INTEGRATED SCIENCE AND ENGINEERING SIMULATION TOOL FOR SMALL BODY MISSIONS.
R. B. Amini[1], S. Bandyopadhyay[1], S. Bhaskaran[1], R. Miller[1], M. Haynes[1], and S. Hernandez[2]. [1]Jet Propulsion Laboratory/Caltech (4800 Oak Grove Dr. M/S 301-165, Pasadena, CA 91109. ramini@jpl.nasa.gov), [2]Continuum Space Systems.

Introduction: The accelerating pace of technology development and maturation for spaceflight has enabled mission architectures that were technically and cost infeasible a decade ago. Missions like *Deep Impact*, *Rosetta/Philae, Hera/Juventas/Milani, DART/LICIA*, and others have or will soon demonstrate that small spacecraft and multi-spacecraft architectures play a critical role in performing science investigations at small bodies.

However, existing mission formulation processes and tools are only well-suited to optimizing single-spacecraft mission architectures where the constraints of cost and risk optimization result in a limited trade space irrespective of the payload. When N > 1 spacecraft are considered, the number of feasible architecture and system configurations grows ~N! (e.g., the difference in combinations of possible orbit and imager configurations to perform a mapping mission for N = 1 and N > 1). Moreover, the preliminary science yield calculations performed in early formulation may overlook the significant limitation in spacecraft resources (e.g., telecom, power), which can impose major constraints to operations and science yield.

To advance the state of mission formulation for small body missions, in particular those with multiple spacecraft, we developed a novel integrated simulation tool that models science yield and mission resources as a function of science payload, mission and system design, spacecraft behavior and modes, and target uncertainties. This provides a comprehensive and self-consistent approach to mission design. Here we demonstrate this tool for the case of a notional three-spacecraft mission to the near-Earth asteroid (99942) Apophis, which will flyby Earth in 2029.

Objective: The principal objective of this work is to optimize science yield (i.e., data return volume and quality versus time), cost, and mission margins. The parameter space for optimization is defined by two independent axes, themselves multi-dimensional. The first axis describes all possible *design choices* for a given architecture, i.e., orbits, systems, and behaviors. The second axis describes possible *small body properties*, i.e., gravity model, shape, spin rate, and spin axis, based on target observations and their uncertainties. A simulation of the mission uses a set of design choices and body properties to generate a timeseries of all mission science samples and data, spacecraft position, mode, and its component states, and data returned to Earth. By simulating different design

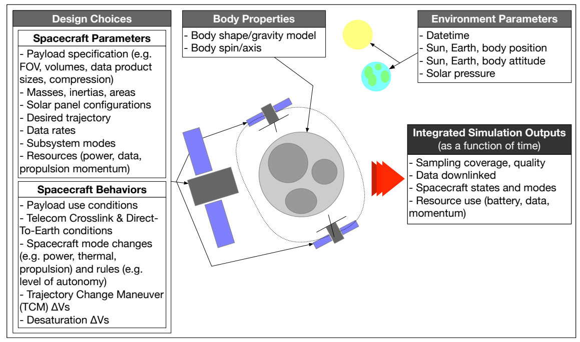

Figure 1. *Summary of optimization simulation inputs, relevant variables, and outputs.*

choices and analyzing outputs, we can optimize mission and spacecraft design parameters. By varying body properties and evaluate a design's robustness to body uncertainty. A similar trade study optimization approach was used for the Habitable Exoplanet Observatory [1]. Figure 1 summarizes the simulation parameter space and outputs.

Integrated Science and Engineering Simulation: This integrated simulation is the natural evolution of different peer-reviewed simulation codes and spacecraft models [2]. Once design choices are defined in code, the Matlab-based simulation framework first computes the orbits of all spacecraft, accounting for the small body's higher-order gravity fields and trajectory correction maneuvers executed by the spacecraft. Alternatively, the software ingests trajectory files in SPICE/SPK format, generated using the Mission Analysis, Operations, and Navigation Toolkit Environment (MONTE) software, that incorporates disturbances like solar pressure, third body perturbation, and actuator uncertainties/errors [3].

Next, the software propagates the state of spacecraft subsystems and components based on modes associated with station-keeping, navigation, science, telecommunications and spacecraft position/attitude. Behaviors are predefined for each mode and modes are conditionally selected at each time step. For instance, the behavior is to maintain spacecraft health has highest priority. At each time step, solar power is first used to power critical avionics. Excess energy can then be used by telecom, attitude control system/propulsion, and then science modes depending on spacecraft state (e.g., wheel saturation). Excess energy is stored or shunted. For each science sample, the software records the sampling parameters (e.g., sampled point, time) and quality (e.g., resolution, viewing angles, flux). The number of possible sampled points for the body are predefined for each instrument depending on its field of view using a Fibonacci Lattice. The final product is time-series of spacecraft state and data products and their metadata, which can then be analyzed. For instance, time series of bistatic radar samples and their sampling parameters (e.g., distances, view angles) can be exported to other software for analysis of reconstruction [4].

Case Study: Optimizing Solar Panel Sizing for a Three-Spacecraft Apophis Mission: Optimizing a mission's design, whether for science yield, cost, or mission margins, requires multiple mission simulations. For this case study, we consider a three-spacecraft constellation that has rendezvoused with Apophis in order to image and take monostatic and bistatic radar measurements during its closest approach with Earth in 2029. The constellation has a mothership and two identical CubeSats – each system type requiring unique specifications (e.g., only the mothership has direct-to-Earth communications). Orbits and maneuvers are pre-computed in MONTE and ingested into the integrated simulation tool, which then propagates the scenario with spacecraft system and behavior assumptions.

Given this mission configuration, we seek to optimize solar panel sizing, i.e. find the smallest panel that will satisfy the science mission and battery margins. We simulate seven days of the science mission with runs assuming 10, 14, 18, and 22 W from each of the two solar panel wings. Table 1 summarizes optimization results where we find 14 W/wing as a design breakpoint. Figure 2 shows examples of plotted timeseries data for camera coverage, radar coverage, and data volume.

Although this case study represents a simple optimization problem and solution, the key benefit of a compressive simulation tool of this kind is that mission-level impacts of minor design decisions become readily identifiable. Second, we can evaluate the mission impact of more complex trades, e.g., changing payload specification, data rates, or other spacecraft component sizing/performance. More complex trades can also include changes to orbits and spacecraft behavior and operational modes (e.g. using autonomy to enable increased cadence of ΔV maneuvers needed for lower altitude orbits). Finally, we can verify the robustness of a mission design against uncertainty in body parameters such as spin rate/axis, gravity.

Table 1. Summarized results from solar panel optimization case study.

Wing Power [W]	10	14	18	22
% Time Battery Margin Violated	84.0%	0.6%	0%	0%
CubeSat Images	56	327	329	329
Radar Coverage	0.9%	5.4%	5.4%	5.4%
Downlinked Data [GB]	200	271	271	271

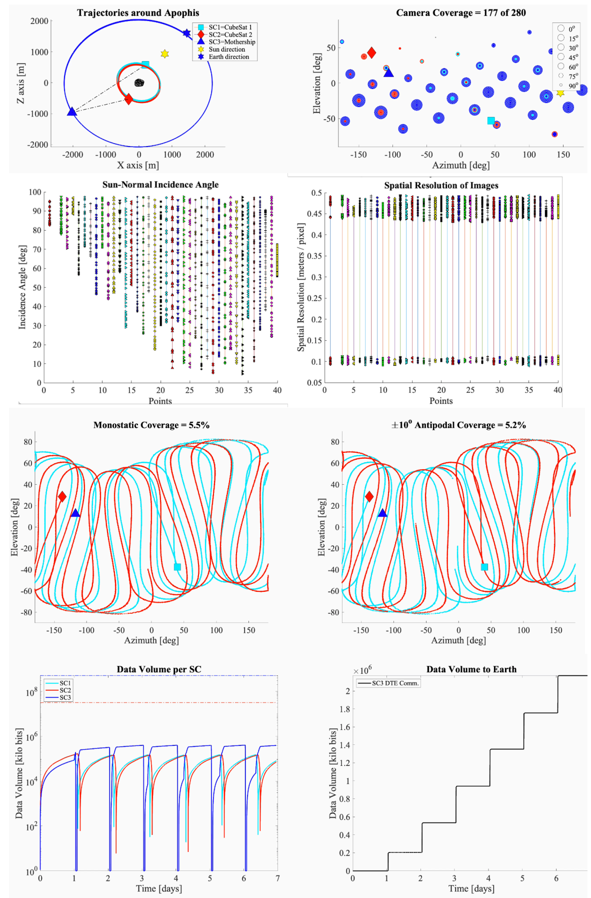

Figure 2. *Sample timeseries data from integrated simulations assuming 18 W/wing. Descending from top panel: trajectory and camera coverage; camera image sun angle and spatial resolution; radar coverage and ground tracks; and data volume present on each spacecraft and Earth.*

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