OSIRIS-REx Entry, Descent, and Landing Performance

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The Origins, Spectral Interpretation, Resource Identification, Security, Regolith Explorer (OSIRIS-REx) was the third mission in NASA's New Frontiers program. OSIRIS-REx launched out of Cape Canaveral, Florida on September 8, 2016, with a science goal to return a minimum of 60 g of a primitive asteroid's surface, specifically the near-Earth asteroid Bennu. The sample return capsule (SRC) successfully touched down at UTTR on the morning of September 24, 2023. The entry, descent, and landing (EDL) sequence had an off-nominal deployment of the parachute, but the spacecraft safely landed within the pre-flight prediction of the landing ellipse and the payload was safely recovered. This paper discusses the pre-flight EDL modeling and simulation and focus on predictions for EDL operations. Flight observations such as timeline are compared to the predicted timeline produced by the EDL simulation.

I. Introduction

The Origins, Spectral Interpretation, Resource Identification, Security, Regolith Explorer (OSIRIS-REx) is the first U.S. mission to retrieve a pristine sample of an asteroid and return it to Earth for further study. It was the third mission of NASA's New Frontiers program [1]. OSIRIS-REx launched from Cape Canaveral, Florida on September 8, 2016, with a destination of the primitive, near-Earth asteroid Bennu. The science goal of the mission was to return a minimum of 60 g of the surface of Bennu to Earth, allowing for scientists to potentially understand how the early solar system formed and how life began.

While close proximity operations (ProxOps) began in December 2018 [2], the sample collection was not attempted until October 2020. A Touch and Go (TAG) maneuver was successfully performed on October 20, 2020 to collect a sample of the asteroid's surface. With the sample collection and ProxOps complete, the OSIRIS-REx spacecraft departed Bennu headed for Earth in May 2021, for an entry, descent, and landing (EDL) scheduled for Sept. 2023. This nearly 29-month journey comprised many trajectory correction maneuvers (TCMs) to keep the spacecraft on target for an Earth reentry at the Utah Test and Training Range (UTTR). Over the course of final weeks preceding reentry, the ground operations team conducted numerous decisional analyses to determine if the OSIRIS-REx sample return capsule (SRC) was on the desired trajectory [3]. Ultimately, the choice was made for the spacecraft to release the SRC for Earth reentry, and the SRC successfully touched down at UTTR on the morning of September 24, 2023.

In this work, the modeling and simulation of the entry, descent, and landing (EDL) sequence is discussed. The EDL simulation was used pre-flight to verify performance against requirements for end-to-end concept of operations, and used during operations to help inform range safety about the landing area. In this paper, the focus is on the operational support and decisional analyses that were conducted for each vehicle maneuver in the final weeks prior to entry is detailed. The post-flight data that was captured is compared against the pre-flight predictions, and some remaining questions are addressed.

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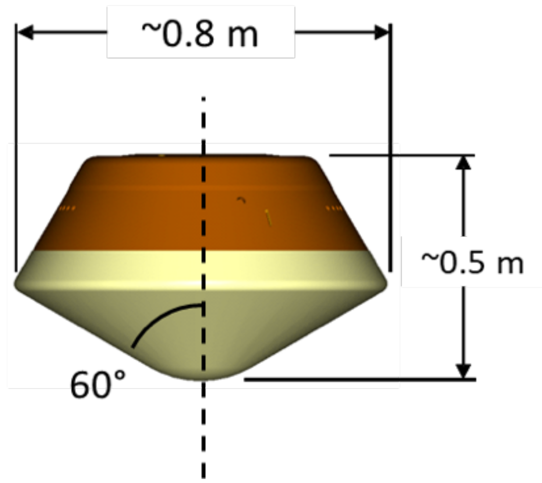

Fig. 1 OSIRIS-REx Sample Return Capsule geometry

II. Entry, Descent, and Landing Overview

The OSIRIS-REx flight system comprised an SRC and a spacecraft. The SRC and parachutes were build-to-print of the SRC and parachutes that successfully flew on the Stardust mission [4]. The outer mold line can be seen in Fig. 1, and is the same 60 degree half-angle forebody as Stardust. A disk-gap-band (DGB) parachute with a diameter of 0.8 m was used for the drogue, and the main parachute was a 7.3 m diameter triconic canopy. The empty SRC weighed approximately 50 kg, and was designed to contain a sample weighing up to 2 kg. Final estimates of the sample mass were 250 $\pm$ 101 g prior to entry [5,6], and the final measured mass after retrieval from the SRC was 121.6 g [6].

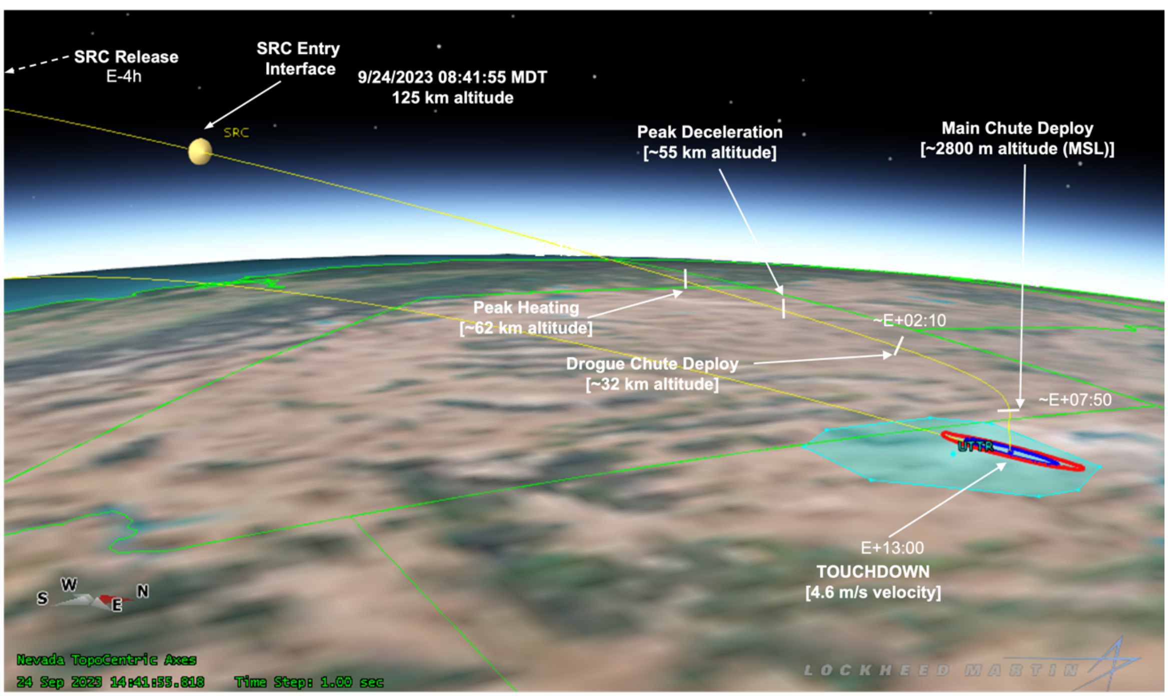

Fig. 2 Nominal EDL sequence for OSIRIS-REx SRC (from Ref. [5])

A. EDL Sequence

The nominal concept of operations for the EDL sequence can be seen in Fig. 2. The SRC released from the OSIRIS-REx spacecraft via a separation-spin mechanism 4 hours prior to atmospheric entry, which is defined at a radius of 6503.142 km from the center of the Earth. The separation-spin mechanism causes the SRC to spin to 13 revolutions per minute (rpm) at a separation velocity of 25 cm/s. For off-nominal situations, the design of the system allowed for releasing the SRC up to one hour later from the spacecraft, although this was not required on the day-of-flight. Atmospheric entry conditions were designed to occur at a flight path angle of -8.2 degrees with a velocity of 12.38 km/s. During the hypersonic and supersonic phases of flight, the vehicle was expected to experience a peak heating of 720 W/cm^2 and peak deceleration of 32 g's [5]. Next, the drogue parachute would deploy via mortar fire nominally at about 32 km altitude. Approximately 6 minutes after the drogue parachute deployment, it is cut from the SRC and the drogue pulls out the main parachute at an altitude of approximately 2800 m. The SRC remains on the main parachute until touchdown at UTTR with a vertical velocity of 4.5 m/s.

The parachute deployment sequence occurs autonomously via an on-board avionics system. Once the mechanical g-switch senses the SRC has reached a deceleration below 3 g's, the drogue parachute deployment timer begins. A signal is sent 14 seconds later to fire the drogue parachute mortar, initiating the inflation process of the drogue parachute. Approximately 363 seconds after the mortar fires, a signal is sent to cut the drogue parachute from the SRC. The drogue parachute releasing from the SRC pulls out the main parachute bag, allowing the main parachute to inflate. In the event this sequence does not occur nominally, a backup pressure transducer is monitored that can trigger the deployment of the main parachute. The pressure transducer was tuned to the approximate pressure at 10,000 ft mean sea level (MSL). This system is modeled in the EDL simulation and the choice of the avionics parameters are informed by the simulation results. Once the SRC has sensed touchdown, the main parachute will be cut to reduce the probability of the SRC being dragged across the desert at UTTR. This minimizes risk of sample containment breach.

Fig. 3 Models incorporated into the POST2 software to simulate EDL sequence.

B. EDL Modeling and Simulation

A tool called the Program to Optimize Simulated Trajectories II [7] was used for simulating the SRC EDL sequence. POST2 is a six degree-of-freedom flight mechanics software that can simulate multiple independent or connected rigid bodies, while incorporating models for many systems such as atmosphere, aerodynamics, etc. NASA LaRC develops and utilizes POST2 for missions of varying maturity (from conceptual phase to active flight operations), and missions with different solar system destinations [8, 9, 10, 11], including Earth-based missions such as Stardust [4] and LOFTID [12]. An alternate version of POST2, which branched from the LaRC version several years ago, was used by Lockheed Martin for EDL independent verification and validation purposes [5], but in this work only the usage by NASA for EDL applications will be detailed.

A six degree-of-freedom (6DOF) simulation of the EDL sequence began at one minute prior to atmospheric entry and ended with touchdown of the SRC at UTTR at a geodetic altitude of 1288 m. The models incorporated into the POST2 simulation are depicted in Fig. 3. The predicted state of the SRC (position and velocity) at one minute prior to entry interface is delivered to the EDL team from the maneuver design and navigation (MDNAV) team. SRC attitude was propagated from release to one minute prior to entry interface in a tool outside of POST2, and this result initialized the SRC attitude in the POST2 EDL simulation. For development and during operations, Earth Global Reference Atmospheric Model (GRAM) [13] was used, with an update from Earth-GRAM 2010 to the GRAM Suite in 2023. Atmosphere forecast modeling provided by the Goddard Earth Observing System (GEOS) [14] was incorporated into the simulation for the final ten days leading up to reentry, but it was not utilized for any decision-making purposes. The aerodynamic database was inherited from Stardust [15] since the outer mold line geometry was the same, and the aerothermal model used was the Sutton-Graves indicator [16]. Avionics for parachute deploys were modeled in the same way as they were for Stardust since the parachutes and avionics were build-to-print from Stardust. An oblate planet gravity model with the first 8 harmonics was utilized to model gravitational forces acting on the SRC during entry. Ephemeris information for the simulation initialization and trajectory output employed the Navigation and Ancillary Information Facility's (NAIF) Spacecraft, Planet, Instrument, C-matrix, Events (SPICE) interface to POST2.

Table 1 Description of Monte Carlo inputs for EDL simulation.

Model Type	Comments
SRC Entry States	Delivery from MDNAV, 3001 unique samples
Entry Attitude and Rates	Samples from propagated attitude separation, 1000 unique samples
Atmosphere	Random seed within GRAM Suite + Range Reference Atmosphere 2019
Capsule Aerodynamics	Uniform and normal distribution of inputs for OSIRIS-REx aero database
Parachute Aerodynamics	Uniform distribution for drogue and main parachute drag coefficient
Mass Properties	Cylindrical, uniform, and normal distribution on inertia, mass, and center of gravity
Ablation Mass	Normal distribution on ablation mass
Avionics	Uniform distribution for g-switches, normal distribution on voltages

For each new entry condition provided by MDNAV, Monte Carlo Simulations (MCS) were performed to generate statistics on specific metrics of interest such as landing ellipse. A total of 3001 trajectories were propagated from one minute prior to entry interface to touchdown, where samples were randomly drawn from the distributions outlined in Table 1 to determine how the models would behave for that particular trajectory. The 3001 case Monte Carlo corresponded to the number states provided by the MDNAV team and was similar to what was done for the Stardust simulation [17].

III. Decisional Analyses for Operations

Each potential maneuver for the spacecraft had a specific set of decisional analyses conducted in order to inform the project of key metrics from each subgroup team (spacecraft, MDNAV, EDL, etc.). These potential maneuvers comprised TCMs, collision avoidance maneuvers (CAMs), and ultimately the release of the SRC from the OSIRIS-REx spacecraft.

Table 2 Potential maneuvers performed by the spacecraft leading up to reentry.

Maneuver Type	Potential Completion Timeline	Execution Status	Comment

TCM-11	E-14 days	Executed	23.814 cm/s dV, first maneuver to target Earth reentry
TCM-12	E-7 days	Executed	0.30 cm/s dV
TCM-13	E-31 hours	Not Executed	TCM-12 was completed successfully, and no collision concerns existed
SRC Release	E-4 hours	Executed	31.3-33.6 cm/s dV

Prior to each possible trajectory event listed in Table 2, the EDL team completed multiple MCS that covered all envisioned potential scenarios for that event. The MDNAV team delivered a set of SRC entry states encompassing burn and no-burn with a nominal SRC release, as well as burn and no-burn with releasing the SRC one hour later than planned. Many of the operations decisions were to determine if a TCM (or a burn) was needed, hence most scenarios had these two cases. The entry states were inputs for the POST2 simulation and then propagated to the ground. This process was repeated for multiple days leading up to each major event, with new orbit determination (OD) solutions providing the MDNAV team with updated spacecraft relative position information. Additionally, there was potential for the process to be iterative if the solution provided by the EDL team suggested that the MDNAV team needed to retarget the maneuver. While a retargeting was not needed during actual EDL operations, the process was exercised during an off-nominal operational readiness test (ORT) prior to active flight operations.

During operations, the timeline was crunched with multiple sets of MCS that needed to be executed each day within a few-hour window, so autonomy and efficiency was critical to the success of the EDL team. Compute resources at NASA LaRC were leveraged to complete these analyses, where the EDL team was given priority access to 3001 central processing unit (CPU) cores. These resources allowed for all 3001 trajectories for each scenario to be simulated simultaneously, enabling a rapid turnaround on EDL performance metrics. The process of starting the MCS and generating deliverable products was cumbersome and prone to human error. Therefore, the EDL team leveraged an automation platform called Jenkins (Ref. [12] discusses usage of this for other projects) to eliminate the human error component that could be introduced into the process; once the entry state file (ESF) was delivered by MDNAV to the EDL team, the file was transmitted to the Jenkins framework, and the EDL MCS, post-processing, and product generation was completed without direct interaction by the flight mechanics analysts. This workflow allowed for the automation the output, leaving the EDL team members to analyze the results in detail to ensure that data reflected the expected behavior of the SRC.

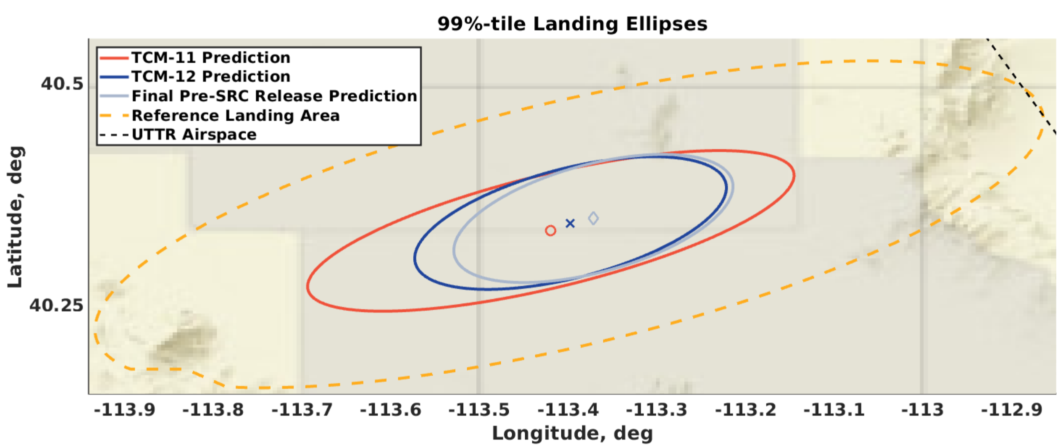

Fig. 4 Landing ellipse prediction evolution as major trajectory events occurred.

For each potential maneuver from 14 days before entry interface (E-14 days) until SRC release, a Go/No-Go meeting was held by the project to determine if that maneuver would be executed. The primary performance metrics for the EDL team included entry interface conditions, peak heat rate and integrated heat load indicators, peak deceleration, parachute deploy conditions, and SRC touchdown conditions. These metrics were presented to the project along with the EDL team's recommended either Go or No-Go recommendation. For SRC release specifically, the metrics were condensed to peak heat rate, integrated heat load indicators, and peak deceleration for SRC survivability purposes, and the percentage of cases that landed within the Reference Landing Area (RLA) as the key metrics for SRC recovery and public safety. During the design phase, the targeted landing ellipse was 84 km x 20 km centered at the landing target. However, prior to entry the targeted landing ellipse was extended due to analysis completed in 2022 and early 2023 detailing off-nominal scenarios, and the agreed upon RLA had dimensions of 95 km x 30 km.

Table 3 Predicted landing ellipse size progression with trajectory events.

Maneuver	Landing Ellipse Dimensions
TCM-11 Prediction	48.72 km x 13.93 km
TCM-12 Prediction	32.08 km x 13.61 km
Pre-SRC Release Prediction	28.21 km x 13.19 km

The first maneuver analyzed by the EDL team was TCM-11, which was the first maneuver that was meant to put the SRC on a trajectory that targeted Earth, making it the only maneuver that was mandatory. TCM-11 was completed 14 days prior to SRC entry. TCM-12 was the second maneuver to be considered, meant to more precisely target the landing target, and it was deemed an optional maneuver. However, the benefits of TCM-12 outweighed the potential drawbacks of firing the thrusters again, and TCM-12 was completed seven days prior to SRC entry. The final corrective maneuver considered, TCM-13, was scheduled for E-31 hours and was meant as either a backup opportunity to complete TCM-12 or was only needed if a CAM was deemed necessary. CAM was a maneuver considered if OSIRIS-REx had a non-negligible probability of colliding with objects in near-Earth orbits before EDL. Since TCM-12 was successfully completed on September 17th and there was no need for a CAM, TCM-13 was not executed.

A progression of landing ellipses during the EDL approach phase is shown in Fig. 4, and the landing ellipse dimensions, stated as 99 percentile confidence interval, for each maneuver are listed in Table 3. Each event resulted in a predicted landing ellipse well within the RLA, with the final pre-SRC release prediction being 28.21 km x 13.19 km.

Finally, a day before planned entry, the decision was made to release the SRC from the OSIRIS-REx spacecraft on September 24, 2023. For the final decision, each critical EDL metric had 100% of MCS cases within the desired criteria, except for peak heat rate indicator, which showed that ten out of 3001 cases exceeded a peak heat rate of 763.30 W/cm^2. However, violation rate of the heating rate indicator was not large enough to affect the Go/No-Go decision.

IV. Post-Flight Observations and Comparisons

Although, the SRC had a safe touchdown at UTTR on September 24, 2023, the entire EDL sequence was not nominal. Release of the SRC from the spacecraft appeared nominal, and the spacecraft team reconstructed the event to show the SRC spun slightly faster than the design value at 13.27 rpm vs. 13 rpm nominally at a relative velocity of 31.3 cm/s which was lower than the design value of 35 cm/s. There were also some anomalies with radar tracking of the spacecraft during EDL, and the SRC was not tracked via during EDL. Thus, flight observables to reconstruct a trajectory or compare to pre-flight predictions are scarce. That said, the SRC trajectory appeared to be within the predicted range from release until the drogue parachute mortar was nominally supposed to deploy.

A. Parachute Anomaly

The nominal parachute sequence is detailed in Section II, but this sequence did not occur on the day-of-flight [5]. Due to an issue due to a mismatch in nomenclature, the word “main” was used to mean two different events by different subsystem groups throughout development of the spacecraft [5]. One group used main to refer to the primary pyrotechnic event, the drogue parachute mortar fire. However, another group used main to refer to the larger parachute that the SRC descends on until touchdown, or the main parachute. This inconsistency between groups caused a critical failure in how the avionics were wired so that when the “main” signal was sent, the drogue parachute was cut from the SRC while still stowed in the parachute cannister instead of firing the mortar to deploy the drogue parachute. Without the drogue parachute, the SRC appears on video to not be able to maintain stable flight through the subsonic regime and began to reach higher angles of attack than expected. Unfortunately, since SRC was not instrumented and radar tracking was unsuccessful, the information here is based on low-resolution video. After the drogue parachute deployment anomaly, the SRC continued to descend towards the UTTR desert floor without a parchute, and the nominal timeline for the main parachute deployment was bypassed. The main parachute finally deployed based on the backup pressure transducer signal for the drogue. At the point of the backup pressure transducer signal, the mortar was fired, which also deployed the drogue parachute; however, since the drogue parachute had already been cut from the SRC, it immediately pulled the main parachute out with it resulting in a successful inflation of the main parachute. Ultimately, the SRC descended to a gentle touchdown at UTTR with the assistance of the main parachute, but it would not have been able to without the backup pressure transducer.

Without the drogue parachute, the SRC appeared to experience unstable flight for several minutes of flight. The higher angles of attack resulted in a lower drag force acting on the SRC, causing the SRC to touchdown much faster than expected.

Table 4 Pre-flight SRC release predicted timeline compared to observed timeline, time since entry interface.

Timeline event	1 %-tile [s]	Mean [s]	99 %-tile [s]	Flight Observed [s]	Delta from Mean [s]
Drogue Mortar Fire	129.13	132.57	136.28	330.358	197.788
Main Parachute Deploy	460.86	476.38	484.91	332.228	-144.152
Touchdown	701.48	811.16	934.31	615.1	-196.06

B. Timeline

The difference between the pre-SRC release predicted and observed timelines is listed in Table 4. Mortar fire to deploy the drogue parachute occurred approximately 198 s later than the EDL simulation predicted. Due to the parachute anomaly, the decreased drag caused the main parachute to deploy 144 s earlier than predicted (in terms of time since entry interface), which resulted in a trajectory that completed 196 s faster than expected. The observed trajectory was approximately 75 seconds faster than the one percentile value of the MCS cases.

Table 5 Reconciled SRC release with corrected parachute sequence timeline compared to observed timeline, time since entry interface.

Timeline event	1 %-tile [s]	Mean [s]	99 %-tile [s]	Flight Observed [s]	Delta from Mean [s]
Drogue Mortar Fire	380.96	391.56	398.76	330.358	-61.206
Main Parachute Deploy	381.09	391.69	398.89	332.228	-59.466
Touchdown	714.79	788.42	875.94	615.1	-173.32

Table 5 shows the difference in timeline when the actual parachute sequence with the drogue anomaly is simulated in a post-flight reconciliation simulation where the reconstructed SRC release entry states are also used as initial conditions. Both the drogue and main parachutes deploy approximately one minute slower than what was observed in flight, and the overall trajectory is 173 s longer than what was observed. Due to still mismatches between the simulation prediction from the reconciled trajectory and flight observables, it can be gleaned that the parachute anomaly was not the only contributor to the much faster timeline.

C. Atmospheric Properties

As described in Section II, the atmospheric model used in the POST2 EDL simulation was Earth-GRAM within the GRAM suite. Earth-GRAM was used during development through active flight operations and for Stardust development [17]. While Earth-GRAM is an ideal tool during development, it may not be optimal for flight operations, especially those which require a recovery. Earth-GRAM blends data from multiple sources to provide an estimate atmospheric profile based on long term averages. However, these averages do not always contain data from the most recent years, and they are averages that are meant to be bounding and conservative, but maybe not always precise. The use of forecast models, such as GEOS may provide a better option for a more precise landing location, given than the atmospheric profile being used is based on measurements and data taken from the most recent days instead of averaging over many years. See Ref. [18] which discusses the usage of forecast atmospheric data for recent Earth EDL missions.

Table 6 Reconstructed SRC release with corrected parachute sequence and GEOS atmosphere timeline compared to observed timeline, time since entry interface.

Timeline event	1 %-tile [s]	Mean [s]	99 %-tile [s]	Flight Observed [s]	Delta from Mean [s]

Drogue Mortar Fire	380.29	390.92	399.28	330.358	-60.56
Main Parachute Deploy	380.43	391.05	399.41	332.228	-58.82
Touchdown	750.34	782.87	814.55	615.1	-167.77

In the days leading up to entry, the GEOS atmosphere was included in the EDL simulation, but the results of the GEOS atmosphere in the loop were not used for decisional purposes. However, there was a clear trend of the atmospheric density being much lower than was Earth-GRAM was predicting, especially during the deceleration pulse [5]. Table 6 shows how the addition of using GEOS as the atmospheric model affects the timeline. Overall, the only significant impact is to the timing of the complete trajectory, which is approximately 167 s slower than the observed timeline (6.5 s faster than when Earth-GRAM is used).

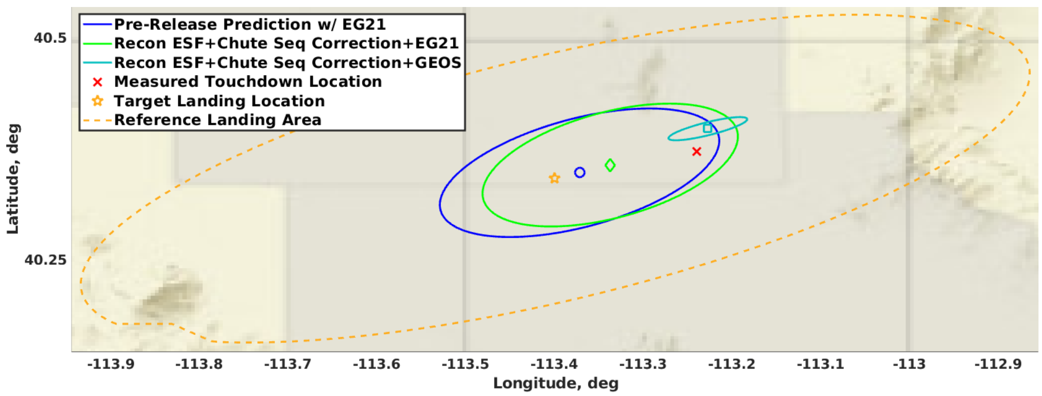

Fig. 5 Landing ellipses for different simulation scenarios.

The incorporation of the GEOS atmosphere does little to correct the timeline, but it does move the landing ellipse to be close to the measured touchdown location, depicted in Fig. 5. The two ellipses generated from using Earth-GRAM contain the touchdown location point while the GEOS ellipse does not; however, the GEOS touchdown locations are an average of approximately 2.5 km from the measured touchdown location, while the Earth-GRAM points are on average 9 km away. In a scenario where recovery operations are critical and knowing a more precise location of where to set up the recovery team is imperative, utilizing forecast models like GEOS may provide a more accurate touchdown location prediction.

In terms of biggest impact to the trajectory timeline, the reconciliation to the actual parachute sequence seen in flight due to the drogue deployment anomaly has the largest effect. The use of a forecast atmosphere, such as GEOS instead of global models like Earth-GRAM, had the most significant effect on landing ellipse location. However, the combination of the reconstructed entry states, corrected parachute sequence, and forecast atmosphere still did not reconcile the discrepancy in time of flight of 168 s between simulation predictions and flight observations. A key part of the SRC flight that is not accurately captured by the EDL simulation currently is the higher angles of attack experienced by the SRC during the unsteady phase experienced after the drogue did not deploy on time. The simulation does not show high angles of attack, even with no drogue parachute modelled. Results are shown in [5] where the pitching moment coefficient is arbitrarily increased by a factor of 9.5 to induce high angles of attack, yielding a trajectory that closely resembles the SRC trajectory timeline. However, there is no aerodynamic computation effort that has justified such a discrepancy in the pitching moment coefficient in the aerodatabase. If there is a follow-on to an OSIRIS-REx like flight, further wind tunnel tests may be needed to update the aerodynamic database.

V. Summary

The OSIRIS-REx mission successfully returned a sample from the near-Earth asteroid Bennu on September 24, 2023. This paper details the EDL portion of the SRC trajectory and how it is modeled within the POST2 simulation. EDL metrics that were critical for decisional purposes are discussed, as well as how POST2 is used to calculate the statistics of those metrics. Although flight observables were sparse, comparisons to the observed timeline and landing location are shown, and differences in timeline are highlighted. The parachute anomaly was a major reason the SRC trajectory was off-nominal, since the drogue not deploying properly caused the SRC to experience unstable flight through the supersonic regime. Another discrepancy that was identified was a difference in atmospheric profiles being used for design and operations compared to atmosphere from forecast models.

A trajectory reconciliation effort is attempted here and in Ref. [5], but since the SRC was not instrumented and radar tracking measurements were unsuccessful, many discrepancies remain unanswered. An open question remains about the SRC angle of attack at main parachute deployment. Video observations suggest high angles of attack. Since the parachute deployed on the backup pressure transducer and there is very little data to produce a full trajectory reconstruction, the angle of attack at main parachute deploy has not been determined. Additionally, if the main parachute deployed at a higher angle of attack than the parachute system was designed for, and it was a successful inflation, this observation could have impacts on future missions that utilize parachute systems.

Acknowledgments

The authors acknowledge the significant partnership with the members of the EDL team from Lockheed Martin, Mark Johnson and Scott Francis.

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