THE INTERIOR STRUCTURE OF ASTEROIDS AND COMETS REVEALED BY CHIPSAT SWARM GRAVIMETRY. W. G. Ledbetter[1], R. Sood[1], and J. T. Keane[2]; [1]Astrodynamics and Space Research Laboratory, Department of Aerospace Engineering and Mechanics, The University of Alabama, Tuscaloosa, AL 35487, USA (wgledbetter@crimson.ua.edu); [2]Division of Geological and Planetary Sciences, California Institute of Technology, Pasadena, CA 91125, USA.

Introduction: Asteroids, comets, and other small, primitive solar system bodies represent the leftover building blocks of our solar system. The interior structure of these small bodies provides important clues to their formation and evolutionary histories. For example, measurements of bulk porosity, density, and density variations on different scales have been hypothesized to reflect differing planet formation processes (e.g. runaway accretion vs. pebble accretion, etc. [1,2,3]). Unfortunately, these investigations generally require high precision and resolution gravity measurements from spacecraft in close proximity to the object of interest. Proximity operations can be risky and resource intensive.

In this work, we investigate methods to employ SmallSats to characterize the interior structure of small solar system bodies (asteroids, comets, etc.). Similar methods proposed by [4] and [5] consist of a primary ("Chief") spacecraft releasing and tracking multiple smaller, passive, reflective probes ("Deputies"), and obtaining range and range-rate data that is then used to recover a gravity model. However, technological advancement and modern computer manufacturing capabilities motivate a reconsideration of the above use of "dumb" probes. Taking inspiration from the work of [6] and [7], we investigate the use of Silicon Wafer Integrated Femtosatellites (SWIFT) satellites, or ChipSats, to augment the quality and quantity of data obtained by traditional small body characterization.

ChipSat Design: Micro-Electro-Mechanical System (MEMS) devices already see widespread use on Earth. Due to their size and material composition, they are ideal candidates for use in space applications. Their small size increases launch survivability [8] and silicon's reasonable durability in radiation implies longevity in the deep space environment [9]. In this work, we explore the possibility of using ChipSat swarms to measure the gravity fields of small bodies (asteroids, comets, etc.). Gravity gradient measurement relies on accurate knowledge of the observer's orientation. Each ChipSat would be initialized while still inside a larger parent spacecraft (the "Chief") to create a known attitude reference point before a MEMS gyroscope onboard each ChipSat is given orientation measurement responsibility. A controlled launch from the Chief will serve to mitigate tumble. After ejection from the Chief, MEMS accelerometers will begin measuring gravity gradient data, with ChipSat position being measured by the Chief. Intra-ChipSat position determination methods will also be investigated to counteract line-of-sight losses.

Gravity Determination: The mathematics of gravity characterization are well documented by missions such as GRAIL [10], GRACE [11], and GOCE [12]. Methods for spherical harmonic coefficient determination exist for many types of input data. Previous work has investigated the transformation of spherical harmonic data into polyhedron density distribution [13]. The method can be expanded to provide a three-dimensional map of a celestial body's density. The crucial assumption of the aforementioned approach is, of course, the existence of a polyhedral shape model of the body. Recent work at U.C. Boulder [14] makes this assumption reasonable.

We have developed a computational framework for recovering the gravity field of small bodies using ChipSat swarms. For a given a central body, we simulate spacecraft trajectories and gravity gradient data, which we then pass on to recovery algorithms. Accuracy is measured by how well the reconstruction matches the predefined gravity properties. Stochastic simulations can be performed by introducing uncertainty in position and gravity gradient measurements. **Figure 1** compares the deterministic result of a spherical harmonic reconstruction of asteroid (433) Eros with multiple uncertain samples.

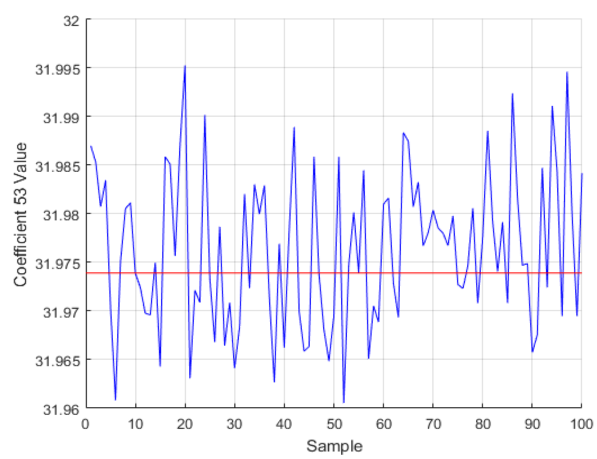

Figure 1: Deterministic (red) vs. Sampled (blue) values of intermediate Stokes coefficient. Each sample represents a unique set of random values applied to the true position and gravity gradient data. The uncertainty in position data was 3 meters (accuracy of some

LiAISON simulations [15]) and the gravity gradient sigma was 2e-12 s^{-2} (accuracy of GOCE accelerometers [16]).

These results were generated with a single satellite performing three near-polar orbits of (433) Eros as shown in **Figure 2**, which implies limited measurement of gravitational anomalies in the east-west direction. The introduction of swarms to the gravity characterization algorithm will address this problem through a diverse range of trajectories about the body of interest.

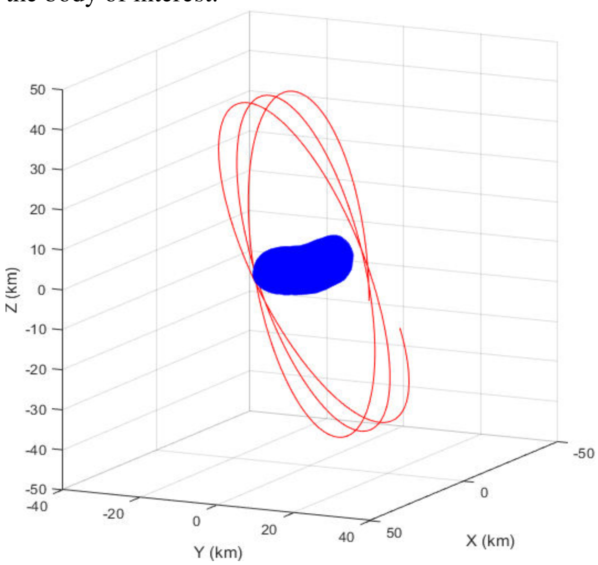

Figure 2: Single satellite near-polar orbits about (433) Eros for gravity measurement. Three-day propagation implies an orbital period of about one day. The perturbations causing inclination to change are detected by position tracking and are used to recover the gravity model.

Algorithm Verification: To ensure the accuracy and repeatability of the gravimetry procedure detailed above, stochastic simulations will be performed with different types of central bodies. NASA's Planetary Data System (PDS) contains many polyhedral models like the (433) Eros model used in preliminary research. Success will be measured by the degree to which the addition of GG data to the gravimetry algorithm results in a more accurate reproduction of initial central body assumptions.

Mission Architecture: Once the algorithms for gravity determination have been tested and are robust, higher-level analysis of the mission will be undertaken. In conjunction with the stochastic simulations, trade studies will be used to suggest an optimal balance of sensor accuracy, ChipSat population size, and cost. The addition or removal of systems will also be considered. What if the SWIFT satellites were slightly larger and had basic control authority? How long could data be captured if the Chief satellite moves on to another body? These topics are potential future paths for the research and are meant to be somewhat open-ended at this stage of the investigation.

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