

Lessons from OSIRIS-REx applied to NASA's Apophis Explorer mission design

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Abstract

The highly capable and healthy spacecraft and instruments used by NASA's OSIRIS-REx mission are now en route to asteroid Apophis, flying a new mission called OSIRIS-Apophis Explorer (APEX). The APEX mission provides an opportunity to directly incorporate lessons learned from the proximity operations campaign at Bennu and improve operational efficiency. At the same time, Apophis has some important differences from Bennu, such as a longer rotation period and non-principal axis rotation, so the APEX mission design necessarily differs from that of OSIRIS-REx. For example, the OSIRIS-REx concept of operations involved a series of weekly hyperbolic flybys optimized for a single observation geometry, with individually customized observations that occurred over a few-hour period. APEX will instead observe modularly every few hours as the spacecraft slowly moves through multiple observing geometries to build up coverage while Apophis rotates and precesses. Like OSIRIS-REx, the APEX mission is split into phases that are each focused on meeting specific objectives. Some of these phases are directly analogous to OSIRIS-REx phases, whereas others address similar goals but differ in strategy. The lengths and order of the phases reflect lessons learned from OSIRIS-REx.

Keywords: Apophis, asteroid, deep space operations, mission design, small body

Acronyms/Abbreviations

Design Reference Asteroid (DRA)

Design Reference Mission (DRM)

Origins, Spectral Interpretation, Resource Identification, and Security-Regolith Explorer (OSIRIS-REx)

OSIRIS-Apophis Explorer (APEX)

concept of operations (ConOps)

stereophotoclinometry (SPC)

Baseball Diamond (BD)

Equatorial Stations (ES)

non-principal axis (NPA)

Spacecraft Thruster Investigation of Regolith (STIR)

Touch and Go (TAG)

1. Introduction

The Origins, Spectral Interpretation, Resource Identification, and Security-Regolith Explorer (OSIRIS-REx) spacecraft characterized and sampled the asteroid (101955) Bennu, completing its nominal mission with delivery of the sample to Earth on September 24, 2023 [1,2,3]. Twenty minutes after releasing the sample, the spacecraft diverted into an orbit around the Sun that allows for subsequent close Earth flybys. On this trajectory, the spacecraft will fly by Earth 1 hour after asteroid (99942) Apophis makes its own dramatic close Earth approach on April 13, 2029, enabling a mission to another small body using the same intrepid spacecraft and state-of-the-art instruments that led to OSIRIS-REx's groundbreaking scientific results: OSIRIS-Apophis Explorer, or "APEX" [4]. The spacecraft will characterize Apophis over 18 months in 2029 and 2030.

The initial mission design and planning for APEX was undertaken during the 2022 NASA Senior Review for Planetary Science. This gave the team an opportunity to directly incorporate lessons learned from the recent proximity

operations around asteroid Bennu. However, Apophis has some key differences from Bennu that will make operations more challenging, which required tailoring the new mission to address these challenges.

2. OSIRIS-REx challenges and lessons learned

The ambitious plan for operations at asteroid Bennu included high-resolution global mapping of the asteroid from many different viewing and illumination geometries, followed by extremely high-resolution (sub-centimeter) regional characterization, sample site selection, and sample collection [2,5]. The two years of proximity operations at Bennu was split into multiple mission phases (detailed in Section 4) that each had their own custom-built trajectory and bespoke observation designs to address specific objectives.

Preparation for operations at Bennu began with the creation of a Design Reference Mission (DRM) early during mission development to guide the design of the OSIRIS-REx flight and ground systems. The DRM documented the planned spacecraft trajectory, science observations, downlink schedule, and required science data products, so the entire team could work from the same assumptions and develop the flight and ground systems to meet requirements and execute the plan. A Design Reference Asteroid (DRA) was also essential to guiding the design of the mission. The DRA contained the best pre-encounter estimates for Bennu's orbital, rotation, photometric, spectroscopic, thermal, surface analog, and operational environment properties [6]. The DRA fulfilled the need for standard, agreed-upon asteroid properties to which to design the reference mission and allowed verification that observations would satisfy the science requirements.

To achieve the OSIRIS-REx mission objectives [1], the spacecraft had to be highly capable, and a world-class navigation team was needed to address the unique challenges posed by operating in a microgravity environment around Bennu, where forces such as solar radiation pressure and spacecraft thermal re-radiation contribute significantly to trajectory propagation errors [7]. In this environment, even very minor trajectory errors result in significant offsets to observation targeting. Due to the tight targeting constraints required to achieve the science objectives, operationally complex 24-hour ground-in-the-loop target ephemeris updates were used >140 times throughout proximity operations. Post-launch, it was determined that more of these updates would be needed than originally envisioned, which led the team to develop a flight software patch that implemented nadir and time-relative targeting, reducing the 24-hour update process from three-shift to two-shift work for the team and implementing observation pointing updates from ephemeris uploads.

The navigation effort to operate around Bennu and the science planning effort to direct the instrument observations and spacecraft slew patterns were both originally under-scoped for OSIRIS-REx due to the unprecedented complexity of the mission. Significant work was required by mission scientists and observation planners to develop observational geometry constraints that fed into the design of the spacecraft trajectory by the navigation team, followed by design of the pointing and attitude profile to meet the identified constraints. In addition, the science planning team conducted extensive sensitivity analysis of the observation designs against perturbed trajectories to ensure the designs were robust to navigational uncertainties [8]. The sensitivity analysis was used for verifying the safety of the plans (slew time and flight rule compliance analysis) as well as coverage and observation constraint analysis.

During the approach to Bennu, the team was surprised by the rocky surface of the asteroid, which required a complete rethinking of the sample site selection effort, the addition of new reconnaissance mission phases, and a change to the (more precise but less well-developed) backup navigation technique for sample collection [2]. Despite this and other surprises, the team was able to respond and complete all mission objectives. Multiple world records were achieved during proximity operations around Bennu, including smallest object orbited by a spacecraft, closest orbit of an asteroid, and highest-resolution global satellite map of any planetary body [9,10].

3. Differences in APEX operations

We turned our attention to the APEX mission proposal shortly after the spacecraft departed Bennu on the journey to deliver the sample to Earth. With the recent experience of conducting the complex operations at Bennu, the team was able to use their hard-won expertise and incorporate lessons learned to create realistic plans for Apophis early in the design of the mission. On APEX, we continue the operations organization and management structure that we used successfully on OSIRIS-REx [1]. We also incorporate the DRM and DRA concepts and keep many of the same tools and operational processes used for OSIRIS-REx [8,11,12].

The knowledge we gained from the complex operations at Bennu included a thorough understanding of spacecraft constraints, observation requirements, and navigation performance. The close coordination between navigation, spacecraft operations, and science planning achieved during operations at Bennu allowed the team to come up with comprehensive, well-thought-out plans. The team also considered human factors early in the concept of operations (ConOps) design to make proximity operations more sustainable than at Bennu.

Differences in the APEX mission plan based on lessons learned from OSIRIS-REx include:

- (1) Designing the APEX trajectories to allow a more relaxed cadence of proximity operations than at Bennu, with one maneuver per week versus three or four. The team is also considering simplifications of the maneuver design process [13].
- (2) Changes to mission phase plans to either allocate more time or consolidate mission phases (Section 4).
- (3) Planned development of a new, autonomous onboard ephemeris update capability to precisely target science observations, which will substantially reduce the operational complexity of Apophis operations relative to those at Bennu and enable adequate coverage to fulfill the science objectives [13].
- (4) Simplification of safe-mode response to avoid execution of pre-planned burns in the sunward direction upon safe-mode entry that could severely delay execution of the next mission phase and require extensive contingency planning [13].
- (5) Improvements to the processes and tools used for planning, implementation, and data processing across all mission elements, including automation of ground-based ephemeris updates [13].
- (6) The use of modular, reusable observations to reduce operational complexity instead of the individually custom-built observations used for most OSIRIS-REx mission phases. With the adoption of modular observing modes, the team will plan observations two weeks at a time instead of one week as on OSIRIS-REx.

These changes require modest investments during the cruise period to Apophis but will allow more efficient operations at Apophis, with reduced staffing levels compared to OSIRIS-REx.

4. New challenges posed by Apophis

Bennu's properties (Table 1) were well characterized prior to the spacecraft arriving [6, 14]. There is significantly more uncertainty about Apophis' properties (Table 1), such as mass and shape. In addition, the close encounter with Earth on April 13, 2029, will change Apophis' orbit and rotation state. The orbit of Apophis after the close encounter is well understood [15], and the variation in solar range will be very similar to that of Bennu, which allows us to directly translate some of the operations planning constraints from OSIRIS-REx to APEX. However, the post-encounter rotation state has a broad range of potential values [16], and the APEX mission must therefore have a robust ConOps to accommodate the possible rotation state changes [17].

The smaller expected mass and elongated, bilobate shape of Apophis will make navigation even more challenging than at Bennu [18]. The shape may also make it harder to obtain imagery of some portions of the surface with the

Table 1. Physical and orbital properties of Bennu compared with those of Apophis after the Earth encounter. Current values for Apophis are shown in brackets.

Property	Asteroid Bennu	Asteroid Apophis post-encounter [pre-encounter values in brackets]
Perihelion	0.897 au	0.89 au [0.75 au]
Aphelion	1.36 au	1.31 au [1.1 au]
Mean Diameter	490 meters	~340 meters
Shape	Spheroidal (spinning top)	Elongated, bilobate
Mass	7.329×10^{10} kg	$\sim 4 \times 10^{10}$ kg
Rotation State	Principal axis	Non-principal axis
Rotation Period	4.29 hours	~30.56 hours (18-49 hours 2-sigma)
Composition	Carbonaceous	Stony
Geometric Albedo	4.4%	29%

desired illumination. The much higher albedo of Apophis risks saturation of the detectors for the imagers, which were designed for the lower-albedo Benu, so low solar phase angles have been avoided in some portions of the mission.

Most importantly, the spin state of Apophis is non-principal axis (NPA) with a current average sidereal rotation period of 30.56 hours and precession and rotation periods of 27.38 and 263 hours, respectively [19,20]. The slow NPA rotation requires a fundamental change from the OSIRIS-REx ConOps. At Benu, the spacecraft engaged in a series of ~weekly hyperbolic flybys that were each optimized for a particular observation and illumination geometry [2]. Since Benu is in principal axis rotation with a very low obliquity, the instrument suite could observe for ~4.5 hours while Benu completed one rotation and therefore map the entire surface of Benu from a single observation geometry. With the longer and more complex Apophis rotation, it is not possible for the spacecraft to maintain its position at a single observation geometry for an entire rotation. Instead, the instrument suite will observe at regular intervals every few hours as the spacecraft moves through multiple observing geometries to slowly build coverage.

5. Mission phase design

The first few phases of OSIRIS-REx were designated the Navigation Campaign because the emphasis was on initial characterization of Benu and learning to operate the spacecraft near the small asteroid. OSIRIS-REx next transitioned into the Site Selection Campaign, which focused on acquiring detailed global observations to support the selection of a sample collection site. The Sample Acquisition Campaign that followed included characterization of the primary and backup sample sites, rehearsals for the Touch and Go (TAG) sample collection maneuver, and TAG itself [2,5].

Some APEX phases are directly analogous to OSIRIS-REx phases; e.g., both missions have an approach phase (Fig. 1). Others address some similar goals but differ in strategy; e.g., the capability to collect a sample is no longer available, so APEX will investigate the near-surface physical and mechanical properties of Apophis by excavating material using the spacecraft thrusters (Fig. 1) [4]. Whereas the objective of collecting and returning a sample drove OSIRIS-REx planning, decision-making, and risk tolerance, the focus for APEX is addressing the rendezvous science requirements.

APEX imaging will begin in March 2029 and acquire Apophis with the PolyCam instrument [21,22] as a disk-integrated point source no later than April 2, 2029, providing unresolved images before the Apophis encounter with Earth. The spacecraft will make a close approach to Earth on April 13, 2029, only 1 hour after the Apophis-Earth encounter. Observations beginning ~5 hours after the encounter will search for dust released by tidal forces on Apophis, which will inform our understanding of the degree to which transient tidal forces generate seismicity and induce surface modification at Apophis. During the Acquisition and Approach phases, we will acquire images to develop the shape model, determine Apophis' rotation state, and search for natural satellites and dust around Apophis (Table 2). APEX Acquisition and Approach is analogous to OSIRIS-REx Approach, except APEX Acquisition and Approach will include the exciting Apophis close encounter with Earth.

Preliminary Survey for OSIRIS-REx was extremely challenging due to the rapid cadence of observations and maneuvers. For APEX, we have split this phase into the two discrete phases of Gravity Survey and Triangle Survey to accomplish the analogous objectives. Gravity Survey is necessary to determine Apophis' GM to <1% before proceeding to the more challenging later phases of the mission. It consists of a set of hyperbolic flybys to measure the mass and obtain initial close-up views of Apophis. This phase will also be used to improve knowledge of the rotation state and collect observations at the right lighting conditions and viewing geometries to build a global shape model using stereophotoclinometry (SPC) to aid in precise navigation. Triangle Survey will collect a global image dataset with the right lighting conditions to produce a basemap and will provide additional imagery to supplement the shape model. We will also obtain initial estimates of bulk composition with the OVIRS and OTES spectrometers [23,24]. The Triangle Survey consists of three stations in a triangular pattern as viewed from the Sun. Observing stations occur along each of the three legs of the triangle, when the spacecraft is ~15 km from Apophis.

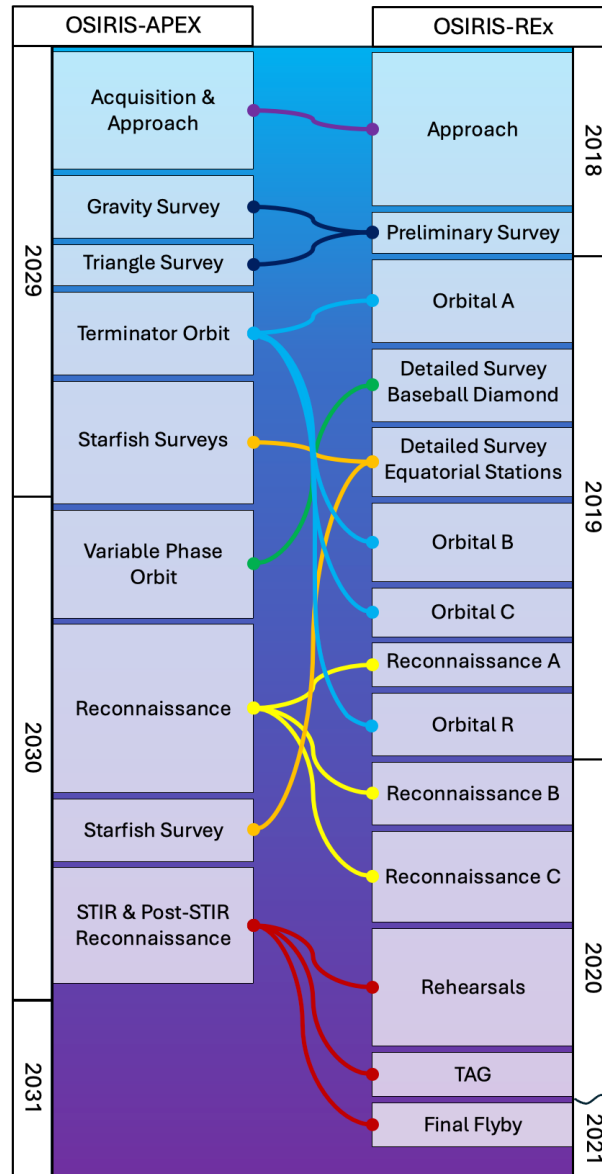


Fig. 1. A comparison of the OSIRIS-REx and OSIRIS-APEX mission phases. Lines connect the most analogous mission phases. STIR, Spacecraft Thruster Investigation of Regolith. TAG, Touch and Go sample acquisition.

After Triangle Survey, the spacecraft will enter the Terminator Orbit at approximately 1 km altitude above the surface of Apophis. This orbit will allow (1) high-spatial-resolution observations with the scanning lidar instrument, OLA [25]; (2) predawn and post-dusk observations of thermal properties with the thermal emission spectrometer, OTES; (3) initiation of the Yarkovsky measurement; and (4) a viewing geometry to search for evidence of particle shedding. The orbital configuration matches the frozen terminator orbit design that was successfully used at Bennu [26], and the planned data collection will enable estimation of second-order gravity field terms and detection of higher-order terms. This phase will accomplish what OSIRIS-REx completed in Orbital A, B, and C. For OSIRIS-REx, Orbital A was dedicated time for the navigation team to accomplish the history-making terminator orbit of a small body and for the accompanying optical navigation transition from center-finding to landmark-based optical navigation. Thanks to this prior experience, APEX does not require a dedicated orbital period for the navigation team and can proceed directly into science observation collection.

Table 2. APEX mission phase summary.

OSIRIS-APEX Mission Phase	Goal	Design Description	Length
Acquisition and Approach	Rotation state, dust and natural satellite search, initial size and shape	Earth gravity assist followed by asteroid approach maneuvers targeting a slow approach	10 weeks
Gravity Survey	Mass, shape model	Hyperbolic flybys	6 weeks
Triangle Survey	Medium-resolution basemap	Hyperbolic flybys in the shape of a triangle	4 weeks
Terminator Orbit	Shape model	Frozen terminator orbit	8 weeks
Starfish Surveys	Imagery and spectroscopy at different geometries	Hyperbolic flybys in the shape of a star	12 weeks (plus another 6 weeks)
Variable Phase Orbit	High-resolution basemap and spectroscopy	Resonant terminator orbit	8 weeks
Recon	High-resolution imaging and spectroscopy	Low-altitude sortie or resonant terminator orbit	14 weeks
STIR and post-STIR Recon	Surface modification and high-resolution imaging and spectroscopy	Near-surface sortie and low altitude sortie	14 weeks

Starfish Surveys will position the spacecraft around six waypoints and transition through local solar hours from 5 AM to 7 PM, at a distance to Apophis between 5 and 7.5 km, to collect global photometric and spectral datasets (Fig. 2). This mission phase will consist of two full passes through each of the six arcs to accumulate coverage using the MapCam color imager [21, 22], OTES, and the visible-infrared spectrometer, OVIRS. To observe seasonal variations in global spectral data, a third Starfish Survey (one pass through the six stations) will occur at Apophis perihelion (0.89 au) in August 2030; this pass will not obtain full coverage but will capture a representative fraction of Apophis. Starfish Surveys are analogous to the OSIRIS-REx Detailed Survey Equatorial Stations subphase, a 7-week period during which the spacecraft observed Bennu from a different local solar time each week. OSIRIS-REx did not include observations of seasonal variations in global spectral data, however.

Variable Phase Orbit is a resonant terminator orbit [27] with a minimum phase angle of $\sim 40^\circ$ and periapsis and apoapsis distances of ~ 600 m and ~ 4.3 km, respectively (Fig. 3). This phase will sample a wider variety of viewing and illumination geometries at higher resolution than the Starfish Surveys. It will include thermal observations of the night side of Apophis, though it will not achieve complete spectrometer coverage. The primary objective for this phase

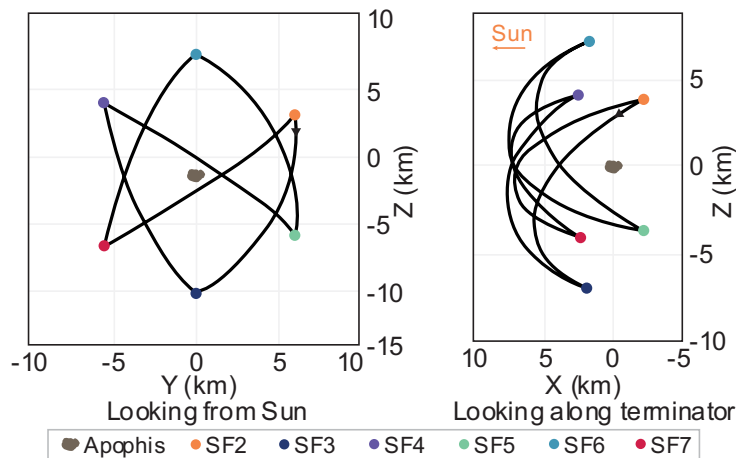


Figure 2. Graphical representation of the Starfish Survey trajectory (one set of six waypoints). The Sun is located along the +X axis. Observations occur along arcs, with maneuvers (SFs) at the junctions.

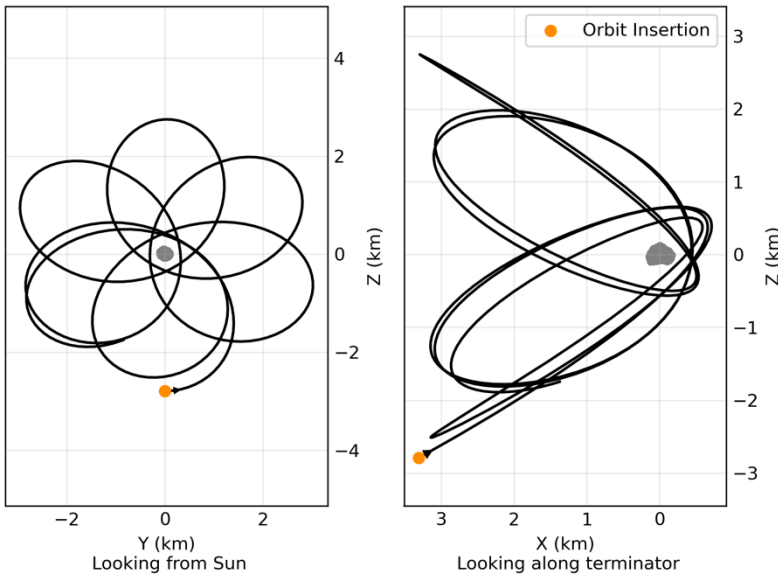


Figure 3. Graphical representation of the Variable Phase Orbit trajectory. The Sun is located along the +X axis.

is to collect PolyCam images to construct a ~ 6 cm/pixel global basemap. This phase is later in the mission than the analogous Detailed Survey Baseball Diamond subphase was during OSIRIS-REx because this phase must occur near Apophis aphelion, where the balance between solar radiation pressure and Apophis' gravity make this unique resonant terminator orbit design more stable. OSIRIS-REx's Baseball Diamond was used to acquire images for a higher-resolution SPC shape model and a global mosaic. APEX will have previously acquired high-resolution lidar data with OLA to create a shape model, so higher-resolution imagery from multiple viewing geometries for SPC is not required in this phase.

After completing global characterization of Apophis, we will transition into the Reconnaissance phase, which entails regional mapping of one or more sites of interest from altitudes of 1 km down to several hundred meters. APEX will collect high-resolution images (<0.5 cm per pixel) and spectral data (<3 m spots) at several hundred meters altitude to examine any recent surface disturbance on Apophis ostensibly triggered by tidal forces during the Earth encounter. APEX will also search for relatively undisturbed areas of the surface to select for the Spacecraft Thruster Investigation of Regolith (STIR) near-surface sortie [4]. For OSIRIS-REx, Reconnaissance was split into Recon A, B, and C. Recon A characterized four candidate sample sites, while Recon B and C mapped the primary and backup sample site in detail. Recon B was required for Natural Feature Tracking [28], and Recon C was required to confirm sampleability of the surface [29]. Due to the challenges of finding a sample site on Bennu, the Recon phases for OSIRIS-REx were completely redesigned after arrival [2]. For APEX, we have investigated using OSIRIS-REx-like Recon passes as well as a dark-side resonant terminator orbit to acquire regional detailed mapping. We expect to finalize the Reconnaissance plan once we have gathered initial data on Apophis during proximity operations.

After the Reconnaissance phase, the spacecraft will perform the STIR near-surface sortie to study the properties of Apophis' subsurface and understand Apophis' geotechnical properties. STIR will use a similar strategy to approach the surface as the TAG maneuver at Bennu. The spacecraft will descend to 2–5 m above the target site, and thruster plumes from the back-away maneuver will excavate and expose subsurface material. Because the primary objective for OSIRIS-REx was sample return, we were required to demonstrate that the spacecraft could adequately navigate to the selected site, it was safe for the spacecraft, it was sampleable, and the sample would be pristine carbonaceous material [2]. For APEX, since the spacecraft will not descend all the way to the surface during STIR and this activity is one of many objectives, the selection of a site for this near-surface sortie does not need to be as rigorous.

The spacecraft will then conduct a final Reconnaissance flyby over the site disturbed by STIR to collect high-resolution imagery and document the surface changes and newly exposed subsurface materials. OSIRIS-REx similarly

included a final flyby over the TAG site to characterize the change due to spacecraft interaction [5]; however, it was analogous to a Detailed Survey hyperbolic flyby. A Reconnaissance-distance flyby will enable more detailed study of the newly exposed surface.

6. Conclusions

Operations at asteroid Bennu were exceedingly complex and required close coordination across all mission elements to achieve success. Operations at Apophis may be even more challenging; however, the team has the benefit of experience and lessons learned at Bennu that have been applied to APEX mission design and will serve the team during the 2029 and 2030 proximity operations around Apophis.

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