“Asteroids Inside Out: Radar Tomography”
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Executive Summary

The interior structures of small bodies, also known as *primitive bodies* in the 2003-2013 *Planetary Science Decadal Survey*, provide key constraints on their formation and the origin of planets. Interior structure is also of vital importance for developing mitigation strategies for potentially-hazardous near-Earth asteroids (NEAs), should they be needed for planetary defense, and for successful landed operations. NEAs, in turn, are representative and accessible samples of Main Belt and other solar-system populations [1]. Yet to date there is only limited knowledge of asteroid interiors from a few determinations of gravitational potentials and magnetic fields. We know next to nothing about typical asteroid structure, or the variability amongst populations.

Long-wavelength radar, that penetrates the interiors, can deliver 3D characterizations of small asteroid structure, and, in particular, it has the potential to provide information about composition by mapping the dielectric properties throughout the interior. Radar tomography involves monostatic or multistatic observations that sample the interior propagation and scattering from different orientations relative to a target body. Radar reflections are then processed to improve image resolution or invert for the dielectric properties. Radar can propagate through kilometers of cometary materials, as demonstrated by the *Rosetta* mission at Comet 67P/C-G. Asteroids are likely to be more conductive, but propagation through hundreds of meters is expected. There is also potential synergy between ground-based radar telescopes that can be combined with low-cost asteroid orbiters or precise flybys that could change our understanding of small bodies in the coming decades.

This white paper summarizes the science opportunities, state of the art, and outstanding knowledge gaps, with a particular emphasis on the 99942 Apophis encounter when it flies by within six Earth radii (near the outer geostationary satellite belt) on April 13, 2029 (WP Binzel et al. 2020).

Recommendations:

- One or more science-driven missions in the next 10 years (separate from ESA's Hera mission) to conduct bistatic radar transmission and probing of an NEA in a rendezvous or flyby configuration.
- Science-driven, long-wavelength radar tomography mission with one or more spacecraft to perform detailed interior mapping of a medium-sized near-Earth or Main Belt asteroid that fits under a Discovery class mission.
- Development of ground-based and ground-to-space radar tomography before the Apophis encounter, also enabling multi-decade population surveys of cislunar NEA interiors.
- Feasibility studies, and any subsequent upgrades, in low-frequency radar ground assets and infrastructure specialized for tomography of Apophis during the 2029 encounter.
- Investment in deep-space, low-size/weight/power (SWaP), low-frequency (2-500 MHz) radar technologies to enable small-sat and multi-spacecraft radar tomography missions that can be afforded under SIMPLEX or Discovery missions.
- Simulation and laboratory studies of small body permeability.
- Encourage NASA investment in full-wave electromagnetic simulation and laboratory studies (e.g., ROSES) specialized for small body interiors to aid mission studies and maximize the scientific return of radar tomography measurements.

Science of Small Body Interiors and Knowledge Gaps

Interiors of small bodies give crucial clues about the formation mechanisms and the evolution of planetesimals in the protoplanetary disk, as well as their collisional/rotational/tidal evolution in the billions of years that followed. Radar exploration of small body interiors was proven at Comet 67P by *Rosetta* [2] and the approach can be applied to other comets and to more accessible targets in near-Earth space.

The three sub-kilometer NEAs that have been studied in detail so far by spacecraft (Itokawa, Bennu, and Ryugu) appear to be rubble piles, as expected from models of the NEA population. They are thought to be at least second-generation bodies from gravitational accretion after collisional disruption [3-5]. Their surface appearance is consistent with rubble piles [6], and there is evidence in shape and rotation rates that give clues about the transition from granular to monolithic structure [7]. As for the size distribution of the rubble inside these small bodies, we know only the blocky exterior, which might extend through the body or be an exterior feature (convective segregation or Brazil-nut effect). We have no direct knowledge of the distribution of porosity inside a small asteroid, the depths of “ponds,” or how interior structure relates to the strength of their surfaces – and these uncertainties pose risks to landing, sample acquisition, and resource utilization.

Interior structures and compositions of asteroids also affect Earth-impact scenarios—whether an asteroid will disrupt in the atmosphere or make an impact crater [8]—as well as mitigation techniques involving deflection or disruption—whether it will be nudged and by how much, whether it will fragment and into what size pieces. This leads to NEA knowledge gaps imperative to planetary defense (WP Mainzer et al., 2020; [9] *NASA Science 2020-2024: A Vision for Science Excellence; Defending Planet Earth: Near-Earth Object Surveys and Hazard Mitigation Strategies*). A low-cost radar characterization program to investigate the interior structures of NEAs would greatly support modeling efforts aimed towards planetary defense (WP Stickle et al., 2020). At the same time, it would help answer the science questions related to the formation of primitive bodies specified as 2003-2013, 2013-2023 *Decadal Survey* science goals for primitive bodies, e.g., modernize ideas about rotational stability, formation of satellites and multiple-body asteroids, and reshaping by YORP spin-up, impacts, and tides during very close terrestrial planetary flybys.

The science potential for radar tomography technologies extends beyond NEAs, which would be a proving ground, to a wide range of objects in the Main Belt, Phobos and Deimos, comets, KBOs, and Trojans and at small moons of other planets (primitive bodies at large). For example, understanding interior structures of asteroids is necessary to investigate their potential past and present habitability (WP Castillo-Rogez et al., “Habit...”, 2020), and future in-situ resource utilization.

Why is Long-Wavelength Radar the Best Method for Interior Probing?

Long-wavelength radar is one of the few remote-sensing techniques that can directly probe the deep interior of a small solar system body or icy world and is the only technique that is directly sensitive to an object’s electromagnetic properties in the radio and microwave spectrums. Electromagnetic properties are related to the structure and distribution of an object’s density, porosity, mineralogy, conductivity, magnetization and material composition [10].

How Radar Tomography Characterizes Interiors

Radar tomography (RT) uses long-wavelength radio waves (150-0.5 meter wavelengths, 2-500 MHz) to image the 3D interior electromagnetic structure of a small solar system body. Radar echoes are acquired at many viewing angles, processed using inverse scattering techniques, and used to reconstruct 3D variations in an object's complex permittivity, revealing its interior structure [11-16]. RT leverages techniques from X-ray computer tomography (CT) in medical imaging and terrestrial seismology, and this technique has been used to probe the interior structure and underlying bedrock of the Greenland and Antarctic ice sheets [18]. Instrument performance depends on the observation geometry and diversity of scattering angles collected. Penetration depth and resolution also depend on the attenuation characteristics of the body. Therefore, optimal system configurations depend strongly on the overall mission profile and target [10], and can be informed by other remote observations. RT differs from state-of-the-art planetary radar sounding (e.g., MARSIS on Mars Express, SHARAD on Mars Reconnaissance Orbiter, Mini-RF on Lunar Reconnaissance Orbiter, REASON on Europa Clipper, and RIME on JUICE) in that the diversity of observation angles and possibility of transmission measurements around a small body enable dielectric inversion.

State of the Art Radar Tomography

To date, only *Rosetta*/CONCERT [17,32] has made limited transmission measurements of a comet nucleus at 90 MHz (3.3 m wavelength). Even this coverage allowed retrieval of average and statistical interior properties of 67P/CG with only two "cuts" of a part of the nucleus. This gave significant results on deep composition and nucleus accretion mechanism by revealing the homogeneity of the nucleus. The Juventas 6U CubeSat will hitch a ride on ESA's Hera mission to the Didymos-Dimorphos binary asteroid system, launching in 2024; Juventas will carry a low-frequency radar to probe the interior of the smaller asteroid of the binary pair [30].

Full 3D coverage of any small body would allow full-wave tomography to rebuild the entire image of the interior. While RT has yet to be applied to any solar system objects, it is the most promising technique for closing knowledge gaps in small body interior structure. Numerical modeling shows promising potential for tomographic observations to reveal boulders and voids inside asteroids [16,19].

Closing Knowledge Gaps

Direct measurements of asteroid interiors will close knowledge gaps by addressing the most fundamental questions in small body science identified by the Small Bodies Assessment Group [WP] on solar system formation and evolution and NEA threats and hazard mitigation:

- Direct measurement of the dielectric properties of an NEA's deep interior would allow retrieval of average composition and density as well as spatial variability at different scales (e.g., voids, constitutive block size) to answer questions on accretion processes.
- Higher resolution imaging of the shallow subsurface would give crucial information on the small body's evolution processes and interactions with its environment (activation processes, surface material redistribution, space weathering and presence of exogenous materials), supporting also thermal and mechanical modeling [10]. This is critical for understanding and comparing the surface and depth/size/frequency distribution.
- Knowing the dielectric constant can reveal the presence and distribution of near-surface and subsurface water ice and its relation to solar system formation and evolution (e.g., Trojans).
- Radar tomography as a technique for studying the interior structure of NEAs will complement, and provide possible calibration for passive techniques used to probe interiors, using for example magnetometers and energetic particle instrument suites (WP Villarreal et al., 2020) and studying global geodynamics (WP Eubanks et al., 2020).
- Radar tomography of Phobos and Deimos (~6 km) can provide information on their structural and compositional properties critical to supporting human exploration missions (WP Adamo et al., 2020, WP Ernst et al., 2020).
- Ongoing efforts to provide contextual data for space observations through Earth-based laboratory experiments (WP Iacovino et al., 2020) can provide further calibration data that is also crucial to interpretations of radar tomography data [20-22].

Radar Tomography Mission and Measurement Concepts

Radar instrument configurations strongly depend on the mission concept. A rendezvous benefits from low relative speed (<10 m/s) and low altitudes allowing small instruments. Rendezvous also allows two measurement geometries: bistatic transmission (Tx) tomography, which is suited to characterizing average composition, and monostatic reflection (Rx), which is suited to detecting geological structure (Concepts 1, 2 & 3 in Table 1). Rendezvous is also required for ground+space joint measurements (Concept 6 in Table 1): bistatic transmission measurements would be possible at a lower frequency when close to Earth (e.g., observing Apophis with Arecibo). A flyby can support both Tx/Rx geometries but requires a radar system with a higher operation speed (Concept 4 in Table 1) which is similar to previous generations of planetary radar sounders. In all cases, radar instruments on spacecraft or landers need dipole antennas (single- or cross-polarized), medium power RF electronics, and digital backends capable of limited on-board processing. Bistatic concepts require phase synchronization between radar units and longer mission durations.

Pre-mission estimates of a targets' diameter and electric properties, which give the total radar attenuation, are critical for instrument and mission design, where lower frequencies are traded for increased penetration depth but lower resolution. Small body candidates for RT are C- and S-type rocky asteroids [23] composed largely of silicates with estimated real part of the dielectric constant <10 [10]. More than 95% of NEAs are made of silicate and carbonaceous materials (i.e., non-metallic) and about 200,000 larger than 50 m in diameter are thought to exist [24, 25]. The population of NEAs greater than 10 meters in diameter is thought to be close to 40 million. To date, among NEAs of all sizes, just over 23,000 have been discovered.

Table 1. Existing/conceptual mission and data acquisition configurations for radar tomography.

	Configuration	Past, Future, or <i>Potential Missions</i> and <i>Observational/Mission Concepts</i>	Description or Science Application
1	Bistatic with lander	ROSETTA/CONCERT, <i>LFR/MASCOT2-AIDA</i>	Limited-angle transmission using radar relay on lander
2	Orbital monostatic	JuRA/JUVENTAS-HERA, <i>CORE</i>	Monostatic reflection observations from orbiter
3	Orbital bistatic/multistatic	<i>Coordinated multi-craft small-sats</i>	Bi-/multi-static transmission and reflection among synchronized radar units
4	Flyby monostatic or bistatic	<i>SIMPLEx-scale small-sat(s) flyby of NEA with REASON-like instrument(s)</i>	Significantly higher relative speed and altitude
5	Ground-only	Arecibo (430 MHz), Jicamarca Radio Observatory (50 MHz), Middle and Upper Atmosphere Radar (45 MHz), Owens Valley Radio Observatory	Regular observation of cislunar NEAs (reflection-only)
6	Ground-to-space	<i>Near-earth rendezvous, earth-orbiting, or sentinel radar observatories (L2-based) used with ground assets</i>	Diverse bistatic observation of cislunar NEAs

Opportunities and Technology Investments for the Next Decade and Beyond

- **Missions Over the Next 10 Years:** One or more science-driven missions should be developed in the next 10 years (separate from ESA’s Hera mission) to demonstrate bistatic radar transmission and probing of an NEA in a rendezvous or flyby configuration. Also, a dedicated science-driven Discovery-class tomography mission with one or more spacecraft (e.g., similar to the previously proposed Comet Radar Explorer (CORE) [26]) should be considered to complete detailed interior mapping of a medium-sized near-Earth or Main Belt asteroid. These should be preceded by mission architecture studies and trajectory analysis to catalog multiple candidate targets and launch dates.
- **Ground-Based and Ground-to-Space Assets, Cislunar NEA Survey:** Ground-based planetary radar systems have a legacy of solar system observing (WP Rivera-Valentín et al., 2020; WP Lazio et al., 2020; WP Virkki et al., 2020, WP Taylor et al., 2020, WP Kofman et al., 2020). Upgrades to existing facilities, new facilities (WP Lazio et al., 2020), and improved data analysis techniques (WP Rivera-Valentín et al., 2020) provide the opportunity to incorporate the necessary infrastructure for bistatic ground-based and ground-to-space radar tomography, enhancing the existing broad scope of planetary radar small body science [27,28]. Once proven, ground-based tomography would enable low-cost, multi-decade population surveys of cislunar NEA interiors, with the goal of making ground-based interior probing as mature as delay-Doppler shape inversion.
- **Apophis Opportunity:** The close approach of Apophis in April 2029 will provide one of the best opportunities for planetary radar observations, as Apophis will pass the Earth at a distance as close as 37,500 km (~0.1 lunar distance (LD), or less than 6 Earth radii) on April 13th. Asteroid tomography has not yet been tested fully in practice, but the close-approach of Apophis could provide the opportunity. The most power-effective options would be a fully space-based mission or space+ground-based measurements. A dedicated radar transceiver spacecraft sent to Apophis could answer questions on interior structure, electric permittivity, and absorption of asteroids at microwave wavelengths, and help conduct high-precision astrometric measurements to answer how the close approach affects the asteroid’s orbital

parameters/spin. Arecibo and Deep Space Station-13 (DSS-13) of the Deep Space Network have transmitted to the Lunar Reconnaissance Orbiter's Mini-RF instrument since 2011 when the spacecraft's radar transmitter failed. A similar concept could observe Apophis with a spacecraft equipped with an appropriate radio receiver either orbiting Apophis or as a lander on its surface [28]. Alternatively, a ground-based radio telescope could act as a receiver for a transmitting spacecraft or lander. Apophis will enter Arecibo Observatory's field of view on April 14th and remain observable for several weeks. April 14th and 15th would be optimal for ground-based or ground+space-based tomography observations, when Apophis is closer than 3 LD, and at a declination of 18-20 degrees. At that time, it will also be in the fields of view of the Green Bank Telescope and the Goldstone Solar System Radar (GSSR) [29]. Also, some European telescopes could be used as receivers, such as the 70-meter DSS-63 of Madrid Deep Space Communications Complex or the 100-meter Effelsberg Telescope when considering a space-based radio transmitter.

Table 2. Radar tomography science opportunities and technology investments.

Science Opportunity	Description	How to Obtain	Required Technology and Technology Investments	Time horizon and needs
Apophis Interior	Interior mapping of Apophis during 2029 encounter	Ground-only, Space-only, Ground +space	<ul style="list-style-type: none"> - High-power (MW), ground-based 50 MHz radar in monostatic or bi-static configurations - Tech demos (e.g., moon-bounces, other NEAs) in next 5 years. - Small-sat radar technology - Rendezvous mission concept studies - Small-sat + ground bistatic measurement concept studies 	2029 Needs immediate and broad investment
Near-Earth or Main-Belt Asteroid Interior Imaging	Full-wave inverse scattering imaging of asteroid interior dielectric structure	Space-only (monostatic or bistatic radar)	<ul style="list-style-type: none"> - Multi-static, small-sat radar mission, 2-100 MHz radar - Mission concept studies - Low-SWaP deep-space small-sat radar components (antennas) - Autonomous space-craft navigation - On-board radar processing alg. - Electromagnetic simulation of large objects 	Mid-decade Needs targeted radar/space technology investment
Cislunar Small Body Survey	Multi-decade survey of cislunar NEA interiors	Ground-only, Ground +space	<ul style="list-style-type: none"> - Ground-based 50-500 MHz high power radar assets - Feasibility, proof-of-concept and sensitivity studies - Development of rapid-response protocols - Observational and mission concepts 	Mid- to late-decade Broad, long-term investment in physical/soft infrastructure and proofs-of-concept
NEA Flyby Mission	Flyby mission for radar transmission measurements of NEA	Space-only (bistatic radar)	<ul style="list-style-type: none"> - Low SWaP small-sat radar technology - Flyby mission concepts and candidate targets 	Mid-decade Needs radar/space technology investment

- **Deep-Space Low-SWaP (size/weight/power) Radar Technologies:** While radar hardware has historically performed well outside of earth orbit (e.g., Magellan Radar, Cassini Radar, MARSIS, SHARAD), development is needed to mature low-frequency radar for deep-space small-sats that can be afforded under SIMPLEX or Discovery missions. This includes RF component miniaturization, efficient power amplifiers, and compact deployable low-frequency antennas (dipoles, folded-dipoles). GPS-denied bistatic radar synchronization needs to be demonstrated with autonomous navigation and data collection (WP Castillo-Rogez et al. “...SmallSats” 2020).
- **Advanced Concepts:** Simulation and laboratory studies should investigate what constraints RT can provide on small body permeability, which includes low-level ferrous material and dispersed magnetite. Efforts should also continue to develop libraries of dielectric responses for a wide range of compositions. In addition, synergistic and complimentary science between RT and other instruments such as gravity, thermal IR cameras [31], and seismology should be explored. Finally, advancements in electromagnetic simulation and inversion algorithms are needed to aid mission system engineering, sensitivity studies, and to help maximize scientific return of RT missions.

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