SOFIA Observatory Automated Scheduling After 5 Years of Operations

Thomas Civeit
Deneb Aerospace
123 10TH Street
San Francisco, CA 94103
thomas.civeit@denebaerospace.com

B-G Andersson, Elizabeth Moore, James De Buizer
USRA-SOFIA Science Center
NASA Ames Research Center
Moffett Field, CA 94035
{bgandersson|emmoore|jdebuizer}@sofia.usra.edu

Abstract—**This paper describes a new framework for scheduling that has been developed for the NASA Stratospheric Observatory for Infrared Astronomy (SOFIA). Key to successful and cost-efficient operations of the SOFIA airborne observatory is the optimized scheduling of operational activities. These include instrument, observation and maintenance schedules, as well as Southern Hemisphere deployments. The most distinctive aspect of the SOFIA flight scheduling problem is the interdependency of the targets than can be observed in a same flight, which makes automated scheduling techniques available for ground-based and space-based telescopes unsuitable. SOFIA began early science operations in 2011 and is currently completing its fourth annual cycle of operations, which consists of about 550 hours of observer time carried out during ~100 science flights. Although early conceptual studies on the SOFIA scheduling problem were previously conducted, flights still had to be manually created when operations started. Here, we introduce the new automated scheduling system based on a tree search algorithm that is used to generate long-term and short-term operational schedules. We provide a formulation of the SOFIA scheduling problem, as defined after 5 years of operations, including all constraints that a valid schedule must satisfy. We list the flight operational tasks that must be efficiently simulated while building the global search tree. We discuss the foundations of the scheduler and describe the constraint representation, algorithm and heuristics that guide the search. Finally, we report on the integration of the automated system in mission operations and its current and future expected performance.**

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1. INTRODUCTION

SOFIA is an airborne astronomical observatory consisting of a 2.5-m aperture telescope permanently installed in a specially modified Boeing 747SP aircraft [1]. The observatory, with its open port telescope provided through a partnership with the German Aerospace Center (DLR), provides routine access to nearly all of the visible, infrared, far infrared, and sub-millimeter parts of the electromagnetic spectrum. The observatory is able to incorporate new or upgraded instruments over its lifetime. The SOFIA Program is executed jointly at two NASA centers. Armstrong Flight Research Center is responsible for flight operations and maintenance of the SOFIA aircraft, which is based in Palmdale, California, while program and science management is at Ames Research Center at Moffett Field, California.

The SOFIA observatory essentially operates in queue mode, carrying out a science program defined by peer review of community-based observing proposals. Currently completing its fourth annual cycle of operations, SOFIA annually performs over 1,000 astronomical observations and conducts approximately 100 science flights. This translates to about 6 hours of science per flight (excluding calibration activities), with a flight rate of approximately 3 nights per week, with several weeks per year dedicated to aircraft maintenance. It is the responsibility of the science operations to create the global flight schedule and to assign the requested observations to each flight.

The most distinctive aspect of SOFIA flight scheduling is the interdependency of the targets observed in a flight. Because the azimuthal pointing is controlled primarily by the aircraft heading and because, in normal operations, the takeoff and landing air fields are the same, efficient flight schedules must balance East-bound with West-bound flight legs and South-bound with North-bound legs. Such constraint makes automated scheduling techniques available for ground-based and space-based telescopes unsuitable. Although early conceptual studies on the SOFIA scheduling problem were previously conducted in 2003-2006 [2][3][4], flight schedules still had to be manually generated with the help of a visual editor when operations started in 2011. At that time, the failure to integrate an automated scheduling system to the operations fell to (1) the actual flight scheduling requirements that significantly diverged from the early theoretical assumptions and (2) the efficiency of the available automated solutions that were too low compared to the schedules manually created [5].

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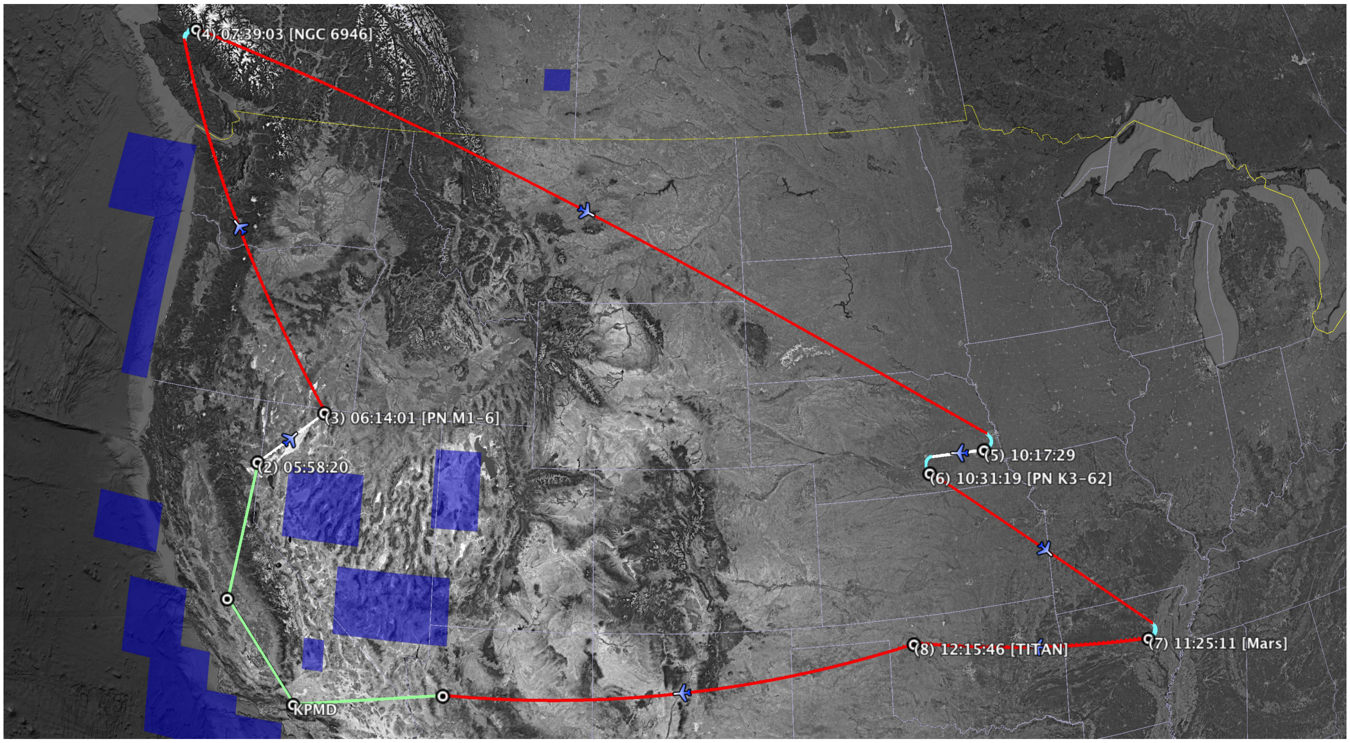

Figure 1 – Course over ground of an illustrative flight schedule, displaying departure, setup and arrival legs (green), observation activities (red), repositioning (white), banked turns (cyan), and restricted flight areas (blue).

Key to successful and cost-efficient operations of the SOFIA observatory is the optimized scheduling of operational and developmental activities. We present in this paper the automated system that has been implemented over the last 5 years to successfully solve the SOFIA scheduling problem in the context of routine science operations [6]. Our new framework based on a tree search algorithm decomposes the problem into the generation of a long-term schedule and a short-term schedule. The Long-Term Scheduler (LTS), originally introduced in [7] at an earlier development stage, generates the global instrument, observation and maintenance schedules over a yearlong observing cycle. The Short-Term Scheduler (STS), presented here for the first time, creates a fully ordered sequence of activities for each specific flight. In this paper we provide a formulation of the SOFIA scheduling problem, as defined after 5 years of operations, including all constraints a valid schedule must satisfy. We list the flight operational tasks that must be efficiently simulated while building the global search tree. We discuss the foundations of the scheduler and describe the constraint representation, algorithm and heuristics that guide the search. Finally, we report on the integration of the automated system in mission operations and its current and future expected performance.

2. THE SOFIA SCHEDULING PROBLEM

The SOFIA airborne observatory operates at observing altitudes between 37,000 and 45,000 feet, above 99% of atmospheric water vapor, allowing greater atmospheric transmission than available from ground-based observatories. The telescope, mounted aft of the wings on the port side of the aircraft, is controlled by motorized fine balancing weight drives that modify its orientation. Elevation pointing can be adjusted from about 20° to 60° above the aircraft plane. The cross-elevation pointing however is mostly fixed (±2.5° range) and must be controlled by changing the aircraft heading while flying. Consequently, the course over ground of the aircraft is driven by the set of objects being observed and can be altered by the actual weather conditions when the schedule is being executed. SOFIA flight scheduling thus consist in finding an ordered sequence of observations that alternates north, south, east and west trajectories to keep the aircraft in the vicinity of the airport, while minimizing repositioning maneuvers and avoiding a set of special areas where flight operations are prohibited. A sample course over ground of a flight schedule is shown in Figure 1.

The visibility of a celestial object and the aircraft course over ground resulting from its observation depend on:

- The current time
- The object position
- The aircraft position

This triple dependency contributes to make the scheduling problem considerably different from ground-based and space-based telescopes in 2 major ways:

- Observation feasibility is a nonlinear function over the solution to the equations of motion of the aircraft. The course over ground must be progressively calculated while building the sequence of observations to know if an observation is suitable or not, i.e. the observation suitability time windows are not globally defined.

- Unlike the Travelling Salesperson Problem (modeled as graph), there are no fixed edges to connect the vertices. Edges and connected vertices are indeed redefined after each observation is performed.

We thoroughly describe the SOFIA scheduling problem in the following sections, as well as our approach to handle it by dedicated long-term and short-term solvers.

Science Program

SOFIA carries out a science program defined by peer review of community-based observing proposals. Additionally, SOFIA guarantees observations for instrument developers and conducts a limited number of discretionary investigations defined by the Science Mission Operations Director. The observatory operates in queue mode. For each yearlong observing cycle, a peer-reviewed allocation committee ranks and assigns a grade to each accepted observing proposal. According to its grade, each proposal falls into one of the following categories that determines its priority:

- MUST-DO category. Observing proposals of prime importance that shall drive the flight schedule and shall be completed at the highest priority by the end of the observing cycle.

- DO-IF-TIME category. Observing proposals to be scheduled when no other MUST-DO proposals could fit while improving the overall efficiency of a flight.

- SURVEY category. Large observing proposals to be partially scheduled when no other MUST-DO or DO-IF-TIME proposals could fit.

Each observing proposal provides all the required data to properly perform an observation, essentially: the celestial object position for a fixed target, the ephemeris reference for a moving target, the duration of the observation, and the scientific instrument to be used. The requester can for instance also specify if the observation can be split into multiple blocks, or if some specific constraints apply to the observation. It is the scheduling system's duty to generate a global flight schedule that will maximize the completion of the observing proposals according to their priorities.

Instrument Schedule

Each observation requires a specific scientific instrument and only one instrument at a time can generally be mounted to the telescope assembly. As it can take up to several days for operators to switch instruments, it is desirable to define multiple 2+ weeklong time windows in which the same instrument is used. Currently 7 instruments are available: EXES, FIFI-LS, FLITECAM, FORCAST, GREAT, HAWC+ and HIPO, all described in [8]. Moreover, a few instruments have multiple configurations available, which require extra work from operators on the ground to be switched (e.g. GREAT currently has 3 configurations). A single instrument configuration is therefore assigned to each week, which limits the observations that can be performed to the ones requiring the same configuration. The assignment of a same instrument over multiple contiguous weeks is referred to as a *flight series*. The latter may however include multiple instrument configurations.

In practice, about 600-900 hours of observations are assigned to about 100-150 flights each year, efficiently grouped into flight series that define the instrument and configuration specific weekly blocks. In the most complex scenario, instruments would be switched every 2 weeks, 26 times in total over the year, which corresponds to billions of possible instrument permutations. Moreover, in addition to the flexible assignments, the instrument schedule must include:

- Several weeks of predetermined instrument assignments, which are provided by the observatory management for scientific or technical reasons;

- Aircraft maintenance or engineering activities (i.e. no instrument assignment) for several dedicated weeks, which can be predetermined or flexible;

- Possible aircraft deployments to other bases at different locations for several dedicated weeks, which can be predetermined or flexible.

Although SOFIA primary base is at Palmdale, CA, operations can be conducted over virtually the entire globe. The most common observatory deployment is in Christchurch, New Zealand, to observe targets visible from the southern hemisphere.

Long-Term & Short-Term Schedule Decomposition

The daunting problem of maximizing the completion of the observing programs is not limited to the instrument schedule. Assigning 1,000+ observations to individual flights is indeed more complicated as an ordered sequence of 10-15 observations has to be generated for each flight, which requires the expensive simulation of the aircraft course over ground and the satisfaction of numerous constraints (see next 2 subsections). It is actually impractical to generate and simulate the exact flight schedules while generating the global instrument schedule. We therefore developed a solution that decomposes this complex problem into 2 sub-problems that can be handled by dedicated solvers:

- A Long-Term Scheduler (LTS) that generates yearlong schedules using global optimization. The LTS assigns instruments and maintenance activities to weeks, and it provides observation candidates for the individual flights. As the exact flight date, actual aircraft position and observation time cannot be known in advance, the LTS generates partially ordered/specified sequences of observations allotted to time windows (i.e. least commitment scheduler) and makes relevant approximations to generate realistic schedules. LTS assignments ensure that each observation is feasible within a flight or a flight series, but also ensure that the pool of observations as a whole is well balanced to minimize the usage of repositioning maneuvers.

- A Short-Term Scheduler (STS) that generates and simulates the individual flights given by the instrument schedule. The STS combines the selection of feasible observations returned by the LTS and schedules all the science activities, calibration activities, and maneuvers required to satisfy all flight constraints and requirements. The STS also takes weather data into account to ensure a realistic execution of the flight schedules. As the most accurate weather forecasts can only be obtained a few hours in advance, a monthly average model is used during the initial scheduling phase.

Such long-term/short-term schedule decomposition has been successfully used by multiple space-based observatories, notably including the Hubble Space Telescope [9] and the Spitzer Space Telescope [10]. In addition to routine operations, the LTS/STS toolkit is flexible and efficient enough to be rerun with short notice, to react to changes in the executed schedule and to produce "what if" schedules to support science program selections, observatory deployment campaigns, and evaluate the impact of last-minute observation requests (e.g. targets of opportunity).

Flight Structure

All flights share a same overall structure that is summarized in Figure 2. The total nominal duration of a flight schedule is 9 hours and 45 minutes. The maximum duration allowed for a flight is set by the crew working day of 14 hours (including pre and post flight briefing) and the aircraft maximum fuel consumption. A 5-minute safety margin is kept to adjust the schedule after the last weather forecast is received. Although SOFIA can fly in operations from/to any base, routine operations assume that the departure and arrival airports are the same. The sequence of tasks to be performed in each flight include maneuvers, calibration and science activities:

- One 30-minute long departure leg executed at the beginning of the flight from the departure airport to a flexible location generally selected from a pool of options. It is assumed that the departure leg final altitude is 35,000 feet.

- One 30-minute long arrival leg executed at the end of the flight from the last aircraft location and altitude to the arrival airport at the ground level. It implicitly assumes that the aircraft must be close enough to the airport to land in less than 30 minutes.

- One 30-minute long "setup" leg, performed right after the departure leg, starting at an altitude of about 37,000 feet as part of the configuration procedure (e.g. initializing the guide camera). As a large collection of celestial objects can be used to perform this activity, any aircraft heading can be selected for the setup leg, as long as the resulting course over ground is within the allowed flight area.

- Multiple science observations having variable durations, as requested by the observing proposal, performed from 39,000 to 43,000 feet while the aircraft altitude increases over the flight. A flight altitude of 45,000 feet can be requested at the expense of additional fuel consumption. Each observation leg begins with a "preparation" activity (from 5 to 10 minute long depending on the instrument) during which the aircraft heading must be set to the target but the telescope elevation does not have to be in the 20-60° operational range. The actual observing duration is counted from the end of the preparation activity. Moreover, for technical reasons, each instrument has a minimum observing duration, which may artificially extend the duration of the leg if the requested duration is too short.

- Zero or multiple instrument-specific calibration observations, in general up to 1-hour long in total. Various calibration rules exist for each instrument, described in the next subsection, specifying which objects shall be observed and the duration of the observations. Calibrators also require scheduling a preparation activity before the actual observation starts.

- Zero or multiple repositioning maneuvers that are used if no observations can be performed and the aircraft position must be modified. Ideally flight schedules should not include any repositioning maneuvers but may require some short ones to avoid prohibited flight areas for instance. A repositioning maneuver consist of a fixed aircraft course and leg duration, or alternatively a fixed final latitude and longitude for the leg.

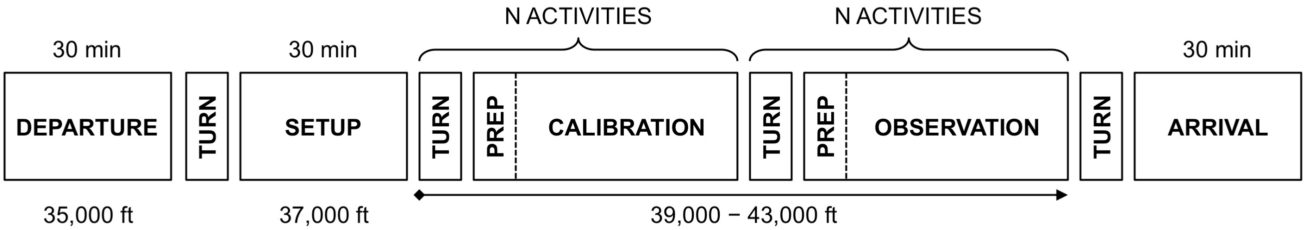

Figure 2 – Flight structure and altitude profile. Order of calibration and observation activities is in general flexible.

- Multiple banked turn maneuvers, lasting about 2-3 minutes in average, to change the aircraft heading. All the aforementioned activities require scheduling a turn.

All flights also share a similar altitude profile: science and calibration observations start at 39,000 feet (about 1 hour after departure), then 41,000 feet is reached 6 hours before landing, then the final altitude of 43,000 feet is reach 4 hours before landing. Typical flight activity durations are displayed in Table 1. The resulting effective time dedicated to science observing is 6 hours per flight in average, as most instruments require some calibration activities.

Table 1 – Typical Flight Activity Durations

Activity	Total Duration (h)
Departure Leg	0.5
Arrival Leg	0.5
Setup Leg	0.5
Science Observing	5.5 – 6.5
Calibration	0 – 1
Obs. Preparation	1.5
Banked Turn	0.3
Repositioning	0
Entire Flight	**9.8**

Operational Constraints

SOFIA's operational constraints include a mixture of discrete, continuous, temporal, ordering and resources constraints. All constraints summarized below must be satisfied by the generated flight schedules. We indicate for each constraint if it applies to the LTS, STS, or both.

Instrument [LTS]. A scientific instrument may not be available during the whole observation cycle (e.g. maintenance). Mission operations staff specifies the time window during which an instrument is operational.

Flight Date [LTS/STS]. Observatory policies might forbid flights during U.S. Federal holidays and weekends. In addition the observatory is not operational during maintenance weeks. In contrast, the observatory must be operational for observations requiring specific observation date (e.g. occultation event).

Sun Avoidance [LTS/STS]. Observation and calibration activities are performed while the sun is below the horizon. The maximum sun elevation angle is generally -6° at the beginning of the setup leg, and -2° at the end of the arrival leg. Observers can also specify a minimum allowable object-sun angle.

Moon Avoidance [LTS/STS]. Observers can specify a minimum allowable object-moon angle. The same applies for the moon phase.

Object Elevation [LTS/STS]. The object elevation must fit within the telescope elevation limits, from about 20° to 60° (some instruments reduce this range by a few degrees). The observer can also specify a more restricted elevation range, for instance in order to benefit from a higher elevation angle.

Observing Window [LTS/STS]. Optionally, observers or mission operations staff can specify time windows during which an observation must be performed.

Minimum Observing Duration [LTS/STS]. For technical and operational reasons, each instrument has a minimum observing duration in the 20-40 minutes range. If a proposal specifies an observation duration shorter than the minimum, it must be then extended to satisfy the constraint.

Split Restriction [LTS/STS]. As in general an observation may be split into several blocks, scheduled in one or multiple flights, observers specify the minimum contiguous duration of an observation, which provides the rule to split (or not) the observation into multiple blocks. Calibration observations are however always performed in one piece.

Awarded Time [LTS/STS]. Each accepted observing proposal is granted a global observing awarded time for all the proposed observations. It may however happen that the sum of all the observation requested durations is larger than the awarded time. This is especially the case for survey programs. The scheduler must therefore ensure that the total scheduled duration in within the awarded time limit, ignoring some of the requested observations.

Group [LTS/STS]. Optionally, observers may define a group of multiple observations to be performed in the same flight.

Water Vapor [LTS/STS]. As atmospheric water vapor attenuates infrared signals, observers can specify a maximum line-of-sight water vapor (LOS WV) overburden for an observation. At the LTS level, which has very limited temporal and spatial information, this translates into a temporal constraint to schedule the observation near the end of the flight when the altitude is maximal. At the STS level, which accurately knows the location, elevation and time of the observation, the LOS WV is calculated based on a water vapor model and compared to the observer requirement.

Flight Area [STS]. SOFIA must abide by Federal Aviation Administration (FAA) rules, which include Special Use Airspace (SUA) incursions and international boundaries. However, some SUA geographical constraints may be relaxed, as clearance to fly through lower-severity warning areas has historically been possible. Consequently, the aircraft course over ground must remains within the limits of predefined flight areas. There are many restricted areas around Palmdale, CA, where the aircraft is based. Flying over Canada is generally possible with advance notice, but use of Mexican airspace is generally not allowed.

Calibration [STS]. Most flights include instrument-specific calibration observations. Although each instrument is different, the generic calibration rules that should be supported by the scheduler are listed below.

- **Flight Calibrators.** Schedule one or multiple observations from one or multiple calibrator groups in each flight of a flight series (e.g. "schedule 1 calibrator from group A and 1 calibrator from group B in each flight"). The calibrator can be freely selected within a group, depending on the object visibility and resulting aircraft heading. Any time can be assigned to the observation. The rule may also specify to alternate the calibrator group for each flight (e.g. "schedule 1 calibrator from group A in the first flight, then schedule 1 calibrator from group B in the second flight, etc.").

- **Configuration Calibrators.** Schedule one observation from a defined calibrator group at the beginning of the flight (i.e. right after the setup leg) in the first fight of the flight series or each time the instrument configuration is changed.

- **Flight Series Calibrators.** Schedule one or multiple observations from one or multiple calibrator groups in a flight series (e.g. "schedule 2 calibrators from group A in each flight series"). The observations can be assigned to any flights in the series as long as they are evenly distributed.

Each specific instrument uses a combination of flight, configuration, and flight series calibration requirements. The calibration constraint is a strong constraint as the availability of calibration objects is limited and the observation of a calibrator can significantly affect the course over ground of a schedule.

Asteroid Flux Density [STS]. When using asteroids as calibrators, their time variable flux density must be larger than an instrument-specific minimum defined at a given wavelength (e.g. 150 Jy at 38 microns). The flux density is calculated from a model and ephemeris data.

Guide Star [STS]. SOFIA's Focal Plane Imager (FPI) and Fine Field Imager (FFI) are tracking cameras designed to determine where the telescope is pointed on the sky and provide telescope pointing corrections via optical tracking on guide stars. While most observations are performed using the FPI, the ones requiring the FFI shall not be scheduled during the first 3 hours of the flight while the imager focus stabilizes.

Evaluation Criteria

A solution to the SOFIA scheduling problem is a set of flight schedules maximizing the completion of the observing proposals according to their priority levels. The 2 major criteria to evaluate a solution will therefore be (1) the efficiency of the flight schedules and (2) the priority of the objects being observed. It is always possible to perform a specific observation, but the resulting scheduling conflicts may significantly lower the efficiency of the schedule. Oppositely, it is always possible to fill a flight with observations, but the most important objects may then be absent from the schedule. The trade of priority vs. efficiency shall be weighted by operator-specified parameters.

3. FLIGHT SCHEDULE SIMULATION

It is mandatory to calculate the aircraft course over ground to know the feasibility of the observing and calibration activities. Indeed the STS spends most of its computation time simulating thousands, or millions, of possible flight schedules, which makes this compute-intensive requirement critical. Overall it is desirable to simulate at least 1,000 10-hour long flight schedules per second to make the scheduling system fast enough to achieve the operational responsiveness required by the mission. In this section we describe how airborne observatory activities can be efficiently modeled and simulated.

It is notable that the aircraft trajectory is generally simulated backward when exploring schedules: from the arrival leg to the departure leg of the flight. As the latest observing activities are performed at the highest altitude (i.e. best observing conditions), it is always preferable to select the solutions that ensure that the most valuable part of the flights will have complete observation assignments.

Equation of Motion

As in traditional air navigation, the motion of the aircraft over the ground is the resultant of adding the motion of the aircraft through the air mass and the motion of the air mass over the ground. The former is dictated by the time-varying aircraft heading and fixed Mach number (0.85 for SOFIA), while the latter is provided by the weather model or forecast available. At a given altitude and assuming the Earth is modeled as an oblate spheroid, the flight path consists in geodesics on the Earth ellipsoid. An excellent compromise between speed and accuracy consists in calculating the aircraft trajectory using the Vicenty's direct and inverse solutions of geodesics on the ellipsoid [11] and performing an integration by Euler method with a short 1-minute time step. It is reasonable to keep the integration of the equation of motion simple, as the weather forecast error bars are large relative to the additional accuracy provided by more sophisticated methods (e.g. the wind speed error bars are often larger than one nautical mile per hour).

Weather Data

Weather model or forecast data required to simulate flight schedules consists of the air temperature, the wind speed and the wind direction. The relative humidity is also needed to satisfy possible water vapor constraints in the STS. All are defined at multiple time points, altitudes and positions. Accessing and interpolating these data is prohibitive when exploring solutions. To solve this problem the STS, which uses a monthly average model, reads a half-degree latitude/longitude grid defined for 5 altitude levels (from 35,000 to 43,000 feet) at the median time of the flight. Data are efficiently accessed via pre-calculated lookup tables, no interpolations are performed (i.e. nearest neighbor method), and fixed altitudes are assigned to activities. The departure/arrival activities performed below 35,000 feet do not require solving the equation of motion (see below) and thus do not depend on the weather data.

Departure & Arrival Legs

At the flight schedule level, the departure and arrival legs are created under the simple assumption that the aircraft can reach a final waypoint from/to the airport within a given amount of time, equal to 30 minutes in general. It is the responsibility of the pilot to select the proper airways and steer the aircraft to the targeted position. Departure and arrival waypoints are realistically defined according to the pilot requirements.

Observation Legs

Calibration and science observation activities are simulated the same way. The aircraft heading and telescope elevation angles are set to point to a specific celestial object, which could be fixed or moving (e.g. asteroids). Explicit formulas of the heading and elevation angles are established in Section 3 of [7]. Both depend on the current time, telescope relative bearing, aircraft pitch and roll angles, aircraft position, and object right ascension and declination. Using explicit formulas significantly reduces the computation time, as it is necessary to recalculate the heading and elevation angles at each simulation time step.

Repositioning Legs

Repositioning maneuvers consist in simulating a trajectory dictated by a course angle and leg duration, or by a targeted final waypoint (the duration is then implicit). Solving the aforementioned equation of motion is straightforward in this case as the aircraft heading is simply set to compensate for the air mass motion induced by the wind.

Banked Turns

Between activities, the aircraft banks to change its direction. SOFIA default operational bank angle is 15° and the simulation is performed at a shorter 10-second time step due to the rapid change of the trajectory.

4. LONG-TERM SCHEDULER

The LTS is a least commitment scheduler that generates partially ordered/specified sequences of observations allotted to time windows. Although the LTS assigns observations to individual flights, all the assignments within a same flight series are practically considered as a same single time window for the observations as the visibility of an object is similar over a few weeks. The LTS nevertheless ensures that the visibility windows are reasonably distributed and there are no scheduling conflicts within the set of observations (e.g. having all the objects visible at the exact same time). It will be the responsibility of the STS to assign one or more specific flights for each observation. The LTS automatically splits long observations into shorter blocks, as the observing time available per flight is limited. The maximum duration for a block is typically around 3 hours. The LTS processes the same way all the resulting scheduling blocks and we will simply refer to them as "observations" in the following discussion. The LTS has 3 types of input data:

- The set of observing proposals to schedule;
- The user-specified control parameters that drive the LTS decision mechanisms;
- And the possibly existing instrument or observation schedules to be reused.

The input schedules can be partially or completely defined. It is especially common to force an instrument assignment to particular weeks (e.g. the science team supporting the instrument operations has a restricted schedule). The LTS output products are the newly generated schedules as well as a set of reports the operator uses to review the results.

Overall, the LTS maximizes an objective function using a user-specified weight for each criterion. The objective function is global, i.e. maximizing the completion of the proposals over the yearlong observing cycle, as opposed to maximizing the efficiency of a subset of individual flights. Another LTS key ability consists in estimating the amount of repositioning maneuvers during a flight. It is indeed challenging, as the aircraft position and the exact time of an observation are not accurately known, so we developed several heuristics (described below) based on relevant approximations.

Constraint Representation

With the exception of the relative Awarded Time and Group constraints (see Section 2), all the constraints handled by the LTS are absolute. Moreover, absolute constraints are either

- Taken into account when processing the proposal input data (Minimum Observing Duration and Split Restriction constraints);
- Or in all other cases translated into temporal constraints, which are internally stored as sets of time intervals during which constraints are satisfied.

Both the Awarded Time and Group relative constraints are easily integrated into the search algorithm by considering a proposal completed after the total scheduled time is larger than a threshold, and by handling all the grouped observation together (i.e. forcing assignments to the same flight). When the constraint calculation requires the position of the aircraft, the LTS assumes a fixed location for the observatory, generally the departure airport, which yields results reliable enough in the context of long-term scheduling.

As a result, each observation has a suitability window, consisting of one or multiple time intervals, which represents the intersection of all the absolute temporal constraints.

Tree Search Algorithm

The smallest assignable time unit for a schedule is referred to as a *time segment*. Although the segment duration is adjustable, weeklong time segments are always used in practice. Each time segment assignment specifies an instrument, instrument configuration, a number of flights, and a set of observations to be performed during each flight. For a given week, the specific days of the flights are not specified; the LTS uses the night in the middle of the week as a reference when calculating the suitability of an observation.

The focus of the LTS tree search algorithm, summarized in Figure 3, is on the analysis of the most promising assignments, expanding the search tree based on random sampling of the search space. Each node corresponds to 1 instrument, 1 configuration and 1 or multiple flights having multiple random observation assignments for a given time segment.

```
search(max_height, pre_assignments)
for each iteration
    for each segment
        expandTree(max_height, pre_assignments)
        evaluate(tree)
        set assignment at segment
    if schedule evaluation is best
    then set best_ schedule
return best_schedule

expandTree(max_height, pre_assignments)
while tree height <= max_height
    if segment in pre_assignments then set assignment
    for each valid instrument and configuration
        for each flight randomly assign observations
        add node

evaluate(tree)
for each leaf node of tree
    calculate objective function
```

Figure 3 – LTS tree search algorithm. Multiple iterations are performed to explore the search space, as observation assignments are random.

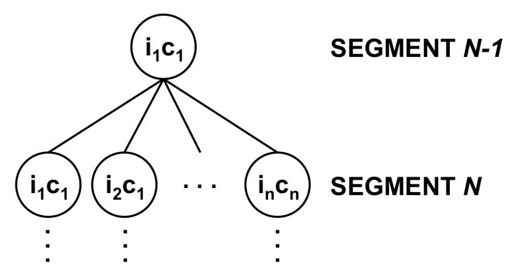

Figure 4 – LTS search tree. Each node corresponds to 1 instrument (i) and 1 configuration (c) assignment, and 1 or multiple flights having multiple random observation assignments (not depicted).

For each time segment, the algorithm recursively builds a tree of all the possible valid instrument sequences for the next segments. When processing the first segment, the root node has no assignment. When processing segment *N*, the root node corresponds to the assignment at segment *N-1*, as shown in Figure 4. Assignments can be pre-assigned, or null, e.g. if the observatory is not operational. The branching factor is not limited but the height of the tree (i.e. number of future segments explored) is limited by a parameter generally equal to 6-8, to avoid a combinatorial explosion. Each possible instrument sequence is then evaluated based on criteria and weights, and the sequence maximizing the objective function dictates which assignment will be selected for the segment being processed. The process is repeated for each time segment. This non-greedy strategy allows the algorithm to take multiple weeks of flights into account when making decisions. As it is common to force

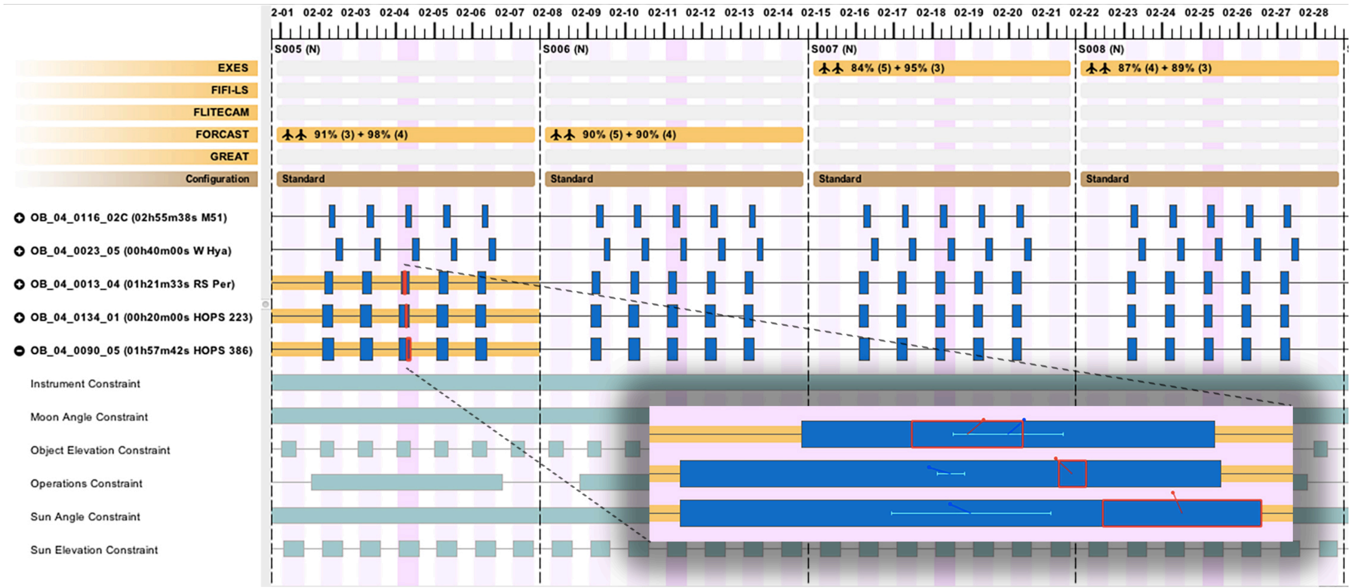

Figure 5 – Long-Term Scheduler Graphical User Interface. Instrument FORCAST is assigned to time segments S005 and S006 while instrument EXES is assigned to segments S007 and S008; 2 flights per week are scheduled, all having an observing efficiency over 80%. Suitability windows and heading profiles are displayed for scheduled observations.

the minimum number of contiguous weeks for an instrument assignment, a mechanism must detect when one efficient week is followed by one or more inefficient weeks for instance.

For each flight, observation assignments are random, but are restricted by the observation suitability windows and the predicted amount of repositioning maneuvers. The algorithm randomly searches for the best selection and permutation of observations that:

- Maximizes the observing time during the flight while avoiding scheduling conflicts (i.e. it ensures the assigned time windows have no overlap).
- Ensures the aircraft heading angles to be used to observe the selected targets will be reasonably distributed. This can be achieved by using one of these two heuristics:
  - Calculating the observation heading profile that corresponds to the fraction of time spent on each [north, south, east, west] quadrant while the target is visible. This average heading profile can be then weighted by the observation duration and combined with other observation profiles to estimate how balanced is the heading variation (as described in [7]).
  - Calculating the average angular distance between the objects to be observed in a same set. Ensuring that the average angular distance is larger than a minimum ensures that objects will be distributed in different direction in the sky, thus requiring different aircraft headings. It is a fast efficient method as it only requires to compute $N(N-1)/2$ angular distances between N target direction vectors.

The objective function that globally evaluates assignment sets for all the segments is based on 2 criteria:

- Maximum observing efficiency
- Maximum completion of higher-priority proposals

Both criteria are normalized, then weighted and combined according to the user parameters. As the observation assignments are random, the search algorithm generates multiple random schedules that explore different observation distributions over the year. The schedule having the highest evaluation is eventually selected (see Figure 3). In general, generating and evaluating 1,000+ schedules per run gives satisfactory results. A common strategy consists in running the LTS using only the MUST-DO highest priority observing proposals to drive all the assignment decisions and create a base schedule. The latter is then used as an input for a second run of the LTS, this time using all the proposals (MUST-DO, DO-IF-TIME and SURVEY) to complete the flights and increase the observing efficiency.

User Interface

In addition to a console application, the LTS also includes a graphical user interface. It is critical to provide a quick and intuitive way to the operator to analyze the generated schedules. The interface, shown in Figure 5, displays the calculated constraints, instrument assignments, observation assignments, and observation heading profiles. The interface can thus be used as a diagnosis tool to report on scheduling issues and conflicts.

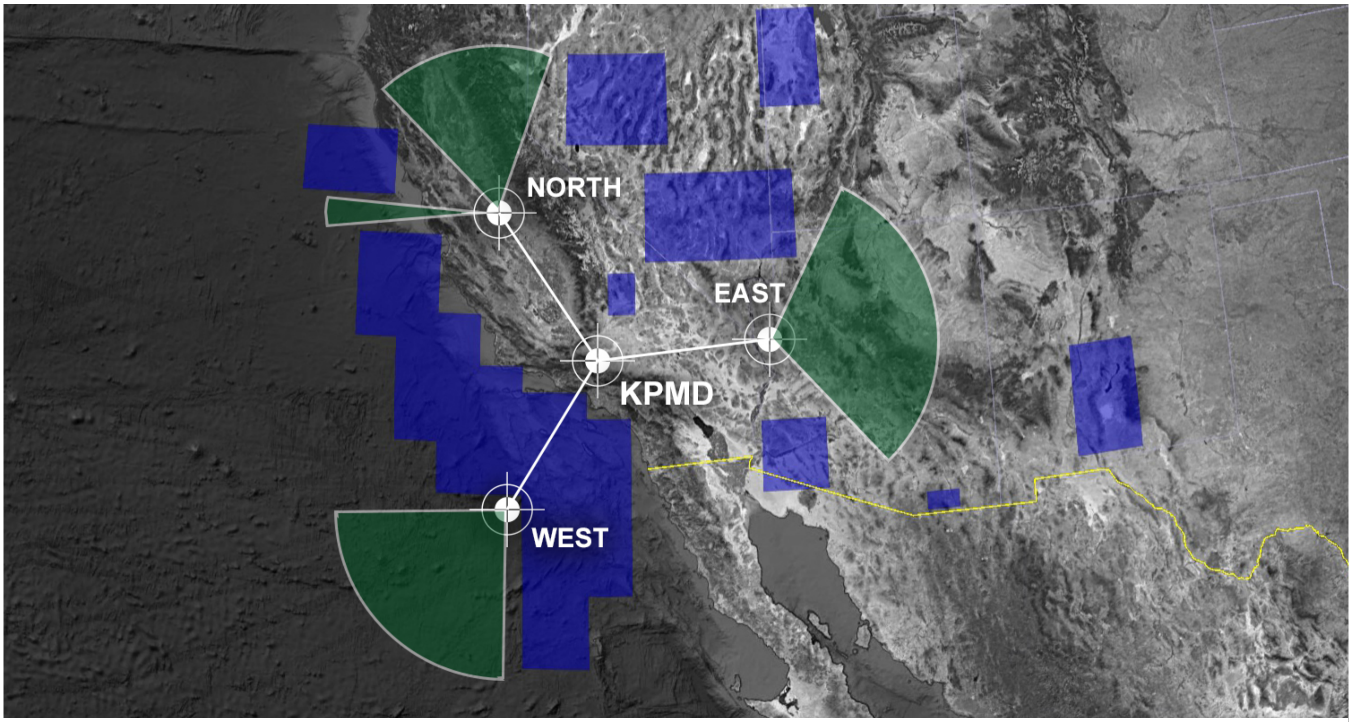

Figure 6 – Flight routes around the Palmdale airport (KPMD). The predefined arrival/departure legs (white) and range of setup legs (green) avoid the restricted flight areas (blue) or use a permitted corridor to the Pacific Ocean. Flight schedules can use any route from West to West, West to North, West to East, North to West, etc.

5. Short-Term Scheduler

The STS generates fully ordered sequences of science activities, calibration activities, and maneuvers required to satisfy all flight constraints and requirements. It also assigns a specific starting time for each activity. The STS has 5 types of input data:

- The set of observing proposals to schedule;
- The user-specified control parameters that drive the STS decision mechanisms;
- The instrument schedule defining the flight series;
- The possibly existing flight schedules to be reused;
- And a set of observations to be scheduled at the highest priority, referred to as *preferred* observations.

The core ability of the STS is to efficiently schedule observations according to a ranking system, which refines the one defined at the science program level:

- PREFERRED observations have the highest priority. They are generally the assignments indicated by the long-term schedule for each flight series, but can also be arbitrarily specified by the operator.
- HIGH-PRIORITY observations are the subset of MUST-DO observations that are not PREFERRED.
- DO-IF-TIME is as defined for the science program.
- SURVEY is as defined for the science program.
- REDO observations are the ones previously attempted or performed but have been approved to be scheduled again at a lower priority (generally because the execution of a prime observation failed).

The built-in logic of the STS considers that a PREFERRED observation is always more desirable than a HIGH-PRIORITY one, the latter more desirable than a DO-IF-TIME, and so forth. This aggressive scheduling approach translates the observatory policy regarding the completion of the observing proposals. If no observation, whatever its rank, is suitable at a given time and aircraft location, then a short repositioning maneuver is scheduled.

The STS takes into account the observing time already scheduled in previous flights (if any) and adjusts the remaining observation duration accordingly. It also automatically splits observations into blocks, as necessary to fit within a flight, and as permitted by the proposal requirements. These blocks, which are typically shorter than 2 hours, are then scheduled in one or multiple flights.

Constraint Representation

The STS has accurate knowledge of the aircraft location at a given time. Unless a constraint does not depend on the latter (e.g. Asteroid Flux Density constraint), the constraint satisfaction mechanism is integrated into the search algorithm that progressively simulates the flight schedule. For all absolute and relative constraints, the schedule of an activity will be rejected if the simulation indicates a constraint violation.

To minimize the computation time, the Flight Area constraint is represented as a set of rectangle-shaped latitude/longitude bounding boxes. A set of positive areas defines where the aircraft must fly, and a set of negative areas defines where the aircraft must not fly. Moreover, as many restricted areas exist in the vicinity of the Palmdale airport, the flight schedules are forced to follow some predefined flight routes for the departure, setup and arrival legs. Each flight route consists of an airport location, a takeoff final waypoint, a setup leg track angle range, and a landing initial waypoint, as shown in Figure 6. In general, 12 predefined flight routes are available from/to Palmdale airport: from West to West, West to North, West to East, North to West, etc.

Calibration constraints are translated into a set of mandatory observations that must be performed during a specific flight. Each mandatory calibrator may be freely chosen from a group of candidates or forced to be a specific object. If no suitable calibrator can be selected for a flight, the STS reports a scheduling error to the operator.

Tree Search Algorithm

As previously mentioned, schedules are generated backward: from the initial waypoint of the arrival leg to the final waypoint of the setup leg. Overall, the STS must explore a 2-dimensional search space, representing when and where the flight will take place. Regarding the time dependency, the STS evaluates different flight arrival times based on the Sun Avoidance constraint and the total ~10 hours flight duration. Because of the varying length of the nights, during winter, there is up to about 60 possibilities assuming a 5 minutes time step (generally used for best results), while there are just a few arrival options during summer. Regarding the spatial dependency, the STS evaluates all the aforementioned flight routes.

The STS tree search algorithm is summarized in Figure 7. At a high level, for each arrival time and for each flight route, the algorithm builds a search tree with root node representing an empty schedule and leaf nodes representing the complete flight schedule from the arrival leg to the setup leg, as shown in Figure 8. Each node corresponds to a science observation, a calibrator, or a repositioning maneuver. The related turn and preparation activities are implicitly represented by the node.

```
search(pre_assignments)
for each flight series
    set preferred_observations
    for each flight
        if flight in pre_assignments then set schedule
        else generateSchedule(preferred_observations)

generateSchedule(preferred_observations)
for each flight route
    for each arrival time
        for each iteration
            while tree can be expanded
                expand tree by scheduling observations
                expand tree by scheduling calibrators
                prune tree
                evaluate(tree)
                if schedule evaluation is best
                then set best_ schedule
return best_schedule

evaluate(tree)
for each leaf node of tree
    if all calibrators are scheduled
    then calculate and return flight observing efficiency
    else return zero
```

Figure 7 – STS tree search algorithm. It performs a random breadth-first search, guided by the priority of the observations.

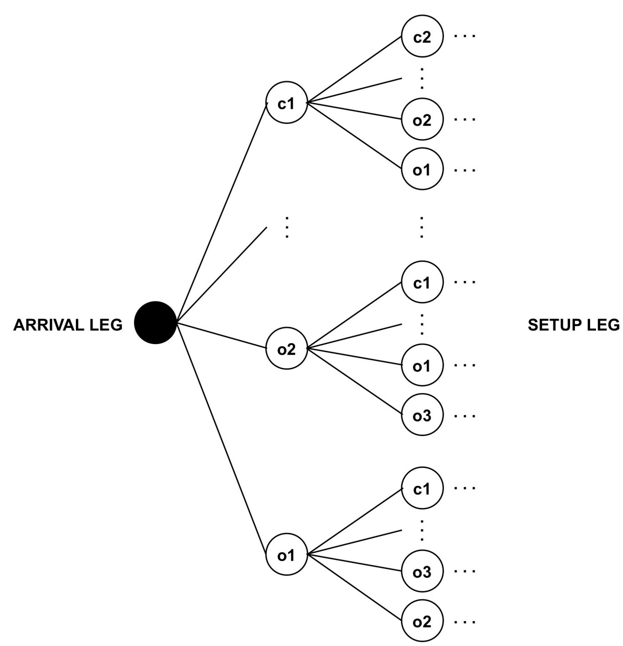

Figure 8 – STS search tree. Each node corresponds to an observation (o), a calibrator (c), or a repositioning maneuver (not depicted).

The branching factor while exploring observation nodes is limited by a user-specified parameter that rarely exceeds 3 in practice. Moreover, in order to avoid a combinatorial explosion, the factor is dynamically reset to 1 if the number of leaf nodes is larger than a user-specified threshold. The branching factor while exploring calibrator nodes is not limited as calibration activities are mandatory and usually very constrained, which ensures the algorithm will take advantage of all options available. Assuming a flight consists of 10 observations and the search tree has about 3 children per node in average, evaluating 30 arrival times and 12 flight routes gives about 20 million possibilities.

The algorithm performs a random breadth-first search, guided by the priority of the observations. The exploration consists in evaluating observations from the highest-priority to lowest-priority category (i.e. from PREFERRED to REDO), until all possible children have been added to the tree. Within a same category, observations are randomly selected. If no observation is suitable, then 1 random valid repositioning maneuver is scheduled (e.g. random track angle for 10 minutes, having no Flight Area constraint violation). If an observation was split into multiple blocks and 2 blocks of the same observation are sequentially selected, then the first block duration is extended and the second turn and preparation unnecessary activities are removed. After selecting a node, if the awarded time of an observing proposal is reached, then the proposal is considered completed and the descendant nodes cannot select an observation from this proposal. Unlike observations, calibrators are always scheduled when possible. Within a same group, the calibrator selection is random. As both observation and calibrator selections are random, the algorithm performs multiple search iterations (generally around 10) to yield different results.

Nodes are pruned by calculating the distance from the aircraft to the end of the setup leg. If the aircraft cannot reach (by using the most direct path) the targeted waypoint within the time limit of the total flight duration, then the schedule is not valid and the exploration is stopped. The algorithm continues to explore nodes until there are no nodes to explore, which is necessarily the case when the total activity duration exceeds the total flight duration.

Even in the best-case scenarios, it is expected that the last added observation or calibration activity would not perfectly start where the setup leg ends. Then the algorithm either:

- Adjusts the setup leg trajectory, as permitted by the leg valid track angle range, to connect its last waypoint to the first waypoint of the next activity;
- Or schedules a repositioning maneuver that connects the setup leg to the next activity.

For every leaf node, flight schedules are evaluated by verifying that the calibration constraints are satisfied and by calculating the total observing time. As the search is already strongly guided by the priority of the observations, the observing efficiency is the only evaluation criteria. In general, generating and evaluating 10-20 million schedules per flight gives satisfactory results.

User Interface

The STS is a console application. In addition to the flight schedules, its output products include scheduling reports that the operator can review, as well as Keyhole Markup Language (KML) files for schedule visualization in Google Earth or NASA's World Wind software.

6. PERFORMANCES IN OPERATIONS

SOFIA began early science operations in 2011 and is currently completing its fourth annual cycle of operations, which consists of about 550 hours of observer time to be carried out during 100 science flights. Each call for proposal yields 1,000+ observation requests that have to be evaluated, possibly accepted, then executed. Since the first observing cycle the science operations have used the LTS in order to:

- Perform preliminary analysis and simulations before the Science Mission Operations Director selects the accepted proposals. (e.g. determining which scheduling conflicts are likely to occur);
- Evaluate the optimal time window to deploy the observatory to the Southern hemisphere (SOFIA was deployed to Christchurch, New Zealand, in July 2013, July 2015, and June 2016);
- Evaluate optimal downtime periods to perform aircraft maintenance;
- Create the observatory instrument schedule after all observing proposals are accepted.

The personnel required to create long-term schedules is minimal. A single operator assisted by the LTS is able to generate or update the long-term schedule of the observatory within a few hours. Both the LTS and STS tree search algorithms take advantage of parallel computing. The software can be run on personal computers or dedicated multi-core servers for faster performances.

The STS has been gradually integrated to the science operations procedures over the last 2 observing cycles. The creation of each flight series is generally overseen by a single dedicated agent several weeks in advance. As part of the operational procedures, the agent always starts by running the STS to generate the flight series. It takes about 1 hour for the automated system to evaluate ~10 million schedules and return the best one to be reviewed by the agent. The schedules can be submitted to the science group without modifications or the agent may decide to alter the schedules if it better serves the science program (e.g. replacing or swapping observations). It is notable that most modifications concern the priority of the observations, rather than the overall observing efficiency or the constraint satisfactions, which are already optimized and outperform manual assignments. The agent may also decide to relax some STS constraints to improve the completion of an observing proposal or ease the execution of a schedule (e.g. having the schedule more robust in case of an unexpected change of weather).

Computation time wise, the LTS/STS performances allow an observing cycle consisting of about 100 flights equally distributed on 5 instruments (20 flights per instrument) to be fully generated in less than 24 hours. As there are no scheduling dependencies between the multiple instrument-specific flight series, multiple dedicated computers (1 per instrument) can generate all the instrument-specific flight in parallel. In this case 5 computers running for 20 hours will complete the short-term schedule generation of the full observing cycle.

7. Conclusion and Future Work

We presented a new automated framework to solve the SOFIA scheduling problem, as defined after 5 years of operations. We described the set of constraints to be satisfied, the flight structure, and the mixed spatial and temporal dependencies, which make the problem non-solvable by scheduling techniques available for ground-based and space-based observatories. Our solution decomposes this complex problem into 2 sub-problems that can be handled by dedicated tree-search based solvers: a long-term scheduler and a short-term scheduler. We described the heuristics we use to primarily guide the search by the priority of the observations. Finally, we reported on the successful usage and performances of the automated system in operations.

A natural direction for future work is to optimize the generated flight schedules by modifying the observation and calibration activity durations. Although the duration is fully specified in each observing proposal, the observatory policy generally allows extending or shortening the duration by up to 10%. Such modifications can suppress the need for repositioning maneuvers (e.g. after the setup leg) and provide more flexibility to avoid restricted flight areas. Similarly, observations that are split into multiple blocks would benefit from variable block durations, rather than evenly dividing the observation total duration.

Another potential extension of this work is to incorporate into the solvers the satisfaction of soft constraints that improve the robustness of the generated flights. The concept of flight schedule robustness results from years of experience operating the SOFIA observatory. It basically consists in maximizing the chances to successfully execute or repair a flight schedule. A robust schedule will for instance allow the flight crew to intercept an existing schedule if the flight departure is late (e.g. by skipping the first observations); or will ensure that the schedule is not too dependent on the weather conditions (e.g. relying on the wind to land on time); or will preferably avoid some flight areas likely to have traffic from regular airliners.

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BIOGRAPHY

Thomas Civeit *received a Master's degree in Space Systems Engineering from Observatoire de Paris, Paris, France in 2003. He has been working for NASA and ESA space missions, notably including the Hubble Space Telescope, the James Webb Space Telescope, the Stratospheric Observatory for Infrared Astronomy (SOFIA), the Far Ultraviolet Spectroscopic Explorer (FUSE) and the Huygens interplanetary probe. He has extensive experience designing and developing AI-based scheduling software systems for space mission operations. He is the owner of Deneb Aerospace, a San Francisco-based company providing engineering services and solutions to design and operate space and aerospace systems.*

Dr. B-G Andersson *is the SOFIA Associate Director for Science Operations. He supports the Science Mission Operations Director in the process of soliciting and selecting science proposals. With a team of instrument and user support astronomers, he works with the Mission Operations team to define and execute the resulting SOFIA science operations. In addition, Dr. Andersson works with an international group of astronomers to conduct research, primarily on interstellar medium polarization, and on issues relating to understanding how gas transitions between the dense and the diffuse phases of the ISM.*