Gravity Poppers: Hopping Probes for the Interior Mapping of Small Solar System Bodies

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NASA Innovative Advanced Concepts

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Objective

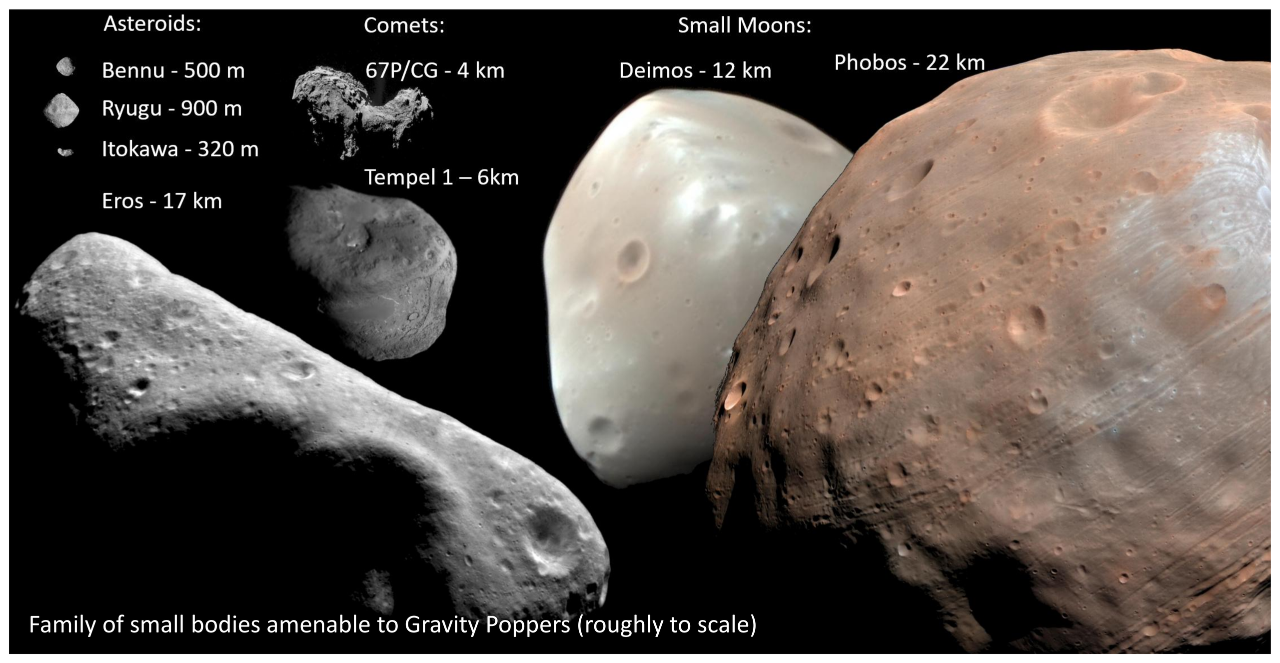
Develop a robust, low-cost mission architecture that enables the **gravitational density mapping of small body interiors** (< 20 km) at spatial resolutions of **10 – 100 m**.

The Challenge:

Measuring the interiors of small solar system bodies such as asteroids and comets can help us to better understand solar system formation processes, design deflection strategies for hazardous asteroids, and understand the distribution and accessibility of space resources. However traditional methods for probing planetary interiors face many challenges for small bodies, especially **gravity science**.

Targets:

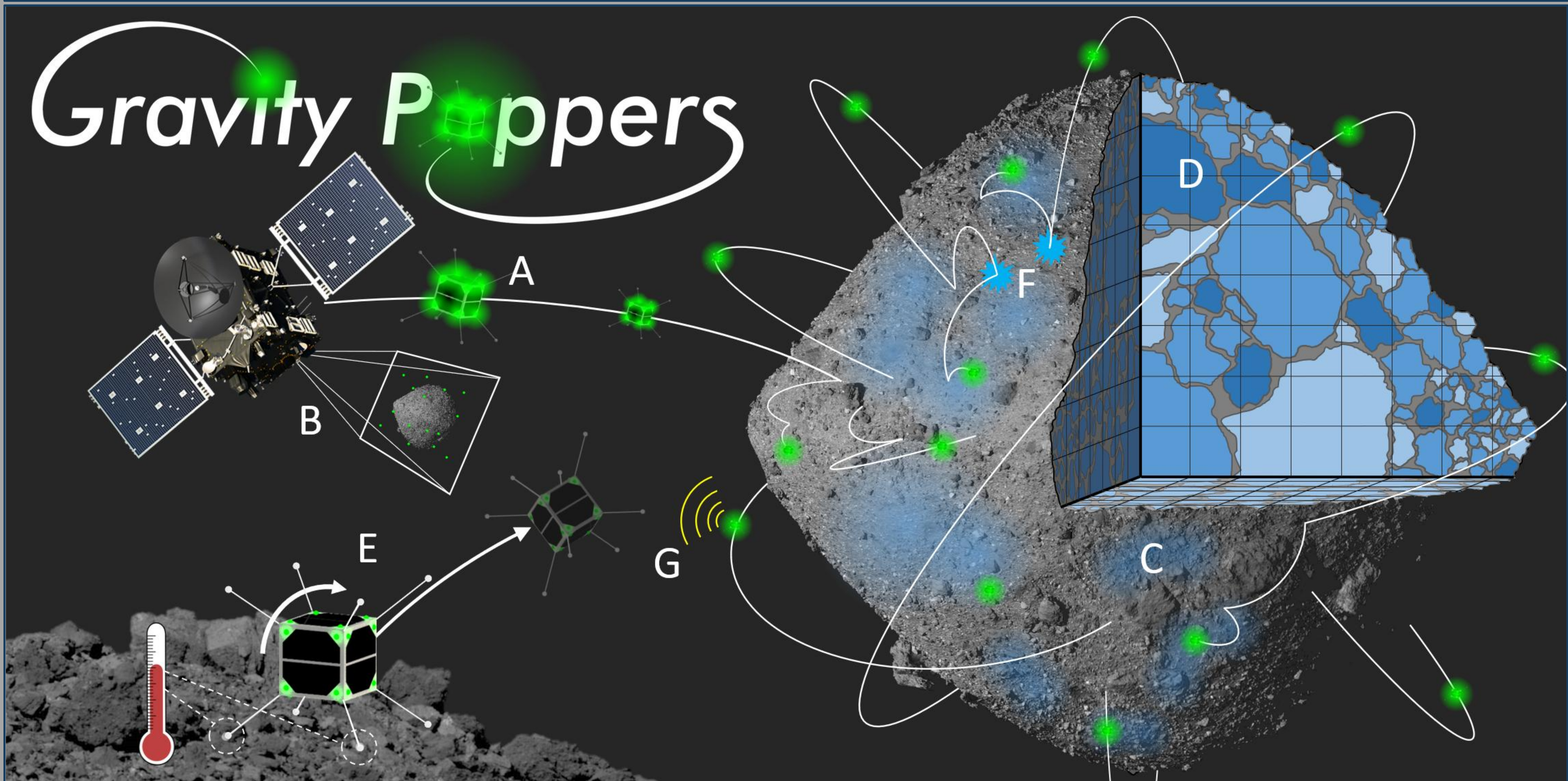
A diverse set of objects ranging from < 100m to over 10km



Family of small bodies amenable to Gravity Poppers (roughly to scale)

Our Phase II study is composed of three research pillars: (1) the **Tracking System**, (2) the **Probe Design**, and (3) the **Gravity Estimation.**

Mission Concept



A spacecraft deploys a swarm of hopping probes to the surface of a small body (A) and tracks their trajectories (B) to estimate a high-resolution model of the body's gravity field (C) and internal structure (D). Landed probes (E) measure surface temperature before exciting an internal momentum device to hop. Bouncing probes (F) measure surface compliance properties via IMUs during each collision. In-situ data is transmitted back to the mother spacecraft (G). Tens of probes continue to hop for weeks to months, generating an immense data set for detailed geophysical characterization.

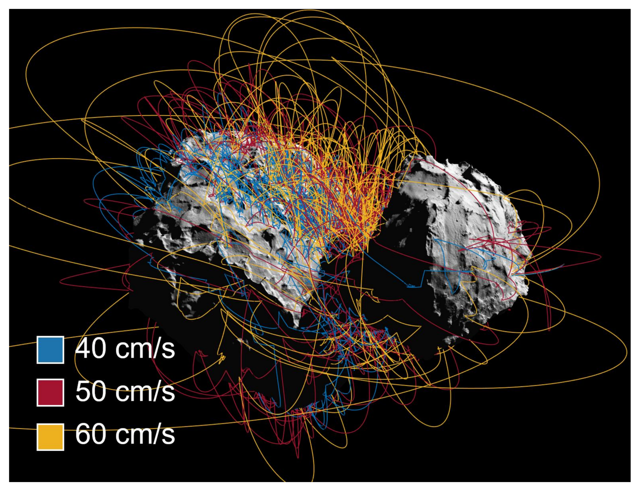
Gravity Estimation

Big Questions:

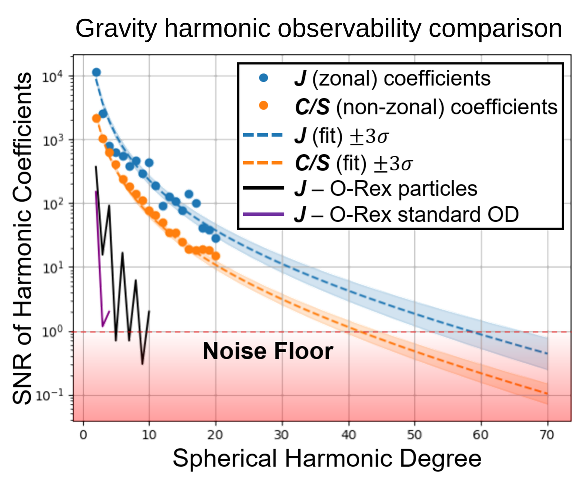
- What **gravity field resolution is achievable** with this mission concept?
- What are **key mission design parameters** that impact gravity observability?
- How can existing estimation algorithms be **adapted for a hopping swarm**?

Leveraging JPL software for simulation and gravity estimation: *Mission Analysis, Operations and Navigation Toolkit Environment (**MONTE**):*

- State-of-the-art astrodynamics and orbit determination libraries
- Used to model orbital and sub-orbital trajectories of probes and mothership
- High-precision force model including non-uniform gravity, Solar Radiation Pressure, stochastic accelerations, maneuvers, etc.
- Measurement simulations, such as optical and radiometric observations
- Navigation filter to evaluate realistic performance, execute covariance analyses and Monte Carlo simulations

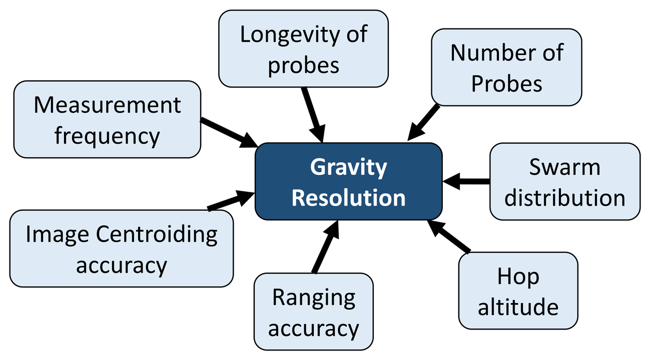


Results for baseline mission concept simulation to Asteroid Bennu:



Sensitivity Studies:

We are investigating the impact of key mission design parameters on gravity estimation performance:



Initial estimates suggest gravity may be resolved to degree 50 – 100: ***two to three orders of magnitude better than current methods***!

Tracking System

Big Questions:

- How might the motion of the hopping probes be **measured**?
- What is the **accuracy** associated with various tracking options?
- What **requirements** does this impose **on the probes and spacecraft**?

Phase I considered three tracking modalities:

1. Imaging from spacecraft

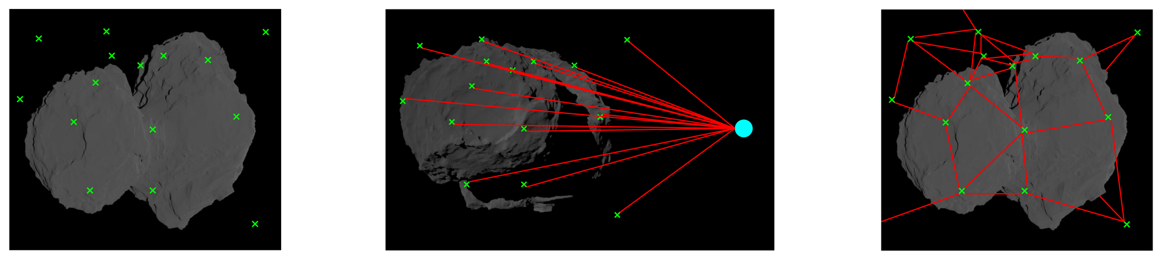
- Provides ***angles*** from S/C to probes
- Requires "bright" probes
  - Reflected sunlight or
  - Emitted light

2. Ranging from spacecraft

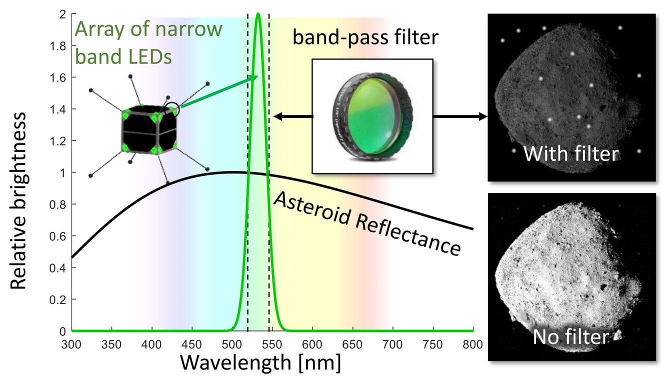
- Provides ***distance*** and ***rates*** to probes
- Requires either:
  - Retroreflective probes (range) or
  - Onboard radios (Doppler/range)

3. Ranging between probes

- Provides ***distance*** and ***rates*** *between probes*
- Requires:
  - Onboard radios
  - Communication protocol

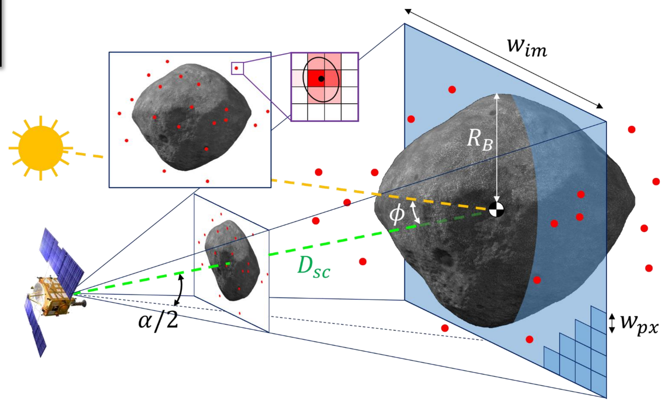


Baseline **optical tracking** system consists of astrometric-quality camera on spacecraft with optical bandpass filter tuned to LEDs from strobing probes:



Tracking camera views the whole body and surrounding region to capture all probes in single frame. Onboard computer extracts centroids for probe detections **(0.01 – 0.1 pixel accuracy)** for dramatic data compression.

Active LED strobing allows for high-SNR detection even against bright body background through **optical bandpass filtering** and adjacent background frame subtraction.



Probe Design

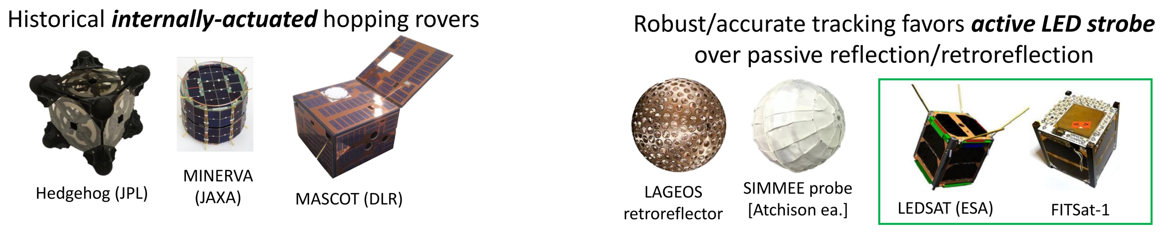
Big Questions:

- How must the probes be **designed to facilitate tracking**?
- **How should they hop** and what **mechanisms** may be used for hopping?
- What **electronics** are required and how can they be **safely integrated**?

Two fundamental requirements for probe performance. They must:

(1) Perpetuate ballistic motion around the body through hopping and bouncing.
(2) "Be visible" to the tracking system of the mother spacecraft.

Phase I considered a broad spectrum of solutions for **hopping** and **tracking**. Baseline design combines flight-proven internally-actuated hopping and LED strobe tracking:



Preliminary design is based off a 5 cm cube form factor, with a mass of ~200g.

Exterior:

- Omnidirectional array of strobing LEDs on faces
- Multipurpose elastic "leg" appendages to:
  - encourage bouncing,
  - protect main body from rock/dust contact
  - serve as radio antenna
  - measure surface temperature/dielectrics.
- Solar cells for battery recharge (primary also possible)

Interior:

- Single-DOF reaction wheel device for hopping.
- Battery and capacitors for energy/power storage
- Power and control electronics for autonomous ops.
- LoRa radio for small data packet transmissions
- RF pulse receiver for LED strobe sync signal