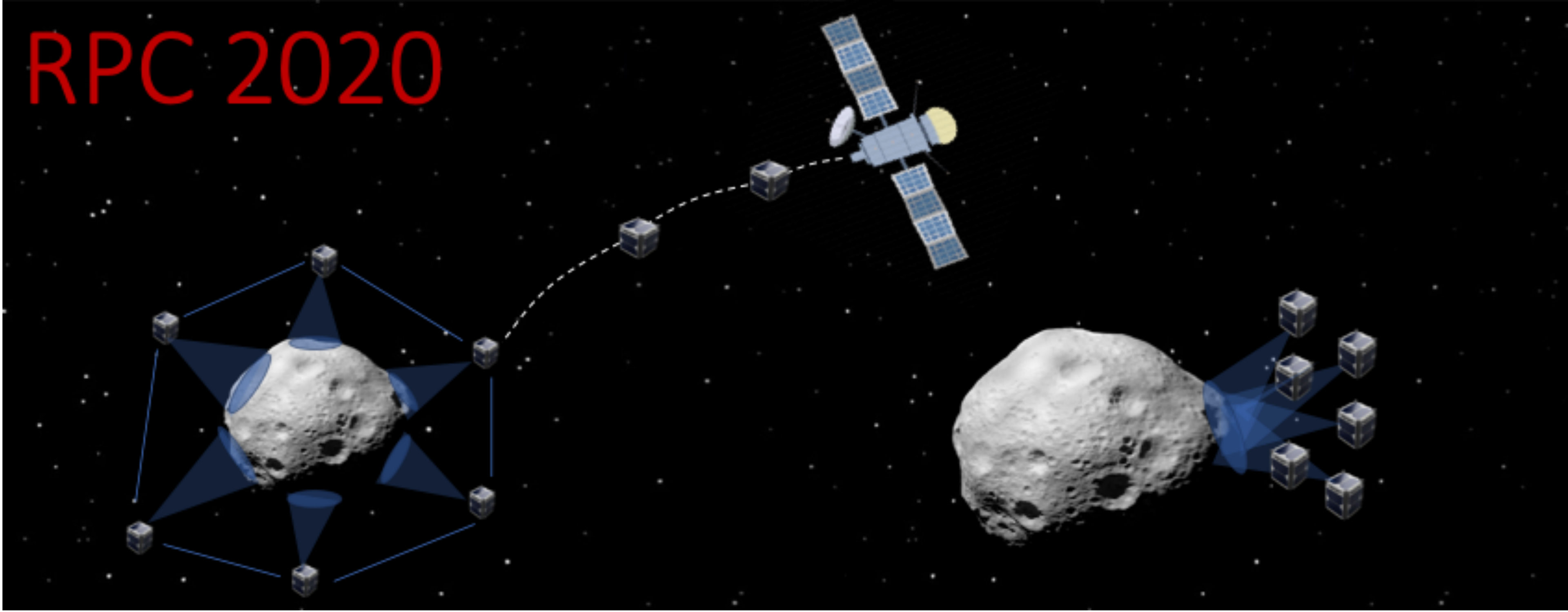
RPC 2020



Virtual Research Presentation Conference

Autonomous Coordination Algorithms for Swarms of Small Spacecraft Performing a Radar Mission Around a Small Body

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Program: Spontaneous Concept

Assigned Presentation #57

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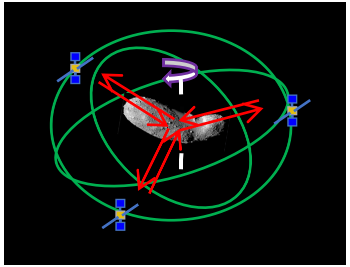
Tutorial Introduction

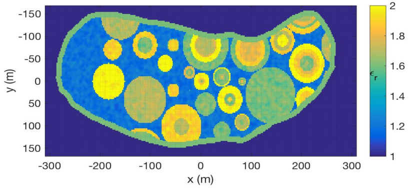
Abstract

Fundamental answers about the origin and evolution of the Solar System hinge on our ability to image in detail the 3D interior structure of small bodies at high-resolution.

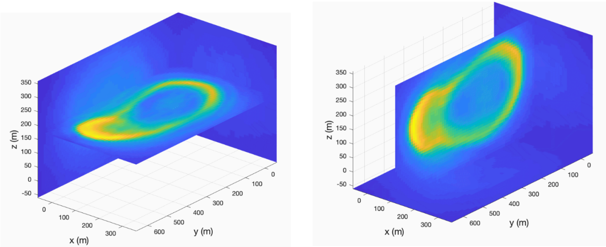
Mapping of the interior structure requires ***simultaneous observations*** of low frequency radar reflections that are observed from multiple, diverse viewing angles using independent spacecraft, analogous to medical tomography like CAT scans. By collecting the full set of possible monostatic and bistatic radar measurements, we can ultimately create 3D maps of the interior dielectric properties, which provides ***both structure and composition*****.**

The focus of this proposal is to design ***autonomous coordination algorithms*** for a swarm that needs to simultaneously ***observe a small body from different directions***, which is currently an open problem in literature.



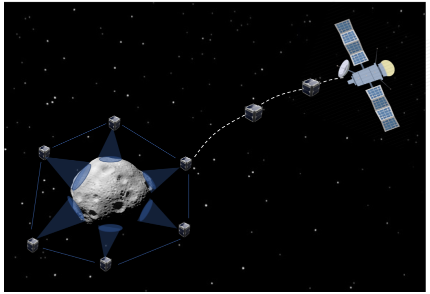


3D cross section of a small body dielectric interior model



3D cross section of simulated tomographic SAR imaging using full bistatic sampling to probe the object above at 5 MHz operating frequency.

Problem Description



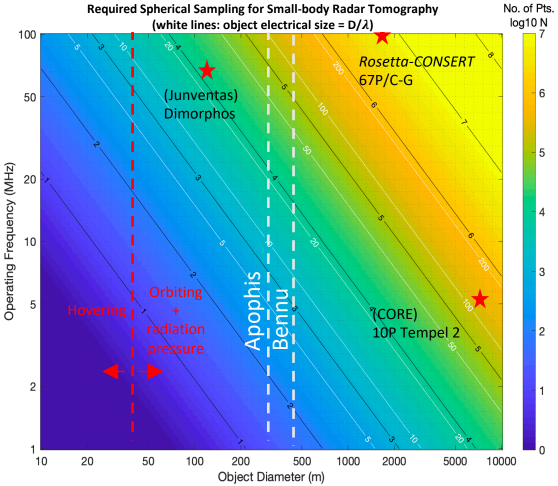
A ***carrier spacecraft rendezvouses with a small body*** and releases a swarm of small satellites. The swarm uses propulsive maneuvers to autonomously disperse around the body and ***initially build surface coverage maps.***

To map the interior structure, ***the carrier spacecraft transmits a radar signal, which travels through the small body and is received by the swarm***. The goal is for the swarm to autonomously evolve and reconfigure itself in order to improve resolution.

In order to accomplish complete coverage of bistatic radar measurements around the small body, 10,000s to 100,000s of thousands of echoes need to be recorded.

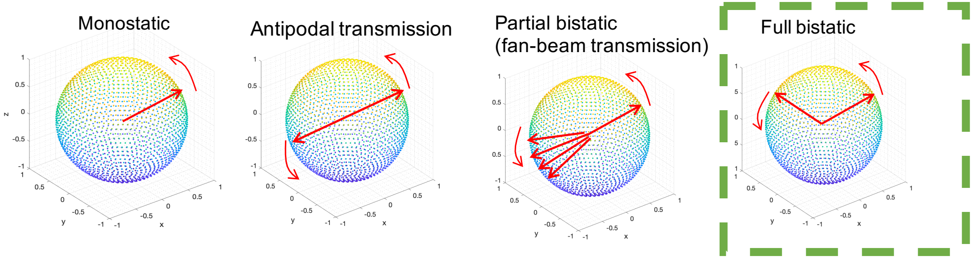
This task sought to answer the following questions:

- Can the orbits of a swam of small satellites (SmallSats) be designed to complete the coverage requirements for small body bistatic radar tomography?
- How long does it take to achieve maximum coverage and what is the optimal number of spacecraft needed to complete the mission?
- Is reconfiguration of the swarm necessary to achieve the science objective? If so, can the swarm autonomously evolve and reconfigure itself in order to improve resolution over time?



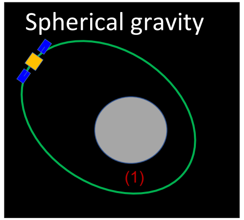
Methodology

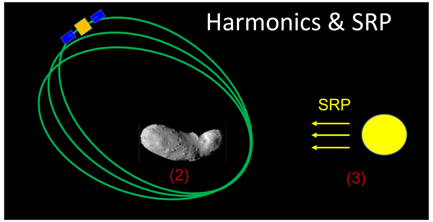
- There are different types of radar sampling geometries:



We focus on full bistatic radar sampling

- ***Finding the optimal orbital geometry to give maximum coverage is key in understanding desirable swarm configurations and potential costs for swarm reconfigurations***
  - Use several levels of dynamical model fidelity for the swarm: spherical gravity, harmonics, and solar radiation pressure
  - Perform Monte Carlo runs to optimize coverage of the body based on number of spacecraft and orbit geometry

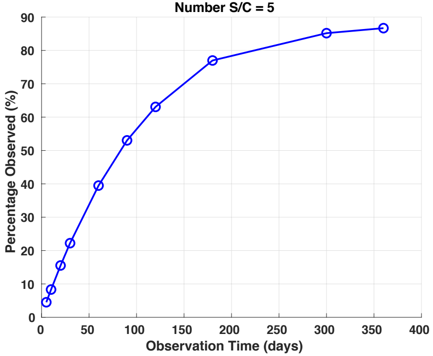




- **Goal**: understand the trade between number of receivers / spacecraft, types of orbits, and other architecture factors to accomplish radar-mapping science objective.

Results

- Different orbit geometries for a swarm of 5 spacecraft orbiting Eros (17 km radius) using a total of 500 points was simulated.
  - The best performing solution yielded 85% coverage of the body
- ***Optimal orbital spacecraft configuration***:
  - Near polar inclination (maximize accessible surface regions)
  - Evenly spaced out in right ascension of ascending node and true anomaly (spatially spread around primitive body)
- Percentage of body observed reaches a **saturation limit**
  - Swarm reconfiguration might be necessary after saturation limit is reached for a particular swarm configuration



Percentage of body observed for a 5 spacecraft swarm orbiting Eros. Saturation limit reached at 85% observation.

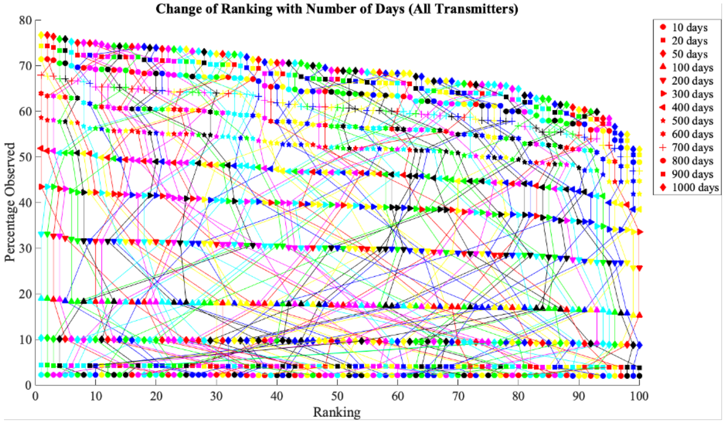


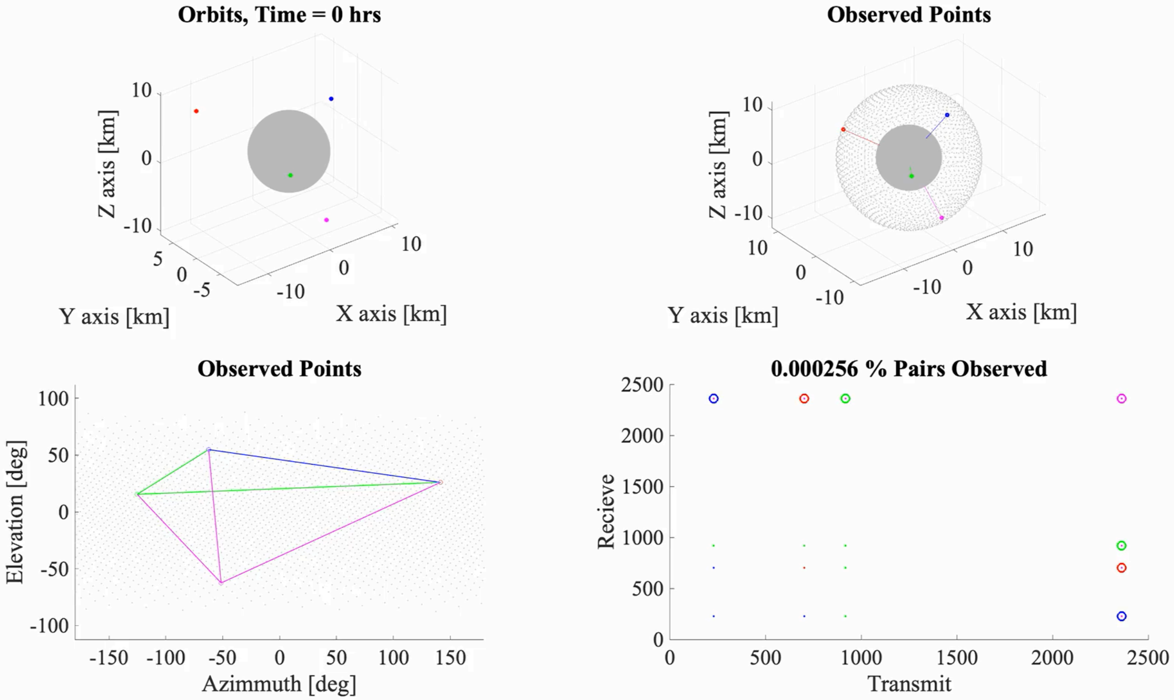
Figure shows Monte Carlo results of percent body coverage for 100 different random swarm configurations

- **Percentage observed cost function is not linear**
- I.e., cannot determine outcome by computing 10-day solution
- Need to run entire mission duration to know the outcome
- Curse of dimensionality means long computation times

100 simulations of different orbital geometries for a 5 s/c swarm around Eros ranked from best (Ranking 1) to worst (Ranking 100).

Results

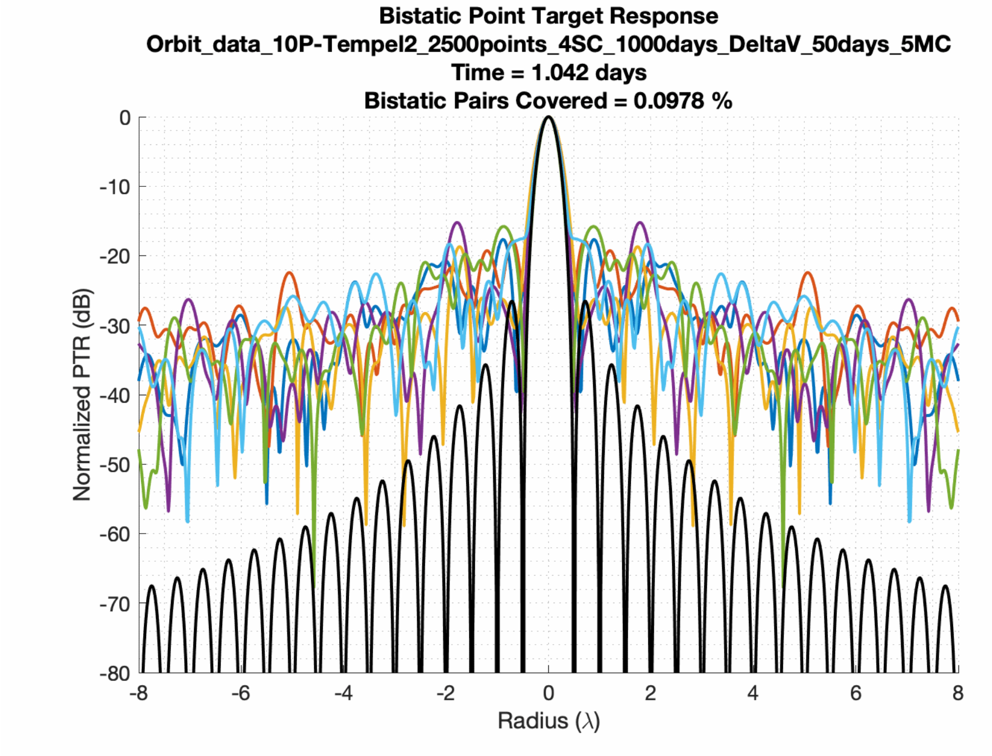
4 Spacecraft Swarm Around Tempel-2



- Video simulation of a ***4 spacecraft*** swarm orbiting the ***comet Tempel-2.***
- The gravity of the comet is approximated as spherical, with random small impulses imparted to each spacecraft to simulate additional perturbations to the model
- Near polar orbits for all spacecraft in the swarm.
- All spacecraft are assumed to transmit as well as receive
- 2500 points – *point density corresponds to resolution of interior images*

Results

4 Spacecraft Swarm Around Tempel-2

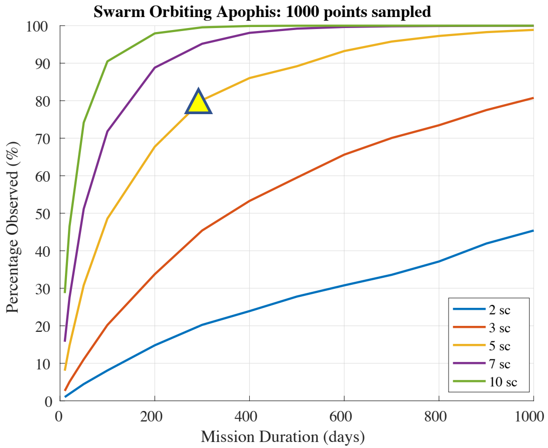


- Results are for the same ***4 spacecraft*** swarm configuration orbiting the ***comet Tempel-2.***
- This simulation shows how the point target response of the radar tomography processing improves and converges to the ideal value as the percentage of bistatic measurement pairs collected increased over the course of the mission.

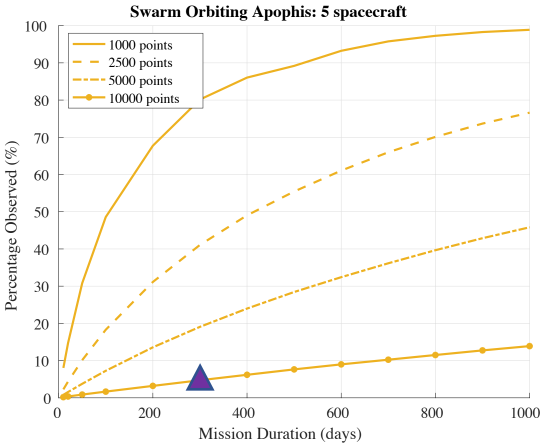
Results

Swarm Around Apophis

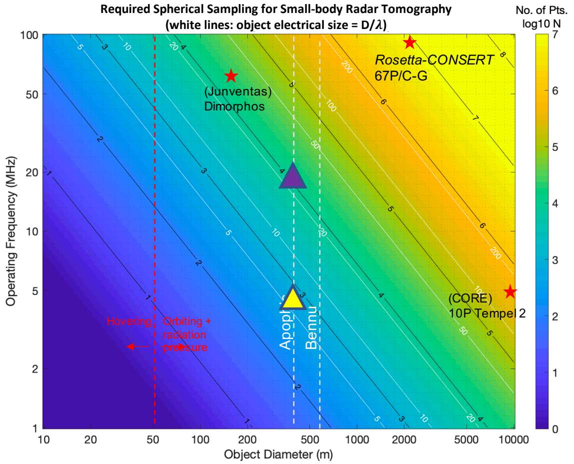
(1) Varying number of spacecraft



(2) Varying number of sampled points



(3) Spherical Sampling Points



- Case 1: △ For a swarm operating at a frequency of 5 MHz, 1,000 samples would suffice to completely sample the scattered field (3). For a mission duration of one year, a swarm of 5 spacecraft could collect 80% of the total number of bistatic pairs under these orbital parameters (1).
- Case 2: ▲ For a swarm operating at a frequency of 20 MHz, 10,000 samples would be required to completely sample the scattered field (3). For a swarm of 5 spacecraft, after one year, less than 10% of the bistatic pairs would have been observed (2). In this case, spacecraft reconfiguration is likely necessary, and this will be an avenue we will explore in future work.

Conclusion and Future Work

Relevance

There is growing interest in using SmallSats for small body radar tomography in order to advance solar system science and aid planetary defense. In addition, there is active interest in developing and testing autonomous algorithms for deep-space SmallSats. The ***combination of radar tomography with SmallSat autonomy*** is a timely and relevant application to advance both.

This study is a critical step in understanding orbit design, coverage requirements, and autonomy requirements for small body interior mapping using low frequency radar.

Future Goals

- Simulate swarms in higher fidelity gravitational models
- Add autonomous reconfiguration to determine if amount of coverage and the time it takes to reach maximum coverage can be improved
- Potential infusion into SIMPLEx mission concepts (e.g., DROID)

Publications

S. Hernandez, S. Bandyopadhyay, M. Haynes, and J. Stuart, “Optimal Orbit Configuration of Swarms of Small Spacecraft Performing a Multistatic Radar Mission Around a Small Body”, AAS/AIAA Astrodynamics Specialist Conference, Big Sky, Montana, August 2021 *[Pending]*