Title: Mission ACE: Apophis Close Encounter

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Mission Objectives (where and why?)

Understanding asteroids and their threat of impact is one of the major responsibilities of mankind when it comes to the sustainability of the species. Fortunately, nature is bringing us an unprecedented opportunity which is an extremely close passing of a Potentially Hazardous Asteroid (PHA), 99942 Apophis, to witness and learn the possible consequences in the near future. PHAs are a group of specific near-Earth objects (NEOs) with absolute magnitudes $H \leq 22$ (approximately corresponding to diameter ≥ 140 m by assuming the albedo of 0.14 [1]) and the minimum orbit intersection distance (MOID) ≤ 0.05 AU of Earth's orbit. The peculiar orbit and size of PHAs make them very likely to destroy a region on Earth in case of a collision, thus it is crucial to monitor and study these small bodies for designing successful planetary defense strategies. On April 13th, 2029, Apophis will visit Earth at a distance of around 36700 ± 9000 km, which is ten times closer than the moon and almost the altitude of geosynchronous satellites [2]. Such a distance will not disintegrate Apophis as it is well beyond the Roche limit of the asteroid but may result in tidal deformations shown as alterations in shape, spin states, surface topography, and internal structure of the body [3-5]. Observing and studying these physical characteristics and their changes induced by tidal force will shed light on the nature of Apophis and its likelihood on an actual impact trajectory. However, the solar elongation of Apophis' close encounter will restrain ground-based observations immediately from the day of the Earth flyby until September 2029 [6]. In-situ observation and measurement for this once-per-thousand-year event carried out by space probes thus becomes essential. Therefore, we propose a mission concept "ACE (Apophis Close Encounter)" which aims to orbit and observe Apophis with a panchromatic imager onboard a small spacecraft before, during, and after the asteroid's 2029 Earth flyby. The mission objectives of ACE are as follows:

1. Determine the effect of tidal force on the shape, surface structure, and rotational dynamics of an asteroid
   - 1.1 Survey the shape of Apophis before and after the close encounter
   - 1.2 Investigate the spin state and rotation period of Apophis before and after the close encounter
   - 1.3 Explore the surface of Apophis before and after the close encounter at sufficient resolution
   - 1.4 Search for dust plumes of Apophis at sufficient resolution
2. Search for possible natural satellites (mini moons) of Apophis
3. Raise public awareness of planetary defense

Concept of Operations including orbital design

We designed a preliminary spacecraft trajectory based on the Lambert solver [7]. Considering relatively short lifetimes of small space probes, we set a maximum time-of-flight (ToF) of 180 days as the main boundary condition of our calculation. On account of a low arrival Δv (velocity impulse) and an ideal arrival date being few months before the close encounter (i.e., April 13th, 2029), the best launch window of ACE goes from mid-July to mid-August 2028 as shown in Fig. 1.

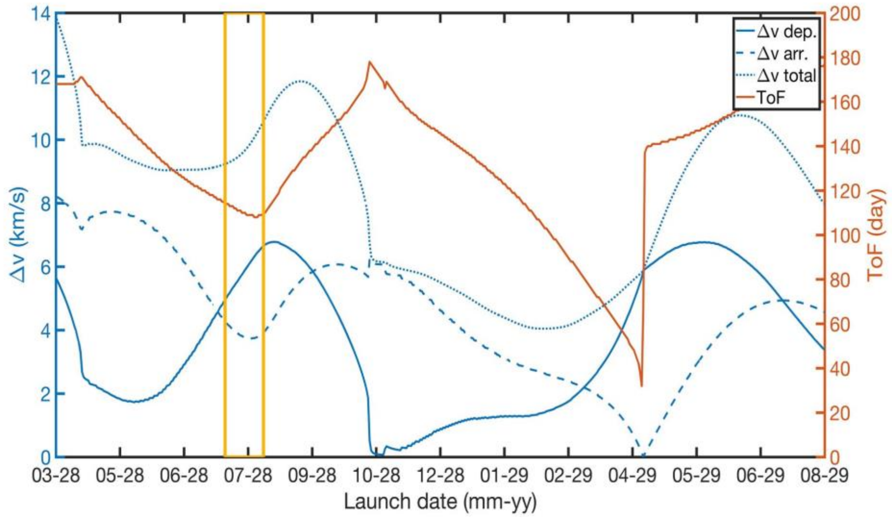

Figure 1. The estimated values of (departure, arrival and total) Δv and ToF of ACE versus the departure date. The orange box marks the best launch window from July 16th to August 10th, 2028.

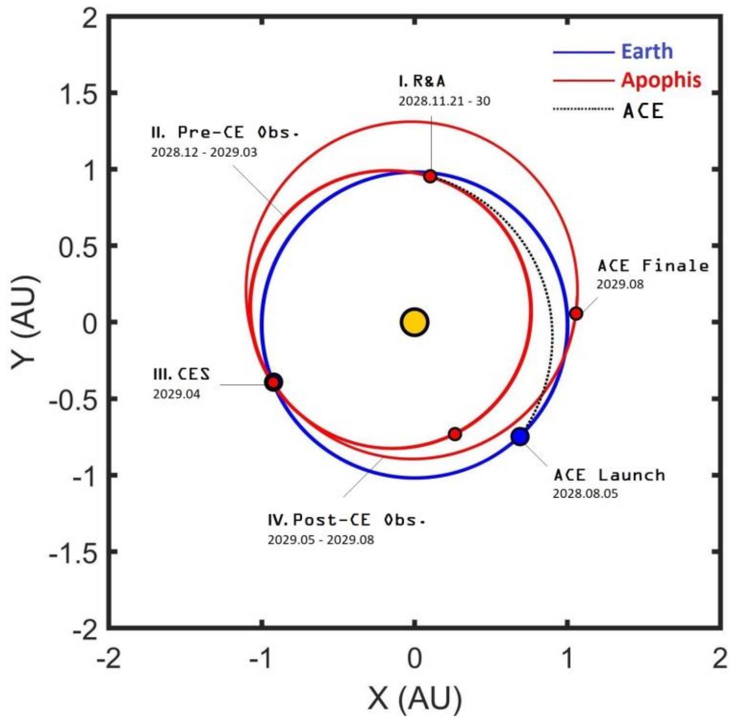

Figure 2. The trajectories of Earth (blue), Apophis (red) and ACE (dot) and their relative positions with the corresponding mission stages.

Fig. 2 illustrates mission stages of ACE with relative positions of Earth, Apophis, and the spacecraft along their trajectories. Note that the orbit of Apophis is not stable and thus it fails to converge as an ellipse as viewed from the top of the ecliptic plane. ACE is scheduled to launch on August 5th, 2028 within a 25-day launch window. After 108 days of travel, the spacecraft is expected to rendezvous with Apophis on November 21st, 2028 with the arrival Δv = 3.76 km/s. Upon arrival, ACE will perform a series of observations according to mission stages below:

I. Rendezvous & Approach (R&A)

- Operation timeline: 2028.11.21 – 2028.11.30
- ACE is planned to rendezvous with Apophis at a distance of 50 km away from the asteroid. The spacecraft will make a stop to scan Apophis' entire Hill Sphere in a mosaic pattern to search for its natural moons scaling around a few dozen meters. Next, ACE will cruise toward Apophis slowly (~10 cm/s) until 10 km away and then halt again to take another series of mosaics covering the area around the asteroid to hunt for smaller moons (few meters in size) and dust plumes to see if Apophis has comet-like activities before the upcoming close encounter.

II. Pre- Close Encounter Observation (Pre-CE Obs.)

- Operation timeline: 2028.12 – 2029.03
- First, ACE will stay within a small region at an altitude of 10 km from Apophis' surface to perform Global Survey 1 (GS1), which defines as observations at low phase angles (≤ 20°, ideally 0°) with sufficient solar irradiation for determining the shape, spin states and surface colors. GS1 will run for ~55 days (i.e., 5 spins of Apophis) with image resolution ~1.7 m/px. After operating GS1, ACE will move down to the height of 2.5 km and orbit Apophis to carry out Global Survey 2 (GS2) for ~56 days completing 5 orbits with orbital speed ~1.63 cm/s. GS2 will focus on mapping topographic features (e.g., craters, grooves, and ridges) which require high spatial resolution (~0.4 m/px for ACE at 2.5 km) and high contrast imaging. As shown in Fig. 3, the orbital plane of ACE is parallel to the one of Apophis in order to realize the photometry from all phase angles (0° – 180°) during GS2. A full surface coverage of Apophis can be achieved after 132 hours, which is almost half of ACE's revolution.

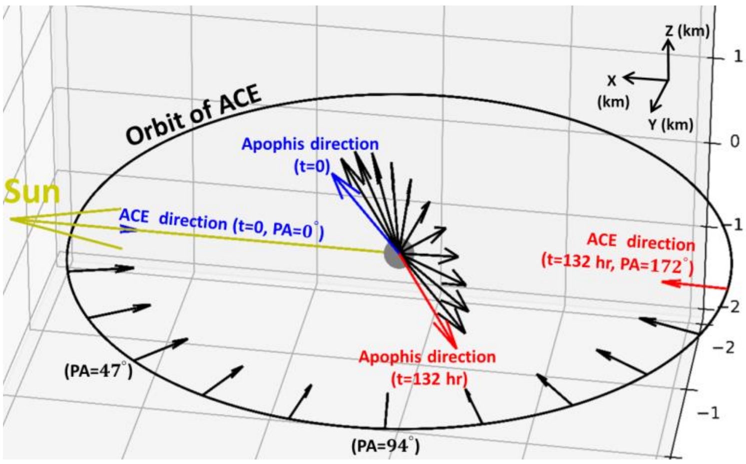

Figure 3. The orbit of ACE with the Sun at the direction of +x axis. The arrows indicate the pointing of the imager at a given time (t) and phase angle (PA) as examples. Note that we assume the orientation of Apophis' spin axis in the X-Z plane since it is still unclear due to Apophis' tumbling rotation state [8].

III. Close Encounter Surveillance (CES)

- Operation timeline: 2029.04
- The spacecraft will transfer back to the 10-km height again and stay at a surveillance position in order to observe Apophis for its near-Earth flyby from a safe distance and favorable viewing geometry.

IV. Post- Close Encounter Observation (Post-CE Obs.)

- Operation timeline: 2029.05 – 2029.08
- The operation procedure of this stage will be the same as the one of the Pre- CE Obs. to ensure

images of Apophis taken under similar conditions (e.g., distance, phase angle, exposure time) for justifiable comparisons between the images before and after the close encounter.

The entire mission is expected to end in late August or early September of 2029 with a lifetime of around 280 days, yet it is possible to extend depending on the spacecraft condition.

Key Performance Parameters

1. S/N (signal-to-noise ratio) and resolution of images: An ideal value of S/N is ~100 (i.e., the noise is about 1% of the total signal). The desired image resolutions are 1.7 m/px for GS1 and 0.4 m/px for GS2 as elaborated in the *Pre-CE Obs.* section in *Concept of Operations*.
2. Accuracy of attitude determination: ACE shall be able to implement the pointing accuracy of ±0.001° (3σ) which ensures the operations of GS1 and GS2.
3. Communication rate: ACE plans to take several hundreds of images which will require ~7.2 GB of storage. The data rate shall reach ~0.1 Mbps which allows data transmitting within 24 hours.

Space Segment Description

The envelope size of the ACE spacecraft is 84 cm x86 cm x90 cm (folded state) with ~98.2 kg in weight. Table 1 displays the mass and power budgets of the spacecraft. A system context diagram of the mission and a model layout are shown in Fig. 4. Brief descriptions of ACE's subsystems are as follows:

Table 1. Mass and power budgets.

ACE Subsystem	Mass (kg)	Power (W)
SMS	39.65	0
TCS	3.82	10
AOCS	19.2	26.75
EPS	24.8	10
C&DH	0.9	2
TT&C	4.8	100
Payload	0.36	3.5
Sum	93.53	152.25
Margin	4.68	30.45
Total	98.21	182.7

➢ **TCS (Thermal Control Subsystem):** The thermal design of ACE will mostly be passive, except for those of payload (camera) and TT&C. Heat pipes and pumps will be implemented to dissipate the heat of LNA of TT&C and CCD of the camera. TEC will be used to prevent CCD from the occurrence of dark current.

➢ **Propulsion:** The propulsion system implements the maneuvers of ACE for approaching and moving away from Apophis. The spacecraft uses four 20N monopropellant hydrazine (N_2H_4) thrusters with 8-kg propellant for propulsion amounted to a total Δv of 181.5 m/s.

➢ **SMS (Structural and Mechanical Subsystem):** The dimensions of ACE are 84 cm x86 cm x90 cm when in the folded state. The main structures are rails and panels, which are both made with Al-7075-T6. Antenna and solar panels will be deployed after ACE is released from the rocket.

➢ **EPS (Electrical Power Subsystem):** EPS consists of a solar panel, battery, power distributor, power controller. EPS and C&DH are strongly correlated as EPS sends data (e.g., voltage, current, temperature) to C&DH and C&DH sends switching command (ON/OFF) to EPS.

➢ **TT&C (Telemetry, Tracking, and Control):** A multi-band transceiver will be used for data telemetry (S/X band) and receiving command and sending beacon signals (UHF band). S and X bands share a common 2-meter deployable dish antenna. The spacecraft connects to the Deep Space Network (DSN) for its well-developed service and infrastructure. JPL's Iris transponder or another multi-band transceiver as competent as Iris will be an ideal candidate for ACE.

➢ **C&DH (Command and Data Handling):** C&DH includes a real-time clock and a mass storage memory.
➢ **ADCS (Attitude Determination and Control Subsystem):** The ADCS board contains an attitude sensor and actuator interface assembly (actuator drivers and electronic circuits for sensor interfacing). External components connected to the ADCS board are a reaction control system, star tracker, and momentum wheel.
➢ **Payload:** The payload consists of a camera, data compressor, and memory. High resolution images will be taken by the camera, processed by the data compressor, and then stored in the memory temporarily.

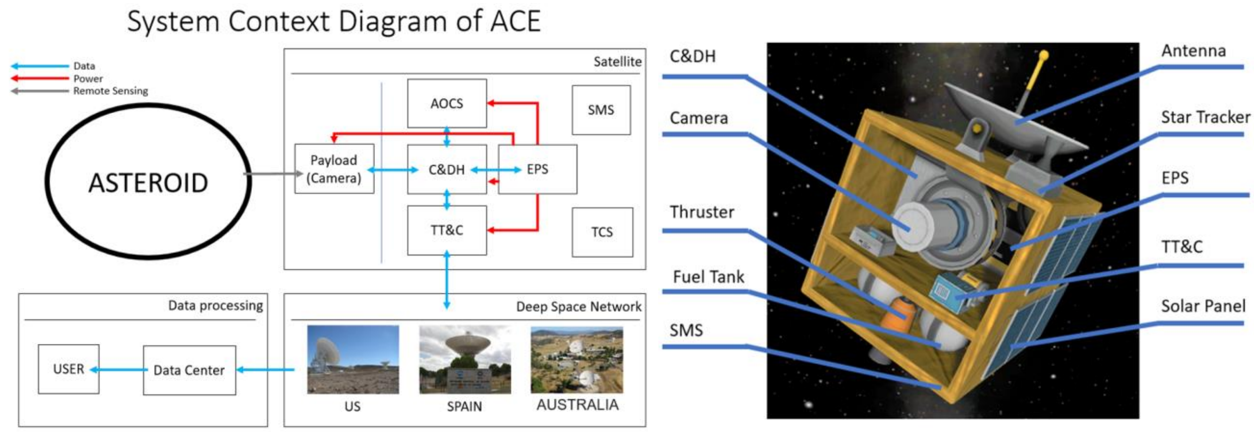

Figure 4. A system context diagram of ACE (left) and an illustration of ACE spacecraft layout (right). The system context diagram defines the boundaries and shows the relations between the systems and its environment in the mission.

Additional considerations

Our mission ACE resonates with the *SDG (Sustainable Development Goal) 9: Industry, Innovation, and Infrastructure* and the *Vision of UNISEC-Global "2030-ALL": university students in all countries can participate in practical space projects*. First, the primary goal of ACE is to advance our understanding of PHAs. The design and practice of this mission will certainly enhance scientific research and upgrade the technological capabilities of industrial sectors in Taiwan (Target 9.5). Second, the majority of the ACE team is university students from Taiwan. The development of ACE will be very stimulating to Taiwanese space communities and encourage other university students to get involved in practical space missions.

References

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