The DROID MISSION CONCEPT TO ACCOMPANY AND CHARACTERIZE APOPHIS THROUGH ITS 2029 EARTH CLOSEST APPROACH. C. A. Raymond[1], R. B. Amini[1], P. C. Adell[1], S. Bandyopadhyay[1], J. Bellerose[1], S. Bhaskaran[1], P. Bousquet[2], B. J. R. Davidsson[1], L. Fesq[1], M. S. Haynes[1], A. Herique[3], R. Karimi[1], J.T. Keane[1], P. Michel[4], Y. Takahashi[1]. [1]Jet Propulsion Laboratory/California Institute of Technology (4800 Oak Grove Dr. M/S 321-625, Pasadena, CA 91109. carol.a.raymond@jpl.nasa.gov), [2]Centre National D'Etudes Spatiales (CNES), [3] Institut de Planetologie et d'Astrophysique de Grenoble (IPAG), CNRS, CNES, Grenoble, France, [4]Univ. Côte d'Azur, Obs. Côte d'Azur, CNRS, Nice, France.

Introduction: The Earth Closest Approach (ECA) of asteroid (99942) Apophis on April 13, 2029 presents a unique opportunity to achieve breakthrough science and strengthen planetary defense goals.

As discussed in [1], low-frequency (VHF) radar observations can probe the interior structure of small bodies, as demonstrated by CONSERT at comet 67P [2, 3], and the planned JuRa low frequency radar on Hera/Juventas at the Didymos system — the target of the DART mission. Radar measurements can determine the distribution of monolithic objects and voids within the body at 10's of meter scale, which inform potential deflection and disruption attempts. This is best accomplished by multi-static, low frequency radar [4].

A mission concept to exploit the Apophis opportunity has been developed in a collaboration between NASA/JPL and CNES. Here we report on the current status of the concept previously reported at the T-6 and T-7 workshops [5, 6]. The Distributed Radar Observations of Interior Distributions (DROID) mission would launch Oct 2027-Apr 2028, rendezvous with Apophis in early 2029, and escort it through the encounter. DROID's measurements would determine the interior structure and properties, the body's shape, morphology and rotation state and observe any resolvable changes due to tidal forces during the close encounter. DROID provides unique high fidelity in situ data that complements and enhances Earth-based optical and radar observations of Apophis, as well as data collected by OSIRIS-APEX which is due to flyby Apophis in late April 2029 and rendezvous in June [7].

As illustrated in Figure 1, DROID's architecture calls for three spacecraft: a Mothership and two 12U CubeSats. The Mothership carries the CubeSats to Apophis, achieves the rendezvous cruise trajectory, performs high resolution imaging, and acts as a Direct-to-Earth (DTE) node for the constellation. The requirements of the Mothership can be met by several platforms, including the ExLabs Arachne platform [8]. Once Apophis's physical characteristics (shape, spin, gravity field) are sufficiently characterized, the Mothership deploys both CubeSats, which then insert themselves into coordinated low orbits to perform monostatic and bistatic radar observations.

Mission Goals: The DROID mission has two primary goals, designed to complement the OSIRIS-APEX investigation. The first goal is to understand the interior structure of a rubble pile asteroid and the implications for its formation, evolution, and response to a deflection attempt. Objectives include determining shape and density, and determining the internal size, distribution, and arrangement of blocks and voids within Apophis.

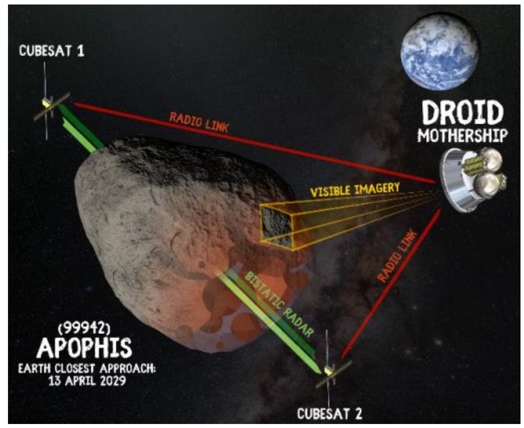

Figure 1. The DROID mission employs three spacecraft to characterize Apophis's interior and other physical characteristics prior and through ECA.

DROID's second goal is to understand how close planetary encounters affect asteroids. DROID will provide critical pre-ECA high-resolution imagery of Apophis necessary for change detection. Objectives include determining if material moves on the surface of Apophis during the Earth flyby, and determining how the spin state of Apophis changes during ECA.

Payload: Given the goals above, DROID employs four payload subsystems distributed over three spacecraft (Figure 1). Objectives requiring surface imaging are to be met with a narrow-angle camera (NAC) on-board the Mothership spacecraft that is used to map the surface of Apophis at a spatial resolution of ≤ 2.5 cm/px from an altitude of ~ 10 radii. Wide-angle navigation cameras are carried on the two CubeSats for optical navigation.

The objective to map internal structure is achieved using the Low Frequency Radar (LFR) on the CubeSats. The LFR is baselined as a version of JuRa (60 MHz), [9], modified to operate in a bistatic mode [1]. Inter-Spacecraft Link (ISL) S-band transponders on all three

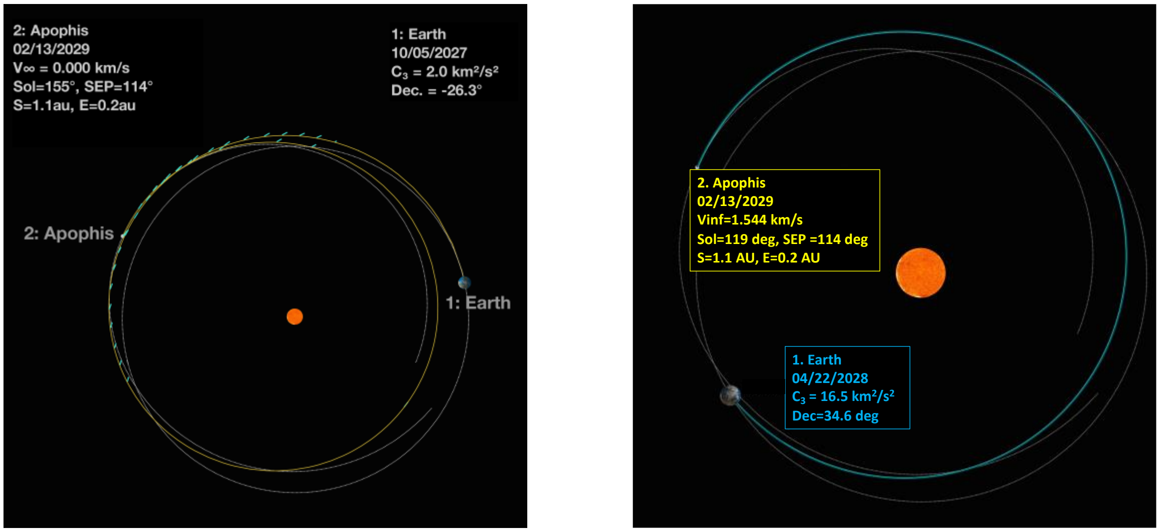

Figure 2. *Left* shows notional electric propulsion-based trajectory with a C3 = 2.0 km^2/s^2. GTO and TLI rideshares can also be accommodated. *Right* shows an impulsive trajectory. In both cases the mission $\Delta V < 2$ km/s.

spacecraft perform data transfer between CubeSats and Mothership, and synchronize the CubeSat clocks for accurate bistatic radar measurement. ISLs are also used with the Mothership's direct-to-Earth (DTE) link to map the gravity field. The current estimate of the total payload mass, including CubeSat dispensers, is 70 kg.

Mission Architecture: The DROID mission design requirements can be achieved with either electric or bipropellant chemical propulsion. The use of electric propulsion prefers earlier launch opportunities within the Oct 2027-Apr 2028 timeframe but is more robust in accommodating rideshare options. A bipropellant chemical system prefers a dedicated launch of C_3 = 10-17 km^2/s^2 which allows launch as late as April 2028 while still arriving at Apophis months before ECA. Two reference trajectories are shown in Figure 2.

Operations: DROID concludes its cruise phase when it arrives at Apophis at least two months before ECA. The Mothership NAC begins the preliminary characterization of Apophis's shape and spin. Approach imaging is followed-up by several flyby maneuvers to characterize the gravity field with DTE communication.

The Mothership then deploys the CubeSats, which maneuver into a 5 body radii altitude, sun-synchronous terminator orbits using their own cold gas propulsion [10]. Following CubeSat deployment, the Mothership positions itself in a ~10 body radii altitude orbit where it continues its imaging investigations using the NAC.

The CubeSats will continuously collect both monostatic and bistatic radar echoes and will capture transmission through the body when antipodal (±15°). Radar data products include: (1) 3D volumetric backscatter via monostatic/bistatic tomographic SAR, (2) average dielectric constant along interior bistatic ray paths with assessment of internal heterogeneity [11].

The DROID mission has been simulated using the Multi-Spacecraft Concept And Autonomy Tool (MuSCAT) simulation tool [12] to determine its science yield as a function of design parameters, in order to optimize its configuration. Preliminary analysis identified that CubeSat thruster accuracy drives stationkeeping frequency, which drives the requirement for ground contact and optical navigation imaging. At 5 body radii altitude, meeting the ±15° antipodal constraint with daily commanding requires $\Delta V_{Error} \leq 0.2$ mm/s [8]. Monte Carlo analyses show this performance enables 20% bistatic coverage of Apophis within 40 days [13] vs 5% coverage when uncontrolled. In both cases monostatic coverage rate remains 20% over 40 days. The mission also offers a unique opportunity to operate an advanced, self-contained onboard navigation system as a technology demonstration for future small body missions.

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