Flight Mechanics Modeling and Post-Flight Analysis of ADEPT SR-1

Soumyo Dutta*
NASA Langley Research Center, Hampton, VA 23681, USA

Sounding Rocket One (SR-1), the first flight test of the Adaptable Deployable Entry and Placement Technology (ADEPT), was performed on Sept. 12, 2018. ADEPT is a deployable aeroshell that can be stowed during launch and then opened after launch to increase the drag area of the spacecraft when entering into a planetary atmosphere. The main objectives of the SR-1 flight test were to demonstrate that the ADEPT vehicle can be opened exo-atmospherically and to characterize the stability of the vehicle during atmospheric flight. The SR-1 test vehicle was a 0.7 m diameter 70 degree half-angle, faceted, sphere-cone, which was the primary payload on an UP Aerospace Spaceloft (SL) launch vehicle from the White Sands Missile Range (WSMR). ADEPT successfully separated from the spent booster in its stowed configuration, opened above 100 km altitude, and then landed in the deployed configuration within WSMR. The flight mechanics of the vehicle was modeled pre-flight for performance and range safety predictions. This paper describes the pre-flight ADEPT trajectory simulation and how the flight data compared with the predictions from the simulations.

I. Introduction

At 7:30 am Mountain Time on September 12, 2018, a 0.7 m diameter version of the Adaptable Deployable Entry and Placement Technology (ADEPT) launched on-board a sub-orbital sounding rocket from Spaceport America within the grounds of the White Sands Missile Range (WSMR) in New Mexico. Sounding Rocket One (SR-1) was the first ADEPT shape to be tested in non-laboratory or wind tunnel conditions.

The ADEPT entry body was been developed to increase the capabilities of planetary probe missions to decelerate larger payloads to the ground. Unlike traditional rigid aeroshells, that are packed into launch vehicles at their full size, deployable aeroshells like ADEPT can be stowed in a smaller form factor during launch. They can open or deploy prior to entry to attain a larger diameter that increases the total drag force and reduces the ballistic coefficient of the vehicle during entry. The benefits of a lower ballistic coefficient include lower peak deceleration at higher altitudes, leading to a larger altitude margin before touchdown.

ADEPT has been proposed as an enabling technology for many planetary entry proposals, including for human scale Mars missions [1], Venus landers [2, 3], and nano-satellite missions [4]. The SR-1 flight article falls within the nano-ADEPT class of vehicles and was been tested in arcjet conditions to understand aeroheating, wind tunnel loading tests to quantify structural characteristics [5], and laboratory deployment test to characterize the mechanisms. SR-1 was the full end-to-end system test of the nano-ADEPT vehicle from the stowed configuration, deployment in the upper atmosphere, and then entry, descent and landing (EDL).

Flight mechanics simulations were created to provide pre-flight predictions of various metrics of interest for ADEPT SR-1. The modeling of the powered portion of the flight was handled by UP Aerospace, while the test portion of the flight was modeled using NASA Langley Research Center's Program to Optimize Simulated Trajectories II (POST2). This paper is focused on the POST2-based simulation and the Monte Carlo analyses to provide statistical predictions for ADEPT SR-1's trajectory during separation, apogee, and EDL.

II. Background

The SR-1 concept of operations is shown in Fig. 1. ADEPT launched on-board an UP Aerospace Spaceloft XL Sounding Rocket as the primary payload. During ascent, the sounding rocket spun up to 7 Hz for gyroscopic stability. Near apogee a yo-yo de-spin mechanism reduced the spin rate to 200 deg/s. The yo-yo de-spin was been intentionally biased to produce a non-zero residual spin rate, which provided the test article gyroscopic stability during the exo-atmospheric flight once it deployed. After yo-yo de-spin, the payload section separated from the spent booster,

*Aerospace Engineer, Atmospheric Flight and Entry Systems Branch, 1 N. Dryden St., M/S 489, and AIAA Member.

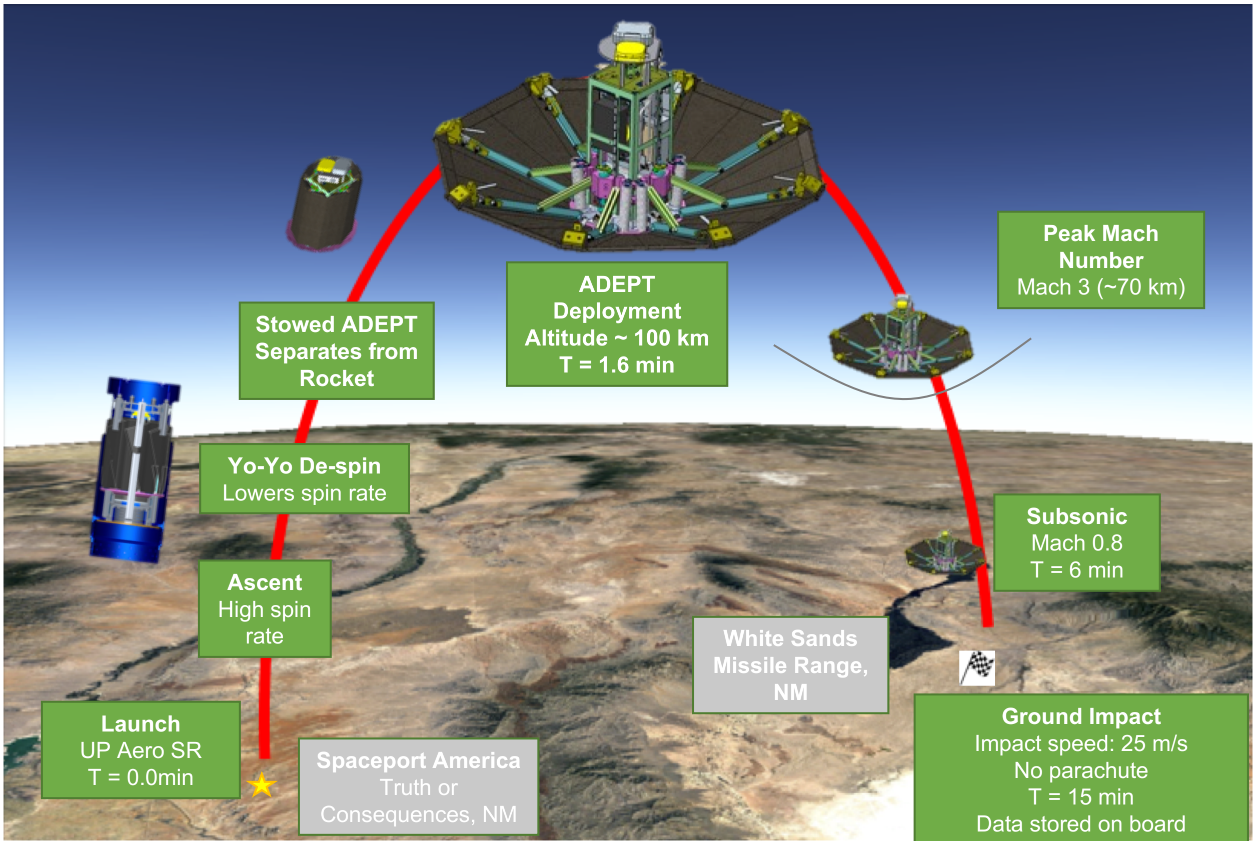


Fig. 1 ADEPT SR-1 concept of operations [6].

and shortly afterwards the nosecone separates from the payload section while starting a timer within the ADEPT payload. Based on the timer, the ADEPT stowed vehicle is ejected from the payload section and then prior to reaching apogee, the ADEPT deploys when the rigid rods lock to hold the 70 degree half-angle, sphere-cone faceted shape. No further configuration changes occur during its descent back into sensible atmosphere. The ADEPT SR-1 flight was part of a technology demonstration and the trajectory was designed to reach peak velocities around Mach 3 and 70 km geodetic altitude and then quickly decelerate to subsonic speeds before impacting the ground within WSMR at close to 25 m/s. No parachute was used for stability or to slow down the vehicle.

Due to the sub-orbital trajectory of the SR-1 flight, the ADEPT shape does not reach mission-relevant conditions for many planetary entry situations. However, since SR-1 is the first end-to-end test of the ADEPT shape, the key performance parameters (KPP) of SR-1 flight are more fundamental: deploy the ADEPT shape exo-atmospherically and maintain the shape through the rest of the flight; and provide aerodynamic stability without active control during EDL [6].

ADEPT SR-1 was instrumented, as shown in Fig. 2, to recreate the six degree-of-freedom (DOF) flight profile. There were two inertial measurement units (IMUs) to capture the vehicle acceleration and angular rates. A GPS unit, C-Band Transponder for radar tracking, and magnetometer provided redundant sources of data for the vehicle position, velocity, and attitude. The vehicle was equipped with a GoPro camera to take videos of the flight and record light emitting diode (LED) lights that indicated if the various ribs that are part of the latching mechanism holding the ADEPT deployed shape were locked. WSMR also tracked the vehicle using radar skin tracking and a C-Band Transponder. The launch provider provided meteorological profiles of atmospheric information. A GPS-based tracking device, Spot Trace, which was on-board ADEPT was planned to be used during recovery operations to locate the vehicle after impact. No sensor data was telemetered during the mission; thus, energy attenuation systems in the nose of the vehicle had to prevent damage to the data recording devices on-board the vehicle.

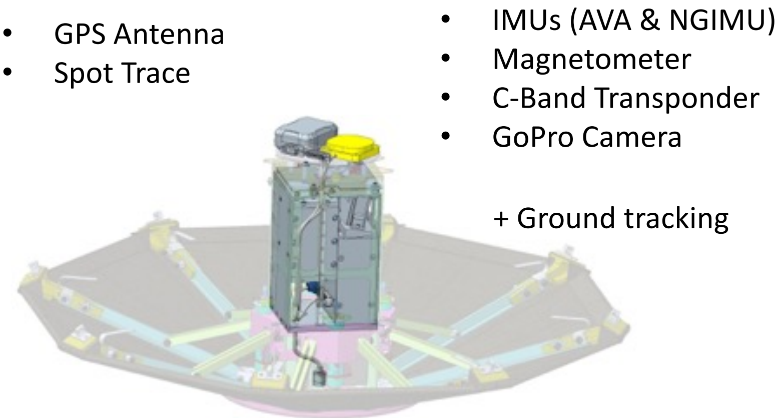


Fig. 2 Instrumentation to record ADEPT SR-1 flight trajectory.

III. Modeling and Simulation

The POST2 was the flight mechanics modeling and simulation tool used to characterize the behavior of ADEPT after separation from the payload section. It is a six degree-of-freedom flight mechanics simulation tool that can simultaneously simulate the trajectories of up to 20 independent or connected rigid bodies. POST2 is a generalized point mass, discrete-parameter targeting and optimization trajectory simulation program with multi-vehicle capabilities that integrates translational and rotational equations of motion along the trajectory. The simulation tool has significant EDL flight heritage as it has been used in the past for several EDL missions, such as Mars Pathfinder [7], Mars Exploration Rovers [8], Genesis Earth Entry Capsule [9], Stardust Earth Entry Capsule [10], Mars Phoenix [11], and Mars Science Laboratory [12]. More recently, it has been used on several Earth atmospheric and sub-orbital missions like the Low Density Supersonic Decelerator [13–17] and Advanced Supersonic Parachute Inflation Research and Experiment [18]. The NASA Langley Research Center (LaRC) version of POST2 [19] has been integrated with engineering models of the atmosphere, such as the Earth Global Reference Atmospheric Model (GRAM) [20], and can interact with high fidelity aerodynamic databases. The models and their uncertainties are varied using Monte Carlo approaches to provide statistical estimates of various flight performance parameters, such as trajectory conditions at entry interface or attitude predictions at various points during the flight.

The ADEPT SR-1 POST2 simulation models two vehicles, ADEPT SR-1 and the payload section from which ADEPT separates, from ADEPT separation down to impact on the ground. The payload section is modeled as a 3-DOF vehicle with simplified mass and aerodynamics and is used to quantify re-contact risk to ADEPT. ADEPT SR-1 is modeled as a 6-DOF vehicle with an aerodynamic database generated using direct simulation Monte Carlo (DSMC), computational fluid dynamics (CFD) simulations, and wind tunnel test data [21]. The aerodatabase provides force and moment coefficients of the vehicle at the moment reference point of the vehicle, the nose tip, and covers aerodynamic regimes from free-molecular all the way down to subsonic continuum flow. When ADEPT separates from the launch vehicle payload section, the nose tip is nominally pointed towards the ground and the vehicle velocity vector is pointed towards zenith. After apogee, the vehicle's velocity vector always points towards nadir, making the angle of attack between the body axis going through the nose of the vehicle and the velocity vector less than 180 degrees. Due to this configuration, the free-molecular and transitional portion of the aerodatabase provides coverage for angles of attack from 0 to 180 deg. The continuum regime of the aerodatase is limited to total angles of attack up to 20 deg. The vehicle's dynamics were expected to be bound by that limit in pre-flight analysis.

An assumption in this portion of the aerodatabase is axisymmetric congruity, i.e. change in angle of attack is assumed to have the same effect as change in sideslip angle. This assumption is typically used for blunt body aerodynamics and allows the aerodatabase to be parameterized by total angle of attack rather than individual matrix based on angle of attack and sideslip angle. However, ADEPT SR-1 has a faceted shape where there are sharp changes in angles between the facets or sides of the forebody. During pre-flight review of the aerodatabase, it was decided that the axisymmetric assumption should be maintained for pre-flight analysis, since wind tunnel testing had not revealed a strong tendency for the vehicle to autorotate [5, 22] due to rolling moments generated by sideslip or angle of attack variations; however, this assumption was subject to change based on flight data from the ADEPT SR-1 mission.

The vehicle dynamics are modeled by POST2 from ADEPT separation until landing on the surface (defined by a digital elevation map of the White Sands Missile Range). Prior to ADEPT separation, the launch provider uses their simulation to model launch, spin-up, and yo-yo de-spin. The launch provider hands off six-degree of freedom states at the prescribed ADEPT separation event from their Monte Carlo simulations, and these states are used to initialize the simulation which is the focus of this paper.

Earth-GRAM was chosen for pre-flight analysis as it provides nominal and dispersed estimates of atmospheric parameters for the full range of flight conditions. Earth-GRAM contains multiple choices of thermospheric models to provide atmospheric estimates above 90 km geodetic altitude, and for ADEPT the 2008 Jacchia-Bowman (JB2008) was used in simulations as that particular model had shown better agreement with exo-atmosphere flight data in past missions [23]. Below 90 km, the atmospheric estimates are based on historical data at the location of interest. Specifically, closer to the ground, range reference atmosphere for the White Sands Missile Range is used. These historical datasets are created for each month and are based on data that are averaged across many years; thus, the average weather for that month is represented but the day-to-day variations may not be captured.

Finally, the simulation incorporated higher fidelity models to capture the dynamics of the vehicle during critical events. ADEPT SR-1 vehicle is initially in the stowed configuration but then unfurls during the deployment process. Although the deployment process is fast (approximately 100 ms), the rapid change in mass distribution with springs could impart a pitch or yaw rate due to differential rates of deployment on each side of the vehicle. Pre-flight analysis showed that the vehicle attitude during atmospheric entry had a slight sensitivity to the exo-atmospheric pitch and yaw rates on the vehicle. Thus, data from ground deployment tests were used to create a model that imparted a variable pitching and yawing moment on the vehicle during deployment. In a Monte Carlo analysis, where the pitching and yawing moment profiles would be varied stochastically, the resulting pitch and yaw rates on the vehicle would envelop the conditions seen on the vehicle during ground tests.

IV. Flight Mechanics Performance Results and Comparison with Flight Data

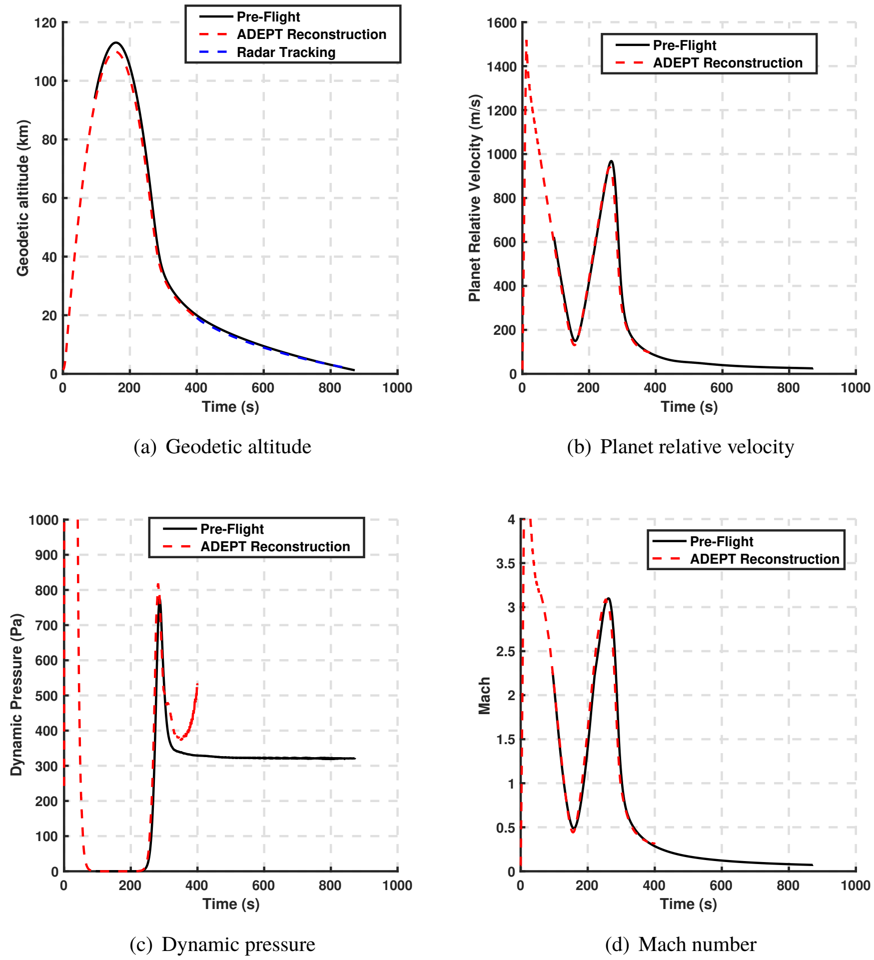
The ADEPT SR-1 vehicle trajectory was reconstructed from a variety of on-board and off-board instruments [24]. The IMU, GPS, radar, and reconstructed atmosphere were used within an Extended Kalman Filter (EKF) based tool called New Statistical Estimation Program (NewSTEP) to provide a post-flight best estimated trajectory. The following sections compare flight performance estimates from the pre-launch flight mechanics simulation and the reconstructed trajectory. One of the outcomes of such a comparison is to point out how well the flight mechanics simulation was able to capture the behavior of the actual flight and the process elucidates gaps in modeling. In many instances, the reconstructed performance values fall within the bounds of the simulation predictions; however, in cases where the Monte Carlo predictions do not bound the reconstructed values, a process known as reconciliation is used to systematically update flight simulation settings to see if the reconstructed performance can be replicated by a simulation. This reconciliation process was used successfully after recent Earth flight tests [15, 17, 18] to support model changes, which in future flights improved the comparison between the simulation and flight data.

A. Comparison of Reconstructed Trajectory with Pre-Flight Estimate

Figure 3 shows comparison of the nominal trajectory from the flight mechanics simulation and the reconstructed trajectory. The reconstructed trajectory extends up to 400 s of flight. After 400 s, the vehicle started tumbling and the on-board gyroscopes saturated, which precluded IMU-based integration of the trajectory needed for the reconstruction. Ref [24] discusses the assumptions and limitations of the reconstruction, and section IV.B of this paper will also describe the vehicle trajectory post 400 s of flight. Radar tracking data of the position of the vehicle was available to the end of the flight and is shown in Fig. 3(a). Recall the pre-flight trajectory is only available 95 s after launch, since the simulation models the vehicle post ADEPT separation from the launch vehicle payload section.

The comparison shows that the reconstructed altitude and velocity profile from ADEPT separation onwards was lower than the nominal pre-flight estimate. Later figures will show that even in a statistical sense, the reconstructed altitude and velocity at separation were on the lower end of the pre-flight uncertainty envelope. The lower values mean the ADEPT SR-1 vehicle had lower kinetic and potential energy than pre-flight estimates.

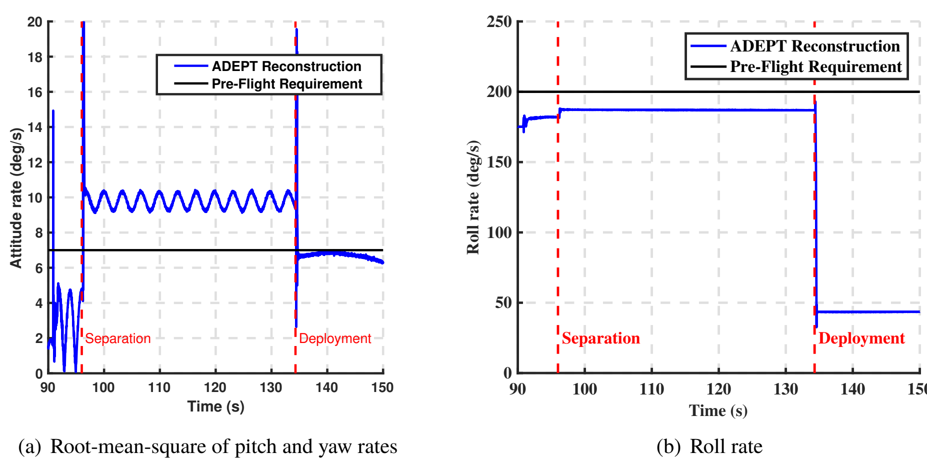
Figure 4 shows the root-mean-square (RMS) of the pitch and yaw rate during the ADEPT separation and deployment process. Also listed is the pre-flight expectation of the parameter. The RMS of pitch and yaw rate at separation is the *tip-off rate* that is imparted to the vehicle and is a significant contributor to the vehicle attitude stability in exo-atmospheric flight. The vehicle has a non-zero roll rate in exo-atmospheric flight for gyroscopic stability and this value changes when ADEPT reconfigures from the stowed to the deployed shape. Large tip-off rates can offset the gyroscopic stability of the vehicle and create an undesired attitude (large angle of attack) when sensible atmosphere



(a) Geodetic altitude (b) Planet relative velocity

(c) Dynamic pressure (d) Mach number

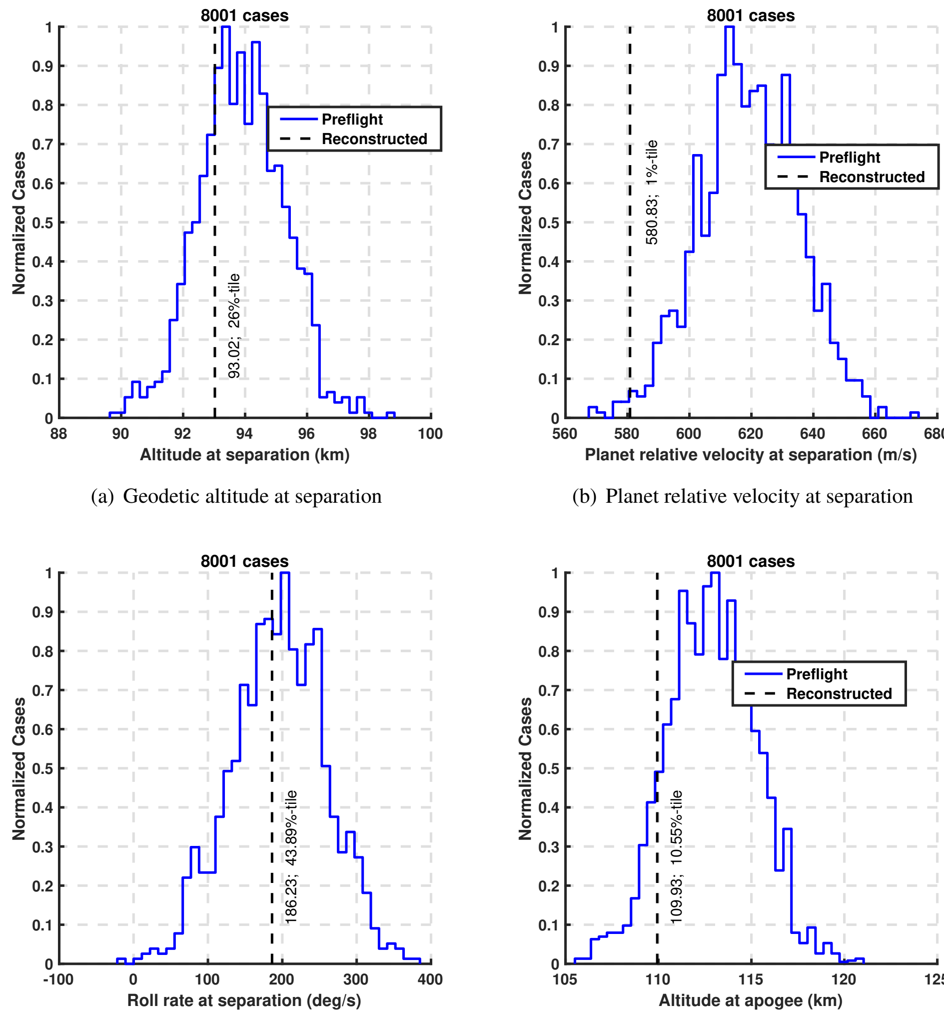
Fig. 3 Comparison for pre-flight nominal predictions and reconstructed trajectory.



(a) Root-mean-square of pitch and yaw rates (b) Roll rate

Fig. 4 Comparison of the reconstructed attitude rates during ADEPT separation and deployment and pre-flight requirement.

is reached. Since the reconstructed tip-off rate was higher than the pre-flight expectation, initial post-flight analysis focused on the impact of the larger rate. However, as the roll rate imparted to the vehicle during separation was close to the nominal expectation, the slight increase in tip-off rate did not adversely affect the vehicle attitude at entry and is discussed later in this section.



(a) Geodetic altitude at separation

(b) Planet relative velocity at separation

(c) Roll rate at separation

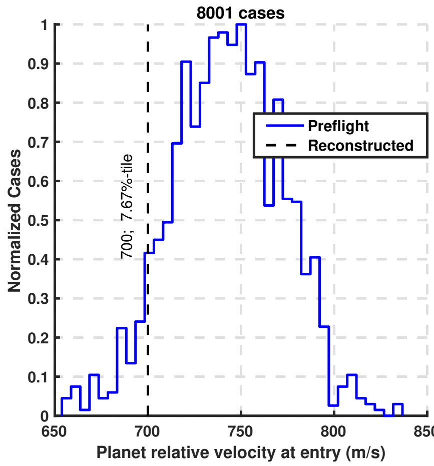
(d) Geodetic altitude at apogee

Fig. 5 Comparison for pre-flight Monte Carlo predictions and reconstructed trajectory during the exo-atmospheric portion of flight.

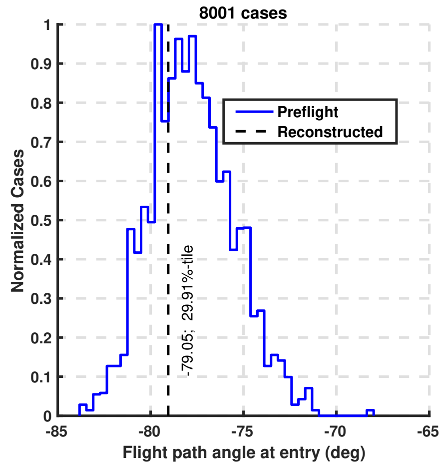
Figures 5- 6 show the histograms of the pre-flight Monte Carlo predictions of flight performance at various events during the exo-atmospheric and atmospheric portion of flight. The pre-flight predictions are a result of Monte Carlo analysis where simulation models, such as atmosphere, aerodynamics, and mass properties, were dispersed randomly for 8001 cases to aggregate statistics about events of interest. The reconstructed values are listed as percentiles of the Monte Carlo result, where a low (close to 1) or high (close to 100) percentile denotes that the reconstruction is a low probability event while a percentile close to 50 denotes that the value is close to the median of the prediction; thus, a high probability event. In general, as one approaches the tails of a Monte Carlo distribution, the probability decreases greatly and a small percentile difference in the tails of a distribution corresponds with a large probability difference of that event according to the distribution.

Figure 5, which shows the trajectory states at separation and apogee, demonstrates the earlier observation that the reconstructed trajectory had a lower altitude and velocity at separation than pre-flight predictions. The roll rate of the vehicle post yo-yo de-spin was close to the pre-flight estimate value of 200 deg/s.

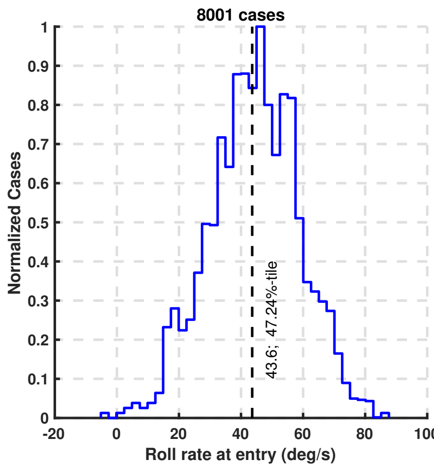
Entry interface for ADEPT was defined as 85 km geodetic altitude and the states at that event are presented in Fig. 6. The entry states show a similar story to separation and apogee. The vehicle velocity was lower than expected, but attitude related quantities (e.g. roll rate) or velocity attitude quantities (e.g flight path angle) were close to the median. The peak Mach number, shown in Fig. 6(d), was also close to the desired the value of Mach 3. The reconstructed dynamic pressure (Fig. 6(e)) and maximum sensed acceleration (Fig. 6(f)) also are high probability events (between 5-95 percentile) within the pre-flight Monte Carlo predictions. The reconstructed value and pre-flight predictions for several events are summarized in Table 1.



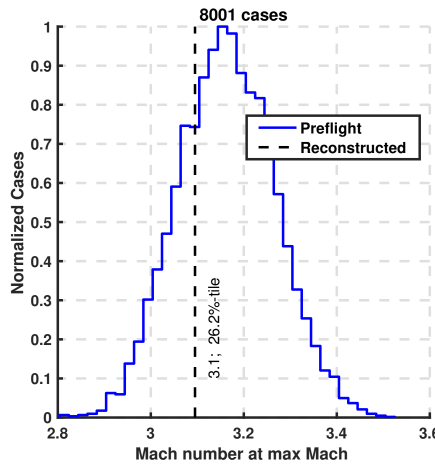
(a) Planet relative velocity at entry



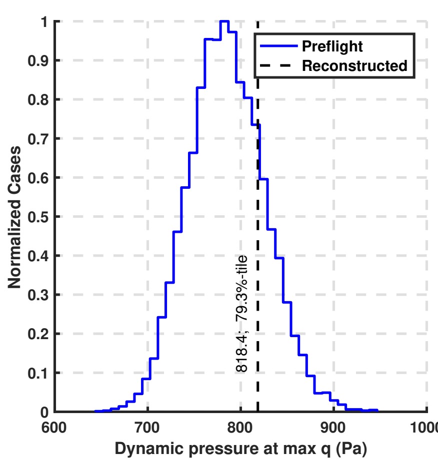
(b) Flight path angle at entry



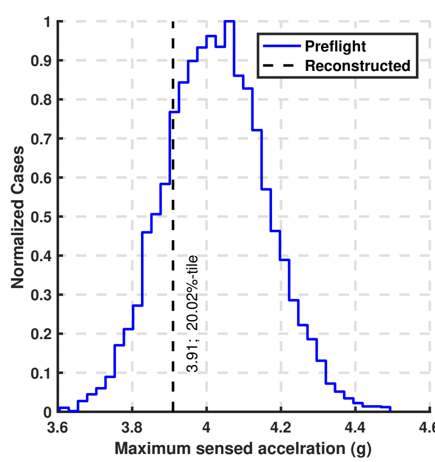
(c) Roll rate at entry



(d) Peak Mach number



(e) Peak dynamic pressure



(f) Peak sensed acceleration

Fig. 6 Comparison for pre-flight Monte Carlo predictions and reconstructed trajectory during the atmospheric portion of flight.

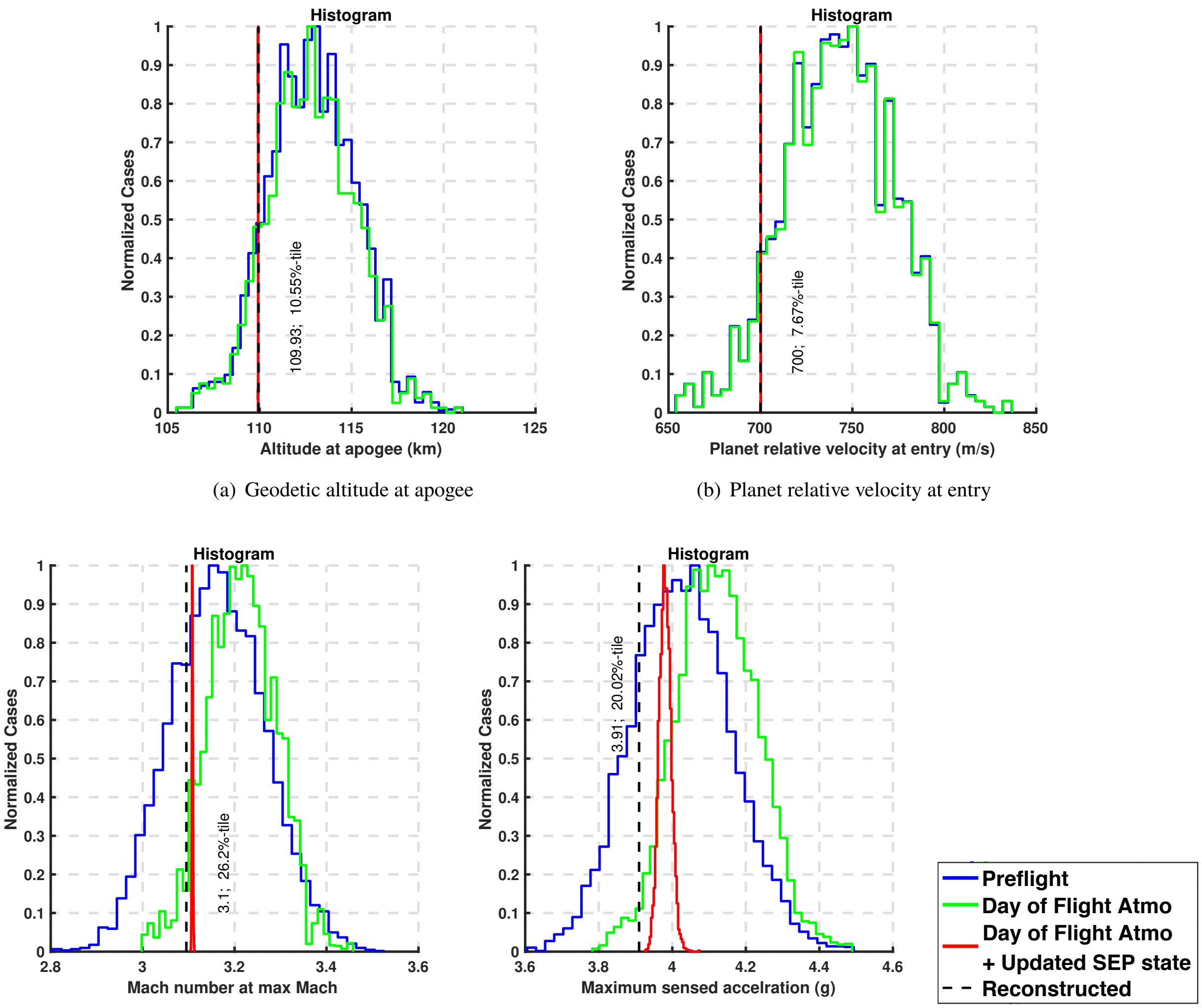
Table 1 Comparison of Pre-Flight Predictions and Reconstructed Trajectory.

Parameter	5%-tile prediction	50%-tile prediction	95%-tile prediction	Reconstruction [24]	Percentile of prediction
ADEPT Separation					
Altitude (km)	91.7	93.9	96.1	93.0	26.0
Velocity (m/s)	592.9	619.1	644.8	580.8	1.0
Flight Path Angle (deg)	71.0	75.5	79.3	76.7	68.7
Roll Rate (deg/s)	85.5	196.6	301.9	186.2	43.9
Apogee					
Altitude (km)	109.1	112.8	116.7	109.9	10.6
Entry Interface (85 km)					
Velocity (m/s)	695.5	742.9	789.5	700.0	7.7
Flight Path Angle (deg)	-81.1	-77.9	-73.9	-79.0	29.9
Roll Rate (deg/s)	19.4	44.6	68.4	43.6	47.2
Peak Mach Number					
Mach	3.0	3.2	3.3	3.1	26.2
Altitude (km)	58.3	63.5	70.3	64.6	60.5
Roll Rate (deg/s)	19.4	44.6	68.4	49.2	62.1
Peak Dynamic Pressure					
Dynamic Pressure (Pa)	720.3	784.3	853.9	818.4	79.3
Altitude (km)	39.7	41.0	42.2	40.9	43.2
Peak Acceleration					
Acceleration	3.8	4.0	4.3	3.9	20.0
Altitude (km)	39.2	40.7	42.0	40.6	48.1
Mach 2.0					
Altitude (km)	40.1	40.8	41.5	40.5	23.3
Total Angle of Attack (deg)	0.6	2.3	4.8	3.9*	87.2
Roll Rate (deg/s)	19.0	44.5	68.3	218.8	100.0
Mach 1.0					
Altitude (km)	33.5	33.9	34.4	33.9	38.2
Total Angle of Attack (deg)	0.6	2.3	7.3	15.8*	99.9
Roll Rate (deg/s)	18.5	44.6	68.8	339.9	100.0
Mach 0.8					
Altitude (km)	31.6	32.0	32.5	31.4	1.8
Total Angle of Attack (deg)	0.6	2.3	8.9	15.1*	99.4
Roll Rate (deg/s)	18.4	44.5	69.1	357.1	100.0
Touchdown					
Time from launch (s)	854.7	886.8	911.2	855-885†	5.2-45.0
Geodetic latitude (deg)	33.03	33.14	33.25	33.144	52.0
Longitude (deg) (s)	253.4	253.5	253.7	253.438	10.0

*Reconstructed total angle of attack is the maximum value in 1 s bins

†Due to uncertainty of the time when flight data stopped writing to the flash memory card, there is a 30 s variation in estimated touchdown time

B. Reconciliation of Reconstructed Trajectory and Flight Mechanics Simulation



(a) Geodetic altitude at apogee

(b) Planet relative velocity at entry

(c) Peak Mach number

(d) Peak sensed acceleration

(e)

Fig. 7 Reconciliation Monte Carlo results compared to reconstructed trajectory. Vertical black line shows the what percentile the reconstruction constituted of the pre-flight prediction.

Reconciliation involves updating pre-flight simulation assumptions using flight observables in order to encompass flight data within statistical predictions from the simulation. For ADEPT SR-1, the flight observables included the actual estimated state of the vehicle at separation, reconstructed atmosphere [24], and observed attitude dynamics of the vehicle captured on IMUs.

Figure 7 shows reconciled Monte Carlo results. The pre-flight prediction and the reconstructed values are also shown for comparison. The percentile noted on the reconstructed line is compared to the pre-flight estimate. As different flight observables are incorporated into the simulation, the predictions become more focused and the reconstructed trajectory is closer to the simulation prediction. For example, matching the separation states made the Monte Carlo predictions of apogee geodetic altitude and entry interface planet relative velocity match the reconstruction, even though previously the reconstructed value was a low probability item from the pre-flight prediction. Similarly, the reconstructed atmosphere improved the range for the prediction of an atmospheric-relative quantity like peak Mach number, while updates to both atmosphere and separation states improved the prediction of maximum sensed acceleration. However, the reconciliation of Mach number and peak acceleration shows that the simulation predictions do not encompass the reconstruction; the difference could be due to some other factor not captured in the simulation or adjustments needed to existing models

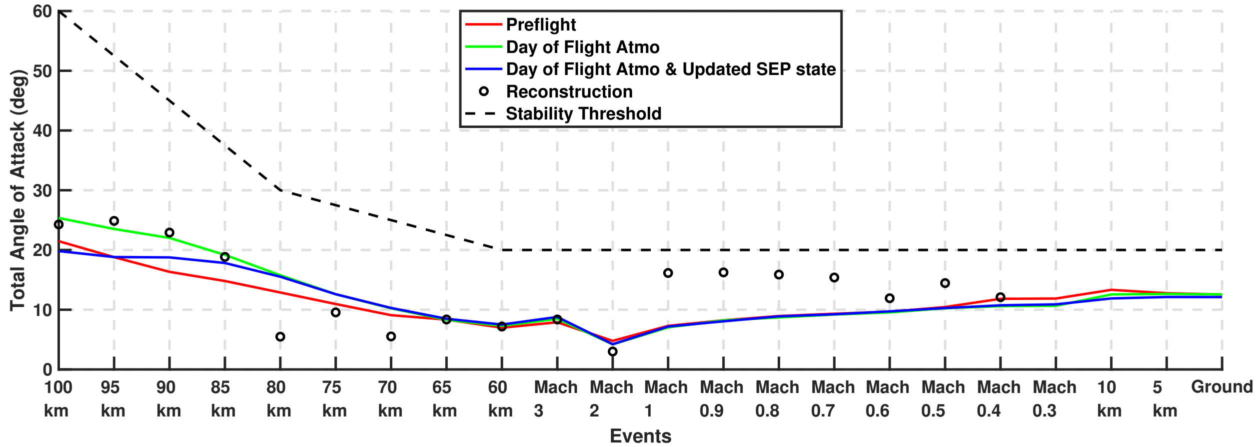


Fig. 8 The 95th percentile prediction of total angle of attack compared with the reconstructed values. Stability threshold is the targeted goal for the mission. Reconstructed total angle of attack is the maximum value in 1 s bins.

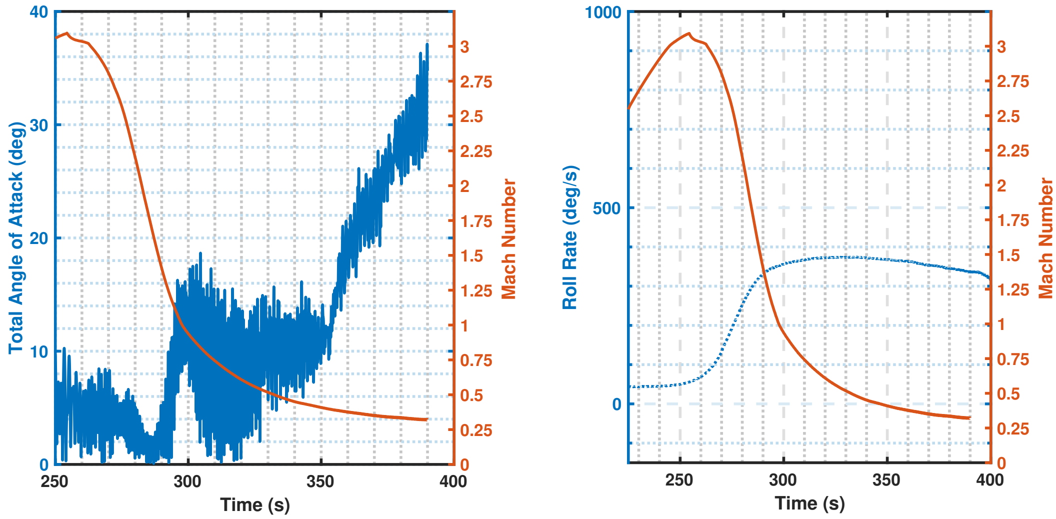
such as the aerodatabase. In these two cases, the difference was small and did not warrant additional changes.

The two KPPs for ADEPT SR-1 were to demonstrate deployment of the shape exo-atmospherically and to demonstrate stability of the vehicle based on total angle of attack less than 90 deg during supersonic and transonic flight. The first KPP was verified via the on-board GoPro camera, which recorded that the rib deploy LED was active throughout entire flight once ADEPT was deployed; thus, the ribs were locked [6]. The second KPP is verified by comparing the angle of attack history over the course of flight. Figure 8 shows various estimates of the 95th percentile total angle of attack prediction from the flight mechanics simulation. The pre-flight estimate as well as two updated reconciliation Monte Carlo estimates based on post-flight data, updated atmosphere and updated separation states, are shown in the figure. The stability threshold, which was not the key performance parameter but a desired mission goal, is also shown. The maximum reconstructed total angles of attack in 1 s interval bins are shown.

All three Monte Carlo estimates for total angle of attack 95th percentile estimate are similar in Fig. 8, especially in the atmospheric portion of the flight (85 km geodetic altitude and below). The reconstructed total angle of attack at different events is higher than expected, since the values either match the 95th percentile expectation or exceed them. However, it should be noted that the values do not cross the 20 deg threshold through Mach 0.4, showing stability through supersonic and transonic flight [6]. Increase in angle of attack in transonic and subsonic flow has been observed on rigid bodies in the past [25] and was expected for ADEPT SR-1 as well. Nevertheless, the larger than expected total angle of attack history suggests that even the reconciled simulation, which was updated to the reconstructed atmosphere and the best estimated states at separation, cannot predict the subsonic attitude history of the vehicle. Further work in refining the aerodynamics, especially in the subsonic regime, is suggested by the results in Fig. 8. Korzun et al. [21] discusses further modifications planned for the aerodatabase, which can help reconcile the simulation with reconstructed values.

An unexpected phenomenon observed during the ADEPT SR-1 flight was the large roll rate increase in the vehicle during supersonic flight after peak Mach number was reached. Figure 9 shows the roll rate and angle of attack for the latter portion of the flight together with the reconstructed Mach number. After the vehicle starts decelerating from its peak Mach, ADEPT SR-1 increased its roll rate from 44 deg/s to 370 deg/s as the vehicle went from Mach 3 to Mach 0.7. This increase in roll rate was not predicted by pre-flight simulations (see Fig. 10) nor could it be recreated during reconciliation with changes, such as updating to the day of flight atmosphere or using the actual separation states. During reconciliation, rolling moments caused by large radial center of gravity were considered, but even with a radial center of gravity on the rib tips of the vehicle (which is the extent to which a radial center of gravity offset is possible), the simulation could not re-create the roll rate increase seen in flight.

In fact the large roll rate increase observed in the flight data necessitates a rolling moment coefficient in the supersonic regime that is outside bounds of the current ADEPT SR-1 aerodatabase. One of the reasons for the underestimation of the rolling moment is the axisymmetric assumption made in the aerodatabase. Recall, one of the ramifications of the axisymmetric assumption is that moments created by a change in angle of attack are equivalent to moments created by a



(a) Total angle of attack

(b) Roll rate

Fig. 9 Reconstructed attitude dynamics profile comparison with Mach number.

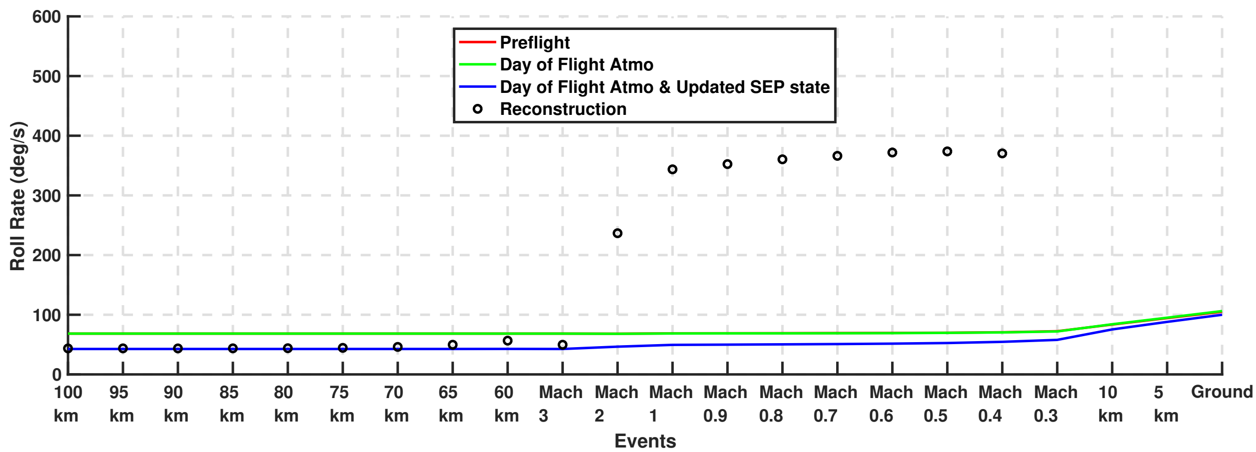


Fig. 10 The 95th percentile prediction of roll rate compared with reconstructed values.

change in sideslip angle. Korzun et al. [21] notes that recent CFD tests where angle of attack and sideslip angle have been independently varied do create rolling moments larger than the current aerodatabase. However, CFD itself may not be well suited tool to capture the rolling dynamics observed in this flight regime. Newer dynamic CFD methods from Stern and Brock [26–28] shows promise but are still in their infancy. The large rolling moment increase could be due to the faceted forebody shape, warping of the fabric, or the prism, non-axisymmetric aftbody shape. Fully capturing the rolling dynamics in a flight mechanics simulation may require additional ground tests with the ADEPT shape to quantify the rolling moment during supersonic and transonic phases of flight.

Reconciliation was also used in comparing the pre-flight estimates of the ADEPT landing location to the actual recovery site. Figure 11 shows various 99th percentile confidence landing ellipses from the flight mechanics simulation. The mean pre-flight landing location is 9 km from the recovery location, while the mean of the landing ellipse from the most up-to-date reconciliation Monte Carlo (updated atmosphere and separation state) is 4.6 km from the recovery location.

The difference between the latest reconciliation and the recovery location could be potentially improved if the aerodatabase is extended to a larger angle of attack grid. Recall that the pre-flight aerodatabase in the supersonic and subsonic regimes was limited to 20 deg total angle of attack, which pre-flight simulation results seemed to show was

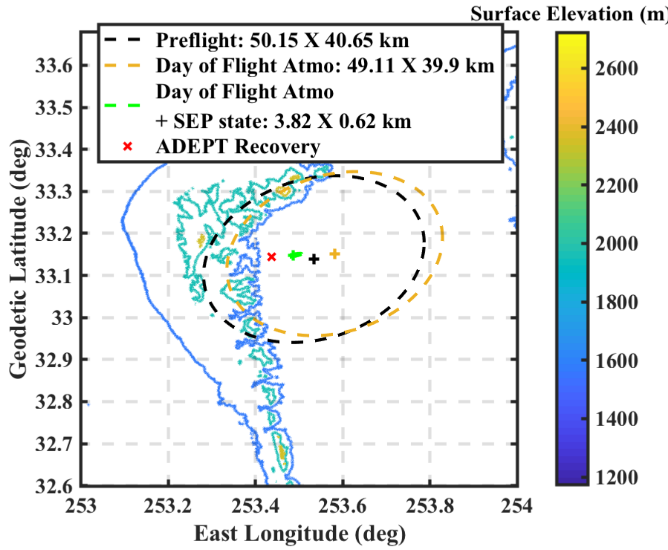
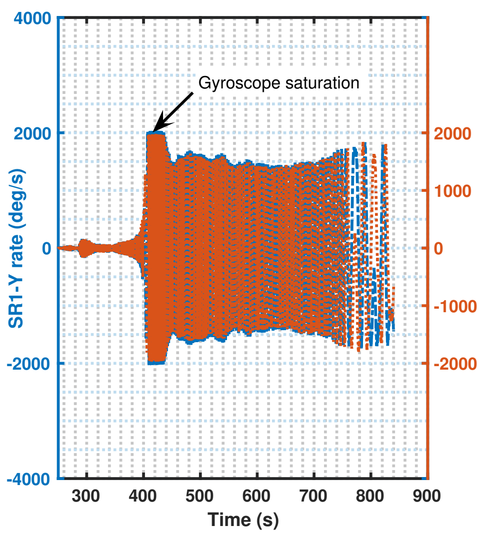
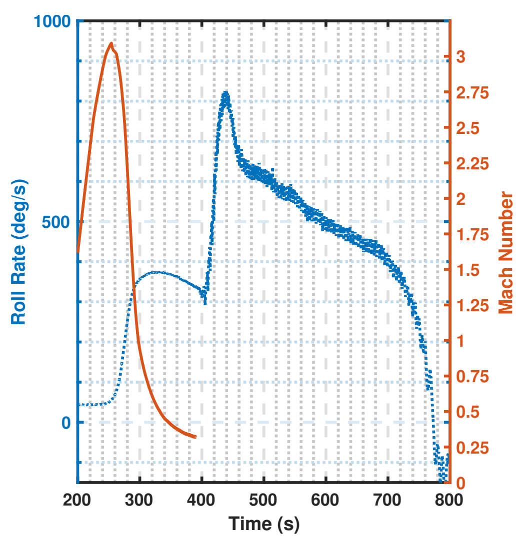


Fig. 11 The 99th percentile confidence landing ellipse estimates and comparison with actual ADEPT recovery location. Landing ellipse sizes are major x minor axes.

sufficient; but ADEPT SR-1 tumbled below Mach 0.2 and the aerodatabase is not really valid for the large angles of attack in that Mach number range. Figure 12 shows the roll, pitch, and yaw rates of the vehicle below Mach 0.2, and it is visible from Fig. 12(a) that the vehicle tumbled shortly after 400 s. In fact, the on-board gyroscope saturates around 2000 deg/s and the pitch and yaw rate exceeded that value for approximately 20 s. Analysis of the GoPro video suggests that the pitch and yaw rate reached 3000 deg/s. Due to the IMU saturation, the vehicle trajectory could not be reconstructed past 400 s [24].



(a) Pitch and yaw rate



(b) Roll rate

Fig. 12 Reconstructed attitude rate profile during transonic and subsonic portions of the flight.

C. Future Work with Reconciliation

Issues such as the rolling moment experienced during supersonic flight and the tumbling behavior observed below Mach 0.2 are still unresolved in the reconciliation process. Both of these observations will be best addressed via an updated aerodatabase, which would be done either through more CFD solutions or ground testing. The current aerodatabase does not model the rolling moments observed in flight, but Korzun et. al's recent work has suggested that an updated CFD-based aerodatabase, where the axisymmetric assumption has not been applied, might exhibit larger rolling moments. Incorporating this newer aerodatabase in the simulation and re-doing the reconciliation analysis in Fig. 10 would be a future update. Other changes, such as expanding the range of angles of attack achievable in the aerodatabase might help resolve smaller discrepancies between the simulation and reconstruction, such as not matching the recovery location (Fig. 11). An updated flight mechanics simulation that can match the performance seen by ADEPT SR-1 is essential for planning and targeting a follow-on mission.

V. Conclusions

ADEPT SR-1 was the first end-to-end test of the novel aeroshell that can enable many types of planetary entry missions. The primary objectives of the flight were to open the stowed ADEPT in exo-atmosphere and to demonstrate stability during the atmospheric entry portion of the flight through Mach 0.8 without active control. This paper showed results from the pre-flight simulations and compared them to the flight data. ADEPT was able to demonstrate both objectives based on pre-flight metrics and the simulation predictions were shown to bound the flight data for many of these parameters. Through reconciliation processes and updating the simulation with flight observables, such as the day of flight atmosphere and separation states, the simulation predictions came closer to the reconstructed states. However, ADEPT SR-1 flight had an unexpected roll rate increase observed during the supersonic flight and also tumbled at speeds lower than Mach 0.2. These observations were beyond the envelope of pre-flight simulations; updating the aerodatabase and incorporating that within the simulation will be part of ongoing work.

Acknowledgments

The authors acknowledge several ADEPT team members who have contributed to the flight mechanics work presented in this papers. These team members include Justin Green, Brandon Smith, Ashley Korzun, Ryan McDaniel, Joseph Williams, Jake Tynis, Chris Karlgaard, Alan Cassell, Bryan Yount, Juan Cruz, Shak Ghassemieh, and Paul Wercinski. Parts of this research was funded by NASA Space Technology Mission Directorate's (STMD) Game Changing Development Program (GCDP).

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