TRADE-SPACE ANALYSIS TOOL FOR DESIGNING CONSTELLATIONS (TAT-C)

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ABSTRACT

While there is growing interest in implementing future NASA Earth Science missions as Distributed Spacecraft Missions (DSMs), there are currently very few tools available to help in the design of DSMs. The objective of our project is to provide a framework that facilitates DSM Pre-Phase A investigations and optimizes DSM designs with respect to a-priori Science goals. Our Trade-space Analysis Tool for Constellations (TAT-C) enables the investigation of questions such as: "Which type of constellations should be chosen? How many spacecraft should be included in the constellation? Which design has the best cost/risk value?". This paper provides a description of the TAT-C tool and its components.

Index Terms— Mission Design, Trade-space Analysis, Distributed Spacecraft Mission (DSM)

1. INTRODUCTION

A "Distributed Spacecraft Mission (DSM)" is a mission that involves multiple spacecraft to achieve one or more common goals. Multipoint measurement missions can provide a significant advancement in science return, and this science interest coupled with many recent technological advances is driving a growing trend in implementing future NASA missions as DSMs. As illustrated in Figure 1, this is the result of a combination of *driving factors*, such as budget cuts, maturing technologies and new science requirements; *existing and developing capabilities* such as secondary launches, hosted payloads and smaller launch vehicles; and *new enabling technologies being currently developed* such as instrument and component miniaturization as well as scalable mission ops and "big" data analytics applied to telemetry and science data. All of these combined with the development of SmallSats (CubeSats and MiniSats) and of all the necessary DSM technologies will enable new Science, and will provide benefits such as: enabling new measurements, improving existing measurements, mitigating missions risk, facilitating data continuity, facilitating mission survivability. Constellations will also represent a key component of future multi-organization and international cooperation.

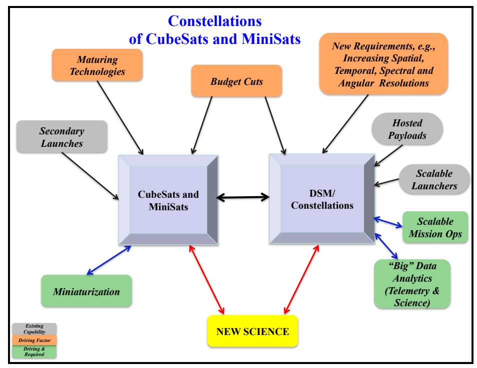

Figure 1 - *Driving Factors and Technologies for the Development of Constellations of CubeSats and MiniSats*

But while the interest in DSMs is growing, there are currently very few open-access and integrative tools available to explore the trade-space of DSM variables, minimize cost and maximize performance for pre-defined science goals, and therefore select the most optimal mission design. The objective of our project is to provide a framework that facilitates DSM Pre-Phase A investigations and optimizes DSM designs with respect to a-priori Science goals. Our Trade-space Analysis Tool for Constellations (TAT-C) enables the investigation of questions such as: "Which type of constellations should be chosen? How many spacecraft should be included in the constellation? Which design has the best cost/risk value?"

This paper describes the overall architecture of TAT-C (illustrated in Figure 2) that includes: a *User Interface (UI)* interacting with multiple users - scientists, missions designers or program managers; a *Trade-space Search Request (TSR)* gathering requirements from UI and formulating requests for the *Trade-space Search Iterator (TSI)*, which in collaboration with the *Orbit & Coverage (O&C)*, *Reduction & Metrics (R&M)*, and *Cost & Risk (C&R)* modules generates multiple potential architectures and their associated characteristics. UI, still in development, will eventually include Graphical, Command Line and Application Programmer Interfaces to respond to the demands of various levels of users expertise. Science inputs are grouped into various mission concepts, satellite specifications, and payload specifications, while science outputs are grouped into several types of metrics - spatial, temporal, angular and radiometric. Orbit & Coverage leverages the use of the Goddard Mission Analysis Tool (GMAT) to compute coverage and ancillary data that are passed to Reduction & Metrics. Then, for each architecture design, Cost & Risk will provide estimates of the cost and life cycle cost as well as technical and cost risk of the proposed mission. Additionally, the *Knowledge Base* (KB) module is a centralized store of structured data readable by humans and machines. It will support both *TAT-C analysis* when composing new mission concepts from existing model inputs, and *TAT-C exploration* when discovering new mission concepts by querying previous results.

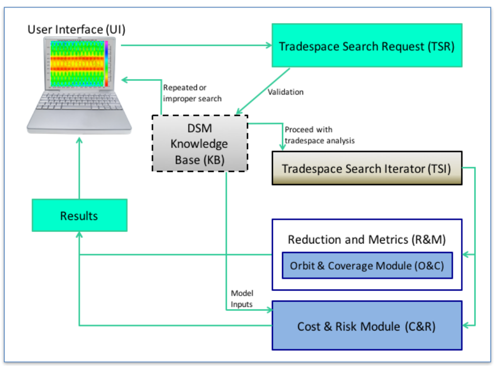

Figure 2 – *Trade-space Analysis Tool for Constellations (TAT-C) Modular Architecture*

2. DESIGNING TAT-C

Although DSMs can be very finely organized according to many variables [1], in the following description, we mainly refer to DSMs that are designed as distributed from inception; we broadly categorize them into "Constellation", "Precision Formation Flying" and "Fractionated":

1. *A Constellation* is the most general form of DSM, with two or more spacecraft placed into specific orbit(s) for the purpose of serving a common objective (e.g., THEMIS[1], CYGNSS[2] and TROPICS[3]);
2. *A Precision Formation Flying* DSM is a mission in which the relative distances and 3D spatial relationships (i.e., distances and angular relationships between all spacecraft) are precisely controlled, e.g., through direct sensing by one spacecraft of at least one other spacecraft state (e.g., PROBA); and
3. *A Fractionated Mission* is a satellite architecture where the functional capabilities of a conventional monolithic spacecraft are distributed across multiple modules that are not structurally connected and that interact through wireless links (e.g., DARPA/F6).

TAT-C currently addresses mainly the design of general constellations, although it is being extended to other DSM types. Its main innovation lies in the modular architecture of represented in Figure 2, and in its ability to allow the mission designer/user to quantify each step of the Science traceability matrix. DSM design is a function of a much larger number of variables than a monolithic mission and it is therefore important to conduct trades that will assess the impact of the different variables on the final mission design, its Science return and its estimated cost and risk.

The main objectives of TAT-C are to:

- Provide a framework to perform pre-Phase A mission analysis of DSMs
  - Handle multiple spacecraft sharing mission objective
  - Include sets of smallsats up through flagships
  - Explore trade-space of variables for pre-defined science, cost and risk goals and metrics
  - Optimize cost and performance across multiple instruments and platforms, vs. one at a time
- Create an open access toolset which handles specific science objectives and architectures with the capabilities:
  - To increase the variability of orbit characteristics, constellation configurations and architecture types
  - To provide a flexible, evolvable framework including optimized computations.

After interviewing a number of potential users, we identified specifications for the user interface (described in Section 7), as well as the inputs and outputs science requirements. These requirements are detailed in Section 3.

As stated above, Figure 2 illustrates the overall TAT-C architecture. TAT-C is first initialized with the user requirements, i.e., with the trade-space bounds or the trade-space options, depending on the type of user. These inputs are first validated by the Trade-space Search Request (TSR) at 2 levels: (1) to check analytically the physical validity of the inputs, and (2) to coordinate with the DSM Knowledge Base which eventually will have extensive knowledge of previous designs and will be able to prune the trade-space search according to similar designs, therefore speeding up the search for an optimal design. Once the inputs have been checked, the trade-space analysis starts. This analysis is conducted by the Trade-space Search Iterator which selects and generates subspaces to analyze, sending requests to: the Orbit & Coverage Module to compute the grid coordinates based on lat/long bounds and grid resolution, propagate the satellite orbits, compute the coverage to points/grid of interest and to the Ground stations, and accumulates coverage and angles of access over all events of interest; and to the Cost & Risk Module to calculate the probabilistic distributions of cost and risk over mission lifetime. For each potential architecture, TSI then reduces all of those data and

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[1] THEMIS: Time History of Events and Macroscale Interactions during Substorms
[2] CYGNSS: Cyclone Global Navigation Satellite System
[3] TROPICS: Time-Resolved Observations of Precipitation structure and storm Intensity with a Constellation of Smallsats

creates the metrics that will be presented to the user through the (Graphical) User Interface. Both C&R and TSI consult with the Knowledge Base for getting general information about past missions and/or simulations, as well as information about launch opportunities, spacecraft specs, etc.

Information between modules is exchanged either in memory or through JSON (JavaScript Object Notation) files, an open-standard format using human-readable text.

3. TRADE-SPACE SEARCH ITERATOR

As shown in Figure 3, TSI inputs include: *the mission concept* (e.g., the area of interest, the mission duration and the launch options); *the satellite specs* (e.g., the existing satellites, the altitude/inclination ranges, specific orbit needs, and communication bands); *the payload specs* (e.g., the concept of operations, the number and the type of instruments, the mass, volume, and optical characteristics); *any constraints* on the range of output values.

Mission Concept	
Attribute	**Characteristics**
Start Epoch	UTC time
Area of Interest	exact Earth locations
Ground Stn options	Select and/or file
Launch preferences	Select and/or file
Propagation fidelity	low, med, high
Output options	Select
Output bounds	min, max

Satellite Specs	
Attribute	**Characteristics**
Existing Sat options	Select and/or file
Number of new Sats	min, max
Number of satellite types	exact
Altitude Range of Interest	min, max
Inclination Range of Interest	min, max
Special Orbits only	Select
Angular Rate	min, max
Maximum pointing	exact
Comm band	exact bands

Payload Specs (unnecessary for Stereo)	
Attribute	**Characteristics**
Number of payloads/sat	Exact
Occulation or Imaging or Pairs	Select
Payload Mass	Approximate
Payload Volume	Approximate
Payload Power	Approximate
Radiometric resolution	min
Occultation or Pairs coupling	Exact
Nadir swath or FOV	min, max OR exact
Nadir GSD or FOV	min, max OR exact
Object/s of Interest	Select then specify
Occultation Altitude	max, min
Measurement time	min, max
Solar conditions	Select
Sun Glint preference	Select
Spectral or other Channels	Exact wavelengths
Spectral resolution	exact binwidths

Figure 3
Input Science Requirements

Spatial Metrics	
Attribute	**Characteristics**
Effective Spatial Resolution	min, max, average
Effective Swath	min, max, average
Percentage Image overlap	min, max, average
Covered positions (w/ FOV)	lat, lon
Occultation positions	lat, lon
Inter-Sat Range and Rate	min, max, average
Possible positions (w/ FOR)	lat, lon

Temporal Metrics	
Attribute	**Characteristics**
Occultation time*	min, max, average
% period time in Sun*	min, max, average
Time to Coverage*	min, max, average
Access Time*	min, max, average
Latency to downlink*	min, max, average
Repeat Time*	min, max, average
Revisit Time*	min, max, average

Angular Metrics	
Attribute	**Characteristics**
View Zenith Angle	min, max
View Azimith Angle	min, max
Solar Zenith Angle	min, max
Solar Azimuth Angle	min, max
Lunar phase	min, max, average

Radiometric Metrics	
Attribute	**Characteristics**
Signal to Noise Ratio	min, average

Figure 4
Output Science Requirements

TSI reads the user's inputs given to the GUI to create the JSON files that will be used as iterator's inputs. Default inputs are part of the system and have been generated using Landsat 8 with the Enhanced Thematic Mapper (ETM+) payload. TSI then generates DSM multiple architectures for a combination of variable values that satisfy the iterator inputs. A DSM architecture is a unique combination of variable values (altitude, inclination, FOV, number of satellites, etc.). For each architecture, TSI creates files and send commands to the C&R module to compute the architecture cost, and to the "Reduction and Metrics" (R&M) module to compute the architecture performance as it relates to the science requirements. R&M is also responsible for calling the O&C module to propagate the orbit of every satellite and to compute the coverage given the payload specs. R&M then integrates coverage and computes all performance metrics.

As shown in Figure 4, TSI outputs include: *all metrics* computed for each architecture (e.g., average, spatial and temporal distributions); the *spatial information* (e.g., spatial resolution, swath overlap percentage, occultation positions, coverage); the *temporal information* (e.g., revisit, access and repeat times); the *angular information* (e.g., view zenith, solar illumination); and the *radiometric information* (e.g., signal to noise fall-off). See [2] for more information.

4. ORBIT AND COVERAGE MODULE

The purpose of the Orbit and Coverage module is to model orbits while balancing accuracy and performance. Since the trades are performed for Pre-Phase A analysis, orbits do not require the same level of accuracy than higher mission design phases. On the other hand, since TAT-C examines multiple architecture, these computations need to be very fast, although still require enough accuracy to enable meaningful trades. O&C also computes coverage metrics data for each constellation/sensor set and the ancillary orbit data necessary for the performance, cost and risk computations. All coverage models are prototyped in MATLAB and then converted to C++. They are either based on or extensions of the tools included in GMAT. Currently, O&C handles evenly spaced grid points as well as custom grid points. To improve performance, the coverage utility performs a feasibility test to determine if line-of-site coverage is possible before analyzing sensor coverage. O&C models orbits using semi-analytic propagation that includes the effects of J2 averaged over a single orbit. Orbits are propagated using osculating Keplerian elements for performance reasons. Current functionality assumes nadir pointing conical sensors, however the design is general and development for more general sensor masks is under way.

5. COST AND RISK MODULE (C&R)

Previous work [3] has highlighted the limitations of existing cost models with respect to constellation missions, therefore traditional cost estimating assumptions need to be challenged before being applied to constellations. There is currently no comprehensive cost model for satellite constellation architectures.

Our approach has been to develop an aggregate model consisting of Cost Estimating Relationships (CERs) from widely accepted and publicly available models [4] whose output is a probability density function showing the most likely cost for the total mission lifecycle and for the selected mission components, including recurring, nonrecurring, spacecraft bus and payload costs. Figure 5 shows the high-level flow of the cost module. The model accepts an input file of DSM characteristics, including a list of observatories, mission owner specifications, and ground stations.

A contextual assessment of the DSM architecture is formulated according to the number and distribution of satellites within the architecture, as well as assessing the number of unique spacecraft within the architecture. This information, in conjunction with satellite mass, is used to select appropriate learning curve factors and spacecraft bus cost reliability factors [4]. CERs for the spacecraft parameters as well as the mission operations are assessed from various sources including the Unmanned Space Vehicle Cost Model (USCM), the Small Satellite Cost Model (SSCM), the Mission Operations Cost Estimation Tool (MOCET), and established best practice [4]. The risk portion of C&R is still under development. More details will be presented at the conference.

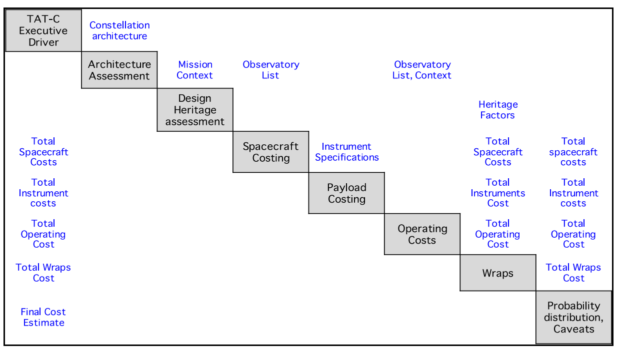

Figure 5 – *High Level Cost Module Flow*

6. KNOWLEDGE BASE (KB)

The KB is a centralized store of human- and machine-readable data loosely coupled with TAT-C modules and other interfaces. The KB is still under development but its key objectives are to support two main tasks:

- TAT-C Analysis: by composing new mission concepts from existing model inputs
- TAT-C Exploration: by discovering new mission concepts by querying pervious results.

The proposed KB design uses a layered architecture with loose coupling between client and server components achieved via a Representational State Transfer (REST) web service. Clients access KB functions via a simple HTTP request-response interface similar to how other web resources are accessed. The current prototype KB application uses a custom web server built on a Node.js/Express/Mongoose technology stack with a MongoDB database. Similar applications have been proposed and developed to manage a plurality of data sources and formats in healthcare information systems and to manage data in model sensitivity analyses. While this approach leverages web technologies, a local implementation does not require intra- or inter-network resources and associated security implications. Upcoming KB efforts will also include gathering publicly- available information on existing and proposed Earth science missions to support TAT-C validation and enable rapid generation of new concepts by composing existing instruments, spacecraft busses, and mission scenarios.

7. USER INTERFACE

Although only a prototype Graphical User Interface (GUI) is currently implemented, TAT-C is planned to include three types of user interfaces:

- *GUIs (Graphical User Interfaces)* will be portable to any typical graphical computing environment, and will be designed to function like familiar “Software Wizards”, walking users systematically through DSM trade space choices, and their consequences. GUIs will be designed to isolate basic, required, non-expert choices from more expert options typically accessed by more advanced users. GUIs will intuitively blend interactive choosing with visual browsing of analysis output characterizing the results of choices.
- *CLIs (Command Line Interfaces)* will be portable to typical command-line environments, and will be designed to enable scripting of interactions equivalent to those possible via GUIs, especially once users establish (and want to automate) their preferred workflows.
- *APIs (Application Programmer Interfaces)* will expose internal software interfaces to skilled programmers with the expert ability to develop software applications in the “TAT-C Ecosystem”.

8. CONCLUSION

This paper introduced a new framework, the Trade-space Analysis Tool for Constellations (TAT-C), being currently developed at NASA Goddard Space Flight Center, and that will enable the design of future Distributed Spacecraft Missions (DSM). TAT-C, through a modular architecture including a knowledge base, a cost and risk module, an orbit and coverage module and carefully designed trade-space search iterator and user interface will enable to quickly assess and validate a very large number or potential architectures in response to input and output science requirements.

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