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ENTRY, DESCENT, AND LANDING ANALYSIS FOR THE OSIRIS-REX SAMPLE RETURN CAPSULE

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The Origins, Spectral Interpretation, Resource Identification, and Security – Regolith Explorer (OSIRIS-REx) sample return capsule (SRC) returned to Earth on September 24, 2023, safely landing in the Utah Test and Training Range (UTTR). To ensure a safe and successful landing, a pair of high-fidelity EDL simulations, based on the Program to Optimize Simulated Trajectories (POST) architecture, were used to regularly assess the latest orbit determination (OD) solution from the navigation team, making predictions on Entry, Descent, and Landing (EDL) performance and SRC landing location. The results from these analyses fed into the decision processes for the final trajectory correction maneuvers (TCM's) and SRC release. The models and methods of analysis will be discussed and a comparison of the final pre-entry landing prediction against the observed landing location will be presented along with an assessment of the best estimates of day-of-entry environmental conditions.

INTRODUCTION

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[1].

After successfully acquiring a sample from the surface of Bennu in October 2020, the OSIRIS-Rex spacecraft departed in May 2021 and began a nearly 29 month journey back to the Earth[2]. Several trajectory correction maneuvers (TCM's) were conducted during this period to refine the spacecraft's course and target a return to the Utah Test and Training Range (UTTR). The ground operations team conducted multiple decisional analyses during the final two weeks, confirming that the spacecraft was on the desired trajectory and that the entry would be within the design capabilities of the sample return capsule (SRC).

The SRC was released four hours prior to atmospheric entry interface (EI) by a "sep-spin" mechanism on the spacecraft, which imparted a spin to the capsule which kept it pointed in the correct orientation for entry. Atmospheric entry was predicted to occur at 14:41:54 UTC, at which point the SRC was expected to experience a deceleration of approximately 40 g's prior to deploying two parachutes to stabilize and slow its decent to a gentle touchdown in UTTR.

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Radar tracking and camera video data were planned to have been collected to aid the reconstruction of the entry and descent, however only video was ultimately captured. This paper will describe the simulations and models used to assess the predicted performance of the SRC during its entry and descent as well as a summary of the observed sequence of events made from the available video sources. Finally, a discussion of the anomalous parachute deploy sequence is made, with the entry, descent, and landing (EDL) simulations used to best estimate a trajectory that supports the observed timeline. A future paper is expected where novel video processing techniques are applied to better estimate the actual SRC trajectory.

MISSION OVERVIEW

The OSIRIS-Rex flight system consisted of a spacecraft and sample return capsule. The spacecraft hosted a sample collection system – a robotic arm with a sample cannister at the end – that made contact with the surface of Bennu. Upon contact, a nitrogen gas bottle was expended to mobilize the regolith, which was then captured in the sample cannister. Once the sample was collected, the SRC backshell was opened, the cannister stowed inside, and the aeroshell was closed in preparation for Earth entry.

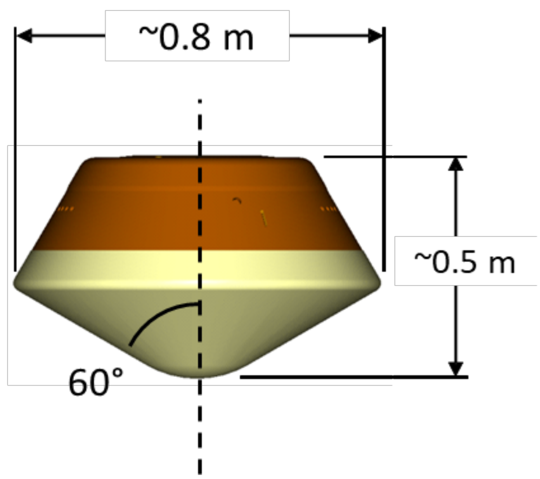


Figure 1. Geometry of the OSIRIS-REx Sample Return Capsule.

Approach Overview

The final approach phase was considered to be the two week period starting with the design and execution of TCM-11 and culminating in the entry and landing of the SRC at UTTR. Within this period, near-daily assessment of the entry trajectory and EDL performance was conducted to determine performance trends and ensure the operations team was not surprised by the evolution of the trajectory at the critical SRC release decision point.

A summary of the planned and executed TCM's is listed in Table 1. TCM-11 was mandatory, since it was the maneuver that actually targeted the desired Earth entry trajectory for the first time. TCM's 12 and 13 were "as-needed" – executed if the trajectory needed to be adjusted to meet requirements. There was also a possible TCM (TCM-13) to avoid a collision with other Earth-orbiting objects, or clean up any significant residual targeting errors, but that maneuver was ultimately not needed.

Table 1. The possible major trajectory events occurring prior to entry interface.

Event	Event Time	Executed?	OD	Comment
TCM-11	E-14 days	Yes	OD367 (final design)	23.814 cm/s
TCM-12	E-7 days	Yes	OD372 (final design)	0.30 cm/s
TCM-13	E-31 hours	No	OD379	No collision concerns
SRC Release	E-4 hours	Yes	OD380 (decision mtg)	Nominal release time

Prior to each TCM opportunity and the final SRC release event,, a "Go/No-Go" meeting was held, where the operations team would present their assessment of the current state of the spacecraft, approach trajectory, and predicted EDL performance. Any of these areas could drive the need to perform a maneuver, or prevent a maneuver from happening. This paper focuses on the analysis conducted by the EDL team in support of these decisional events.

One of the key EDL metrics used in the decision process was the predicted landing ellipse with respect to predetermined boundaries. During the design phase (pre-launch), an 84 km x 20 km ellipse centered at the landing target was used as a constraint to ensure the SRC performance uncertainties (primarily driven by entry flight path angle, atmospheric, and aerodynamic errors) were sufficiently bounded to result in a safe entry at UTTR. Later, during the months leading up to entry, a slightly larger reference boundary (elliptical, with a small cutout to avoid populated areas) was negotiated with UTTR that added margin to account for navigational uncertainties that could otherwise have increased the likelihood of a late TCM. Figure 2 shows the progression of some of the key decisional landing ellipses during the last two weeks before entry with respect to these constraints.

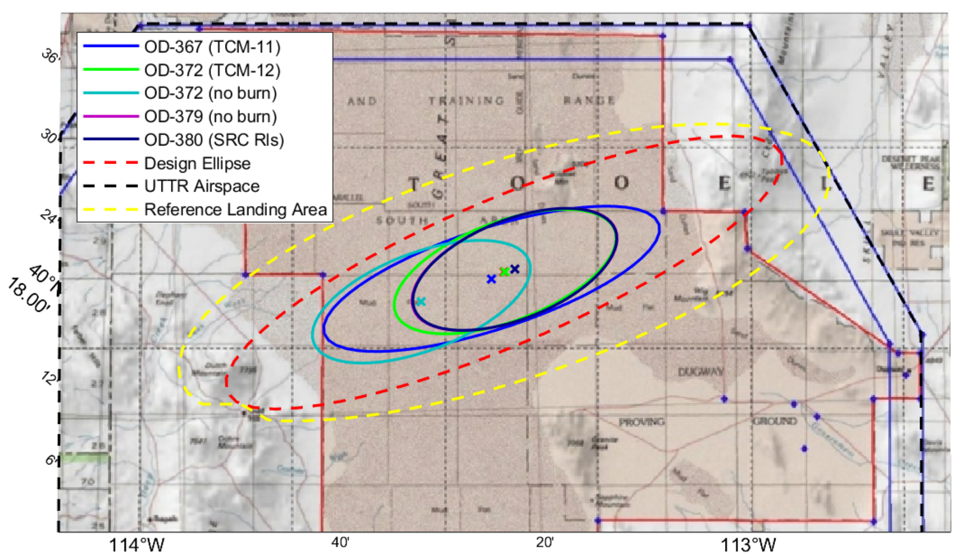


Figure 2 - Progression of Decisional Landing Ellipses (with and without TCM's) During Final Approach

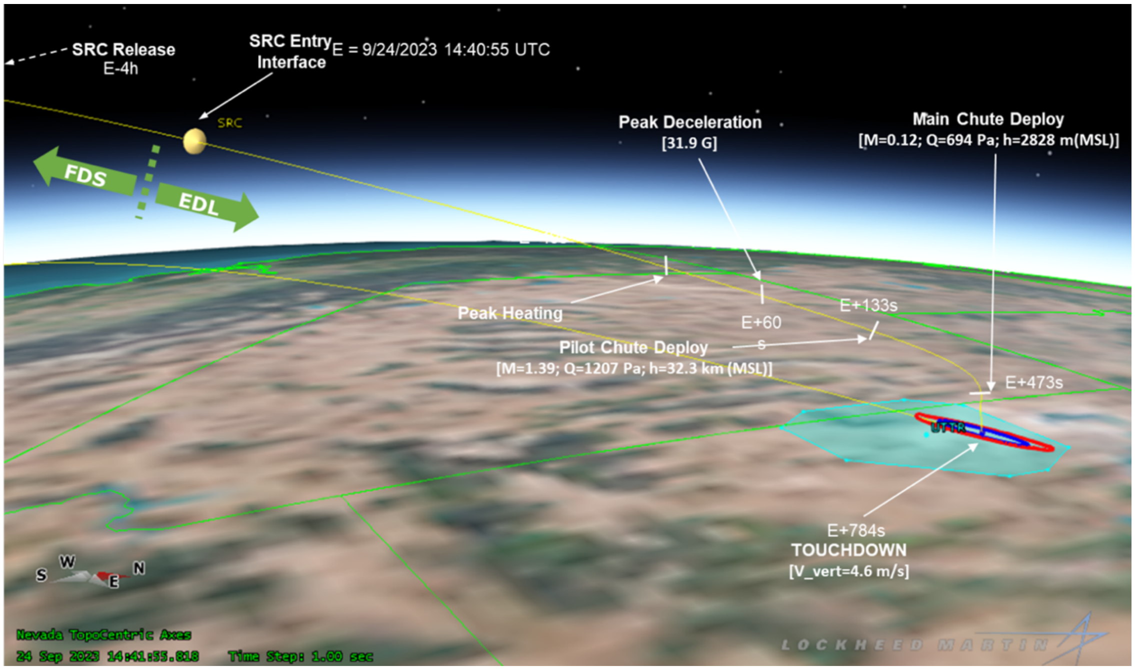


Figure 3. Notional concept of operations for the OSIRIS-REx Sample Return Capsule.

Entry Overview

The OSIRIS-REx SRC is a near copy of the SRC successfully flown on the Stardust mission[ref]. The outer mold line geometry (see Figure 1) is the same 60 deg half-angle forebody, it has the same maximum diameter, with the bulk of the differences being related to the sample collection hardware. The Thermal Protection System (TPS) configuration is the same as well, using Phenolic-Impregnated Carbon Ablator (PICA) for the heatshield and SLA-561V on the backshell, with build-to-print thicknesses. The avionics are identical, save for parts obsolescence issues. The parachutes are also build-to-print, with a 0.8 m diameter Disk-Gap-Band (DGB) for the drogue, and a 7.3 m diameter triconic canopy for the main.

The SRC was designed for a maximum entry mass of 55 kg, which included a collected sample of up to 2 kg. The as-built empty SRC was weighed at 49.64 kg, and the best estimate of the sample mass is 250 +/-101 g [ref].

The SRC entry phase begins with the release of the capsule from the spacecraft bus, nominally at four hours prior to EI, and concludes with touchdown in the UTTR. A one hour window for SRC release was designed into the mission operations process to accommodate delays resulting from off-nominal scenarios. The SRC was released at 10:41:55 UTC in the early morning of September 24, 2023 via a separation/spin mechanism, which imparts both a spin of the capsule (nominally 13 rpm) and separation velocity (nominally 35 cm/sec). The probe is passive and there is no attitude control. The spin rate provides gyroscopic stability to keep the SRC spin axis stably oriented during the four hour coast to minimize angle-of-attack when sensible atmosphere is reached. Mass properties variability and tip-off rates at separation will result in several degrees of nutation by the time entry interface is reached. Later reconstruction of this event by the spacecraft operations team indicated that the SRC was released with a 13.27 rpm spin and a 31.3-33.6 cm/s relative velocity. This was slower than expected given the observed mechanism temperatures, but within the analyzed design range. No explanation for the observed velocity has yet been developed.

After release, the spacecraft performed a divert maneuver of 65.5 m/s to put the spacecraft bus on a flyby trajectory where it would later continue on to perform as the OSIRIS-APEx mission[3]. This maneuver executed nominally.

A diagram of the nominal sequence of events is shown in Figure 3. The approach trajectory is nominally targeted such that the SRC crosses entry interface (6503.142 km radius) with an inertial flight path angle of -8.2 deg +/-0.08 deg. Additional analyses conducted in 2023 supported widening of that range to approximately 2 times the design value. The peak heating and peak deceleration load requirements are inherited from Stardust (build-to-print), so the mission design was constrained to find approach trajectories with velocities < 12.4 km/sec. This velocity is slightly lower than that used by Stardust (12.8 km/sec), but was adjusted to compensate for the heavier design mass of the OSIRIS-REx SRC (55 kg vs 45.8 kg).

The parachutes are deployed by avionics utilizing hardware G-switches, a charging circuit to facilitate arm/fire logic, and hardware timers. A pressure transducer is also present for main chute deployment, if needed. All avionics cards are redundant with the exception of the main chute cutter. The deployment process is as follows:

- A pair of mechanical G-switches are used to sense the deceleration pulse during entry. Upon rising past 3-g's (nominal), the switch closes and the charge circuit begins charging. Once past an upper threshold value, the circuit is considered armed.
- As the SRC slows and entry deceleration decreases below 3-g's, the switch will reopen and the charge circuit will begin to discharge. Once the voltage falls below a lower threshold, the circuit is considered to have "fired". This initiates a timer-based sequence of events.
- Approximately 14 seconds after trigger fire, a signal is sent to fire the drogue chute mortar.
- Approximately 363 seconds after trigger fire, a signal is sent to release the drogue and deploy the main chute.
- A pressure transducer is also monitored as an alternate means of deploying the main chute. It was tuned to a pressure corresponding to 10000 ft Mean Sea Level (MSL). Whichever method indicates first (timer or pressure transducer) will initiate the main chute deployment.
- Upon impact with the ground, a 10-g switch will activate and cause the main chute bridle to be cut, minimizing the risk of the SRC being dragged across the ground if high winds are present.

The trigger characteristics are "hard-wired" and were defined prior to launch – they are unable to be changed in flight. Additional redundancy is provided by a second avionics card with the same sensors and programming. Both cards are active during entry, and either card can initiate deployments. The SRC has very basic avionics and no telemetry capabilities (broadcast or recorded), thus no further contact with the capsule would be made until its descent was observed by air and ground assets.

MODELING AND SIMULATION APPROACH

During operations, there were two EDL simulations used to assess predicted EDL performance characteristics during entry, both based on the same underlying framework: the Program to Optimize Simulated Trajectories II (POST2)[10]. Each simulation completed identical analyses of the potential entry scenarios, the results of which were used to inform the decision making process for major maneuvers and events.

Description of POST sims

POST2 is a six degree-of-freedom flight dynamics simulation tool that can simultaneously simulate the trajectory of up to 20 independent or connected rigid bodies. Since POST2 is generalized, it has been utilized on a wide range of mission maturity, from pre-Phase A to active flight operations, including EDL for Stardust[11], Mars InSight[12], Mars 2020[13], and LOFTID[14].

Table 2. EDL Model and Assumptions in Simulations.

Model	Langley POST2	Lockheed Martin POST2	Comments
Aerodynamics	OREX SRC V5	OREX SRC V5	Derived from Stardust
Atmosphere	Earth Global Reference Atmospheric Model (GRAM) Suite v1.5	Earth GRAM Suite v1.5	
Winds	GRAM RRA 2019	GRAM RRA 2019	Dugway RRA
Movable Mass	Yes	No	
Entry DoF	6-DoF	6-DoF	
Parachute DoF	6-DoF SRC, drag-only parachute	3-DoF SRC, drag-only parachute	
Ephemeris	SPICE Toolkit	N/A	Used for time calculations
Ablation Mass Model	Yes	Yes	Mass change due to ablation

For operations, the two versions of POST2 were in use by flight mechanics engineers at NASA's Langley Research Center and Lockheed Martin Space. The models leveraged and assumptions made by each version of POST2 are listed in . While both organization's simulations are based on the same framework, the overall application differs in its code base and trajectory setup. These differences allow for independent verification and validation (IV&V) of results. The Langley POST2 was considered the prime EDL simulation during operations, while the LM results were used as IV&V.

Analysis Process

For OSIRIS-REx, POST2 was used to simulate the EDL sequence of the SRC beginning one minute prior to EI down to touchdown at UTTR. To inform the decision making process for major trajectory events (e.g., TCMs, SRC release), the EDL team would complete a nominal trajectory simulation, as well as Monte Carlo dispersion analysis for each entry scenario. For any potential maneuver to be completed, the potential outcomes analyzed considered whether the maneuver was completed or not and either a nominal SRC release or a release that was delayed by one hour. The navigation team would provide updated predictions of the SRC state at one minute prior to EI, and these states then were propagated through the POST2 simulations to determine a predicted landing location and track performance metrics during entry.

The simulation outputs are too numerous to be fully considered for each operational decision, so months before the final approach phase, a subset of the full set of EDL metrics was generated that represented those that were most critical to the survival of the SRC and the safe return of the sample within the UTTR. This data was presented in the form of a "scorecard" that could be easily checked to confirm that a given analysis scenario met the imposed requirements. In maneuver decision situations where multiple sets of analyses were compared, these scorecards were used to help identify whether any of the scenarios being considered (e.g. perform a TCM or not) significantly affected the SRC's chances of a safe return.

Table 3. EDL Monte Carlo Inputs.

Model	Description
Entry States	Position and velocity from covariance
Entry Attitude and Rates	Samples from propagated attitude after separation
Atmosphere/Winds	Random Seed within Earth-GRAM + RRA 2019
Capsule Aerodynamics	Uniform and normal distribution of inputs for OREX Database
Parachute Aerodynamics	Uniform distribution on parachute drag coefficient
Mass Properties (Capsule and Sample)	Uniform, normal, and cylindrical distribution on mass, c.g., and inertia
Ablation Mass	Normal distribution on ablation mass
Avionics	Model dispersions from samples based on as-built avionics

The models that involved dispersed parameters and a brief description are listed in . A total of 46 parameters were dispersed in each Monte Carlo dispersion analysis. For each entry scenario assessed, 3000 samples of each parameter distribution were drawn and simulated for the entire EDL phase, in order to generate probability statistics on metrics of interest.

Analyses Completed Prior to Entry Operations

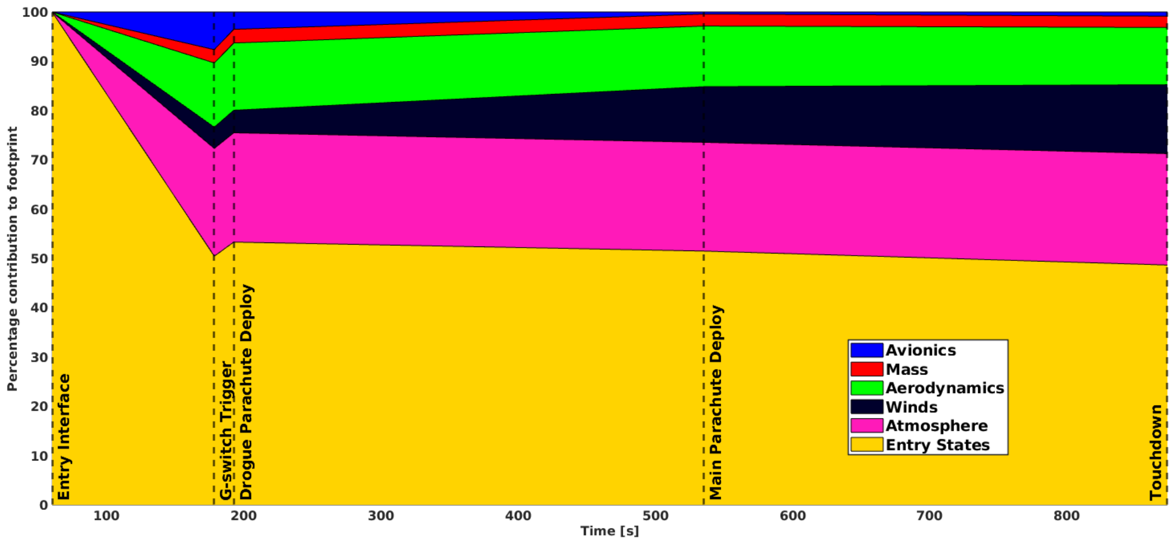


Figure 4. System uncertainty contribution to major axis of footprint at major milestones during trajectory.

Analyses were completed in early 2023 to determine how sensitive the overall system was to each type of uncertainty. The uncertainties were grouped into six categories: entry states, atmosphere, winds, aerodynamics, mass properties, and parachute avionics. Contributions from each group of uncertainty to the touchdown footprint major axis are shown in . Entry state uncertainty has the largest impact on landing location, while the second largest contributor is atmospheric density. It is important to note that entry state dispersions decrease significantly as EDL approaches nearer, resulting in the atmosphere uncertainties becoming an even larger factor.

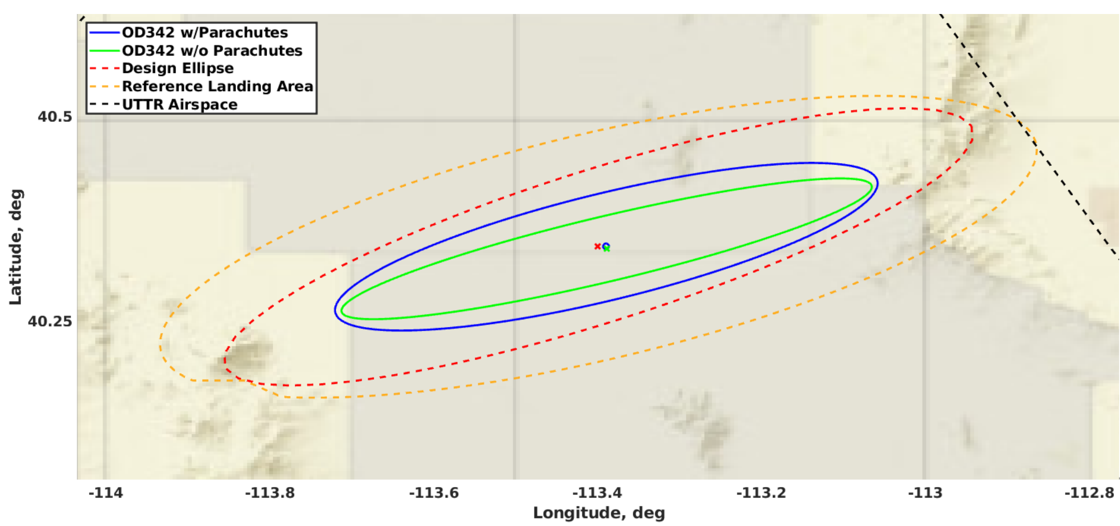


Figure 5. Predicted landing ellipses when parachutes deploy nominally and when no parachute deploys.

Additionally, multiple contingency scenarios were investigated upon suggestion from a project review board. Notably, one of the main contingency scenarios was that of a "dead capsule" – a situation where an issue occurred that resulted in neither the drogue nor the main parachute to deploy. This scenario occurred during the Genesis reentry, which resulted in the capsule impacting the Earth surface. Figure 5**Error! Reference source not found.** shows the predicted landing footprints for nominal parachute operation and neither parachute deploying. Perhaps somewhat interestingly, the mean touchdown location with no parachutes is within 100 m away from the nominal parachute mean touchdown location, thus providing evidence that the parachutes deploying properly are less significant for affecting touchdown location than they are for touchdown velocity. Further investigation into this result confirmed that the drogue parachute, which is deployed after the bulk of the entry deceleration has occurred, adds little drag to that of the SRC. Additionally, minimal movement in the footprint due to wind drift while on the main parachute is seen because of a high degree of directional variability in the low altitude (<5 km) winds.

FINAL ENTRY ASSESSMENT

Once all TCMs were completed and no collision avoidance maneuvers (CAMs) were deemed necessary to avoid colliding with space debris or assets in low Earth orbit (LEO), the final major milestone for the mission before EDL occurred was the release of the SRC. The release decision was made at the E-7 hour mark, which required a final analysis cycle to allow the release decision to be fully informed with the most up to date predictions.

Final Landing Ellipse

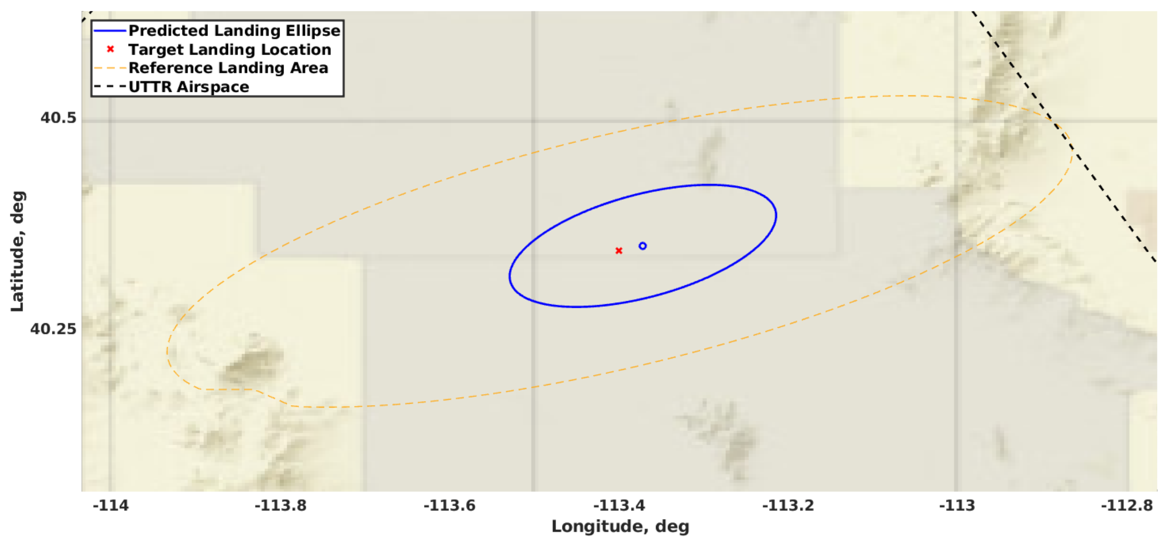


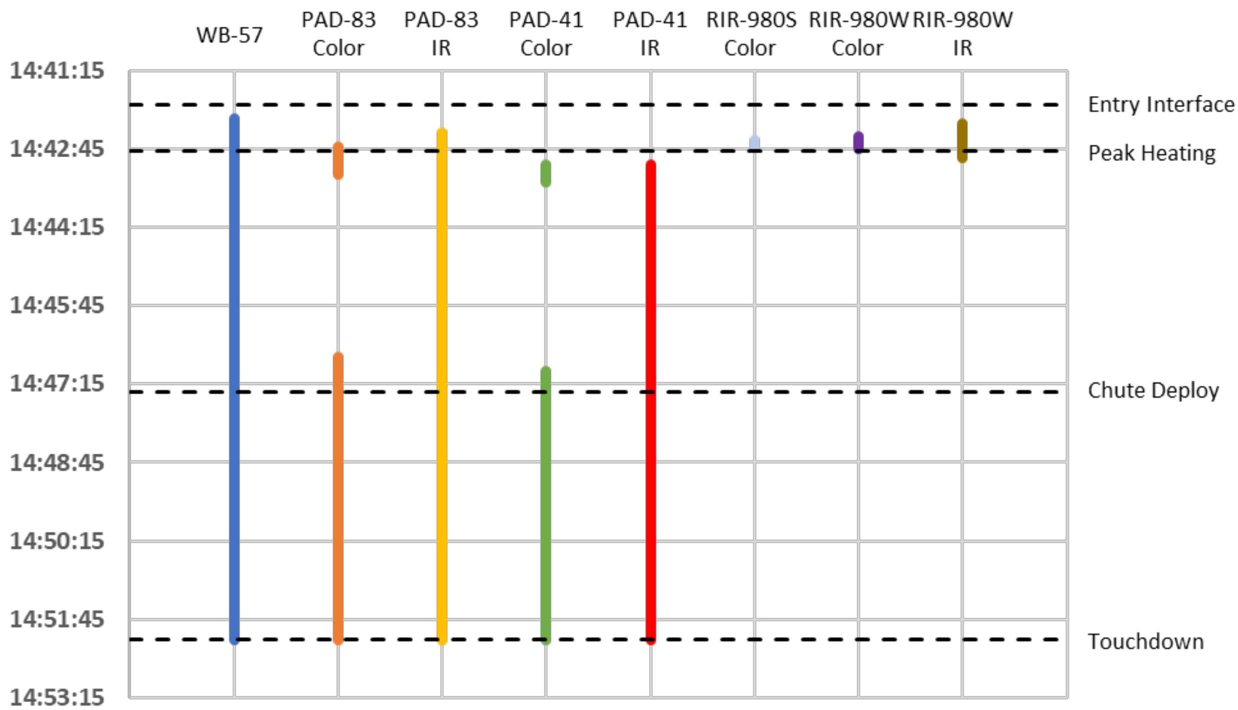
Figure 6. Final predicted 99 percentile landing ellipse prior to SRC entry.

Predicted performance was excellent in all scorecard metrics. shows the final predicted landing ellipse prior to entry. With no concerns from any of the operations teams, the GO was given to release the SRC

The final landing location was measured as 40.3719 N, -113.24 W by the recovery team.

Tracking Assets and Data

There were multiple assets planning to track/image the SRC entry – aircraft-based visual and IR cameras, and ground-based cameras and radar tracking stations. At graph of the time span these assets covered is shown in Figure A, indicating that there was generally good coverage of the entry from cameras. However, there was an anomaly in the radar tracking process (cause still being investigated), that resulted in no usable radar data being captured.



Without radar tracking data, a direct measurement of the SRC's trajectory is not possible. However, the EDL team is investigating using the known pointing data from the cameras and the known touchdown location of the SRC to approximately triangulate a position estimate for the capsule. This effort is ongoing and may be presented later in 2024 or 2025 if successful.

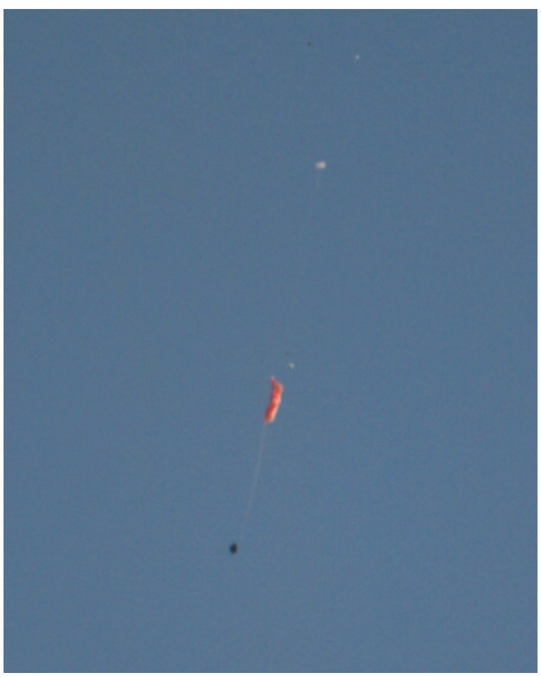
A list of the video data available is captured in Table 4. The camera video (specifically, the high-speed video captured by the TS-83 color camera) is the direct source for determining the times of the parachute deploy sequence, as it was the only asset with a clear view of the event. Multiple stations were used to estimate the time of touchdown, and the IR video was used to estimate the time of peak heating. These were the only events observable through visual methods.

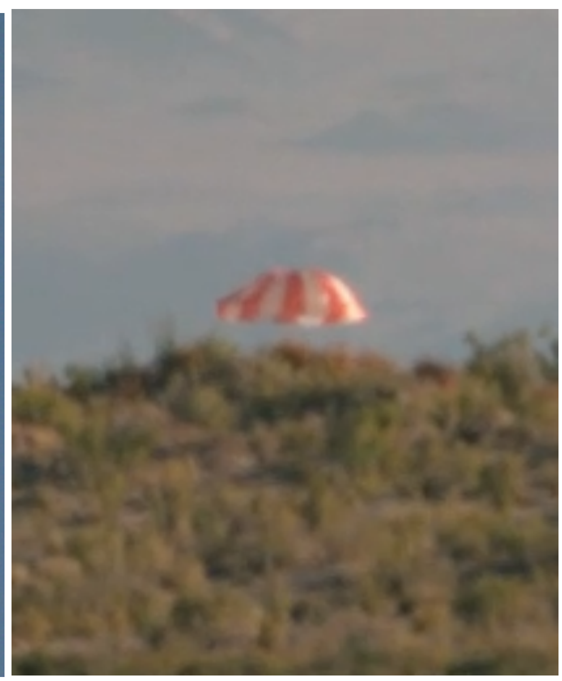
Table 4. Video data captured during OSIRIS-REx SRC entry.

Source	Type	Description
WB-57 aircraft	Medium-wave Infrared	Colorized and grayscale infrared
WB-57 aircraft	Visual wavelength	Visual, with camera tracking data
UTTR Cine-T, station 83	Color	High-speed

UTTR Cine-T, station 83	Infrared	
UTTR Cine-T, station 41	Color	
UTTR Cine-T, station 41	Infrared	
UTTR radar camera, station 980S	Color	Co-boresighted with radar
UTTR radar camera, station 980S	IR	Co-boresighted with radar
UTTR radar camera, station 980W	Color	Co-boresighted with radar
UTTR radar camera, station 980W	IR	Co-boresighted with radar
UTTR "phantom" camera	Color	

Multiple cameras witnessed the touchdown event and were used collectively to estimate that time. The best indicator (in the author's opinion) was the "Phantom camera", which although could not directly see the impact of the SRC due to terrain obscuration, was able to clearly see the instant that the main chute canopy began collapsing upon touchdown (offloading). Camera motion and resolution challenges of the other camera assets made precise estimates too difficult, compared to the stable view provided by the "phantom" camera.





Observed Sequence of Events

Examination of the available video files showed an apparently nominal entry through the hypersonic phase of flight. The onset and progression of the heat pulse did not exhibit any unexpected behavior as evidenced by the IR videos. However, the visual video does not show any evidence of a drogue parachute deployment at the expected time (approx. 14:44:06 UTC predicted). Furthermore, variability in the capsule's projected area, detectable at ~14:45:10 UTC, indicates that the SRC was likely oscillating at moderate-to-large angles-of-attack for the remainder of its free flight. This is corroborated by the EDL simulation's prediction of significant angle-of-attack growth upon slowing to subsonic speeds (see figure X). Although difficult to prove due to the small size of the SRC in the field-of-view and the relatively slow video frame rate, there are periods where it looks like the SRC may be completely tumbling (or at least oscillating near ~90 deg angle-of-attack) for some periods. Close inspection of the video once the ground is visible in the background confirms the lack of deployed drogue chute.

The successful initiation of the mortar, and deployment of both parachutes, can be seen in the ground-based videos. It was not captured in the WB-57 "visible" video due to blockage by the camera mounting hardware. Fortunately, slow-motion video of the sequence was captured by the UTTR "phantom" camera, which confirmed the correct sequence of deployments, albeit at an anomalous time. Once the main parachute inflated, the capsule appears to have performed the remainder of the descent nominally. Further discussion of this period of flight will be examined below.

A compilation of observable EDL events and their times compared to the final pre-entry EDL analysis is seen in Table A.

EDL Event	Actual Time	Sim Prediction	Delta (sec)
Entry Interface	14:41:54.000	14:41:54.000	0.000
Peak heating	14:42:47.854	14:42:46.000	1.854
Peak deceleration	14:42:56.000	14:42:56.000	0.000
Drogue mortar fire	14:47:24.358	14:44:06.500	197.858
Start of main bag extract	14:47:24.618	-	-
Drogue full inflation	14:47:24.738	14:44:06.930	197.808
Main chute starts extracting from bag	14:47:24.998	14:49:50.790	-145.792
Main chute bag strip complete	14:47:25.088	-	-
Main chute full inflation	14:47:26.228	14:49:56.200	-149.972
Touchdown	14:52:09.100	14:55:05.870	-176.770

An important observation is the divergence in the actual EDL timeline from the predicted timeline. Understanding how touchdown occurred nearly three minutes earlier than planned, and how the actual landing location was realized is an important part of this reconstruction. In order to dive into these topics, we need to first explain what actually happened during EDL, how things differed from expectations, and what we were able to do to make the simulation best fit reality.

Parachute Anomaly

Firstly, as is evident in the videos of entry, the drogue parachute did not deploy as planned. A detailed summary of the anomaly, root cause findings, and lessons learned was generated by members of the OSIRIS-Rex project and Lockheed Martin subject matter experts. It has not been released to be public, but a simplified summary is as follows:

Recalling the description of expected operation of the SRC avionics given earlier, it is important to note the two timer circuits that are initiated upon triggering of the G-switches. One circuit executes a ~14 sec timer, which is intended to then fire the NSI's connected to the drogue mortar. This time was selected to correspond to approximately Mach 1.5 – the desired deployment condition for the drogue chute. The other circuit, running in parallel, executes a ~363 sec timer, in conjunction with monitoring a pressure transducer. In this path, either the timer or pressure actuation would trigger NSI's connected to cutters to fire, severing the ties holding the drogue parachute bridle in place over the main chute bag, which in turn would allow the drogue to pull the main parachute out of the cannister. The time and pressure values here were selected to result in main deployment at approximately 10000 ft above mean sea level.

Unfortunately, confusing in nomenclature used in the avionics and harness signaling, along with other complicating factors, resulted in the mortar and cutter signals being reversed. This had the effect of firing the drogue release cutters at the original Mach 1.5 mortar fire event, and of firing the mortar at the 10000 ft main deployment point. At the first event, triggered by the 14.2 sec timer, the cutters were fired, releasing the drogue bridle tie loop. But since the parachute cannister lid was still in place due to the mortar not being fired, nothing happened external to the SRC – both parachutes remained in place. Thus the SRC continued to fly on its own, and without the added stability of the drogue chute, began to oscillate at larger and larger angles of attack. The captured video does not show sufficient detail of the SRC geometry to determine the attitude, however there are points in the video where its possible that the capsule may indeed be tumbling.

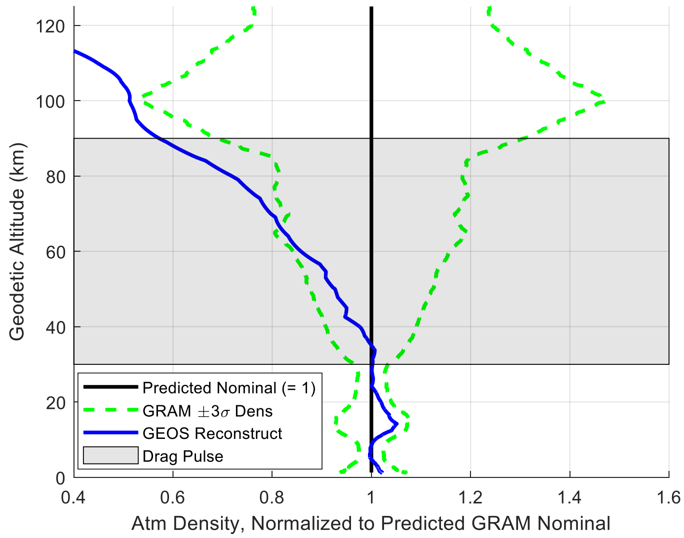
This oscillating state continued until the SRC descended to where the main chute was observed to deploy. This happened at least two minutes [TBR] earlier than expected, thus the timer portion of the affected circuit would not have been involved – only the pressure transducer could have initiated the deployment. This actuation caused the mortar to fire, resulting in the deployment of the drogue. However, since the drogue riser was no longer secured inside the cannister, it kept receding from the capsule once the canopy was inflated and immediately began to extract the main parachute bag from the cannister, allowing it to inflate with no additional delay. These two deployments happened within the span of two seconds, and can be seen in Figure X above..

Since the drogue parachute did not stay attached to the SRC long enough to provide significant deceleration, the main parachute deployed at a higher velocity (and thus dynamic pressure) than intended. This is corroborated by evidence that the main parachute's load limiter was completely ripped out. However, robustness in the main chute design and construction resulted in no damage to the chute canopy and the descent under the main performed nominally from that point forward, resulting in a nominal touchdown and safe landing of the SRC and its enclosed sample.

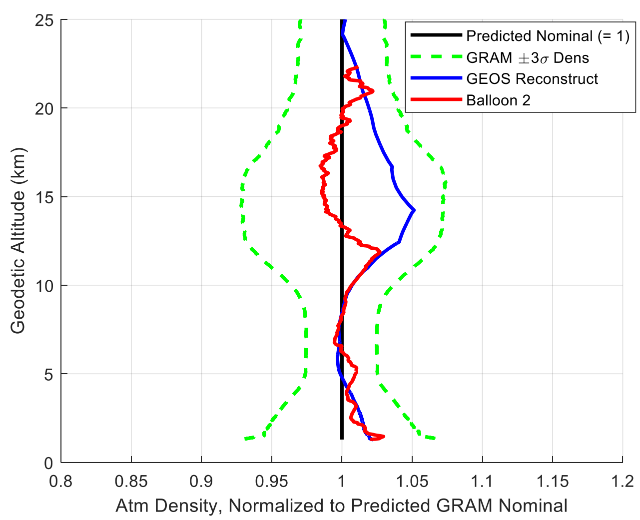
Simulated Reconstruction

Day-of-Entry GEOS and Balloon Atmosphere Data

Several weeks after landing, a reconstructed atmosphere for the day and time of EDL was obtained from the GEOS database. Similar to the predictions in the days leading up to Entry, the reconstruction showed notably lower atmospheric densities in the upper atmosphere than the nominal GRAM atmosphere predicted, and was even lower than the predicted GRAM 3σ low density for a significant portion of the drag pulse. The following figure shows the GEOS reconstructed atmospheric density versus altitude compared to the GRAM predicted ±3σ density all normalized to the GRAM predicted nominal density profile that was used for the official landing site prediction before landing.

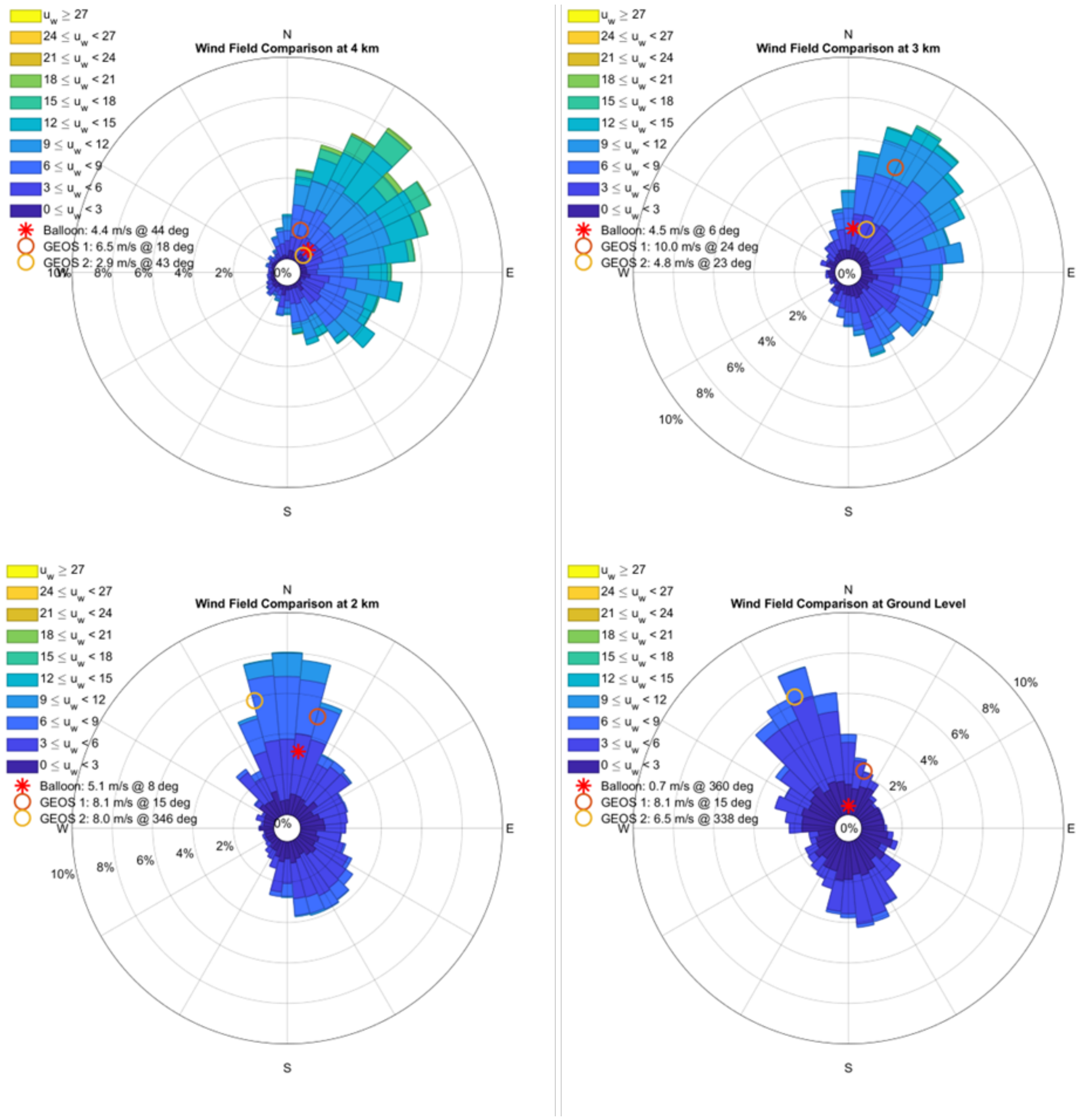


Another source of atmospheric data were the weather balloons that were launched shortly after EDL, with the first being launched 40 minutes after capsule touchdown. That balloon had a malfunction and stopped reporting data earlier than expected, so a second balloon was launched approximately 65 minutes after touchdown. While the balloons were not capable of reporting atmospheric conditions into the upper atmosphere, balloon 2 did agree relatively well with the GEOS reconstructed atmospheric density up to an altitude of approximately 12 km but then generally reported lower densities than GEOS from 12 km up to the balloon maximum altitude of 22 km. Balloon 1 reported densities in good agreement with balloon 2 over the range for which data was reported. A plot of the balloon 2 densities compared to the GEOS and GRAM densities are shown in the following figure.



Earth-GRAM provided wind data over the entire range of altitudes that the trajectory traversed. The EDL team used the Range Reference Atmosphere functionality within Earth-GRAM, which leverages statistical weather data from multiple weather sites around the world. One of those site is the Dugway Proving Grounds, within the UTTR. However, since weather balloons and the

GEOS model also provided wind information, the EDL team assessed these data to see how they compared against Earth-GRAM. While the balloon and GEOS data were not included in any pre-entry assessments, they were used to inform whether the predicted environments were out of family and might affect where recovery teams should be directed. A comparison of the winds at 4 different altitudes during the main parachute phase is illustrated in figure X. It shows that both the GEOS forecast and the balloon measurements at the time of entry were in good agreement with the Earth-GRAM model.

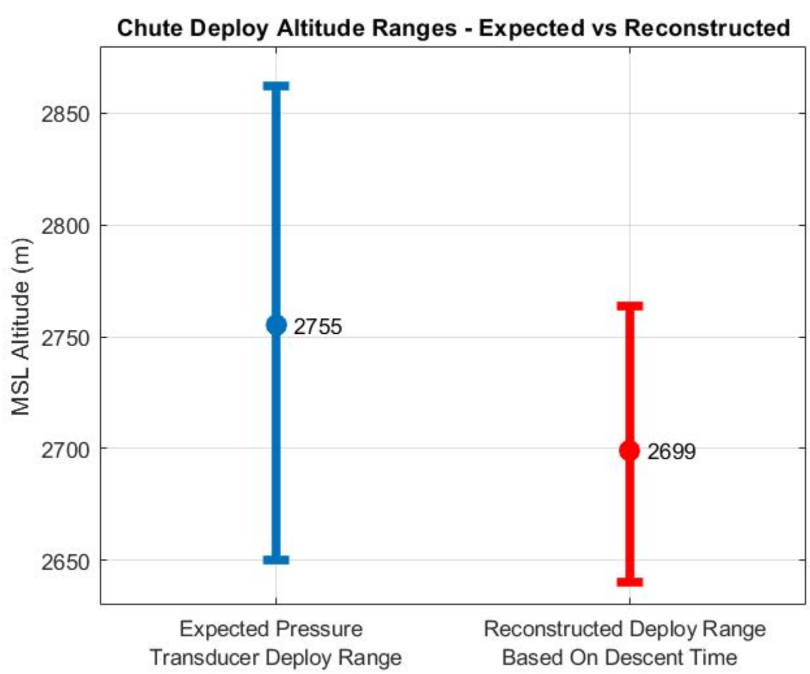


<u>Parachute Deploy Altitude</u>

Without radar data or onboard telemetry, the only measured data available for determining parachute deploy conditions are the timeline as observed in video footage and the lower atmospheric conditions as measured by weather balloon. In order to determine whether the main parachute deploy trigger was activated at the desired altitude, the expected capsule and parachute aerodynamics from the POST2 simulation were assumed, and the required chute deploy altitude in order to meet the observed duration from chute deploy to touchdown was determined. The simulation was updated to match the as-flown parachute deploy sequence, with the drogue parachute being deployed on the main parachute trigger and deploying the main parachute immediately after full drogue inflation. The durations of the line stretch and inflation events were set to correspond to video observations. The atmospheric pressure and density were assumed to be those measured by the first weather balloon launched after EDL took place, approximately 40 minutes after landing. Given these assumptions, the distance traveled in the simulation from chute deploy initiation to touchdown is 1400 m, resulting in a chute deploy altitude of 2699 m MSL considering the 1299 m touchdown site altitude. Assuming the reported balloon atmospheric density profile as truth, simulation Monte Carlo dispersions on mass properties and chute and capsule aerodynamics result in an uncertainty of -59/+64 m.

The main parachute deploy event could be triggered by either a timer initiated at the descending 3 g crossing of the drag pulse or by atmospheric pressure as measured by an onboard pressure transducer. Since the expected timeline of events was significantly accelerated due to the upper atmospheric density modeling errors and the decrease in drag due to lack of expected drogue parachute drag and an unstable capsule, the parachute deploy event was observed to occur approximately 212 seconds after the simulated 3 g crossing and timer start event. Since the timer-based trigger was set to deploy the main parachute once the timer reached 362.9 seconds, it is almost certain that the parachute deploy event occurred based on the pressure transducer. Based on pre-launch pressure transducer testing and estimated flight temperatures, the pressure-based trigger would be expected to fire at a pressure range of 10.57 to 10.84 psi and a midpoint of 10.70 psi. Using the atmosphere measurements from the first weather balloon launched after the SRC landing, these pressures correspond to MSL altitudes of 2650 to 2862 m, with a midpoint of 2755 m.

Comparing the range of expected deploy altitudes based on pre-launch pressure transducer testing and thermal estimates to the reconstructed deploy altitude range based on observed descent time, we see that the chute deploy event likely occurred within the expected range as illustrated in the following figure.



Landing Location and Timeline

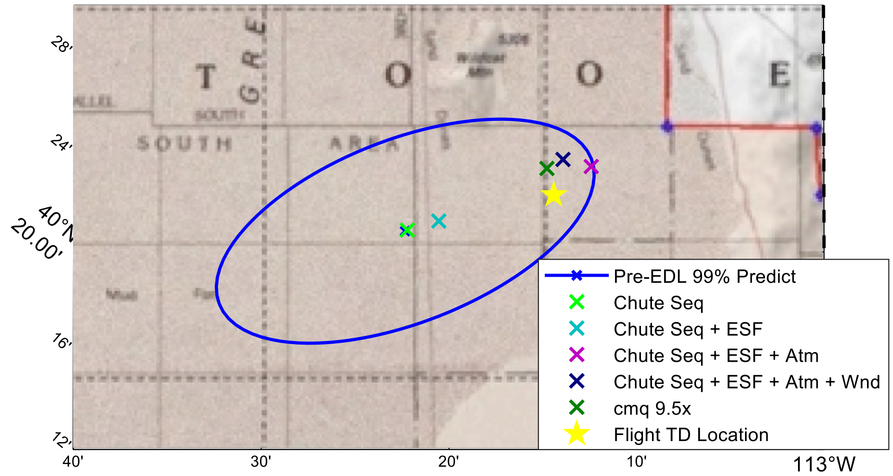
The two most notable differences between the final predicted trajectory prior to EDL and the observed flight performance besides the delayed drogue chute deploy event were that the flight touchdown location was significantly downrange of the predicted nominal (although still within the 99% landing ellipse) and that the touchdown event occurred much earlier than expected, almost 3 minutes before the predicted nominal and 75 seconds earlier than even the 1% "early" Monte Carlo trajectory. In order to assess the cause of the discrepancies, the available observed and reconstructed data were incrementally applied to the simulation in order to see the effect each had on touchdown time and location relative to the predicted nominal and the observed flight performance. An additional case was run that combines all of the reconstructed data and then includes a manually adjusted pitch damping aerodynamic coefficient that will be described below. The various comparison cases are summarized in the following table.

Comparison Case	Description
Cht Seq Only	Simulation updated to mimic flight parachute deployment sequence, deploying drogue at reconstructed deploy altitude and deploying main chute immediately after.
Cht Seq + ESF	Cht Seq reconstruction plus reconstructed Entry State
Cht Seq + ESF + Atm	Cht Seq and ESF reconstruction plus reconstructed GEOS atmosphere and wind estimation
Cht Seq + ESF + Atm + Wind	Cht Seq, ESF, and GEOS atmosphere reconstruction, replacing winds with those measured by weather balloon 1
cmq 9.5x	Cht Seq, ESF, Atm, and Wind reconstruction plus 9.5x multiplier on max cmq aero coefficient
Flight Observed	Observed flight performance

Below are the touchdown locations and EDL durations relative to the pre-EDL predicted nominal and the observed flight performance for each of the comparison cases.

	Compared to Predicted Nominal Touchdown			Compared to Flight Observed Touchdown		
Comparison Case	Distance (km)	Azimuth (deg)	Entry to Touchdown Time Difference (m:ss)	Distance (km)	Azimuth (deg)	Entry to Touchdown Time Difference (m:ss)
Predicted Nominal	-	-	-	11.8	256.3	+2:57
Cht Seq Only	0.4	68.2	-1:45	11.4	256.6	+1:12
Cht Seq + ESF	2.9	73.2	-1:45	8.9	257.3	+1:12
Cht Seq + ESF + Atm	15.1	70.9	-1:43	3.5	53.1	+1:14
Cht Seq + ESF + Atm + Wind	13.3	65.8	-1:43	2.7	14.7	+1:14
cmq 9.5x	11.9	66.3	-2:55	2.0	345.4	+0:02
Flight Observed	11.8	76.2	-2:57	-	-	-

The following figure shows the respective touchdown locations for each of the comparison cases relative to the pre-EDL best estimate 99% landing ellipse.



As shown, simply accounting for the observed chute deploy sequence results in a touchdown 1 minute and 45 seconds earlier than originally predicted, but does not have a significant effect on the touchdown location, shifting it only 0.4 km compared to the actual flight touchdown site 11.8 km away. Incorporating the reconstructed entry state shifts the simulation touchdown point 2.9 km from the prediction. Due to the large difference in upper atmospheric density, incorporating the reconstructed GEOS atmosphere model provides a significant shift downrange towards the observed flight touchdown location, resulting in a landing site 15.1 km northeast of the prediction. This overshoots the flight touchdown location and slightly lengthens the trajectory duration to land 1 minute and 43 seconds earlier than originally predicted, or 1 minute and 14 seconds later than the observed Flight touchdown time. Finally, incorporating the winds observed by the weather balloon shift the landing site slightly closer to the observed touchdown location to a site 2.7 km away. This "Cht Seq + ESF + Atm + Wind" comparison case incorporates all the observed or reconstructed data currently available and lands reasonably close to the observed Flight location, with the remaining 2.7 km discrepancy possibly being attributable to imperfect atmosphere and wind reconstructions and imperfect aerodynamics predictions. This reconstructed trajectory, however, still has a notably longer duration than desired, at 1 minute and 14 seconds longer than the observed 10 minute and 16 second EDL flight duration.

Since the capsule was expected to maintain stability throughout EDL either through hypersonic and supersonic capsule aerodynamics or via the drogue parachute in the transonic and subsonic regimes, large angles of attack were not included in the aerodynamic database used in the simulation. As a result, when the simulations were updated to delay the drogue deploy event to low subsonic velocities as observed in flight, the simulated capsule only reaches total angles of attack of approximately 22 degrees at drogue deploy despite the fact that it is known to be aerodynamically unstable in the transonic and subsonic regimes. Since the capsule drag coefficient is highest at 0 deg total angle of attack and decreases as the total angle of attack increases, an artificially low angle of attack in the simulation leads to an artificially high level of drag in the simulation compared to reality. This phenomenon will lengthen the timeline in the simulation and is believed to be the primary contributor to the remaining 1 minute and 14 seconds of timeline discrepancy between the reconstructed trajectory and the observed flight time as noted above. Unfortunately, rederiving the aerodynamic database to include the full range of unstable attitudes was beyond the scope of this reconstruction effort, but the existing aerodynamic database is configured to extrapolate aerodynamic coefficients if forced off the end of existing tables with respect to angle of attack. An experiment was performed by manually increasing the pitch damping coefficient, C_{mq}, in order to force higher angles of attack during the transonic instability and thus using extrapolated aerodynamic coefficients. Gradually increasing cmq produced the expected result of increasing maximum total angles of attack beyond those seen in the original reconstructed simulation and thus shortening the timeline. Starting with the previous best estimate reconstructed trajectory, it was determined through trial and error that forcing a C_{mq} of 9.5x that of the original aerodynamic database dispersed maximum value results in higher total angles of attack and a timeline in rough agreement with the observed flight Entry to Touchdown duration.

It should be noted that C_{mq} was only used as a mechanism to force a large angle of attack and no physical significance should be inferred from the fact that it was the C_{mq} value that was manipulated or that a 9.5x increase is what resulted in a matching timeline. It should also be noted that this experiment results in significant extrapolation of aerodynamic coefficients compared to what was derived for the original aerodynamic database and may not be accurate. What is noteworthy, however, is that the angle of attack profile and timeline do seem more realistic compared to what was observed in flight and may lend some support to the theory that it is indeed the decreased drag associated with the higher, unstable angles of attack that may account for the remaining timeline discrepancy. Note in the above comparison table that the Entry to Touchdown Time Difference for the "C_{mq} 9.5x" case is within 2 seconds of the Observed Flight timeline. The new C_{mq} 9.5x case also shifts the landing site slightly closer to the observed Flight touchdown site, landing 2.0 km to the north-northwest.

CONCLUSION

The OSIRIS-REx Sample Return Capsule EDL analysis strategy was largely modeled off that which was successfully used for the Stardust sample return mission and other successful EDL missions. Monte Carlo analyses using the POST2 trajectory simulation tool informed Entry Interface targeting and successfully captured the actual landing site within the final 30.1 km x 13.7 km 99% predicted landing ellipse and well within the 84 x 20 km design ellipse agreed upon with UTTR. Despite an anomaly leading to the late deployment of the drogue parachute, the main parachute deployed as expected resulting in a nominal landing and successful science collection. Although there were plans to track the capsule with UTTR radar assets during entry, the stations were not able to lock up on the capsule and the expected position data was not available. This made the reconstruction of the entry trajectory more difficult, forcing the team to rely more heavily on the EDL simulation, with model adjustments based on video-based timeline information and observed atmosphere measurements, rather than direct measurements of the trajectory. Given that updating the simulation to use the GEOS-derived atmosphere moves the simulated landing site much closer to the observed touchdown location than the nominal GRAM atmosphere predicted, it appears that the GEOS atmosphere prediction was indeed the better estimate in this case and should at least be considered in future Earth return missions. Finally, given the anomalous nature of a portion of the entry, it is suspected that the limited range of angles of attack in the aerodynamics database caused notable errors in the reconstruction of the timeline, which may be of interest to future missions attempting to consider contingency scenarios..

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