Title: PARS: Precursor Asteroid Remote Survey
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Organization: METU, ITU and YTU
(×) We apply for Student Prize.

Mission Objectives (where and why?)

Asteroids that have been attracted by the Earth's and other nearby planets' gravitational pull resulting with close encounters are ones of the most important near-Earth objects (NEOs). These leftover structures are from initial formation of inner planets such as Mercury, Earth, and Mars and they carry information from the earlier times of our Solar System. So, if the humanity desires to know more about its own existence in the cosmos, these "precious gemstones" must be investigated via the aid of cutting-edge technology, science, and engineering. Furthermore future economies of the Earth, interplanetary travels will be dependent on asteroid-based mining operations since the raw materials found in asteroids are rich and various [1]. Last but not least, we, humanity must be cautious about the potential threats from these rocky structures since a possible collision can bring end to the known life on the Earth. Deflection strategies are widely investigated in the literature and the determination of interior structure for these potential threats play an important role in these studies since without knowing how their interior are composed, an appropriate deflection strategy cannot be established.

Purpose of the Precursor Asteroid Remote Survey mission is to understand the effect of tidal forces, investigate the internal structure and also demonstrate a precursor assessment mission for the future deflection missions.

99942 Apophis, shortly Apophis, which is originated from the word Apep, the serpent of chaos in Egyptian mythology, is one of the most famous NEOs after its discovery in 2004 by Tucker and Tholen. Initial studies raise the concern of impact threat especially in 2029 when Apophis comes closer than 40.000 km. Even though the latest studies showed that our world is safe from Apophis for more than 100 years [1,2], when we consider how close Apophis comes near the Earth, it becomes obvious that this asteroid is to be one of the most important test-benches for future's asteroid exploration, investigation and deflection strategies.

Our goal is to send a micro-sized satellite to Apophis asteroid, which can both accomplish scientific exploration, investigation and can provide us information for deflection strategies via providing information about the interior structure of Apophis using state-of-the-art, on-orbit laser Doppler vibrometry (LDV) technology that is to have large impact in near-future asteroid exploration studies [3]. We aim to demonstrate such a small satellite system can be used on-orbit for achieving both of the goals mentioned without carrying any large-sized equipment such as seismometers and other ground-coupled instruments. The mission objectives are understanding the effect of tidal forces of Earth on the Apophis during the flyby, comprehending the internal structure, estimating the gravity field, observing the dynamical behaviour and topography and demonstration of a precursor assessment mission for the future deflection missions.

Scientific impact: Understanding the effect of tidal forces and the internal structure may provide valuable information related to early phase of the Solar System, and may help to understand the origin of planets, asteroid belt, the shape evolution of the fly-by asteroids and even the origin of life on Earth. Also, internal structure is crucial for the asteroid deflection missions. Since the kinetic impactor technique is the most promising deflection method among the others due to the simplicity and technological readiness, the assessment of the efficiency of this method is important and this can be acquired from the internal structure. Then, the deflection mission can be designing according to this knowledge.

Technological impact: Recently, a way to measure seismic activity from the orbit is proposed with use of LDV [3]. In our mission proposal, aim is to demonstrate LDV is to eliminate lander seismometer requirement, which reduces the cost and complexity of the mission.

Social impact: Our mission proposal serves to the planetary defense. It has obvious social impact in terms of saving the world. Also, this proposed project can be carried out in cooperation with space agencies and universities to raise awareness of the space science and exploration. Especially in Turkey, this kind of projects could lead lots of young people and children to interest in science.

Economical impact: Asteroids may include valuable resources for different purposes. Increase in the resources may have impact on Earth's economy. In this sense, mining operations may have economical impact. Investigation of the internal structure may provide some insight on whether asteroid includes precious resources or not, and indeed this gives an idea for the future asteroid mining missions.

Concept of Operations including orbital design

In order to fulfill the mission objective, the spacecraft will meet with Apophis and start taking measurements before the close approach of the Apophis to the Earth. In the transfer orbit design, Lambert problem is solved with different departure and arrival dates for one year period before the Apophis enters the SOI of Earth. Since the departure delta-v is provided by the launcher, the departure and arrival dates for minimum arrival delta-v is chosen in our orbit design. The orbital transfer is scheduled to begin on the 14th of April, 2028. The launcher delivers the spacecraft into deep space trajectory orbit with excess velocity as about 5.5 km/s. Since the total launch mass is 82.3 kg, reauired delta-v is within the limits of launcher provided delta-v with a maximum of 9km/s for this mass. After departure from the launcher, the spacecraft is to execute its commissioning phase for ensuring all systems operate in optimal condition. Then, after a relatively short cruise, the spacecraft is to use its ammonium dinitramide-based chemical propulsion, aka high performance green propulsion (HPGP) in order to inject the satellite into 2 km above the Apophis' orbit which is mission orbit. The mission orbit is defined such that the satellite will perform mission objectives. Due to the orbital perturbations such as solar radiation pressure, third-body perturbations and non-uniform gravity field of the asteroid, we need to make station-keeping maneuvers to remain on the mission orbit. The duration of the orbit transfer was calculated as 358 days. Illustration of the CONOPS diagram and the transfer orbit in GMAT (General Mission Analysis Tool) are given in Figures 1 and 2 respectively.

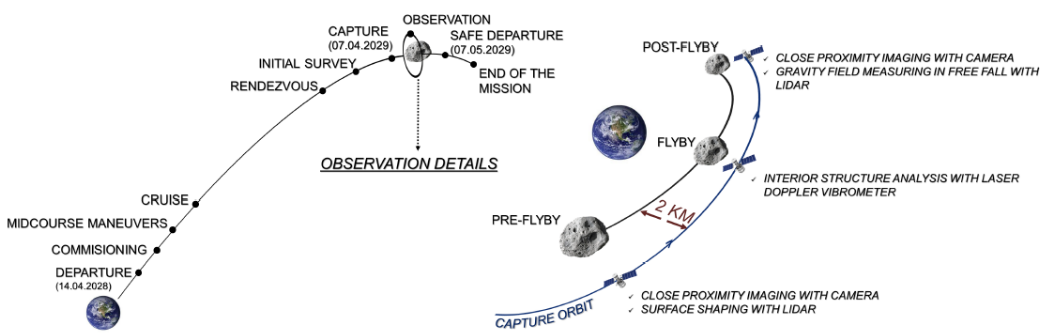

Figure 1: Concept of Operations (CONOPS) Diagram of Proposed Mission

The spacecraft will remain in the mission orbit for 1 month. The mission orbit is designed in such a way that the spacecraft will remain nearly at a distance of 2 km to the Apophis within 1 month. We have divided the missions in this orbit, which will be reached before the near-earth transition of the Apophis, into 3 phase which are described below.

Pre-flyby Observation: To observe the tidal effect of the Earth on Apophis, before flyby, surface is to be imaged closely. Moreover, surface shaping is to be done simultaneously via the use of LIDAR. While keeping the spacecraft at a constant distance, the entire surface can be scanned in the 5 days before the flyby by the help of the rotation of the Apophis.

Flyby Observation: It is thought that vibrations will occur on the Apophis during the flyby due to the gravitational effect of the Earth. In the meantime, we will take measurements with laser Doppler vibrometry by staying in orbit at a fixed distance to the Apophis. Since the seismic waves caused by the vibrations propagate with different frequencies in different elements of Apophis, the measurements taken from the LDV will enable us to understand the internal structure of the Apophis.

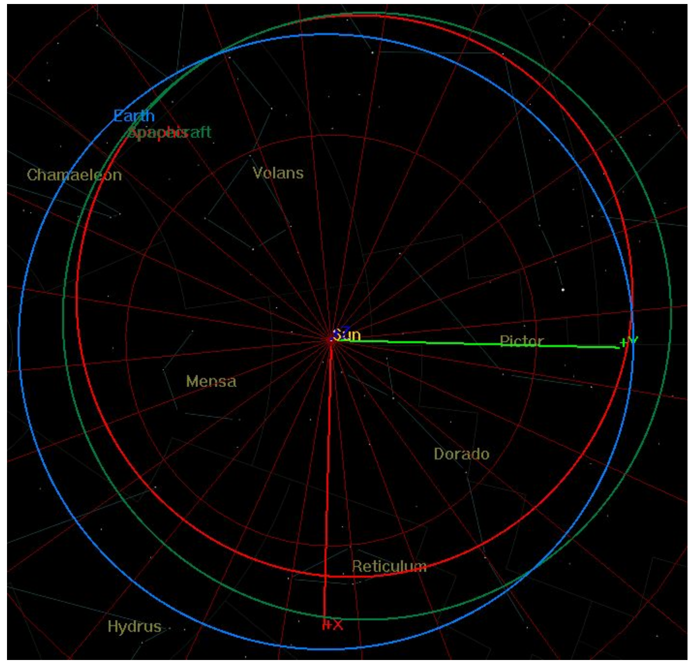

Figure 2: Illustration of the transfer orbit in GMAT. Blue, red and green orbits are the orbits of Earth, Apophis and spacecraft, respectively.

Post-flyby Observation: It is planned to observe the tidal effect with the images taken after the flyby and compare them with pre-flyby measurements. In addition, the gravitational field of Apophis will be measured as the spacecraft descends enough to enter the gravitational field of Apophis and is in free fall. Altitude change during free fall will be measured with lidar. Gravity field information of Apophis will be obtained using altitude change during free fall at different locations on Apophis. Besides, spin rate and position data of Apophis will be obtained precisely during the close-proximity operations.

Key Performance Parameters

Laser Doppler Vibrometer (LDV): LDVs, widely used in industry (such as aerospace, acoustics, automotive,...) for making non-contact vibration measurements from surfaces via the aid of the Doppler effect (Doppler shift) on a reflected laser beam, have been recently proposed for the space missions aiming to obtain adequate information about the interior of asteroids and comets by Sava and Asphaug [3]. Figure 3 summarizes the basic principles of operation behind the LDV technology as follows where BS is abbreviation for beam-splitter. Although, LDVs are proposed theoretically for future's space missions [4], none of them are used in a detailed project proposal. Therefore, realization of this novel technology should be explained clearly here since it is one of the most critical technologies for success of this mission. Highlight of key performance capabilities and design features can be listed as; Eliminating the requirement for using landers and coupled seismometers, On-orbit data acquisition, Not relying on sensitive mechanical components but electronics and With advancements in engineering and technology, data acquisition can be done at much longer distances ($\sim 2km$) with smaller mass/volume/power instrumentation. It should be noted that for the success of LDV operation, following requirements and constraints to be appeared. Size and resolution constraint appear as seismic wavelength resolution available from 0.3-30km diameter small body of arbitrary shape structures [3]. The satellite should operate the mission from determined science orbit (2km) with a pointing accuracy of $\pm 0.01^{\circ}$. Increasing orbital velocity of the satellite to degrade the

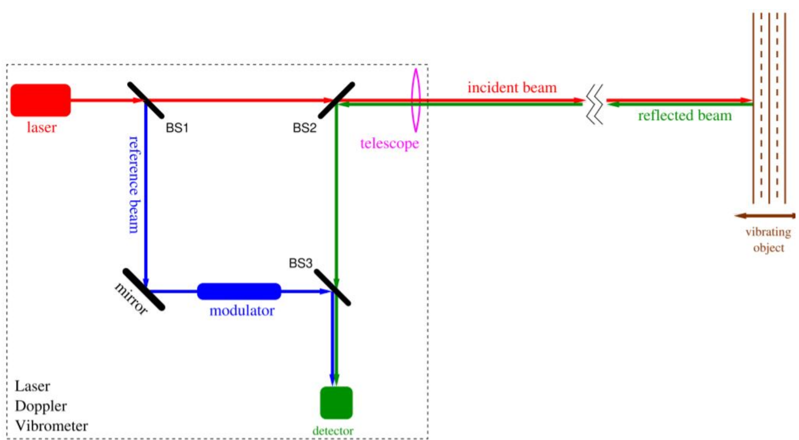

Figure 3: Key Components of a LDV system and Operation Principle [3]

data accuracy. Number of signals recorded should be high enough for data accuracy. Data transmission rate should be optimized with increasing data recording rate. Rough surfaces may lead contamination in data, data recording avoidance or multiple signal detector combinations are required (speckle noise reduction) [5].

Small-Sized Light Detection and Ranging (LIDAR): Ultra-compact LIDAR can be used for science applications including topology and terrain mapping, surface compositional mapping and for navigation, communication, proximity operations and 3D imaging. Fibertek 2U Cubesat LIDAR concept design includes long-range and short-range capability, that is, it has multi-function capability. Long-Range capability supports ranging 1m to 100km and allows precise 3D positioning. It also enables finding/-tracking objects far away. Short-Range capability allows operating over a 60 degree cone up to 500m for rendezvous and 3D imaging [6]. Highlight of key performance capabilities and design features are ready-for-use sensors and space-qualified electronic technology, ultra-low size, mass and power consumption, wide field 3D imaging LIDAR for proximity operations, astrodynamics studies, exterior shape analysis, terrain mapping and the gravity measurement operations [7] can be done with lower mass/volume/power instrumentation. In addition, following parameters to appear as key performance constraints and requirements. The satellite should be able to obtain data with LIDAR from 2km to 100km range with average $\sim 15-20cm$ range resolution. Up to 10-degree cone angle is required for appropriate scanning of asteroid surface with LIDAR.

Space Segment Description

Table 1: Overall Summary of Components

	Mass (kg)	**Size (m×m×m)**	**Power Consumption (W)**
Payload			
Fibertek 2U LIDAR	2	0.1×0.1×0.2	14.3
Malin Space ECAM-C50	0.356 (with optics)	0.078×0.058×0.044	1.75 (idle), 2.5 (imaging)
Optomet NOVA SWIR LDV	3 (min.) - 8 (max.)	0.380×0.180×0.148	27
Power Systems			
ABSL Li-Ion Battery	0.98	0.098×0.086×0.060	
DHV Solar Panel	3.5	0.70×0.70	
AOCS Systems			
Blue Canyon RW1	3 (4 Reaction Wheels)	0.11×0.11×0.038	9 (each)
Innalabs Polaris IMU	2	0.112×0.132×0.145	10
Adcole Space Star Tracker	0.282	0.055×0.065×0.070	3
Solar MEMS Sun Sensor	0.150 (6 Sun Sensors)	0.040×0.030×0.012	0.036 (each)
Bradford 100mN Thruster	0.32 (8 Thrusters)	Length: 0.055	8 (each)
Bradford 22N Thruster	1.1	Length: 0.26	50
Extended HPGP Fuel Budget	44		
Communication			
PROCYON's Transponder	6.60		85
Structure and Safety Margin	10		

In order to accomplish the mission, the instruments are selected as given in Table 1. The total launch mass with the safety margin is calculated as 82.3 kg satisfying the mass constraint of 100 kg. The spacecraft structure was calculated considering the safety margin as 10 kg. Since the departure delta-v 5.4905 km/s is provided from the launcher as it mentioned before, no change in mass is expected. The delta-v required for the satellite to reach Apophis and enter the mission orbit is 1.3112 km/s. Fuel consumption is considered by assuming that the Bradford 22 N Thruster will provide 22 N force during the satellite's arrival. Since the specific impulse of the thruster is 250 seconds, the required fuel mass is 34 kg and burn duration time of the arrival is 3693 seconds. The remaining 10 kg fuel will be used for orbit correction maneuvers and momentum dumping. ADCS consists of mainly 4 modes. The task of the angular rate damping mode is to detumble the spacecraft after separation. The spin stabilization will be used during the cruise. Safe mode will be activated when energy level is low. The three-axis stabilization will be used to control the attitude during the mission. The pointing accuracy in the three-axis mode is expected to be less than 2 arcsec by the help of fiber optic gyro, star tracker and 3 reaction wheels. This will enable us to perform the desired scientific operations during the close-proximity. Most of the time, the spacecraft will be located in between the Sun and Apophis. This will give the possibility for panels to see the Sun during the nadir-pointing scientific operations. For the Earth communication, the spacecraft will be headed to the Earth in three-axis mode and will send-receive the signals by the Deep Space Network. While Table 1 demonstrates the overall summary of the instruments used in this mission, according to our analysis and Table 2, the selected solar panels can produce 300 W and, battery and the solar panels will be sufficient to accomplish the mission's power demand.

Table 2: Maximum Power Requirements for Various Operations

Operations	**Max Power Requirement (W)**
Commissioning	185.2
Cruise	132.2
Rendezvous firing	185
Observation set 1	66.8
Observation set 2	79.5
Observation set 3	93.8
Scientific Data Transmission	135
Orbit Correction	199.3

In the Figure 4, preliminary CAD model is given. The scientific instruments are all located at the bottom of the spacecraft, attitude thrusters (red coloured) located on the satellite for momentum dumping of reaction wheels around each axis. Dimensions are decided as initially, they can be changed during detail design.

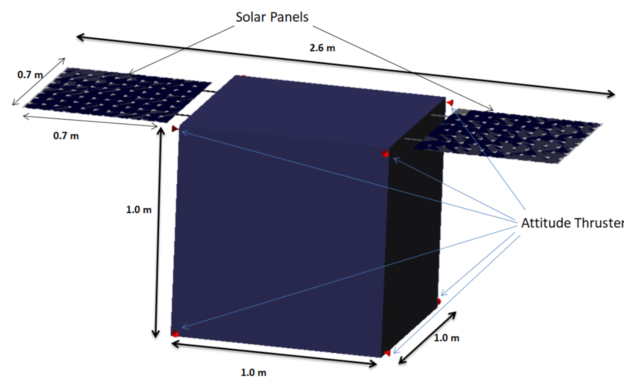

Figure 4: CAD Model of Micro satellite

Additional considerations

The novelty of this mission is originated from basically two important points. First, the use of laser Doppler vibrometry as an orbital seismometer without any ground-coupled instruments and the second one is to use such small mass/volume/power ratio instrumentation (e.g. our 2U LIDAR that can accomplish the same objectives as OSIRIS-REx does) in order to complete mentioned objectives, providing us the information of early solar system and defending our world again threatening asteroids.

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