(Preprint) AAS XX-XXX

OSIRIS-REX CONJUNCTION SCREENINGS: EARTH GRAVITY ASSIST AND EARTH RETURN ANALYSIS AND RESULTS

Dolan E. Highsmith* **and Roger C. Thompson†**

The NASA OSIRIS-REx asteroid sample return mission performed an Earth gravity assist on September 22, 2017, and returned to Earth to drop off the sample on September 24, 2023. In each case, the NASA Conjunction Assessment Risk Analysis (CARA) team screened the OSIRIS-REx trajectories against the satellite catalog in search of high-risk close approaches. This paper describes the preparation for collision avoidance and screening results, along with lessons learned, providing a baseline for support of future missions in this category, particularly as space traffic around the Earth and in cis-lunar space continues to rapidly expand.

INTRODUCTION

The NASA Origins, Spectral Interpretation, Resource Identification, and Security-Regolith Explorer (OSIRIS-REx) asteroid sample return mission launched on September 8, 2016, flew past Earth for a gravity assist on September 22, 2017, collected a sample of asteroid (101955) Bennu on October 20, 2020,[1,2] and returned to Earth to drop off the sample on September 24, 2023.[3] During the 2017 Earth gravity assist (EGA) and the 2023 Earth return, the NASA Conjunction Assessment Risk Analysis (CARA) team screened the OSIRIS-REx trajectories against the satellite catalog to protect against high-risk close approaches with resident space objects (RSOs). Until relatively recently, NASA did not screen Earth flyby and sample return missions for close approaches. The conjunction environment was not considered for the predecessor NASA sample return mission Stardust, which brought its sample back to Earth on January 15, 2006.[4] However, given the significant increase in recent years in the number of RSOs, it has become imperative for EGA and entry missions to assess and, if necessary, remediate their risk of collision to ensure both mission preservation and space environment protection. Figure 1 shows a comparison between the number of RSOs in the public catalog versus altitude on the respective entry dates for the Stardust and OSIRIS-REx sample capsules. The figure shows the number of objects in low Earth orbit (LEO) with eccentricity less than 0.25 that pass through each 1 km altitude bin.

NASA conjunction screening began with the Human Spaceflight program during the 1980s for the Space Shuttle program, providing a baseline for CARA to initiate that safety function in 2005 for the wider range of orbits occupied by the NASA uncrewed (aka "robotic") fleet.[5] The first NASA Earth flyby mission screened for conjunctions was the Juno Earth flyby in October 2013.[6,7] CARA first screened a sample return mission in December 2020 for the Japanese Aerospace Exploration Agency (JAXA) Hyabusa2 asteroid sample return.[8] In between the OSIRIS-REx 2017

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* Senior Project Leader, The Aerospace Corporation, affiliation, 14301 Sullyfield Circle, Unit C, Chantilly, VA 20151.
† Retiree Casual, The Aerospace Corporation, 14301 Sullyfield Circle, Unit C, Chantilly, VA 20151.

EGA and 2023 Earth Return, CARA screened the October 2022 EGA of Lucy, the NASA Trojan asteroid mission.[9] Despite the rarity of these types of missions, CARA has been able to develop insight from its operational experience toward supporting EGA and entry missions. As such, the goal of this paper is to document the OSIRIS-REx screening experience to highlight the acquired knowledge and lessons learned by CARA and to provide information for entities outside NASA who support similar mission profiles.

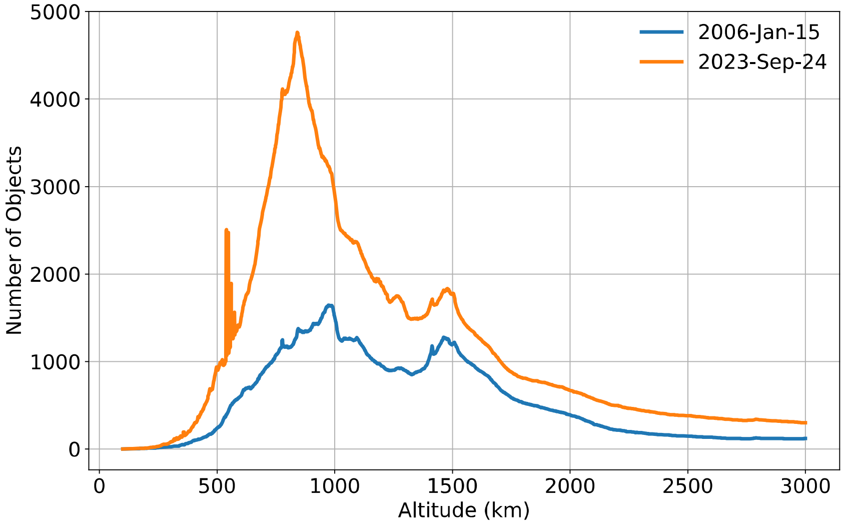

Figure 1. Number of RSOs passing through each 1 km altitude bin.

The following sections cover a brief overview of the OSIRIS-REx Earth Return mission phase and operational preparations, details of the CARA interface with the mission, and pre-arrival testing. Next follows a description of analysis to forecast objects in Earth orbit with the potential to conjunct with the OSIRIS-REx trajectories based on slowly changing orbital parameters, then a summary of the CARA operational screening process and results. The final section covers conclusions and suggestions for future work.

OSIRIS-REX MISSION OVERVIEW AND CARA INTERFACE

The OSIRIS-REx mission design included numerous complex phases between launch and sample return, two of which are the focus of this paper: the Earth gravity assist in 2017 and the sample return and Earth flyby in 2023. Details of the 2017 flyby mission design and performance can be found in Reference 10; an overview of the 2023 entry and flyby can be found in Reference 3, with details of the maneuver design and orbit determination in References 11 and 12, respectively. The following subsections provide a summary of the aspects pertinent to conjunction assessment and collision avoidance.

2017 Earth Flyby Overview

OSIRIS-REx performed a gravity assist flyby at 17,237 km altitude over Antarctica in September 2017 to change its orbital plane to match that of the target asteroid Bennu.[10] **Error! Reference source not found.** depicts two views of the flyby trajectory through dots representing objects in the satellite catalog at the time. Trajectory Correction Maneuver (TCM)-4, the final maneuver to target the flyby, was scheduled 10 days out, far too early to reasonably account for avoiding close approaches because of the long propagation time required for the RSO catalog states and the associated uncertainties. Thus, contingency maneuver TCM-5 was used for the collision avoidance maneuver (CAM) opportunity at one day out, if needed, to change the perigee time by +2 seconds.

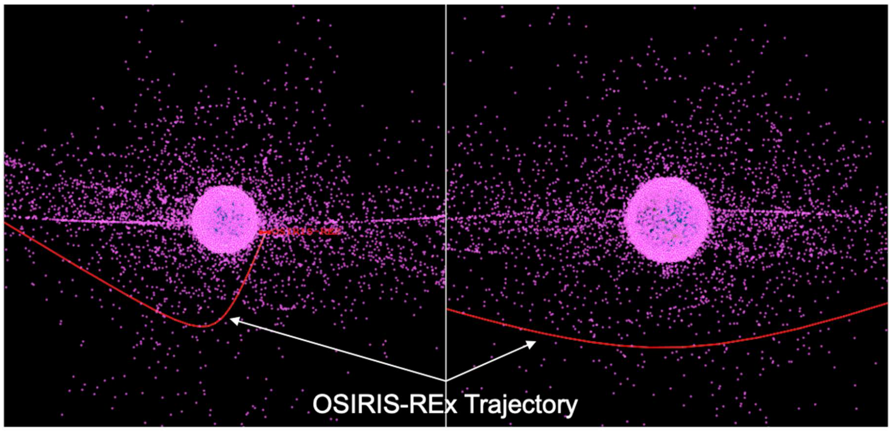

Figure 2. Trajectory of OSIRIS-REx 2017 Earth flyby with dots for each object in the RSO catalog

Because there was not enough time for a full custom maneuver design and test cycle based on conjunction screenings in the final few days prior to the flyby, a CAM design had to be chosen well in advance, with maneuver command products tested and ready to uplink to the spacecraft. Without knowledge of a specific conjunction geometry and secondary object covariance, the +2 second time change (15.7 cm/s ΔV) maneuver size was chosen to adjust perigee timing by more than 3σ of the OSIRIS-REx perigee timing uncertainty. Additional CAM options could have been implemented with different timing changes, but unlike Juno which had two CAM options of +/- 1 second for a 559 km altitude flyby,[6] OSIRIS-REx deemed one CAM to be sufficient given that the flyby altitude of >17,000 km presented far fewer opportunities for conjunctions.

CARA performed an initial test screening of the nominal ephemeris at 30 days out and began daily operational screenings at 10 days out. Both the nominal and CAM ephemerides were screened starting at 3 days out, with the final decisional delivery schedule shown in Table 1. Forecasting analysis of the conjunction environment was also produced in the weeks ahead of EGA based on orbit crossing distances, i.e., separation of the orbits along the relative line of nodes, to assess which objects could possibly pose a collision risk independent of predicted along-track location. This analysis, described in more detail later, showed very few objects could pose a risk at such a high perigee over the South Pole, so a CAM was not expected. Nevertheless, the mission and CARA teams were prepared to react. Ultimately, a CAM was not required.

Table 1. Final delivery and screening schedule for 2017 flyby.

Event	Hours to EGA	Hours to CAM	Date (UTC)	Comment
Deliver OD to CARA	47	23	9/20/17 18:00	Deliver nominal and CAM ephemerides.
Receive CARA Report	41	17	9/21/17 00:00	2-4 hr turnaround for CARA. Allowing 6 hr.
Command Conference	39	15	9/21/17 02:00	CAM Go/No-go decision.
Start of CAM Upload Window	37	13	9/21/17 04:00	Uplink opportunities from two Deep Space Network complexes.
TCM-5/CAM Execution	24	0	9/21/17 17:00	If needed.

2023 Earth Return Overview

The situation was more complex in 2023 with two objects to screen through more densely populated orbits: the OSIRIS-REx spacecraft bus and the Sample Return Capsule (SRC), both of which flew through LEO as shown in Figure 3. The RSO population had changed significantly in between 2017 and 2023, with 17,036 objects in the September 2017 catalog and 25,214 objects in the September 2023 catalog – a 48% increase. Most of the increase was in LEO with the launch of the SpaceX Starlink constellation, beginning in 2019, with 4,720 Starlink satellites in orbit at the time of the 2023 flyby.

OSIRIS-REx had to be on an impact trajectory with Earth when it released the SRC, which had no ability to adjust its trajectory, and then the spacecraft bus had to perform a large divert maneuver so it would not also impact Earth. Figure 4 shows a graphical overview of the maneuver strategy for targeting Earth entry and flyby. The timing on the graphic is relative to Entry Interface (EI), the location and flight path angle (FPA) at the top of the atmosphere required for the SRC to land at the Utah Test and Training Range (UTTR). Using a walk-in strategy so the spacecraft would not be on an impact trajectory with Earth until the final targeting maneuver, TCM-10 at 60 days out moved the aimpoint from approximately 2,000 km off the limb of the Earth to about 200 km, followed by TCM-11 at two weeks out to target EI. TCM-12 at one week out was a cleanup maneuver to recenter on the EI target due to execution errors with TCM-11. As with the 2017 flyby, the final targeting maneuver was too far out to use for collision avoidance, so a CAM opportunity was inserted at 13 hours from entry. After that, the SRC was released at 4 hours out, followed by a divert burn by the spacecraft bus 20 minutes later resulting in a perigee altitude of about 780 km.

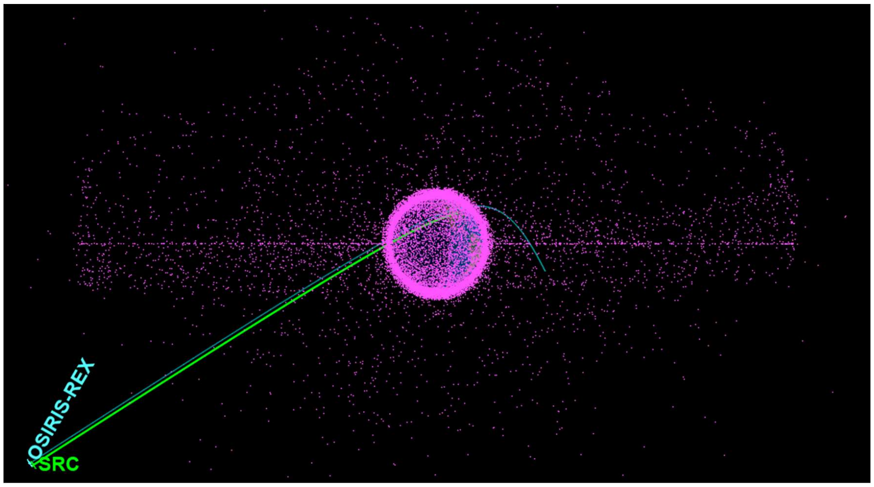

Figure 3. Trajectory of OSIRIS-REx bus and SRC during 2023 Earth flyby with dots for each object in the RSO catalog.

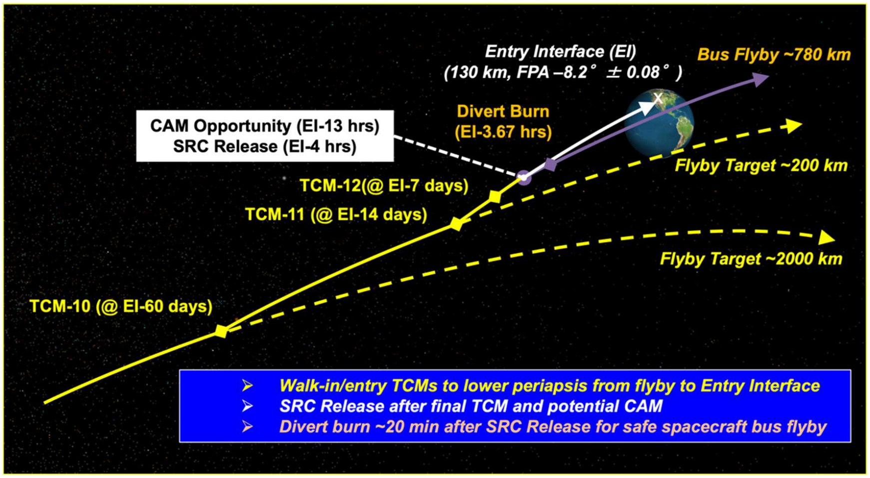

Figure 4. Graphical overview of nominal 2023 entry and flyby trajectory plan.

Note that the CAM would affect the trajectory of both the SRC and spacecraft bus since it would occur prior to SRC release. This introduced the remote possibility that a single CAM option could clear a high-risk conjunction in the nominal trajectory of one object but introduce one in the CAM trajectory of the other object. Given that possibility combined with the fact that the SRC and bus would be traversing the densely populated LEO regime, the mission chose to implement three CAM options. As with the 2017 flyby, the maneuver command products had to be pre-built and tested well in advance to have on the shelf if needed. With stringent EI targeting requirements, the CAMs were designed to adjust the arrival time at EI while hitting the same Earth-fixed location and FPA. The CAM options would adjust entry time by -0.5 second, -1.0 second, and -2.0 seconds. That is, if a CAM were performed, entry would occur *earlier* than nominal at the same Earth-relative geometry. These values were chosen based on a Monte Carlo analysis that produced a post-divert maneuver 1σ perigee timing uncertainty of 0.5 second for the spacecraft bus.[3] Thus, the largest CAM could adjust the bus and SRC timing by more than 3σ, with smaller options available if they provided effective remediation. For reference, the corresponding ΔV magnitudes of 7.6 cm/s, 15.2 cm/s, and 30.4 cm/s would produce changes in inertial position of 6 km, 12 km, and 24 km, respectively, at perigee and EI.

The CARA involvement for the 2023 Earth Return was more substantial than for the 2017 EGA. In the months leading up to arrival, there were numerous operational readiness tests conducted by the mission that required simulated CARA scenarios and products for both no-burn and CAM situations. While CARA routinely creates products for preflight simulations of Earth orbiters, the unique nature of the OSIRIS-REx mission required bespoke products. For operations, daily screenings of the nominal trajectories of the SRC and bus started 12 days out, and the six CAM trajectories (three CAM trajectories each for the two objects) were added to the screenings at three days out. The schedule for the final decisional ephemeris delivery is shown in Table 2.

Orbit crossing forecasting analysis (described later) was performed in the months and weeks ahead of entry to identify potentially risky crossings, particularly for the International Space Station (ISS) and Chinese Space Station (CSS). While this analysis showed the SRC would be clear of the space stations, there were many other opportunities for conjunctions through LEO for both objects.

Table 2. Schedule for final ephemeris delivery and screening for 2023 Earth Return.

Event	Hours to Entry	Hours to CAM	Date (UTC)	Comment
Deliver 8 ephems to CARA	46	33	9/22/23 16:41	2 no-burn & 6 CAM ephems.
Receive first CARA Report	40	27	9/22/23 22:41	Updates at ~0200 & ~1000 UTC.
Command Conference	21	8	9/23/23 18:00	CAM Go/No-go decision.
Start of CAM Upload Window	20	7	9/23/23 18:41	Passes at Canberra, Madrid.
CAM Execution	13	0	9/24/23 01:41	If needed.

The decision to perform a CAM was based on the requirements set forth in NASA Procedural Requirement (NPR) 8079.1[13] released in June 2023, that specifies a baseline conjunction mitigation threshold defined by a probability of collision (Pc) value greater than 1E-04 (1 in 10,000) with the post-remediation Pc reduced by 1.5 orders of magnitude to 3E-06 (1 in 333,333) or lower. If the secondary object were maneuverable, CARA would begin negotiation with the secondary owner/operator (O/O) three days in advance to determine right of way. If OSIRIS-REx were to perform the mitigation, the mission would choose the smallest magnitude CAM that clears the current high-risk conjunction and does not introduce others. Given that a CAM would change the trajectory of both the SRC and bus, there was a remote possibility that no option cleared both objects. While this scenario was considered in the pre-arrival testing, it was an extremely unlikely situation with three CAM options. With details to follow, it turned out that there were no high-risk conjunctions for either object.

PRE-ARRIVAL TESTING

The OSIRIS-REx team conducted numerous tests ahead of each key phase of the mission with collision avoidance being a key aspect of the 2023 Earth Return phase. However, performing conjunction analysis for the Earth encounters was not levied as a requirement during the pre-launch development phase. In fact, working with CARA and including the CAM option for the 2017 EGA was not added to the mission plan until after launch in 2016. With years to plan ahead for 2023, the option to include multiple CAMs was incorporated into the Earth Return mission plan well ahead of time. This section summarizes the CARA involvement in the pre-arrival testing for Earth Return.

Test Exercises

Beginning in April 2023, five months prior to Entry, CARA participated in three Operations Proficiency Integrated Exercises (OPIEs) and two Operational Readiness Tests (ORTs), the difference in the test types being the level of sophistication. An OPIE brought the project and external teams together for a table-top exercise to test simulated products from each team and the process for key decisions. An ORT brought all the teams together for a simulated scenario with sophisticated modeling in a spacecraft testbed, sometimes including anomalies, and was typically run in real time at the same time of day as the actual event.

For test interactions in general, CARA provides simulated conjunction summary reports containing content described in Reference 5, in which boilerplate products are customized to a scenario based on input from the mission or test director. In the case of OSIRIS-REx, there would be two separate reports: one containing conjunction information for the bus and one for the SRC. To roll up that information into one summary chart for the CAM decision meeting, CARA created a table of Pc values from the screenings of each of the eight ephemerides. An example from one of the OPIE tabletop exercises is shown in Table 3: the Ephemeris column indicates the CAM option, including the nominal no burn case; the Pc columns show the highest Pc (assuming only one conjunction would be notable) for the SRC and bus; the Combined Pc uses De Morgan’s law to compute the likelihood of either occurring; the CARA Recommendation is highlighted; and brief Notes are provided for each scenario.

Table 3 is an entirely fictional and unlikely scenario with high-risk events for all but the largest CAM option, resulting in an obvious tabletop decision to perform that CAM. In a different OPIE, CARA presented an even less likely scenario with a red (Pc >= 1E-04) conjunction in every row to foster discussion of relative risk acceptance: would the deciding factor be the combined Pc, the Pc for the SRC, the fact that no options were clear so there would be little value in performing a CAM, or some other factor? The mission opted in this case to favor lower risk to the SRC, but the discussion relied heavily on the specifics of the conjunctions, as would be the case in reality. Despite the highly contrived scenarios, the mission played along earnestly during the exercises and had valuable discussions in preparation for both nominal and stressing scenarios.

Table 3. Example summary table of simulated highest Pc conjunctions for 2023 Earth Return.

	Pc		Combined Pc		
Ephemeris	**SRC**	**Bus**	**1-(1-Pc1)(1-Pc2)**	**CARA Recommendation**	**Notes**
No CAM	1.70E-04	0	1.70E-04		SRC secondary object well tracked debris with consistent OD over last several updates
-0.5 sec	1.11E-05	2.52E-04	2.63E-04		Bus secondary object well tracked debris with consistent OD over last several updates
-1.0 sec	1.35E-04	6.76E-05	2.03E-04		SRC secondary object well tracked rocket body with consistent OD over last several updates
-2.0 sec	2.25E-08	8.52E-09	3.10E-08	<---	Only option that's green for both

Key

🟥	Pc >= 1E-4	Maneuver required by SRC/Bus or active secondary payload
🟨	1E-7 <= Pc < 1E-4	Watch
🟩	Pc < 1E-7	No concern

Field Code Changed

This table was presented during each test that conducted the CAM Go/No-go decision meeting, with simulated CARA reports being delivered in the days leading up to it during the "live" ORTs. While a limited number of simulations are routinely supported by CARA for Earth orbiting missions, OSIRIS-REx required more involvement than usual due to the unique nature of the mission, which included trying to coordinate both realistic and stressing CAM scenarios with the other mission teams in a way that produced a cohesive overall test. Going forward, the CARA team will define the level of involvement in these types of tests and interactions well ahead of time for Earth flyby/entry missions that typically know their testing and event schedule years in advance. Additional coordination and preparation time could lead to more realistic integrated scenarios.

CARA Screening Test

In addition to the project-level tests, CARA performed ephemeris delivery and screening tests with the OSIRIS-REx Flight Dynamics Systems (FDS) team. To run a screening test weeks ahead of time against the RSO catalog, it is not practical to propagate the catalog to the actual event time. Instead, the FDS team changed the time stamps on Earth-fixed ephemerides from the actual entry date of September 24, 2023, to August 30, 2023, to preserve the Earth-relative geometry at the earlier time. CARA then performed screenings of the eight ephemerides (bus and SRC, nominal and CAM options) at the end of August against the current catalog and reported the results.

The primary purpose of this test was to produce realistic operational products and conduct conjunction briefings with the FDS team so they would know what to expect during the actual event. It had been six years since the previous CARA interaction during the 2017 EGA, and the current situation was much more complex.

A secondary objective was to confirm the effectiveness of the CAM sizes in remediating a conjunction with a typical RSO. Since the maneuver magnitudes were chosen based on the flight time uncertainty of OSIRIS-REx, the covariance of the secondary object remained an unknown variable. This test screening did not produce a high-risk conjunction, but a debris object passed relatively close to the SRC. Changing the debris position to be the same as the SRC nominal position at TCA created a zero-miss scenario with a Pc of 3.6E-04 (1 in ~2800) due to the combined uncertainty of the two objects. Figure 5 shows a perspective view of the conjunction: the left panel shows the objects at the TCA of the nominal case with the SRC approaching from the southwest and the debris object approaching from the north; the right panel shows a closer view with the debris at the same location as the nominal SRC (zero miss), along with the locations of the CAM trajectories at that same time. The right panel also shows 3σ position uncertainty ellipses superimposed on each object. Note that the SRC uncertainty is much smaller than the OSIRIS-REx bus uncertainty used to size the CAMs, which is driven by execution uncertainty of the 65.5 m/s divert maneuver performed after SRC separation.

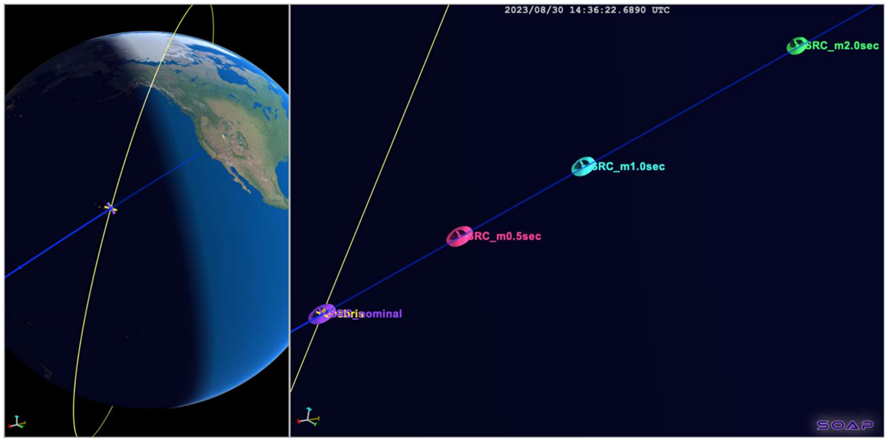

Figure 5. Simulated zero-miss conjunction between nominal SRC and debris object.

Since the CAMs are designed to cause the SRC to arrive earlier, the figure shows them to be past the original conjunction location by corresponding amounts ("_m0.5sec" = -0.5 seconds, etc.). In fact, in increasing ΔV order, they are 5.9 km, 11.8 km, and 23.6 km away, respectively, at the nominal TCA, slightly less than the targeted changes at entry due to this conjunction occurring several minutes prior. The actual close approach distances of the CAM trajectories to the debris object are less because the respective TCAs occur earlier, but in all cases, the Pcs resulting from the CAM trajectories are zero. While this is only a single sample, it provides a sanity check that the CAM strategy performs as intended and is likely to remediate typical conjunctions.

Finally, a test screening is important to confirm that the software does not filter out valid conjunctions due to the relative velocity being too high. With hyperbolic velocities in the 12 – 14 km/s range for Earth flyby/entry missions, the relative velocity with an Earth orbiting object can exceed 20 km/s. If the upper limit for filtering out high relative velocities is set too aggressively, the most potentially energetic collision risks would get thrown out.

ORBIT CROSSING FORECASTING ANALYSIS

The forecasting analyses were intended to provide an early look at the potential collision risk of the flyby and reentry trajectories. The results would not provide actionable data for maneuver planning but would provide a measure of the density and complexity of the space environment through which OSIRIS-REx and the SRC must pass. In 2017, the altitude of OSIRIS-REx was high enough that only MEO, some HEO, and GEO objects would be potential hazards. However, the 2023 flyby for OSIRIS-REx and entry for the SRC was deep within the LEO population and many more objects would pose a threat.

Orbit crossing forecasts began three months before the EGA in 2017, and six months before the 2023 encounter. A typical conjunction assessment would be of little value this far in advance because the in-track uncertainty would be too large. In addition, some of the “deep space” Earth orbit objects are not well tracked, resulting in much larger covariance, and those orbits are more affected by higher-order perturbations. Consequently, we chose to calculate the nodal separation between the mission trajectories and the orbits intersected by the trajectories. Nodal separation is one of the methodologies incorporated in the NASA Multi-mission Automated Deep-space Conjunction Assessment Process (MADCAP)[14] used as early as 2011 for conjunction assessment in environments beyond Earth, and a similar technique, called the “Launch COLA gap” that has been used since 2007 to protect the ISS.[15] The technique described here was also used for the Lucy Earth flyby in 2022.

In 2017, analyses were completed at three, two and one month before the flyby. A typical conjunction report for the day before the EGA was completed afterwards for comparison to the forecasts. Assessments for the 2023 flyby and reentry were completed six, three, and two months in advance, and then final assessments, including an object-to-object miss distance calculation were completed five days and one day before the flyby and reentry. These analyses also included a visualization of the intersecting orbits using the Satellite Orbit Analysis Program (SOAP). Once completed, the SOAP scenario could step through each intersecting orbit providing a visualization of the orientation of the orbit planes and the relative positions of the objects. A sample of the visualization, shown in Figure 6, illustrates a case in which the nodal separation is relatively small (79 km) but the predicted location of the object, in this case a rocket body, is almost at the opposite side of the orbit. The predicted location of the object has the greatest uncertainty, but it is unlikely to be near the node at the time OSIRIS-REx arrives.

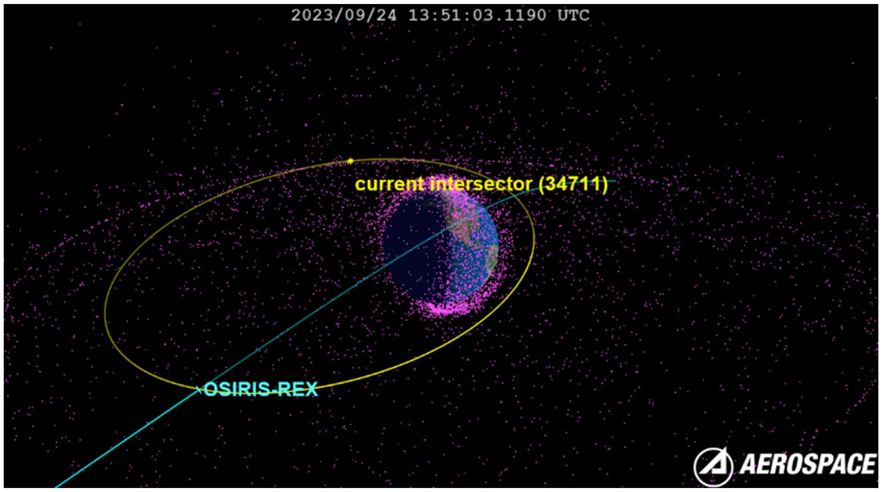

Figure 6. Nodal separation and relative position of an intersecting orbit.

To build the analyses, we start with a catalog of two-line element sets. Using this orbit data as an initial state, all objects are propagated using a high-fidelity integrator to create a set of state vectors at the beginning of the flyby. For our purposes, the flyby was defined as the interval when OSIRIS-REx was within 500,000 km of Earth. The integration parameters included a 4x4 EGM-

2008 gravity model with lunar and solar third body gravity included. Solar radiation pressure and drag were not included because reliable surface area data for most of the objects was not available.

With a catalog now propagated to the epoch of the approach, we calculate the times when the crosstrack position of the OSIRIS-REx bus or SRC relative to each RSO changes sign. From this list of intersecting orbits, an apogee filter is applied where an object apogee must be greater than or equal to 100 km below the bus/SRC at the time of the intersection. That is, filter out a secondary object if its apogee is more than 100 km lower than the altitude of the bus or SRC at the relative nodal crossing. This process, in the case of the 2023 flyby, reduced the number of objects that required further processing from an original count of 25,214 to a subset of 10,442 objects.

From the list of objects and the times at which the orbits intersect, the nodal separation is calculated using the intersecting orbit parameters and the position of the bus/SRC in the orbit-relative frame of the intersecting object. Finally, we can use the detailed orbit data to calculate the "time to node" of the RSO to provide an estimate of how close the RSO is to the relative node at the time of the bus/SRC crossing. This is the time it would take the secondary object to reach the relative node from its current position, taking the smaller of forward or backward motion, and is analogous to the angular difference divided by the mean motion for a circular orbit. The time to node gives a sense of how much the timing or intrack location of the secondary object would have to change over the remaining time until Earth encounter to arrive at the relative node at the same time as the bus or SRC, risking a collision depending on the nodal separation distance. The CAMs achieve their objective by altering the timing of the nodal crossing, so the time to node data provide important context for secondary objects that may pose a risk. The nodal separation and time to node values are summarized in spreadsheets so they can be easily sorted and filtered, and the same data can then be imported into a SOAP scenario for visualization.

The two primary goals of this forecasting analysis are to 1) identify the objects with the smallest nodal crossing distances to assess the number of objects with the potential for collisions independent of the object location relative to that node and 2) to identify objects with a combination of small nodal crossing distances and small time to node values relative to the orbit period as the objects with the most potential for conjunctions. This provides additional context to evaluating just miss distance far ahead of time since the crossing distance at the relative node, assumed to be relatively stable over time, indicates how small the miss distance *could* get at the point where the objects could actually collide.

2017 Earth Flyby Forecast

As expected with the high altitude of the OSIRIS-REx flyby in 2017, there were only a handful of orbits that had nodal separations less than 100 km as shown in the top five rows of Table 4. The June 2017 run was two and a half months prior to EGA, while the August 2017 run was one month prior. The September 2017 results are from the day before EGA and represent the knowledge at the time of a CAM decision. The bottom three rows of Table 4 show the objects with the smallest miss distances at the time of the day-before EGA run, none of which were a concern. Note that "N/A" in the table means that for that run the object did not pass the apogee filtering described above.

There was significant variation in the nodal separations among most of the orbits when comparing the early analyses with the last two from August and September. However, the consistency between the last forecast (August) and the conjunction report from the day prior (September) is quite good in every case. Most of these orbits are very large and highly elliptical, so it is likely that the fidelity of the propagation over a long period is the source of the discrepancies in the earlier forecasts.

Table 4. Nodal separation results for 2017 EGA.

Object ID	Object Name	Jun 2017 Nodal Separation (km)	Aug 2017 Nodal Separation (km)	Sep 2017 Nodal Separation (km)	Sep 2017 Time To Node (sec)
10089	SL-6 R/B(2)	735.1	20.8	15.1	19053.9
42458	CZ-3B DEB	124.4	30.7	44.0	-11431.1
7298	SMS 1	N/A	56.4	56.0	29872.8
13205	COSMOS 1367	1659.9	68.1	72.3	-7752.0
11623	TITAN 3C TRANSTAGE R/B	N/A	84.8	85.6	-17475.7
36406	SL-12 R/B(AUX MOTOR)	327.1	277.9	276.7	811.7
24876	NAVSTAR 43 (USA 132)	N/A	186.6	187.1	-1033.7
33473	SL-12 R/B(AUX MOTOR)	N/A	9574.5	9570.5	162.4

Table 5. OSIRIS-REx bus nodal separation results for the 2023 flyby.

Object ID	Object Name	Jun 2023 Nodal Separation (km)	Jul 2023 Nodal Separation (km)	Sep 2023 Nodal Separation (km)	Sep 2023 Time To Node (sec)
56276	CZ-6A DEB	18.6	1.4	3.7	-2998.0
136	THOR ABLESTAR DEB	11.9	2.6	2.8	-606.2
54491	CZ-6A DEB	7.8	3.1	7.5	84.5
29963	FENGYUN 1C DEB	26.3	5.1	7.5	1410.5
31113	HAIYANG 1B	12.8	6.3	16.8	2019.9
22551	SL-16 DEB	19.3	17.7	21.6	5.9
37658	DELTA 1 DEB	25.9	33.6	29.5	6.0
55819	ONEWEB-0658	36.3	30.3	27.0	9.0
54960	CZ-6A DEB	21	9.6	20.7	14.2
30244	FENGYUN 1C DEB	67.3	54.4	64.5	1.6
42181	COSMOS 1275 DEB	84.5	89.2	78.0	-4.3
54572	CZ-6A DEB	N/A	94.5	90.9	4.3
29360	COSMOS 1823 DEB	9.4	12.3	9.1	-14.9

2023 Earth Return Forecast

Parsing through the data in 2023 was much more difficult because the number of intersecting orbits was much greater. For the last analyses, the day before the Earth approach, there were 709 intersecting orbits with nodal separations less than 25 km for the OSIRIS-REx bus. In this case, there was much more consistency across the board for the intersecting objects. A sample of the nodal separation results for the bus is shown in Table 5. The top five objects in the table represent the minimum absolute time to node from the July 2023 run from the subset of crossings with a nodal separation less than 10 km. All five node timings were within 65 seconds at that time, compared to the values in the last column of Table 5 in the day-before run which show significant changes in timing except for object 54491. This is not an unexpected result, clearly demonstrating the relative stability of the nodal separations versus the variability of the nodal crossing times.

The last eight rows in Table 5 show the objects that appeared in the object-to-object conjunction report in order of their miss distance (see Table 7). Although there are only eight examples with miss distances less than 100 km, the correlation between nodal separation/time-to-node and a typical conjunction report is 100% in this case. Object 22551 was the RSO with the closet combination of nodal separation and time-to-node, and it also had the smallest miss distance at 43.8 km from the object-to-object conjunction report. The visualization of that intersection is shown in Figure 7. Note that in the July 2023 run, the time to node for Object 22551 was -1714 seconds, so the timing changed by almost 29 minutes in the intervening two months, further demonstrating the large variability possible in long-term predictions of intrack position.

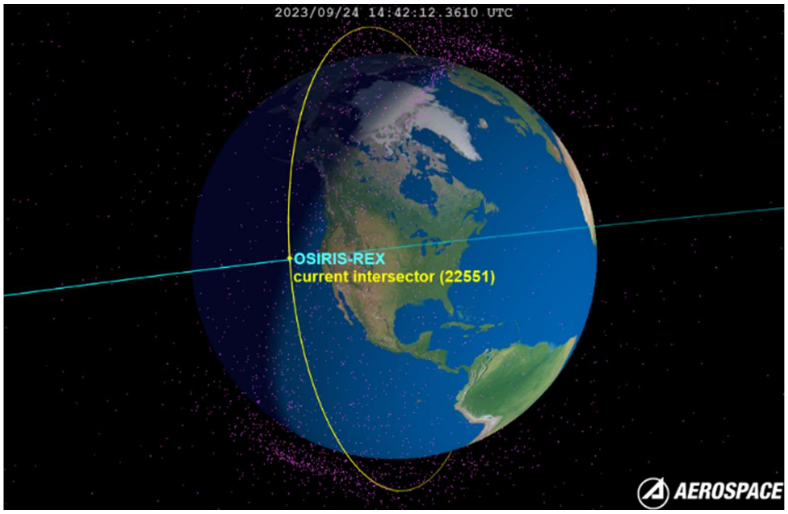

Figure 7. Nodal separation and relative position of the closest conjuncting object.

The results from the analysis for the SRC show 142 intersecting orbits with nodal separations less than 25 km, and a sample of the results are shown in Table 6. As with the bus results, the top five objects in the table represent the minimum absolute time to node from the July 2023 run from the subset of crossings with a nodal separation less than 10 km, but in this case ignoring SpaceX Starlink vehicles, which would maneuver away from the SRC if necessary. With fewer overall conjunctions with the SRC, there is a wider distribution in the timing of the top five nodal separations within 10 km, ranging from 181 to 1677 seconds. In all cases, the timing shown in the last column of Table 6 changed by hundreds of seconds over the two months. The nodal separations show some variability in this sample, as well.

The last two rows in the table show the smallest miss distances from the final conjunction screening (see Table 8), representing the smallest combination of nodal separation and time-to-node. Object 17017 had a time to node of 0.7 seconds and a nodal separation of 85.2 km, but had a miss distance of just 66.5 km. This may seem counter-intuitive; however, a look at the animated visualization shows that the SRC intersects the orbit plane at a steep angle vertically, but a shallower angle laterally, and they are both moving in the same direction. The orbit intersection occurs at 14:37:45.437 and the time of closest approach is almost 7 seconds later at 14:37:52.384. Object 57057, launched in June 2023, has a nodal separation of 5.9 km and a time-to-node of 13.4 seconds with the conjunction report showing a miss distance of 107.8 km.

Table 6. SRC Nodal Separation Results for the 2023 reentry.

Object ID	Object Name	Jun 2023 Nodal Separation (km)	Jul 2023 Nodal Separation (km)	Sep 2023 Nodal Separation (km)	Sep 2023 Time To Node (sec)
22971	TUBSAT B	24.9	0.1	18.5	2849.7
39627	CZ-2C DEB	16.2	1.0	1.1	-2610.1
7050	DELTA 1 DEB	4.8	1.4	1.9	-195.8
4276	THORAD AGENA D DEB	15.4	3.2	20.4	2418.5
33408	SHIJIAN 6 03A (SJ-6 03A)	19.1	3.8	6.4	1068.9
17107	COSMOS 1375 DEB	71.0	N/A	85.2	0.7
57057	STARLINK-6223	N/A	N/A	5.9	13.4

Overall, the results of the orbit crossing forecasting were mixed. The analyses provided a good sense of the number of orbits that the OSIRIS-REx vehicles would cross, e.g., not many for the 2017 EGA and hundreds for the 2023 flyby of the bus, within the context of specific potentially threatening objects. The results also identified secondary objects that would *not* be a concern, such as the International Space Station (ISS) and the Chinese Tiangong space station for the SRC trajectory. The nodal separation predictions showed tens of kilometers of noise at one to two months out, with less consistency for high eccentricity objects and longer prediction intervals. The nodal crossing times were interesting to trend in terms of confirming their volatility and do not offer substantial insight into which of the small nodal crossing objects would pose a risk. Results may improve with different long-term propagation methods, offering a potential avenue of further study.

OPERATIONAL SCREENING EXPERIENCE

This section focuses on CARA operations during the 2023 Earth Return. There were custom setups and output products beyond the typical Earth orbiter support that highlighted the need for

CARA to update the baseline of support for Earth flyby/entry missions. Such missions are rare but do happen every year or two, often enough to standardize the process.

Screening Volume Size

CARA does not have a baseline screening volume size specific to hyperbolic trajectories. A hyperbolic trajectory has a significant radial velocity magnitude as it descends to and ascends from perigee, unlike Earth orbiters with orbital motion mostly aligned normal to the radial direction (i.e., intrack). This means that typical rectangular prism or ellipsoidal volumes with significantly smaller radial components may not be appropriate, suggesting the use of a volume that is large in all three directions. The largest CARA volume is the one used for the highly elliptical orbit (HEO) regime at 40 km x 77 km x 107 km in radial, intrack, crosstrack (RIC) coordinates, followed by the geosynchronous (GEO) regime which uses a 40 km sphere. The Artemis lunar missions use a +/-50 km cube for Earth return screenings.[*] Any of these would likely be sufficient, particularly if the hyperbolic object is well tracked with realistic covariance, as is usually the case for NASA deep space missions. However, the question remained as to whether something might get missed.

Previous CARA studies of screening volume sizing[16,17] have endeavored to define them based on a 95% capture rate for "serious" conjunctions, but have not touched on the EGA regime, which makes sense given the infrequent cadence. So, it is unclear what size would be appropriate at the 95% confidence level. Without enough empirical conjunction events with this class of mission to develop a high confidence, a conservative approach would be warranted. CARA used the large HEO volume for past EGA support, but for OSIRIS-REx, opted to use a 250 km spherical volume that is sometimes used for launch screenings. This is a similar approach to the analysis in Reference 17 that used a custom 50 km x 250 km x 250 km RIC volume to ensure capture of events well beyond the expected 95% level in common CARA orbit regimes. While a 250 km spherical volume sounded good in theory, it proved to be a challenge in daily operations.

Screening Logistics

The operational screenings introduced several logistical challenges, including excessive run times, incorporating a non-standard screening volume, and separate screenings for the SRC and bus. For context, the flight time within the GEO altitude shell for the bus was 2 hr 48 min to its 783 km perigee and back out, and for the SRC was 1 hr 21 min to Entry Interface. Thus, there was a limited amount of time close to Earth during which the OSIRIS-REx objects could experience a conjunction, requiring the RSO catalog to be propagated all the way to the time of Earth encounter plus several hours to obtain any screening results.

The original intent to beginning screenings 12 days out as outlined in the support plan above was to evaluate the conjunction environment ahead of the final design of TCM-12, the entry targeting clean-up maneuver which executed at seven days out (see Figure 4). However, CARA commenced screening at 16 days out, ahead of the execution of TCM-11 at two weeks out. Conjunctions that far out, particularly in low LEO, would not be actionable from a collision avoidance standpoint due to the long propagation time, but the idea was to at least check if either maneuver would introduce a close approach. However, the RSO catalog is propagated only 10 days into the future for the twice-daily NONLEO (i.e., HEO, GEO, EGA) conjunction analysis, meaning the catalog had to be propagated for 16 days in a separate run. Coupled with the tremendous 250 km spherical screening volume, the process consumed an excessive amount of computing resources. The lesson here is that there is no need to screen beyond the nominal 10-day period when results

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[*] Stuit, Timothy (2023), personal communication on November 14, NASA JSC Flight Dynamics, Houston, TX.

that far out are not actionable, so the CARA process for supporting flyby/entry missions should restrict operational screenings to within 10 days of Earth encounter.

Another challenge was that the non-standard 250 km volume was not an option in the baseline CARA screening run, so even within 10 days to Earth encounter, the OSIRIS-REx screenings required two separate runs, one for the bus and one for the SRC. This was an unintended complication that caused the operators to spend additional time on the OSIRIS-REx analysis, with run times amplified by the large screening volume. One obvious lesson here is to use only screening volumes that are available in the CARA baseline for operations; studies of custom volumes can be accomplished offline. When evaluating special requests from a mission, CARA must consider the implications to the nominal workflow and the risk of unforeseen consequences. In addition, as is shown later, the 250 km volume did not result in any surprises, indicating in a single case study sense that one of the baseline large screening volumes could be sufficient for hyperbolic trajectories.

Despite these challenges, CARA was able to successfully screen the SRC and bus trajectories within 10 days of Earth encounter. Beginning at three days out, CARA produced maneuver screening analyses for the full set of eight ephemerides (nominal and three CAM options for both objects). No conjunctions of concern were identified for either object.

CARA Reports

The CARA automated system creates and sends out summary reports of every conjunction of a supported mission to the email distribution of that mission. In the case of OSIRIS-REx, the automated system could not be used because of the custom screening volume, so a manual Maneuver Screening Analysis (MSA) was performed instead for both objects. MSA was used from the beginning with the two nominal trajectories, and then incorporated the CAM trajectories at three days out. MSA only creates a report for conjunctions with Pc >= 1E-07, including the “yellow” or “watch” category of risk from 1E-07 <= Pc < 1E-04 and the “red” or “warning” risk levels at Pc >= 1E-04. Since no such conjunctions were encountered, no MSA reports were delivered to the mission; CARA operators would send an email after each screening stating that there were no events of concern for either object.

For a deep space mission unaccustomed to conjunction analysis reporting, additional context would help, particularly at such a critical phase of the mission. Based on the conjunction data output from MSA, CARA created a summary table of all the secondary objects that penetrated the 250 km volume to show what was “nearby” regardless of the risk level. Table 7 and Table 8 show the top 10 closest objects to the OSIRIS-REx bus and SRC, respectively, based on the final screening. The columns are primary object name, secondary object name and RSO catalog ID, TCA, miss distance, Pc, equatorial altitude of the primary at TCA, relative speed, and approach angle. The events are sorted by increasing miss distance. The closest object to the bus would pass ~44 km away, and the closest object to the SRC would pass ~66 km away. In all cases, the Pc values are zero or round to zero. This information provided important context to the mission to confirm that there were no conjunctions lurking just below a Pc of 1E-07 that might produce a late surprise. Going forward, CARA will incorporate this product into the baseline support for flyby missions.

Table 7. Top 10 closest objects to OSIRIS-REx bus for 2023 Earth flyby.

PRI	SEC NAME	SEC ID	2023 TCA (DOY UTC)	MISS (KM)	Pc	ALT (KM)	REL SPEED (KM/S)	APPR ANGLE (DEG)
Bus	SL-16 DEB	22551	267T14:42:13	43.86	7.42E-18	927.92	14.46	96.29
Bus	DELTA 1 DEB	37658	267T14:47:41	46.43	6.42E-48	970.00	15.62	106.62
Bus	ONEWEB-0658	55819	267T14:48:54	54.99	1.68E-24	1162.16	14.50	97.53
Bus	CZ-6A DEB	54960	267T14:42:30	60.18	1.62E-70	896.38	17.60	130.21
Bus	FENGYUN 1C DEB	30244	267T14:44:58	65.16	2.83E-44	773.88	14.20	91.26
Bus	COSMOS 1275 DEB	42181	267T14:45:56	83.59	6.57E-111	804.03	12.16	74.37
Bus	CZ-6A DEB	54572	267T14:44:20	92.98	2.96E-109	777.98	17.21	122.19
Bus	COSMOS 1823 DEB	29360	267T14:50:40	93.41	1.74E-100	1545.69	13.17	88.19
Bus	COSMOS 1275 DEB	39962	267T14:42:45	101.86	3.89E-60	871.97	10.26	59.45
Bus	FENGYUN 1C DEB	36681	267T14:44:27	103.92	3.68E-214	775.85	17.04	121.12

Table 8. Top 10 closest objects to OSIRIS-REx SRC for 2023 Earth entry.

PRI	SEC NAME	SEC ID	2023 TCA (DOY UTC)	MISS (KM)	Pc	ALT (KM)	REL SPEED (KM/S)	APPR ANGLE (DEG)
SRC	COSMOS 1375 DEB	17107	267T14:37:52	66.49	0.00E+00	955.22	7.41	36.71
SRC	STARLINK-6223	57057	267T14:39:24	107.83	0.00E+00	554.29	11.74	69.98
SRC	STARLINK-6211	57059	267T14:39:20	119.29	0.00E+00	571.37	11.66	69.46
SRC	STARLINK-3124	49456	267T14:39:02	126.99	0.00E+00	641.62	13.45	84.68
SRC	DMSP 5D-2 F13 DEB	40519	267T14:39:36	133.34	0.00E+00	508.25	12.00	70.89
SRC	STARLINK-4724	53702	267T14:40:04	141.73	0.00E+00	409.92	13.01	79.72
SRC	COSMOS 2251 DEB	33804	267T14:39:23	155.00	0.00E+00	559.07	8.50	44.37
SRC	COSMOS 2553	51511	267T14:34:40	161.62	0.00E+00	2027.07	7.85	43.60
SRC	STARLINK-30338	57718	267T14:40:29	172.84	0.00E+00	332.52	10.88	61.86
SRC	STARLINK-30133	56837	267T14:39:25	193.85	0.00E+00	552.32	11.58	68.67

CAM Go/No-go

As shown in the results above, there were no high-risk conjunctions in the operational screenings that would warrant a CAM execution. At the CAM Go/No-go decision meeting, CARA presented a summary table like in Table 3 but with all green and zero Pcs. That particular bespoke product that had to consider the risk to two separate hyperbolic objects is unique to OSIRIS-REx and does not have a use on foreseeable CARA missions. However, the experience of testing the decision process ahead of time and ensuring the criteria for executing a CAM are well defined for non-routine CARA missions will be incorporated into the baseline support for such missions.

CONCLUSION

This paper describes the NASA CARA conjunction screening experience for the OSIRIS-REx 2017 EGA and 2023 Earth Return and Entry. Even though no conjunctions of concern were identified during operations, the preparations, analysis, testing, and operations efforts successfully supported the mission while highlighting areas of improvement for supporting future Earth flybys. The key lessons can be summarized as follows:

- Clearly define simulation/testing and operations support for non-routine missions well ahead of time and clearly understand any special requests and their implications to the CARA system and process.
- Understand that orbit crossing forecasting analysis defines the conjunction environment in broad strokes and the results are subject to the limitations of long propagations.
- Develop a baseline for support of flyby and entry missions, including an appropriate screening volume and expanded reporting of results.

As the near-Earth space environment becomes increasingly congested, low-altitude flybys will experience increased collision risk, posing a threat not just to the high-value flyby mission, but to space safety in general due to the potential for creating a large amount of long-lived debris. The experience gained in supporting OSIRIS-REx will help CARA normalize its support for future flyby missions, ensuring successful conjunction assessment support and space environment protection for this type of mission.

ACKNOWLEDGMENTS

This work was performed under contract to NASA. The authors would like to thank the CARA Orbital Safety Analysts and CARA Operations Team for their dedication and hard work in supporting the testing and operational activities, particularly the off-nominal requests.

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