OSIRIS-REx Extended Mission Trajectory Design & Target Search

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After jettisoning its Sample Return Capsule (SRC) containing regolith samples from the near-Earth asteroid (101955) Bennu to Earth in September 2023, the Origins, Spectral Interpretation, Resource Identification, and Security–Regolith Explorer (OSIRIS-REx) spacecraft will perform a divert maneuver and safely fly by Earth at an altitude of 250 km. SRC return and the divert maneuver officially mark the completion of the spacecraft's primary mission; however, it will continue on in heliocentric orbit with a nearly fully-functional instrument suite and enough propellant for nearly 600 m/s Delta-V. The post-Earth flyby trajectory fortuitously enables an exciting extended mission opportunity: rendezvous with the near-Earth asteroid (99942) Apophis immediately following its historic Earth close approach in April 2029. In this paper, we detail the discovery, optimization, and analysis of the Apophis rendezvous trajectory for an extended OSIRIS-REx mission. We also present the technical approach for an alternate target search and corresponding results, assessing the alternate trajectories compared to the baseline Apophis rendezvous from a trajectory design standpoint.

I. Introduction

In September of 2023, the Origins, Spectral Interpretation, Resource Identification, and Security–Regolith Explorer (OSIRIS-REx) spacecraft [1] will approach Earth and jettison its Sample Return Capsule (SRC), targeting a landing location inside the Utah Test and Training Range (UTTR) approximately 80 miles west of Salt Lake City [2]. Approximately four hours after SRC release, the OSIRIS-REx spacecraft bus will execute a divert maneuver and

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safely fly by the Earth at an altitude of 250 km. These events mark the end of OSIRIS-REx's primary mission to collect a sample from the near-Earth asteroid (101955) Bennu and return it to Earth [3]. Following the divert and Earth flyby, the OSIRIS-REx spacecraft will continue on in heliocentric orbit with a nearly fully-functional instrument suite and enough usable propellant for nearly 600 m/s Δv. The prograde flyby reduces the spacecraft's heliocentric periapsis to around 0.5 Astronomical Units (au), well outside the original design regime of the spacecraft, and exceeding operational limits for power and thermal subsystems. However, studies performed by the spacecraft team indicate the spacecraft and instruments can survive the thermal loads by re-configuring to a special solar array configuration and quiescent spacecraft attitude around perihelion. Assuming OSIRIS-REx does indeed survive the first perihelion passage as expected, the spacecraft offers a highly-capable, New Frontiers-class platform and instrument suite for in-depth study of another body in the inner solar system.

The post-flyby trajectory returns OSIRIS-REx to Earth roughly two years later in 2025, and the spacecraft's propulsion system can be used to target additional Earth flybys to manipulate its heliocentric trajectory. The near-Earth asteroid (99942) Apophis happens to make its own serendipitous flyby of Earth at an approximate distance of 40,000 km in April of 2029 [4], making it an opportunistic target for an OSIRIS-REx extended mission.

We therefore explored possible trajectories for the OSIRIS-REx spacecraft to rendezvous with Apophis. The baseline Apophis rendezvous trajectory was originally designed in AGI's Systems Tool Kit (STK) [5] and further optimized in NASA Goddard Space Flight Center's (GSFC) Evolutionary Mission Trajectory Generator (EMTG) [6–9]. The current baseline consists of four Earth gravity assists (EGAs) including the initial post-divert flyby, and three Deep Space Maneuvers (DSMs). OSIRIS-REx would arrive at Apophis on April 21st, 2029, shortly after the asteroid's scheduled close approach with Earth. The total Δv cost for the extended mission would be approximately 271 m/s including the divert maneuver (not considering statistical clean-up maneuvers). A heliocentric distance constraint of 0.5 au was placed on the entire trajectory due to thermal limits. Additionally, a tighter heliocentric distance constraint of >0.65 was placed on maneuvers. A plot of the Apophis rendezvous trajectory with key events (EGAs, DSMs, and Apophis rendezvous) annotated is shown in Figure 1.

While Apophis is an appealing target from a science, public interest, and accessibility standpoint, the OSIRIS-REx project performed an extensive assessment of alternate targets and trajectory design options in order to perform a comprehensive comparison of all possible extended mission concepts. The alternate target trajectory analysis consisted of three separate searches:

1) Rendezvous (e.g., near-zero relative velocity) opportunities other than Apophis
2) Dedicated flyby targets (one or more) instead of an Apophis rendezvous
3) Flyby targets-of-opportunity en route to rendezvous with Apophis

In all three cases, the search began by coarse filtering all objects in the entire small body database [4] based on orbital and physical characteristics. For the rendezvous and dedicated flyby searches, the filtered target lists were analyzed using EMTG and the Python EMTG Automated Trade Study Application (PEATSA) [10] for feasible trajectory designs. The dedicated flyby search also limited flyby velocities to ≤5 km/s. For the flyby targets-of-opportunity analysis, both a simple "bubble" search and a linearized, rapid propagator to approximate Δv [11] were used to find potential targets along the baseline Apophis rendezvous trajectory. Potential targets were analyzed in EMTG, using PEATSA, to determine if feasible flyby trajectories exist while maintaining an Apophis rendezvous in April 2029.

In this paper, we detail the trajectory design methodology and results for the proposed OSIRIS-REx extended mission concept to rendezvous with Apophis in 2029. We also present the technical approach for the alternate target search and corresponding results, and assess the alternate trajectories compared to the baseline Apophis rendezvous from a trajectory design standpoint.

II. Initial Discovery of Apophis Rendezvous Trajectory

Following the successful Touch and Go (TAG) collection of Bennu regolith and verification that the surface optical properties of the spacecraft were relatively unchanged by dust, the possibility of a potential extended mission opportunity for the OSIRIS-REx spacecraft after sample return to Earth started to become a reasonable line of inquiry. Selection of the May 2020 departure from Bennu decreased the Earth-return propellant requirements below the nominal allocation, freeing up additional propellant for a possible extended mission. Preliminary estimates indicated that almost 600 m/s of Δv margin might be available for an extended mission, assuming the spacecraft survived the 0.5 au perihelion passage after SRC release. Conventional wisdom initially guided the search for potential flyby targets using a similar process used by the Lucy mission to develop its Trojan tour. However, a rather serendipitous observation indicated that a rendezvous mission may be possible within the available allocation of propellant.

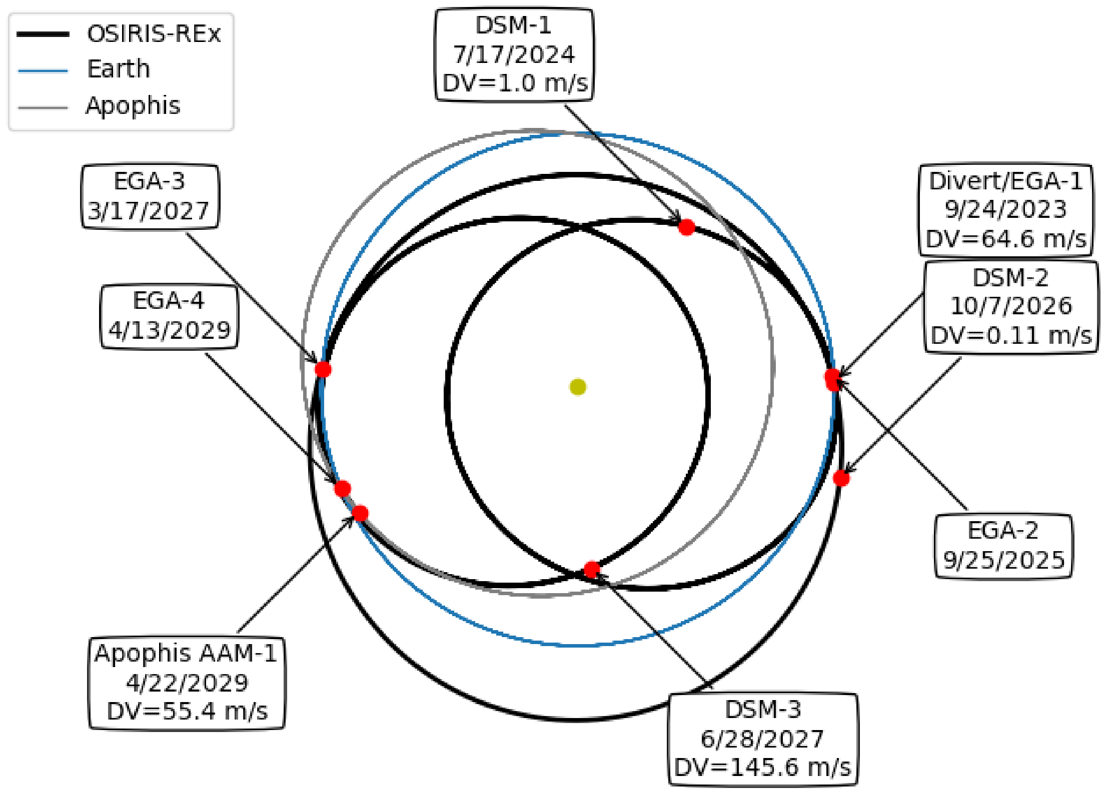

Fig. 1 Trajectory diagram for the proposed OSIRIS-REx extended mission concept to rendezvous with the near-Earth asteroid Apophis (99942) shortly after its close approach with Earth in April of 2029. Key events (EGAs, DSMs, and Apophis rendezvous) are annotated.

The ballistic cruise from Bennu to Earth delivers the OSIRIS-REx spacecraft and SRC with a hyperbolic excess velocity, v_∞ of 6.24 km/s. While searching for possible low-encounter-velocity near-Earth object (NEO) flyby targets, a close match with the hyperbolic excess velocity of Apophis was found for its April 13, 2029 close approach of Earth. Although separated by 5.5 years, the Apophis hyperbolic excess velocity value of 5.84 km/s was close enough to that of OSIRIS-REx to merit further investigation as a possible rendezvous target. Additionally, the 5.5-year separation of the SRC release event and the Apophis close approach was such that a rough blueprint of 3 distinct heliocentric orbits with 2-, 1.5-, and 2-year gaps, respectively, between EGAs could be used to line up the OSIRIS-REx spacecraft and and Apophis.

The deflected, post-SRC-release trajectory of the OSIRIS-REx spacecraft places it in a heliocentric orbit with a 0.5-au perihelion and a 243-day period. This near-resonant orbit with Earth would return the spacecraft to the vicinity of Earth on September 23, 2025, 2 years after deflection and after completing 3 orbits about the Sun. However, remaining in this orbit is not beneficial for delivering OSIRIS-REx to Apophis in the April 2029 timeframe, so a September 2025 EGA would be leveraged to provide another EGA opportunity closer to spring 2027. The 2027 EGA helps to reacquire the earlier 3:2 resonant orbit and return the spacecraft to Earth in April 2029, albeit on the opposite heliocentric node. Such an orbit was found that crossed Earth's orbit in both the September and March epochs, enabling an EGA transition to the opposite node after about 1.5 revolutions. From there, it was a simple matter to reestablish the 3:2 resonant orbit with Earth that would return the OSIRIS-REx spacecraft to Earth in April 2029—approximately the same time as Apophis's Earth close approach. A final EGA in April 2029 could be used to match OSIRIS-REx's hyperbolic right ascension and declination with that of Apophis.

This trajectory profile was initially modeled at Lockheed Martin using STK and refined using the embedded Design Explorer Optimizer. From this analysis, it was determined that a rendezvous with Apophis using the strategy outlined above was possible within the limitations of the remaining propellant onboard. DSMs were designed to exactly match the hyperbolic excess velocities of the OSIRIS-REx spacecraft and Apophis. Having established feasibility relative to the physics of the problem, a few focused investigations regarding survival of the spacecraft through the low perihelion passage were begun to evaluate the spacecraft survival in this extreme environment, which the spacecraft was not designed to tolerate. Fortunately, mitigation strategies to limit the effects of the 0.5 au passage on the spacecraft were developed that indicated that this opportunity had potential worthy of further characterization. Upon clearing this milestone, additional resources from National Aeronautics and Space Administration (NASA) GSFCs Navigation and Mission Design Branch (NMDB) were brought to bear, namely rendering the trajectory in the EMTG to perform further trajectory optimization and refinement of constraints.

III. Optimization of Apophis Rendezvous Trajectory in EMTG

NMDB proceeded to use the EMTG to produce a number of iterations of the Apophis rendezvous trajectory, eventually resulting in a trajectory that served as the initial guess for targeting the flight-fidelity trajectory render described later in this paper.

EMTG is a trajectory optimization tool primarily designed for interplanetary missions that performs global searches and can model a low-thrust or high-thrust trajectory in a variety of model fidelities [6, 7]. EMTG was previously used by OSIRIS-REx to optimize Earth-return trajectories [9] and has also been used by numerous other missions and proposals, including Lucy and DAVINCI. The work described in this paper exercised multiple EMTG execution capabilities and utilized new features of EMTG.

The earliest EMTG optimizations of the Apophis rendezvous scenario used as an initial boundary point a fixed state and time following the spacecraft divert maneuver that occurs shortly after SRC release. This state and time were obtained from Lockheed Martin. At this early stage, EMTG was used in a low-fidelity mode: all spacecraft motion was modeled as Keplerian, all gravity assists were modeled as zero sphere of influence (ZSOI) patched-conic events, and all DSMs were modeled as impulsive Δv events. As input information, EMTG was given the gravity assist sequence suggested by Lockheed Martin—three additional EGAs subsequent to the EGA performed immediately following SRC release—and a constrained Apophis rendezvous date in 2029. EMTG optimization successfully produced an Apophis-rendezvous trajectory requiring significantly less deterministic Δv than the original Lockheed Martin trajectory.

In parallel, EMTG was also used to optimize OSIRIS-REx Earth-return trajectories, beginning with the asteroid departure maneuver (ADM) and ending with arrival of the SRC at Earth [9]. Stitching together these two trajectory segments—Bennu to Earth and Earth to Apophis—would allow for full-problem optimization, including the extended mission. In other words, instead of optimizing the extended mission trajectory starting from a fixed state and time post-divert, the EMTG optimization problem could take into account maneuvers and constraints all the way from ADM to Apophis arrival. This problem formulation was realized using the EMTG "Probe Entry Phase," a specialized trajectory phase type that models one spacecraft splitting into two (in this case, the OSIRIS-REx bus releasing the SRC). The EMTG Probe Entry Phase is presented in graphically in Figures 2 and 3. As seen in Figure 2, the trajectories of the bus and SRC are modeled as sequences of forward/backward shooting segments, like most trajectories in EMTG. The SRC separates from the bus and coasts to a control node representing atmospheric entry interface (AEI), at which point constraints on quantities such as altitude and flight path angle may be applied. Optionally, EMTG can continue to model the trajectory of the SRC through the atmosphere of the central body. This feature is used for OSIRIS-REx SRC trajectory modeling in order to target the coordinates of the landing site, UTTR. Meanwhile, after releasing the SRC, the bus performs a divert maneuver, which is modeled as an impulsive Δv. Then, the bus continues its trajectory through and out of the central body's sphere of influence (SOI). In the specific case of OSIRIS-REx, an additional control node is placed within the central body's SOI in order to constrain the Earth closest-approach distance of the bus. At this point, the SRC is no longer modeled, and the trajectory of the bus may be augmented by additional phases, as is done for OSIRIS-REx extended mission design.

Using this modeling strategy, the Apophis rendezvous trajectory was re-optimized, starting from ADM. As previously described, initial feasibility was obtained using low-fidelity dynamics modeling. Modeling fidelity was then gradually increased to take into account finite SOI gravity assists, third-body gravitational forces, Earth J_2 gravity when the spacecraft is in Earth's SOI, and solar radiation pressure (SRP). In general, modeling fidelity was increased one parameter at a time, with the previously obtained feasible solution used as an initial guess for the next optimization problem. Additionally, previously written EMTG support scripts for converting ZSOI gravity assist decision variables to finite SOI gravity assist decision variables were used and resulted in nearly effortless decision variable conversion.

With the entire Earth-return trajectory plus the Apophis rendezvous trajectory modeled as a single optimization problem in medium-high fidelity in EMTG, EMTG and its trade study support scripts were then used to rapidly analyze

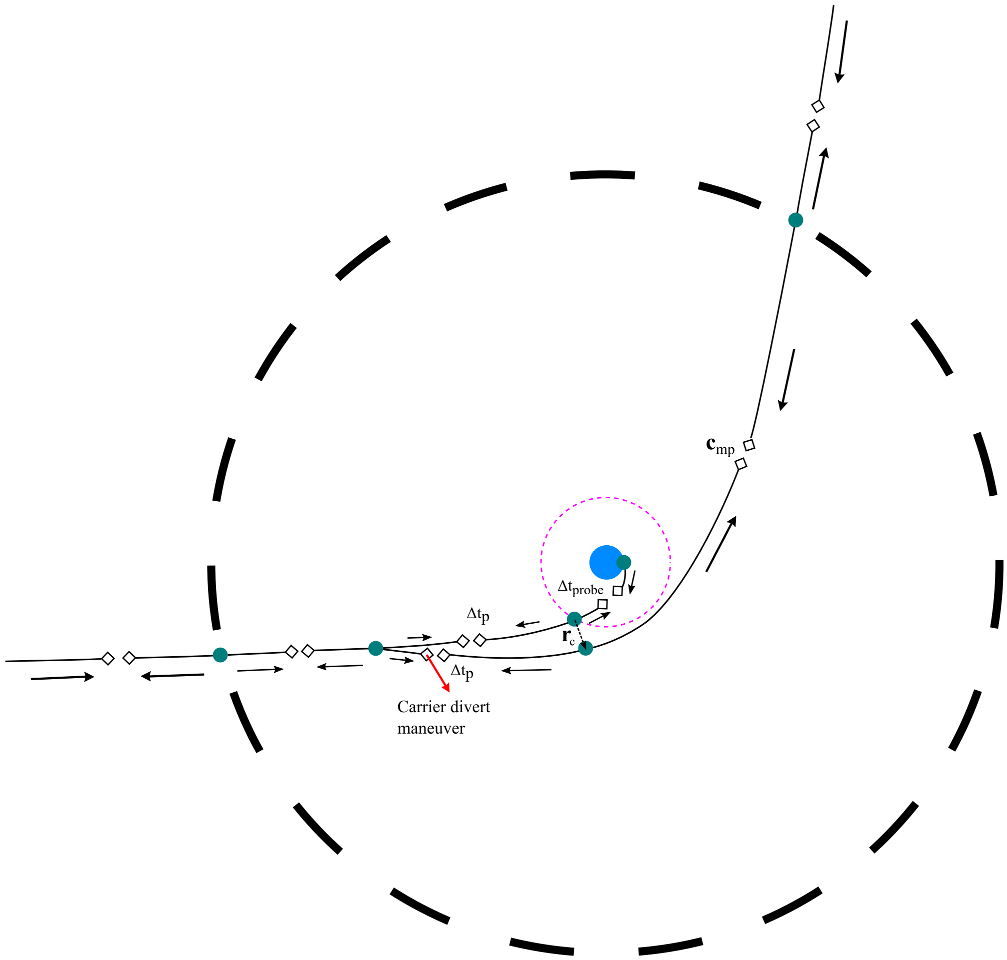

Fig. 2 EMTG Probe Entry Phase. The black dashed circle represents the SOI of the central body (in this case, the Earth), the pink dashed line represents the AEI, and the blue circle represents the central body itself. Green circles represent control nodes, diamonds represent match points, and black arrows indicate the direction of propagation.

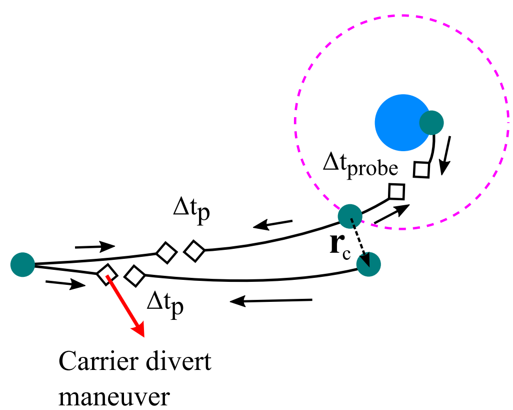

Fig. 3 EMTG Probe Entry Phase: detail. The black dashed circle represents the SOI of the central body (in this case, the Earth), the pink dashed line represents the AEI, and the blue circle represents the central body itself. Green circles represent control nodes, diamonds represent match points, and black arrows indicate the direction of propagation.

the effects on deterministic Δv requirements on factors such as:

- ADM date
- Apophis rendezvous date
- Divert maneuver size
- Closest Solar distance limits
- Closest Solar distance limits at which a DSM is performed

In each case, built-in EMTG boundary and/or maneuver constraint definitions were used to constrain the optimization problem to produce new solutions.

Following performance of the ADM on May 10, 2021, subsequent extended-mission trajectory optimizations model the trajectory as starting from a fixed state and time prior to Earth approach. The states and times are extracted from orbit determination (OD) solutions produced by the OSIRIS-REx navigation team. The most recent of these optimizations was used as the basis for the flight-fidelity trajectory render and navigation analysis described in the next section of this paper.

It is worth noting that the science team expressed a desire to arrive at Apophis prior to its Earth close approach on April 13, 2029 to collect pre- and post-encounter observations and assess changes in the surface, structure, and spin state. The navigation team rigorously investigated trajectory opportunities that allowed for the earliest possible spacecraft rendezvous with Apophis. However, no viable trajectory solutions were found with an arrival date prior to Apophis's close approach with Earth. The orbital mechanics are such that the final spacecraft EGA (EGA-3) on April 13 is required to match the Apophis post-Earth flyby orbit within the remaining Δv capability of the mission. The initial flyby of Apophis occurs eight days later on April 21.

IV. High-Fidelity Trajectory Propagation and Statistical Maneuver Analysis

The trajectory, developed with EMTG for the Bennu ADM in 2021 through Apophis rendezvous in 2029 was used as a reference for constructing a high-fidelity simulation using the MIRAGE navigation software suite. MIRAGE incorporates gravitational models of all solar system bodies, including solar, lunar and planetary masses (as GMs), the JGM-3 Earth gravity field (50 x 50) and the LP150Q Lunar gravity model (8 x 8). Additional models include SRP incorporating a 10-plate representation of the spacecraft with both specular and diffuse reflectivities. MIRAGE provides both propagation of trajectories as well as design of maneuvers to achieve specific target conditions, as provided from the reference trajectory. In this way, the EMTG trajectory was rendered by MIRAGE into an equivalent reference that provided a basis for further navigation analysis.

The effects of errors associated with OD and maneuver execution were explored using additional simulations based on the MIRAGE reference, using the process shown in Figure 4. Initial sample states were derived from final truth states associated with the baseline OSIRIS-REx Earth return, starting with the effect of the predetermined SRC release and Earth divert burn on the spacecraft bus to be used for the extended mission. Subsequently, estimated states and associated OD covariances were derived via covariance analysis, which were then sampled within a Monte Carlo simulation to create estimated states to support a set of maneuver designs (commanded Δv). Maneuver execution errors are applied to commanded Δv to derive the actual Δv, which are then applied to the actual or "truth" states sample by sample and the resultant states are propagated forward. This process is carried out maneuver by maneuver through all three EGAs and arrival near Apophis. For each EGA, some biasing/walk-in to nominal target location was necessary to ensure range safety according to similar criteria as for the preceding Earth return.

Trajectory states and uncertainties for Apophis were downloaded from the Jet Propulsion Laboratory (JPL) HORIZONS database. Possible Apophis trajectories were created initially using a similar Monte Carlo process as described above as a source of potential target states for the spacecraft in this analysis. However, based on updated information from the OSIRIS-REx science team, it was determined that such uncertainties were relatively small and could nominally be discounted [12]. In operations, these will be accounted for as a component of the OD covariance to support final approach maneuvers to Apophis following EGA-3 in early 2029 with application of $Deltav$ margin available to account for any "unknown-unknowns" that may arise.

Placement of statistical maneuvers was informed by the behavior of target gradients of the B-Plane parameters B.R, B.T., and Linearized Time of Flight (LFT) [13] for each of the three EGAs, as determined by MIRAGE. Maximum angular separation of these gradients is needed to ensure maximum efficiency of maneuvers and avoid unnecessary or prohibitive expenditure of Δv. Additional spacecraft thermal constraints must also be taken into account (no maneuvers can be performed below a solar range of 0.72 au). Any solar conjunctions, areas with low Sun-Earth-Probe (SEP) angles, were avoided as well, due to the limited availability of radiometric tracking during these periods. These constraints are

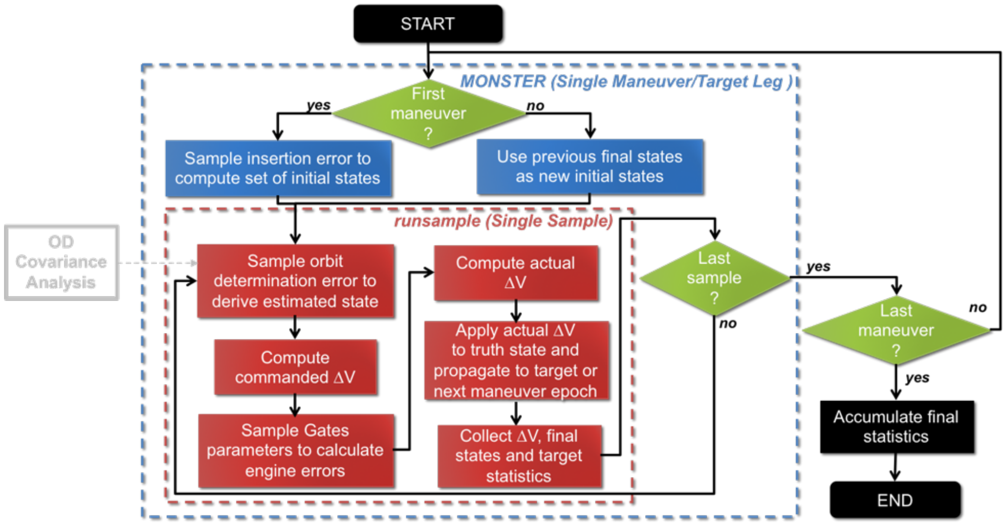

Fig. 4 Overview of the extended mission cruise Monte Carlo simulation and analysis process using the MONSTER (Monte Carlo Operational Navigation Simulation for Trajectory Evaluation and Research) software suite.

illustrated in Figure 5 for the first leg of the extended mission leading up to EGA-1. Optimal locations for trajectory correction maneuver (TCM) placement are indicated as vertical dashed lines. A subset of these were chosen for inclusion in the Monte Carlo simulation.

Selected maneuvers and preliminary results are indicated in Table 1, along with resultant Δv estimated from a 1000-sample Monte Carlo run. The column "99%" provides the DV99 or 99-percentile level of Δv allocated by individual maneuver, trajectory leg and overall. The allocation for statistical Δv in excess of the deterministic requirement is highlighted at the bottom of the table, as well as the expected remaining capabilities of the spacecraft at SRC release and at Apophis rendezvous. The amount of DV99 required is well within available Δv margin and easily accommodates continued proximity operations at Apophis and beyond.

V. Alternate Target Search

While the serendipitous existence and discovery of an Apophis rendezvous trajectory represented an immediate strong candidate for an extended mission target, the OSIRIS-REx team also endeavored to find feasible trajectories to other targets of scientific interest. Targets were investigated based on three different mission scenarios: 1) alternate targets for rendezvous, 2) targets for a dedicated flyby-only mission (no rendezvous), and 3) targets of opportunity for flyby en route to the Apophis rendezvous. Multiple avenues of investigation were used for these three searches. In all cases, a “bubble" search was used to identify targets (out of a set of 700,000) that passed with 0.1 au of the baseline trajectory to Apophis. Parallel to this bubble search, EMTG’s low-fidelity modeling mode was used, along with existing large-scale trade-study support scripts, to rapidly optimize trajectories to a select number of targets. In the search for targets of opportunity, an additional method was used that rapidly approximates the Δv required to fly by a new target en route to Apophis, based on a propagation of the state transition matrix (STM) [11, 14–16].

A. Rendezvous Target Search

A large target search was conducted in an attempt to identify all bodies that the spacecraft could rendezvous with after the release of the SRC. The targets selected for investigation were curated from a list of asteroids and comets based on back-of-the-envelope spacecraft intercept feasibility and scientific interest. Filtering criteria included:

- Asteroids
  - Brightness and size: $H \leq 24$ (conservative upper limit) or diameter $\geq$ 200 m
  - Orbit condition code ≤ 2
  - Perihelion $\geq$ 0.5 au (spacecraft limit)
  - Aphelion $\leq$ 1.4 au (spacecraft limit)

Table 1 Overview of the statistical Δv results for the cruise portion of the OSIRIS-REx extended mission.

TCM	A.K.A.	Nominal Epoch (UTC)	Deterministic (m/s)	Mean (m/s)	SD (m/s)	95% (m/s)	99% (m/s)
—	Post-SRC Release Divert	9/24/23 11:02	64.646	64.650	0.256	65.061	65.432
14	Divert Cleanup	10/9/23 20:00	—	3.639	1.923	7.097	9.838
15	DSM X1	7/17/24 20:00	1.031	1.351	0.361	2.032	2.69
16	DSM X1 Cleanup	12/4/24 20:00	—	0.081	0.047	0.173	0.251
17	Pre-EGA2 Cleanup	8/23/25 20:00	—	0.073	0.048	0.167	0.237
First Cruise Leg Total			65.677	69.794	2.635	74.530	78.448
18	Post-EGA2 Cleanup	10/3/25 20:00	—	2.939	1.611	6.006	7.876
19	DSM X2	10/7/26 20:00	0.109	0.42	0.458	1.289	2.053
20	DSM X2 Cleanup	11/29/26 20:00	—	0.026	0.019	0.061	0.121
21	Pre-EGA3 Cleanup	1/13/27 20:00	—	0.005	0.007	0.018	0.026
Second Cruise Leg Total			0.109	3.39	2.095	7.374	10.076
22	Post-EGA3 Cleanup	4/7/27 20:00	—	11.492	7.751	27.142	40.783
23	DSM X3	6/28/27 20:00	145.581	145.602	1.394	147.851	149.369
24	DSM X3 Cleanup	10/27/27 20:00	—	1.058	0.502	1.965	2.536
25	1st Pre-EGA4 Cleanup	2/14/29 20:00	—	0.202	0.145	0.499	0.701
26	2nd Pre-EGA4 Cleanup	3/7/29 20:00	—	0.004	0.006	0.015	0.02
Third Cruise Leg Total			145.581	158.358	9.798	177.472	193.409
27	Post-EGA4 cleanup targeting Apophis Flyby	4/17/29 20:00	—	12.035	6.306	23.039	31.918
28	Approach #1 (Rendezvous)	4/22/29 20:00	55.387	55.084	4.55	63.162	66.607
29	Approach #2	5/8/29 20:00	3.834	3.999	0.667	5.115	5.942
30	Approach #3	5/15/29 20:00	1.352	1.502	0.382	2.123	2.488
Approach Rendevous Total			60.753	1.502	0.382	2.123	2.488
TOTAL (Divert –> Apophis Rendezvous)			271.940	304.162	26.433	352.815	388.888
Allocation for Range Safety Biasing and Statistical Delta-V:							116.948
Remaining Spacecraft Capability at SRC Release							597.45
Delta-V Remaining after Apophis Rendezvous							208.562

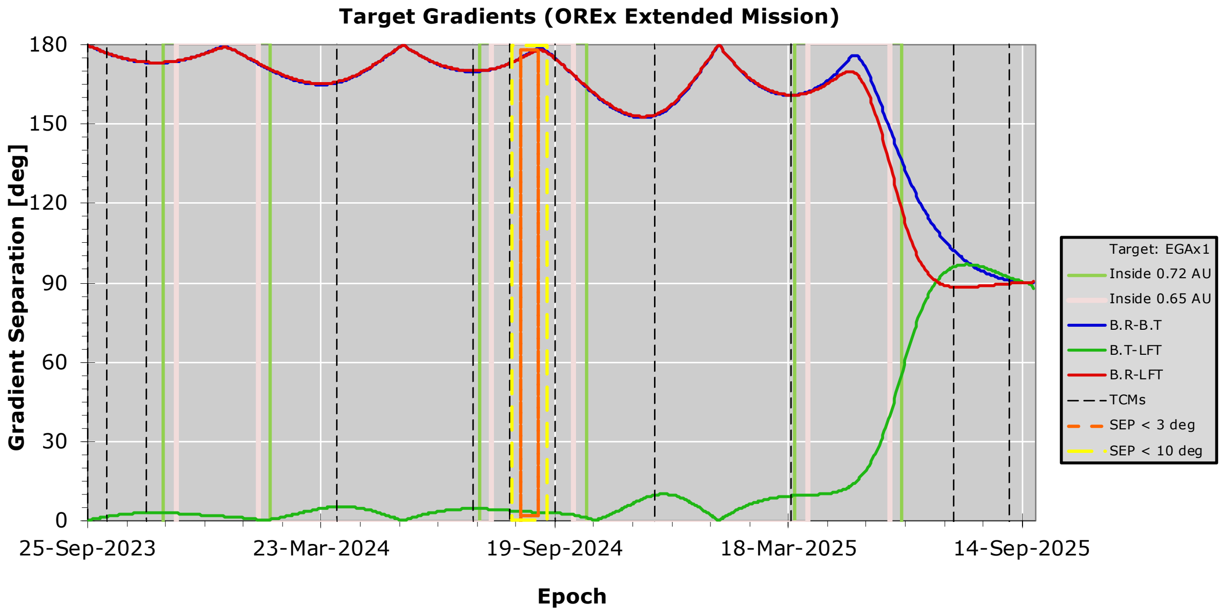

Fig. 5 Separation of target gradients and additional constraints prior to EGA-1. Optimal TCM locations are indicated by vertical dashed lines. A subset of these opportunities were modeled as TCMs in the Monte Carlo simulation.

  - Ecliptic inclination ≤ 15°
  - Exceptions added based on scientific interest:
    * 4015 Wilson-Harrington (1979 VA)
    * 138911 (2001 AE2)
    * 132173 Ryugu (1999 JU3)
    * 175706 (1996 FG3)
- Comets
  - Orbit condition code ≤ 2
  - 0.5 au ≤ perihelion ≥ 1.4 au
  - Ecliptic inclination ≤ 20°

Applying these filters resulted in a target set of 214 asteroids and 58 comets. Additionally, a set of 42 targets were identified with orbit condition code greater than 2 that would have observation opportunities within 6 years of the SRC return. Trajectories to each of these targets were evaluated in EMTG.

For this investigation, the trajectory optimization problem was simplified from that described in the Apophis rendezvous section in order to decrease execution time and increase the permissible autonomy of each individual optimization case. In particular:

- Only the post-divert trajectory of the spacecraft bus was modeled. In other words, the Earth-return trajectory and the trajectory of the SRC were *not* modeled.
- The starting state of each trajectory was modeled as the center of the Earth (with Earth's gravity turned off in force modeling) with inequality-constrained v_∞ magnitude, right ascension, and declination. The v_∞ magnitude and direction constraints formed a 3-dimensional box around the expected post-divert velocity vector. When selecting the upper and lower bounds of the box, the team erred on the side of permissibility, deeming false positives—which could be weeded out later through more detailed analysis—preferable to false negatives.
- The starting time of each trajectory was inequality-constrained within a several-hour box surrounding the predicted Earth-arrival time for the primary mission.
- Arrival at the target of interest was modeled as a ZSOI patched-conic intercept, where the gravity of the small body is completely ignored. In this model, the capture maneuver Δv is simply the magnitude of the arrival v_∞ of

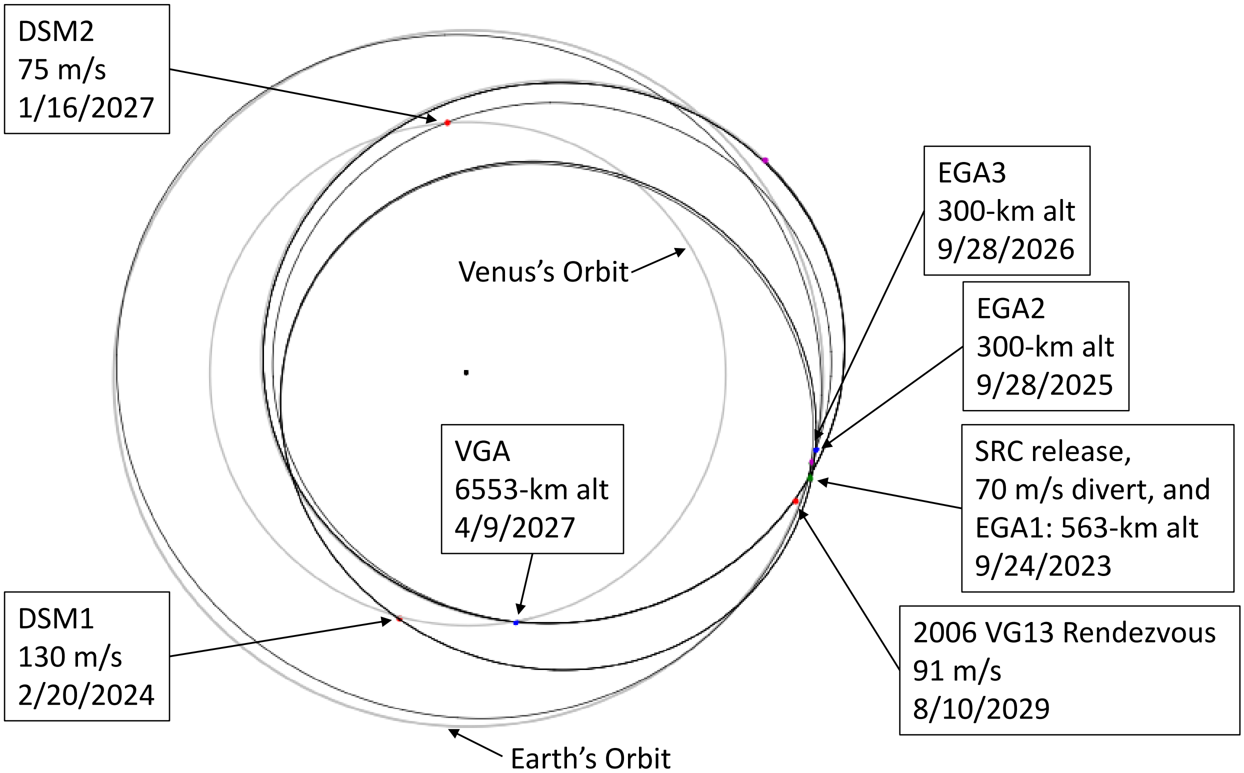

Fig. 6 Top-down, inertial, ecliptic view of the trajectory to rendezvous with 2006 VG13.

the spacecraft relative to the target body.

- For each target, trajectories were optimized using every one of an analyst-selected set of 32 ZSOI patched-conic gravity assist combinations using Venus and Earth. The spacecraft was allowed to perform one DSM between each gravity assist.
- Trajectories were optimized with the total flight time from divert maneuver to target intercept limited to 3 years and 6 years.

In addition to the small-body targets, the same methodology was used to examine the feasibility of entering into a highly elliptical, 5-day orbit around Venus with periapsis altitude of 300 km.

The results of the search identified only one solution, other than Apophis, within the spacecraft's maximum available Δv of 600 m/s—a rendezvous with the asteroid 2006 VG13. 2006 VG13 is an Aten-type near-Earth asteroid (NEA) with absolute magnitude H = 21.4. The total Δv required to rendezvous with this target is 366 m/s using an Earth-Earth-Venus gravity-assist sequence over a 6-year flight time after SRC release. The EMTG trajectory from SRC release to 2006 VG13 is shown in Fig. 6.

2006 VG13 was not selected for the extended mission primarily because it has a perihelion of 0.57 au, and, due to thermal limitations, the spacecraft is only able to perform science operations above 0.89 au. As a result, the spacecraft would need to remain in a thermally-safe attitude for about 20% of the time spent in orbit at 2006 VG13, and science operations would remain limited for a larger portion of the remaining orbit. Additionally, the required Venus gravity assist presented unique thermal constraints that likely exceeded the spacecraft's capabilities. Lastly, 2006 VG13 provided no known increase in science return over Apophis, and takes a similar amount of time (about 6 years) to reach after SRC release.

B. Dedicated Flyby Target Search in EMTG

The team also investigated extended mission scenarios that focused on hyperbolic flybys of target bodies, rather than rendezvous. Such targets are referred to as dedicated flyby targets. The targets selected for this investigation were identified using similar criteria to those described in Sec. V.A. One exception was that the maximum absolute magnitude, H, considered for flyby targets was 20.2, matching the brightness of Bennu. With this more constraining filter, a target set of 67 asteroids and 58 comets was identified, where the set of comets here is identical to those considered for rendezvous.

The smaller H value in the target-selection filter was used to reduce the size of the search and maximize the possible science return for a flyby-only target (e.g., the object is of equivalent or greater size compared to Bennu, using brightness as a rough proxy for size). The OSIRIS-REx instrument suite was designed and optimized for up-close observations during proximity operations, and thus is poorly suited to conduct flyby observations at distances of hundreds to thousands of km. Consequently, the science team ultimately determined that observations collected during a flyby would result in significantly less impactful science return compared to those taken during a rendezvous mission. Regardless, the navigation team was tasked to identify potential flyby candidates, so that the science team and larger science community could assess for themselves the relative value of a flyby of one or more particularly interesting targets (if found) compared to the Apophis (or 2006 VG13) rendezvous.

Flyby trajectories were computed in EMTG for each of the candidate targets. The methodology was nearly identical to the rendezvous analysis, except that a capture maneuver was not modeled. This greatly reduces the Δv required to reach a given target (in most cases), and yielded a much larger set of candidates. In total, 85 candidate trajectories were found to 68 different targets. Solutions were limited to those with encounter velocities no greater than 5 km/s and a total Δv no greater than 600 m/s. A subset of these solutions is provided in Table 2, highlighting six of the more attractive cases. Note that the Δv listed in the table only includes deterministic maneuvers, and the gravity-assist sequences listed exclude the first Earth closest approach immediately following SRC release.

Table 2 Select set of candidate trajectories for dedicated flyby-only extended mission targets.

Target	H	Δv, m/s	Flight Time, yrs	Encounter Velocity, km/s	Gravity-Assist Sequence
1989 UQ	19.5	73	2.6	4.8	E
1992 FE	17.3	80	2.6	4.9	E
2010 KD149	21.7	73	4.9	4.5	E
2000 NG11	17.1	264	4.5	1.2	E-E
3908 Nyx	17.4	96	5.4	1.7	E-E
2004 FM17	19.4	73	5.9	2.7	E-E-E-E

Of the candidate flyby-targets found, combinations of these encounters were also investigated to identify opportunities to encounter multiple targets along the same trajectory. No feasible solutions were identified within the Δv capabilities of the spacecraft.

Ultimately, the OSIRIS-REx project determined that the science return for a rendezvous mission far outweighed that of a potential flyby given the spacecraft's capabilities and suite of instruments. Consequently, the team moved forward with the baseline Apophis rendezvous concept with concurrence from NASA's Science Mission Directorate (SMD).

C. Search for Flyby Targets of Opportunity En Route to Apophis

Once Apophis was identified as the most scientifically interesting target reachable within the capabilities of the OSIRIS-REx spacecraft after SRC release, a search was conducted for flyby targets en route to Apophis, referred to in this paper as targets of opportunity.

Utilizing the baseline Apophis rendezvous trajectory, two low-fidelity searches were conducted to identify potential candidate targets of opportunity before optimization in higher fidelity in EMTG.

1) The first method is a bubble search, seeking out targets that pass within 0.1 au of the spacecraft as it travels along its baseline trajectory.
2) The second method is a Δv-based bubble search which approximates the Δv needed to deviate from the baseline trajectory, fly by a target, and then return to the baseline trajectory [11, 14–16].

The spatial bubble search is extremely computationally efficient and considers a very large set of 700,000 targets.

The Δv-based search is used on a reduced set of targets, to identify targets that may not be in the path of the baseline trajectory, but that may be reachable with maneuvers. The target set was identified from [4] with the following filters:

- Perihelion between 0.5 au and 1.4 au
- Inclination $\leq$ 20 deg with respect to the ecliptic plane
- Aphelion $\leq$ 5 au

These filters yielded a total of 2996 asteroids. Additionally, the same set of 58 comets mentioned in the two previous sections was also included in the target search. To rapidly estimate the Δv of such maneuvers for this large set of targets (albeit much less than 700,000), the baseline trajectory's STM is used to provide low-fidelity Δv approximations for the spacecraft to divert from its baseline trajectory, encounter the target of opportunity, and return to the baseline trajectory.

These two methods identified two candidate targets of opportunity (both from the spatial bubble search): 2000 EA14 and 2003 WT153. Both targets were investigated in EMTG for feasibility, with the results shown in Table 3. In the table, note that the Δv listed is the total deterministic Δv from SRC release to capture at Apophis. The team also investigated a trajectory that encountered both targets, but was deemed infeasible due to a required total deterministic Δv of over 1 km/s.

Table 3 Trajectory Characteristics for Targets of Opportuntiy On Route to Apophis

Target	H	Δv, m/s	Flyby Month/Year	Flyby Velocity, km/s
2000 EA14	21.1	516	Oct 2025	2.6
2003 WT153	28.0	507	Dec 2025	9.4

Although within the spacecraft's capability, the two trajectories found require a large amount of propellant (with small remaining Δv margin) for the anticipated science return. As a result, the current baseline trajectory to Apophis does not include flybys of either of these targets. The propellant saved may be used for extended observations at Apophis, or possibly for exploration of a new target, although an investigation of such missions has yet to be done. However, the navigation team will continue to search for additional flyby targets of opportunity after selection of the extended mission.

VI. Conclusions

An encounter and rendezvous with the near-Earth asteroid Apophis in 2029 presents a captivating and scientifically-valuable opportunity for an extension of the OSIRIS-REx mission. The OSIRIS-REx navigation team discovered, optimized, and analyzed a feasible trajectory that connects the post-SRC release and Earth divert orbit to the Apophis rendezvous approximately 6 years later. The trajectory leverages three EGAs, three deterministic DSMs, three approach maneuvers, and multiple statistical TCMs. The total DV99 of approximately 390 m/s is well within the expected post-divert Δv margin of nearly 600 m/s.

Despite the obvious appeal and intrigue of the Apophis rendezvous concept, navigation performed a comprehensive alternate target and trajectory search that included both rendezvous and dedicated flyby opportunities. Given the paucity of feasible trajectories to alternate targets and the relative science return, the OSIRIS-REx team decided to move forward with the Apophis rendezvous concept with concurrence from NASA SMD. At the time of submission of this paper, the team has not yet discovered a feasible and scientifically interesting flyby target of opportunity along the baseline rendezvous trajectory, but will continue to search for options en route to Apophis.

The Apophis rendezvous concept and corresponding trajectory, as well as a proximity trajectory design and operations concept that is beyond the scope of this paper, were documented in a proposal that will be submitted to the NASA SMD Planetary Senior Review in January 2022. A decision on whether or not the proposed extended mission concept will move forward into the planning and implementation phase is expected in mid-2022.

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