SMALL SPACECRAFT SWARMS ENABLING ASTEROID RADAR OBSERVATIONS: APOPHIS MISSION STUDY

S. Hernandez[1], S. Bandyopadhyay[1], M. S. Haynes[1], R. R. Karimi[1], J. R. Stuart[1], B. Davidsson[1], and Carol Raymond[1]
[1] Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, CA 91109
(Corresponding author email address: Sonia.Hernandez-Doran@jpl.nasa.gov)

Introduction: 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. Simultaneous observations of low frequency radar reflections observed from multiple, diverse viewing angles using independent spacecraft can provide this mapping of the interior structure, 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 the work presented herein is to identify candidate orbits for a minimal swarm that needs to simultaneously observe a small body from different directions.

Problem Statement: As a sample mission architecture, consider a carrier spacecraft that rendezvouses with a small body and releases a swarm of small satellites (SmallSats). The swarm uses propulsive maneuvers to autonomously disperse around the body and initially build surface coverage maps, as illustrated in Figure 1. To map the interior structure, either a) the carrier spacecraft transmits a radar signal, which travels through the small body and is received by the swarm, or b) all spacecraft in the swarm transmit radar signals to be received by the other spacecraft. In order to accomplish complete coverage of bistatic radar measurements around the small body, 10,000s to 100,000s of echoes need to be recorded.

The goal of this study is to help answer the following questions: Can the orbits of a swam of SmallSats be designed to complete the coverage requirements for small body bistatic radar tomography? How long does it take to achieve maximum coverage? Is reconfiguration of the swarm necessary to achieve the science objective? These are broad questions, so in this preliminary study we focus our attention on a specific mission scenario which consists of a mothership and two daughter spacecraft sent to orbit the asteroid (99942) Apophis. Apophis will perform a close approach with our planet at ~38,000 km on April 13th 2029. Apophis is a potentially hazardous asteroid and understanding its interior structure via radar measurements may be critical for future deflection or mitigation strategies.

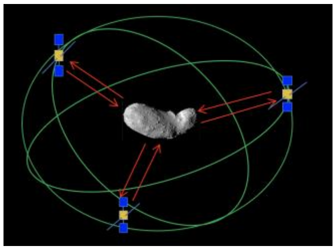
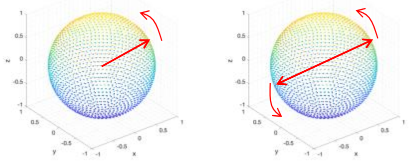


Figure 1: Multiple spacecraft orbiting a small body collecting reflection and transmission radar measurements as well as optical images for mapping.

The images in Figure 2 represent the spherical points that a spacecraft and radar need to sample in order to form tomographic images of the small body interior. In general, there are four classes of coverage options: full monostatic, in which radar echoes from every spherical sampling point is taken once; antipodal transmission, in which all possible transmission measurements are taken through the center of the body and are needed for dielectric inversion; partial bistatic, which consists of taking additional transmission measurements; and full bistatic, in which echoes are taken from all possible pairs of spherical sampling points. We study all four types of coverage options and compare the amount of time required to completely cover Apophis.

1) Monostatic 2) Antipodal transmission



3) Partial bistatic 4) Full bistatic

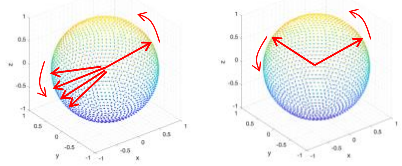


Figure 2: Spherical points that a radar pair need to sample in order to form tomographic images of the body interior. There are four types of coverage options: monostatic, antipodal transmission, partial bistatic, and full bistatic.

Gravity Model: The dynamics of a spacecraft around a minor body are dominated by different type of forces. These forces can be modeled at different levels of fidelity. The model used here is represented by a two-body gravity model with spherical harmonics of 4th order. This dynamical model represents a good approximation for preliminary design studies [2]. The harmonic coefficients are obtained by the latest shape model from Brozovic et al. [2]. The shape model assumes a uniform density $\rho = 2$ g/cm^3, a mean radius $R_{Apophis} = 221.6$ m, and a GM = 2.6459e-09 km^3/s^2.

Preliminary Results: For example, in order to take antipodal transmission measurements, we can require that two spacecraft must be opposite of each other (180° +/- Δ) at any point in time, where Δ is the deviation from the center line through the object. Figure 3 shows an example of two spacecraft orbiting Apophis at an initial radius of 3RApophis for a total of 20 days, where RApophis = 221.6 m is the mean radius assumed for Apophis. The trajectory is shown on the top, whereas the angle between both spacecraft over time is shown on the bottom. Notice how the two spacecraft begin at 180° from each other, by design, but due to the nonlinearities in the dynamics of the asteroid, the trajectories become perturbed and exact antipodal geometry cannot be maintained. Both spacecraft must move around Apophis in similar orbits, but opposite of each other: the goal is to choose the optimal initial conditions of both spacecraft such that they maintain a geometry as close as possible to 180° for the mission duration, therefore maximizing antipodal coverage.

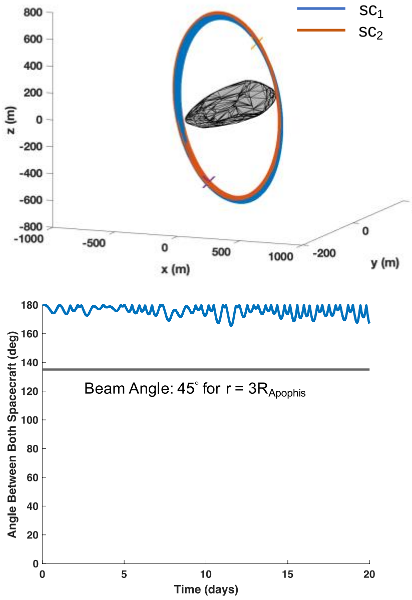


Figure 3: (Top) Two spacecraft orbiting Apophis at an altitude of 3R$_{Apophis}$ for a simulation time of 20 days. (Bottom) Angle between both spacecraft as a function of time.

In Figure 4 we can visualize just how critical it is to choose the right initial conditions for both spacecraft in the swarm. Assuming two spacecraft in initial circular orbits, with a radius of 3RApophis, and inclination of 90°, we vary the right ascension of ascending node (precession in the orbit) and the initial true anomaly of the first spacecraft (ν1). Note, ν2=ν1+180°. We record the percentage of time that both spacecraft are in antipodal configuration (180° +/- Δ), where Δ is the beam angle (45° for this example) and the total simulation time is 20 days. There are optimal regions of initial conditions where antipodal configuration is met all the time, and regions where the orbits are extremely perturbed and antipodal configuration is met less than 10% of the time. Of course, there is a trade-off between how large the angle Δ can be while still being able to take the desired radar measurements. In this study we compare how the variation in parameters such as Δ and the orbiting altitude and inclination changes the amount of time required to complete coverage of the asteroid for the different types of radar transmission. Using this insight into the coverage trade space, mission architects will be able to select the appropriate number of SmallSats, observation strategies, and other key aspects for future mission development to characterize the interior of primitive bodies in the Solar System.

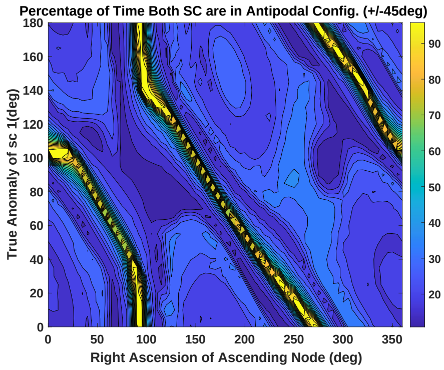


Figure 4: True anomaly versus right ascension of ascending node for two spacecraft in initial antipodal configuration at an altitude of 3R$_{Apophis}$ and 90^o inclination.

Acknowledgments: Special thanks to Marina Brozovic for providing the Apophis shape model. This research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

References:

[1] Aljbaae, S., et al. "First approximation for spacecraft motion relative to (99942) Apophis." *arXiv preprint arXiv:2012.06781* (2020).

[2] Brozović, Marina, et al. "Goldstone and Arecibo radar observations of (99942) Apophis in 2012–2013." *Icarus* 300 (2018): 115-128.