

Flight Mechanics Analysis of Low-Earth Orbit Flight Test of an Inflatable Decelerator

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The Low-Earth Orbit Flight Test of an Inflatable Decelerator (LOFTID) successfully demonstrated the capability of an inflatable aeroshell. Prior to launch, flight mechanics analysis was conducted to better understand the predicted splashdown point of the re-entry vehicle and ejectable data recorder. Best estimated trajectory separation states were utilized to understand the LOFTID trajectory over the entire 36 minute launch window. Weather forecasting model were integrated into the simulation to improve trajectory prediction accuracy. Automation tools were developed to facilitate the rapid generation of trajectory predictions during operations. The resulting improvements to the flight mechanics modeling and simulation allowed for pre-launch splashdown point to be within 3 nautical miles of the actual splashdown point.

I. Nomenclature

<i>BET</i>	=	Best Estimated Trajectory
<i>EDR/EDM</i>	=	Ejectable Data Recorder/Module
<i>GRAM</i>	=	Global Reference Atmosphere Model
<i>GEOS</i>	=	Goddard Earth Observing System
<i>LOFTID</i>	=	Low-Earth Orbit Flight Test of an Inflatable Decelerator
<i>OPM</i>	=	Orbital Parameter Message
<i>POST2</i>	=	Program to Optimize Simulated Trajectories II
<i>PT</i>	=	Pre-Launch Trajectory
<i>RV</i>	=	Re-Entry Vehicle

II. LOFTID Overview

THE Low-Earth Orbit Flight Test of an Inflatable Decelerator (LOFTID) was a flight test of a 6m diameter inflatable heat shield for atmospheric re-entry [1]. On November 10th 2022, LOFTID was launched as a secondary payload from Vandenberg Space Force Base aboard a United Launch Alliance (ULA) Atlas V. After the primary payload, Joint Polar Satellite System-2, was delivered to orbit, an inflated and spin-stabilized LOFTID separated from Centaur upper stage on a re-entry trajectory. LOFTID entered Earth's atmosphere at more than 18,000 miles per hour and successfully conducted entry, descent, and landing (EDL) splashing down in the Pacific Ocean 375 miles east of the coast of Hawaii. The overall concept of operations for LOFTID flight test is shown in Figure 1. This paper will present the flight mechanics analysis conducted for LOFTID prior to launch.

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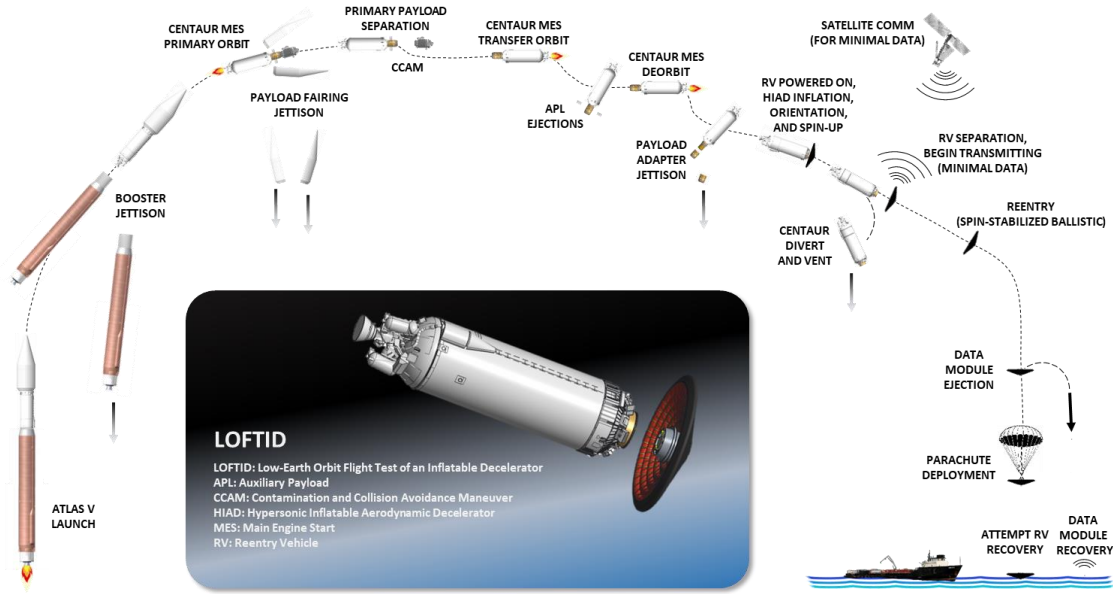


Fig. 1 LOFTID Concept of Operations

III. Flight Mechanics Modeling

A. Trajectory Simulation

Flight mechanics analysis for LOFTID was conducted using Program to Optimize Simulated Trajectories II (POST2) [2]. POST2 is a system-of-systems software that allows for the ingestion of subsystem models to simulate the overall 6 degrees of freedom (DOF) EDL trajectory. The framework for POST2 implementation for LOFTID is shown in Figure 2. Many of the subsystem models are built in-house at NASA Langley Research Center (LaRC), including the ejectable data module, aerothermodynamic indicators, aeroshell mass properties, and aerodynamics database. The atmosphere models utilized include EarthGRAM 2010 [3], developed at NASA Marshall Space Flight Center (MSFC), and atmosphere profiles generated by Goddard Earth Observing System (GEOS), which is operated by NASA Goddard Space Flight Center (GSFC) Global Modeling and Assimilation Office [4, 5]. The parachute system model is developed by Airborne Systems. The portion of the overall test timeline analyzed using POST2 occurs from re-entry vehicle (RV) separation (e.g. LOFTID separation) to LOFTID splashdown. For simulation initialization at separation, two methods were developed. The first method, utilized during pre-launch, initial state and separation attitude provided by NASA Kennedy Space Center (KSC) Launch Service Provider and ULA, respectively. The second method, utilized during operations, included an orbital parameter update (OPM) file provided by ULA that contained information of the LOFTID trajectory position/velocity and RV attitude angles/rates at separation.

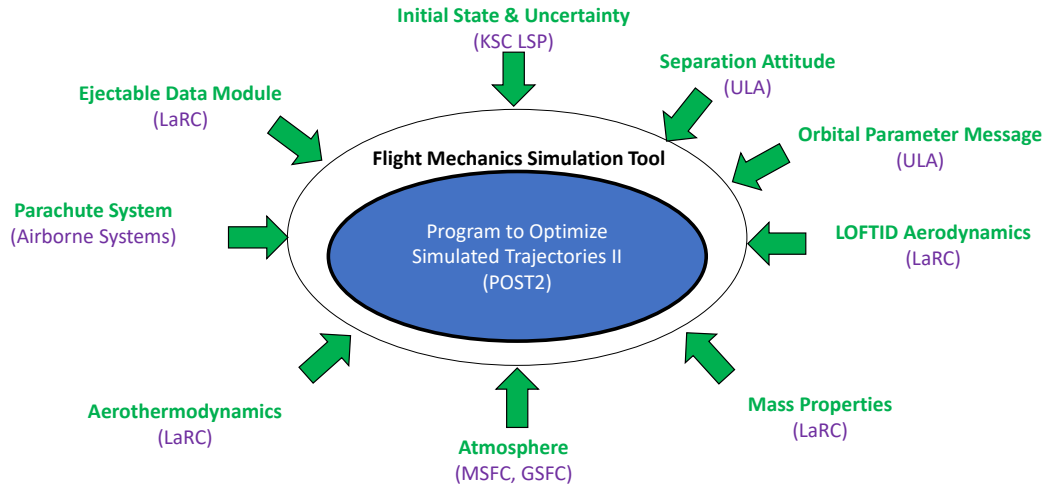


Fig. 2 LOFTID Flight Mechanics Simulation Tool

B. Forecast Atmosphere Model and Integration

During the design phase for LOFTID, various launch opportunities were evaluated targeting landing areas over unpopulated regions over the Pacific Ocean. Coverage from site-specific atmospheric data, such as range reference atmosphere or radiosonde data, is not available in these areas, so the Earth Global Reference Atmospheric Model (GRAM) [3] was used to provide an engineering atmospheric profile. EarthGRAM is a general model that utilizes climatological data to define atmospheric properties, but it is not a forecast model that predicts the atmospheric properties on a certain day. For example, for EarthGRAM the atmospheric properties predicted will be based on a November-average properties with small variations for the time of the day.

When the LOFTID project reached the operations phase of flight, improved atmospheric conditions were needed that pinpointed the landing performance and location, especially when a recovery boat was to be directed to retrieve the ejectable data recorder (EDR) and the LOFTID test article. From previous experience [6, 7], EarthGRAM is not well suited in situations where time of the day forecast information is needed.

In order to provide better predictions for operational assets, the LOFTID POST2 simulation incorporated data from the Global Modeling and Assimilation Office (GMAO) tool developed by Goddard Space Flight Center (GSFC) which provided temperature, pressure, density, and wind speeds from the surface up to approximately 60 km altitude. The GMAO model is Goddard Earth Observing System Model Version 5 (GEOS-5), which provides forecasts of Earth's atmospheric properties in increments of every 3 h [8]. The forecast is provided in increments of 0.5° in latitude and 0.625° in longitude, and uncertainties are calculated from a combination of analysis error and forecast error. Based on analysis during operational support, it was decided to use the vertical profile at 22° North and 148.75° West from the GEOS-5 analysis for atmospheric parameters. Various latitude and longitudes along the flight path were tested, but the trajectory predictions were not found to be very sensitive. Additionally, GMAO had provided forecast uncertainties at this particular point as well, which was useful for modeling in the simulation.

Since LOFTID was an orbital return mission, atmospheric forecast needed for the simulation also included altitudes above 60 km limit of the GEOS-5 data. Similar to past missions that have used GEOS-5 based forecast data for orbital and sub-orbital flights [7], the 1976 US Standard Atmosphere [9] was used to augment data from GEOS-5. The lapse rate, or the rate of change of temperature with respect to altitude, from the 1976 atmosphere was used at corresponding altitudes above 65 km to extend the GEOS-5 temperature prediction. Then, the hydrostatic equation and the perfect gas law was used to calculate the respective pressure and temperature. Wind speeds were assumed to be zero at the atmospheric interface point and linearly varied to the top of the GEOS-5 profiles. The linearly varying assumption is similar to what is used for other EDL missions [10] to avoid simulating an artificial wind shear by instantaneously

making the wind speed zero.

Figure 3 shows a comparison of the 24-hour forecast GEOS-5 atmosphere and its equivalent from EarthGRAM. One can see deviations between the two models in critical areas such as maximum heating and maximum deceleration, and during parachute flight which occurs below 10 km altitude and affects the landing location.

Figure 4 shows a plot comparison of splashdown ellipses for the RV and EDR generated with EarthGRAM and the 24-hour GEOS-5 forecast from the same initial conditions and vehicle states. The actual landing location, from reconstruction, is also shown in comparison. One can see that the GEOS-5 forecast-based simulation prediction is closer to the actual RV and EDR splashdown points than the EarthGRAM-based prediction. This observation is similar to what was seen in past missions [6, 7]. The ability of forecast model-based predictions to show deviations from original design due to late-breaking atmospheric conditions can allow for improved operational planning of the placement of the recovery boat to facilitate faster recovery. One interesting side effect was that when utilizing the GEOS-5 forecast, there was a reduction in the splashdown ellipse size in both the major and minor axes. This is expected since general models such as EarthGRAM have large uncertainties to account for the large areas of space and time these models need to provide predictions.

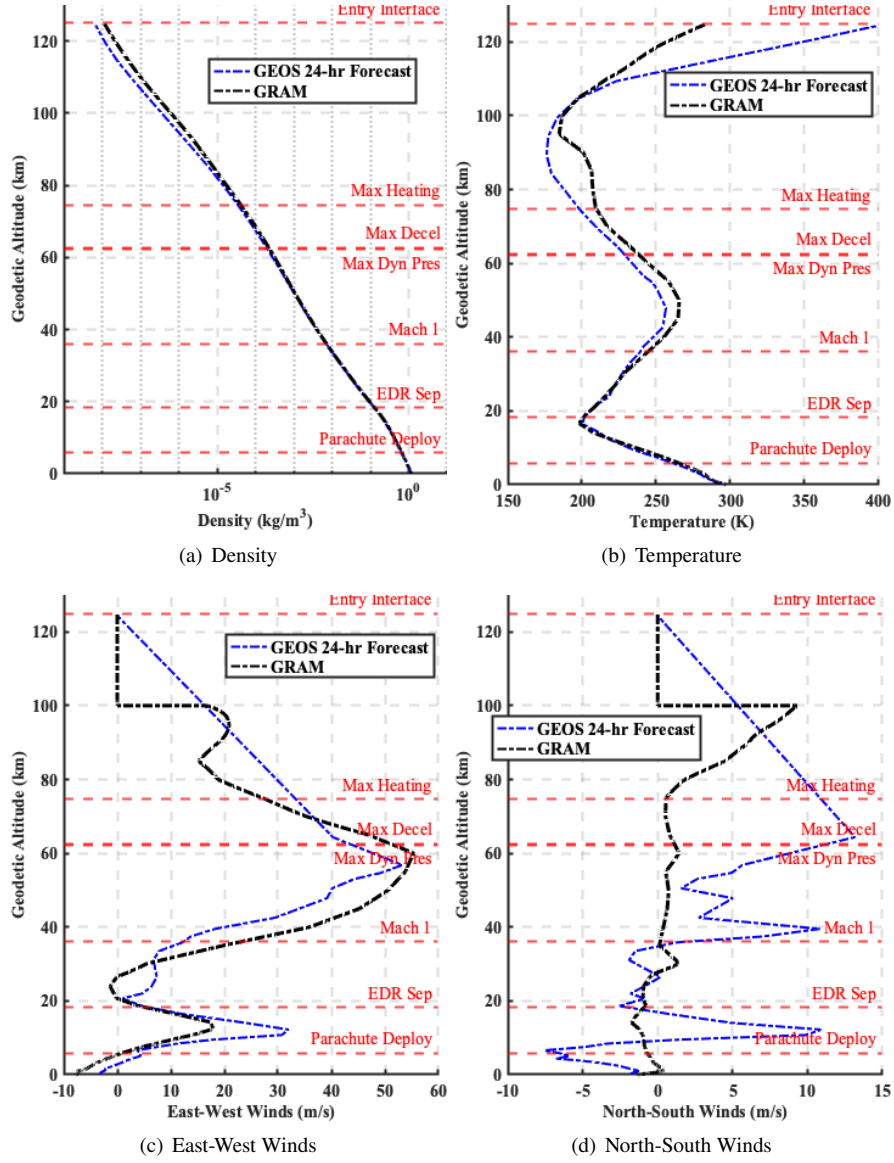


Fig. 3 Comparison of generalized atmosphere from EarthGRAM and forecast data from GEOS-5 for the LOFTID launch date and site.

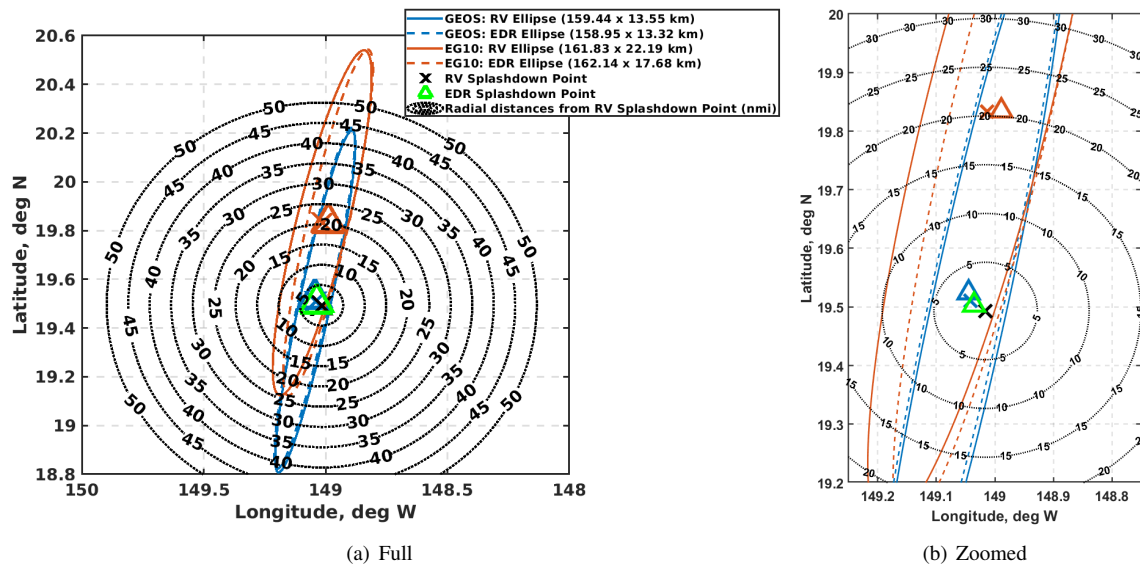


Fig. 4 Comparison of GEOS-5 vs EarthGRAM 2010 atmosphere model splashdown ellipses

C. Use of Automation for Trajectory Prediction

LOFTID was a secondary payload on the flight of Joint Polar Satellite System (JPSS)-2 and hence the mission was dependent on trajectory conditions after the separation of the primary payload. The launch provider, ULA, would provide an OPM after JPSS-2 separation and then again at LOFTID separation, with which the LOFTID trajectory team had to conduct a Monte Carlo analysis and provide the splashdown ellipse and best estimated landing location to the crew of the recovery boat. Due to the short timelines (less than 1-hour) between the LOFTID separation OPM-generation, touchdown time, and the slow speed of the recovery boat, it was imperative to optimize speed of the Monte Carlo runs and reduce human errors.

Similar to past projects that have needed fast turnaround of trajectory analyses [6, 11], LOFTID used an automation program called Jenkins to script the running of the trajectory analysis. The user would input the OPM file that was emailed by ULA to the LOFTID team into the graphical user interface, and the automation system, that was connected to the computer cluster used for trajectory analysis, would automatically start a Monte Carlo run. Although the system was integral for the real-time run after LOFTID had separated, the trajectory analysis team generalized the system for other pre-flight predictions, including the 72-, 48-, and 24-hour predictions that were sent to the recovery team based on GEOS-5 data. In the case of the pre-flight predictions, the automation program would monitor the HTTPS server of GMAO, see if a new prediction file for the specific time span in question has been added, and then use that data to start a Monte Carlo simulation. Figure 5 shows the dashboard of the pre-flight automation used for Monte Carlo analysis. One can see several steps that are executed in a chain to create the final analysis results. The automation and scripting reduced chances of human error, such as inputting the wrong setting, and allowed the analyst to concentrate on the results to see if it was useful for recovery operations.

W	Name ↓	Last Success	Last Failure	Last Duration
	0_Check_Weather	11 mo #351	N/A	2 min 58 sec
	1_Download_Weather	11 mo #938	N/A	13 sec
	2_Parse_Weather_and_Create_Table	11 mo #783	N/A	19 sec
	3_Setup_Monte_Carlo	11 mo #219	1 yr 4 mo #80	0.44 sec
	4_Parallel_Monte_Carlo	11 mo #227	1 yr 0 mo #208	22 min
	5_Run_Monte_Carlo	11 mo #683	1 yr 0 mo #626	11 min
	6_Generate_Monte_Carlo_Products	11 mo #658	1 yr 4 mo #238	11 min

Fig. 5 Dashboard of the automation system used for fast Monte Carlo analysis during operations. Snapshot taken in November 2023.

IV. Pre-Launch Trajectory Analysis

Prior to launch, a trajectory simulation campaign was conducted based on the ULA-provided best estimated trajectories. The launch window, from open to close, for Atlas V was 36 minutes long. LOFTID EDL trajectory analysis was conducted for three time periods within the launch window (open -> M18, middle -> P00, and close -> P18) using ULA-provided Centaur separation state data. Table 1 provides a summary of the flight mechanics error modeling used in the Monte Carlo analysis.

Table 1 Flight Mechanics Error Modeling.

Error Source	Uncertainty (3σ or Min/Max)	Distribution
Total Mass	± 6.75 kg	Normal
C.G. Location (x,y,z)	± 0.01 m (x,y) ± 0.026 m (z)	Normal
Moments of Inertia (Ixx, Iyy, Izz)	± 102.1 kg-m ² (Ixx) ± 101 kg-m ² (Iyy) ± 100.4 kg-m ² (Izz)	Normal
Products of Inertia (Ixy, Iyz, Ixz)	± 6.7 kg-m ² (Ixy) ± 6.8 kg-m ² (Iyz) ± 6.7 kg-m ² (Ixz)	Normal
LOFTID Aerodynamics	From aerodatabase	Normal and Uniform
Parachute Aerodynamics	From Airborne data	Uniform
Atmosphere (density, temperature, pressure, winds)	From EarthGRAM 2010	Normal
Separation State (position, velocity)	From ULA BET data	Table
Separation Attitude (pitch, yaw, roll)	± 2.5 deg	Uniform
Separation Tip-off Rate (pitch, yaw)	± 2 deg/s	Cylindrical
Separation Roll Rate	± 3 deg/s	Normal

8001 Monte Carlo simulations were run for the open, middle, and close launch windows. Table 2 provides a summary of the key EDL trajectory metrics. Statistics are reported to the $\pm 2\sigma$ confidence interval. The main effect the launch window has on the LOFTID EDL trajectory is on the separation state. The time propagated from LOFTID RV separation to entry interface at 125 km altitude is shown to vary. Open and close of launch windows have similar times whereas middle of launch window is approx 50 sec longer. The entry velocities and entry total angles of attack are comparable over the launch window but there are noticeable difference in the entry flight path angle. The middle window produced a entry flight path angle distribution that is shallower (e.g. less negative) than the open and close windows. This leads to longer time-of-flight from entry to splashdown and slight increase in max heat load on the vehicle's nose along with slight reductions in peak deceleration, peak dynamics pressure, max nose total heat rate. Given that the LOFTID EDM and pilot chute triggers are timer-based (2260 sec since RV separation for EDM trigger and 2509 sec since RV separation for pilot chute trigger), the increase in time-of-flight evidently leads to these two triggers occurring at higher altitudes and mach numbers. The pilot chute trigger deploys at an average total angle of attack of less than 5 deg over the entire launch window. It provides sufficient vertical deceleration for splashdown of less than 15 mph. The non-zero horizontal splashdown speeds are driven by horizontal winds. Figure 6 shows 2σ ellipses with ellipse major and minor lengths along with latitude/longitude of the ellipse center produced over open, middle, and close windows. Figure 6(a) shows the entry ellipse comparison, which shows the middle window producing the largest ellipse size and the close of window with the smallest ellipse size. The center of each ellipse are initially offset. Upon both EDM and RV splashdowns, Figure 6(b) and Figure 6(c) show the ellipse semi-major axes aligning up. The ellipse size trend at entry is also seen at splashdown.

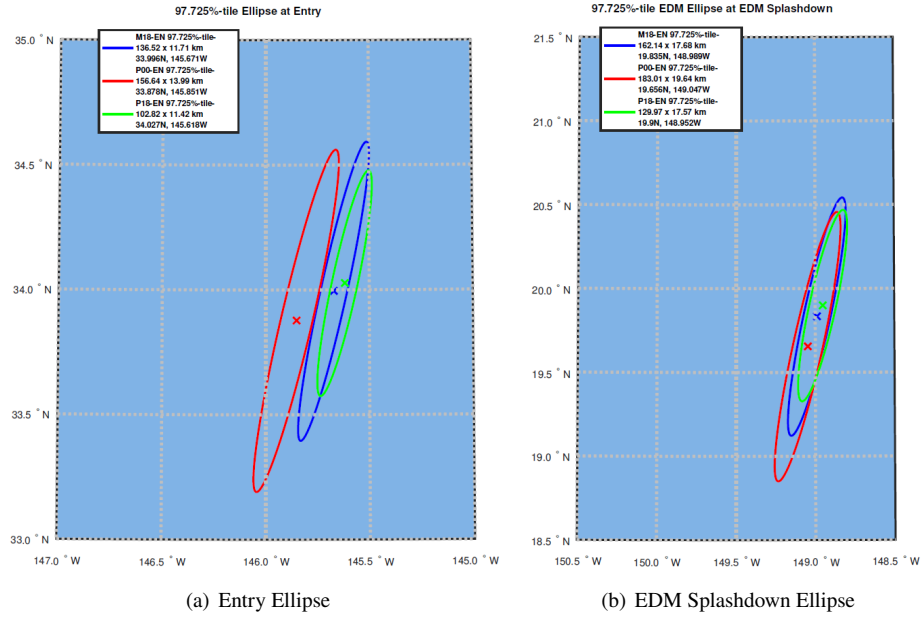
The information obtained from this pre-launch trajectory cycle was used to inform planning for LOFTID mission timeline and recovery. A timeline was developed to inform when key EDL events will occur during launch operations. Splashdown ellipses were used to inform the recovery boat on what region of the Pacific Ocean the LOFTID RV and EDM were expected to land. Going into launch a series of improvements to the trajectory simulation architecture were developed. These included the utilization of atmosphere forecast data in lieu of EarthGRAM 2010 as well as integration of simulation automation into trajectory result generation process.

Table 2 Pre-Launch LOFTID EDL Trajectory Analysis Results. Triad of data for each performance metric corresponds to open, middle, and close BET trajectories respectively.

	2.275%-tile	Mean	97.725%-tile
Time from RV Separation to Entry (s)	1804.88	1811.77	1818.90
	1851.79	1860.00	1867.04
	1810.29	1815.72	1821.21
Entry Flight Path Angle (deg)	-2.2969	-2.2845	-2.2714
	-2.2974	-2.2809	-2.2651
	-2.3027	-2.2899	-2.2770
Entry Velocity (km/s)	8.0212	8.0219	8.0226
	8.0204	8.0218	8.0230
	8.0214	8.0221	8.0228
Entry Total Angle of Attack (deg)	0.4654	3.0672	7.5490
	0.4514	3.1553	7.5985
	0.4434	2.9578	7.3822
Peak Deceleration (Earth g)	8.7872	9.6586	9.6597
	8.7659	9.5112	9.6221
	8.8029	9.6487	9.6751
Peak Dynamic Pressure (Pa)	2035.2842	2158.2550	2242.8670
	2028.6395	2130.0579	2234.9646
	2038.4477	2139.8698	2246.9269
Max Heat Rate at Nose (W/cm ²)	38.0537	39.2735	40.5231
	37.9843	39.1956	40.4554
	38.1141	39.3295	40.5942
Max Heat Load at Nose (kJ/cm ²)	3.4410	3.5222	3.6076
	3.4422	3.5245	3.6103
	3.4379	3.5186	3.6030

*Table continued on next page

	2.275%-tile	Mean	97.725%-tile
Altitude at EDM Jettison (km)	14.5655	15.2421	15.9077
	17.8863	18.7503	19.5566
	14.8514	15.4586	16.0256
Mach Number at EDM Jettison	0.2073	0.2178	0.2312
	0.2761	0.2967	0.3178
	0.2130	0.2220	0.2350
Altitude at Pilot Chute Trigger (km)	3.4440	4.3394	5.0785
	5.2102	6.0492	6.7307
	3.5662	4.4461	5.1619
Total Angle of Attack at Pilot Chute Trigger (deg)	0.3392	4.7271	24.5274
	0.3567	4.6577	23.2903
	0.3503	4.7362	25.0208
Time from Entry to Splashdown (s)	1199.74	1364.85	1519.95
	1379.76	1544.94	1723.52
	1215.29	1376.85	1531.01
Horizontal Velocity at Splashdown (m/s)	2.5895	8.1665	13.8537
	2.6353	8.1377	13.8407
	2.6035	8.1690	13.8974
Vertical Velocity at Splashdown (m/s)	4.7575	5.6464	6.5653
	4.7344	5.6498	6.5677
	4.7539	5.6457	6.5481



97.725%-tile Footprint at Splashdown

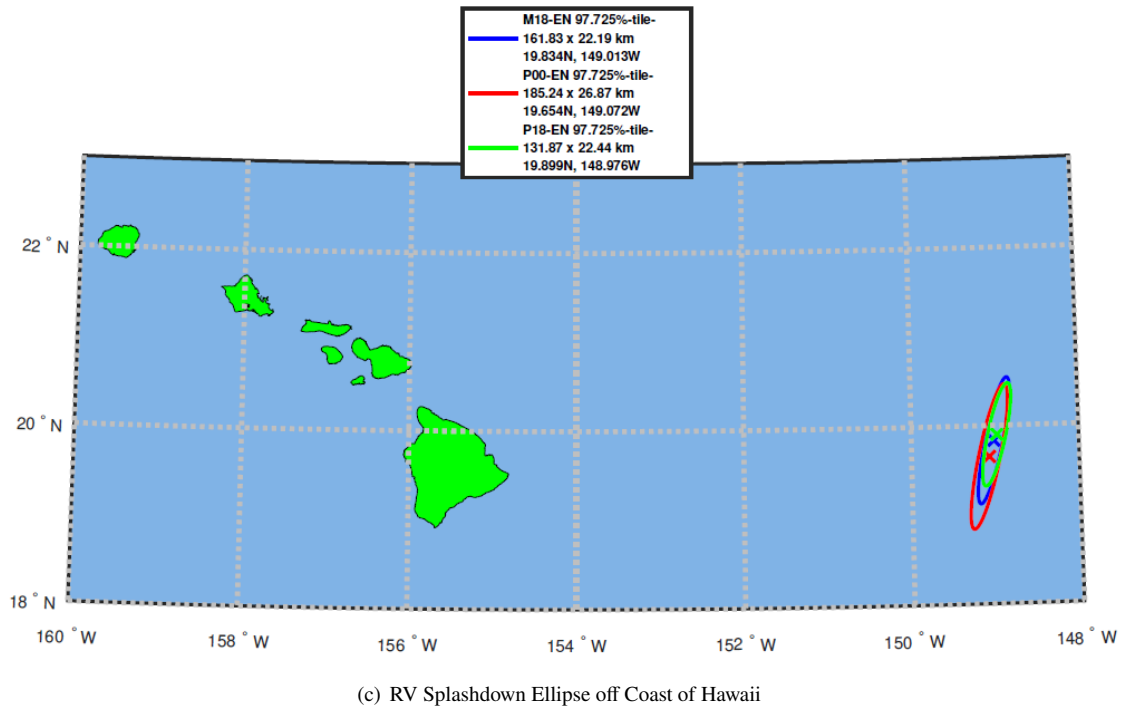


Fig. 6 Pre-Launch BET Analysis Ellipses

V. Day of Launch Performance

Figure 7 shows the day-of-launch splashdown ellipse with the pre-launch trajectory (PT) prediction for RV and EDR as well as GPS data. The locator beacon provided GPS data of the LOFTID RV EDL trajectory up until 1.4 km altitude. The black x shows the estimated RV splashdown point using the estimated lat/long change over the remaining 1.4 km. Centered about the black x are radial distance contours in nautical miles. The green x shows the GPS data at splashdown of the EDR. The center of both the RV and EDR PT ellipses are located within 3 nautical miles of the RV splashdown point, thereby demonstrating the excellent prediction capability of the LOFTID trajectory simulations utilizing GEOS weather forecasts. Figure 7 also shows the GPS movement of the recovery board as well as RV and EDR post-splashdown. Prior to launch, the recovery boat moved to within the vicinity of the PT ellipse centers. Due to launch delay within the 36 min launch window and need to be outside Centaur re-entry debris field, the recovery boat moved outside the splashdown ellipse. At a distance of approx. 9 nautical miles, the recovery board was able to view LOFTID on parachute all the way down to splashdown as shown in Figure 8. Upon visual confirmation of splashdown, the recovery boat moved to rendezvous with LOFTID RV while sailing past EDR (visual confirmation of successfully EDR splashdown). After recovery of LOFTID RV, the recovery board sailed to recover the EDR. Within the span of a few hours, the recovery team was able to successfully recover LOFTID RV and EDR.

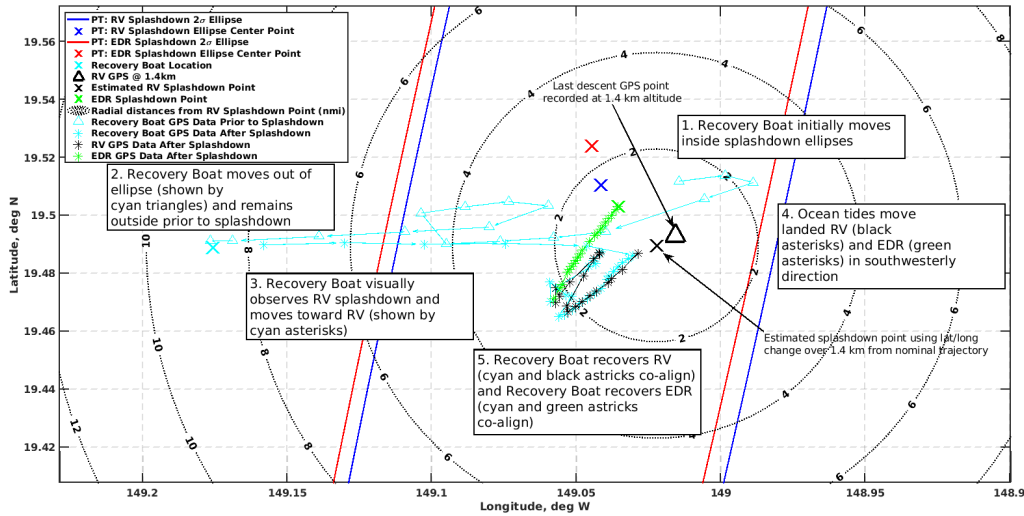


Fig. 7 LOFTID Day-of-Launch Splashdown



Fig. 8 Infrared Camera picture taken from recovery boat of LOFTID on parachute prior to splashdown

VI. Conclusion

The Low-Earth Orbit Flight Test of an Inflatable Decelerator (LOFTID) launch on November 10th, 2022 successfully demonstrated entry, descent, and landing of the largest aeroshell to-date. The flight mechanics analysis conducted in preparation for launch operations allowed for both accurate predictions of LOFTID RV and EDR splashdown points as well as faster recovery times. Pre-launch trajectory analysis over the entire 36 min Centaur launch window allowed for a better understanding of anticipated EDL metrics and facilitated the formulation of mission timeline to be used by the flight mission team. The integration of atmosphere forecast models and automation tools allowed for both improved trajectory predictions as well as improvements in flight mechanics data generation and delivery during operations.

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