Apophis 2029: Synergy between Numerical Models and Radar Tomography Data from the Caltech Mission

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Introduction

- Caltech is leading a mission to rendezvous with (99942) **Apophis** in collaboration with JPL, Rocket Lab, and other industry partners
  - Two CubeSats and one mothership
  - Targeting Feb 2028 launch
- The mission will escort Apophis through its Earth encounter, observe its response to Earth's gravity, and use bistatic radar to map its interior
- Key measurements:
  - Shape, mass, and density
  - Surface and spin state changes
  - Internal block and void distribution
    - Apophis's internal structure will be mapped at ~10s of meters resolution, offering groundbreaking insights into rubble-pile interiors
    - Methods for interpreting such data remain an open challenge

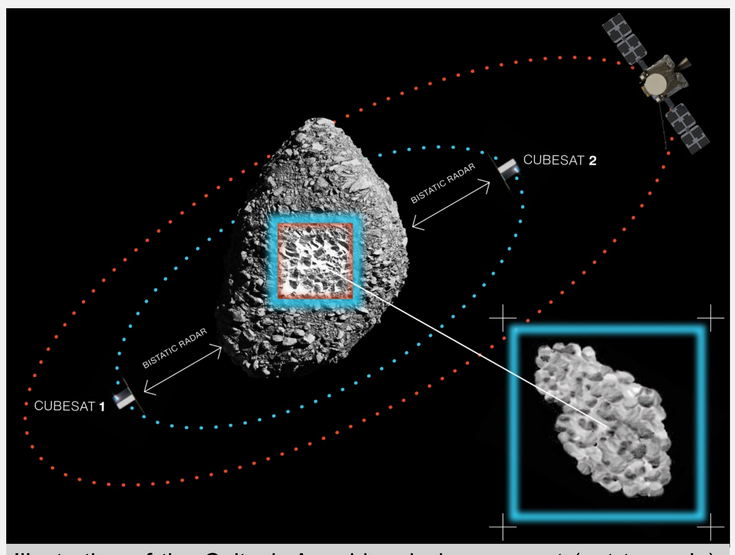
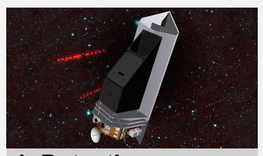


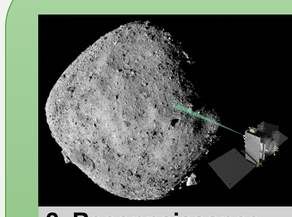
Illustration of the Caltech Apophis mission concept (not to scale). Inset from Asphaug+, 1999.

Radar and Modeling Inform Planetary Defense



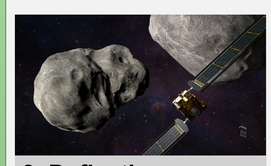
1. Detection

NEO (Near-Earth Object) Surveyor detects and tracks Potentially Hazardous Asteroids



2. Reconnaissance

To successfully deflect an asteroid, need knowledge of its composition and interior structure



3. Deflection or Disruption

E.g., NASA's DART (Double Asteroid Redirection Test) mission

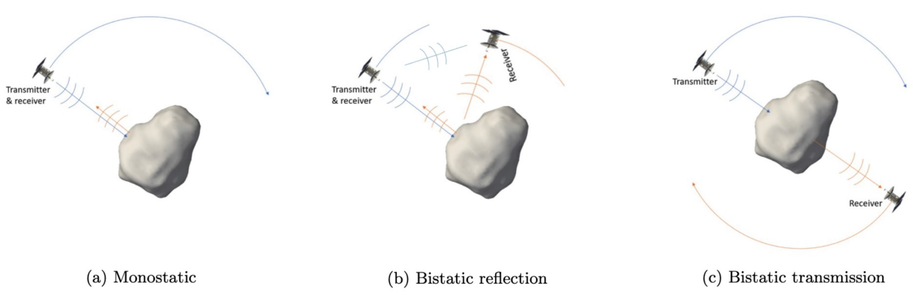
- The Caltech Mission will characterize Apophis's internal structure and composition with bistatic radar measurements (reconnaissance)
- Internal structure/composition informs mechanical strength and momentum enhancement factor (β), critical for predicting deflection outcomes (The NEO WARP Working Group, 2024)
- DEM models informed by in-situ radar data can be used for deflection predictions

Radar Tomography

Radar tomography data validates and improves models

Modeling

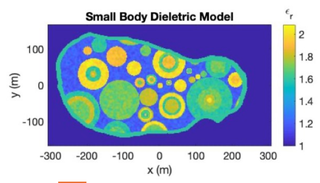
Caltech Mission to Apophis: Radar Modes



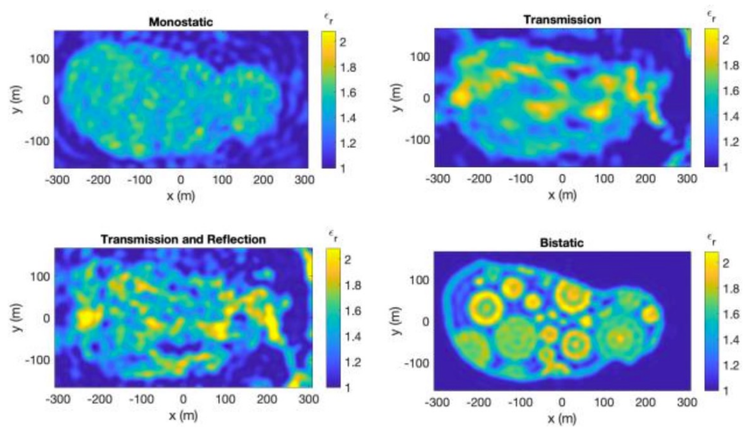
(a) Monostatic (b) Bistatic reflection (c) Bistatic transmission

Radar modes implemented by the Caltech Mission to Apophis. Image credit: Alain Hérique and Mark Haynes.

Tomography using inverse scattering reconstruction

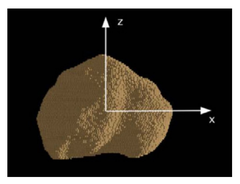


Inverse scattering reconstructions of the 2D object (left) under four different sampling geometries (below) (Haynes+, 2021).

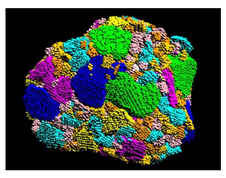


Previous work: *PKDGRAV*

- Soft Sphere Discrete Element Method (SSDEM) (Schwartz+, 2012) simulations of Apophis Earth encounter with *PKDGRAV* software
  - k-D tree to parallelize *N*-body gravity computation (Richardson+, 2000)

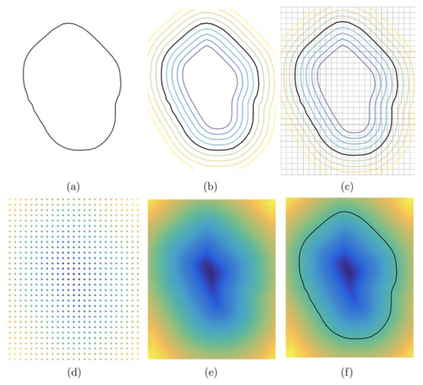


DeMartini+ (2019) simulated Apophis as a collection of hexagonally close packed spheres.



Liu+ (2023) modeled irregularly-shaped particles as aggregates of spheres.

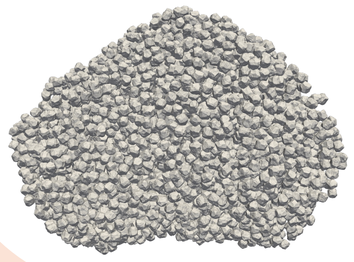
Level Set Discrete Element Method (LS-DEM)



- Particle shapes dictate mechanical properties of granular materials (e.g., Suh+, 2017)
- In LS-DEM, level sets are used to efficiently and accurately represent irregular particle shapes

(a) Particle surface, (b) Contour lines representing signed distance from surface, (c) Superimposition on grid, (d) Discretized level set function, (e) Level set function with interpolation, (f) Reconstruction of original grain surface, (g) Boundary node discretization and signed distance values. (Kawamoto+, 2016)

LS-DEM + *PKDGRAV* = LS-*PKDGRAV*



- Contact mechanics of irregular shapes with efficient n-body gravity computation
- Currently comparing simulations of Apophis's Earth encounter with previous methods

Simulated radar images help define mission requirements and refine data interpretation methods

Future Work

- Itokawa is the most analogous asteroid to Apophis for which in-situ data exist (S-type, similar size)
  - Randomly generated boulder shapes (Zhou & Wang, 2017) with similar roundness metrics to those observed on Itokawa (Robin+, 2024)
  - Simulate different boulder size distributions e.g., Itokawa (Michikami+, 2008)
- Deflection simulations

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