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LDSD POST2 SIMULATION AND SFDT-1 PRE-FLIGHT LAUNCH OPERATIONS ANALYSES

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The Low-Density Supersonic Decelerator (LDSD) Project's first Supersonic Flight Dynamics Test (SFDT-1) occurred June 28, 2014. Program to Optimize Simulated Trajectories II (POST2) was utilized to develop trajectory simulations characterizing all SFDT-1 flight phases from drop to splashdown. These POST2 simulations were used to validate the targeting parameters developed for SFDT-1, predict performance and understand the sensitivity of the vehicle and nominal mission designs, and to support flight test operations with trajectory performance and splashdown location predictions for vehicle recovery. This paper provides an overview of the POST2 simulations developed for LDSD and presents the POST2 simulation flight dynamics support during the SFDT-1 launch, operations, and recovery.

INTRODUCTION

NASA's Low-Density Supersonic Decelerator (LDSD) Project is a Technology Demonstration Mission led by NASA's Jet Propulsion Laboratory (JPL). It includes a series of full-scale ground tests and balloon-dropped stratospheric Supersonic Flight Dynamics Tests (SFDT) to advance decelerator Technology Readiness Level (TRL) for use in safely landing heavier spacecraft and increasing landing site accessibility at Mars.[1,2,3] The first SFDT (SFDT-1) successfully flew on June 28, 2014 from the Pacific Missile Range Facility (PMRF) in Kauai, Hawaii with a 6 meter torus Supersonic Inflatable Aerodynamic Decelerator (SIAD) and a 30.5 meter Supersonic Disksail (SSDS) parachute. All test objectives were met; however, the parachute behavior was off-nominal.[4]

The nominal SFDT mission is designed to achieve a set of in-flight conditions for the SIAD deployment (Mach 3.8 and 17 km Mars Equivalent altitude for SFDT-1) and parachute line stretch (Mach 2.5 for SFDT-1).[5] The mission profile begins with the test vehicle attached below a high altitude balloon (i.e. “hung”) which is launched and floats up to ~120,000 feet above the Earth’s

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surface where the test vehicle is released from the balloon. Once dropped, the vehicle is spun up to provide roll stability, and a STAR-48 motor accelerates the test vehicle to the required speed to achieve the desired in-flight conditions for SIAD deployment. The vehicle de-spins prior to SIAD deployment. The SIAD flight marks the beginning of the "test phase" of the SFDT and serves to decelerate the vehicle further to achieve the desired conditions for the SSDS parachute. The parachute is deployed using a ballute (i.e. Parachute Deployment Device or PDD), and the vehicle is designed to stay under the parachute until splashdown into the Pacific Ocean. Figure 1 provides an illustration of the nominal SFDT trajectory mission sequence.

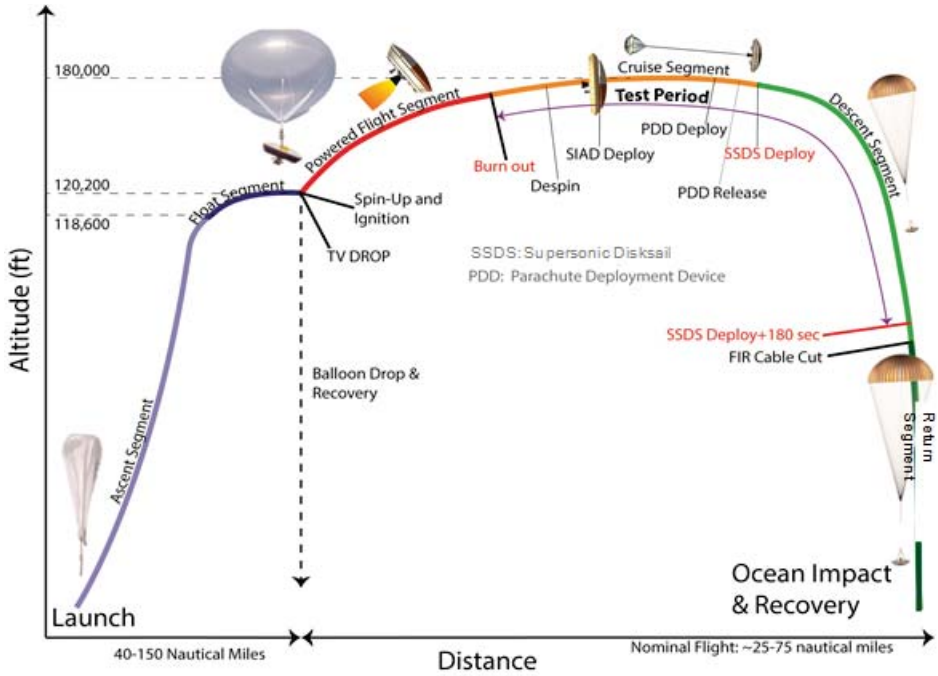

Figure 1: LDSD Nominal SFDT Mission Events Sequence[1]

Independent Program to Optimize Simulated Trajectories II (POST2)[6] six-degree-of-freedom (6DOF) and multi-body 6DOF trajectory simulations characterizing all SFDT flight phases were developed at NASA's Langley Research Center (LaRC). The LaRC POST2 simulations are part of a simulation suite employed by the LDSD Project for various flight dynamics analyses and in support of the LDSD Project's SFDT-1. This paper describes the POST2 LDSD simulations and presents an overview of their role in LDSD flight dynamics analyses. Additionally, the POST2 simulation support provided during SFDT-1 launch and operations is described.

POST2 SIMULATION OVERVIEW

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. It is used for mission, vehicle, and system development support and evaluation, engineering trade studies, flight dynamics analyses, and mission flight operations.[7,8,9] Both the 6DOF and multi-body POST2 LDSD simulations begin with initialization of the vehicle state at balloon drop and model all trajectory events of the vehicle flight to splashdown in the Pacific Ocean: spin-up; STAR-48 ignition, burn, and tail-off/burnout; de-spin; SIAD deploy

and cruise; PDD deploy and release; and SSDS deploy and float. The multi-body simulation is identical to the 6DOF simulation until PDD deployment, at which point it leverages POST2's multi-vehicle capabilities to model the PDD pack, PDD, SSDS parachute bag, and SSDS parachute as separate 6DOF bodies from the LDSD test vehicle (coupled through flexible lines where appropriate) in order to gain increased modeling fidelity of the dynamics of each of the decelerator systems.

The end-to-end LDSD POST2 simulations incorporate the latest engineering models of the LDSD vehicle and environment that were provided by many different groups. The STAR-48 burn profile was originally provided by Alliant Techsystems Inc. (ATK) to the propulsion group at JPL. The LDSD project-defined vehicle configuration, mass properties, uncertainties, spin motor propulsion characteristics, PDD, and SSDS parachute models were also provided by JPL.[10] The vehicle aerodynamics model containing aerodynamic coefficients and uncertainties for all SFDT vehicle configurations and flight regimes (drop/free-fall, powered flight, cruise, SIAD flight, PDD, SSDS) was provided by LaRC with data input from Ames Research Center (ARC) and Marshall Space Flight Center (MSFC).[11] The PDD and the SSDS each possess detailed aerodynamic models (produced by LaRC and JPL, respectively) which are used in the multi-body simulation. Physical balloon properties and release/separation characteristics were provided by the Columbia Scientific Balloon Facility (CSBF). Gravity is modeled using J2 and J3 coefficients from the latest GRACE Gravity Model (GGM03C)[12]. The most recent global engineering model of the Earth's atmosphere, Earth Global Reference Atmospheric Model (Earth-GRAM 2010[13]), was used for atmosphere modeling during all pre-flight analyses. The Range Reference Atmosphere options inside Earth-GRAM 2010 were utilized. Global Forecast System (GFS)[*] data from Lihue, HI was incorporated in lieu of Earth-GRAM 2010 during SFDT-1 launch and operations. Additionally, the simulations include a flight software in-the-loop model provided by Wallops Flight Facility and JPL which was used to establish the timing triggers of the various flight phases in SFDT-1. The POST2 simulations also include the use of markers attached to the vehicle and, in the multi-body simulation, attached to the PDD and SSDS components as well. Markers provide the capability to solve the rigid body dynamics and give the state at any arbitrary point on the rigid body. In the LDSD simulations, the markers are used to model the location and gather information of components such as the Inertial Measurement Unit (IMU) or cameras attached to the vehicle. Each model underwent an extensive validation and verification process to ensure both that the model itself was an accurate representation of its intended use and that that the model was implemented and working as planned in the simulation. Figure 2 is a diagram showing the various models integrated into the POST2 LDSD simulations described above. Some of the simulation modeling is discussed in more detail next.

The vehicle state (latitude, longitude, altitude, velocity, azimuth, and flight path angle) at balloon drop is determined in the POST2 simulations by finding the altitude and wind conditions in Earth-GRAM corresponding to the balloon release density conditions provided by CSBF at the drop location. Because the balloon has been floating for some time, it is assumed to be in steady state with the wind. Thus, the vehicle planet relative-velocity and direction are initialized to be equal to the north-south and east-west components of the wind speed and direction, while the flight path angle is set to zero. Both simulations have the ability to determine the required vehicle attitude at drop by targeting the desired SIAD deployment conditions (altitude and Mach) and parachute line stretch conditions (Mach). The vehicle attitude is defined in terms of relative Euler angles (yaw, pitch, and roll) with respect to the vehicle local horizontal coordinate system (North-East-Down) at balloon drop. The resulting vehicle "hang angle" with respect to the local gravity vector can also be reported as shown in Figure 3.

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[*] http://www.emc.ncep.noaa.gov/index.php?branch=GFS

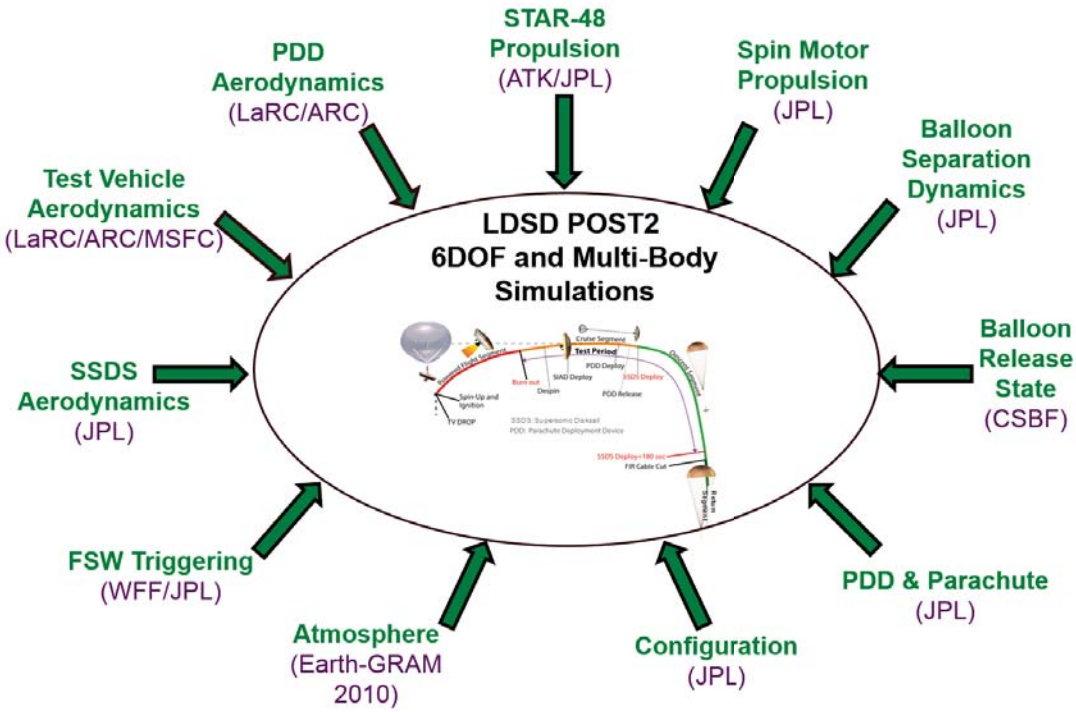

Figure 2: LDSD POST2 Simulation Modeling Overview

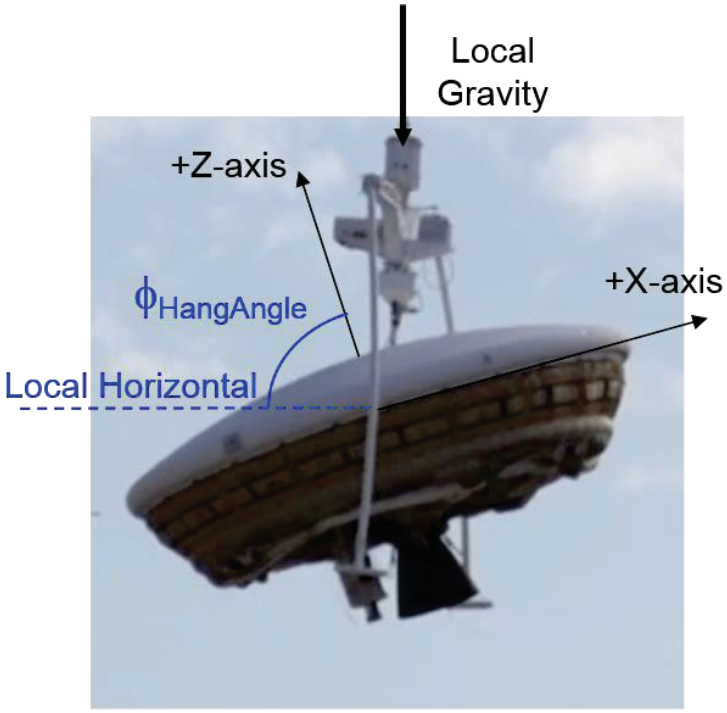

Figure 3: LDSD Vehicle "Hang Angle" Below Balloon

Spin-up begins in the POST2 simulations based on a timer relative to drop, and the spin motors thrust until all of the propellant is exhausted. STAR-48 ignition also begins based on a timer relative to drop, and the engine is considered in tail-off/burnout mode once the sensed longitudinal acceleration of the test vehicle is less than zero. The vehicle spin-down is initiated based on a timer relative to sensed STAR-48 shutdown and, once again, the motors thrust until all propellant is consumed. SIAD deployment is triggered using either a velocity criteria or no-later-than timer relative to the sensed STAR-48 shutdown. The SIAD flight is modeled using the aerodynamic coefficients from the SIAD flight regime in the aerodynamics model and by updating the test vehicle properties to reflect the vehicle configuration with a fully inflated SIAD. Finally, the PDD is also triggered using either a velocity criteria or no-later-than timer. The PDD is mortar-fired, so it is modeled in the POST2 simulations as an engine firing on the test vehicle in order to properly capture the reaction force imparted to the test vehicle. During the time from PDD mortar fire until PDD line stretch, the force from the PDD is modeled as zero since the line is not taut enough to transfer the force from the PDD to the test vehicle.

In the 6DOF simulation, once the PDD reaches full line stretch, it is modeled as a drag-only device with the force applied to the test vehicle at the triple bridle confluence point holding the PDD to the test vehicle. The drag force is determined by aerodynamic coefficients specific to the PDD (as found in Reference 10) and is assumed to act in line with the test vehicle relative velocity vector. Initially, an inflation model is used based on a predefined (input) rate of inflation.

In the multi-body simulation, a separate vehicle is modeled once the PDD mortar is fired. The characteristics of the un-deployed PDD pack (i.e., mass) are related to this new PDD vehicle. At mortar firing, a thrust is imparted to the PDD pack along with an equal, but opposite, force on the test vehicle. As the PDD separates from the test vehicle, no drag is assumed to act on the PDD pack. The distance between the two is tracked so that once that distance equals the PDD line length, the inflation model is used to transition the PDD pack to the fully deployed PDD. Also at this time, connections between the PDD and the test vehicle, based on triple bridle characteristics, are activated to transfer forces between the two. During inflation and subsequent flight, the full 6DOF aerodynamics are used as specified in Reference 10; however, the forces are determined from the PDD flight characteristics (atmospheric relative velocity, attitude) and not that of the test vehicle. Figure 4 shows a snapshot of an animation made of the PDD trailing behind the test vehicle using the POST2 multi-body simulation output.

Figure 4: Visualization of PDD Trailing Behind LDSD Test Vehicle Based on POST2 Multi-Body Simulation Output

Similar modeling to that for the PDD is used for the parachute, with the main difference being in the characteristic data (mass, aerodynamics, etc.) and the method of deployment. Both the 6DOF and multi-body POST2 simulations use the PDD to extract the parachute pack and begin the parachute deployment process based on a pre-defined time from the PDD trigger. Also, in both simulations, the PDD and parachute pack masses are removed from dynamics computations for the test vehicle. The 6DOF simulation temporarily creates a second vehicle at parachute extraction comprised of the PDD and parachute pack. The PDD drag-only aerodynamics are now based on the velocity of this new vehicle rather than the test vehicle. Also, this PDD and parachute pack combination begin moving away from the test vehicle immediately. However, the multi-body simulation includes a flexible joint model in POST2 to simulate the friction force between the parachute bag (modeled as a new vehicle) and its containing canister on the test vehicle. This model allows the effect of the bag scraping or binding in the canister during extraction to be included while constraining the motion to be along the axis of the housing; thus, the effects on parachute deployment time can be evaluated. The LDSD Project ran tests to determine the friction force as a function of pull angle and distance along the parachute canister, and this data was then used in the POST2 LDSD multi-body simulation.

After the parachute extraction, both simulations use the PDD flight dynamics to drive the motion of the parachute pack away from the test vehicle. Once the parachute bag reaches a predefined distance, the PDD is released. For the 6DOF simulation, the parachute is then re-integrated to the test vehicle and connected at the parachute confluence point, making a single vehicle again. As with the PDD, the parachute acts as a drag-only device based on the atmospheric velocity of the test vehicle with aerodynamic coefficients specific to the parachute as found in Reference 10. The inflation model to transition the drag from zero to the fully inflated value based on pre-defined parachute inflation rate is used.

For the multi-body simulation, the parachute becomes its own vehicle and (unless PDD tracking is desired) both the PDD and parachute pack are no longer actively modeled. As with the PDD, the parachute is attached to the test vehicle using the location and characteristics of the triple bridle to transfer the interacting forces between the parachute and test vehicle. Characteristics specific to the parachute (such as mass, 6DOF aerodynamic coefficients as found in Reference 10) are used for the flight dynamics of this new vehicle. Also, the parachute inflation is modeled using a predefined inflation velocity to adjust the aerodynamic coefficients from zero to the fully deployed parachute values.

Figures 5 and 6 show snapshots of an animation made of the canister and parachute during extraction and inflation using the POST2 multi-body simulation output. In the figures, the yellow cylinder highlighted by the red circle is the parachute bag canister being pulled from the test vehicle. Figures 5a-5c show the distance of the parachute bag from the test vehicle increasing with time. Figures 6a-6b show the parachute bag and parachute at the point where inflation begins and then again after full inflation. The test vehicle's oscillatory attitude during the extraction and inflation processes can be observed in these figures.

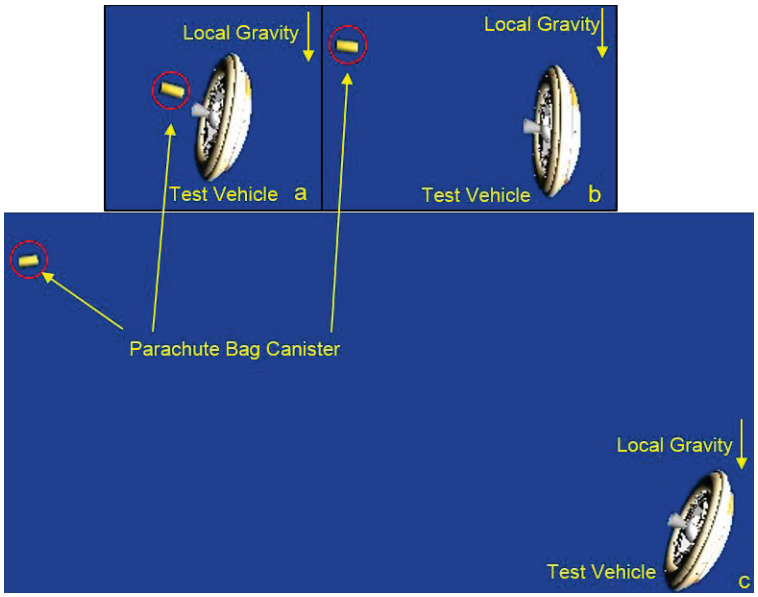

Figure 5: Visualization of Parachute Extraction Process Based on POST2 Multi-Body Simulation Output

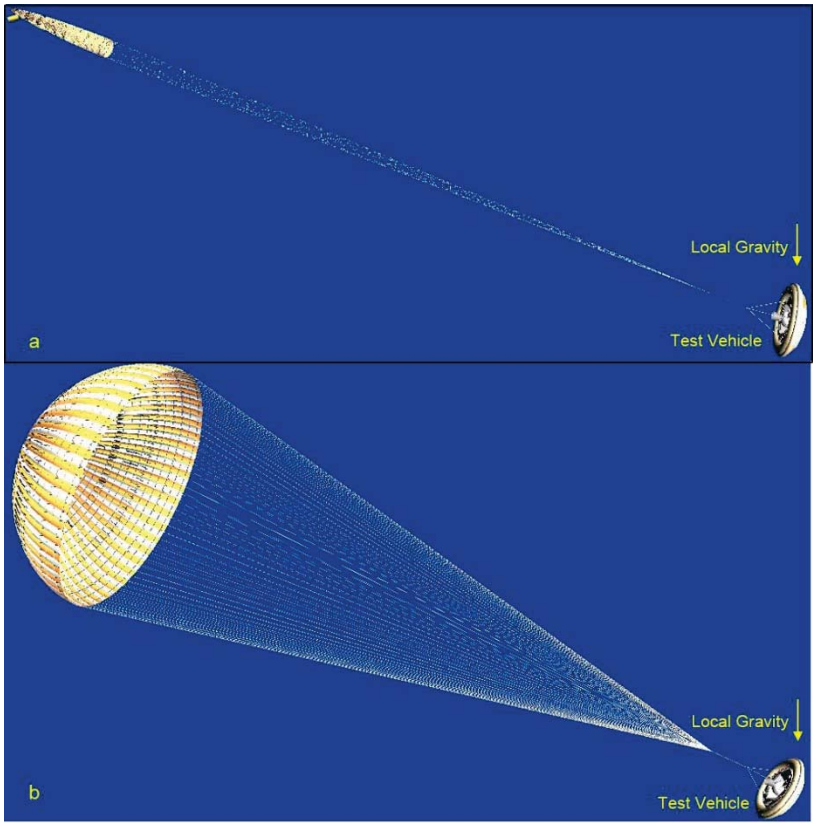

Figure 6: Visualization of Parachute Inflation Process Based on POST2 Multi-Body Simulation Output

The objectives of the simulation suite utilized in the LDSD Project include the following:

1. Establish the vehicle targeting and triggering parameters required to achieve the desired flight path characterization and nominal mission design for each flight test.
2. Predict performance and understand the sensitivity of the vehicle and nominal mission designs using Monte Carlo uncertainty analyses.
3. Assess compliance and margin to LDSD Project requirements.
4. Support flight test operations with trajectory performance and splashdown location predictions for range safety and vehicle recovery purposes.
5. Support SFDT reconstruction.

As part of the LDSD Project simulation suite, the 6DOF and multi-body POST2 LDSD simulations have been used to provide a variety of products to the LDSD project in addition to delivering analyses supporting the above objectives. The POST2 simulations provided analyses to confirm the target conditions (SIAD deploy and SSDS line stretch) chosen for SFDT-1 and were used to validate the final hang angle targeting and triggering used in SFDT-1. (A full discussion of the nominal mission design and targeting development can be found in Reference 5). The POST2 simulations were used to determine the effects of specific un-modeled but potentially real issues such as spin motor plume interactions, spin motor differential heating, and water/ice accumulation on the test vehicle during balloon flight. The POST2 simulations helped to advance the reconstruction infrastructure pre-flight by producing simulated output that included sensor model (such as IMU,GPS, and radar) data of stressing trajectories. This data was used to develop and test the reconstruction software. The multi-body simulation was used extensively to provide analyses supporting the camera orientations that were flown on SFDT-1 to capture specific parachute extraction events.[14] Sun-angle analyses were a part of these investigations and were subsequently used during SFDT-1 operations. Additionally, the multi-body simulation has also been utilized post-flight in comparison to the reconstructed trajectory of SFDT-1.[15] Studies were completed pre-flight to model and understand the effects on the splashdown footprint under both coning and gliding parachute dynamic behaviors. The POST2 simulations were also used to verify splashdown footprints of various spin-up motor out scenarios and to confirm the mitigation strategy of changing the timing between spin-up motor firings in order to fully meet range safety requirements. The details of some of these analyses can be found in the references cited above. The POST2 simulation support provided during SFDT-1 launch and operations is described next.

SFDT-1 LAUNCH AND OPERATIONS SUPPORT

The LDSD POST2 6DOF simulation (rather than the POST2 multi-body simulation) was used during SFDT-1 launch and operations in order to provide rapid turn-around Monte Carlo results. A few modifications were made to the pre-flight 6DOF simulation. As mentioned previously, the Earth-GRAM atmosphere was replaced with the latest available GFS atmosphere forecast data. Additionally, when available, the most recent prediction of the balloon drop latitude, longitude, altitude, and heading were incorporated to initialize the test vehicle state at drop. An option to fly without the PDD and parachute portions of the simulation was also incorporated in order to predict the splashdown location of the test vehicle without a parachute. Additionally, preparations were in place to use GPS position and velocity, sent via telemetry, as the initial state once the parachute was deployed to estimate the splashdown location.

The GFS atmosphere forecast data was included in the POST2 simulation as tabular data as a function of atmospheric pressure since the GFS forecast is given at set pressure levels. In the GFS forecast, a predicted altitude, temperature, wind speed, wind azimuth, and dew point temperature

are provided for each pressure level. Available pressure levels go up to ~ 48 km altitude; linear extrapolation was used to obtain atmosphere information for trajectory altitudes above the available GFS data. The wind speed and azimuth were converted to northerly and easterly components for use in the POST2 6DOF simulation. Vertical winds were assumed to be zero. Density was calculated from the GFS temperature and pressure using the Ideal Gas Law and the specific gas constant for dry air. The speed of sound was also computed using the GFS pressure levels and calculated density. Dew point temperature data provided in the GFS forecast was not necessary for the LDSD simulation purposes; hence it was discarded. Atmosphere uncertainty was constructed from GFS data across a 31 day period (i.e. monthly variation was used for the daily uncertainty; this will be updated to use daily uncertainty in future SFDTs) such that high and low values for altitude, temperature, east-west winds, and north-south winds at each pressure level were available. In Monte Carlo analysis, a random number was selected somewhere between the high and low values for each parameter; thus the shape of the original GFS forecast profile as a function of pressure was maintained with some uncertainty applied. The distribution is uniform (i.e. continuous or rectangular) in shape.

Figures 7, 8, and 9 show a comparison of the GFS forecast temperature, east-west, and north-south winds and upper/lower limits to Earth-GRAM +/- 3σ bounds for the launch attempt that was to take place on June 3, 2014. The green and cyan lines in these figures represent the maximum and minimum bounds used for the GFS uncertainty in Monte Carlo analyses, while the blue dotted line represents the actual GFS forecast profile for that day. In Figures 8 and 9, a positive value indicates winds towards the east or north directions, respectively, while a negative value indicates winds towards the west or south directions, respectively. Note that the nominal temperature profile and maximum/minimum limits lie outside the Earth-GRAM +/- 3σ bounds between ~10-20 km altitude. The maximum/minimum limits for both the east-west winds and north-south winds also lie outside the Earth-GRAM +/- 3σ bounds at select altitudes, although the original GFS forecast profile is within the Earth-GRAM uncertainty at all altitudes for the both east-west and north-south winds. The GFS forecast plus uncertainty for the east-west winds tends to be closer to the +3σ Earth-GRAM bound on that particular day, indicating that the test vehicle would likely be pushed in a more easterly direction when using the GFS atmosphere than would most Monte Carlo cases using the Earth-GRAM atmosphere. The GFS forecast plus uncertainty for the north-south winds tends to be closer to zero until below 20 km altitude where the winds become somewhat more southerly and closer to the -3σ Earth-GRAM bound, albeit still slight in magnitude.

Monte Carlo analyses consisting of 2000 dispersed trajectories (varying all vehicle properties, event timing, atmosphere, mass properties etc.) were initially run 24 hours prior to launch using the most recent GFS forecast and the original initialization of the vehicle state as described in the previous section. This Monte Carlo analysis was compared to the original pre-flight 6DOF simulation using Earth-GRAM to determine the effects of the predicted atmosphere on the trajectory. Figure 10 shows the variation in splashdown locations due to the incorporation of the 24 hour GFS forecast data described above into the simulation for the launch attempt that was to take place on June 3, 2014. The blue data points show the POST2-predicted splashdown locations assuming the Earth-GRAM atmosphere model and its built-in dispersions. The magenta data points show the POST2-predicted splashdown locations assuming the GFS forecast for June 3, 2014 plus the uncertainty described previously. These data points are plotted on top of each other, so some blue points lie underneath magenta points. The green and black "x" markers show the mean of each of the Earth-GRAM and GFS splashdown locations. Note how the GFS splashdown locations are grouped closer together than the Earth-GRAM splashdown locations. This was expected since the maximum/minimum bounds used in the GFS uncertainty are narrower than those in Earth-GRAM. The GFS splashdown location footprint is also somewhat elongated and shifted east of those using

Earth-GRAM, as was expected based on the data shown in Figure 8. The north-south latitude extent of the splashdown location footprints is quite close regardless of atmosphere used. A slight shift northward in the footprint using the GFS atmosphere is likely a reflection of the winds being mostly northerly above 20 km when using the GFS atmosphere, as seen in Figure 9.

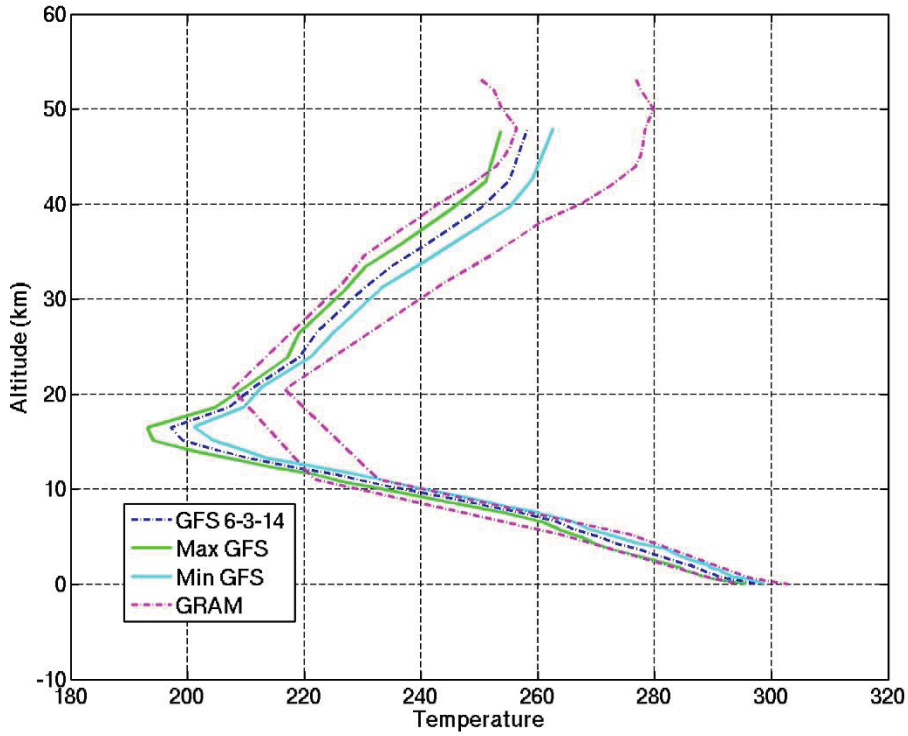

Figure 7: Comparison of GFS and Earth-GRAM Temperature Profiles

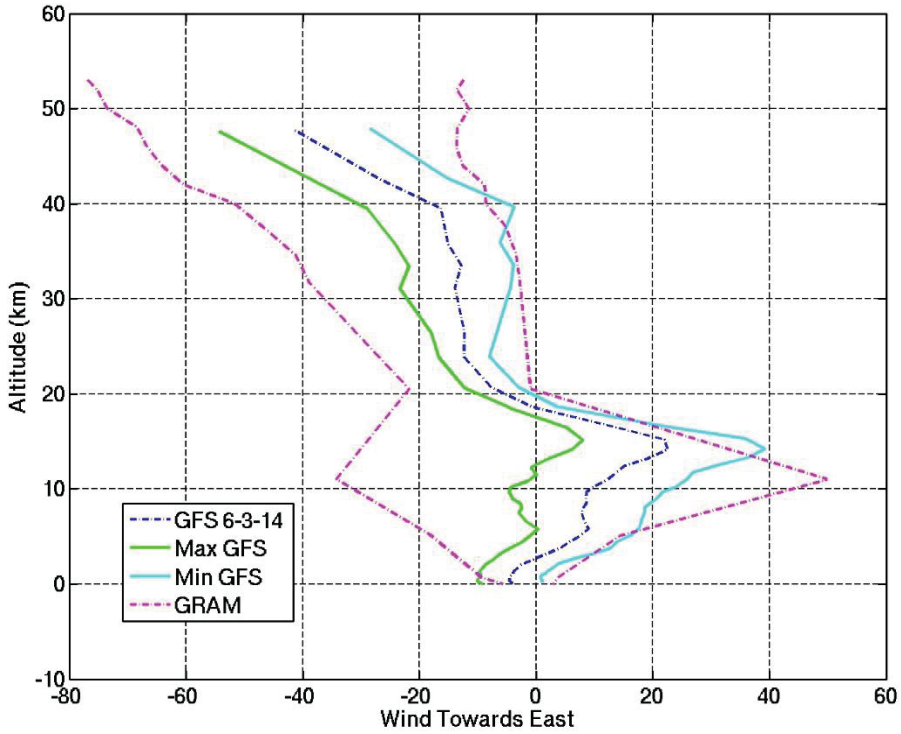

Figure 8: Comparison of GFS and Earth-GRAM East-West Wind Profiles

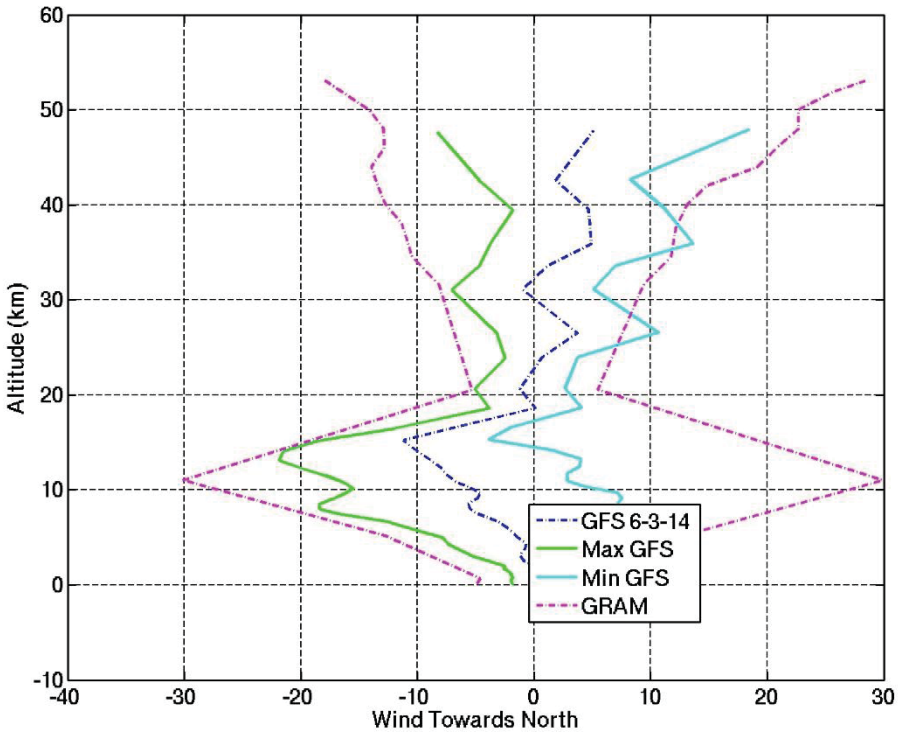

Figure 9: Comparison of GFS and Earth-GRAM North-South Wind Profiles

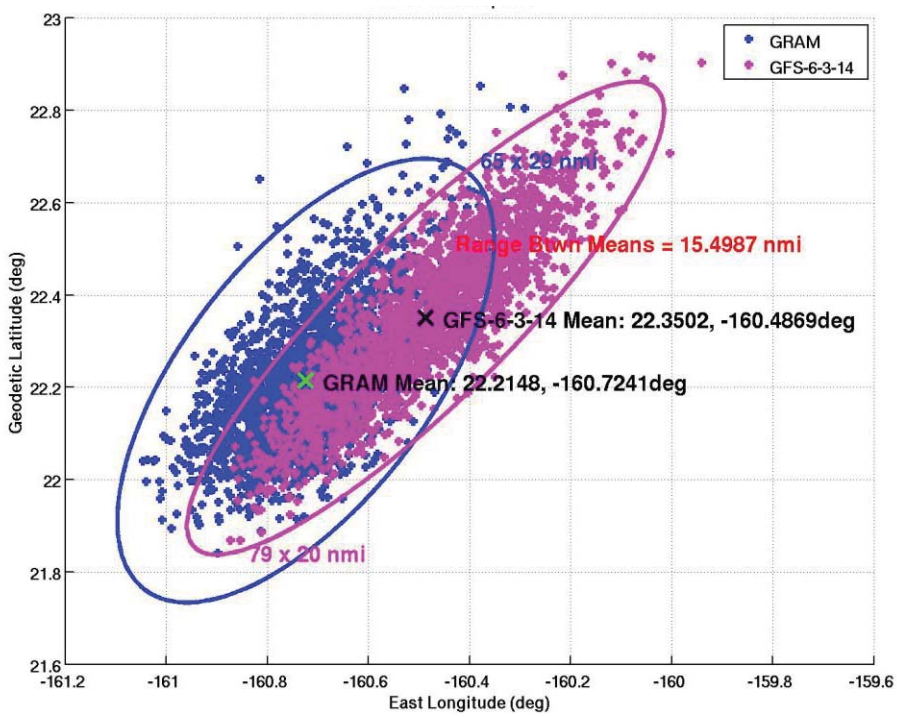

Figure 10: POST2 Splashdown Footprint Comparison of GFS and Earth-GRAM

The same Monte Carlo analysis was repeated when the 12 hour GFS forecast data became available for each launch opportunity, then at Launch minus 2 hours, and again post launch with the latest predicted balloon location information (at drop) incorporated each time. Monte Carlo analyses were run with and without the chute in order to inform the recovery assets where to go. Each of these 2000 case Monte Carlo analysis processes (from balloon/GPS state delivery to splashdown footprint and mean location determination) was streamlined and used multiple compute assets to ensure completion within 5 minutes (usually faster). The Monte Carlo runs using GPS state information were to begin shortly after full parachute inflation and continue as often as possible until a consistent mean splashdown location was determined. These runs were planned to provide the splashdown location estimate for recovery support. However, since the parachute did not deploy, this process was never executed.

Figure 11 shows the splashdown location analysis Monte Carlo results used during SFDT-1. The data used in this plot was based on the predicted drop location when the balloon and test vehicle were at an ascent altitude of 80,000 feet. This was the last predicted drop location prior to the flight test. The magenta data points show the POST2-predicted splashdown location assuming a working parachute system. The blue data points show the POST2-predicted splashdown location assuming a non-deployed parachute system. These data points are plotted on top of each other, so some blue points lie underneath magenta points. The yellow and cyan "x" markers show the mean of each of the no-parachute and working parachute system data points. The TSP (Test Support Position) location, or location transmitted to the recovery ships prior to drop, was then determined by picking a latitude and longitude location as close to the mean of the working parachute data points, and at the edge of the non-parachute data points. The objective was to give a predicted location as close to the best predicted mean under nominal Monte Carlo conditions while avoiding the footprint

under off-nominal parachute conditions (assuming no parachute system) as a safety measure. This TSP location (23.1 degrees latitude, -160.5 degrees longitude) was communicated to the recovery ships via satellite phone texts. The recovery ships successfully recovered the test vehicle at 23.398560 latitude, -160.152078 longitude[16], as well as the PDD and SSDS parachute based on the TSP location provided from the POST2 6DOF simulation Monte Carlo analyses and position information provided down to ~5 km altitude by the Flight Imagery Recorder (FIR) located on the test vehicle. This location was within both splashdown footprints depicted in Figure 11. A photograph from the recovery process is shown in Figure 12.

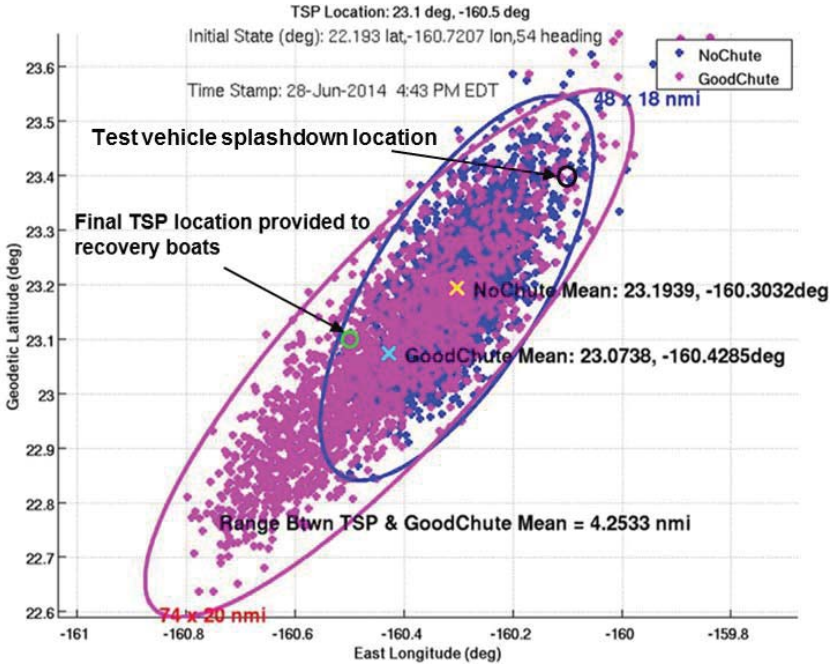

Figure 11: POST2 SFDT-1 Splashdown Location Footprints

Figure 12: Recovery Team with Test Vehicle

CONCLUSION

The POST2 6DOF and multi-body LDSD simulations are part of a simulation suite that provides detailed test vehicle simulation capability to the LDSD Project. These comprehensive simulations, which include multiple system models, have been used to provide analysis and pre-flight predictions to support various design decisions, high-fidelity parachute extraction modeling, and launch and splashdown recovery operations. Additionally, the POST2 multi-body simulation has been used as a baseline for SFDT-1 reconstruction work. An overview of the LDSD POST2 simulations has been described, as well as some of the POST2 support during SFDT-1 launch and operations. The simulation support provided for the LDSD Project, including the POST2 flight dynamics simulations, was an integral component of the successful design and delivery of the LDSD vehicle to the desired SFDT-1 test conditions.

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