Using Automated Scheduling for Mission Analysis and a Case Study Using the Europa Clipper Mission Concept

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Abstract

We describe the use of an automated scheduling system intended to assist in the early development of space missions. This tool creates observations of both (a) targeted geographical regions of interest and (b) general mapping observations, while respecting spacecraft constraints such as data volume, observation timing, visibility, lighting, season, and science priorities. This tool therefore must address both geometric and state/resource/timing constraints. We describe a tool that maps geometric polygon overlap constraints to set covering constraints using a grid-based approach. These set covering constraints are then incorporated into a greedy optimization, scheduling algorithm incorporating operations constraints to generate feasible schedules. The resultant tool enables mission designers to analyze the effect of different spacecraft trajectories, spacecraft designs (e.g. solid state recorder capacity, power) as well as operations concepts (downlink volume, data rate). We demonstrate the application of this tool to analyzing proposed trajectories and evaluation of achievement of mission science criteria for the Europa Clipper mission concept.

1   Introduction

Space mission design is a challenging task in which a spacecraft is custom designed along with a trajectory to it's target destination to study science phenomenon of interest. With the introduction of automated scheduling technology, it is now possible to take a baseline mission concept and using models of science observations, spacecraft operations, downlink, and trajectory design, and in effect simulate to some extent the mission to support analysis of mission return. This analysis can then be folded back into many aspects of mission design – including trajectory, spacecraft design, operations concept, and downlink concept.

Tour and flyby missions impose particularly challenging constraints for mission design. In this mission type, which includes the past and present Galileo and Cassini missions as well as the future Jupiter Icy Moons Explorer (JUICE) and Europa Clipper mission concept, the demands of trajectory design require extreme creativity and analysis in order to design flyby trajectories within a strong gravity environment to optimize science opportunities that are dependent on complex geometric relationships.

Europa Clipper [Europa 2015] is a mission concept under study by NASA for a spacecraft to fly to the Jovian planet-moon system in order to study the icy moon Europa. Europa is a target of significant interest because of the possibility that this icy moon could harbor life, perhaps in a subsurface ocean. Because of the intense radiation in the Jovian system the mission would perform repeated close flybys of Europa using a highly eccentric orbit around Jupiter. The mission might perform over 40 flybys of Europa at altitudes ranging from 25 to 2700 km.

The Europa Clipper concept considers a number of possible science instruments, including a radar to study the ice shell and subsurface properties, and infrared instrument to study surface composition, a topographic imager to gather high resolution images of surface features, and an ion and neutral mass spectrometer to investigate Europa's trace atmosphere during flybys.

In order to support the mission design process, an automated scheduling system requires certain inputs. Specifically, to generate Clipper concept observation schedules for mission analysis, we divide the problem into three primary steps: instrument definition, campaign generation, and target selection.

1.   In the first step, the spacecraft and instruments must be defined along with the constraints that may impact how and when data can be collected. To generate valid schedules, we must model the interactions between the instruments and the spacecraft, as well as how the instruments interact with each other.

2.   In the second step, campaigns are generated to represent the constrained and prioritized requests of the scientists. In order to collect relevant data for a particular scientific campaign, constraints are made on both internal (e.g. instrument mode) and external (e.g. lighting) conditions. Then, a priority is assigned to each campaign to enable the scheduler to make the best choice when different observation types are feasible but constraints prevent them for operating simultaneously (an equal priority between one or more will result in an even distribution of selections).

3.   Finally, the last step is to select observations, using instruments from #1 above, that maximize a priority weighted score defined by the science campaigns

in #2 above. In this selection, relevant spacecraft constraints (e.g. onboard memory), instrument constraints (e.g. field-of-view), and campaign requirements (e.g. lighting conditions) must be respected. For this, we use an adaptation of the Compressed Large-scale Activity Scheduler Planner (CLASP) [Knight and Chien 2006] that uses squeaky wheel optimization (SWO) [Fox 1996, Joslin & Clements 1999] iterative heuristic approach to select observations.

In the remainder of this paper we describe the problem formulation, scheduling algorithm, and project status.

2 Instrument Definitions

The Europa Clipper concept spacecraft has been proposed to carry several scientific instruments to study the Jovian moon Europa. We focus our analysis on the following remote sensing instruments: the Ice-Penetrating Radar (IPR), the Topographic Imager (TI), the Short-Wave Infrared Spectrometer (SWIRS), the Reconnaissance Camera (RC), and the Thermal Imager (ThI). The spacecraft and each instrument must be defined with enough detail to allow observation schedules to be automatically verified against operational constraints. In our initial analysis, we model the following: position and orientation of the spacecraft, position and orientation of Europa (and other celestial bodies), instrument pointing, instrument field-of-view, and the data rate of each instrument mode. This model allows us to manage the primary operating constraints, sufficient for a high-level coverage analysis.

Data for the instrument models was taken from a high-level Europa Clipper mission concept science document outlining the instruments, their requirements, and their observing scenarios. This data was then translated into an input file format supported by CLASP. An example instrument definition is given in Figure 1.

3 Europa Clipper Concept Science Campaigns

In order to perform a particular investigation (e.g. search for an ice-ocean interface), scientists request the use of one or more instruments, operating in one or more modes (e.g. mono, stereo), to collect data from particular regions of Europa (e.g. north pole), under particular geometric conditions (e.g. solar zenith angle). All of this is provided as input to CLASP in the form of a KML (Keyhole Markup Language) file, the file format used by Google Earth. Campaigns are specified with a KML <Placemark>, where surface regions are outlined in a <Polygon>, and the remaining campaign data is given as a table in the <description> of the <Placemark>.

While CLASP supports regional campaigns, our

```
// IPR
sensordefinition(
  start at start,
  spacecraft_name="ClipperIPR",
  generator="spiceKernel",
  ids=4 104,
  time_delta="10s", // 10m
  start_time="0s",
  duration="998d",
  along_track_look="0degs",
  cross_track_look1="-6degs",
  cross_track_look2="6degs"
);

IPR_Science = 4,104;

IPR_Science datarate = 0.024500000;
```

Figure 1: CLASP instrument definition

initial analysis essentially uses a global mapping campaign for each scientific investigation. The high-level Europa Clipper concept science document describes the collection of data distributed over the surface divided into 14 panels: four at each pole (±60 deg in Lat) and six around the equator (±30 deg Lat). These 14 polygons are given as input to CLASP, but

```
<Placemark>
  <name>equator1</name>
  <description>
    campaign{
      IPR_low_alt_mid_sza 35 1
      IPR_Science
      sza        45degs  70degs
      distance   0.0km    400.0km
      asap;
…
    }
  </description>
  <Polygon>
    <outerBoundaryIs>
      <LinearRing>
        <coordinates>
          -30.0404,-30,0
          -29.0404,-30,0
…
        </coordinates>
      </LinearRing>
    </outerBoundaryIs>
  </Polygon>
</Placemark>
```

Figure 2: CLASP campaign definition

identical campaigns are specified for each region. In future work, we will look at the qualitative distinctions that may be made between the different regions of Europa.

All campaigns are assigned priorities based on preferences specified by the scientists. In the end, the generated campaigns and priorities are passed as inputs to CLASP. An example of a campaign definition is given in Figure 2.

4   Observation Selection

In order to assess areal coverage, CLASP uses a gridded representation of regions. In this representation, the planetary surface is represented by a set of roughly equidistant grid points with separation D. Specifically, grid points would exist along lines of latitude that are spaced distance D apart. Along these lines there would be grid points spaced D apart, surrounding the globe.

This gridded representation allows CLASP to compute overlap between regions very efficiently. With this representation, rather than computing polygon overlap on a surface directly, the computation simply intersects grid point sets. Gridded overlap computation is bit set intersection and is $O(n)$ theoretically where n is the number of points in the grid but in practice these bit vector operations are effectively constant time. Polygon overlap computation is $O(n \log n)$ theoretically and in practice $O(n)$ where n is the number of points defining the polygons.

For the Europa Clipper mission concept application, we use 800 grid points around the Europa Equator which converts to ~12.3 km between grid points and divides the surface of Europa into ~200K potential targets of observation.

CLASP currently considers a total of 9 modes across 5 of the proposed Europa Clipper mission concept instruments. Two modes are modeled for SWIRS: a high-res and a low-res mode, each with a different data rate. Both RC and TI are modeled to operate in either mono or stereo. ThI is split into two modes, one for high altitude (>2000km) and one for low, which collect data at different rates. Finally, IPR has a single mode and data rate in our model.

First, CLASP computes the visibility of the Europa surface as seen from each instrument. The proposed trajectories for the Europa Clipper mission concept spacecraft have it orbiting Jupiter and making a series of Europa flybys. Each flyby results in a set of visibility "swaths" across the surface of Europa, where each swath represents observation opportunities for an instrument. The size, shape, and location of the swath depend on the position and orientation of the spacecraft, and the field-of-view of the instrument. To generate swaths, CLASP makes use of the CSPICE Toolkit provided by the Navigation and Ancillary Facility (NAIF) at JPL.

Next, CLASP computes the intersection points between instrument swaths and campaigns. This is done by iterating through instrument swath points and creating a "potential observation" record for each such point, and for each campaign requiring a unique instrument mode. For example, if one campaign requires IPR and another campaign requires TI, and a point is visible by both instruments, then two potential observation records are created. If both campaigns use the same instrument, only one observation record is created. Each observation record is then accorded the highest priority from each of its campaigns.

The observation selection problem is the following:

Given
    a set of potential observation records $O = \{o_1 \ldots o_n\}$
    a set of regions of interest $R = \{r_1 \ldots r_n\}$
    a set of instrument swaths $I = \{i_1 \ldots i_n\}$
        where $\forall o_i \in O \ \exists (r_i, i_i)$ such that
        $(\text{grid}(o_i) \in \text{grid}(r_i)) \ \wedge \ (\text{grid}(o_i) \in \text{grid}(i_i))$
    a scoring function $U(r_i) \rightarrow$ real
    a constraint function $C(S) \rightarrow T, F$
        where $S \subseteq O$ and $C(S)$ is T if S satisfies spacecraft constraints

Select a set of observation records $A \subseteq O$
        To maximize $U(r_i) \ \forall r_i \in R$
        subject to $C(A) \rightarrow T$

CLASP for Europa Clipper mission concept currently validates several operations constraints when selecting observations:

- Onboard Storage – due to limited storage onboard the Europa Clipper mission concept spacecraft, the amount of data collected by instruments is limited by this storage capacity until renewed as indicated by a provided downlink schedule.
- Instrument field-of-view – each instrument has a different field-of-view, which limits the surface visibility during flybys, especially at low altitudes when the spatial resolution is the highest (i.e. best quality).
- Distance from target – the quality of the data greatly depends on the spatial resolution. Because Europa Clipper mission concept will orbit Jupiter, much of its time will be spent too far from Europa to collect reasonable data. For this reason, each campaign specifies a maximum distance from the target of interest.
- Lighting condition – for most instruments, the quality of the data also depends on the lighting conditions. To ensure good lighting, each campaign specifies either a bound on the solar zenith angle, or a range of valid Europa local times.

CLASP uses squeaky wheel optimization (SWO), an iterative heuristic approach to optimization. SWO uses a simple, priority-based, greedy scheduler as an inner loop with an outer loop that iteratively tweaks inputs to the inner loop. Each iteration is a call to SWO_inner below and consists of iterating through the potential observation records in order of decreasing priority. The observation record is added to the schedule if it can be performed without violating any spacecraft operations constraints. Otherwise, the observation record is discarded and the next observation record is considered.

Whenever an observation record is added to the schedule, CLASP must compute which additional observation records are also implied to be in the schedule (the Propagate function below). This propagation occurs based on two checks. The instrument swath polygon associated with the selected observation record may include multiple grid points. For any of these grid points, other observation records with the same instrument mode will also be added to the schedule. The result of SWO_inner is a set of observation records A such that C(A) is satisfied.

The outer loop of SWO consists of first initializing the observation record priorities to the priorities of the parent science campaigns. Then, SWO_outer repeatedly calls SWO_inner to produce a set of selected observation records A. Note that the propagation in SWO_inner only adds observation records that are logically entailed by selected observations. For example, imaging an area (or grid point) with instrument I at 4m spatial resolution subsumes imaging with I and 8m spatial resolution. Or imaging an area with instrument I with spectral bands 2, 4, and 6 subsumes imaging with instrument I with spectral bands 2 and 4. Therefore there is no search

(and no backtracking) in the propagation step. As long as a progress metric is satisfied, we increment the priority of all observation records that did not make it into the current schedule A, and re-run. This re-running proceeds a number of iterations and the best schedule (scored by initial priorities) is returned.

SWO_outer
Initialize priorities
While progress made
    SWO_inner $\rightarrow$ A
    For each o in (O – A)
     increase the priority of o
    Repeat

SWO_inner
O = all candidate observation records
B = {}
For each o in O in decreasing priority order
    If C(B+o+Propagate(o)) = True
      B := B + o + Propagate(o)

5 Europa Clipper mission concept Coverage Analysis

We use CLASP to automatically generate observation schedules that can give us a quantitative comparison of different mission design choices. Specifically, we look at how these resulting observation schedules cover the surface of Europa over the course of the mission. This coverage analysis is then generated for two of the proposed spacecraft trajectories. The impact of this trajectory decision can then be seen in terms of surface covered by each instrument. We also consider relaxing
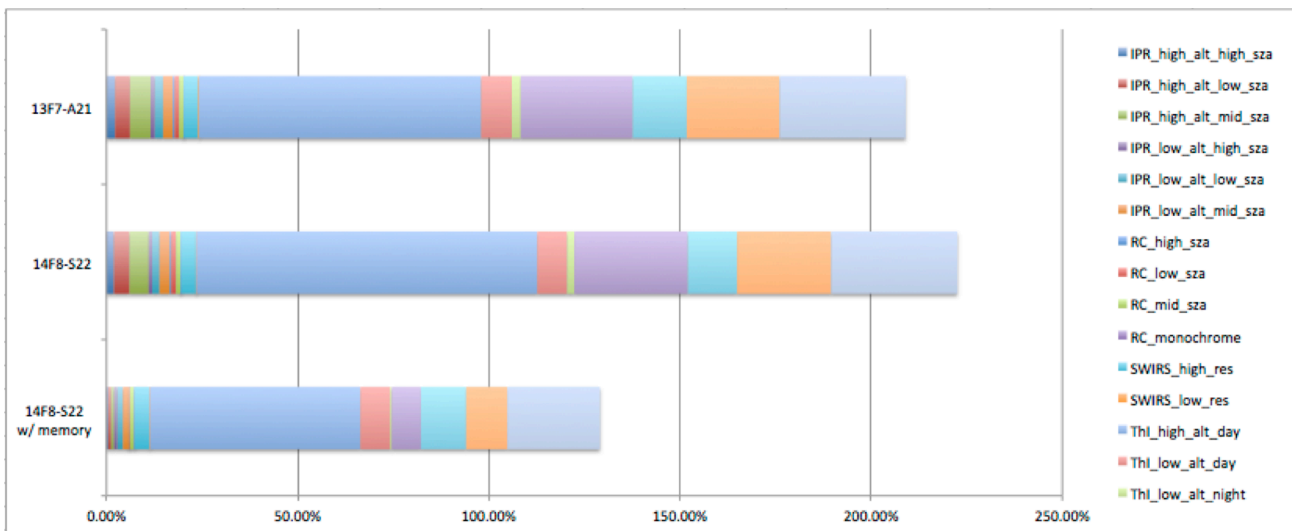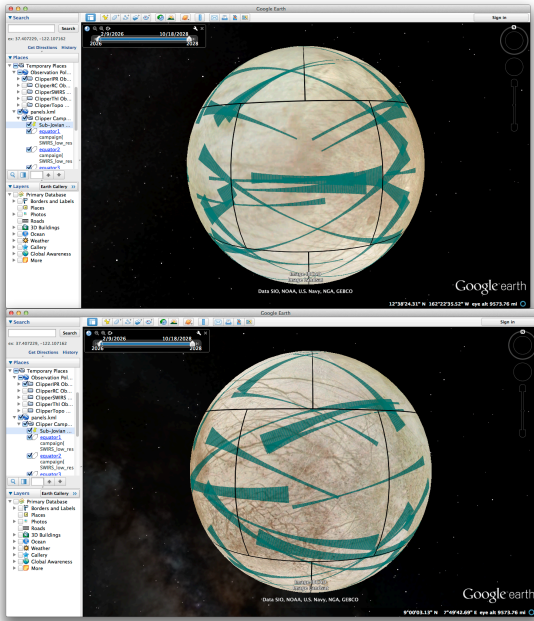

Figure 3: CLASP coverage analysis

Figure 4: Europa Clipper Concept Ice Penetrating Radar coverage anti-, sub jovian.

particular constraints to see their individual impact on the coverage.

Figures 3 summarizes the results of our analysis. First, the top two bars show the coverage results, broken down by campaign, for the two trajectories under consideration (labeled 13F7-A21 and 14F8-S22). Each section of the graph indicates the percent of the surface coverage by one of the campaigns, which is why the total sums to greater than 100. Only distance and illumination constraints where considered when generating these observations schedules. The onboard memory constraint was omitted because it was not expected to significantly impact the results from a change in trajectory. The most significant change was in the coverage of ThI at high-altitudes. The last bar in the graph shows the results for the 14F8-S22 trajectory after adding the memory constraint along with a typical downlink schedule. Because a flyby occurs in a relatively short period of
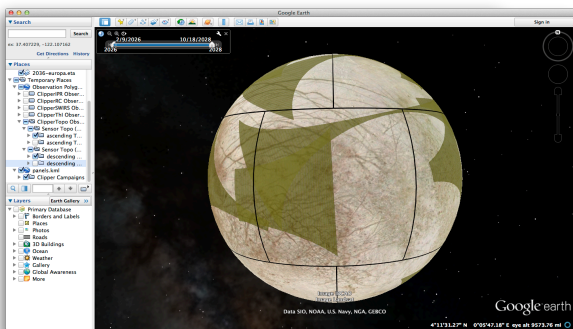

Figure 5: Europa Clipper Concept Topographic Imager Stereo coverage sub-jovian.

time, there is not much time during primary data collection to allow for data downlink. This limits the coverage, showing how automated coverage analysis can be used to make hardware design decisions. In other words, we see that increasing the onboard memory would reduce this limitation and possibly increase coverage significantly.

Figure 4, 5, and 6 show graphically the coverage by various instruments as tracked by CLASP.

6   Discussion and Related Work

Spacecraft operations have been a major area of application for automated planning and scheduling. Numerous space missions have used automated planning & scheduling on the ground to enable significant operational efficiencies including the Hubble Space Telescope [Johnston et al. 1993], space shuttle refurbishment [Deale et al. 1994], shuttle payload operations [Chien et al. 1999], The Modified Antarctic Mapping Mission [Smith et al. 2002], Mars Exploration Rovers [Bresina et al. 2005], Earth Observing One (EO-1) [Chien et al. 2005a] Mars Express [Cesta et al. 2005], and Orbital Express [Chouinard et al. 2008]. Automated planning has even flown as a technology demonstration on the Deep Space One (DS1) Mission [Muscettola et al. 1998] and as the primary operations system on 3CS [Chien et al. 2001] and EO-1 [Chien et al. 2005b].   However, all of the above applications focused on the state, resource, and timing aspects of mission operations rather automating both the spatial coverage as well the state and resource reasoning.   A notable exception is [Knight and Hsu 2009, Doubleday et al. 2014, Rabideau et al. 2010] which also use the CLASP system.   AEOS [Lemaitre et al. 2002] also considered mapping regions but is generally focused on directing an extremely agile earth observing platform to cover small areas from a regular earth orbit generally or potentially within a single overflight.   In contrast we examine a problem with a non-agile spacecraft covering large areas from a highly eccentric flyby typically in multiple overflights.   In [Verfaillie et al. 2012], observation requests are expressed in terms of time instead of geometric locations, and the search explores the space of all possible instrument start and stop times. A heuristic is used to choose times that are expected to have the best impact on the plan, which includes short durations to keep resource use low. CLASP explicitly prunes times that will cause resource violations.

This work represents a preliminary implementation of a scheduling system designed to assist in the evaluation of mission designs for the Europa Clipper mission concept pre-project.   Future work includes both tool enhancements and scheduling algorithm analysis. In the tool enhancement area we would like to investigate means of explaining why observations are or are not selected.   This could include information on the science campaigns that motivated selection of an
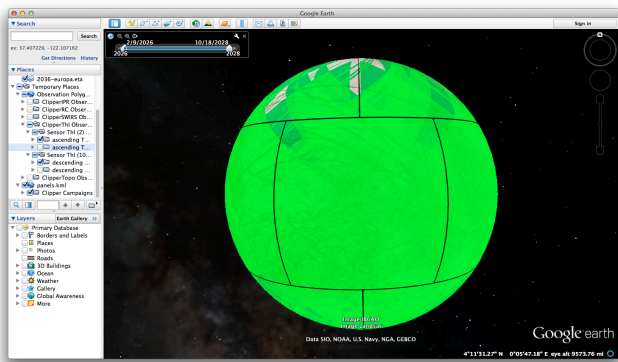
Figure 6: Europa Clipper Concept
Thermal Imager High resolution coverage
sub-jovian.

observation or computation of which selected observations are in conflict with a proposed observation.

Evaluation against other search algorithms besides squeaky wheel would be useful. In particular, approaches that could guarantee optimal solutions such as branch and bound would be ideal. However the large problems sizes for Europa Clipper mission concept scheduling may pose a problem for near exhaustive search. Further analysis of the key pre-processing and scheduling complexities are needed. Derivation of upper bounds on optimal schedules via solution of relaxed versions of the problem (as in [Chien et al. 2010]) seems to offer some promise for analysis. Better characterization of the problem sizes would also be helpful.

7   Conclusions

This paper has described a mission analysis tool for the Europa Clipper mission concept currently proposed to study the Jupiter moon Europa. CLASP first constructs spatial observation candidates for a set of scientific instruments. It then combines geometric constraints with spacecraft operations constraints using the Squeaky Wheel heuristic greedy optimization algorithm. The result is a set of candidate observation schedules used to quantitatively evaluate a given set of mission designs.

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