DROID: ACCOMPANYING AND CHARACTERIZING APOPHIS THROUGH ITS 2029 EARTH CLOSEST APPROACH. R. B. Amini[1], P. C. Adell[1], R. Anderson[1], S. Bandyopadhyay[1], J.-M. Belloir[2], S. Bhaskaran[1], B. J. R. Davidsson[1], F. Esteve[2], L. Fesq[1], A. French[1], Y. Gregoire[2], M. Haynes[1], A. Herique[3], R. Karimi[1], J.T. Keane[1], A. Lamy[2], L. Lorda[2], N. Mastrodemos[1], R. Miller[1], R. Pinède[2], C. Raymond[1], Y. Takashi[1], C. Virmontois[2]. [1]Jet Propulsion Laboratory/California Institute of Technology (4800 Oak Grove Dr. M/S 301-165, Pasadena, CA 91109. ramini@jpl.nasa.gov), [2]Centre National D'Etudes Spatiales. [3]University of Grenoble.

Introduction: Understanding the interior of potentially hazardous asteroids (PHA) is critically important for planetary science and defense. The close approach of asteroid (99942) Apophis on April 13, 2029 presents a unique opportunity to achieve breakthrough science and strengthen planetary defense goals.

Low-frequency (VHF) radar observations at close range can probe the interior structure of small bodies, as demonstrated by the CONSERT experiment on Rosetta/Philae at comet 67P [1, 2], and the planned JuRa low frequency radar experiment on Hera/Juventas at (65803) Didymos/Dimorphos—target of the DART mission [3]. These science experiments can determine the distribution of monolithic objects and voids within the body at 10's of meter scale, which are critical for potential deflection and disruption attempts. Such a measurement is best accomplished by multi-static, low frequency radar [4]. Multi-static radar operations at small bodies require strict timing coordination and navigation, adding complexity to mission architecture and design.

A mission concept to exploit the Apophis opportunity has been developed in a collaboration between NASA JPL and the French space agency, CNES. The Distributed Radar Observations of Interior Distributions (DROID) would rendezvous with Apophis in late Summer 2028, seven months prior to Earth closest approach (ECA) and escort it through the encounter. Its measurements would determine the interior structure and properties, the body's shape, morphology and rotation and observe any resolvable changes. 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-REx if approved for an extended mission at Apophis.

As illustrated in Figure 1, DROID's architecture calls for three spacecraft: an ESPA Grande-class Mothership and two 6U CubeSats. The Mothership carries the CubeSats prior to the Science Phase, achieves the rendezvous cruise trajectory, performs high resolution imaging, and acts as a Direct-to-Earth (DTE) node for the constellation during the science mission. 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.

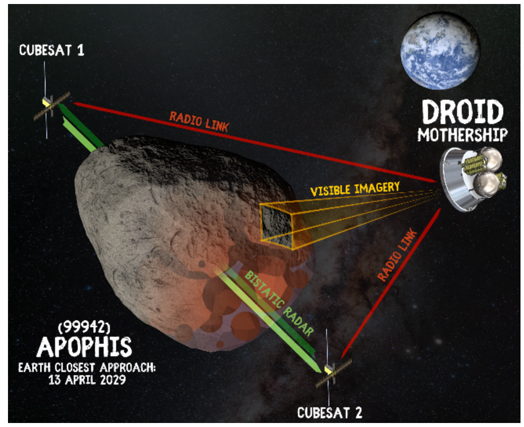

Figure 1. The DROID mission employs three spacecraft to characterize Apophis's interior and other physical characteristics prior and through ECA.

Mission Goals: The DROID mission has been architected to achieve a set of notional mission goals that correspond to NASA's planetary science and defense goals.

DROID's first goal is to understand the interior structure of a rubble pile asteroid and implications for its formation, evolution and response to a deflection attempt. Notional objectives satisfying that goal include: determining Apophis's shape and density, and determining the internal size, distribution, and arrangement of blocks and voids within the body. Characterizing the interior structure in this way is uniquely enabled by bistatic radar observations.

DROID's second goal is to understand how close planetary encounters affect asteroids. DROID will provide critical pre-ECA imagery of Apophis that are necessary for change detection. Notional objectives satisfying that goal include: determining if Apophis's overall structure changes before and after ECA, determining if material moves on the surface of Apophis during the Earth flyby, and determining how the spin state of Apophis changes during ECA.

Finally, DROID is being architected with the possibility of accommodating a contributed <10 kg payload on-board the Mothership. If realized, this can enable achieving additional science and/or planetary defense goals.

DROID Payload Overview: Given the notional goals above, DROID employs four types of payloads 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. The NAC telescope and observing bands are the subject of on-going studies, but its focal plane is to be based on the Advanced CASPEX detector [5]. The Advanced CASPEX focal plane is a 4096 x 3000 pixels array. Additional wide-angle cameras (WACs) are carried on the two CubeSats for optical navigation.

The objective to map internal structure are achieved using the Low Frequency Radar (LFR). The LFR is only manifested on the two CubeSats and is baselined as a version of JuRa (60 MHz), [6], modified to operate in a bistatic mode. Inter-Spacecraft Link (ISL) transponders in S-band are present on all three spacecraft. These ISLs have multiple functionalities: data transfer between CubeSats and Mothership, and clock synchronization between CubeSats for accurate bistatic radar measurement, that is used to help map the gravity field, along with the Mothership's DTE link.

Mission Architecture: To reduce mission cost and risk and maximize launch opportunities, the DROID mission design flowed from three primary motivators. First, to arrive at Apophis and complete its radar science objectives with ample schedule margin prior to closest approach. Second, the architecture and systems shall be compatible with either direct launch or rideshare to GTO, TLI, or $C_3 \geq 0$ km^2/s^2. Third, that DROID shall use heritage bus designs that can achieve the required propulsion performance for a worst-case GTO launch scenario. Given DROID's 3.54 km/s ΔV requirement is be similar to that of ESCAPADE, which uses bipropellant propulsion [7], DROID's reference mission is constrained by a cruise trajectory insertion (CTI) window of about October-November 2027.

Rideshare, Earth Orbit, Cruise: Assuming a GTO rideshare, DROID would separate in advance of CTI. Within the CTI window, the DROID Mothership will perform two burns with a total ΔV = 1.49 km/s in order to escape from GTO and perform the CTI burn. A deep space maneuver of 1.55 km/s during cruise will place DROID on an intercept trajectory with Apophis.

Approach: DROID arrives at Apophis around August-September 2028 and performs a 0.30 km/s burn to reduce its relative velocity. During this phase, the Mothership NAC is used to begin preliminary characterization of Apophis's shape and spin. Approach imaging is then followed-up by several flyby maneuvers used to characterize the gravity field with DTE communication.

CubeSat Deployment: Once Apophis' physical characteristics have been sufficiently characterized, the Mothership deploys the CubeSats, which begin their own checkout. Then, in order to perform their radar science, the CubeSats maneuver into 2-5 body radii altitude, sun-synchronous terminator orbits using their own cold gas propulsion. Following CubeSat deployment, the Mothership positions itself in a 9 body radii altitude orbit where it continues its imaging investigations using the NAC.

Radar Measurements and Science: The CubeSats are positioned antipodally to perform bistatic radar measurements with ±15° margin in their relative position. The pair of radars will continuously collect both monostatic and bistatic echoes. A 2-body radii altitude orbit will enable mapping of 20% of the 3D monostatic Doppler sampling at 60 MHz [8], within 40 days. 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 [9]. Both are used to constrain porosity and block distribution. Should Apophis be bilobed, the radar will be used to distinguish the nature of each lobe as, e.g., monolithic vs rubble pile.

ECA & Post-ECA: The configuration of the DROID constellation during ECA and Post-ECA operations is the subject of on-going studies. Major ECA drivers include positioning of cameras to maximize the likelihood of capturing surface changes and mitigating the risk of collisions with potential ejected debris. The major Post-ECA driver is escaping from Apophis orbit to a safe heliocentric orbit prior to depleting propellent in order to avoid any possibility of impacting the asteroid and perturbing its orbit.

Technology Readiness: To facilitate mission and systems design, a new tool was developed that simulates science yield as a function of mission design and flight-like spacecraft performance and behaviors. [10] This has permitted the DROID team to define a technically-mature design point that reduces cost and affords appropriate mission margins against the uncertainty of Apophis's shape, spin, and gravity.

As a result, DROID does not require any technology development to meet its mission requirements. However, requirements driven by time synchronization for bistatic radar and balanced thrusting for CubeSat desaturation reaction wheel desaturation may drive engineering development.

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