedules based on the choices made. However, an observation on OpTIIX takes one or more orbits, as opposed to dozens of images in one orbit by EarthKAM. Thus, we chose to pre-schedule observations in order to guarantee that observations chosen by students will be observed within a short time frame.

Conclusions and OpTIIX Status

This paper showed how a set of existing planning tools were specialized over the period of a month to provide a proof of concept of the OpTIIX public outreach mission. The OpTIIX system passed its preliminary design review in September of 2012. However, the future of the mission is being debated as NASA determines fiscal priorities.

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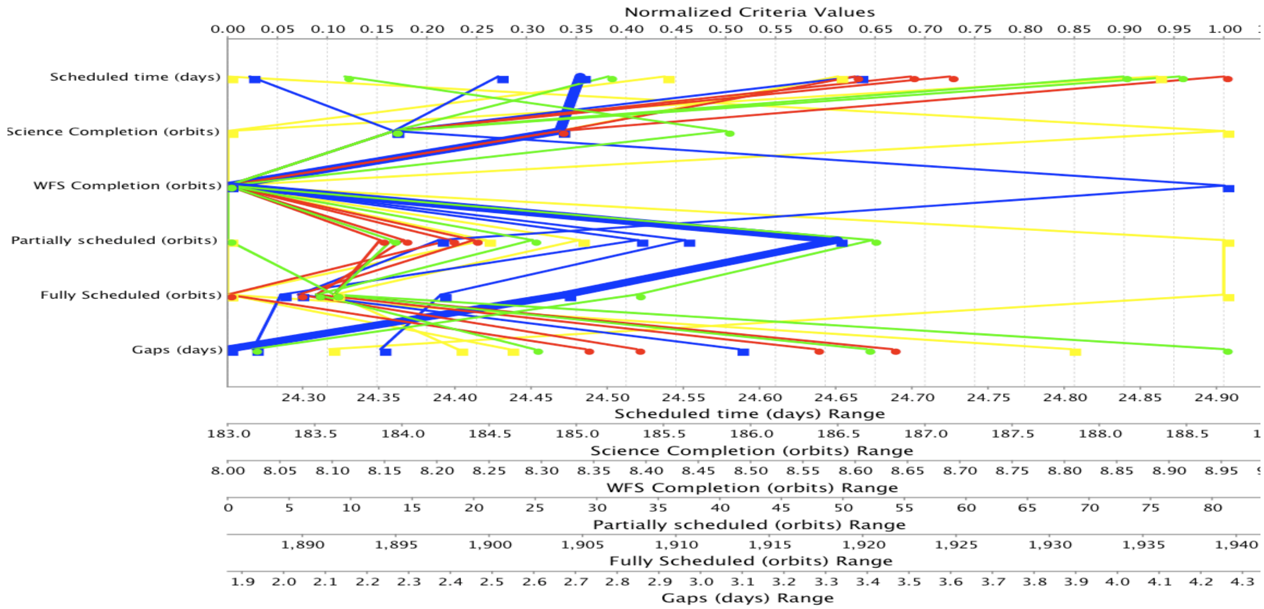

Figure 5: Pareto-optimal solutions

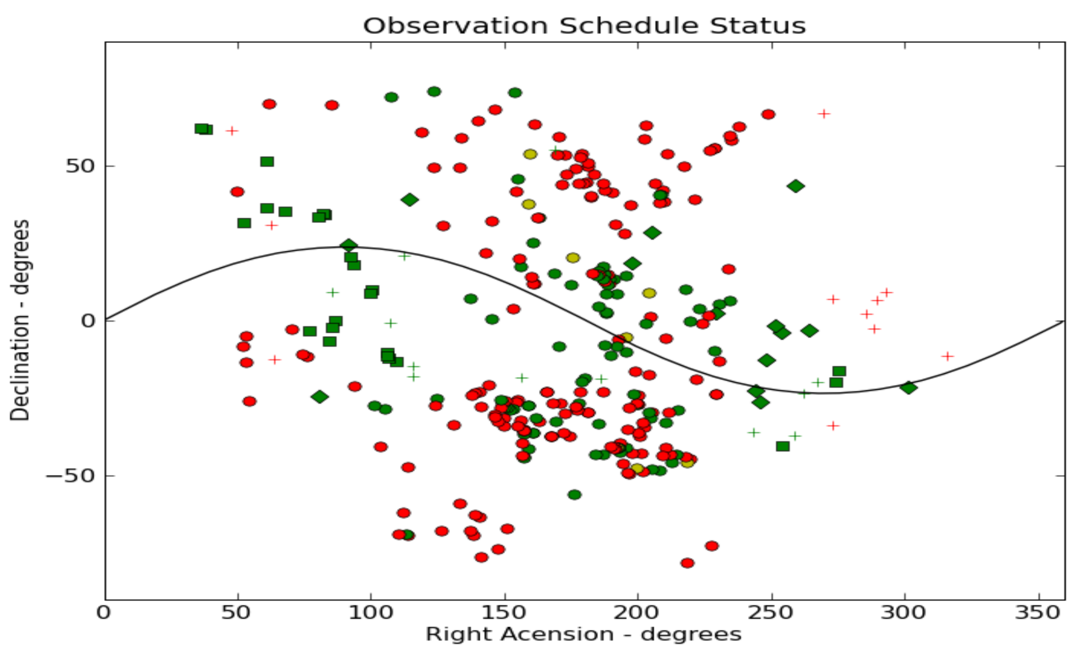

Figure 6: Targets from Selected Schedule.