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SUPERSONIC FLIGHT DYNAMICS TEST 1 - POST-FLIGHT ASSESSMENT OF SIMULATION PERFORMANCE

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NASA's Low Density Supersonic Decelerator (LDSD) project conducted its first Supersonic Flight Dynamics Test (SFDT-1) on June 28, 2014. Program to Optimize Simulated Trajectories II (POST2) was one of the flight dynamics codes used to simulate and predict the flight performance and Monte Carlo analysis was used to characterize the potential flight conditions experienced by the test vehicle. This paper compares the simulation predictions with the reconstructed trajectory of SFDT-1. Additionally, off-nominal conditions seen during flight are modeled in post-flight simulations to find the primary contributors that reconcile the simulation with flight data. The results of these analyses are beneficial for the pre-flight simulation and targeting of the follow-on SFDT flights currently scheduled for summer 2015.

INTRODUCTION

The Low Density Supersonic Decelerator (LDSD) project is a NASA Technology Development Mission tasked with improving the technology readiness level for Supersonic Inflatable Aerodynamic Decelerators (SIAD) and designing an improved supersonic parachute that can be used for future robotic and human exploration missions to Mars.[1] One of the critical components of the project is a series of flight tests that demonstrate the performance of the various technologies at Mars relevant conditions. As seen in Figure 1, the Supersonic Flight Dynamics Test (SFDT) involves a high altitude balloon lifting the test vehicle to around 36 km altitude. Next, the vehicle is spun-up to nominally 300 deg/s to provide roll stability and a STAR-48 motor accelerates the vehicle nominally to approximately Mach 4. The vehicle is spun-down and then deploys the SIAD, which decelerates the vehicle close to Mach 3. Finally, a supersonic disksail (SSDS) parachute is deployed close to Mach 2.5 using a trailing ballute (here labeled as the parachute deployment device or PDD), and the vehicle then decelerates on the parachute until splashdown.

SFDT-1 was conducted off the western coast of Kauai, Hawaii on June 28, 2014. This particular test was designated as a shakeout test that would demonstrate a successful powered flight and would

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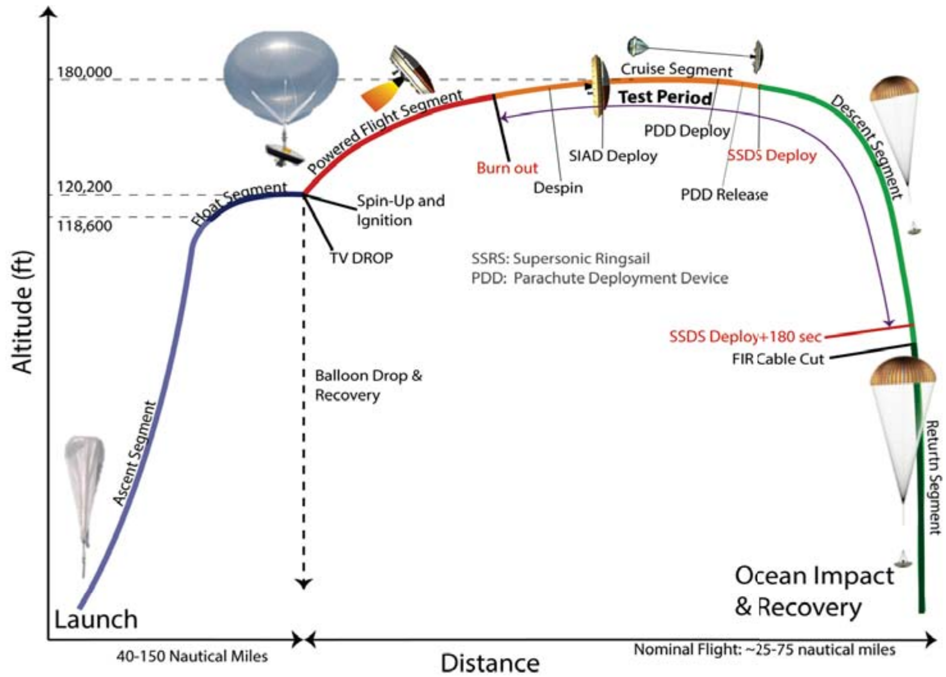


Figure 1. Concept of operations for the Supersonic Flight Dynamics Test 1 conducted in June 2014.[1]

deliver the SIAD and parachute to relevant conditions. These objectives were met for SFDT-1 and hence this was a successful test. However, the flight demonstrated some off-nominal conditions, such as the lofting of the vehicle to approximately 61 km, when nominal pre-flight calculations predicted a maximum altitude of around 53 km. Due to the lofting observed, the SIAD deployed at a slightly higher Mach number and a lower dynamic pressure than the pre-flight estimates and the SIAD experiment phase was longer than expected. The parachute was deployed close to pre-flight predictions; however, the behavior of the parachute was off-nominal for non-trajectory related issues.[2]

Due to the off-nominal conditions observed in flight, it is important to compare the pre-flight predictions from trajectory simulations with the reconstructed flight performance. Such comparisons could lead to the discovery of potential ways the pre-flight models can be reconciled with the reconstructed flight trajectory in order to understand the implications for modeling future SFDT flights. Two flight simulation programs - Dynamics Simulator for Entry, Descent, and Surface Landing (DSENDS)[3] and the Program to Optimize Simulated Trajectories II (POST2) - were used to predict the pre-flight performance of the vehicle. The focus of this paper is analysis using the POST2 tool, which was the main simulation used to model the off-nominal behavior post flight in order to explore the potential contributors to the observed behavior. Such analysis is beneficial in helping to decide the model updates necessary for the pre-flight simulation and targeting of the two follow-on tests - SFDT-2 and SFDT-3 - currently scheduled for summer 2015.

In the following sections, a brief description of the POST2 LDSD trajectory simulation developed for SFDT-1 is provided. Next, results comparing pre-flight predictions of flight performance with the reconstructed quantities are shown. Then, a few different search methods that were employed to understand environmental and modeling parameters that contributed to the discrepancy seen between pre-flight nominal predictions and the reconstructed trajectory are listed. From the search methods, a list of potential top contributors were developed which were then modeled in the simulation to reconcile the pre-flight nominal prediction with the reconstructed trajectory. Finally, implications of the reconciliation process on modeling efforts for SFDT-2 and SFDT-3 are discussed.

SIMULATION DESCRIPTION

In order to support SFDT-1 flight preparation and evaluation, as well as provide independent verification and validation of DSENDS results,[3] the POST2-based simulations included a baseline and a multi-body version of the flight systems model. Both of these trajectory simulations were the same 6-degree-of-freedom (DOF) models from balloon drop to PDD mortar fire, but differed during the PDD and parachute phases. The baseline simulation assumed that the PDD and the parachute were drag-only devices that were an integrated part of the test vehicle. The multi-body simulation modeled various elements (e.g., PDD pack, PDD, parachute pack, parachute) using independent bodies and computed their dynamics independently while accounting for interacting forces as appropriate. For this paper, post-flight trajectory reconciliation is focused on the flight phases before PDD deployment so no further distinction between the types of simulations will be made. Further details of the POST2-based simulations can be found in Reference 4.

The POST2-based LDSD flight simulation begins at test vehicle drop and continues until splashdown. The initial conditions are established by assuming the balloon is moving with the local horizontal wind at the prescribed pressure altitude for 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.

Various models were integrated into the POST2-based simulation. The atmospheric model used predictions from Earth Global Reference Atmospheric Model (GRAM).[5] 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 SIAD has been deployed.[6] 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, mass moments and products of inertia, mass) were supplied by the project for various components as well as the main test vehicle in various configurations.

COMPARISON OF FLIGHT DATA WITH PRE-FLIGHT PREDICTIONS

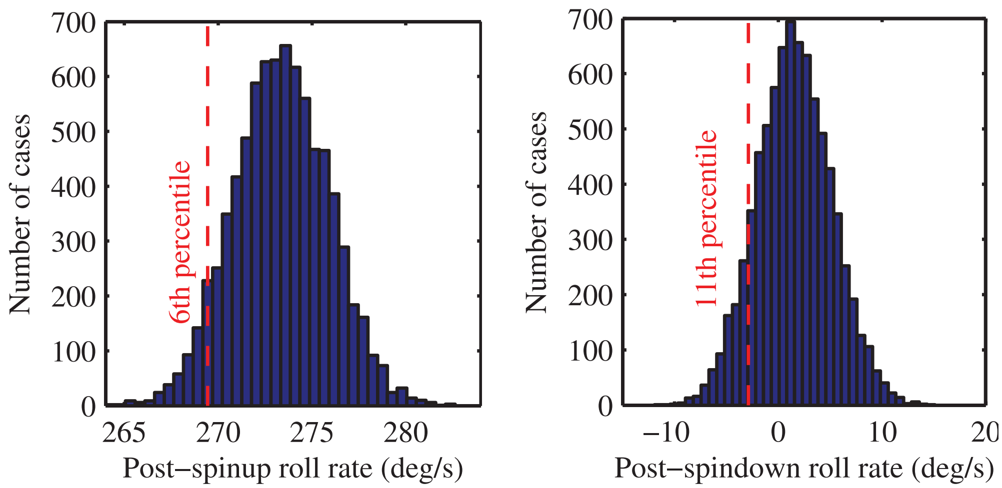
The SFDT-1 flight vehicle was instrumented with many on-board sensors, such as LN-200 accelerometer, GPS, video cameras, and load cells. The vehicle was also tracked by several radars from Kauai. The atmosphere was sampled near the time of the launch by meteorological rockets and Rocket Balloon Instrument (ROBIN) sphere sensors. The resulting data set allowed the reconstruction of trajectory, atmosphere, and aerodynamics of SFDT-1. The trajectory estimation process was conducted using an iterative Kalman Filter which has the advantage of blending several types of observations together and also producing an estimate of the uncertainty in the reconstructed values. Details about the reconstruction process can be found in Reference 7.

SFDT-1 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.[1] In the interest of space, the pre-flight Monte Carlo predictions of only a few of these metrics are shown in Figures 2- 4 along with the post-flight reconstructed values.

From the comparison plots, it is evident that for these metrics of interest, the reconstructed trajectory was a low probability event, signifying off-nominal behavior seen during the flight. Several other metrics of interest that are not shown here demonstrated the same trend. The off-nominal conditions are especially evident at SIAD deploy conditions - Figures 3(a)- 3(b) - due to higher than expected lofting of the trajectory during powered flight. One can see in Figure 3(d) that the maximum altitude achieved by the flight was a 99.1 percentile case of the pre-flight Monte Carlo results. Potential explanations for this behavior are explored in later sections of this paper.

However, the reconstructed parachute deployment Mach number which comes much later than powered flight and SIAD seems to agree surprisingly well with pre-flight nominal predictions in Figure 4(a). This is due to the on-board triggering flight software. SFDT-1 on-board flight software commanded configuration changes using three triggers - one acceleration-based trigger and two velocity-based triggers. The acceleration-based trigger sensed the end of the STAR-48 thrust and armed the flight software that burnout is occurring, while the two velocity-based triggers deployed the SIAD and the PDD. Despite deploying the SIAD at faster speeds and higher altitude than nominal predictions, the flight software was able to correct the deployment conditions for later phases of flight by prolonging the SIAD phase (Figure 3(c)) until PDD velocity conditions were close to the trigger value. Since the PDD trigger also affected parachute deployment conditions, the parachute line stretch Mach number was very close to nominal predictions.

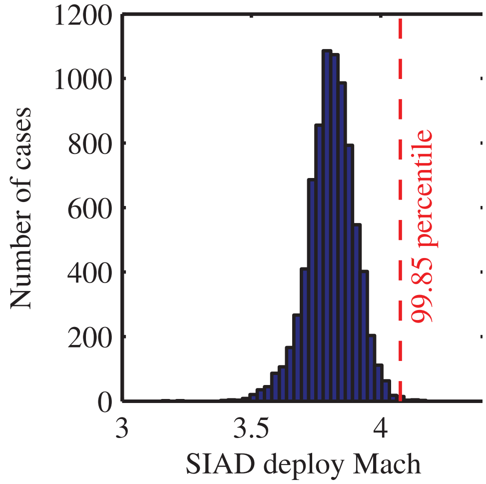


(a) Post Spin-up Roll Rate (b) Post Spin-down Roll Rate

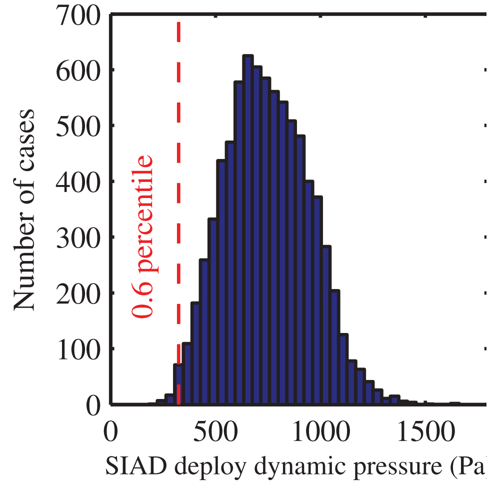
Figure 2. Comparison of vehicle roll rate predictions from SFDT-1 pre-flight Monte Carlos (bar charts) and reconstruction values (red dashed line).

Unfortunately, the parachute developed large tears in the fabric during deployment for reasons other than trajectory conditions, leading to off-nominal behavior in that phase of the flight as well. The parachute reconstruction is not the focus of this paper, but more information on it can be found in Reference 2.

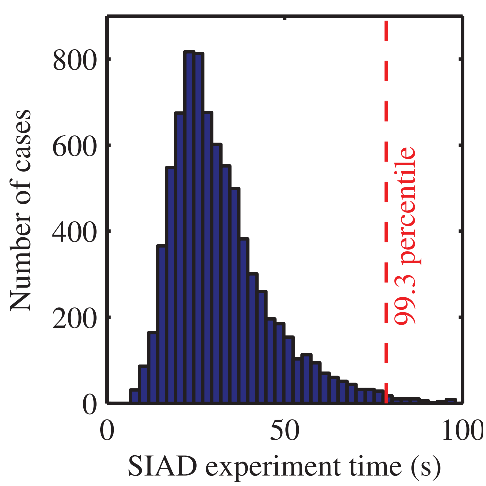
A comparison of pre-flight predicted splashdown footprints, the reconstructed trajectory, and



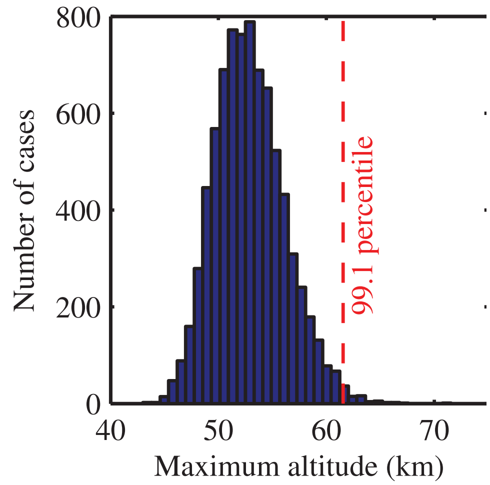
(a) SIAD Deploy Mach Number



(b) SIAD Deploy Dynamic Pressure

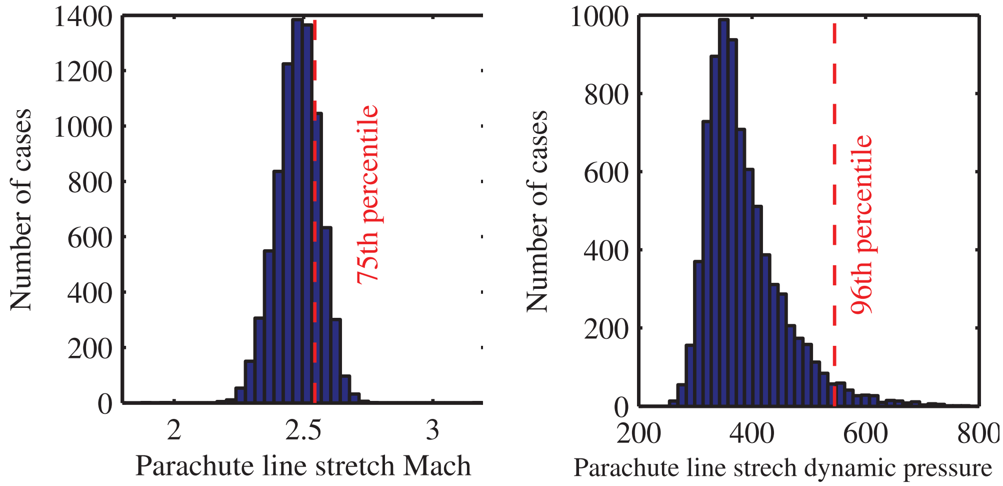


(c) SIAD Experiment Time



(d) Maximum Altitude

Figure 3. Comparison of SIAD phase performance predictions from SFDT-1 pre-flight Monte Carlos (bar charts) and reconstruction values (red dashed line).



(a) Parachute Deploy Mach Number (b) Parachute Deploy Dynamic Pressure

Figure 4. Comparison of parachute phase performance predictions from SFDT-1 pre-flight Monte Carlos (bar charts) and reconstruction values (red dashed line).

recovery point are shown in Figure 5. During flight operations, two different splashdown footprints were generated using the POST2 baseline simulation - one with chute and one with chute completely failed.[4] In the actual flight, the chute did perform off-nominally, but remained attached to the test vehicle and provided some drag. Thus, the resulting trajectory was somewhere between the chute and no chute predictions. The vehicle was recovered approximately two hours after splashdown, so the difference in the reconstructed splashdown point and recovery point can be attributed to ocean drift. As can be seen in Figure 5, the reconstructed trajectory splashdown point is near the outer edges of both splashdown footprint predictions, primarily since the SIAD experiment phase was longer than the nominal prediction, leading the vehicle to continue downrange for a longer period of time; nevertheless, the reconstructed splashdown point is still within the 99th percentile bounds even with off-nominal flight conditions.

POST-FLIGHT ROOT-CAUSE SEARCH

The off-nominal trajectory of SFDT-1, especially the nearly 8.5 km difference in maximum altitude between the nominal prediction and reconstructed value, prompted a detailed root-cause analysis. The root-cause analysis benefited from the availability of a high-fidelity trajectory simulation in the form of the POST2 models. These POST2-based Monte Carlo cases contained the statistical variation of more than 340 input variables, providing a ready source to query what environmental and subsystem performance conditions could have led to the reconstructed trajectory.

The POST2 Monte Carlo simulations for LDSD were typically run with 8000 cases, so it was understood that the likelihood of simulating one case that exhibited all of the characteristics of the reconstructed flight was small. As a result, the root-cause analysis was focused on isolating the set of Monte Carlo cases that best matched the flight trajectory. From that set, the simulation variables that were most likely to have contributed to the off-nominal behavior could be identified.

There are several caveats for this type of analysis. The root-cause search is only as good as the models in the simulation; thus, if the flight exhibited characteristics not captured in the simulation

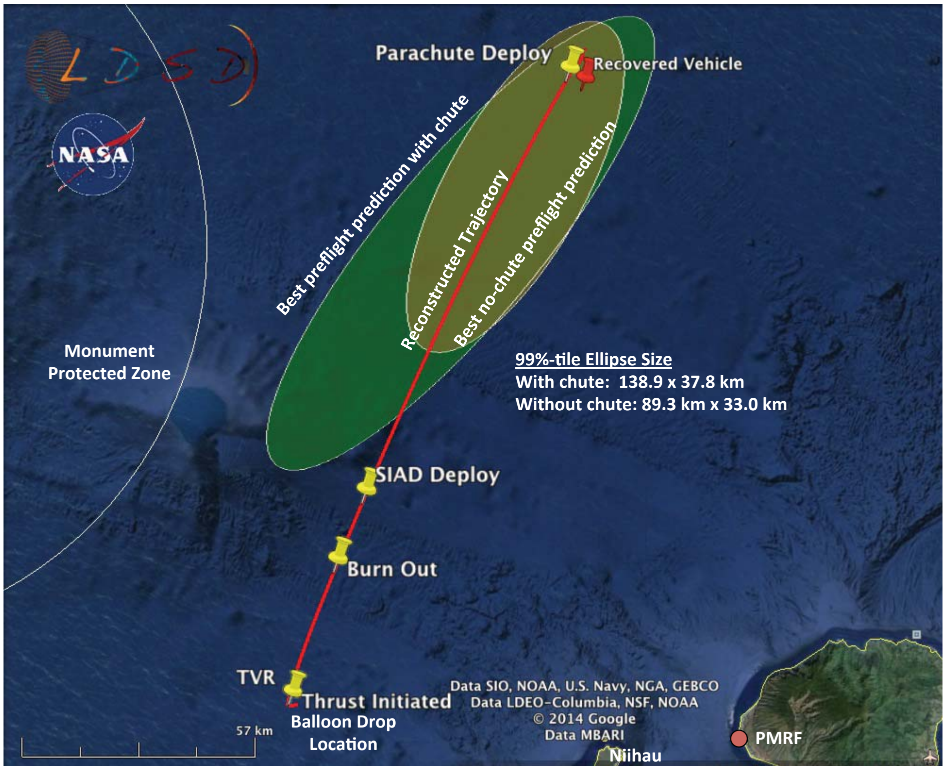


Figure 5. Comparison of splashdown location from pre-flight predictions and reconstructed trajectory.

models, this root-cause search would not point to that contributor. Moreover, the simulation was compared to the estimated flight performance from statistical reconstruction described in Reference 7. The statistical methods used in the reconstruction have their own assumptions and limitations, so the root-cause analysis also works within those bounds. Finally, the characterization of the SFDT-1 performance is highly multi-modal with many combinations of inputs causing potentially similar outputs. Thus, throughout the root-cause search, there is a bias in favor of isolating parameters that best reconcile some flight conditions without violating others and also are the most likely events based on our *a priori* uncertainty distributions used for pre-flight Monte Carlo analysis.

The following sections detail the three major techniques used in the root-cause search: one variable at a time (OVAT) sensitivities, statistical correlations between Monte Carlo inputs and outputs matching flight conditions, and filtering Monte Carlo simulation data to isolate families of flight-like trajectories. Finally, the top potential contributors to SFDT-1's off-nominal behavior that were isolated with the three techniques are presented.

One Variable at a Time Sensitivity

One variable at a time analysis has been a common technique used by POST2 simulation-based analysis for past flight projects. In OVATs, simulation runs are made where each Monte Carlo input variable is set to its minimum and then its maximum value based on the distributions and bounds set for the analysis, while all of the other input variables are held constant to their nominal values. This is primarily a tool to check the proper configuration of the Monte Carlo simulation, but can be treated as a way to capture loosely the partial derivative of the flight performance based on that variable. OVAT analysis results were used to identify which input parameters provided the largest sensitivity to many of the metrics of interest. Since there was such a large variation in the peak altitude between pre-flight nominal and reconstructed trajectories, special emphasis was given to inputs that created large perturbations in the altitude.

Statistical Correlations

Since Monte Carlo analysis is conducted using statistically varied input settings for each simulation run, it was natural to search for correlations between all of the Monte Carlo inputs and outputs of interest. Specifically, the focus was on computing the correlation coefficient (R) defined in Equation (1). Additionally, a test of the null hypothesis was computed for each calculation of the correlation coefficient. In the formulation used for the study, the null hypothesis probability (p) had to be less than 0.05; thus, a p-value of less than equal to 0.05 meant that there was at least a 95% confidence that the computed correlation coefficient could not be as large if drawn randomly from a large enough sample set. In short, the p-value test showed the statistical significance of the correlations. The test ruled out many of the approximately 340 input variables tested that had large correlations but were not statistically significant.

$$R = \frac{\sigma_{x,y}^2}{\sigma_x \sigma_y} \tag{1}$$

The correlations were computed for each Monte Carlo input individually as well as for groups of input variables. Through the groupings, it was hoped that families of conditions that potentially led to the flight-like conditions in the simulation could be isolated. Through trial-and-error and also due to the increased numerical complexity, the multi-variable statistical correlation search was limited to five input variables at a time, after which there was a diminished return in terms of number of top contributors that were identified.

Filtering of Simulation Data

The main objective of the filtering analysis was to find simulated Monte Carlo outputs that match the reconstructed trajectory values and use these to isolate the input parameters and settings that could explain the behavior of these trajectories. Two approaches to filter the output were used and, in order to provide a large enough search space, 100,000 case Monte Carlo data set with pre-flight settings but updated initial conditions to match the reconstructed flight were analyzed.

The objective of the first approach, dubbed the *needle in the haystack* approach, was to filter results such that cases which closely matched as many reconstructed trajectory parameters as possible could be found. Once cases that were the best match to the reconstructed flight were found, the input settings were examined for commonality.

The second approach, referred to as the *statistically relevant sample* approach, was used to filter the Monte Carlo results in a way to create a sample set that was both representative of the reconstructed trajectory but still large enough to conduct the statistical correlation search previously described. Additionally, with the second approach, the input dispersions of the filtered set of cases were compared to those of the full 100,000 Monte Carlo to assess if any biases or trends existed.

The types of filters applied in both approaches were similar. Since there was an emphasis on finding the cause of the lofting of the trajectory, the top level filter contained cases that had maximum altitudes between 60 and 63 km. Approximately 19% of Monte Carlo cases passed the criteria for this top-level filter. Other filters applied as additional layers included the conditions at STAR-48 burnout, such as relative velocity, relative flight path angle, pitch angle, latitude and longitude, as well as the integrated error between a simulation case and the reconstructed trajectory for several metrics of interest during the powered phase of the flight. When using the needle in the haystack approach, the filter criteria for these conditions at burnout were extremely restrictive to isolate exact flight-like cases. Similarly, for the statistically relevant sample approach, the filter criteria had to be a balance between being close to flight conditions while preserving a statistically significant sample size.

Due to the different objectives of each approach, there were some overly limiting filters that were not applied in the statistically relevant sample approach. One such filter was the spin rate of the test vehicle at STAR-48 ignition. As seen in Figure 2(a), the reconstructed spin-up roll rate was 6th percentile of the pre-flight estimates. Applying this filter reduced the number of cases from 1975 to 17. This pointed to a strong correlation between spin-up motor settings and as-seen flight trajectory.

Identification of Top Potential Contributors

Each set of analyses described above helped isolate the top contributors from over 340 input parameters varied in the LDSD SFDT-1 POST2 Monte Carlo analysis. The Monte Carlo inputs that were found to be the top contributors were:

- STAR-48 properties: thrust variation, burn time, and thrust vector pointing
- Atmosphere model dispersions: Earth GRAM or SFDT-1 reconstructed atmosphere
- Spin-up motor properties: thrust variation, burn time, thrust vector pointing
- Specific aerodynamic parameters during powered flight
  - C_A multiplier
  - C_m multiplier in transonic and supersonic phases
  - C_n multiplier in transonic and supersonic phases

Aerodynamic adders and multipliers are used in the trajectory simulations to model aerodynamic uncertainties. In the root-cause search, the multipliers as opposed to the adders were seen to have the largest correlations and sensitivities with the metrics of interest. Additionally, it should be noted that for SFDT-1, the sensors on-board did not include a chamber pressure sensor; thus, the effect of STAR-48 thrust cannot be distinguished from the effect of powered-phase axial force coefficient (C_A) since the sensed accelerations from the IMU capture the effect of both thrust and aerodynamics.

In the simulation, the pitching moment (C_m) and yawing moment (C_n) multipliers are independently varied. However, during the root-cause search, a relationship between the C_m and C_n multipliers was identified. Figure 6 shows the trend and bias in the C_m and C_n multipliers in the transonic regime of powered flight when the filtering approach was applied to the data set using two different ways. Fliter 1 was based on selectivity criteria comparing the flight performance of Monte Carlo cases and reconstructed trajectory at snapshots in time (such as at STAR-48 burnout), while filter 2 compared restricted cases based on the integrated errors between reconstructed and Monte

Carlo cases' trajectories. Note that in the plot a value of 1 indicates that the multiplier must be at its 3σ level of uncertainty. The figure shows that in order to match flight conditions, both C_m and C_n multipliers need to be most likely negative.

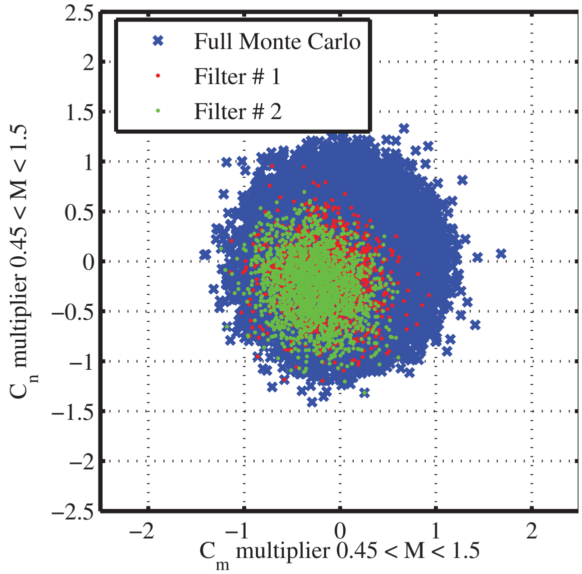


Figure 6. Bias in transonic powered phase pitching and yawing moment coefficient multipliers of Monte Carlo cases matching flight conditions.

RECONCILIATION OF THE SIMULATION WITH FLIGHT RECONSTRUCTION

With a short list of top potential contributors to the off-nominal flight, the pre-flight POST2 simulation was modified with updates to better match the day-of-flight trajectory. Some of the changes were immediately evident, such as matching the day-of-flight initial conditions, while other modifications were made based on data from the root-cause search and other independent, subsystem-level reconstructions. At this phase of the analysis, the goal was 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 LDSD flights.

As mentioned earlier, the first change to the simulation was to match the reconstructed trajectory's initial conditions. The pre-flight POST2 simulation was initialized at a representative latitude and longitude, the altitude was based on a prescribed atmospheric pressure level where the balloon was to deliver the vehicle, and the velocity was based on the horizontal winds at that altitude. For the post-flight simulation modifications, the reconstructed trajectory provided the vector position, velocity, attitude, and attitude rates.[7] Additionally, the generalized Earth GRAM atmosphere was replaced with the reconstructed atmosphere for the flight.[2,7] Both of these changes increased the maximum altitude by 2 km from the pre-flight nominal but had negligible changes in other states, such as flight path angle or attitude.

The STAR-48 thrust, which was on the list of potential top contributors, was reconstructed from the vehicle sensed acceleration.[2] Although not separable from axial force coefficient due to the flight data available, the thrust profile can be estimated with assumptions about the aerodynamics.

Reference 2 provides a comparison of the pre-flight and reconstructed thrust profiles that show the SFDT-1 motor produced higher than expected thrust near the beginning of the burn and then produced lower than expected thrust near the end of the burn. Thus, although the total impulse and burn time were close to nominal, the vehicle experienced a larger-than-expected axial force during the early subsonic and transonic phase of powered flight. Previous OVAT analyses had shown that the vehicle's altitude profile was especially sensitive in the early phase of flight, so a larger axial force during this phase would be expected to increase the maximum altitude. Implementing the reconstructed STAR-48 thrust profile increased the maximum altitude by 3.3 km.

As alluded to before, spin-up motor modeling was strongly correlated with the reconstructed flight-conditions. The correlation was especially strong for maximum altitude, since the spin-up motor model oriented the attitude and attitude rate of the vehicle before the STAR-48 burn. However, reconstruction of the impulse and pointing vectors of the spin-up motor from flight data is complicated due to the spin motor plumes impinging on and interacting with the test vehicle surface as seen in Figure 7. The spin motor interaction in the low dynamic pressure environment prior to the powered phase is costly to model with computational fluid dynamics (CFD), even for the steady-state methodology employed in these analyses.[6] The spin motor interaction is currently thought as one of the explanations for the lower than predicted post spin-up roll rate (Figure 2(a)). However, despite the strong correlation of the spin-motor modeling with the altitude profile, setting the attitude and rates at the start of STAR-48 with reconstructed values - something that a perfect spin motor modeling reconstruction would attempt to recreate - produces only 0.5 km increase in maximum altitude.

Figure 7. Image from cameras on-board SFDT-1 showing spin motor plume interacting with test vehicle surface.

Shortly after SFDT-1, the aerodatabase was modified to update subsonic powered phase aerodynamics with CFD results rather than placeholders taken from the aerodatabase of another vehicle.[6] This update was not based on any post-flight analysis and, as such, was independent of the work presented in this paper. Since this was an update from the aerosciences team, the POST2 simulation was modified. The new aerodatabase, however, did decrease the maximum altitude by about 0.9 km without affecting other states too greatly.

Even with the changes discussed so far that were all rationalized by independent reconstruction of the flight data or independent model updates, the maximum altitude predicted by the simulation was about 3.6 km lower than reconstructed conditions. The remaining parameters from the list of top contributors were the C_m and C_n multipliers during the transonic and supersonic powered phases. Through sensitivity analysis it was found that although the supersonic C_m and C_n multipliers may be correlated with flight conditions, they have much smaller effect on maximum altitude than their transonic counterparts. Thus, when C_m and C_n multipliers for the transonic powered phase were modified to levels that were at -2.7σ of the pre-flight uncertainties, there was a close match in the altitude histories predicted from the flight and reconstructed trajectory. The final set of conditions that were deemed most likely and their effect on one of the metrics of interest - maximum altitude - is summarized in Table 1.

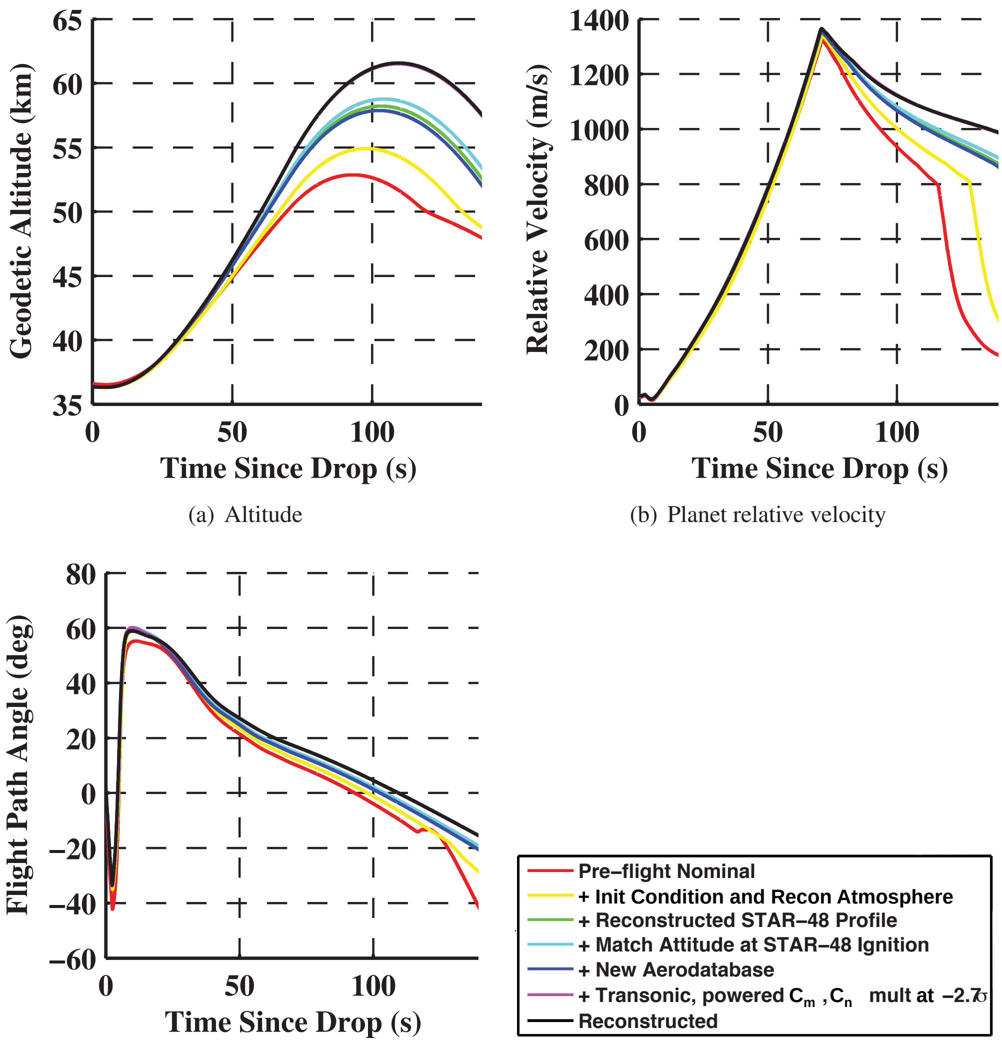
Table 1. Build-up of the maximum altitude prediction from the simulation to match flight reconstruction.

Settings	Max. Altitude (km)	Difference (km)
Reconstructed trajectory	61.57	–
Pre-flight prediction	52.863	-8.707
Initial conditions and reconstructed atmosphere	54.912	+2.049
Reconstructed STAR-48 thrust	58.215	+3.303
Matching observed attitude and rates at STAR-48 ignition	58.766	+0.551
SFDT-1 aerodatabase update	57.872	-0.894
C_m and C_n multipliers for 0.45 < M < 1.5 at -2.7σ	61.514	+3.642

Figures 8- 9 show the build-up of several trajectory parameters from the flight simulation and compares them with the reconstructed values. In Figure 8(a), one can see that as the maximum altitude is reconciled, the time line of the trajectory also matches better. As discussed before, only when the C_m and C_n multipliers are modified does one see a close match in altitude; moreover, not surprisingly, the match in flight path angle also only occurs when the C_m and C_n multipliers are modified to their -2.7σ values. In Figure 8(b), it can be observed that once the reconstructed STAR-48 thrust profile is applied to the simulation, the simulation's velocity predictions are in-line with the reconstructed trajectory through the powered phase of the flight (2 s to 72 s). This again is also not surprising since the reconstructed thrust profile is a surrogate for the axial acceleration history, which is the dominant acceleration component.

Since modeling of the SFDT-1 was multi-modal, there were several potential combinations of environmental and modeling conditions that could lead to similar outputs. Hence, there was great reticence on the part of the analysts during the root-cause and reconciliation process to avoid chasing contributors that improved one metric at the cost of others. For example, besides C_m and C_n multipliers, a radial center-of-gravity (CG) bias could also produce similar altitude profiles. However, the CG bias needed in the simulation to match the reconstructed maximum altitude would also cause large oscillations in attitude histories that were not substantiated by the reconstructed trajectory. In fact, out of the several potential contributors considered, C_m and C_n multipliers were the only inputs that could reconcile both the altitude history and create a good match in the attitude history. In Figure 9(a), one can see that only when the C_m and C_n multipliers were modified does the simulation's pitch history match the reconstructed values during the powered phase.

The focus of the reconciliation work in this paper has been the powered phase of flight which ends around 72 s; hence, one can see separation near 70 s between the last simulation prediction in the build-up and the reconstructed values for some metrics of interest. Since the dominant force on the vehicle is largely aerodynamics after the powered phase, other aerodynamic reconstructions have provided explanations to show differences between pre-flight predictions and reconstructed values.[6] Some explanations include a small CG bias during the cruise and SIAD phases of flight to explain the non-zero trim sideslip angle as well as a stiffer than expected static stability. The reader is referred to References 7 and 6 for more explanation.

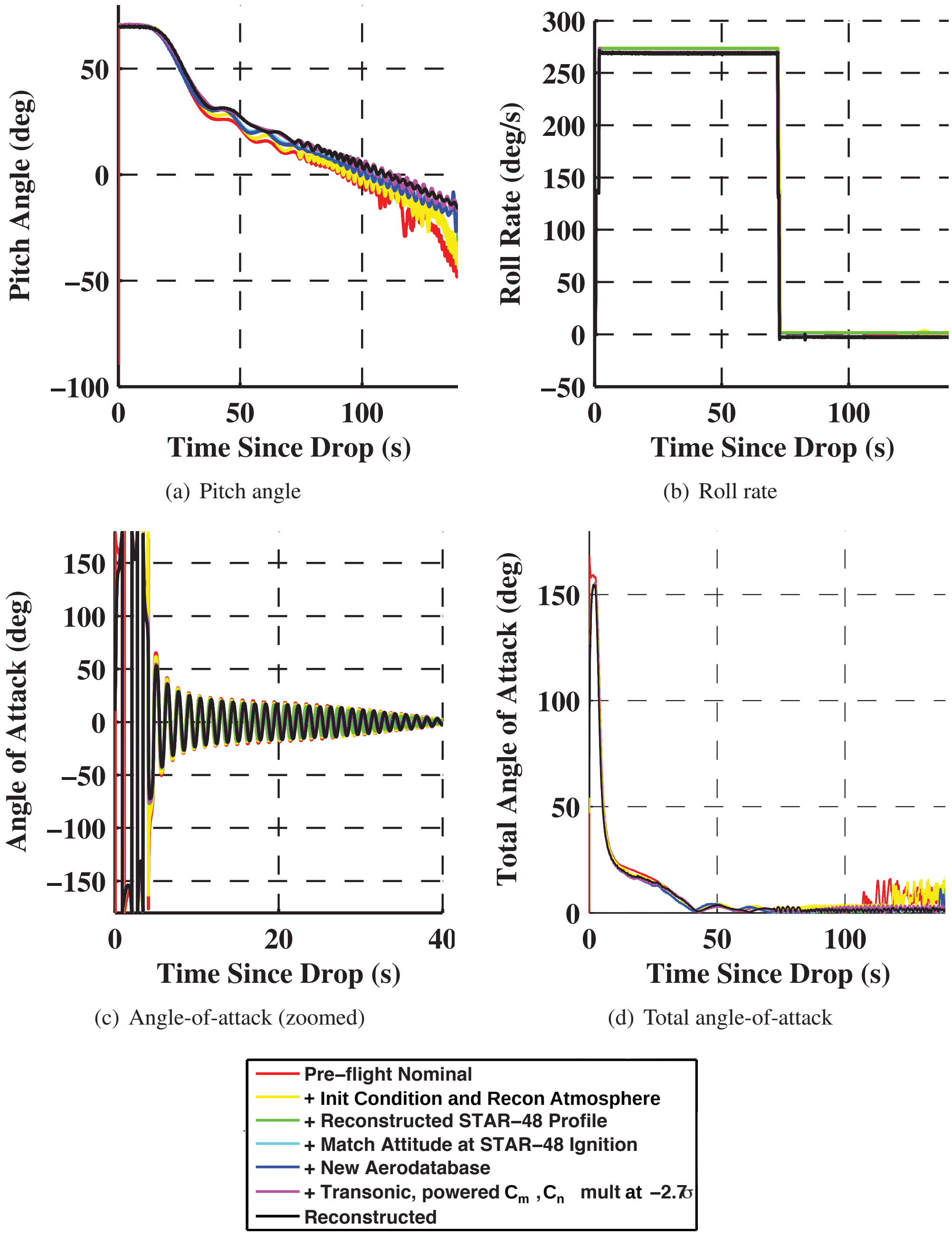


(a) Altitude

(b) Planet relative velocity

(c) Flight path angle

Figure 8. Comparison of altitude and velocity histories from SFDT-1 POST2 simulation build-up and trajectory reconstruction.



(a) Pitch angle (b) Roll rate

(c) Angle-of-attack (zoomed) (d) Total angle-of-attack

Figure 9. Comparison of attitude histories from SFDT-1 POST2 simulation build-up and trajectory reconstruction.

FUTURE FLIGHT MODELING

Current plans are to make small adjustments to the simulation models based on flight data reconstruction. These changes will, in time, affect analyses supporting the next test flights. Potential model changes that have been discussed include the aerodatabase powered phase C_m and C_n multipliers and modifications to the STAR-48 thrust profile. After each of the major model areas (aerodynamics, propulsion, mass properties, and key event initiation values) is evaluated by the appropriate engineer, team, or contractor, modifications to each data set or implementation logic will be made in the SFDT LDSD simulations. Correct implementation of the adjusted models in the simulations will be confirmed with the cognizant engineer for each one and these changes will be an integral part of the modeling effort for the upcoming flight tests.

CONCLUSIONS

The reconstruction of the SFDT-1 flight data showed some off-nominal behavior when compared with pre-flight LDSD trajectory predictions. The POST2-based simulation was modified during post-flight analysis to reconcile differences seen between the simulation and reconstructed values and also identify the top potential contributors to the off-nominal behavior. Implementing day-of-flight initial conditions and atmosphere or inserting reconstructed STAR-48 thrust and attitude before ignition still did not create a good match between the simulation and flight data. However, using root-cause search methods, such as OVATs, statistical correlations between Monte Carlo inputs and outputs that recreated flight conditions, and other filtering methods, certain aerodynamic modeling parameters were found to create good reconciliation between the simulation and flight data in position, velocity, and attitude histories. The work of the post-flight reconciliation analysis provided recommendations for potential model changes that can greatly improve the SFDT simulations and help the planning for future SFDT flight tests.

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NOTATION

C_A	Axial force coefficient
C_m	Pitching moment coefficient
C_n	Yawing moment coefficient
R	Correlation coefficient
p	Probability of null hypothesis
σ	Standard deviation
σ^2	Covariance

REFERENCES

[1] I. Clark, M. Adler, and T. Rivellini, "Development and Testing of a New Family of Supersonic Decelerators," AIAA 2013-1252, *AIAA Aerodynamics Decelerator Systems Conference,* Daytona Beach, FL, 2013.

[2] E. M. Blood, M. Ivanov, C. O'Farrell, J. Ginn, P. Kutty, C. Karlgaard, and S. Dutta, "LDSD Supersonic Flight Dynamics Test 1: Post-flight Reconstruction," *IEEE Aerospace Conference,* Big Sky, MT, 2015.

[3] M. Ivanov and B. Tibbets, "Low Density Supersonic Decelerator Flight Dynamics Test - 1 Flight Design and Targeting," *AIAA Aerodynamic Decelerator Systems Conference,* Daytona Beach, FL, 2015.

[4] A. Bowes, J. D. Davis, S. Dutta, S. Striepe, M. Ivanov, R. Powell, and J. P. White, "LDSD POST2 Simulation and SFDT-1 Pre-flight Launch Operations Analyses," AAS 15-232, *AAS/AIAA Space Flight Mechanics Conference,* Williamburg, VA, 2015.

[5] F. Leslie and C. Justus, "The NASA Marshall Space Flight Center Earth Global Reference Atmosphere Model - 2010 Version," tech. rep., NASA/TM-2011-216467, 2011.

[6] J. Van Norman, "Aerodynamic Models for the Low Density Supersonic Decelerator (LDSD) Supersonic Flight Dynamics Test (SFDT)," *AIAA Aerodynamics Decelerator Systems Conference,* Daytona Beach, FL, 2015.

[7] P. Kutty, C. Karlgaard, E. Blood, C. O'Farrell, J. Ginn, M. Schoenenberger, and S. Dutta, "Supersonic Flight Dynamics Test One: Trajectory, Atmosphere, and Aerodynamics Reconstruction," AAS 15-224, *AAS/AIAA Space Flight Mechanics Conference,* Williamburg, VA, 2015.