Using Operations Scheduling to Optimize Constellation Design

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Abstract

Space mission design is a challenging task. Many factors combine to influence overall mission return, and it is extremely difficult a priori to predict which factors in concert will most influence mission return. These challenges are even greater for constellation missions, in which a potentially large number of spacecraft are used in concert to achieve mission goals, because constellations have additional design choices of number of spacecraft, orbit combinations, and constellation topology.

We describe efforts to use automated operations scheduling to assist in the design and analysis of a family of radio science constellation missions. Specifically, we work to produce a model-based approach to evaluating mission return based on key design variables of: target catalogue selection, constellation topology, size of the science constellation, size of the relay support network, orbit mix, communications capability, communications strategy, ground station configuration, onboard processing and compression, onboard storage, and other elements of operations concept.

In our design methodology, choices on the design dimensions are evaluated by producing mission plans using automated scheduling technology and these resultant plans are evaluated for science return. By this approach we intend to enable evaluation of large numbers of mission configurations (literally 10^6 configurations) with manual assessment of only a small number of the best of these configurations.

Introduction

Space mission design involves concurrent engineering on multiple disciplinary fronts in an effort to produce an overall configuration of spacecraft, orbit, and operations concept, to best achieve overall science objectives.

One of the challenges in space mission design is correctly accounting for a large number of design dimensions that may interact in subtle and hard to predict ways. We address this difficulty by adopting an operations-based approach to evaluating mission designs. We in effect partially simulate the missions, applying any and all operations constraints we can to derive results as realistic as possible. We then characterize the science measurements possible and use these as a proxy for mission return. By performing these simulations and calculations, we hope to estimate mission return and therefore enable devoting resources to the most promising early mission designs.

We investigate the use of this approach in the context of a large scale constellation to perform low frequency radio science measurements. Such a constellation would be placed well beyond Earth orbit – potential locations would be Lagrange points, Earth trailing, or a lunar orbit. Figure 1 shows a screen snapshot of a Cosmographia [NAIF] visualization of a constellation in a lunar orbit. This would enable the constellation to measure signals from beyond the interference of the Earth's ionosphere which restricts Earth-based arrays. The constellation would consist of a number of spacecraft: 16-128 spacecraft constitute a design range under study. Because the purpose of using multiple spacecraft is to synthesize a signal as if measured by a larger virtual antenna, ideally the spacecraft would be spread out at a range of distances from each other (from several km to several 1000 km) in a diverse spatial distribution. This dispersion presents challenges for communications – as communications rates decline with the square of the distance. Additionally – ground-based antenna arrays use antennae each of which weighs many tons and produces a Gigabit of data per second. In order for this constellation to be feasible the launch mass must be reduced to small spacecraft (< 10 kg per spacecraft) to reduce the expense of the mission. Additionally, the data volume must be reduced in order to be brought back to the Earth – bringing back 128 Gb/s from lunar orbit would require an extremely powerful communications setup and small spacecraft have very limited power.

In this paper we discuss the high level approach of the design process, the design dimensions of the constellation mission, the details of our implementation, and some preliminary results.

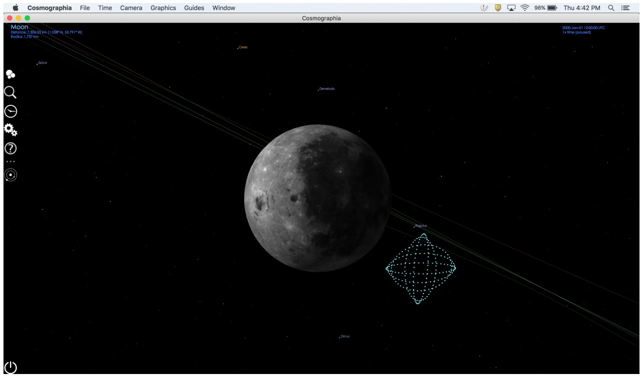

Figure 1: Cosmographia visualization of constellation of spacecraft in lunar orbit.

Mission Design

We formulate of the mission design problem is as follows.

Set of mission design dimensions:

$D_1 \ldots D_i$

For each design dimension D_j there are a set of k alternatives:

$D_{j,1} \ldots D_{j,k}$

Indeed there can be a continuous range of alternatives, for simplicity we restrict to finite discrete alternatives here.

A mission design can therefore be a choice of a single alternative for each of the design dimensions:

$D_{proposed} = \langle D_{1,a}, D_{2,b}, D_{3,c} \ldots D_{M,m} \rangle$

We also presume a set of mission constraints:

$C_1 \ldots C_o$ where $C_j(D_{eval}) \rightarrow$ {True, False}

We also presume a mission score function $F(D_{eval}) \rightarrow$ integer.

The goal of the mission design process is to determine a mission design:

$D_{good} = \langle D_{1,a}, D_{2,b}, D_{3,c} \ldots D_{M,m} \rangle$

Such that Forall constraints $C_{i=1} \ldots C_{i=o}$ $C_i(D_{good})$ = TRUE

(e.g. the mission passes all of the constraints)

and $F(D_{eval})$ is maximized.

Generate and Test Operations Evaluation-based Mission Design

Our overall approach is to enumerate a large proportion of the design space by enumerating a large number of design vectors (e.g. the design vectors D_{good} listed above). For each of these candidate designs that satisfies all mission constraints $C_1 \ldots C_i$, we automatically construct an operations model for the mission design and the use this operations model to generate a mission plan for the mission. This mission plan is automatically scored to estimate the $F(D_{eval})$.

Figure 2 below shows the flow of this general approach.

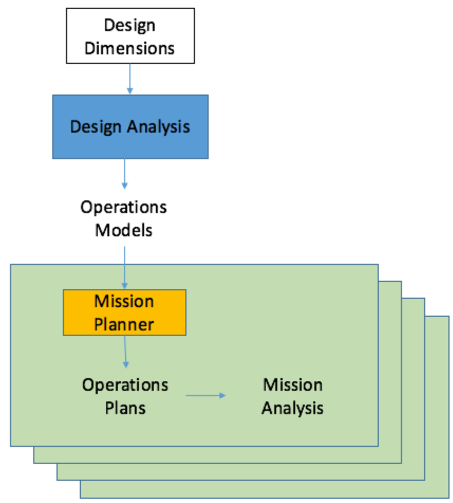

Figure 2: Generate and Test approach to spacecraft design configuration and operations analysis.

Dimensions of Constellation Mission Design Study

We now describe a number of the design dimensions we are analyzing in our constellation mission design study. These dimensions represent set D in the problem formulation.

Constellation Topology

One key aspect of constellation design is constellation topology. One possible configuration is that all of the spacecraft do not directly interact in operations and each directly transmits its data to ground communications stations. An-other configuration uses one or more "mother ships" communicating with a larger number of daughter ships. In this setup commands are uplinked to a mother ship and relayed on to the daughter ships. Similarly, science and engineering data is cross linked from the daughter ships to a mother ship and then downlinked to Earth-based ground communications stations. This "star" configuration has the advantage that the mother ship relays can be higher powered and therefore more suited to the longer distance communication to the Earth. Additionally, the mother ship can be placed into an orbit advantageous for communications to Earth, whereas the daughter ships can be placed into orbits advantageous for science. The constellation topology also interacts with the sizing of the spacecraft onboard storage (e.g. solid state recorder). In a peer-based constellation the individual science craft must have significant SSR storage. In a star topology this storage can be concentrated at the mother ship(s).

Antenna Synthesis

As we are studying a radio science constellation, the primary science driver is the quality of radio antenna that can be synthesized. This quality is driven by several factors: antenna pattern coverage, individual antenna design and performance, and integration time.

Antenna pattern coverage for distributed antennae has been studied previously, mostly in the context of ground-based radio science arrays [Keto 1997, Boone 2001, Boone 2002]. In short, a good antenna pattern provides uniform coverage over a range of baseline lengths and orientations where a pairwise baseline length is the planar projective distance between the two receivers (e.g. spacecraft) and the orientation is the relative orientation of that baseline (all relative to the target).

Data Generation and Representation

The radio science measurements being made represent incredibly large amounts of raw data in a natural uncompressed format. For the low frequency measurement constellation we are studying, sampling and storing the data in the 30MHz regime (twice the frequency of interest) acquired at 12 bit resolution per sample at two polarizations results in a raw data rate of 0.7×10^9 bits per second per spacecraft of science data. A number of other measurements and storage options are possible at a potential reduction in science. These options are listed below. For each of these operational scenarios we evaluate the potential constellation return in terms of length, number, and qualities of science measurements possible.

Type of Data Acquired	Data Volume (bits/second) (2 polarizations, per s/c)
12bCC	0.7×10^9
12bPPCC	12×10^6
3bCC	180×10^6
3bPPCC	3×10^6
1bCC	60×10^6
1bPPCC	1×10^6
12bFx2ms	0.343×10^6

Orbit Selection and Design

The orbit of the spacecraft comprising the constellation drives many of the constellation performance factors. The orbit drives the antenna pattern coverage and therefore a good proportion of the science quality. A good combination of orbits will provide a good variation of baselines and orientations to provide good science.

Orbit selection also significantly affects communications. Communications data rate is proportional to d^{-2} where d is the distance between the two points in communications. Also occlusions by spacecraft or the moon can prevent communications. In a star mothership topology, the orbits dictate the cross link distance each spacecraft must communicate to the mother ship(s). The mothership orbit may be occluded from the Earth by the moon so we also analyze the coverage (visibility) of the mother ship(s) from the three Deep Space Network ground station locations: Canberra, Goldstone, and Madrid.

Spacecraft Design

Spacecraft design influences mission return in many ways. For the mothership relays, their communication capability is directly related to their power capability. Additionally, the mothership design may have one or multiple cross link antennae – each cross link antenna may be able to simultaneously receive a signal from a science spacecraft. There may however be a geometric constraint on the two cross linking spacecraft. Also, whether the mothership can crosslink and downlink to earth simultaneously is a major factor. As is the onboard solid state recorder capacity of the mothership (or each mothership if there are more than one).

The science spacecraft capabilities also will vary. Can each acquire science data and cross link simultaneously? How much power is available to cross link (affecting data rate)? How much onboard storage does each science craft have?

Additionally, for both the mother ship and science craft, what are the onboard maintenance activities that need to be performed and how will they impact science return?

Operations Planning

Once we have determined the above elements of the mission design we drive the design process using operations planning. The idea is that the operations model can be used to derive an estimate of the overall science return of the configuration.

Each full set of candidate design choices are semi-automatically encoded into separate domain models for the ASPEN/CASPER planning system [Chien et al. 2000a, 2000b]. ASPEN is a timeline-based scheduling framework that allows for operations, spacecraft, science, and other constraints to be incorporated in an automated scheduling environment.

The automatic scheduling algorithms then generate a proposed mission operations schedule constrained by those models. Each of the generated mission plans may then be evaluated for various metrics including science data utility, remaining resource margins, etc. The combined metrics for each design choice set can then be compared to select the best candidate mission designs for further evaluation.

The separate domain models for each point in the design space each leverage a common core of action/state models describing the entire space of available mission designs. The actions available in the common model span the entire constellation: some are executed only on individual science craft, some only on the mothership(s), and others require joint simultaneous action by multiple craft. The modeled actions include: repointing the field of view of the sensor, recording data from the sensor, crosslinking data from a science craft to a mothership, downlinking data from the mothership to earth, downlinking data directly from a science craft to earth, as well as placeholders for intermittently required engineering activities. These actions make use of various modeled states and resources: the visibility of each science target, the interferometry baseline utility of each observation window, the number of receivers on the mothership, the visibility of earth ground stations, the bandwidth of each communication link, power generation rate, remaining battery reserves, and so on.

Each complete set of concrete design choices then imposes additional constraints on the common base model. For example, the choice of sensor changes the field of view and scientific utility of observations, the choice of data storage device changes the available storage space and required power, and the selected transmitter power changes the available data bandwidth. These additional constraint inputs to the planner are generated from the mission design choices by a set of scripts dedicated to the task.

The CASPER automated operations planning system then uses the combined core model and design constraints to generate a proposed operations plan. CASPER starts from an empty mission plan and iteratively optimizes it by adding or removing actions to improve a declared utility function. The utility function is directly related to the calculated science utility of the data received at earth, and strongly inversely related to any mission constraint violations. This guides the planner to add observation, crosslink, and downlink activities while also respecting the design limits on view periods, storage space, bandwidth, power etc. As described earlier, the calculated utility of the science data is related to the total observation integration time and how well the selected interferometry baselines cover the space of distances and angles needed to characterize the structure of each radio astronomy target. The final output operations schedule from the planner includes concrete timed actions for each of the constellation craft to execute.

Critical to all of this operations planning is the geometric aspect of the problem. For all of these geometric analyses we use the SPICE package [Acton 1996]. These analyses include: spacecraft position and science target position for antenna analysis, spacecraft and mothership position for cross link calculations, and mothership and groundstation position and downlink calculation.

The operations schedule can then be evaluated versus various metrics that are interesting to the design team. These metrics represent F(D) in the problem definition. Foremost among these will be the overall predicted utility of the returned science data, as calculated by the planner's own utility function. Each of the component metrics of baseline coverage, integration time, target coverage is also reported for comparative consideration by the design team. Additional metrics such as excess unused capacity on some resources (e.g. unused power or bandwidth) are also reported to help inform which parts of each design may be over-engineered and which are the bottlenecks during actual operations.

Implementation

We are currently in early prototyping of our overall design evaluation system. The overall data flow of our prototype is shown below in Figure 3.

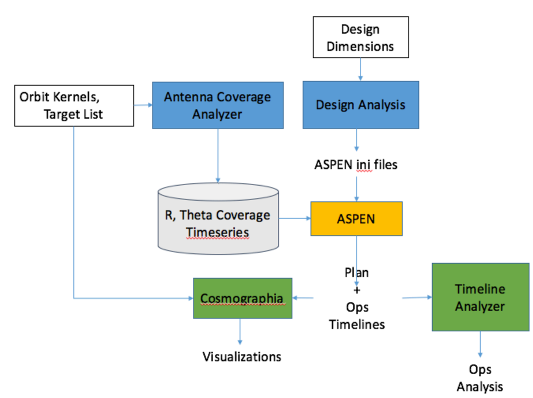

Figure 3: Design Operations Evaluation System Architecture

The overall range of design alternatives is described in an input file. This input file is used to semi-automatically generate a set of ASPEN models. Also input is a list of science targets for evaluation and a set of candidate orbits. These are analyzed by a separate code module which computes the antenna coverage pattern and baselines at each point in time for each target if the orbit were to be used and the relevant target were under observations.

In a run for each constellation configuration, ASPEN produces a plan as well as ancillary operations timelines. These indicate which spacecraft are observing which target at each point in time as well as the communications transfers required to return the data to Earth ground stations. This information can be used to analyze the operations performance of the constellation configuration and also the operations can be visualized within Cosmographia. For example, we can directly observe the state of the science spacecraft solid state recorders, or of the mothership relay solid state recorders. If these are constantly at capacity, we might infer that the bottleneck is the communications rates for either the cross link or the mothership to Earth.

The above architecture is in the process of being implemented and has already revealed some preliminary results which are being investigated further. Specifically, as we add more science spacecraft to the constellation, the number of independent measurements goes up linearly – so that the signal to noise improves linearly. However, addition of a spacecraft increases the number of pairwise observation baselines by n, for n spacecraft, i.e. the number of pairwise baselines increases as n^2 with the number of spacecraft. Therefore, we might expect the antenna coverage ratio to increase with the square of the number of spacecraft. However preliminary runs indicate that it is hard to realize even a linear increase in antenna coverage due to most orbits simply repeat coverage of already existing baselines (in distance and orientation) (Figure 4 below). As shown in this analysis, increases in the number of spacecraft show even declining (sub linear) increase in the antenna coverage pattern. However, this represents only initial results and much further study is needed. Figure 4 shows the antenna coverage ratio as random spacecraft from the orbits shown in Figure 1 are added to the constellation for 512 r bins x 512 theta bins (not equal area bins) computed over one repeat orbit cycles (about 8 hours 40 minutes) with a step size of 1 second theta range 0-110 degrees, and r range from 0 to 700 km.

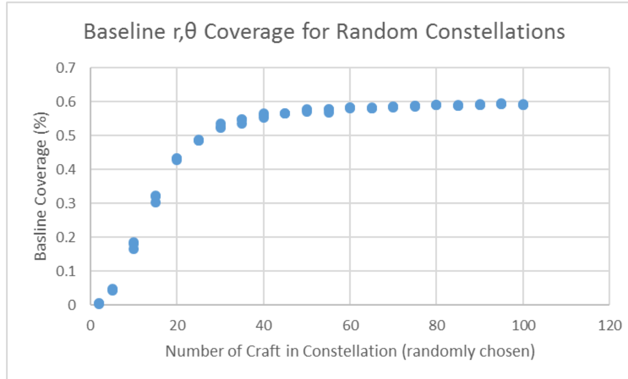

Figure 4: Plot for antenna coverage as a function of number of spacecraft

Related and Future Work

FRACSAT [Do et al 2013] uses forward state space search planning to generate all possible feasible configurations in a constellation design space. This approach is directly relevant to the first part of our methodology, i.e. generation of feasible alternatives to then simulate operations. While we currently use a hard coded approach for this phase, the FRACSAT approach is quite promising to explore and is an excellent area for future work. Also coming out of the F6 program (like FRACSAT), the work by Cornford [Cornford et al. 2012] considers more trades in the project management aspect of the design space such as when to commit to a certain design option or family of options.

The work described in this paper can be considered a continuing evolution of the planning for mission design approach previously described in [Knight et al. 2012] applied to the Desdyni mission (now called NI-SAR) and previously applied to SIM mission design [Smith et al. 2000], Europa mission Design [Rabideau et al. 2015] and Pluto Fast Flyby Misson Design [Sherwood et al. 1997]. In this approach, operations plans are generated for a range of mission configurations and these plans are evaluated with respect to mission objectives. Work on analyzing the BepiColumbo data management and downlink [DelaFuente et al. 2015] using automated downlink scheduling techniques can also be considered in the same approach – specifically using automated operations techniques to analyze and predict possible system performance prior to operations.

Work by Fukunaga [Fukunaga et al. 1997] also addresses automation of spacecraft design. This work also searches in the design space and simulates to evaluate mission performance. However, this approach does not use any planning or scheduling based operations model.

There are many areas of future work – this paper only describes very preliminary efforts towards operations-based constellation design analysis. First, all of the models used thus far are quite primitive – using more refined accurate models would result in better results. Second, intelligent exploration of the design space rather than brute force sparse sampling would be much more effective. Third, we could introduce stochasticity in the operations model to evaluate a designs robustness to a wider range of scenarios. This stochasticity could represent either a wider range of operating scenarios or robustness to execution uncertainties.

Conclusions

We have presented preliminary work in using an operation-based planning model to evaluate design configurations for a radio science constellation mission concept. In this approach we enumerate a number of design alternatives, semi automatically generate operations models for each of these design alternatives, and use these operations models to generate baseline operations plans. These operations plan can then be analyzed to evaluate the constellation designs. This software prototype is in very preliminary stages and still undergoing evolution.

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