MIT Project Apophis: Executive Summary
The SET Mission
Surface Evaluation & Tomography

On April 13, 2029, the asteroid Apophis will pass by Earth at approximately 1/10 Lunar distance. This is a once-in-a-thousand year event in which nature is providing a direct experiment revealing how asteroid surfaces and interiors respond to tidal stress.

The asteroid Apophis is named after the Egyptian god of chaos and evil who was thwarted by the god Set riding a solar boat. Like Set, Mission SET will ride upon Solar Electric Propulsion to meet Apophis at which time the spacecraft will characterize the asteroid inside and out before and after the Earth flyby event.

Launch: August 2026
Apophis Rendezvous: March 2028
Earth Flyby Event: April 2029
Tracking Mission Ends: 2033

The SET Mission: Spacecraft and Instruments

LORRI:
Pan-Chromatic (B&W) High Resolution Imager

Ralph:
Color & Spectral Imager

TES:
Thermal Emission Spectrometer

RRT:
Radio Reflective Tomography

The SET Mission: The Objectives

Mission Objective 1: Bulk Physical Properties
Focussed on the surface properties and orbital characteristics, this objective will improve the scientific community’s understanding of asteroids as well as inform planetary defense strategies.

Mission Objective 2: Internal Structure Changes
Measuring the internal structure of Apophis before and after an Earth Close Encounter will allow for a better understanding of not only how asteroids are constructed, but how tidal stresses affect them.

Mission Objective 3: Yarkovsky Tracking
By following Apophis for multiple orbits and measuring the thermal emissions and orbital characteristics, the components of the Yarkovsky Effect can be decoded, improving our ability to track this Potentially Hazardous Asteroid.

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1 Scientific Motivation

Achieving an understanding of asteroids and their impact hazard is one of the great responsibilities and grand challenges of our era. Natures is cooperating by providing a once-per-thousand year opportunity to study the outcome of an extremely close passage by an unprecedentedly large 350 meter (aircraft carrier-size) 20 million metric ton asteroid name Apophis on (Friday) April 13, 2029. Apophis’ close encounter will be inside Earth’s geosynchronous satellite ring at a near-miss distance of 5.6 Earth radii, less than one-tenth the lunar distance. While previous spacecraft missions have studied asteroids, none has ever had the opportunity to study “live” the outcome of planetary tidal forces on their shapes, spin states, surface geology, and internal structure. All of these physical parameters, and their changing response to induced stresses, represent an incredible opportunity to gain vital knowledge for addressing the eventuality of a known asteroid on an actual impact trajectory. In response to the imperative for knowledge and the once-per-many generations extraordinary “experiment” that nature itself is providing, we propose and outline a mission concept sending a spacecraft to orbit Apophis with the objectives of surveying its surface and interior structure before, during, and after its 2029 near-Earth encounter. The asteroid Apophis is named after the Egyptian god of chaos and evil. The proposed spacecraft is named SET, for the Egyptian god (Set) sent on his solar boat to thwart Apophis.

In recent decades, understanding of asteroids has been transformed from points of light to geological worlds owing to modern spacecraft exploration and state-of-the-art radar and telescopic investigations. Yet internal geophysical structures remain largely unknown. Understanding the strength and internal integrity of asteroids is not just a matter of scientific curiosity, it is a practical imperative for advancing
knowledge for planetary defense against the eventu-
ality of an asteroid impact.

The April 13, 2029 near-Earth flyby of Apophis
will provide the opportunity for internal geophysical
study as well as to test current hypothesis on the ef-
ccts of tidal forces on asteroids. Mounting theoreti-
cal studies [4, 7, 10, 12, 11, 13, 14] and phys-
cal evidence [1, 6], for tidal forces altering the shapes,
spins, and surfaces of near-Earth asteroids all point to
these Earth-asteroid interactions being as fundamen-
tal to the asteroid hazard problem as impact studies
themselves.

The SET mission is motivated by additional fac-
tors and science objectives beyond the unique natural
experiment opportunity. By including a thermal in-
strument and continuing to orbit Apophis after the
Earth encounter, SET will be able to monitor and de-
code the coupling of rotation and thermal cycling re-
sulting in Yarkovsky drift. Direct correlation of ther-
mal properties with the resulting Yarkovsky drift is
important for both future orbit predictions of Apophis
as well as improving general understanding of asteroid
dynamics. The SETs orbiter will also be able to map
Apophis’ global geology and composition and study its
interior structure, increasing knowledge of mid-sized
(100s of meter diameter) asteroids. Spacecraft stud-
ies of asteroids can provide insight into the geologic
and dynamic history of the objects they study and
not only improves our understanding of these individ-
ual objects but also has important implications for
understanding solar system formation [5].

2 Mission Objectives

The SET mission achieves its science and hazard
assessment goals through three key Mission Objectives
(Table 1).

M.O.1 General Characteristics

The first mission objective focuses on the char-
acterization of Apophis’ bulk properties, including:
shape, size, mass, volume, bulk density, surface topo-
graphy and composition, rotation rate, and spin
state and encompasses the surface geology and com-
position mapping goals. Surveying Apophis’ surface
geology and composition will help with under-
standing Apophis’ geologic and dynamical history. Ob-
servations of these properties from throughout the en-
counter can be used to look for signs of tidal de-
formation and seismic resurfacing, as well as changes in
spin state or rotation rate.

M.O.2 Internal Structure

The second mission objective is to characterize the
internal structure before and after encounter. The
strength and cohesion of Apophis’ interior can be de-
termined from observations of Apophis’ interior struc-
ture and how it responds to the tidal torques from the
Earth encounter event. This is useful information for
both general asteroid studies and has implications for
impact scenario modeling and planetary defense.

M.O.3 Orbit Characterization

The final mission objective studies the process of
Yarkovsky drift. Post-encounter the spacecraft will
continue to monitor Apophis until the next ground
tracking opportunity in 2036. These synoptic mea-
urements of position, rotation, and thermal emission
will help decode the coupling of rotation and thermal
cycling resulting in Yarkovsky drift. This will improve
future orbit determination for Apophis and all poten-
tially hazardous asteroids.

3 Science Payload

SET’s science goals and mission objectives are ac-
complished with four instruments. The mission lever-
geases heritage (with instruments based on those flown
on the New Horizons, OSIRIS-REx, Mars Reconnais-
sance Orbiter, and Lucy missions) to provide a capa-
ble, robust instrument suite while keeping cost and
risk low.

3.1 LOng Range Reconnaissance Im-
ager (LORRI)

LORRI is a 20.8 cm Ritchey-Chrtien telescope
with a 1024x1024 pixel panchromatic CCD imager
(with a 0.29° × 0.29° field of view) [2]. It will be the
first instrument to be able to resolve Apophis during
the spacecraft’s approach. During this time it will
work on improving upon ground-based measurements
of Apophis’ rotation rate, spin state, and shape, while
also looking for potential hazards. Once the space-
craft is orbiting Apophis, LORRI will be responsible
for high-resolution imaging of Apophis’ surface, with
0.0099m/pixel resolution at a distance of 2km from
the asteroid’s surface.

3.2 Ralph

Ralph consists of a panchromatic and color imag-
ing camera (MVIC) and a special imager (LEISA).

Multi-spectral Visible Imaging Camera
(MVIC) consists of 7 independent CCD arrays on a
single substrate to produce panchromatic and colored
images. Each CCD has a field of view of 5.7° × 0.037°,
but works in time delay integration (TDI) mode to
produce images with a much wider view [9]. MVIC
will be responsible for broad panchromatic mapping
of Apophis’ surface once SET is in orbit, as well as
color and broad band spectroscopy mapping, to look
for signs of seismic resurfacing during Apophis’ flyby
of Earth.

Linear Etalon Imaging Spectral Array
(LEISA) is a wedged filter infra-red spectral imager
that creates spatially resolved spectral maps. LEISA
is a scanning, imaging instrument, that makes use of
a special filter over which the wavelength varies in one direction. With wavelength coverage from 0.45 to 4.0µm, spatial resolution of 60.8μrad, and a 0.9° × 0.9° field of view [9], LEISA will reveal compositional heterogeneities and any changes in surface composition that may be triggered by Apophis’ tidal interaction with the Earth.

3.3 Radio Reflection Tomography Instrument (RRT)

The RRT instrument for SET will be based on the SHARAD instrument used on the Mars Reconnaissance Orbiter, and will consist of a 10m dipole antenna that can be folded for launch, and deployed solely with the elastic properties of the encasing tube, as well as an electronics box for signal generation and power amplification [8]. This method measures the differences in dielectric properties of materials in the asteroid by recording the echoes of transmitted low-frequency radio waves, thus providing a way of imaging the internal structure. The RRT instrument will have a transmission frequency of 20MHz and a bandwidth of 5MHz. Assuming a refractive index similar to Itokawa, this bandwidth will provide a spatial resolution of approximately 20m, a similar size to the Chelyabinsk meteoroid and thus significant from a planetary protection perspective.

3.4 Thermal Emission Spectrometer (TES)

TES will consist of a telescope, interferometer assembly, electronics, and support structure and achieves its spectral range by implementing an interferometer, beam splitter, and moving mirror assembly [3]. TES will map mineralogical and thermophysical properties of Apophis with a spectral range of 6 to 100µm. TES uses a single detector with a field of view of 8µrad, so at a distance of 2km it will have a field of view on Apophis surface of roughly 16m × 16m. TES can provide insight into Apophis mineralogy, globally map the material distribution, and determine regolith physical properties based on diurnal temperature measurements [3]. Most importantly, the thermal measurements from TES, combined with imaging and ground-based radar tracking, will help decode the coupling of thermal cycling and rotation which results in Yarkovsky drift, which will aid in not only refining future predictions of Apophis orbit, but also the orbits of other potentially hazardous asteroids.

4 Spacecraft

SET will utilize a LEOStar-3 bus, manufactured by Orbital ATK, which has heritage on the Dawn and Deep Space 1 missions (Figure 3.4).

Spacecraft Specifications:
- Length: 1.8m (10m w/ RRT antenna deployed)
- Width: 1.8m (18.6m w/ solar panels deployed)
- Height: 2m
Figure 1: CAD Model of SET spacecraft layout. The instruments are all located at the top of the spacecraft to allow them to be used simultaneously. The RRT antenna and solar panels fold and are deployed after launch. (CAD Model by: Amy Vanderhout)

Figure 2: Proposed timeline of operations for the SET mission.
- Dry Mass: 633.5kg
- Wet Mass: 1024.5kg
- Power: two Orbital ATK Ultraflex solar panels

5 Concept of Operations

The SET Mission will launch in August 2026 within a 6 week launch window, with a back up launch window in August of 2027 (Figure 2). The spacecraft will calibrate its instruments as it exits the Earth’s Sphere of Influence and will use Solar Electric Propulsion (SEP), to gradually match its orbit with Apophis during the plane change and phasing orbit phase. In March 2028, the spacecraft will rendezvous with Apophis at its aphelion and begin the Approach I phase. During the Approach I phase the spacecraft will begin imaging with LORRI and then MVIC. This slow approach allows time for initial science observations and progressively maps the gravity field as SET enter Apophis’ sphere of influence.

Once the spacecraft is 2km from the center of Apophis, it will enter a terminator orbit, beginning the Terminator I phase. This phase will consist of 15 orbits at 2km, which are estimated to last for 48 days, and will serve as the initial characterization campaign of Apophis’ surface for Mission Objective 1. Next, SET will enter Approach II and spiral down from the 2km orbit to a 500m orbit. For Terminator II, SET will orbit apophis in a 500m terminator for 30 days, ideal for the RRT instrument to study Apophis’ internal structure for Mission Objective 2.

The spacecraft will then transfer to leader-follower position to prepare for Apophis’ near-Earth flyby. For the Leader-Follower phase, SET will move to a position 20km ahead of Apophis, in order to observe Apophis from a safe distance and favorable viewing geometry during it’s near-Earth flyby.

After the Earth Flyby Event, the spacecraft will complete a second set of Approach and Terminator phases to complete a second characterization campaign. Ideally, these phases would use the same orbital characteristics as before, using the imagers in the 2km orbit, then the RRT instrument in the 500m orbit. However, since there is uncertainty in the effect of Earths tidal forces on Apophis during the event, these details cannot be set for sure until after the encounter.

Once the second full characterization campaign is complete, the spacecraft enters the Long-Term observation phase, and will stay in formation with Apophis while using TES and the imaging instrument to decode and evaluate the Yarkovsky effect. The plan is to stay in formation with Apophis for at least 7 years. Finally, for the End of Mission phase, SET will perform an exit burn to leave Apophis sphere of influence, entering its own heliocentric orbit, compliant with all constraints for planetary protection.

6 Conclusions

The SET mission will take advantage of the incredible opportunity nature is providing to study the impact of tidal interactions on potentially hazardous asteroids. The mission will launch August of 2026 and arrive at Apophis in March of 2028, allowing for thirteen months of initial characterization before the April 13, 2029 Earth encounter event. The SET mission shows that a scientifically robust mission is well within the range of currently available high heritage proven flight hardware and launch capacity. The science results can directly inform future studies of asteroid impact mitigation, including long-term tracking correlating measured thermal emission and the corresponding Yarkovsky drift.

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References


