AAS 16-222

POST-FLIGHT ASSESSMENT OF LOW DENSITY SUPERSONIC DECELERATOR FLIGHT DYNAMICS TEST 2 SIMULATION

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NASA's Low Density Supersonic Decelerator (LDSD) project conducted its second Supersonic Flight Dynamics Test (SFDT-2) on June 8, 2015. The Program to Optimize Simulated Trajectories II (POST2) was one of the flight dynamics tools used to simulate and predict the flight performance and was a major tool used in the post-flight assessment of the flight trajectory. This paper compares the simulation predictions with the reconstructed trajectory. Additionally, off-nominal conditions seen during flight are modeled in the simulation to reconcile the predictions with flight data. These analyses are beneficial to characterize the results of the flight test and to improve the simulation and targeting of the subsequent LDSD flights.

INTRODUCTION

The Low Density Supersonic Decelerator (LDSD) project is a NASA Technology Demonstration Mission tasked with improving the technology readiness level for Supersonic Inflatable Aerodynamic Decelerators (SIAD) and designing an improved supersonic parachute for future robotic and human exploration missions to Mars.[1,2] A critical component of the project is a series of flight tests that demonstrate the performance of the various technologies at Mars-relevant conditions. These tests, called the Supersonic Flight Dynamics Tests (SFDT), are described in Figure 1. Each test uses a high altitude balloon to lift the test vehicle to approximately 36 km altitude. Next, the vehicle is spun-up to near 300 deg/s to provide roll stability and then a STAR-48 motor accelerates the vehicle to approximately Mach 4. The vehicle is spun-down to nearly 0 deg/s and then it deploys the SIAD, which decelerates the vehicle to Mach 3. Finally, a supersonic ringsail (SSRS) parachute is deployed at approximately Mach 2.5 using a trailing ballute (labeled in Figure 1 as the parachute deployment device or PDD). Finally, the vehicle then decelerates on the parachute until splashdown.

SFDT-2 was conducted off the western coast of Kauai, Hawaii on June 8, 2015. The mission was a follow-on to SFDT-1, which occurred in the summer of 2014.[2] One of the primary objectives

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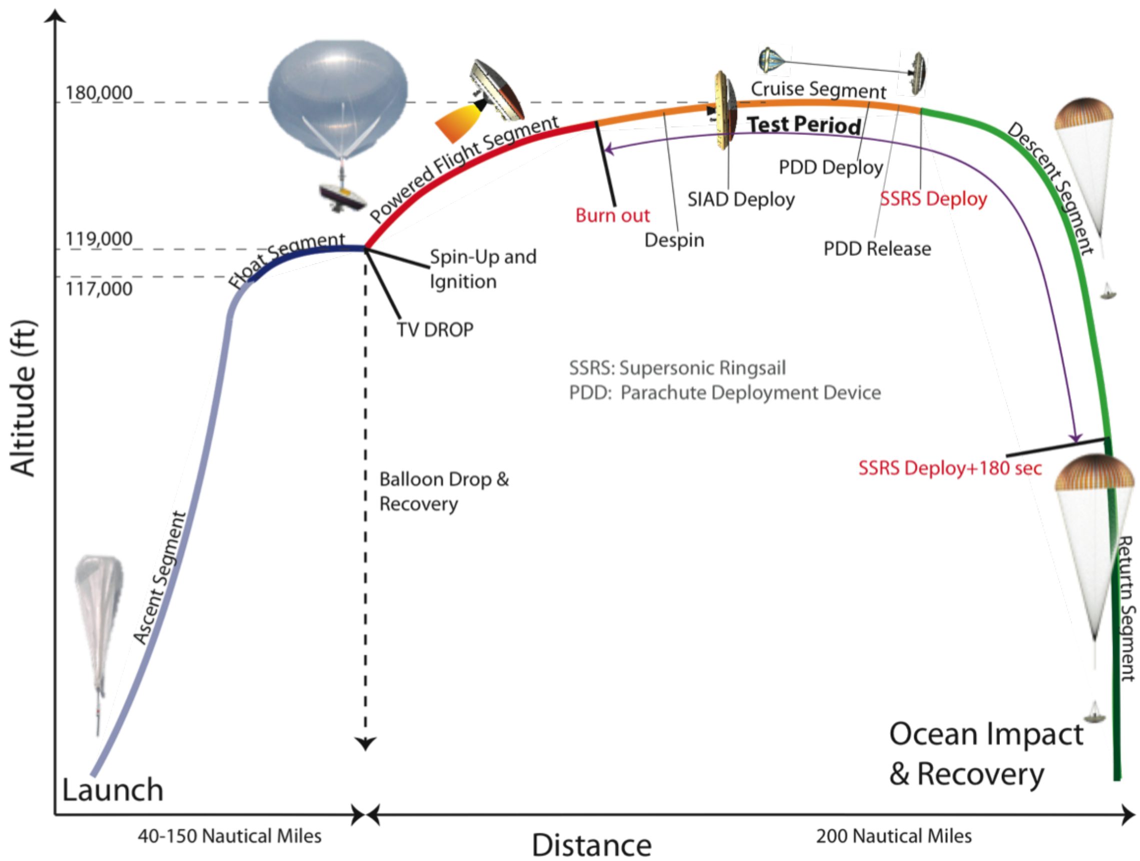


Figure 1. Concept of operations for the Supersonic Flight Dynamics Test 2 conducted in June 2015.[1,3]

of SFDT-2 was to deploy a 30.5 m diameter supersonic ringsail parachute in Mars relevant conditions behind behind a 6 m diameter forebody, which was accomplished during the test. However, some of the other test objectives, such as maintaining the integrity of the parachute after inflation were not accomplished. This paper does not discuss reconstruction of the parachute inflation process, but instead focuses on the reconciliation between pre-flight simulation and actual flight data from the balloon release of the test vehicle through the parachute line stretch condition shortly before parachute inflation. The reader is referred to Reference 3 for a description of the parachute reconstruction.

During these phases of flight, the vehicle underwent several dynamic events, and one significant off-nominal behavior was detected shortly after the vehicle was spun-down. The on-board inertial measurement unit (IMU) detected a large pulse in axial and lateral acceleration for approximately 1 s, highlighted in yellow in Figure 2, followed shortly by the vehicle exhibiting large angle of attack and sideslip angle oscillations that were also observed by the on-board cameras. The large oscillations during this segment of flight were well outside the bounds predicted by pre-flight simulations and had a non-negligible effect on the flight trajectory leading into SIAD and PDD deployment.

The following sections will provide a brief introduction of the flight dynamics performance simulation used to support SFDT-2. The simulation predictions for key flight performance parameters will be compared with the reconstructed trajectory. Finally, a discussion of the reconciliation of the

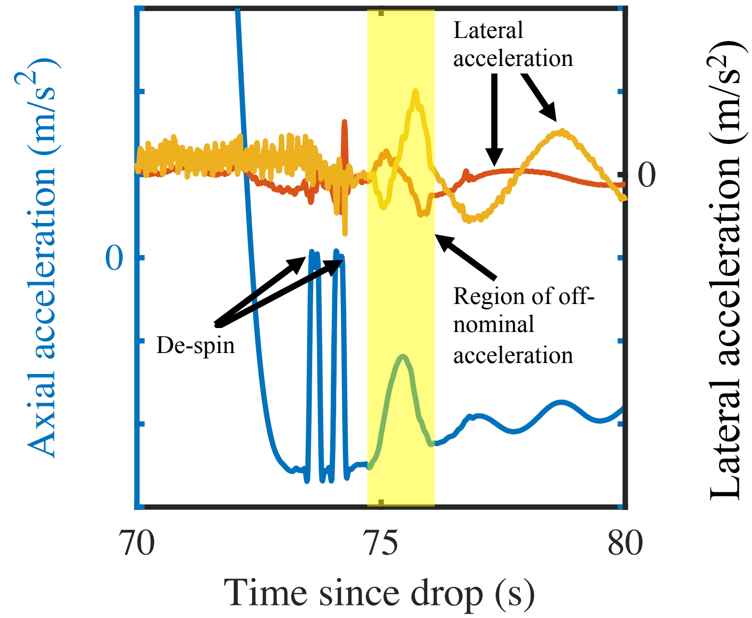


Figure 2. Off-nominal acceleration observed in SFDT-2 flight data after de-spin.

simulation and flight-observed phenomena is presented.

SIMULATION DESCRIPTION

The Program to Optimize Simulated Trajectories II (POST2)[4] was used to model the SFDT vehicle trajectory for SFDT-1.[5] The POST2 simulation was used during SFDT-2 for flight preparation and evaluation as well as to provide independent verification and validation of the primary flight simulation tool, Dynamics Simulator for Entry, Descent, and Surface Landing (DSENDS).[6,7] The POST2-based simulations included a single-body and a multi-body version of the flight systems model. Both POST2 single-body and multi-body trajectory simulations were equivalent six-degree-of-freedom (6DOF) models from balloon drop to PDD mortar fire, but differed during the PDD and parachute phases. The single-body simulation assumed that the PDD and the parachute were drag-only devices that were an integrated part of the test vehicle and this simulation was primarily used to provide independent verification and validation data for the DSENDS simulation. The POST2 multi-body simulation captured the various elements (e.g., PDD pack, PDD, parachute pack, parachute) using independent bodies and computed their dynamics separately while accounting for interaction forces through lines as appropriate. This simulation provided a higher-fidelity simulation of the flight environment. Additionally, similar to what was done to support operations for SFDT-1,[5] the single-body and multi-body simulations were modified to support day-of-flight prediction needs by incorporating atmospheric predictions from 12 and 24 hours before the launch and using Global Positioning System (GPS) coordinates of the balloon before drop to initialize the simulation.

In order to mimic the concept of operations shown in Figure 1, the POST2-based LDSD flight simulation begins at test vehicle drop and continues until splashdown. Before operations when day-of-flight conditions were not yet available, the initial conditions are established by assuming the balloon is moving with the local horizontal wind at the prescribed pressure altitude of the balloon. The simulation also includes logic to initiate key events such as spin motor and STAR-48 ignition based on timers while the SIAD deploy and PDD mortar fire were based on vehicle velocity subject to the actual vehicle altitude at burnout.[7,8]

Various models were integrated into the POST2-based simulation. During the targeting phase of the project, the atmospheric model used in the flight dynamics simulations came from Earth Global Reference Atmospheric Model (GRAM).[9] An aerodynamics database was provided for each phase and vehicle configuration including: large angle-of-attack range, low velocity for phase immediately following drop from balloon; power-on subsonic, transonic, and supersonic data applicable under the thrust from STAR-48; power-off supersonic data for coast phase between STAR-48 and SIAD deploy; and supersonic flight after the SIAD has been deployed.[10] Propulsion data (vacuum thrust profile, specific impulse, thrust application point and orientation, and total impulse) for the spin-up, spin-down, and STAR-48 motor were also provided for the simulation. Mass properties (center of gravity, moments and products of inertia, and total mass) were supplied by the project for various components as well as the main test vehicle in various configurations.

During SFDT-1 operations, all of the articles were recovered but some articles, such as the ballute, were discovered in a serendipitous manner.[2] Thus, a new requirement for the SFDT-2 mission was to retrieve all flight articles after they reached the ocean surface. Therefore, the SFDT-2 simulations also modeled the ballute after it separated from the rest of the vehicle and provided splashdown predictions for the ballute in addition to those of the test vehicle.[8]

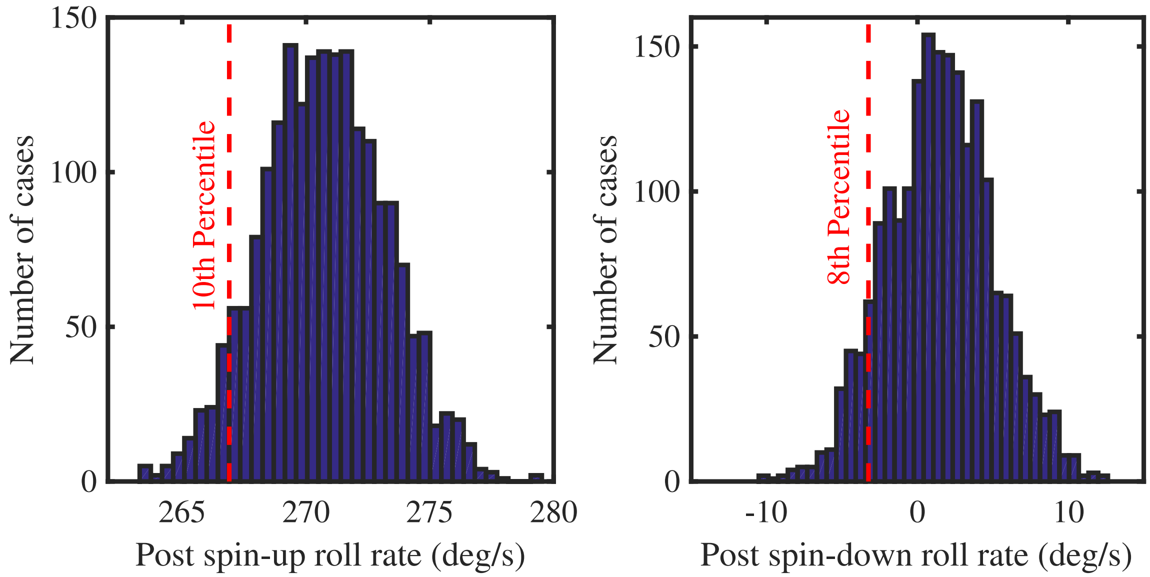
The reader is referred to References 5 and 8 for a more thorough description of the simulation.

COMPARISON OF FLIGHT DATA WITH PRE-FLIGHT PREDICTIONS

Key Metric Predictions

Similar to SFDT-1, the SFDT-2 flight vehicle was instrumented with a suite of on-board sensors that included a LN-200 inertial measurement unit, GPS receiver, video cameras, and load cells. Several radars also tracked the vehicle from the Pacific Missile Range Facility (PMRF) on Kauai. The atmosphere was sampled near the time of the launch by meteorological rockets and Rocket Balloon Instrument (ROBIN) sphere sensors. These data provided independent measurements to reconstruct the trajectory, atmosphere, and aerodynamics of the vehicle. Details about the reconstruction process can be found in Reference 11.

SFDT-2 had several critical requirements on flight conditions, such as deploy conditions of the SIAD and parachute, and many other metrics of interest to quantify the flight performance. The reader is referred to Reference 1 for a discussion on the specific requirements. The POST2 simulations were used pre-flight to ensure that system requirements were being met. The pre-flight Monte Carlo predictions of a few of these key metrics are shown in Figures 3- 5 along with the post-flight reconstructed values presented as percentiles of the pre-flight Monte Carlo predictions. Usually, 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 and is thus a high probability event. In general, as one approaches the tails of a Monte Carlo distribution, the probability decreases greatly, and so even a small percentile difference in the tails of a distribution corresponds with a large difference in probability of that event according to the distribution.

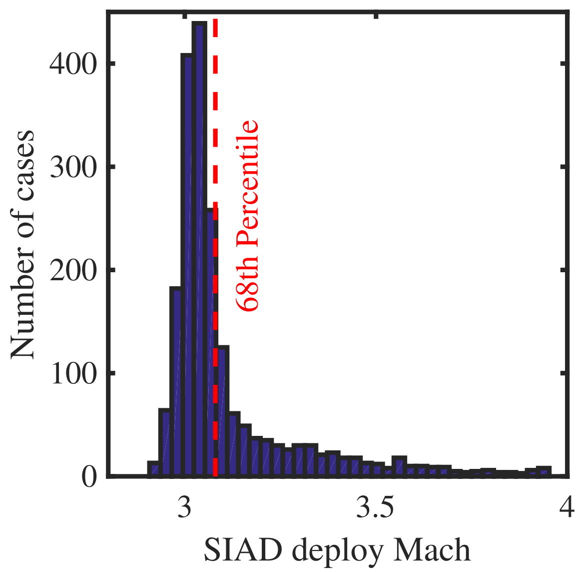


(a) Post Spin-up Roll Rate (b) Post Spin-down Roll Rate

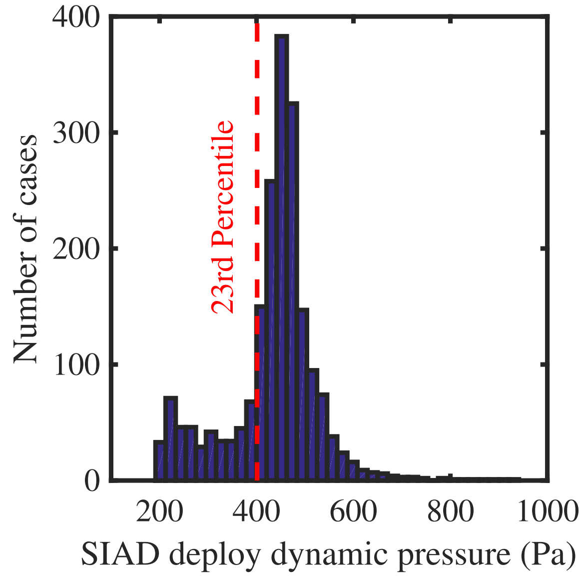
Figure 3. Comparison of vehicle roll rate predictions from SFDT-2 pre-flight Monte Carlos (bar charts) and reconstruction values (red dashed line).

For SFDT-1, many of the metrics of interest showed that the reconstructed trajectory was a low probability event.[12] However, due to the reconstruction and reconciliation process undertaken after the SFDT-1 flight, several models, especially the STAR-48 thrust model and the SFDT aerodatabase during powered flight, were updated based on knowledge gained from the reconstructed values.[2,10] The effect of implementing these changes can be seen in Figures 4 and 5 that show the SIAD and parachute deploy conditions. For SFDT-1, the SIAD deploy Mach number and dynamic pressure reconstructed values were 99.85 and 0.6 percentile cases of the pre-flight predictions.[12] For SFDT-2, the reconstructed values were 68th and 23rd percentile and thus were higher probability cases. The improvement is due to the fact that the apogee altitude was better predicted for SFDT-2 (where the reconstructed apogee altitude was 78th percentile of the pre-flight prediction) than during SFDT-1 (where the reconstructed apogee altitude was a 99.1 percentile of the pre-flight predictions).

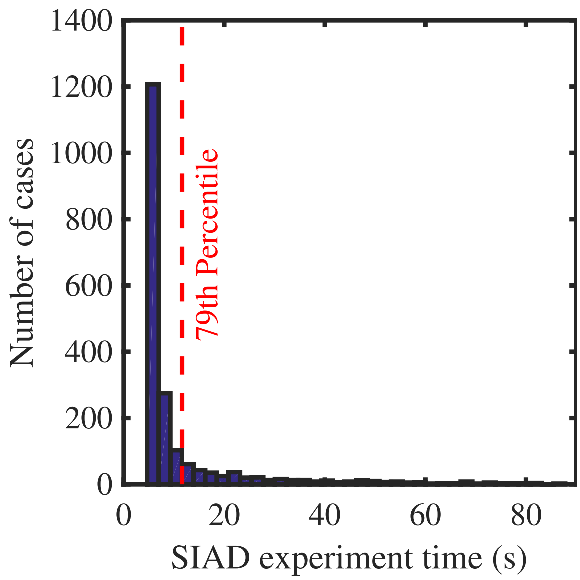
Another decision made after SFDT-1 was to modify the triggering of deployment events based on a dynamic triggering scheme that changes deployment targets based on the on-board state rather than using pre-flight fixed targets. The dynamic triggering system was used during SFDT-2 to target SIAD and parachute deploy conditions based on the altitude at burnout.[7,8] The trajectory was pushed into one of two families of SIAD deploy conditions (named early SIAD or late SIAD) based on if the vehicle was at a higher or lower altitude at burnout than the reference trajectory. Due to the existence of two families of potential triggers conditions, the dynamic pressure distributions at the deployment events, especially SIAD deploy, have a bi-modal behavior as is visible in Figure 4(b). The ultimate goal of this triggering scheme was to achieve parachute deployment conditions for Mach and dynamic pressure that were within the acceptable range of the scientific requirements regardless of the trajectory conditions upstream. Looking at the parachute deployment Mach distribution and reconstructed value, Figure 5(a), the dynamic triggering seems to have achieved its mark in Mach number, since the reconstructed parachute deployment Mach number is the 85th percentile.



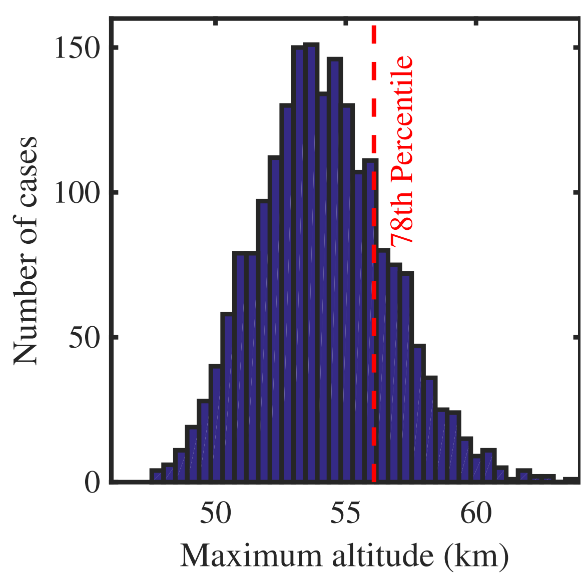
(a) SIAD Deploy Mach Number



(b) SIAD Deploy Dynamic Pressure

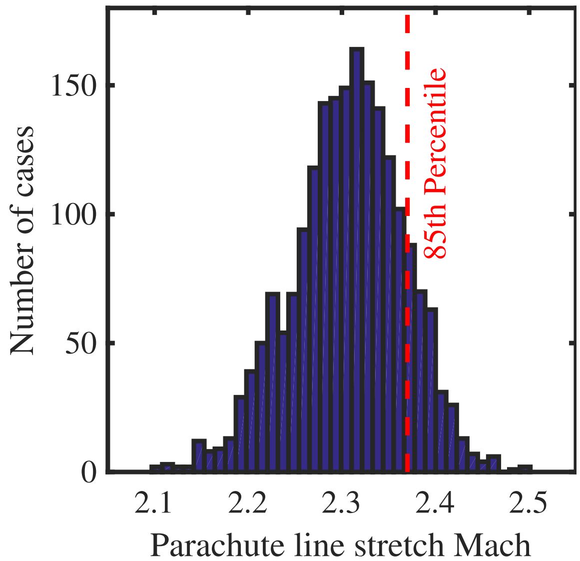


(c) SIAD Experiment Time

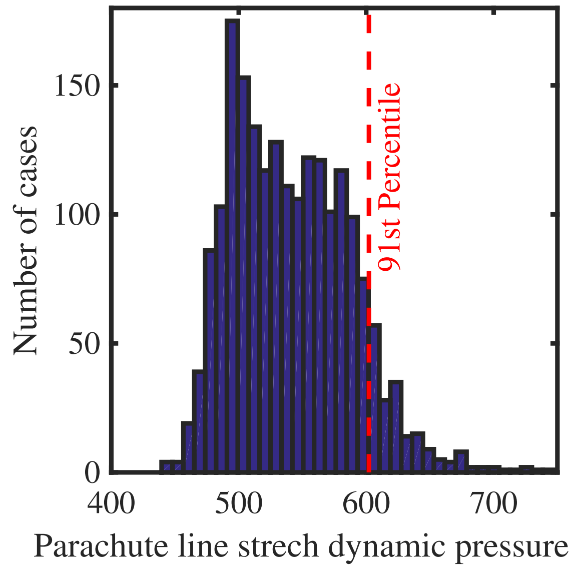


(d) Maximum Altitude

Figure 4. Comparison of SIAD phase performance predictions from SFDT-2 pre-flight Monte Carlos (bar charts) and reconstruction values (red dashed line).



(a) Parachute Deploy Mach Number



(b) Parachute Deploy Dynamic Pressure

Figure 5. Comparison of parachute phase performance predictions from SFDT-2 pre-flight Monte Carlos (bar charts) and reconstruction values (red dashed line).

However, the dynamic pressure at parachute deployment, Figure 5(b), is a somewhat lower probability event (91st percentile). The reason for this difference is the off-nominal acceleration sensed by the vehicle after it stopped spinning. The effect of that acceleration will be discussed more in depth in a later section.

Ultimately, similar to SFDT-1, the parachute for SFDT-2 developed large tears in the fabric during deployment. The reasons for this failure are still under investigation and are covered in more detail in Reference 3.

Splashdown Footprints

A comparison of pre-flight predicted splashdown footprints, the reconstructed trajectory, and recovery point are shown in Figure 6. During flight operations, two different splashdown footprints were generated using the POST2 multi-body simulation (1) with a fully-functioning parachute and (2) one with a no parachute (failed parachute case).[8] Again very similar to SFDT-1, the SFDT-2 parachute performed off-nominally, but remained attached to the test vehicle and provided some drag. Once a parachute failure was observed, the test vehicle splashdown point was given from the failed parachute ellipse and the recovery craft was able to find the test vehicle very close to that predicted point. For SFDT-1, the resulting trajectory was somewhere between the functional parachute and no parachute predictions,[12] but for SFDT-2, the recovered location is very close to the center of the failed parachute ellipse. This suggests that the torn parachute canopy from SFDT-2 provided less resistance during terminal descent than the parachute fragments from SFDT-1. It should be noted that the vehicle and ballute were recovered approximately one hour and two hours respectively after splashdown, so there could be a slight difference between the actual splashdown point and the recovery point due to ocean drift. The drift of softgoods due to ocean currents was not captured in the simulation nor was it accounted for after recovery to bound the uncertainties of the recovery location. Such analysis can be considered for future SFDT flights.

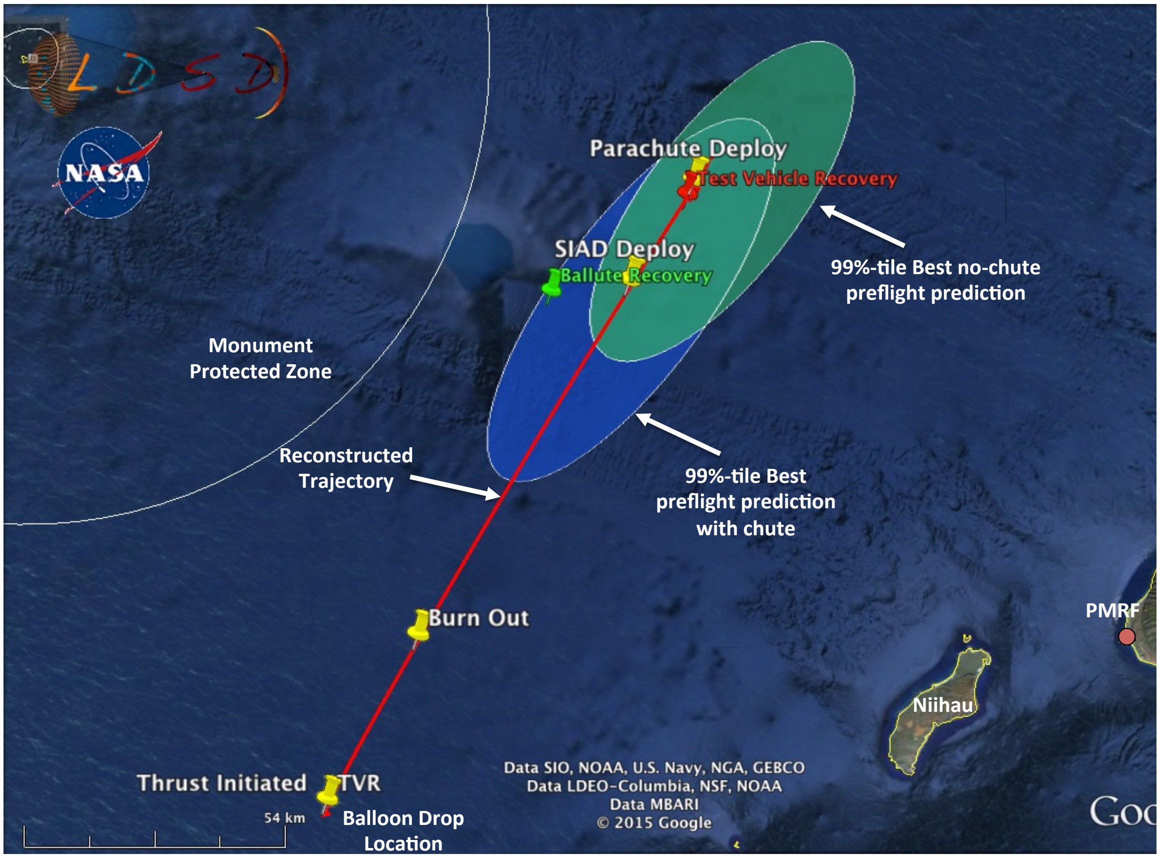


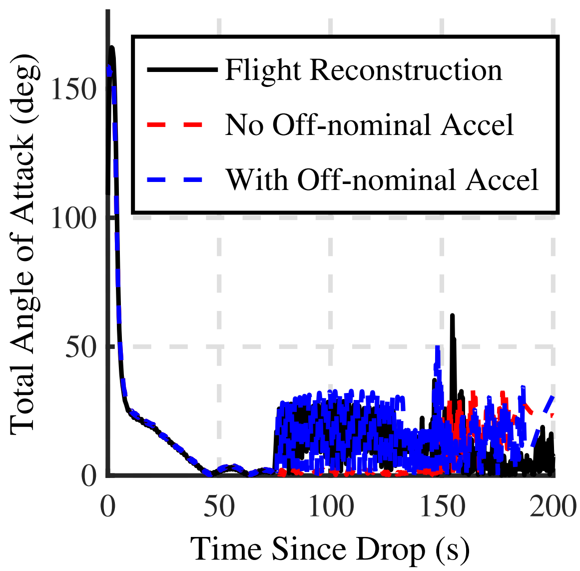
Figure 6. Pre-flight predictions of splashdown points and reconstructed trajectory for SFDT-2.

During operations, the POST2-based flight simulation was also used to predict the splashdown points of the ballute. Similar to the situation with the test vehicle, the predicted ballute splashdown point from the simulation was found to be near the actual location where the ballute was recovered. Overall, despite the parachute failure, the flight simulations predictions displayed an improvement in the prediction quality from SFDT-1, when the test vehicle recovery point was near the outer reaches of the 99th percentile ellipse generated with a failed parachute.[12] The modeling updates made to the simulation since SFDT-1[8] have helped the flight dynamics simulation improve the splashdown ellipse predictions of the test vehicle in both nominal and off-nominal conditions.

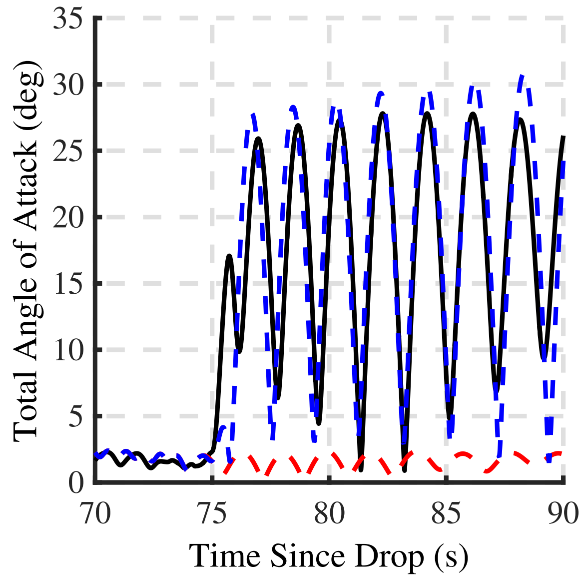
RECONCILIATION OF SIMULATION WITH RECONSTRUCTED TRAJECTORY

The objective of the reconciliation process was to use the simulation to recreate the reconstructed flight trajectory by modifying the simulation and then determine the most likely set of conditions that were present during the flight. The true set of all conditions cannot be reconstructed since not all conditions were observable with flight data; however, inference using the simulation could inform flight dynamicists of potential modeling changes needed for future SFDT flights.

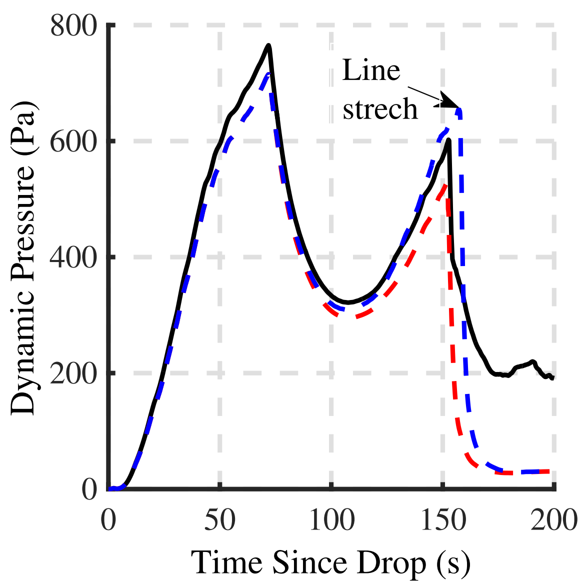
One of the deficiencies of the the simulation for SFDT-2 was its inability to predict the attitude of the test vehicle post de-spin. As shown in Figure 2, an off-nominal acceleration was recorded by the vehicle for approximately 1 s shortly after de-spin. The cause of this off-nominal acceleration remains undetermined and under investigation. However, since the vehicle had de-spun, it was susceptible to torques such as the one caused by this spurious acceleration. It can be noted in Figure 2 the axial acceleration is more than an order of magnitude larger than the lateral accelerations, but even small off-axis accelerations create large angular disturbances. The vehicle pitched more than 30 deg. after de-spin (see Figures 7(a) and 7(b)) even though pre-flight predictions showed angular oscillations within 5-10 deg.



(a) Total Angle of Attack



(b) Total Angle of Attack (zoomed)



(c) Dynamic Pressure

Figure 7. Effect of off-nominal acceleration post de-spin on total angle of attack and dynamic pressure.

As part of reconciliation of the simulation with flight data, the accelerations from the on-board IMU and the knowledge of the mass properties of the vehicle were used to simulate a force acting on the vehicle. This off-nominal force within the simulation provided results that corroborated with the observed angle of attack and sideslip angle oscillations. As seen in Figure 7, the agreement in total angle of attack between the simulation and the reconstruction right after the de-spin event improved after modeling the off-nominal axial and lateral acceleration pulse within the simulation.

The increased oscillation caused by the off-nominal acceleration had a subsequent effect on dynamic pressure at parachute line stretch, where the dynamic pressure increased by almost 100 Pa. Since the vehicle was experiencing larger angles of attack, the vehicle did not sense as much drag force post de-spin as was expected. However, the SIAD and parachute deploy velocity targets had been determined based on the vehicle conditions at STAR-48 burnout, before the off-nominal acceleration had occurred. Thus, the deploy conditions, noticeable the parachute line stretch condition, occurred at dynamic pressures higher than expected as seen in Figure 5(b).

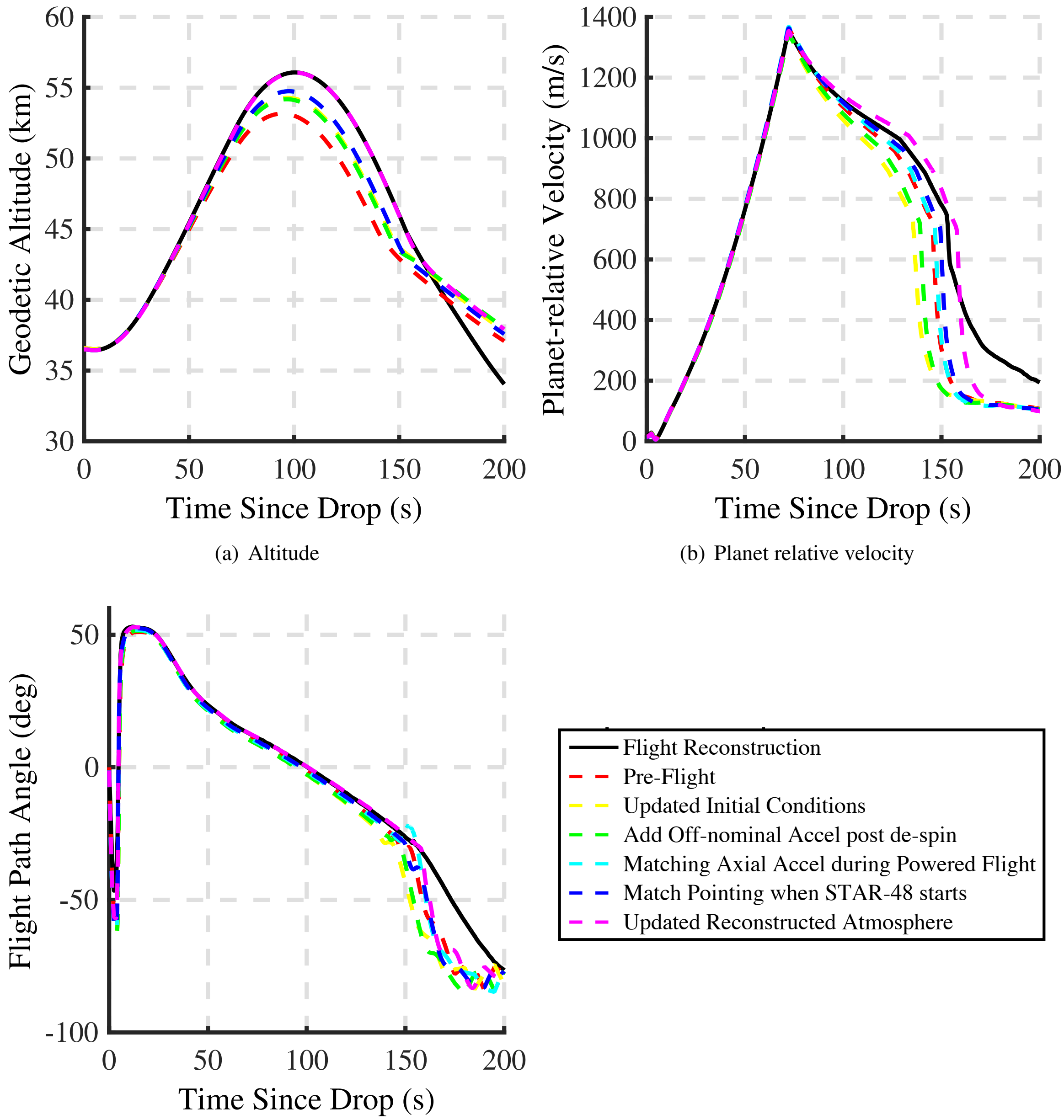
The reconciliation process also included modeling flight observables, such as the reconstructed STAR-48 thrust profile and the reconstructed atmosphere, within the simulation to see if the agreement between the simulation and reconstruction trajectories improved. As detailed in Reference 12, the flight observables modeled within the reconciliation simulation for SFDT-1 were determined after extensive root-cause analysis. These same types of flight observables were applied to the simulation in an incremental manner during the SFDT-2 reconciliation process and Table 1 shows the effect of these flight observables on predicted apogee altitude.

Table 1. Reconciliation of the simulation prediction and flight reconstruction for apogee altitude.

Flight Observables	Apogee Altitude (km)	Difference from line above (km)
Reconstructed trajectory	56.07	–
Pre-flight prediction	53.17	-2.9
Updating initial conditions	54.19	+1.02
Adding off-nominal acceleration post de-spin	54.19	+0.0
Updating to reconstructed STAR-48 thrust	54.75	+0.56
Updating to observed attitude and rates at STAR-48 ignition	54.80	+0.05
Updating to SFDT-2 reconstructed atmosphere	56.10	+1.3

For SFDT-1,[12] including the flight observables in the simulation did not account for all of the differences between the prediction from the simulation and the reconstructed trajectory. Aerodynamic properties during the powered flight phase had to be adjusted to finally achieve an agreement between the simulation and the reconstructed trajectory. However, for SFDT-2, including only the flight observables in the simulation leads to an agreement between the prediction of the apogee altitude from the simulation and the reconstructed maximum altitude within 30 m. The acceleration during the powered flight segment and the differences in the pre-flight and post-flight atmospheric model accounted for the bulk of the difference in the altitude between the simulation and reconstruction. This again underscores that the modeling changes made after SFDT-1 helped make the simulation a good predictor for many flight quantities, such as the altitude profile.

Figures 8 and 9 show the reconciled flight dynamics simulation results and compares them to reconstructed values. By updating the initial conditions to those from the day-of-flight, modifying the STAR-48 acceleration, and applying the reconstructed atmosphere, almost all of the differences between the pre-flight simulation prediction and the reconstructed value of the apogee altitude were resolved as seen in Figure 8(a). Velocity and flight path angle also show good correspondence between the simulation and the reconstruction once the STAR-48 thrust and atmosphere have been updated. The agreement between the simulation and the reconstruction deteriorates after 150 s, at which point the parachute deployed and failed in the real flight. Therefore, statements about agreement between the simulation and the reconstruction are restricted to the time before 150 s.

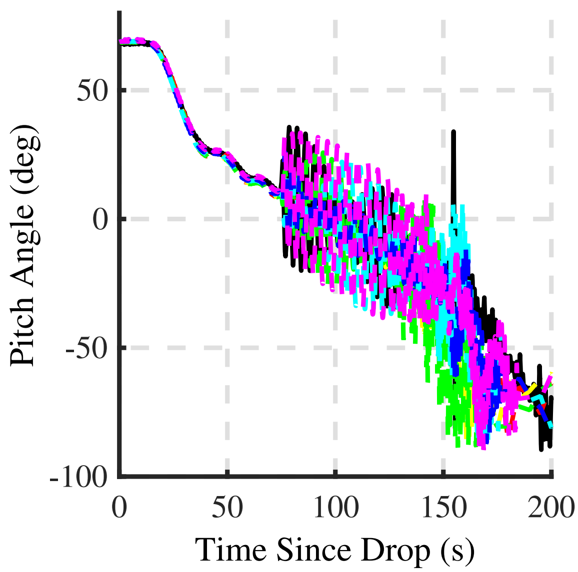


(a) Altitude

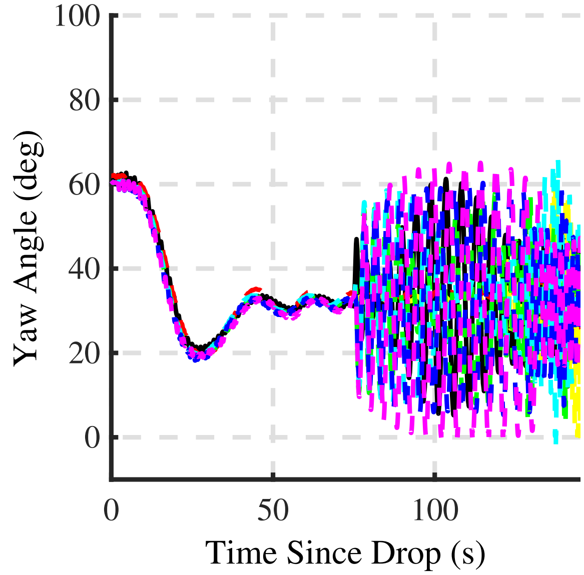
(b) Planet relative velocity

(c) Flight path angle

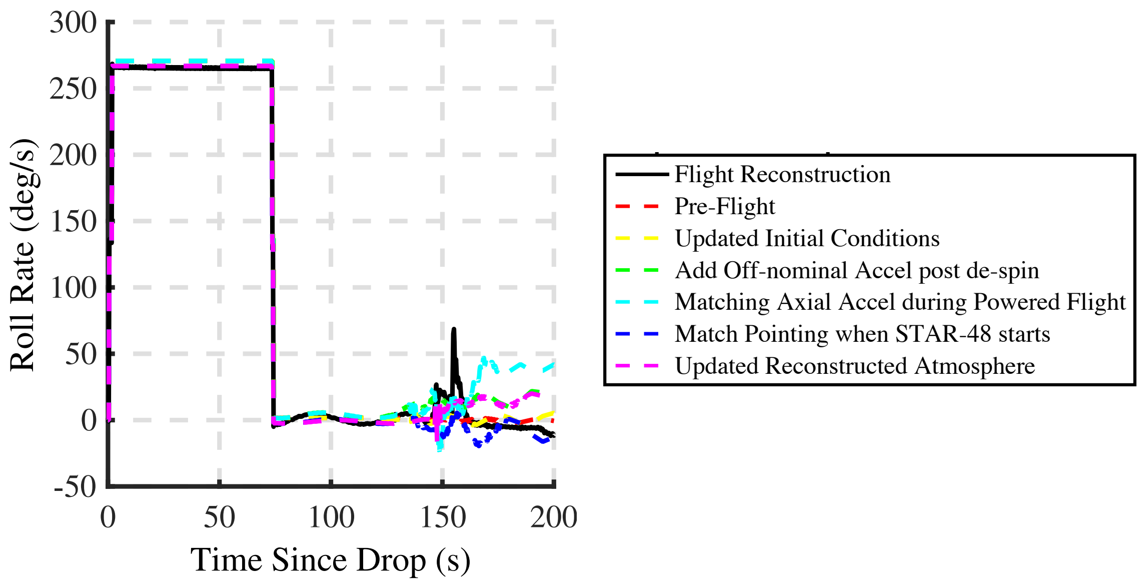
Figure 8. Comparison of altitude and velocity histories from SFDT-2 POST2 simulation reconciliation and trajectory reconstruction.



(a) Pitch angle



(b) Yaw angle



(c) Roll rate

Figure 9. Comparison of attitude histories from SFDT-2 POST2 simulation reconciliation and trajectory reconstruction.

Figure 9 compares reconstruction of the flight attitude from test data to simulation prediction. In this case, once the off-nominal acceleration has been modeled, there is improved agreement in the attitude states between the reconstruction and the simulation. Similar to what was seen for position and velocity states (Figure 8), the agreement between the simulation and the reconstruction deteriorates after parachute failure near 150 s.

SUMMARY AND CONCLUSIONS

Reconstruction of the SFDT-2 flight data revealed off-nominal behaviors not expected in the pre-flight vehicle dynamics simulations. Specifically, larger than expected angle of attack oscillations occurred post de-spin. These oscillations are believed to be caused by off-nominal acceleration that occurred for a 1 s duration shortly after de-spin completed. The POST2-based simulation was used for post-flight analysis to reconcile differences seen between the simulation and reconstructed values and to test the effect of the off-nominal behavior. It was found that for most metrics of interest, the simulation predictions agreed with the reconstructed states. The predictive capability of the simulation improved over its performance for SFDT-1 due to modeling changes recommended after the SFDT-1 reconciliation activities. The unexpected oscillatory behavior seen in SFDT-2 attitude data could be reconciled within the simulation by modeling the off-nominal acceleration seen post-despin. The simulation also showed that due to this off-nominal acceleration, the parachute deploy dynamic pressure increased by approximately 100 Pascals. Both of these simulation results were similar to flight observations and were on the lower probability sides of the pre-flight predictions. The reconciliation analysis has provided data that can be utilized for potential model changes for future simulations and the planning for future SFDT flight tests.

ACKNOWLEDGMENTS

The authors are thankful for the work of other NASA Langley Research Center, Jet Propulsion Laboratory, and NASA Ames Research Center flight dynamics, aerosciences, and reconstruction team members that contributed to SFDT-2 post-flight analyses. These team members include John Van Norman, Christopher Karlgaard, Jason Ginn, Seth Aaron, and Suman Muppudi. The POST2 simulation work was supported by the Atmospheric Flight and Entry Systems Branch (AFESB) in the Engineering Directorate at NASA Langley Research Center. A portion of this research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with NASA.

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