OPTICAL GRAVIMETRY FOR FLYBY MISSIONS: PARAMETRIC STUDY AND VALIDATION.
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Introduction: This research describes a method for resolving the mass of asteroids and comets during flybys or orbital phases. In this concept, called Optical Gravimetry or OpGrav, a host spacecraft releases a group of small white spheres, which it then tracks using an on-board telescope (Figure 1). The spheres, which act as passive test-masses and are called probes, are deployed such that they pass very near to the small body and their trajectories are measurably perturbed. A spacecraft-mounted camera determines the relative measurements of the probes, including right ascension and declination angles. These measurements are then processed on the ground and used to estimate the small body’s mass [1].

The relative measurements have the advantage of being high signal-to-noise and high resolution, owing to the short distance between the host spacecraft to the probes and the probes to the small body. They are also numerous, since multiple probes can be deployed from a single spacecraft, possibly to different relative geometries. These benefits enable the accurate determination of mass for bodies that are too small to study using typical ground-based radiometric tracking with distant flybys (typically required for the safety of the spacecraft). Coupled with a shape model, a mass estimate constrains the small body’s density or porosity, which have implications for asteroid formation models [2] and planetary defense [3].

A hardware implementation of OpGrav, the Small-body In-situ Multi-probe Mass Estimation Experiment (SIMMEE) is currently being prototyped and tested [4]. This prototype informs the flight concept-of-operations and performance simulations, namely the probe deployment timing and accuracy.

Parametric Study: The OpGrav concept is evaluated in a modeling and simulation environment, which incorporates \textit{a-priori} uncertainties due to asteroid ephemeris knowledge, probe deployment knowledge, and solar radiation pressure. The performance is evaluated parametrically using custom MATLAB software developed for the OpGrav study. The asteroid mass, the state of each probe, and solar radiation pressure parameters are estimated using an Extended Kalman Filter, implemented in square root information form. Monte-Carlo simulations of the full concept-of-operations are used to characterize the nonlinear statistics over many (100’s - 1000’s) random draws of the stochastic parameters and states.

Results: These parametric simulations indicate relevant performance during a typical flyby (many kilometers per second) for asteroids as small as 1 kilometer in diameter. For most encounters, 1-3 well placed probes can be very effective, with marginal improvement for additional probes. Figure 2 gives sample results for 3 different asteroid radii (0.5, 1.0, and 2.5 km) and 2 different flyby velocities (3.0 and 8.0 km/s).

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{opgrav_concept_of_operations.png}
\caption{OpGrav Concept-of-Operations. A host spacecraft deploys probes prior to an asteroid flyby, and then optically tracks them before and after close-approach.}
\end{figure}
The asteroid is modeled as a sphere with a uniform density of 2.0 g/cm$^3$. Each flyby simulation includes three probes that each target a 3 km altitude flyby of the asteroid. The probes’ true flyby locations are randomly drawn based on anticipated deployment errors. The results are presented as bars that span the 10th percentile result to the 90th percentile result.

We find that an important input to the simulation performance is the deployment accuracy of the probes because it dictates the close-approach point. This point defines the minimum range to the asteroid, and thus the magnitude of the deflection, and it defines the observability of the deflection in angle-space.

These results represent a meaningful improvement over current methods, as proven out by simulating the same flyby scenarios using two-way coherent Doppler radioscience from Deep Space Network stations.

**Validation:** Sample results from these parametric studies were validated using NASA’s GEODYN precision orbit determination software. GEODYN, a batch estimation tool, has been used operationally in many contexts, including Earth [5], Lunar [6], Mars [7], and small-body [8] orbits. GEODYN incorporates all the relevant dynamics and measurement models and would likely be used to process the measurements in a flight implementation of OpGrav.


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**Figure 2.** Sample OpGrav parametric results for a set of asteroid flyby simulations. Each bar gives the mean (square), 10th percentile (bottom of bar) and 90th percentile (top of bar) mass estimation accuracy from 200 Monte Carlo evaluations. $r$ is the asteroid radius and $v_{fb}$ is the spacecraft flyby speed.