APEX: ASTEROID PROBE EXPERIMENT MISSION. J.B. Plescia[1], O. Barnouin[1], M. Paul[1], N. Schmerr[2], D.C. Richardon[2], H. Yu[3], W. Schlei[1], M. Ozmiek[1], F. Siddique[1], and J.V. DeMartini[2], [1]Applied Physics Laboratory, Johns Hopkins University, Laurel, MD 20723; [2]University of Maryland, College Park, MD; [3]Arizona State University, School of Earth and Space Exploration, Tempe, AZ 85287.

Introduction: The primary objective of the Asteroid Probe Experiment (APEX) mission is to characterize the internal structure, rotational dynamics and surface morphology of the ~400 m asteroid (99942) Apophis and to determine the extent to which those characteristics change as a result of tidal forces during its close encounter with the Earth in 2029. Apophis makes a close approach to Earth on April 13, 2029 passing within geosynchronous orbit at 0.000245 ± 0.000060 AU (36700 ± 9000 km, 3σ). That distance is such that tidal forces would not be expected to disaggregate a body, but close enough to change the rotational state and produce solid-body deformation [1-5]. Apophis' Earth encounter provides a unique opportunity for a detailed study of a Near-Earth Asteroid (NEA) with a small spacecraft as observations would be made at 1 AU and near the Earth, minimizing spacecraft requirements.

Under the auspices of the NASA Planetary Science Division SmallSat Study Program, our objective was to understand whether a mission to the asteroid Apophis to examine its structure and explore how it might change as the result of an encounter with the Earth would fit within the constraints of a 180 kg and $100M mission.

Science Objectives: Four Level 1 Science Objectives are defined: 1) Determine the rotational state and bulk properties; 2) Determine the interior structure; 3) Determine the geology and geologic history; and 4) Determine the tidal effects on surface morphology, interior structure, and rotation. A total of 12 Level 2 Objectives are identified. Preliminary modeling of the encounter, treating Apophis as a rubble pile of gravel-like material and using a soft-sphere discrete element method, shows that bulk deformation will be on the scale of millimeters over a period of a few hours.

Spacecraft: The spacecraft has a total dry mass of 164 kg (including 30% margin) and 101 kg of propellant (Fig. 1). The spacecraft measures ~0.7 x 0.7 x 0.8 m.

We chose solar electric propulsion (SEP) because a chemical system significantly exceeded the mass limits. Propulsion is provided by a throttable Busek Hall thruster (BHT-600) with xenon propellant. Four 3.6-N cold-gas thrusters provide for high-thrust maneuvers. The BHT-600 requires a maximum of 600 W. Communications are conducted with the APL X-Band Frontier Radio using a radial line slot array antenna. 700 W of power is produced at 1 AU from seven solar panels that are unfolded after launch.

Trajectory: APEX could be launched as a secondary payload on many missions that would place it near the L1 Sun-Earth Lagrange point. We examined a launch with the Interstellar Mapping and Acceleration Probe mission that is mandated to launch before December 2024. The inexorable date of the Earth flyby on Friday April 13 drives mission planning. The early arrival date (October 2028) allows time for mapping and multiple attempts at seismometer placement.

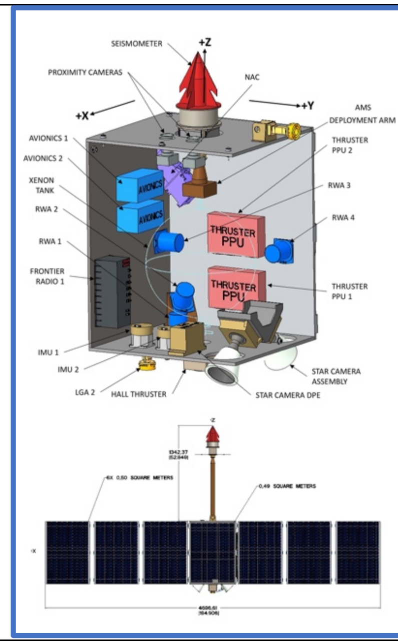

Figure 1. Upper panel: View of the spacecraft illustrating key components. Lower panel shows the 7 solar arrays extended. The boom extending upward holds the seismometer for deployment.

Instruments: The mission science objectives drive the payload instrument selection. The instrument complement includes a panchromatic imager, a proximity camera, and a seismometer.

Narrow Angle Camera: A camera design based on components from the Messenger MDIS and the New Horizons LORRI instrument allow nominal mapping at 20 cm / pixel from a 20-km range. It will include a new 3 Plus D 2048 × 2048 array and a new housing to reduce volume and mass.

Proxops Camera**:** To provide high-resolution stereo images of the surface and support terrain navigation, a pair of panchromatic refractive imagers, cross-strapped to a pair of redundant digital video recorders.

Seismometer**:** This is the most critical instrument as it will provide the data necessary to understand the tidal effects and the internal structure of Apophis. The instrument senses seismic displacement via electrolyte flow through a sensor plate [5]. The seismometer has high performance, similar to that of a terrestrial seismometer. Because there are no moving parts, a critical advantage of the sensor is that it is orientation independent (i.e., it does not need to be leveled).

Operations: The objectives of the pre- and post-encounter imaging are to provide a global data base such that the morphology, photometry, topography and shape of Apophis can be accurately determined. Topography can be derived from photogrammetric techniques as well as photoclinometry (shape from shading). The pre-encounter campaign will characterize the current state of Apophis, and the post-encounter campaign will identify any changes to the surface, the shape or topography caused by tidal forces. The pre- and post-encounter imaging campaigns collect the same systematic data set.

The emplacement of the seismometer is a critical aspect. Once the surface is mapped, an assessment can be made to determine where to locate the surface seismic sensor. Ideally several areas of fine-grain material will be located based on the mapping data and these will be evaluated as target locations. The emplacement requires that the spacecraft descend to within 1 meter of the surface (the length of the boom). The spacecraft must then exert sufficient force to push the sensor into the regolith.

APEX will use a protocol similar to that used for Hayabusa and that planned for OSIRIS-REx. This involves developing a descent trajectory based on the mapping images. A series of low-altitude passes will be conducted to acquire high-resolution image of the approach ground track that can be used by the terrain-recognition software to ensure that the spacecraft is following the planned route. A series of rehearsals will also be conducted, terminated before actual contact, to ensure that the terrain-recognition software and spacecraft attitude control and velocity are operating as planned.

The actual descent will involve slowly decreasing altitude (Fig. 2). Equipped with terrain-relative navigation, APEX will determine if it is on course to the chosen location, and make small adjustments. Given the very low gravity of Apophis, onboard autonomy can abort the descent if the spacecraft is off course, allowing for an assessment and a subsequent deployment attempt. The surface of Apophis will be mapped under a variety of illumination and viewing geometries to allow for the production of a shape model of the body. Once the surface has been mapped and a suitable site located, the seismometer will be deployed. The seismometer is stowed at the end of a 1 m boom. Deployment will require that the spacecraft approach Apophis to within ~ 1 m; the spacecraft thrusters will be used to push the seismometer into the surface after which the seismometer will be released and the spacecraft will back away. The seismometer will collect data before, during and after the encounter with the Earth. The entire surface will be reimaged after Earth encounter to determine the changes that have occurred.

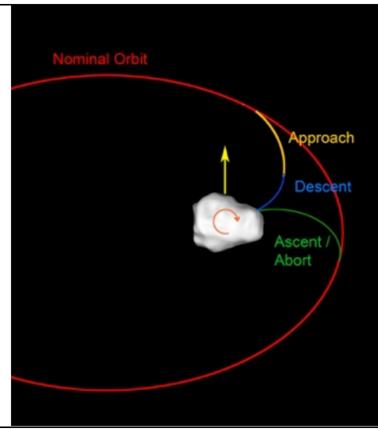

Figure 2. Red: Nominal orbit from which descent is begun. Yellow: Approach Phase during which spacecraft determines and corrects position. Blue: Descent trajectory to the surface to release seismometer. Green: Ascent trajectory used to reach nominal orbit after deployment or abort.

Summary: APEX will rendezvous with the NEA (99942) Apophis to determine its size, shape and rotation characteristics and map its surface and then deploy a seismometer onto the surface. Apophis will be observed as it is tidally deformed during a close encounter with the Earth in April 2029. The seismometer will record the signals from meteoroid impacts, thermal cracking and tidal deformation that in turn allow an understanding of Apophis' interior structure. After its encounter with the Earth, the surface will be remapped to determine the extent of tidally induced changes to the surface and its rotational characteristics. APEX will make the first *in situ* seismic observations of a NEA and will be the first to observe the tidal effects resulting from an encounter with a large planetary body. April 2029 represents a represents a unique opportunity to understand Apophis. This is the closest Earth encounter with an asteroid of this size in modern history.

References: [1] Richardson et al. (1998) *Icarus* 134, 47-76. [2] Scheeres (2001) *Celest. Mech. & Dyn. Astron.*, 81, 39–44. [3] Scheeres et al. (2000) *Icarus*, 147, 106–118. [4] Scheeres et al. (2005) *Icarus*, 178, 281–283. [5] Yu et al. (2014) *Icarus*, 242, 82-96.

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