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CONSTRUCTION OF SUPERSONIC FLIGHT DYNAMICS TEST (SFDT-2) VEHICLE MONTE CARLO SPLASHDOWN FOOTPRINTS FOR USE IN RANGE SAFETY AND RECOVERY OPERATIONS

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The Low-Density Supersonic Decelerator (LDSD) project performed the second test flight of a supersonic inflatable device (SIAD) and ring-sail parachute on June 8, 2015 splashing down in the Pacific Ocean west of Kauai. In order for recovery ships to quickly extract the test vehicle hardware from the ocean, and in the interest of safety to the population of the islands of Kauai and Nihau, statistical estimates of the splashdown location had to be performed. This paper describes the modeling assumptions used to generate the Monte Carlo splashdown trajectory simulation results and the use of the splashdown probability ellipses in support of satisfying range safety requirements.

INTRODUCTION

The Low-Density Supersonic Decelerator (LDSD) project performed the second test flight of a supersonic inflatable device (SIAD) and ring-sail parachute on June 8, 2015 over the Pacific Ocean west of Kauai. Delivered by a balloon launched from the Pacific Missile Range Facility (PMRF), the test vehicle (TV) was released at an altitude of approximately 36.5 km where it was spun-up with rocket motors for dynamic stability, then accelerated to an altitude of approximately 50 km at Mach 4 using a Star 48 rocket engine (Figure 1). After main engine burn out the vehicle was despun, followed by deployment of the SIAD at Mach 3.0, then subsequent deployment attempt of the ringsail parachute at Mach 2.35. The test completed with vehicle splashdown in the ocean approximately 50 nautical miles (nmi) downrange from the point of release where it awaited recovery. Statistical estimates of the splashdown location were necessary to meet three requirements: to aid recovery ships in the safe and rapid extraction of the TV hardware from the ocean, to meet range safety requirements in the interest of safety to the population of the islands of Kauai and Nihau, and to ensure the TV could not splashdown anywhere in the region of the Papahanaumokuakea Marine National Monument located 80 nautical miles to the northwest of Kauai.

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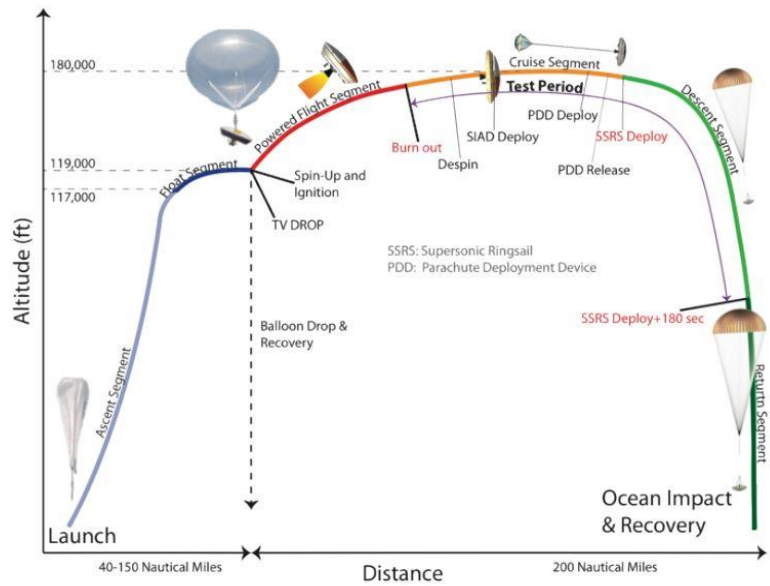

Figure 1. SFDT Flight Profile[1].

Statistical predictions of the TV trajectory and splashdown location had to account for all combinations of nominal and off-nominal flight test scenarios such as control thruster spin-up motor failure, inflatable deployment failure, and TV release from the balloon at an altitude higher or lower than the desired release altitude of 36.5 km. Monte Carlo simulations were performed which included the statistical uncertainties in aerodynamics, attitude, mass properties, and atmosphere that disperse the predicted trajectory of the TV. The dimensions of the probability ellipses for the Monte Carlo splashdown footprints of the vehicle were computed for every combination of nominal and off-nominal flight scenarios. The resulting 3-σ Gaussian ellipses were used to create boundaries around all probable splashdown footprints, which then provided a tool for predicting the total area of the TV splashdown during flight operations.

JPL FLIGHT SIMULATION TOOLKIT- DSENDS

The flight dynamics simulation used to perform the Monte Carlo simulations in support of the range safety work was DSENDS[2], developed at JPL. DSENDS has the capability to model both three degrees of freedom (3-DOF) and six degrees of freedom (6-DOF) dynamic equations of motion for computing the trajectory of the TV. The range safety simulation was modeled using 6-DOF from the time of TV release up through the time of parachute full inflation. Between the time of parachute inflation and splashdown the simulation was modeled using 3-DOF.

DSENDS has the capability of interfacing with third party codes for use with the core dynamics engine. For the LDSD application, the atmospheric model used EarthGRAM Fortran code and for the aerodynamics model NASA Langley Research Center (LaRC) developed aerodynamic database[3] Fortran code was used. DSENDS allows interfacing to the core dynamics with user developed Python modules to simulate external force and torque application. The force models for the Star 48 engine, spin-up/spin-down thrusters, and inflatable devices were all user developed Python modules. The results of the LDSD flight dynamics simulation were validated through comparison of results to the LaRC POST2 flight dynamics simulation.

DESCRIPTION OF MONTE CARLO SIMULATIONS PERFORMED

Table 1 is a summary of all the Monte Carlo cases that were performed in support of range and recovery operations. There were seven different TV release altitudes simulated ranging from 20 km to 38 km to account for the variation at which the balloon reached its float altitude even under anomalous conditions. During operations, the TV heading was selected to direct the trajectory to splashdown between the Marine Monument and the boundaries of PMRF subject to the range safety requirements. In order to cover the widest range of possible headings, four different headings from 56 to 240 degrees were selected for all seven of the TV altitudes. During spin-up of the TV, operational failure of any single or combination of the four spin-up control thrusters could cause the vehicle to veer off the nominal trajectory. There were a total of 14 different combinations of thruster failures and each one of these scenarios was modeled for every TV release altitude and heading. Lastly, it was possible to have a failure to deploy the SIAD or parachute causing the vehicle to travel further down range. Even if a successful deployment was assumed, several different aerodynamic drag configurations were also modeled to account for a partial parachute, tumbling/trimming SIAD, and tumbling/trimming capsule simulated for all of the TV release altitudes and headings. There were a total of 1372 Monte Carlos performed to account for all of the various scenarios shown in the table for the Supersonic Flight Dynamics Test 2 (SFDT-2).

Table 1. Monte Carlo Scenario Permutations Used to Construct Range Safety Splashdown Footprints

Monte Carlo Scenario Permutations Used to Construct SFDT-2 Range Safety Splashdown Footprints							
Flight Test Configuration Variant	Simulation Input Value/Configuration						
Altitude at TV Release (km)	20	25	30	32	34	36.5	38
Heading at TV Release (deg)	56*	90	120	240			
Deployment Conditions (Zero Spin-Up Motors Out)	Full Parachute and SIAD Deploy*	Partial Parachute Deploy (Streamer)	No Parachute Deploy (Trimming SIAD)	No Parachute Deploy (Tumbling SIAD)	No SIAD Deploy	No Deploy (Trimming Capsule)	No Deploy (Tumbling Capsule)
Spin-Up Motor Out (14 Combinations)	Single Motor Out (4 combinations)	Two Motors Out (6 combinations)	Three Motors Out (4 combinations)				
Deployment Conditions (For Spin-Up Motor Out Cases)	Full Parachute and SIAD Deploy	Partial Parachute Deploy (Streamer)	No Parachute Deploy (Trimming SIAD)				

*Nominal test flight configuration with zero spin-up motors out and full deployment of inflatables

Spin-up Motor Off-Nominal Test Scenario

Of particular interest were the off-nominal flight scenarios that would result from a failure to ignite any of the spin-up motors. There are four spin-up and four spin-down motors mounted along the radial axis of the vehicle as shown in Figure 2. The thrust vectors are directed tangentially in the x-y plane to provide rotational acceleration to spin-up/spin-down the vehicle. There is also a z-component of thrust due to canting of the motors to avoid plume impingement on the vehicle. Under nominal operation, the spin-up motors are fired as pairs beginning with the first pair (#1 and #3) firing 0.36 sec after TV release, and the second pair (#2 and #4) firing 1.3 sec after the first pair. The spin-up motors ultimately provide a rotational acceleration about the +z axis such that

after completion of the Star 48 main engine burn the final body rate is 300 deg/s. In the event that any of the spin-up motors fail to ignite, the final spin rate would be less than 300 deg/s. Less spin rate resulted in less angular momentum during the powered phase allowing the aerodynamic torque to more easily pitch the vehicle downward instead of downrange. Therefore, the spin-up motor out cases were predicted to splashdown closer to the TV release location than with nominal spin-up. In addition, a spin-up motor failure would result in an asymmetric rotational acceleration, causing the vehicle to have exaggerated spinning motion with large precession and nutation as well as a large flight path azimuth error. Some spin-up motor out combinations with large asymmetric accelerations were predicted to rotate the flight path azimuth of the vehicle such that the azimuth at splashdown was +/- 35 degrees from nominal. As will be shown later, there were motor out combinations that resulted in flight path azimuths directed toward Kauai and the Marine National Monument.

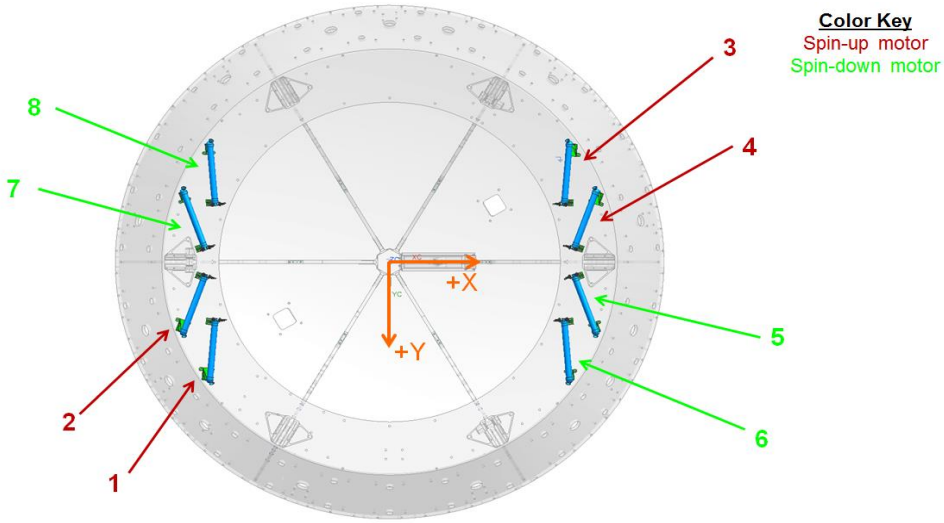

Figure 2. SDFT Vehicle Spin-up and Spin-down Motor Locations.

Off-Nominal Inflatable Deployment Scenarios

Prediction of the vehicle splashdown footprint in the case of off-nominal deployment of the inflatables was important for range safety considerations due to variations in aerodynamic drag on the capsule in the different scenarios. In the event of no deployment of the parachute or SIAD the vehicle was predicted to travel farthest downrange due to the drag reduction in the absence of inflatables. Due to the lack of ballistic range data below Mach 2.0, it was not possible to predict with certainty whether the vehicle would tumble or trim at a known attitude for low Mach. Because the lowest drag configuration was in tumbling, this mode had to be considered below Mach 2.0 as it resulted in the longest downrange trajectory of all scenarios. The highest drag mode with no deployments was with the vehicle trimming at an angle of attack of zero degrees and was simulated because it was the expected trim condition prior to Mach 2.0. Both tumbling and trimming configurations were also simulated for the scenario where the SIAD was successfully deployed but with no deployment of the parachute. In addition to the modeling of full parachute deployment and no parachute deployment, a third configuration called 'streamer' was used to model the intermediate drag condition of partial deployment.

Release Altitude and Heading Scenarios

Due to the variability in atmospheric conditions, the position at TV release could vary considerably. In addition, the atmospheric density on the day of launch affects the time that it takes for the balloon to reach its float altitude. Although the nominal float altitude at TV release was expected to be approximately 36.5 km, for range safety purposes it was necessary to take into account the possibility the balloon was not going to reach its float altitude before releasing the vehicle. Therefore, lower altitudes had to be considered when calculating splashdown footprints. Similarly, over-performance of the balloon was a possibility resulting in TV release altitudes higher than 36.5 km. In order to minimize the number of Monte Carlo cases performed, it was requested by PMRF to simulate TV release altitudes in increments of 2 km between 30 and 38 km, and increments of 5 km between 20 and 30 km.

The variation in winds on the day of launch affect the location of TV release in relation to the PMRF test range boundaries. The variability in the balloon climb-out trajectory to float altitude is shown in Figure 3 that resulted from simulating measured daily wind profiles gathered at PMRF during the month of June from 2007-2009. In order to safely launch the TV within the PMRF test range boundaries, a heading at test vehicle release must be selected such that the splashdown footprint does not cross the range safety boundaries or the Marine National Monument. The range of possible headings expected during flight operations in order to satisfy range and/or camera sun angle requirements was 60 to 170 deg, and 270 to 350 deg.

The direction of the prevailing winds combined with the TV heading at release required some consideration. The direction of the prevailing winds from the PMRF launch site was westerly, with an equal dispersion in the northern and southerly direction. The direction of the TV heading relative to the prevailing wind direction affects the azimuth of the splashdown footprint such that headings in the direction of the wind will travel further downrange while on the parachute. Test vehicle headings that are at an angle offset relative to the prevailing winds will have a splashdown footprint with a larger cross-range component. Because the size of the splashdown footprint could vary as much as 12% depending on the selected TV heading, this effect was deemed significant enough to warrant simulating Monte Carlos with various test vehicle headings. In order to cover the widest range of expected TV headings while minimizing the amount of computer processing time, four headings were selected at 56 deg (nominal), 90 deg, 120 deg, and 240 deg.

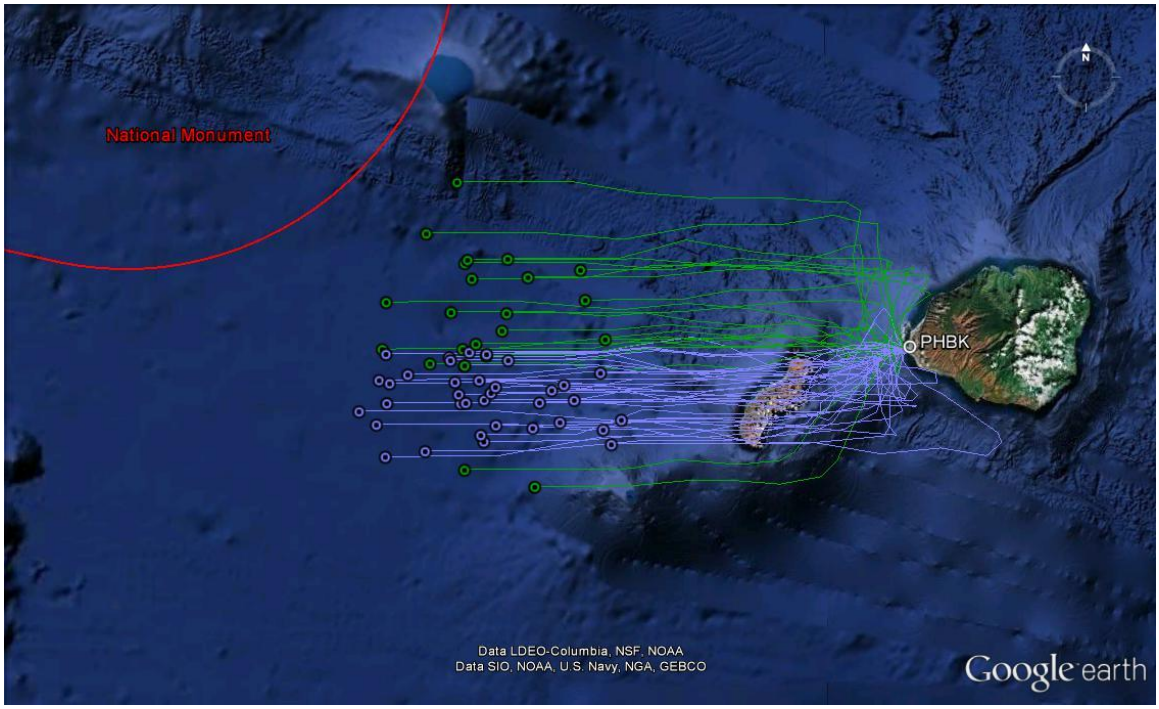

Figure 3. Simulated Balloon Ground track from Launch to Float Altitude using PMRF Wind Profiles 2007- 2009*.

*Analysis Performed by NASA Columbia Scientific Balloon Facility (CSBF)

MODELING and UNCERTAINTIES

The size of the predicted splashdown footprint is dependent on the uncertainties in the modeled forces on the vehicle propagated over time from the point of release to splashdown. Although there were a total of ~250 model parameters dispersed in the Monte Carlo simulation, many of which drove satisfaction of test requirements, only the model parameters that most directly affected the splashdown footprint will be discussed. A subset of these model parameters that affect the size of the splashdown footprint the most are shown in Table 2, along with the value of their uncertainty used in the Monte Carlo simulation. The largest contributor to the splashdown footprint is the performance of the Star 48. Dispersions in the Star 48 burn time create variations in how far downrange the TV travels. The direction uncertainty of the Star 48 engine was modeled using mounting alignment and thrust vector uncertainties.

Aerodynamic Uncertainties

Uncertainties in the aerodynamic axial, normal, and moment coefficients were provided by LaRC[3] for the 6-DOF TV and SIAD configurations, modeled as Gaussian dispersions. The TV and SIAD in their 3-DOF configurations below Mach 2.0 assumed +/- 15% uniform uncertainty in drag coefficient. The drag coefficient for the ringsail parachute in its nominal configuration was varied uniformly at approximately +/- 25% at the start of deployment and +/- 12.5% at splashdown. The parachute streamer configuration assumed 100% uniform uncertainty in drag coefficient due to the wide range of possible configurations in its partially opened condition[4]. A ballute device used to extract the parachute, used a +/- 20% Gaussian dispersion in its drag coefficient.

Uncertainties in TV Release State

Dispersions in the vehicle state at TV release included uncertainty in altitude, related in terms of uncertainty in atmospheric density at release altitude. The initial pitch angle uncertainty (+/- 0.35 deg) and the initial heading uncertainty (+/- 5.0 deg) of the vehicle were defined by the accuracy of the release mechanism attached to the balloon. Although there was a wide range of latitude and longitude at which the balloon could release the vehicle on a given launch day, the use of GPS tracking during flight allowed highly accurate estimates of the vehicle position. Therefore, no dispersion in initial vehicle horizontal position was used in the Monte Carlo simulation.

Table 2. SFDT Monte Carlo Modeling Uncertainty Parameters.

Category	Error Source	Uncertainty (3σ or min/max)	Distribution
Mass Properties	Total Dry Mass	+/- 11.5 kg	Gaussian
Mass Properties	Dry Mass CG Location (x / y / z)	43.0 / 42.0 / 34.0 mm	Gaussian
Mass Properties	Dry Moments/Products of Inertia	Ixx,Iyy,Izz: 100.0 / 82.0 / 160.0 kg-m^2 Ixy, Ixz, Iyz: 100.0 / 20.0 / 17.0 kg-m^2	Gaussian
Mass Properties	Star48 CG Location	start/end: 12.7, 25.4 mm long axis start/end: 9.0, 18.0 mm lateral	uniform
Mass Properties	Star48 Mass Properties: Prop, Dry, Burnout, Slag Mass & MOI	Prop: 5 kg; Dry: 6.3 kg; BO: 10.2 kg Slag: +/- 50% Ixx,Iyy,Izz: 16.6 / 16.6 / 16.4 kg-m^2 Ixx, Iyy, Izz: 3.9 / 3.9 / 2.4 kg-m^2	Gaussian uniform uniform uniform
Propulsion	Star48 Mounting Tilt Alignment	0 to 0.3 deg	uniform
Propulsion	Star48 Mounting Location	+/- 9.0 mm long axis 0 to 10.0 mm lateral	uniform
Propulsion	Star48 Thrust Reaction Offset	+/-20.0 mm long axis 0 to 1.0 mm lateral	uniform
Propulsion	Star48 Thrust / Isp	3.88% / 0.5%	Gaussian
Propulsion	Star48 / Spin Motor Thrust Dir	0 to 0.3 deg / 0 to 2.0 deg	uniform
Propulsion	Spin Motor Delay; Burnout; Temp	0.0075s; 5%; 1.5%	Gaussian
Propulsion	Spin Motor Impulse	5%	Gaussian
Propulsion	Spin Motors Reaction Location	+/-10.0 mm long axis 0 to 10.0 mm lateral	uniform
Aerodynamics[3]	TV/SIAD (6-DOF)	Per sfdt_aero_v1.3.f, 3/11/2013	Gaussian
Aerodynamics[3]	TV/SIAD (Drag Only) Trimming/ Tumbling	+/- 15%	uniform
Aerodynamics[3]	Parachute Full Deployment (3-DOF)	+/-12.5% to 25.0 %	uniform
Aerodynamics[4]	Parachute Partial Deployment (3-DOF)	0.05 to 0.25	uniform
Aerodynamics[3]	Ballute (3-DOF)	Ballute +/- 20.0%	Gaussian
Staging	Balloon Release Density	+/-0.000245 kg/m^3	uniform
Staging	Release Mech / Pendulum Angle	+/- 0.35 deg / 0.34 deg	uniform
Staging	Release Azimuth	+/- 5.0 deg	uniform
Staging	Release Mech/Pendulum Rates	+/- 0.1 / 0.08 deg/s	uniform
Atmosphere[5]	Atm Density,Temp,Press,Winds	EarthGRAM 2010_v3 / PMRF 1983 Range Reference Atmosphere	Gaussian

Atmospheric Model

The atmospheric model used a combination of two models including a PMRF Range Reference Atmosphere (RRA) and an EarthGRAM Global Climate Model (GCM). The RRA was provided as a table of density, pressure, and wind data as a function of altitude using measured observations at the location Barking Sands, Hawaii (Latitude = 22.03N, Longitude = 159.78W) during the month of June, 1983[5]. Although more recent data was available for the year 2006, the 1983 data was used because it provided the altitude range necessary (0 – 70 km) to cover the flight trajectory of the TV. Standard deviations were also provided for the atmospheric data as a function of altitude. Because the RRA data was valid for a vertical column of air over the location of Barking Sands, and the TV flight trajectory was over the ocean at least 60 km west of Barking Sands, it was necessary to include the EarthGRAM GCM to provide any differences in the atmosphere due to latitude/longitude. The atmosphere used by the simulated test vehicle was a blend of the RRA and GCM models, such that a linearly interpolated scale factor was applied as a weight on the data depending on the distance of the TV from the Barking Sands site.

The PMRF RRA tabular data was used within the EarthGRAM functionality to provide the mean and standard deviation for density, pressure, and wind at PMRF. During a Monte Carlo run EarthGRAM applies a randomly varied scale factor to the atmospheric data within the range of +/- 3σ provided in the table. In addition, EarthGRAM applies a random noise scale factor to the atmospheric data as a function of altitude. Dispersed east-west and north-south wind profiles as a function of altitude from 4000 Monte Carlo runs are shown in Figure 4 along with the +/- 3σ wind profile data. The prevailing westerly winds experienced by the TV vehicle while on the parachute are apparent below between 15 and 50 km, whereas the north-south winds are evenly dispersed about roughly zero below 40 km.

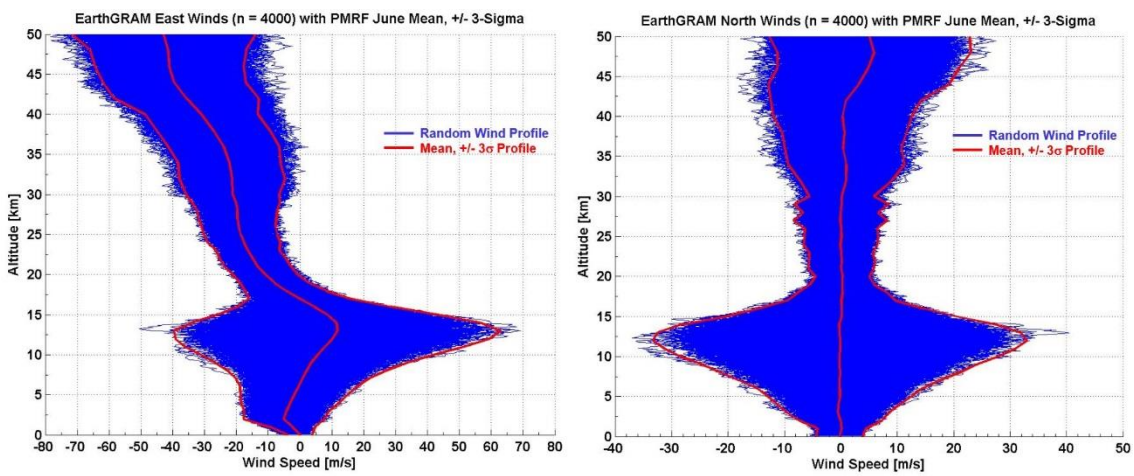

Figure 4. EarthGRAM East and North Monte Carlo (n = 4000) Wind Dispersions for PMRF Month of June.

MONTE CARLO SIMULATION SPLASHDOWN RESULTS

Monte Carlo simulations were performed from TV release to splashdown for every permutation described in Table 1. Each Monte Carlo simulation contained 2000 runs with randomly dispersed parameters provided in Table 2. The 3σ dimensions semi-major axis, semi-minor axis, and azimuth of a Gaussian probability ellipse were computed at splashdown for each set of 2000 trajectories. It was determined that 2000 cases were sufficient for computing accurate footprint statistics, as comparisons with 8000 cases showed a difference of ~ 1% compared to 2000 cases. The method

used to fit the ellipses to the Monte Carlo data is described in Appendix A. Figure 5 is a plot of the Monte Carlo TV splashdown points along with the 3-σ ellipses for the nominal, spin-up motor out, and off-nominal deployment scenarios, using the nominal TV release altitude (36.5 km) and heading (56 deg). The splashdown locations in Figure 5 are plotted as a function of delta latitude, delta longitude, and range from the TV release location (coordinate system origin = 0, 0). The dimensions of the nominal footprint (all deployments, no spin-up motors out) were 29.5 X 12.5 nmi 3σ semi-major X semi-minor axis. The azimuth at splashdown was 30.8 deg, which is a rotation of 25 degrees counter-clockwise from the point of TV release, as a result of the gyroscopic motion turning the vehicle during flight.

As expected, the scenarios related to off-nominal deployment (i.e. no deployment) of inflatables traveled the furthest downrange due to the lower drag on the vehicle compared to nominal deployment. These no deployment splashdown footprints were the driving cases for range requirements, because the downrange end of their ellipse could impinge on land or the monument depending on the selection of TV heading at release. The cases with no parachute deployed had smaller footprints compared to the cases with the parachute deployed due to the lack of the higher drag while on the parachute. The case that had the largest footprint dimensions was the no-SIAD deployment with full parachute deployment, with semi-major X semi-minor axis 31.6 X 12.6 nmi 3σ. The partially opened 'streamer' parachute footprint was an intermediate distance downrange between the no-chute deploy case and the full chute deploy case, due to the reduction in parachute drag coefficient for this configuration.

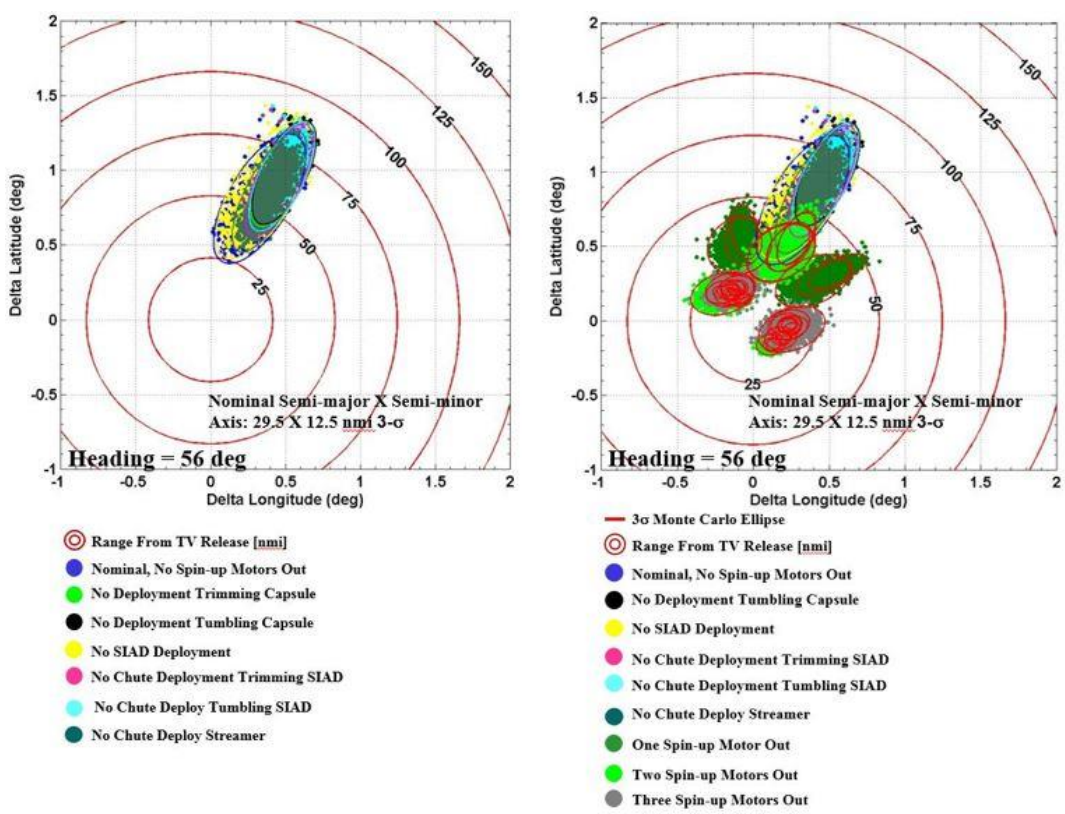

Figure 5. Monte Carlo splashdown footprints for nominal, spin-up motor out, and no deployment scenarios, given as delta latitude, longitude, and range from TV release location. TV conditions at release: altitude = 36.5 km, heading = 56 deg.

Spin-up Motor-Out Splashdown Results

The spin up motor-out splashdown footprints were computed for the three parachute deploy configurations of full, partial, and no deployment. The one spin-up motor out, no deployment cases were important scenarios for the 56 degree TV heading, due to their splashdown azimuths pointing in the direction of the Monument to the northwest and Kauai to the East. The distinction in the results between the three parachute configurations can be seen in the one motor-out 3σ ellipses shown in Figure 5. The no deployment ellipses are furthest downrange with the smallest cross-range dimension of the three scenarios. The full deployment ellipses have the largest cross-range component, appearing almost circular in shape. The partial deployment ellipses are located an intermediate distance downrange between the fully deployed and no deployed cases.

The spin-up motor out cases landed with a shorter downrange distance compared to the nominal footprint and also experienced a shift in azimuth relative to the nominal flight trajectory. The distance that the spin-up motor out cases traveled downrange from the TV release location was dependent on a combination of the reduction in spin-rate and the amount of initial pitch error caused by the asymmetry of the motor firing. For example, in the case of one motor out if one of the first pair (#1 and #3) of spin-up motors failed to ignite, the vehicle immediately pitched downward and the second pair of motors (#2 and #4) created spin stabilization with the steeper pitch angle, forcing the TV downward. As a result, single motor out cases in the first pair of motors landed closer to the TV release location and single motor out cases in the second pair landed further downrange. In the case of two motors out, when both motors in a pair had failed then the TV landed further downrange due to the symmetric spin-up. The three motor out cases landed the closest to the TV release location due to the smallest amount of spin rate in combination with an immediate pitch over of the vehicle due to asymmetric motor firing.

Effect of Wind on Splashdown Ellipse for Varying TV Heading

The computed probability ellipses most accurately fit the Monte Carlo splashdown points for the scenarios where there was no deployment of the parachute. In the case where the parachute is fully inflated, the TV had a significant reduction in velocity resulting in time spent on the parachute as long as 40 minutes. Therefore, wind dispersions become the dominant factor in the shape of the splashdown footprint for cases where the parachute is deployed. Due to the prevailing westerly component of the wind, dispersions in the splashdown footprint are asymmetrically shifted to the west as is evident for the case of TV heading 56 degrees shown in Figure 5. This westerly wind effect in the presence of north pointing flight azimuths resulted in less Gaussian looking splashdown footprints, and a larger degree of asymmetry when fitting the ellipse to the data.

The splashdown footprints and ellipses for TV headings 56, 90, 120, and 240 degrees are shown in Figure 6. The effect of the prevailing westerly winds can be seen when comparing the northerly 56 degree heading footprint with the easterly 120 degree footprint for the nominal chute deployment case. The 56 degree footprint has a larger crossrange component because the TV flight path is nearly perpendicular to the wind and the 120 degree footprint has the smaller crossrange component because it is directly into the wind (after accounting for the ~25 degree azimuth rotation due the gyroscopic effects of the spinning TV). For the case of 240 degree heading, the nominal footprint is 10 to 15 km further downrange than the other headings because the TV flight path is in the direction of the wind.

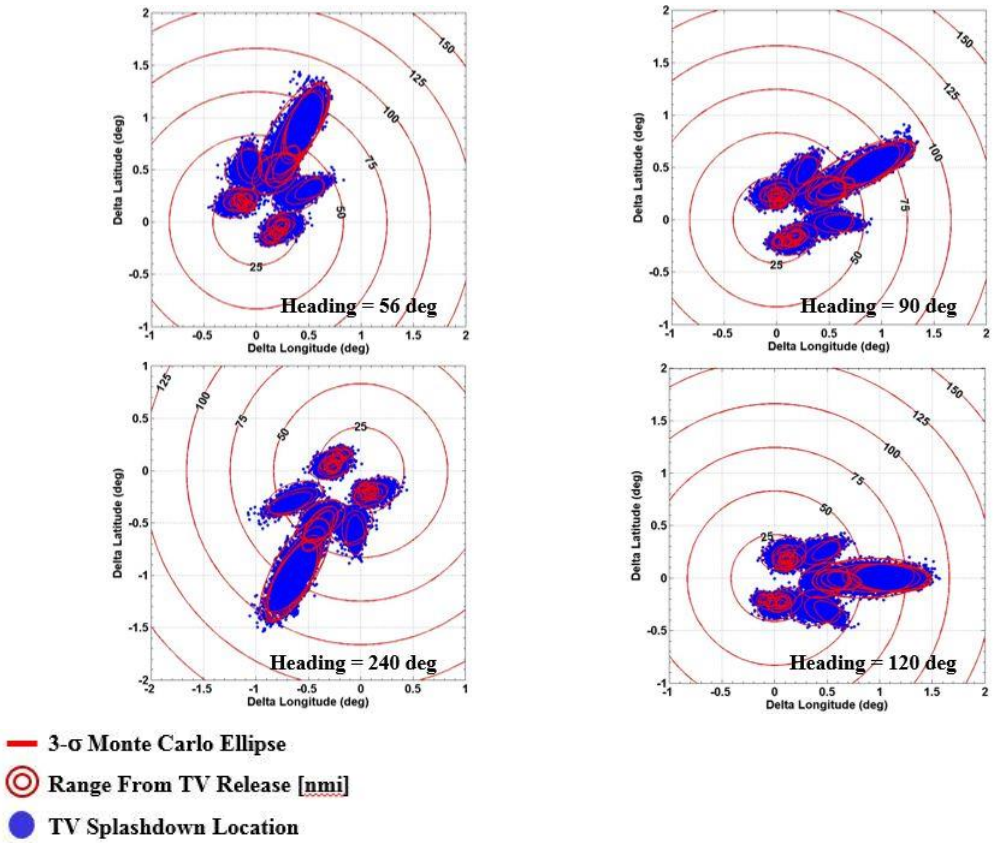

Figure 6. Monte Carlo Splashdown Footprint for TV Heading at Release 56, 90, 120, and 240 deg. Altitude at TV Release = 36.5 Km.

A summary of the splashdown ellipse dimensions and downrange distance from the TV release location is given in Table 3 for each of the TV headings at the nominal release altitude of 36.5 km. As expected, the downrange distance to the center of the ellipse decreases as the heading is directed toward the East and increases as the heading is directed toward the west depending on its direction relative to the westerly winds. The largest difference in the ellipse dimensions is seen when comparing the due east heading (120 deg) with the southwest heading (240 deg), with a 12% difference in the ellipse size for the no-deployment case. The contribution of wind dispersions to the ellipse size is approximately 2.0 X 4.0 nmi 3σ semi-major X semi-minor axis for the case of 56 deg TV heading.

Table 3. Monte Carlo Splashdown Ellipse Dimensions for Nominal and Off-Nominal Deployment Scenarios.

Case	Head-ing at Release	Nominal SIAD, Nominal Chute	No SIAD, No Chute, Tumbling Capsule	No SIAD, Nominal Chute	No Chute Deploy, Trim-ming SIAD	No Chute Deploy, Tum-bling SIAD	No Chute Deploy Streamer
3σ Semi-major Axis [nmi]	56.0	29.5	23.1	31.6	24.9	24.1	27.0
3σ Semi-Minor Axis [nmi]		12.5	9.1	12.6	8.8	9.0	9.2
Azimuth at Splashdown [deg]		30.8	26.1	31.0	26.2	25.9	27.8
Ellipse Center Distance From TV Release [nmi]		*52.1*	64.6	56.1	61.8	63.6	56.0
3σ Semi-major Axis [nmi]	90.0	30.4	23.4	32.9	25.1	24.3	27.5
3σ Semi-Minor Axis [nmi]		10.8	8.1	10.8	7.8	8.0	7.9
Azimuth at Splashdown [deg]		62.3	63.0	62.8	62.5	62.5	62.3
Ellipse Center Distance From TV Release [nmi]		*48.4*	63.0	52.7	59.6	61.5	53.4
3σ Semi-major Axis [nmi]	120.0	29.1	*22.6*	31.8	24.4	23.6	26.5
3σ Semi-Minor Axis [nmi]		11.3	*8.1*	11.4	7.8	8.0	8.1
Azimuth at Splashdown [deg]		86.7	92.3	87.4	91.6	91.9	89.7
Ellipse Center Distance From TV Release [nmi]		*47.2*	62.2	51.6	58.6	60.4	52.6
3σ Semi-major Axis [nmi]	240.0	30.9	*25.6*	33.7	26.6	26.0	28.6
3σ Semi-Minor Axis [nmi]		12.2	*9.7*	12.4	9.4	9.5	9.8
Azimuth at Splashdown [deg]		210.9	205.6	213.7	206.6	206.0	208.6
Ellipse Center Distance From TV Release [nmi]		*63.9*	73.1	67.2	70.0	71.8	66.7

COMBINING ALL FOOTPRINT RESULTS INTO A 'SUPER BOUNDARY'

Due to the effect of changing splashdown ellipse dimensions with varying flight azimuths, along with the necessity to alter the test vehicle heading at balloon release during operations, it was desired to combine the Monte Carlo results of all TV headings to create a 'super boundary' containing all of the ellipses. To accomplish this, the splashdown locations had to first be converted to a frame of reference that was independent of the TV heading. The origin of this reference frame was the TV location at the point of release projected onto the surface of the Earth, the +Y axis was in the direction of the TV heading at the time of release, and the +X axis was 90 deg clockwise from +Y. Once the results of all four headings were combined for each test case in the new reference frame, the dimensions of the ellipses were recomputed using the 8000 points of the combined cases.

The TV splashdown points and ellipses combining all TV headings are shown in Figure 7, for all combinations of the TV release altitudes. The combination of the results of multiple headings created larger ellipse dimensions, with the nominal semi-major and semi-minor axis 35.1 X 14.3 nmi 3σ. The more conservative ellipses sizes were desirable for flight operations to cover the possibility of a wider range of commanded headings.

The effect of lower TV release altitudes on the size of the splashdown footprints is dramatic, as there is a nearly 50% reduction in ellipse size between 36.5 km and 34 km release altitude. The reduction in footprint size is caused by the reduction in TV altitude at apogee following the Star 48 engine burn, due to the increase in dynamic pressure at lower altitudes.

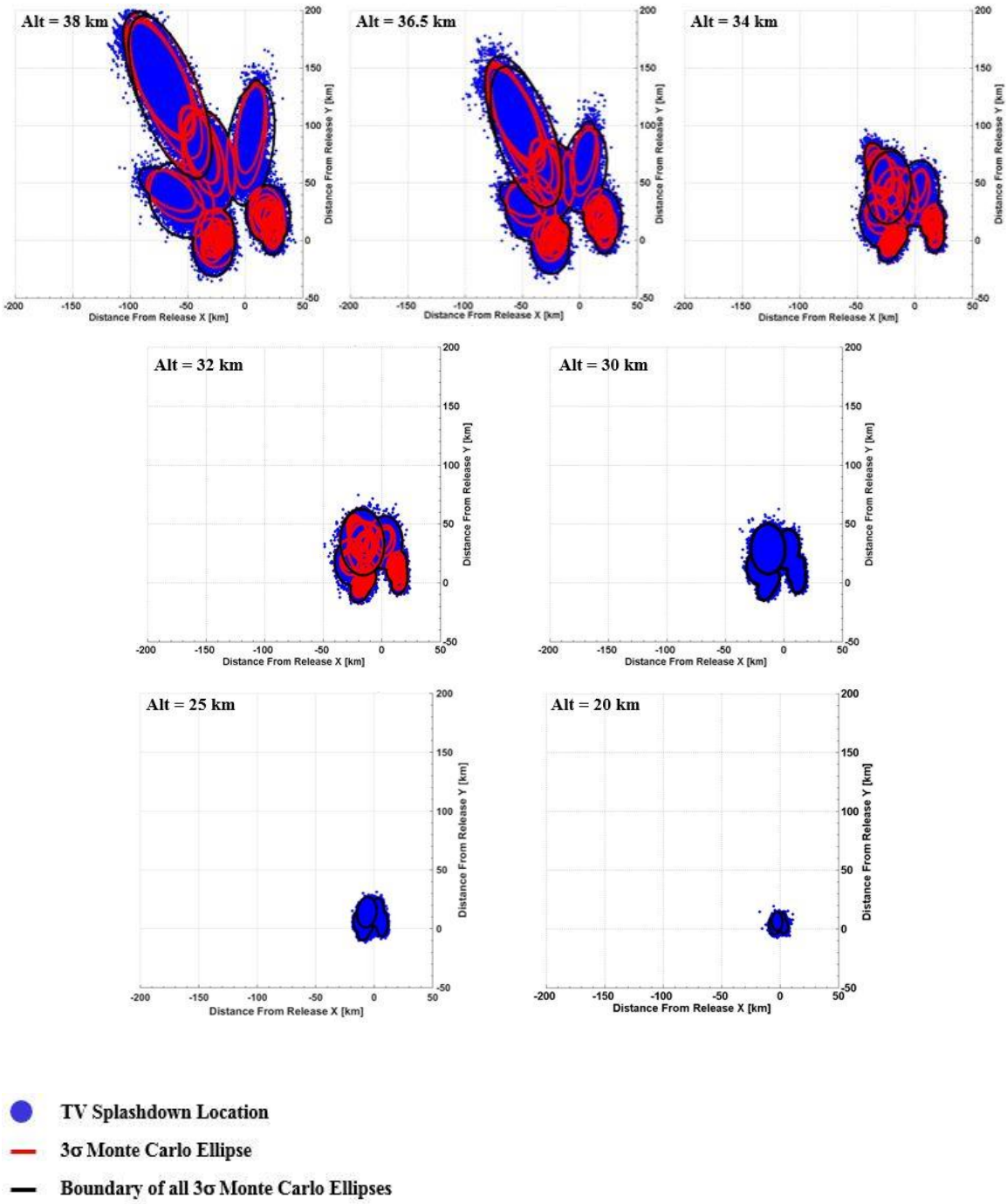

Figure 7. Monte Carlo Splashdown Distance from Test Vehicle Release Location for TV Release Altitudes 36.5, 34.0, 32.0, and 30.0 Km. Data from all TV Release Azimuths Included.

Flight Operations Use of the Splashdown Footprint Boundaries

During Flight Operations the super boundary of all splashdown ellipses was used to predict the full range of possible splashdown locations for the vehicle in nominal and off-nominal test scenarios. The boundary around all splashdown ellipses (i.e. the super boundary) is shown in red in Figure 8 for the case of zero degree heading and 36.5 km altitude at TV release. The downrange boundary of the ellipse was dominated by the case of no-SIAD, no motor out, with full parachute deployment (orange). The nominal ellipse (yellow), and no parachute ellipses (black, pink) were circumscribed by the boundary of the no-SIAD no parachute deploy case. The remainder of the super boundary was defined by the different combinations of motor-out, with the motor #2 out ellipse boundary lying furthest downrange from TV release, and the two/three motor out ellipses contributing to the boundaries closest to the TV release location.

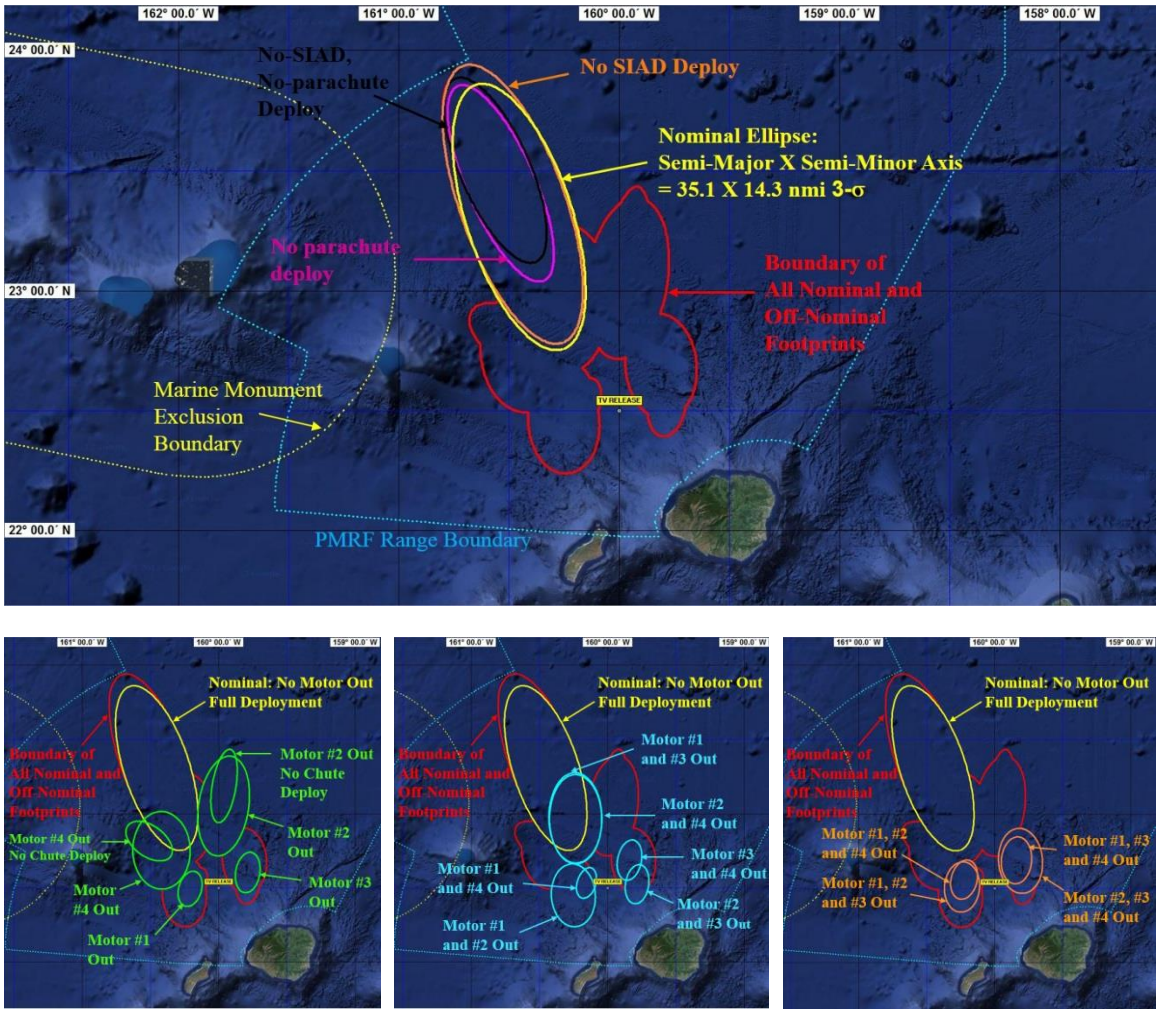

Figure 8. 3σ Splashdown Ellipses for Nominal, Off-Nominal Deploy, and Super Boundary of All Spin-up Motor-Out Footprints.

Because the super boundary was created in a reference frame relative to the TV location and heading at release, the dimensions were considered to be generic for any selection of heading and release location. During operations, the boundary was centered at the desired release location and rotated in the direction of the desired heading. In the scenario that the TV altitude was different

than 36.5 km, a different set of boundaries (i.e. one super boundary) most applicable to the selected altitude was used, either the set closest to that altitude or an interpolation between the two closest altitudes.

Selection of TV Heading Within Prescribed Boundary Constraints

The selection of the TV heading on the day of launch was determined with consideration to the numerous constraints imposed by range safety, mission design, and flight hardware. On-board cameras limited the TV heading due to sun angle impingement that could lead to over exposure. It was determined that a TV heading from 60 to 170 deg sufficiently limited the camera sun exposure issue. TV headings within the 60 to 170 deg range were further limited by the TV release location due to proximity to range boundary constraints. Figure 9 shows contours of the maximum possible TV heading from 60 to 170 depending on the location of the TV release point within the imposed boundary constraints. The light blue boundary is the PMRF test range boundary that extends from the island of Nihau at 22 deg latitude in the south to 26 deg latitude in the north. The PMRF boundary extends from the Marine National Monument in the West to the boundaries of Kauai in the East. The Federal Aviation Administration (FAA) had determined a 'no-fly' region which defined the southernmost boundary as ~21.0 to 21.6 deg latitude, and easternmost boundary as ~159.0 to 159.5 deg west longitude. TV hardware boundary constraints included a 320 km communication limit arc and a 334 km battery power limit arc. The entirety of these constraints led to the creation of the yellow boundary shown in Figure 9 that enveloped the full range of possible TV launch locations. For a given TV launch location, a heading was selected within the limitation imposed by the contours that satisfied the sun angle, range safety, and monument constraints.

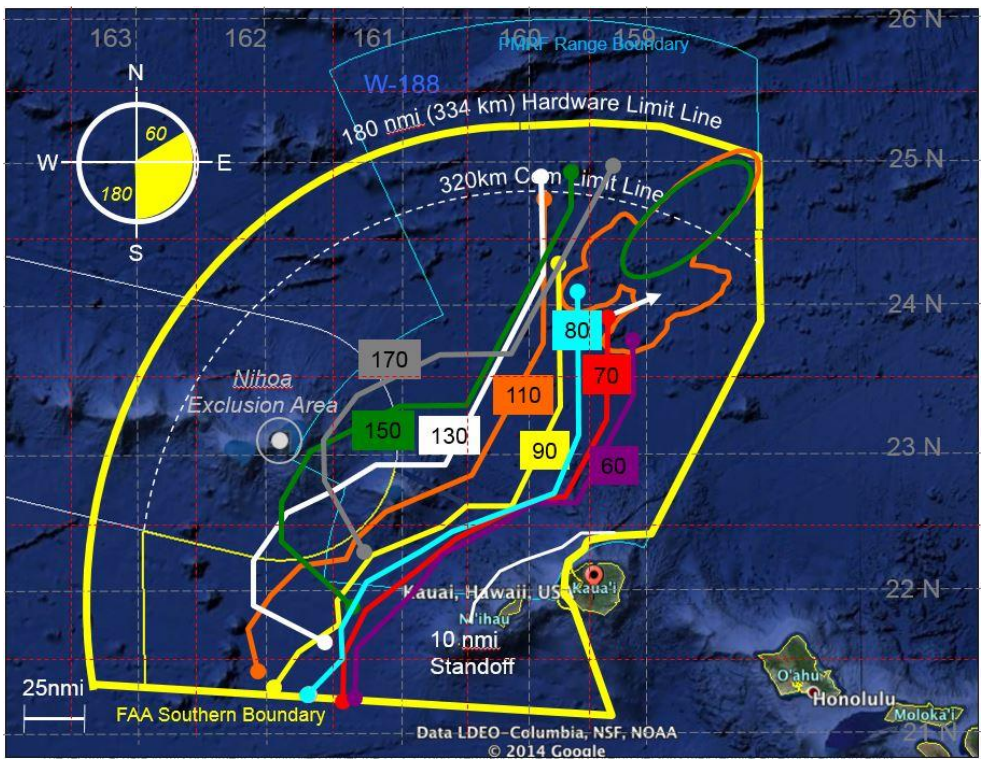

Figure 9. Selection of TV Heading Subject to Range Safety Constraints

Location of Recovery Vessels with Splashdown Footprints

Once a heading was selected, vessels were deployed to locations where they could lie in wait for splashdown to occur then approach for recovery. Two vessels were utilized: one to recover the balloon carcass and one to recover the TV itself. Referring to Figure 10, the TV recovery vessel was placed at the mean location of the nominal footprint to enable the minimum amount of travel time to the actual splashdown location (note that a fast recovery was desired given the probability that the floating TV attached to a deployed parachute could begin to sink ~30min after splashdown). No further consideration was made for any other footprint given their much lower likelihood of occurrence. The balloon recovery vessel was simply placed close to the TV release point but outside of the super boundary.

Both vessels were deployed to their waiting locations 1 day prior to flight operations. During balloon ascent, real-time predictions of the TV release point were performed. The TV recovery vessels position was adjusted based on these real-time periodic predictions.

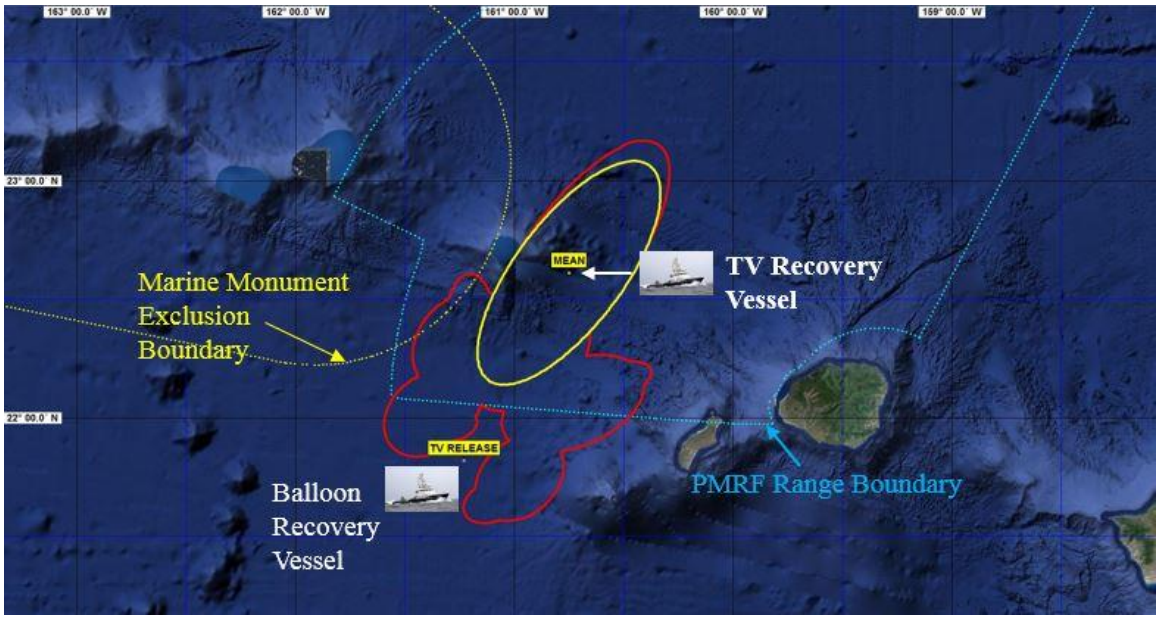

Figure 10. Launch Minus One Day Location of TV Recovery Vessels

Range safety and Marine National Monument Constraints

The constraints imposed by the range were for the populated areas of Kauai and Nihau, along with the Marine National Monument. According to PMRF range safety requirements[6], the probability of casualty in a populated area due to the TV and its hardware must not be greater than $1e^{-8}/1000\ ft^2$. In order to satisfy the population requirement, the most conservative approach was to impose the constraint that *no* region of the super boundary cross *any* area of land. For the Marine National Monument, the constraint was imposed such that no *planned* splashdown of the TV and its hardware cross the exclusion area surrounding the monument. For SFDT-2, a planned splashdown was the nominal deployment, zero motors out ellipse shown as solid yellow in Figure 10. It was acceptable for the motor-out portion of the boundary (red) to cross the Marine monument boundaries because these were un-planned scenarios. Similarly, it was acceptable for un-planned scenario footprints to lie outside of PMRF boundaries so long as they did not impinge on land. Any

of the desired headings selected had to result in a splashdown footprint boundary that satisfied all of these requirements.

Verification of Range Safety Requirements

The super boundary was constructed using 3σ ellipses as representations of the splashdown footprints. It was necessary to show that the selection of a 3σ sized ellipse was sufficiently large enough to satisfy the range safety population probability density requirement of $1e^{-8}/1000\ ft^2$. In order for this requirement to be verified, the computed scale factor applied to the number of standard deviations for an ellipse with probability density $1e^{-8}/1000\ ft^2$ had to be less than 3.0.

The dimensions of the probability ellipse are derived from the probability density function. The equation for a bivariate normal probability density function is[5]:

$$P(X,Y) = \frac{1}{2\pi\sigma_x\sigma_y\sqrt{1-\rho^2}}\left[exp\ \frac{-1}{2(1-\rho^2)}\left\{\frac{(X-\mu_x)^2}{\sigma_x{}^2} - \frac{2\rho(X-\mu_x)(Y-\mu_y)}{\sigma_x\sigma_y} + \frac{(Y-\mu_y)^2}{\sigma_y{}^2}\right\}\right] \quad (1)$$

Where:

$P(X,Y)$ = probability density function of X and Y

σ_x, σ_y = standard deviation of X and Y

ρ = correlation coefficient between X and Y

μ_x, μ_y = mean of X and Y

Assuming a mean of zero for X, Y, and no correlation between X and Y, the term under the exponential function in Equation 1 is equivalent to a family of ellipses equal to a constant:

$$\frac{x^2}{\sigma_x{}^2} + \frac{y^2}{\sigma_y{}^2} = \lambda^2 \quad (2)$$

where the semi-major and semi-minor axis of the ellipse are equal to the standard deviations σ_x and σ_y. The area of the ellipse is equal to $2\pi\ \sigma_x\ \sigma_y$. Substituting Equation 2 into Equation 1 results in:

$$P(\lambda) = \frac{1}{2\pi\sigma_x\sigma_y} exp\ \frac{-\lambda^2}{2} \quad (3)$$

Solving Equation 2 for λ provides a function for computing the scale factor applied to the standard deviation in terms of the probability density per unit area:

$$\lambda = \sqrt{-2\log(P\ (2\pi\sigma_x\sigma_y))} \quad (4)$$

The value λ then represents the number of standard deviations necessary to create an ellipse that is large enough to satisfy the range safety population requirement. Substituting into equation 3 the values of σ_x = 35.3/3 nmi and σ_y = 14.3/3 from Figure 8 for the combined azimuth, nominal deployment, no motor out ellipse with $1e^{-8}/1000\ ft^2$ probability density and converting to nmi:

$$\lambda = \sqrt{-2\log[(\frac{1e^{-8}}{1000ft^2}) * (\ 6076.12\ ft/nmi)^2\ 2\pi(\frac{35.1\ nmi}{3})(\frac{14.3\ nmi}{3})]}$$

Solving for λ results in:

$$\boldsymbol{\lambda = 2.02}$$

Therefore, an ellipse with a size equal to 2.02σ would have been sufficient to satisfy the population requirement for the nominal splashdown footprint. An ellipse size equal to 3σ was selected for the construction of the footprint boundaries for conservatism. Also, there was additional conservatism in restricting the location of the footprints to within 10 nmi distance from land populated areas, whereas the literal interpretation of the range safety requirement takes into consideration the population density in the region where footprints impinge on land.

Table 4 summarizes the computed value of λ for the ellipses that form the super boundary shown in Figure 8. There were cases of motor-out with no parachute deployment that had values of λ that exceeded 3.0, but those ellipses do not contribute to the super boundary and their ellipse sizes were small enough to be completely circumscribed by the larger full deployment ellipses (refer to Figure 5). Furthermore, for range safety purposes the cases of motor-out were considered to have an equal likelihood of occurrence as no motor-out cases, whereas in reality the probability of a motor failure has some small percentage associated with it.

Table 4. Monte Carlo Splashdown Ellipse Dimensions for the Major Contributors to the Super Boundary, with Computed Scale Factor on Standard Deviations λ Needed to Satisfy Range Safety Population Requirement.

Splashdown Ellipses Contributing to the Super-Boundary Around All Ellipses	Semi-Major Axis [nmi]	Semi-Minor Axis [nmi]	λ (Number of Stdev Needed to Satisfy Population Req)
Nominal Deployment, No Motor Out	35.1	14.3	2.0
No Deployment, No Motor Out	25.1	9.3	2.4
No SIAD Deployment, No Motor Out	37.1	14.2	2.0
Motor #2 Out, Nominal Deployment	20.4	11.0	2.4
Motor #2 Out, No Parachute Deployment	15.0	5.2	2.8
Motor #4 Out, Nominal Deployment	15.7	12.6	2.4
Motor #4 Out, No Parachute Deployment	11.3	6.4	2.8
Motor #1 and #2 Out, Nominal Deployment	12.8	9.7	2.6
Motor #2 and #3 Out, Nominal Deployment	8.0	5.1	3.0
Motor #2, #3, and #4 Out, Nominal Deployment	13.2	9.7	2.6

CONCLUSION

The use of Monte Carlo analysis with flight dynamics simulations to predict the size of the SFDT-2 splashdown footprints for the purposes of satisfying range safety requirements was described. The method of using 3σ probability ellipses to represent a set of Monte Carlo splashdown locations was shown to be a satisfactory approximation for determining the dimensions of the splashdown footprint. A 'super' boundary that circumscribed the 1372 splashdown ellipses was created for use in flight operations to predict the total footprint size for all probable nominal and off-nominal test scenarios. The 'super' boundary was normalized to be heading independent and used to translate the dimensions of the footprint to any desired test vehicle release location and rotated to any desired test vehicle heading in support of range safety analysis and recovery operations.

There are limitations in the use of the footprint boundary when applying to a new TV release location and heading. The new TV location will have different assumptions for atmospheric data and uncertainties compared to the location at which the Monte Carlo data was generated. Although within the range of the PMRF test boundaries the differences in atmospheric assumptions between TV locations should be small. The larger error is seen when rotating the footprint boundary to a new heading. In the presence of wind, the change in azimuth between TV release and splashdown differs as a function of the heading at TV release. Therefore, the alignment of the ellipses is an approximation of the actual when rotating to a new heading angle. This effect would be minimized through the generation of Monte Carlo footprints at additional test vehicle headings.

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APPENDIX A: METHOD OF FITTING PROBABILITY ELLIPSES TO SPLASHDOWN POINTS

Because the probability ellipses were used to represent each set of predicted TV splashdown points during flight operations, it was important that the ellipses provided an accurate fit to the Monte Carlo data. The measure of accuracy that the probability ellipse has sufficiently represented the set of splashdown points for each scenario was determined through inspection of the points that lie outside of the ellipse. Using the statistical mean as the center of the ellipse was undesirable for range safety as more of the points outside the ellipse were downrange than closer to the TV release location as shown in Figure A1-A. A more conservative approach was to place the center of the ellipse at the mid-point between the 98.889 and 1.111 percentiles, which correspond to the 3σ tails of the probability density function for the ellipse:

$$(lat_{center}, lon_{center}) = (\text{percentile}(lat(n=2000), 98.889) + \text{percentile}(lon(n=2000), 1.111)) / 2.0$$

The resulting ellipses using the above approach were located further downrange and the number of points lying outside of the ellipse in the downrange direction were reduced (Figure A1-B).

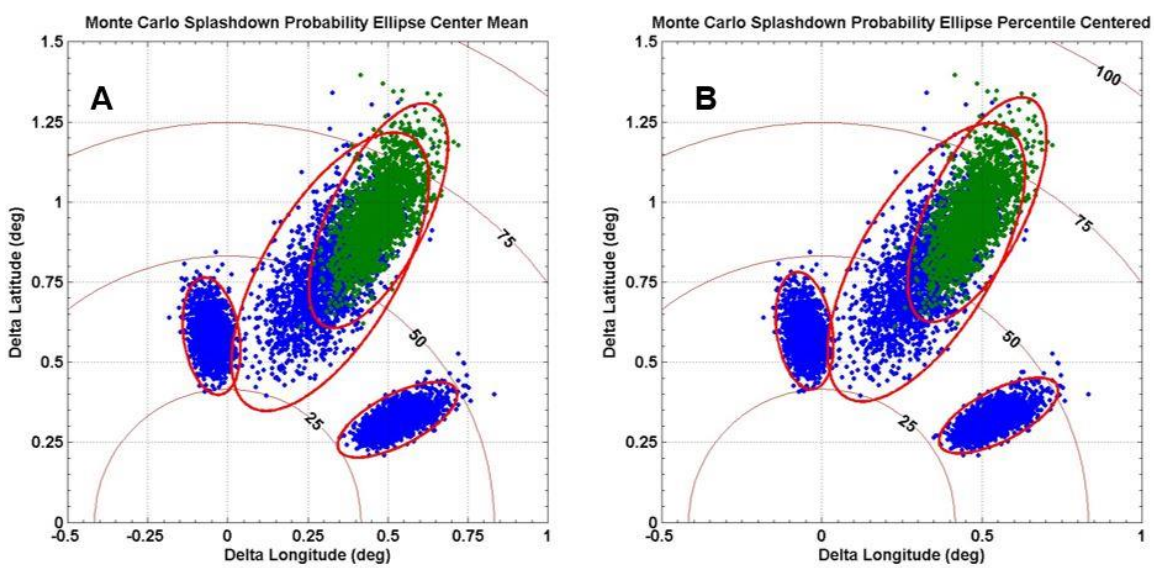

Figure B-1. Comparison of Centering Probability Ellipse Using Mean Lat/Lon vs. Using Mid-point of 99% and 1% Lat/Lon.

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