

Trajectory Reconstruction of the Low-Earth Orbit Flight Test of an Inflatable Decelerator

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The Low-Earth Orbit Flight Test of an Inflatable Decelerator (LOFTID) project conducted a flight test of a 6m Hypersonic Inflatable Aerodynamic Decelerator (HIAD). The LOFTID test article was a secondary payload on an Atlas V launch vehicle that carried the Joint Polar Satellite System-2 as its primary payload. The vehicle launched on November 10th, 2022. After reaching orbit, the LOFTID test article inflated the aeroshell, separated from the upper stage on an entry trajectory, and entered the atmosphere to splash down in the Pacific Ocean under a parachute. This paper describes the instrumentation and results of the post-flight trajectory and atmosphere reconstruction. Data from the on-board inertial measurement unit were not obtained by the data recorder, and so other means of performing trajectory reconstruction were explored, including photogrammetry-based attitude reconstruction and use of a ballistic range-like trajectory reconstruction approach. Flush air data sensors mounted in the vehicle nose cone provided a means to reconstruct the atmospheric-relative trajectory during entry. The results indicated a hypersonic trim angle of attack of approximately 6.5 deg. The reconstruction results are compared with a trajectory simulation that was based on the day of flight entry conditions.

Nomenclature

e_0, e_1, e_2, e_3	=	Quaternion components for EMEJ2000 to LOFTID body frame (e_0 is the scalar)
q	=	Dynamic pressure, Pa
α	=	Angle of attack, deg
α_T	=	Total angle of attack, deg
β	=	Angle of Sideslip, deg
θ	=	Photogrammetry azimuth angle, deg
φ	=	Photogrammetry co-latitude angle, deg
ϕ	=	Aerodynamic clocking angle, deg
$\omega_x, \omega_y, \omega_z$	=	LOFTID body frame components of inertial angular velocity, deg/s

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I. Introduction

The Low-Earth Orbit Flight Test of an Inflatable Decelerator (LOFTID) project conducted a flight test of a 6m inflatable aeroshell [1]. The purpose of the project was to develop and test a hypersonic inflatable aerodynamic decelerator to advance and mature the technology for future applications for entry systems on Earth and other planets. The LOFTID test article was a secondary payload on an Atlas V launch vehicle that carried the Joint Polar Satellite System-2 (JPSS-2) as its primary payload. The vehicle launched on November 10th, 2022. After reaching orbit, the LOFTID test article inflated the aeroshell, separated from the upper stage on an entry trajectory, and entered the atmosphere to splash down in the Pacific Ocean under a parachute. The test concept of operations is shown in Figure 1.

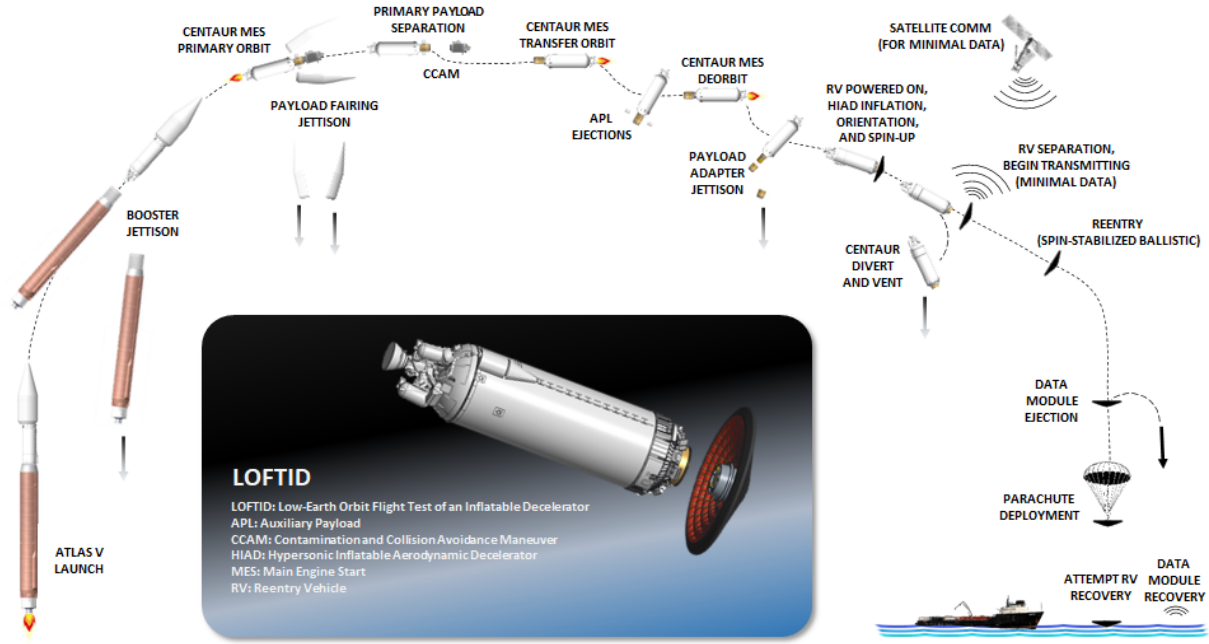


Fig. 1 LOFTID Concept of Operations

The test article was instrumented with a variety of sensors to be used for post-flight evaluation of vehicle performance. Data from one of the key sensors for trajectory reconstruction, the Inertial Measurement Unit (IMU), was not captured in the Ejectable Data Recorder (EDR) due to an unforeseen malfunction in communication between the analog input module and the network switch [4]. Given the loss of the IMU data, alternate methods for trajectory reconstruction were explored. In particular, attitude reconstruction from on-board video was accomplished, even though the cameras were not calibrated for this purpose or intended to be used for attitude determination. Data from pressure ports in the nose cone, arranged as a Flush Air Data Sensing (FADS) system, were acquired, that enabled the reconstruction of the atmospheric-relative trajectory.

The remainder of this paper is organized as follows. Section II gives an overview of the data sources that were available for trajectory reconstruction. These include atmospheric conditions, video cameras, the FADS pressure measurements, locator beacon, and the aerodynamic database. Results of the reconstruction are given in Section III, including an overview of the atmospheric data, photogrammetry results, and the FADS atmospheric-relative trajectory solution. Comparisons of the reconstruction to the trajectory simulation [2] are provided in Section IV. Concluding remarks are given in Section V.

II. Data Sources

A. Atmosphere

The LOFTID ground track spanned a large swath of Earth. After launch from Vandenberg Space Force Base in a near polar orbit, the vehicle circumnavigated the Earth before starting its Entry, Descent, and Landing (EDL) sequence over Alaska. The vehicle splashed down in the Eastern Pacific Ocean to the east of the Big Hawaiian island. Due to

the large ground track and remoteness of the landing location, ground-based atmospheric sources for reconstruction, such as weather balloons and meteorological rockets, were not available. Reconstruction of the atmospheric conditions were planned to be based on in-situ measurements from the on-board FADS and IMU instrumentation. Instead, atmospheric reconstruction was conducted using atmosphere model data because the IMU data were lost. The atmosphere reconstruction process is discussed in Sec. III.A.

B. Video Cameras

LOFTID flew several video cameras attached to the body to record video to be used for visual verification of the heat shield inflation and performance during entry. To this end, a series of six camera pods were placed on the vehicle looking out onto the heat shield to provide full coverage of the entire vehicle, as shown in Fig. 2(a). Note that camera pod 2 was installed on the vehicle but was not functional due to a known hardware issue that could not be fixed prior to flight. A single camera was installed on the body with its field of view pointed aft in order to capture the parachute deployment and inflation. Its installed location is shown in Fig. 2(b).

The purpose of these cameras was to obtain video to be used aid in the assessment of inflatable decelerator system and the parachute. However, during periods of flight time the cameras were able to capture images of the Earth and the Moon. Since the IMU data were lost, an effort was made to attempt to use these cameras combined with ephemeris data to reconstruct the attitude and attitude rates of LOFTID where it would be possible to do so in the given video footage. Note that these cameras were not originally calibrated nor intended to be used as attitude sensors. LOFTID also flew a system of infrared cameras arrayed in a pattern similar to the visual camera pods to obtain additional data on the inflatable heatshield performance. The field of view of these cameras was smaller than that of the visual camera pods such that the Earth and Moon images were not adequately captured for purposes of attitude reconstruction.

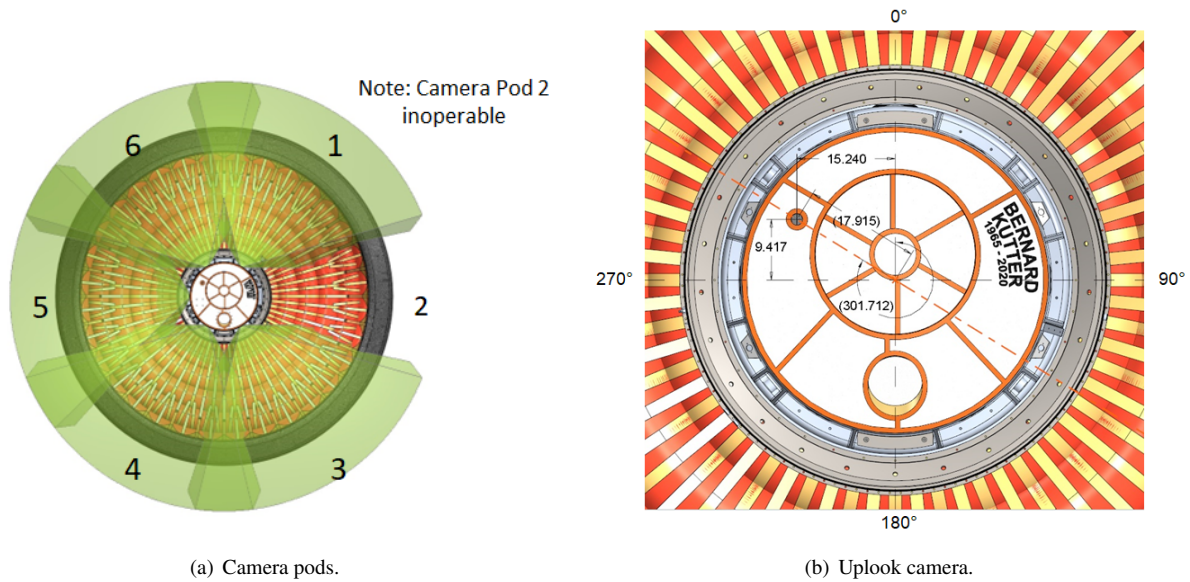


Fig. 2 LOFTID cameras.

Examples of images obtained from the cameras are shown in Fig. 3 and Fig. 4. Examples of the Earth and Moon captured by camera pods are shown in Fig. 3(a) and (b), respectively. Note that the LOFTID inflatable heatshield is in its deployed configuration in these images. The Moon captured from the uplook camera is shown in Fig. 4.

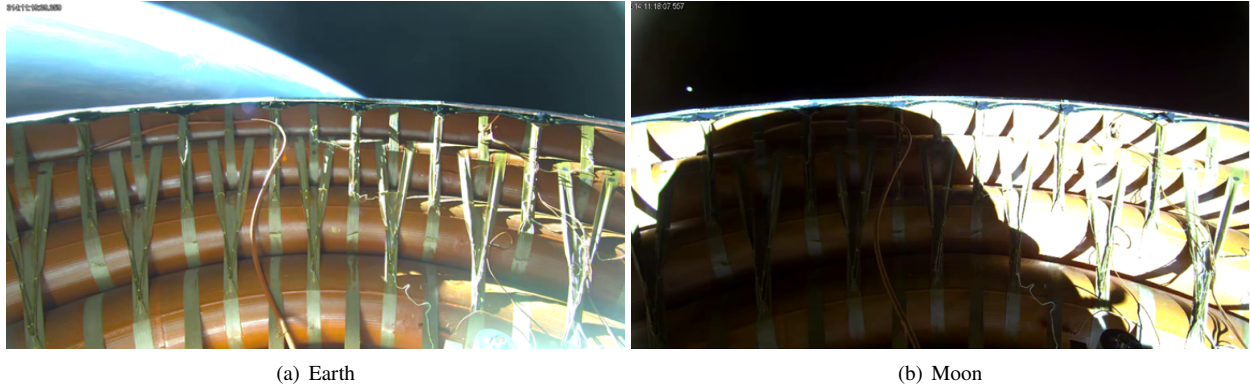


Fig. 3 Earth and Moon from LOFTID camera pod.

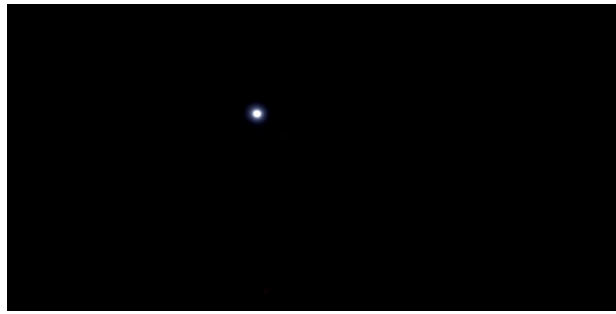


Fig. 4 Moon from LOFTID uplook camera.

C. Flush Air Data Sensing System

The LOFTID nose cone was instrumented with several sensors, which included five pressure ports installed in a cruciform pattern with one port located at the center of the nose, and two ports in each pitch and yaw plane. The center port is labeled LPH70, and starting from the positive pitch plane in 90 deg clockwise increments the ports are labeled LPH71 through LPH74. The port layout is shown in Fig. 5(a).

The pressures were measured by Druck transducers with a full scale range of 5 V, corresponding to a 10 kPa range. The transducers were calibrated for an operating range of -20 to +80 C in a thermal vacuum chamber. The sensors had a rated accuracy of 0.04% of the full scale range, which was confirmed by ground testing. After flight, the recorded pressures were converted to pressure units by applying the calibration coefficients to the sensor's Volt output and measured operating temperature. The resulting pressure measurements along the atmospheric entry trajectory are shown in Fig. 5(b).

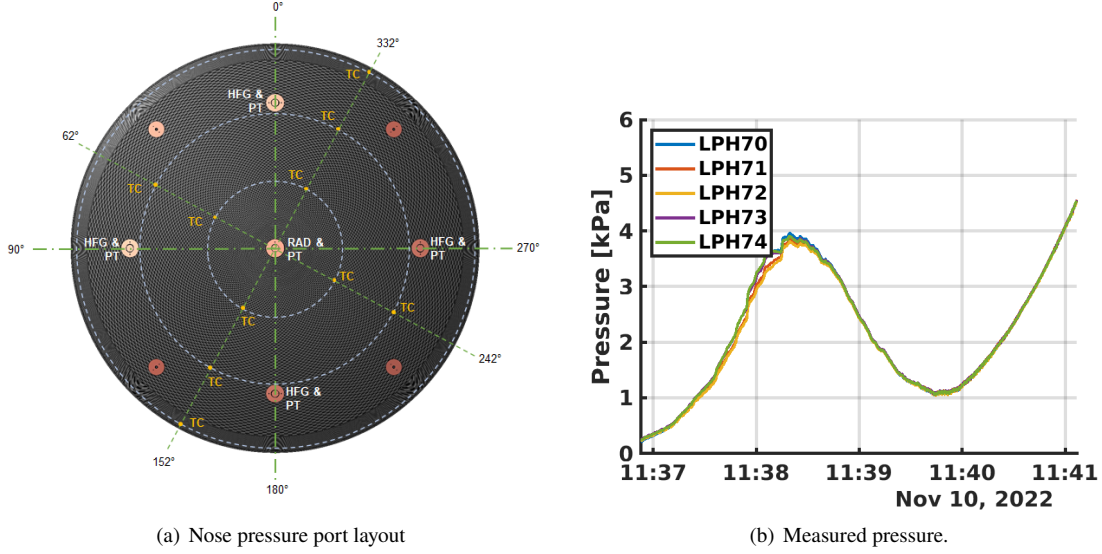


Fig. 5 LOFTID FADS pressures.

D. Locator Beacon

The locator beacon provided Global Positioning System (GPS) measurements of the spacecraft position during a portion of the atmospheric entry. The beacon was able to acquire satellite observations at an altitude of approximately 18.6 km and below. This altitude range corresponds to the subsonic flight regimes and to the parachute flight phase and so are of limited use for evaluating hypersonic and supersonic flight characteristics of the entry vehicle. The data provide a useful comparison for the terminal descent phase of the trajectory simulation [2], described in Section IV.

E. Aerodynamic Database

Aerodynamic forces and moments are key contributors to entry vehicle performance, including drag and stability. The aerodynamics database provides six degree-of-freedom coefficients as a model input to the trajectory simulation as a function of flight conditions and vehicle attitude. The model spans non-continuum and continuum flight regimes, static aerodynamics and dynamic damping, and uncertainties as a function of flight regime and reflection of the tools, methods, and sources for all included data. The aerodynamics datasets, methods, tools, and implementation draw strongly on heritage from IRVE-3 [5] and additional NASA entry capsule missions. The aerodynamics database must span the entire trajectory and range of potential conditions and attitudes. Different computational tools and methods are required for each flow regime, and these tools, methods, heritage, and applicability of each are discussed in detail in [3].

III. Reconstruction Results

A. Atmosphere

Traditionally, on a mission with FADS and IMU data, such as Mars Science Laboratory and Mars 2020 [7, 8], the atmospheric states are reconstructed from a Kalman filter where atmospheric parameters are estimated. However, due to the failure to save the LOFTID IMU data in the data recorder, only FADS data is available. Without an independent estimate of the inertial states from the IMU, it is not possible to separate atmospheric uncertainties from aerodynamic uncertainties in the FADS data. The FADS data has been primarily used for aerodynamic quantities, such as angle of attack. Hence, a separate method was needed for atmospheric reconstruction.

The atmospheric reconstruction method used for LOFTID is similar to the one used for the post-flight analysis of the Adaptable Deployable Entry and Placement Technology Sounding Rocket 1 (ADEPT-SR1) [21]. Data from the Global Modeling and Assimilation Office (GMAO) tool at Goddard Space Flight Center (GSFC) were used to provide temperature, pressure, density, and wind speed information from the surface up to approximately 60 km altitude. The GMAO tool, called Goddard Earth Observing System Model Version 5 (GEOS-5), provides forecasts of Earth's

atmospheric properties in increments of every 3 h [23]. The GEOS-5 predictions are also reanalyzed after the forecast time has passed with local observations to recompute the atmospheric conditions. The observations incorporated include radiosonde data from the National Weather Service, measurements from radar wind sensors, ground station data, and sensors in the ocean [24, 25]. Although some of the incorporated data may not be at the location of the forecast needed for LOFTID, the overall predictions are improved.

GEOS-5 provides data 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. Since LOFTID was an orbital return mission, the trajectory of the vehicle covered a large area of Earth (see Fig. 6). Based on previous analysis during operational support [2], it was decided to use the vertical profile at 22° North and 211.25° East from the GEOS-5 analysis for atmospheric parameters. As discussed in Ref. [2], the trajectory simulation was not found to be very sensitive to other GEOS-5 profiles along the path of the spacecraft. This particular point also had the advantage that forecast uncertainties computed by the GMAO were available. GMAO MERRA-2 forecast uncertainties for two other locations were also provided (as seen in Fig. 6), but only the uncertainties of the point where the vertical profile was chosen from were used.

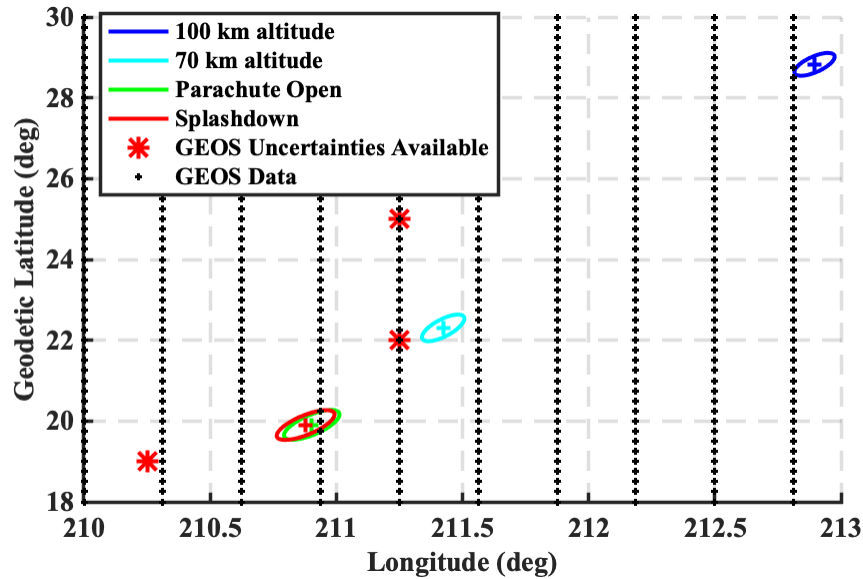


Fig. 6 LOFTID Trajectory at key events and GEOS-5 Forecast Locations

The GEOS-5 reanalysis data from 1200 Coordinated Universal Time or UTC provided the bulk of the data of the post-flight atmosphere model for LOFTID. However, to extend the atmosphere from approximately 65 km altitude to 125 km altitude, which is the entry interface definition, supplemental data was needed. The authors did not have access to any high quality data set for atmospheric measurements for this area of the Pacific Ocean. Hence, similar to the ADEPT SR-1 reconstruction, the temperature profile from the 1976 US Standard Atmosphere [26] was used to extend the temperature profile. The lapse rate, or the rate of change of temperature with respect to altitude, was used at corresponding altitudes above 65 km to extend the GEOS-5 temperature prediction. Then, the hydrostatic equation and the perfect gas law were 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 [22] to avoid simulating an artificial wind shear by instantaneously making the wind speed zero. The post-flight estimates for temperature (Fig. 7), density (Fig. 8), East-West winds (Fig. 9), and North-South winds (Fig. 10) are shown here, along with comparisons to the pre-flight forecast used during operations [2] and the design atmosphere from the Global Reference Atmospheric Model (GRAM) [27]. The forecast matches the reanalysis GEOS-5 data, but there are noticeable differences with the GRAM profiles used during the early design phase.

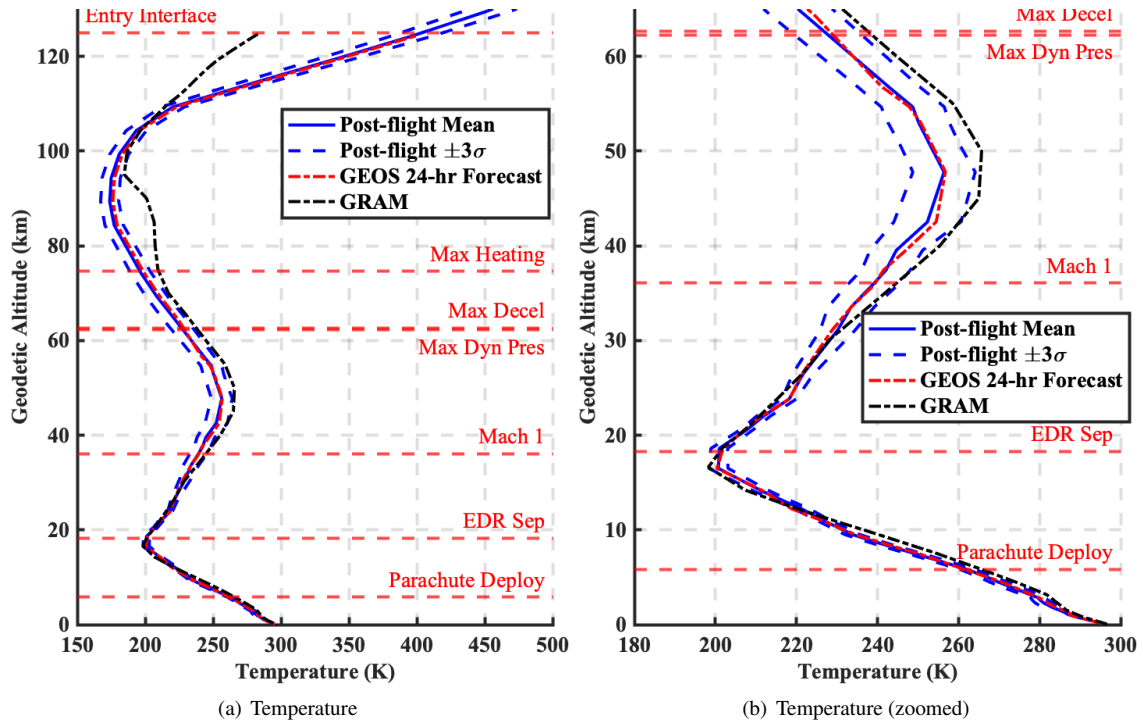


Fig. 7 LOFTID Post-flight Temperature Estimate.

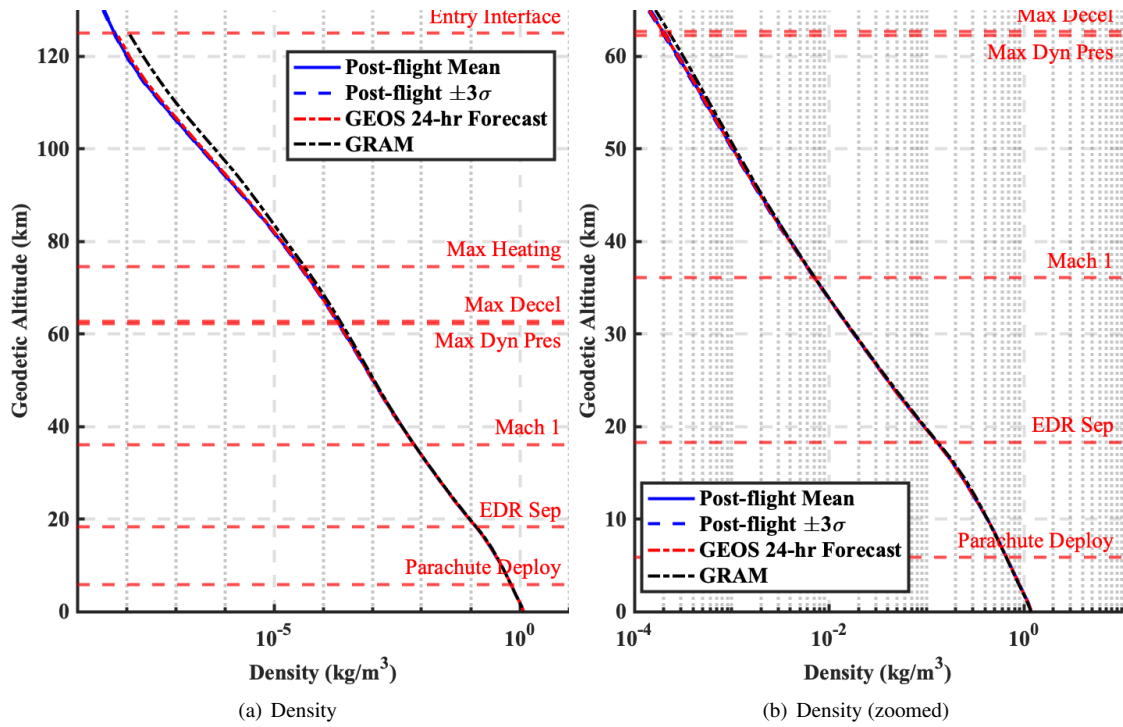


Fig. 8 LOFTID Post-flight Density Estimate.

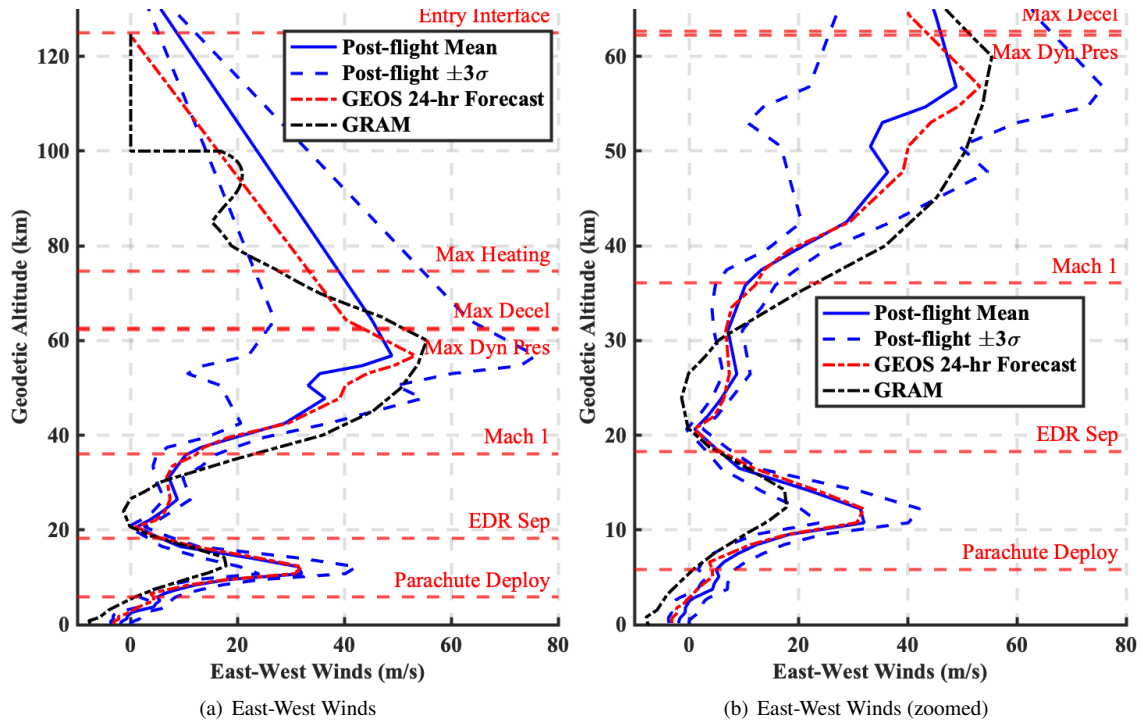


Fig. 9 LOFTID Post-flight East-West Winds Estimate.

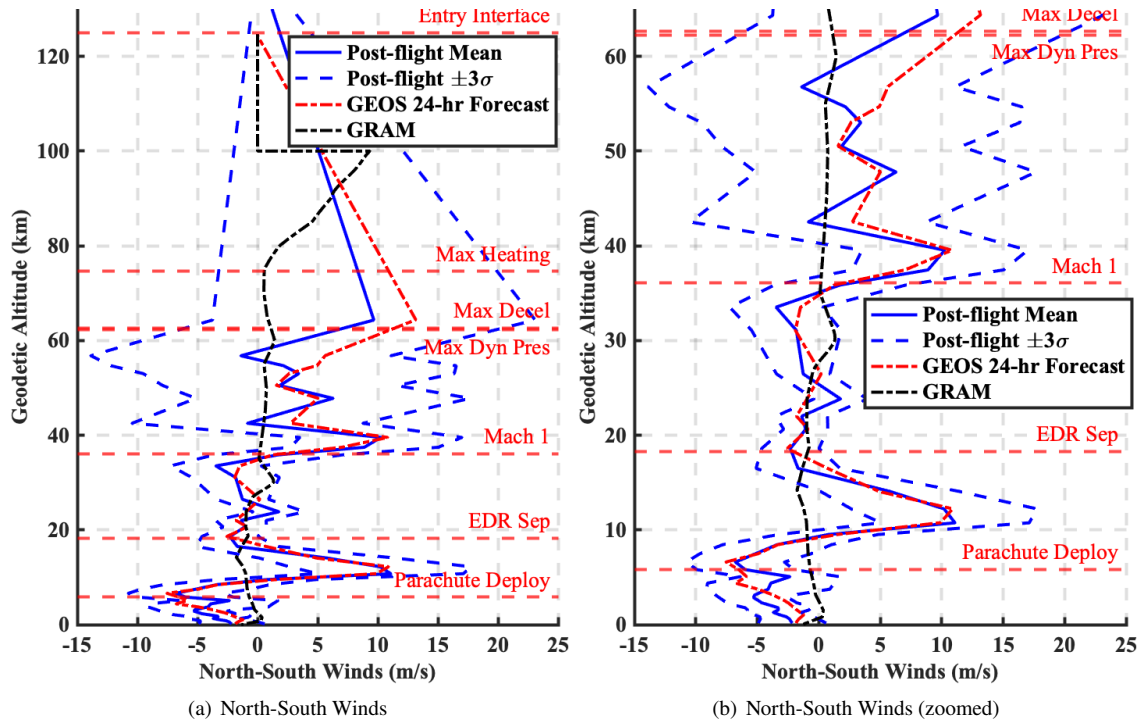


Fig. 10 LOFTID Post-flight North-South Winds Estimate.

B. Video Image Processing

The LOFTID camera pod data were processed to extract Earth and Moon unit vectors in the LOFTID body coordinate frame, illustrated in Fig. 11. These two unit vectors meet the minimum set of measurements to determine the vehicle attitude [18]. The video data was processed frame by frame by first masking the LOFTID heatshield and then processing the images to detect the location of the Moon in the camera frame. Next, the limb of the Earth that is contained in the camera field of view was extracted. The position of the moon within the camera field of view was determined by a simple point detection algorithm. Extracting the position of the Earth in the camera frame was more complicated since only a short arc of the limb of the planet is in view. The position of the center of the Earth in the camera frame was determined by extracting the contour of the visible limb, functioning as a makeshift horizon sensor [15–17], and next generating a sequence of perpendicular bisectors from a set of points along the extracted arc. The Earth center was determined by computing the average intersection point from the family of bisectors. The process is illustrated in Fig. 12. One example image of the Earth limb and bisectors from a camera pod is shown in Fig. 13. Note that the intersection point of the bisectors is located far outside the camera field of view.

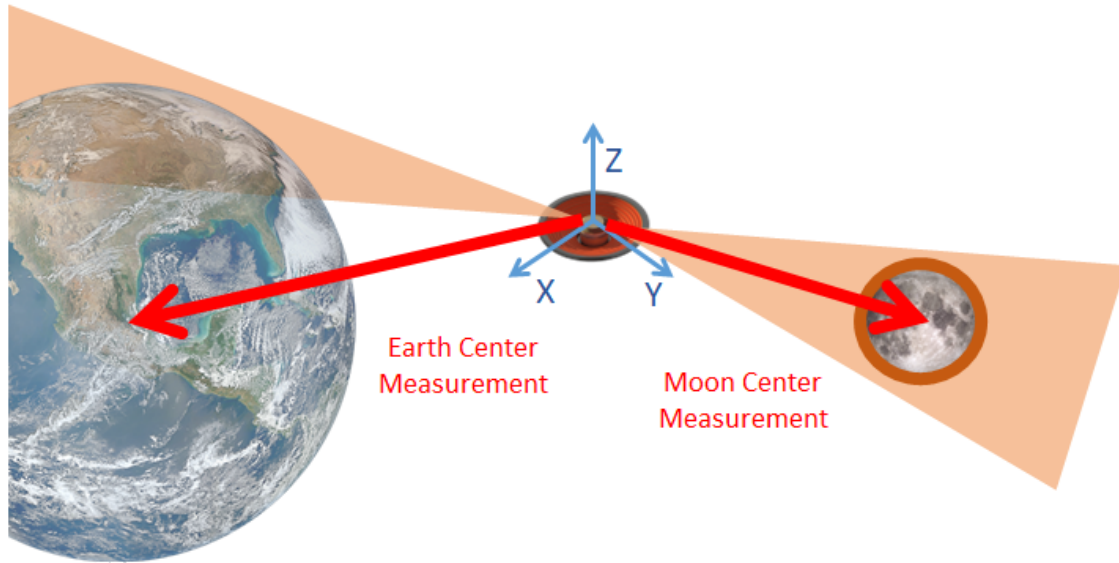


Fig. 11 Earth and Moon vector measurements.

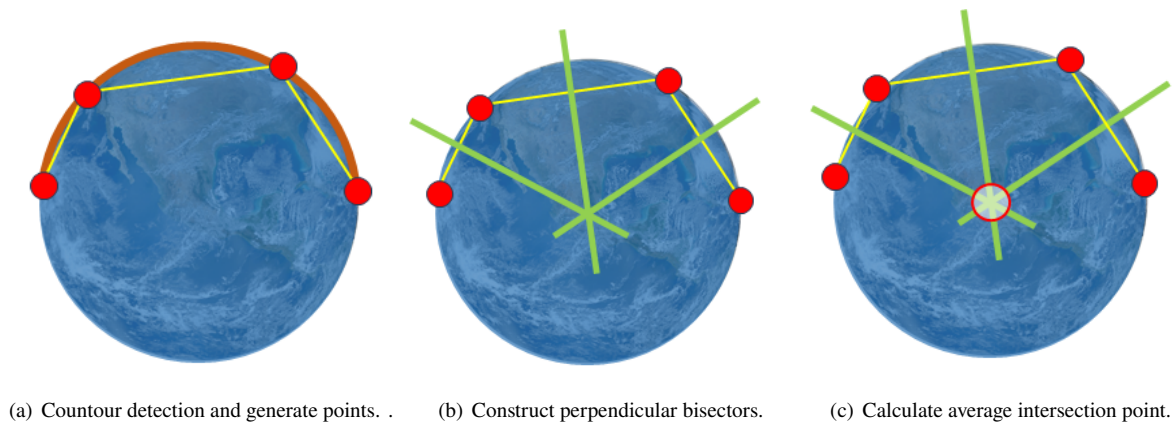


Fig. 12 Determination of Earth center.

After extracting the centers of the Earth and Moon in the camera frame, the camera pointing vectors relative to the LOFTID vehicle and corrections for optical distortions were used to construct angle measurements of the center of

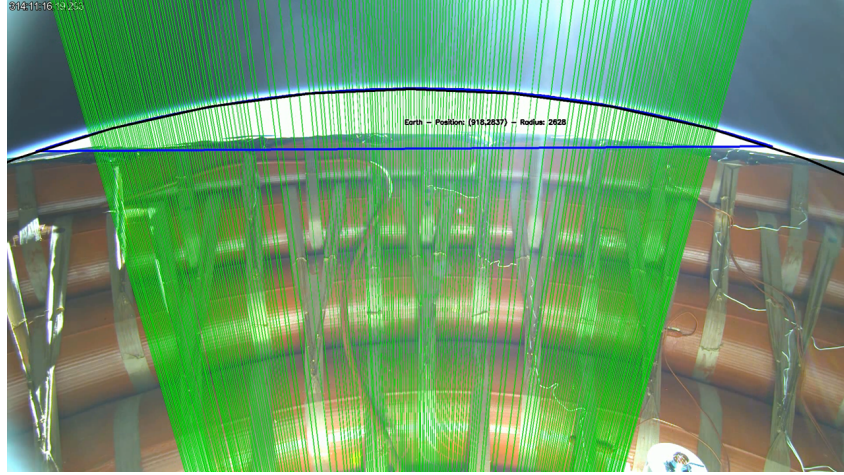


Fig. 13 Earth centering.

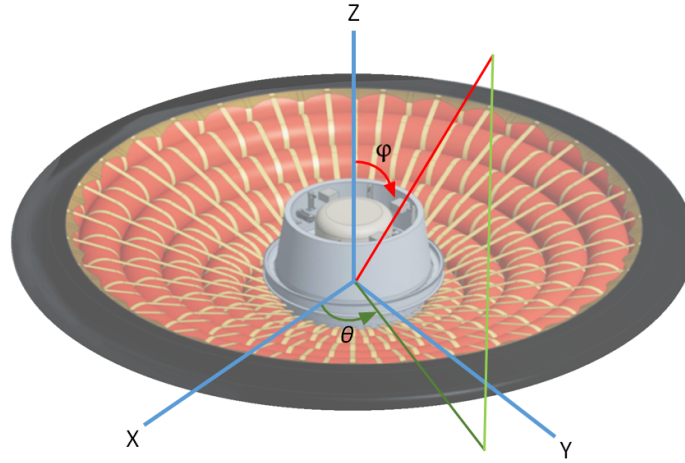
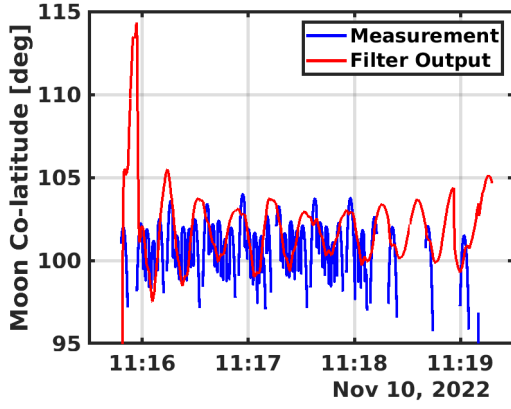


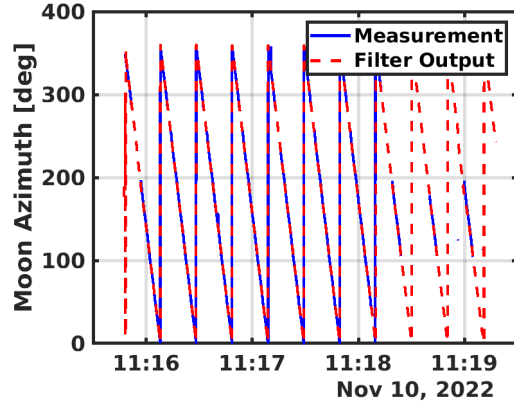
Fig. 14 LOFTID photogrammetry coordinate frame.

each celestial body relative to the LOFTID vehicle. The angle measurements, consisting of an azimuth angle, θ , and a co-latitude, φ , are illustrated in Fig. 14. Recall as previously described, the center of the Earth in the camera frame was well outside the field of view of the camera pod images. As a result, extrapolating beyond the field of view renders the Earth co-latitude angle erroneous due to pixel mapping nonlinearities. The Earth azimuth angle was still valid, however. This result means that three angles are available for determining the attitude of the vehicle: the Moon co-latitude and azimuth, and the Earth azimuth. These three angles meet the minimum required for attitude determination [18]. The measured angle data derived from the Earth and Moon camera observations are shown in Fig. 15 in the blue curves. Note that the Earth co-latitude is not shown as that data was deemed to be invalid as previously discussed.

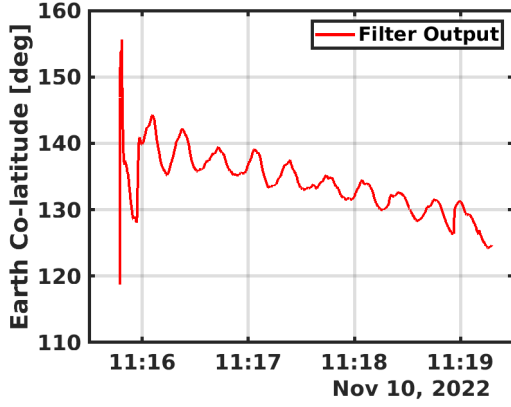
The three angles were processed using a Kalman filter formulated to estimate the attitude and angular velocity of the spacecraft [18]. The filter was formulated to estimate the Earth Mean Equator of J2000 (EMEJ2000) [19] quaternion and the body axis angular velocity from the Earth and Moon angle data. The filter process model made use of a constant-angular-velocity model for propagating the attitude between angle measurements. The measurement model was formed by computing unit vectors from the spacecraft to each celestial body in the EMEJ2000 frame, then rotating the vectors into the spacecraft frame to compute the azimuth and co-latitude angles. The position of the Moon in the EMEJ2000 frame required for the measurement model was computed from the SPICE tool [20]. The measurement noise covariance matrix was scheduled as a function of the position of the object within the camera frame to give more uncertainty to objects at the extremities of the camera field of view to account for unmodeled nonlinearities and other



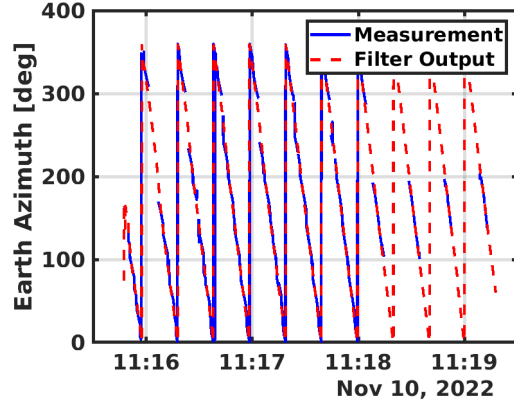
(a) Moon co-latitude angle.



(b) Moon azimuth angle.



(c) Earth co-latitude angle.



(d) Earth azimuth angle.

Fig. 15 Earth and Moon angles.

camera visual artifacts.

The results of the attitude reconstruction are shown in Fig. 16. The reconstructed EMEJ2000 to body quaternion components are shown in Fig. 16(a). The reconstructed angular velocity components are shown in Fig. 16(b). The attitude rate reconstruction shows nearly zero rates in the x and y axes and an approximately steady rate in the z axis with a magnitude of approximately 17.7 deg/s, which is a match with the expected nominal spin rate of 18 deg/s [2]. This match confirms that the photogrammetry approach applied to LOFTID reconstruction produces a reasonable result.

Lastly, the uncertainties of the reconstructed attitude and angular rate are shown in Fig. 16(c). This plot shows the 1σ uncertainty of the total attitude and total rate error. After initial transients, the attitude uncertainty oscillates between approximately 2 to 4 deg and the total rate uncertainty is 0.4 deg/s.

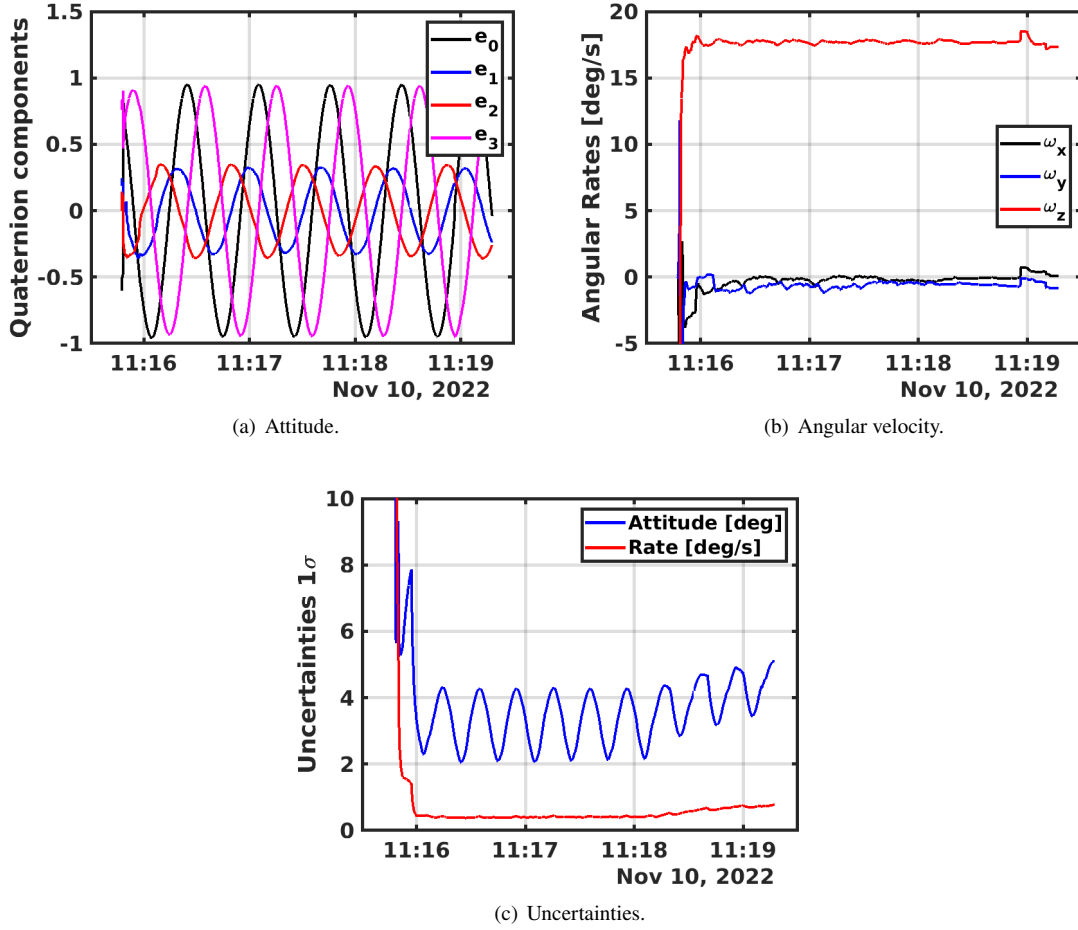
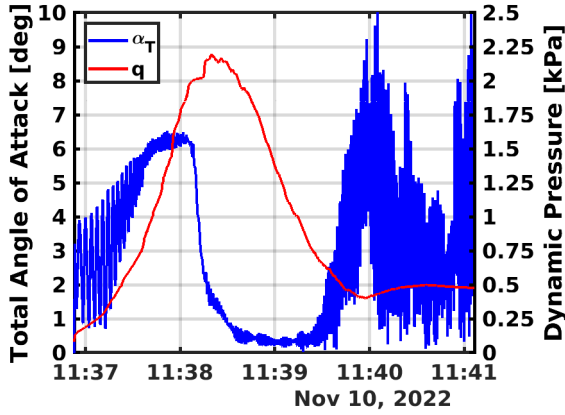


Fig. 16 Attitude and angular velocity.

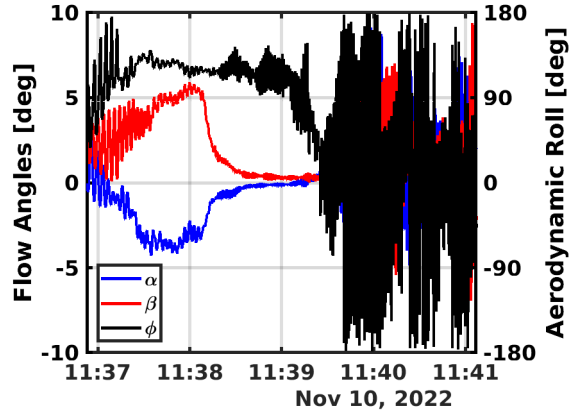
C. Flush Air Data Sensing System Reconstruction

The FADS data were combined with a Newtonian flow pressure model [6, 7] to produce estimates of the atmospheric relative trajectory. A Mach number anchoring technique given in [7] was used to stabilize estimates in high speed flight conditions. Since no IMU data were available, a trajectory simulation [2] was used to provide the Mach number time history. The resulting estimates of the atmospheric-relative trajectory are shown in Figures 20.

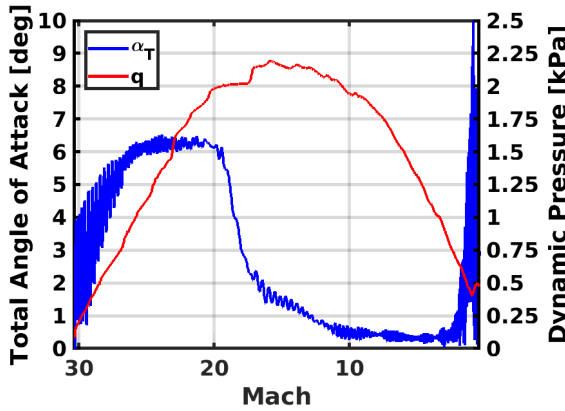
The peak total angle of attack in the hypersonic flight phase was approximately 6.5 deg. Just prior to peak dynamic pressure, the total angle of attack dropped to approximately 0.5 deg. The hypersonic aerodynamic clocking angle was approximately 120 deg, which was consistent with observations from the uplook camera wake video analysis [4]. The peak dynamic pressure was 2.19 kPa. The peak drag force and peak acceleration were 102.8 kN and 9.52 g's, respectively, calculated by assuming nominal aerodynamics database evaluated along the reconstructed trajectory. Note that the slight bump in the dynamic pressure prior to the peak pressure could correspond to a density "pot hole," an atmospheric phenomenon that has been observed in Space Shuttle entries [9, 10], IRVE-3 [5], and possibly in the Low-Density Supersonic Decelerator (LDSD) second flight test [11]. Other onboard instruments such as load sensors confirmed this bump in dynamic pressure [4]. The atmospheric density along the trajectory was computed from the reconstructed dynamic pressure and the velocity from the trajectory simulation [2]. Comparisons of the density to the atmospheric data are shown in the following section.



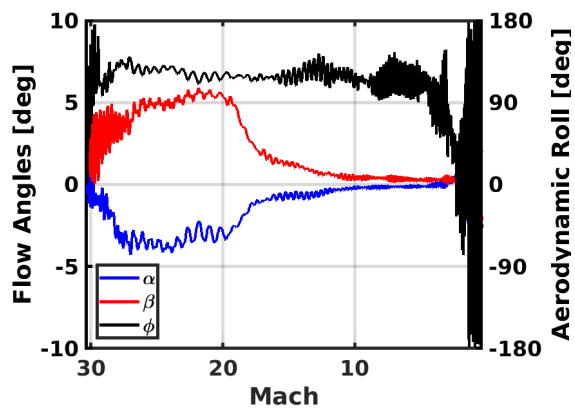
(a) Total angle of attack and dynamic pressure vs. time.



(b) Clocking, sideslip, and angle of attack vs. time.



(c) Total angle of attack and dynamic pressure vs. Mach.



(d) Clocking, sideslip, and angle of attack vs. Mach.

Fig. 17 FADS reconstructed trajectory.

D. Trajectory Reconstruction

Typically an IMU forms the most basic set of inputs for purposes of post-flight trajectory reconstruction [12, 13]. Recently, a new capability in a Kalman filter tool for solving post-flight trajectory reconstruction problems known as the New Statistical Trajectory Estimation Program (NewSTEP) was added for processing data from magnetic suspension wind tunnels and ballistic range tests [14]. In this mode, the filter does not rely on IMU measurements, instead using an aerodynamic model of the capsule as the process model for propagating state estimates. Parameters of the aerodynamic model are additional filter states that are estimated by fitting the equations of motion to the observed motion of the capsule. In the case of LOFTID, the observed quantities that can be used to fit the aerodynamic model are the FADS-derived dynamic pressure and angles of attack and sideslip shown in Fig. 20. The application of NewSTEP to the LOFTID trajectory reconstruction is an ongoing work and will be reported on in future documents.

IV. Best Estimated Trajectory

The lack of IMU data caused an engineering challenge in trying to ascertain the reconstructed flown trajectory of LOFTID. Trajectory reconstruction processes for past EDL missions have predominantly relied on IMU accelerations and rates to reconstruct the flown trajectory (position, velocity, attitude). In lieu of IMU data, the Program to Optimize Simulated Trajectories 2 (POST2) trajectory simulation [2] is utilized wherein available data sources are utilized to reconcile the day-of-flight simulation model inputs. During the reconciliation process, a series of best predicted flown trajectories (BPFT) are generated. Version 0 pertained to the pre-launch trajectory (PLT) generated prior to LOFTID EDL (see [2] for more information). Version 1.0 of the BPFT (BPFTv1) is identical to the PLT with the exception of the

utilization of reconciled day-of-flight GEOS atmosphere (see Section II.A). Version 2.0 of the BPFT (BPFTv2) utilizes the orbital parameter message of the the initial position and attitude state at RV separation. This section provides a comparison of the generated BPFT trajectories to available flight data introduced in Section II.

A. GPS comparison

The location beacon (LB) GPS data is utilized in comparison to the PLT and BPFT versions. Figure 18 provides a trajectory position comparison in latitude/longitude/altitude space. The LB data generally agrees well with the reconciled trajectories. The differences in the trajectories can be attributed to differences in the atmosphere model.

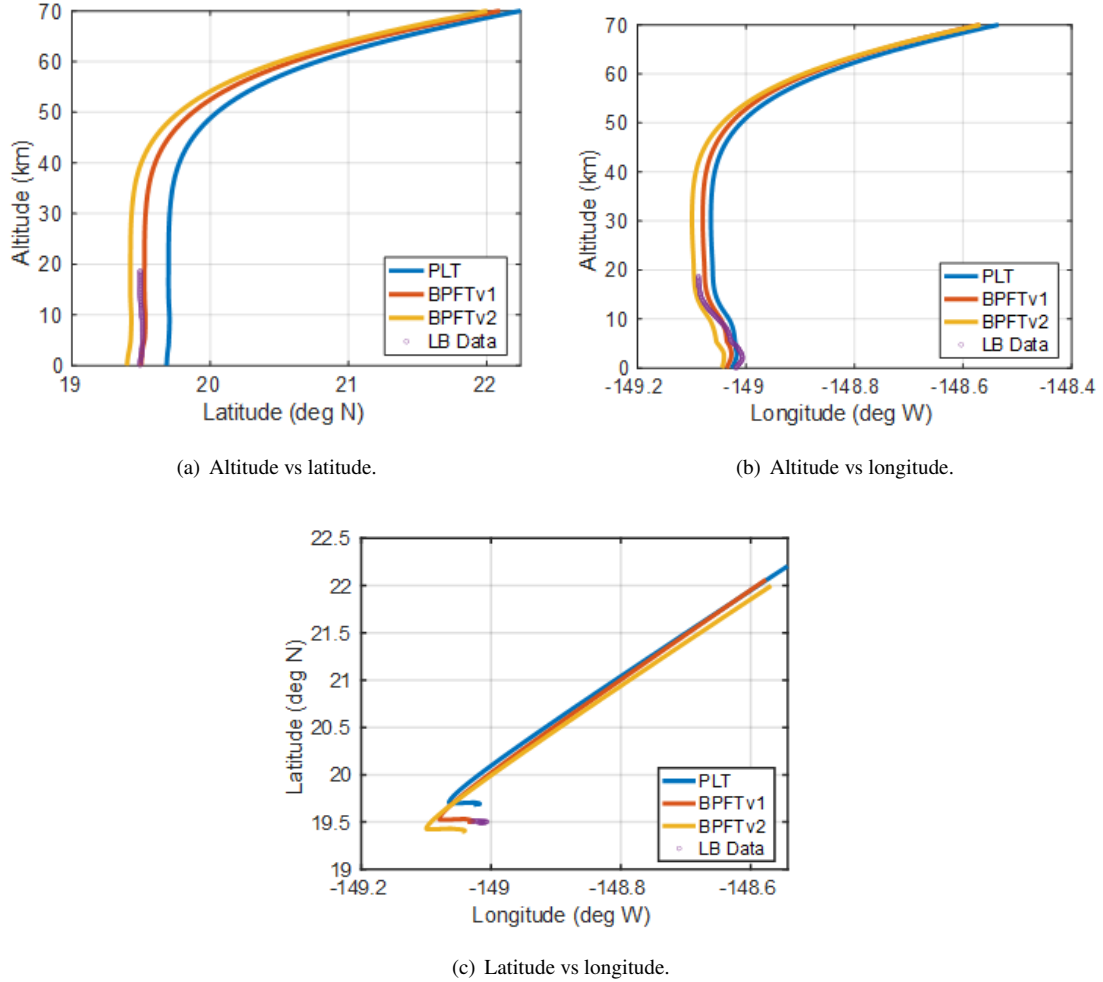


Fig. 18 Trajectory comparison with locator beacon position.

Figure 19 provides a trajectory velocity comparison between the LB data and the reconciled trajectories. At a zoomed out view (subplot a), not much difference can be seen between the datasets. Zooming into a region below 10 km altitude (subplot b), the LB data tracks well with both BPFT trajectories. Between 7-10 km, the LB data suggests slower deceleration than the trajectories. The two rapid changes in velocity are representative of LOFTID pilot and main parachute deployments. The LB data agrees extremely well with the BPFT trajectories indicating pilot chute deployment at 5.8 km and main chute deployment at 5.4 km. The PLT predicted parachute deployments to occur at lower altitudes. Zooming in on the last 1 km shows LB data indicating slightly higher splashdown velocity (7.5 m/s) than the trajectories (all three on top of each other) along with oscillations in velocity. These oscillations are most likely caused by horizontal winds while on parachute prior to splashdown. Overall, LB data agrees well with trajectory estimates and provide quantitative confirmation of successful parachute deployment.

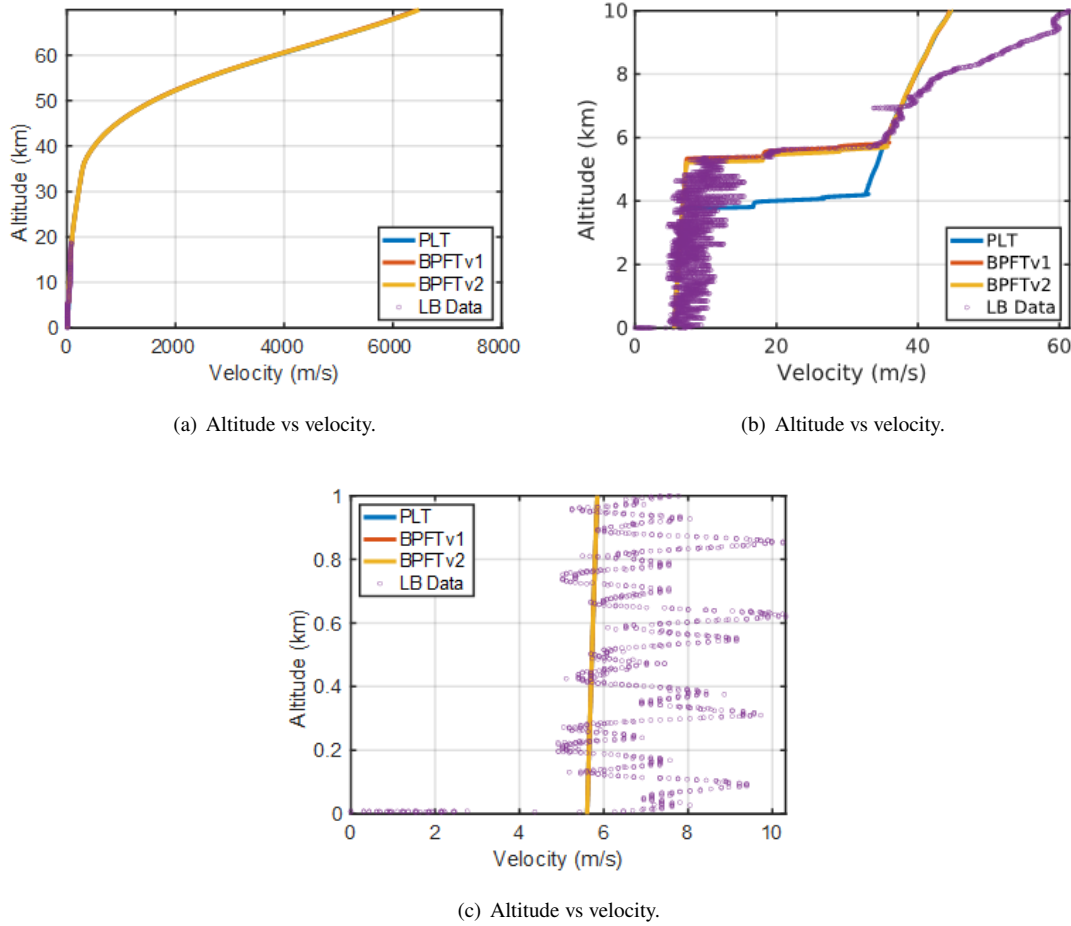


Fig. 19 Trajectory comparison with locator beacon velocity.

B. FADS comparison

The FADS provides engineering measurements of the LOFTID as-flown freestream conditions. The reconstructed dynamic pressure can be utilized in conjunction with the atmosphere relative velocity to obtain an estimate of the atmospheric density. FADS does not directly measure atmosphere relative velocity, so the reconstructed trajectory from IMU and atmosphere wind data would be needed. The POST2 generated trajectories are utilized in lieu of IMU data to provide a FADS-estimate of the as-flown density profile. This density profile is utilized in lieu of reconciled GEOS atmosphere model in BPFTv2 to see what affect it has on the subsequent trajectory output. Figure 20 provides a comparison between the reconstructed FADS data and the POST2 generated trajectories. The FADS density profile generally tracks well with BPFTv1 and BPFTv2 but suggests higher density at altitudes above 60 km (subplot a) (note: FADS and BPFTv2 w/FADS Density will have the same density profile). This slight difference in density leads to faster deceleration when the BPFTv2 trajectory is rerun using the FADS density profile (subplot d). Note that the FADS and BPFTv2 will have the same velocity profile. The combination of higher densities but lower velocities leads to the BPFTv2 run with the FADS density profile to generate a lower peak dynamic pressure than both the original BPFTv2 trajectory and FADS data (subplot c). The bump in dynamic pressure measured by FADS can be incorporated into density to produce the same subsequent effect in the rerun trajectory. This change in result demonstrates is the challenge of mixing dependent data sources (e.g. density dependent on trajectory data) in trying to reconcile differences seen in FADS and BPFT trajectories. Nevertheless, BPFTv1 and BPFTv2 generally agree well with the FADS data for dynamic pressure but do not agree with total angle of attack (subplot b). The FADS data suggests a larger increase in total angle of attack prior to peak dynamic pressure, which is caused by an aeroshell torque not captured in the BPFT trajectories. These rotational dynamics would have been sensed by an IMU.

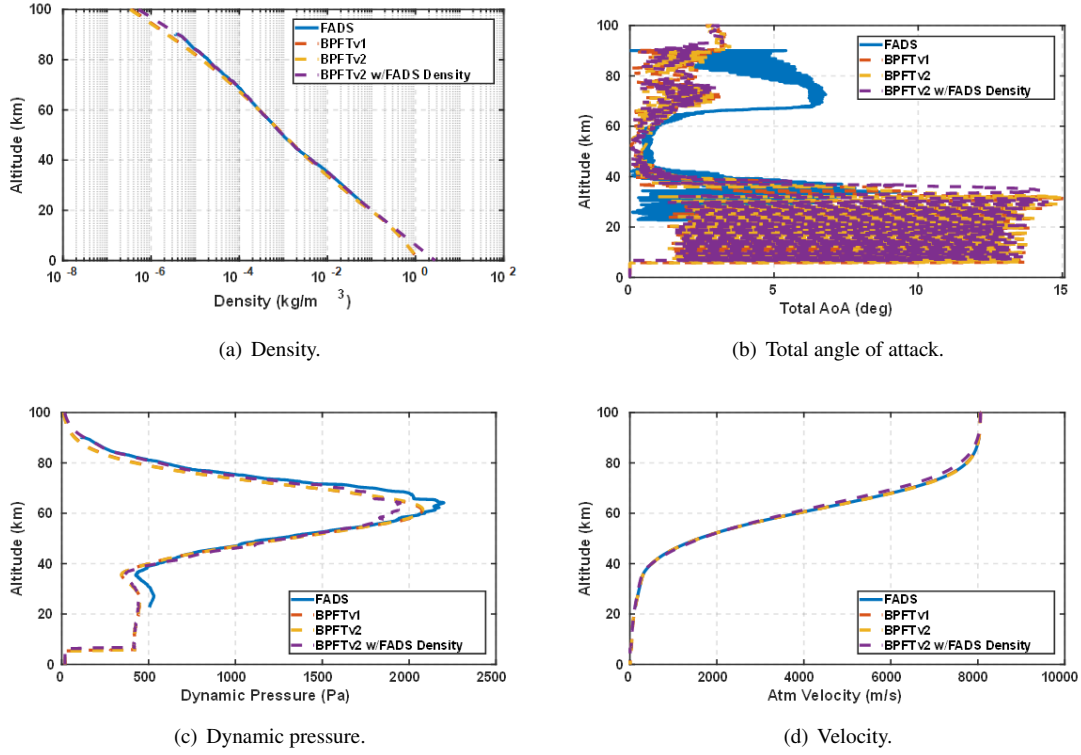


Fig. 20 Trajectory comparison.

C. BET at-a-glance

The best estimated trajectory (BET) for LOFTID is generated using BPFTv2. Figure 21 shows a ground track of the trajectory from Centaur separation above the Sinai Peninsula thru entry interface and finally splashdown off the coast of Hawaii. Table 1 provides quantitative results for the BET.

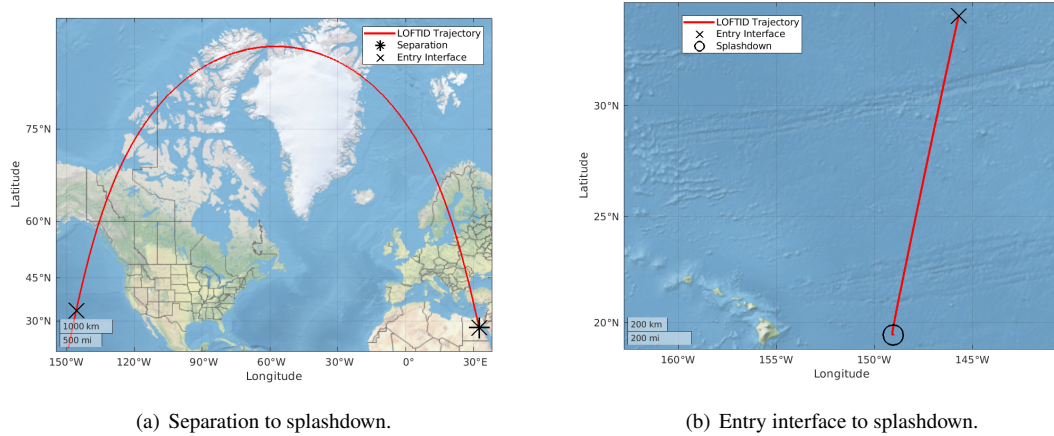


Fig. 21 LOFTID best estimated trajectory.

Table 1 LOFTID best estimated trajectory data.

RV Separation		Entry Interface	
Earth Centered Earth Fixed (ECEF) X (km)	5268.7913	Time Since Separation (sec)	1853.8567
ECEF Y (km)	3349.8203	Inertial Velocity (km/s)	7.9466
ECEF Z (km)	3224.9374	Inertial Flight Path Angle (deg)	-2.2933
ECEF Vx (km/s)	-1.9751	Geodetic Latitude (deg)	33.8818
ECEF Vy (km/s)	-3.1591	Longitude (deg)	214.2874
ECEF Vz (km/s)	6.4241	Azimuth (deg)	189.6399
Pitch Angle (deg)	-60.4903	Geodetic Altitude (km)	125.0000
Yaw Angle (deg)	164.8808	Total Angle of Attack (deg)	1.2258
Roll Angle (deg)	-143.8753	Pitch Rate (deg/s)	-0.1197
Pitch Rate (deg/s)	0.0428	Yaw Rate (deg/s)	-0.1290
Yaw Rate (deg/s)	-0.0628	Roll Rate (deg/s)	-18.0223
Roll Rate (deg/s)	-18.0230		
EDL Metrics		EDR Jettison	
Peak Deceleration (Earth G)	8.9842	Time Since Separation (sec)	2260.0000
Peak Dynamic Pressure (Pa)	2079.7396	Geodetic Altitude (km)	18.1705
Total Angle of Attack @ Max Nose Heating (deg)	0.1294	Total Angle of Attack (deg)	4.3587
Max Nose Heat Rate (W/cm^2)	39.7720	Mach Number	0.2878
Max Nose Heat Load (kJ/cm^2)	3.4516	Time to EDR splashdown	330.7363
Time Since Entry @ Peak Nose Heating (sec)	161.2433	Pilot Chute Trigger	
Time Since Entry @ Peak Deceleration (sec)	201.3633	Time Since Separation (sec)	2509.0000
Time Since Entry @ Peak Dynamic Pressure (sec)	202.4633	Geodetic Altitude (km)	5.7164
Geodetic Altitude @ Peak Nose Heating (km)	73.8274	Total Angle of Attack (deg)	2.0889
Geodetic Altitude @ Peak Deceleration (km)	61.7327	Mach Number	0.1084
Geodetic Altitude @ Peak Dynamic Pressure (km)	61.3921	Velocity (m/s)	35.2081
Mach @ Peak Nose Heating	25.3898	Time to Main Chute (sec)	3.8720
Mach @ Peak Deceleration	14.2717	Splashdown	
Mach @ Peak Dynamic Pressure	13.9253	Time since separation (sec)	3356.4389
Main Chute Begin		Horizontal Velocity (m/s)	2.8577
Geodetic Altitude (km)	5.5917	Vertical Velocity (m/s)	5.6033
Mach Number	0.0881	Off-Vertical Angle (deg)	0.0039
Velocity (m/s)	28.6530	Geodetic Latitude (deg)	19.3982
Time to RV splashdown (sec)	843.5669	Longitude (deg)	210.9555
		Distance from GPS Splashdown Point (nmi)	5.5346

D. Future Development

This section has shown that the reconciled trajectories generated by POST2 simulation agree well with available flight data. The lack of IMU data makes it difficult to generate a pure trajectory reconstruction of the flown LOFTID trajectory with independent data sources. To further refine the best estimated trajectory, novel reconstruction techniques are needed. Combining overlapping GPS and FADS attitude data can be utilized in NewSTEP to force the flight dynamics to follow the measured data. This capability has been recently developed to support ballistic range trajectory reconstruction and can be utilized in the future for further updates to the LOFTID trajectory reconstruction.

V. Conclusions

The Low-Earth Orbit Flight Test of an Inflatable Decelerator (LOFTID) project conducted a successful flight test on November 10th, 2022. Though the critical inertial measurement unit data were not captured, other data sources were used to reconstruct the flight performance of the vehicle during atmospheric entry. Data from pressure transducers located on the vehicle nose section indicated that the vehicle flew a hypersonic trim angle of attack of up to approximately 6.5 deg. A possible atmospheric density “pot hole” was observed in the dynamic pressure reconstruction. Future work will be focused on the application of ballistic range data reduction approaches to the LOFTID trajectory reconstruction problem.

Acknowledgments

The authors would like to thank John DiNonno, Greg Swanson, Ruth Miller, and Cole Kazemba for assistance with the video data, Jacob Fleck for assistance with SPICE, Larry Coy and Robert Lucchesi for their help with the GEOS-5 data and analysis, and Ron Neale for generating some graphics used in this paper.

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