National Aeronautics and Space Administration

Trajectory Dispersed Vehicle Process for Space Launch System

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SPACE LAUNCH SYSTEM

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Outline

- **SLS Trajectory Analysis**
- **Trajectory Dispersion (TD) Background**
  - Definition
  - Case Matrix
- **TD Vehicle Process Overview**
  - Process Inputs & Flow
  - Design Space
  - Polynomial Fit/Residuals
  - Maximum Likelihood Estimates
- **Conclusion**

3-DOF SLS Trajectory Analysis

- **Ascent trajectory analysis for an SLS Design Analysis Cycle (DAC) begins with the reference trajectories.**

Reference Trajectories
Nominal trajectory for each mission. For DAC-2 8 nominal cases made including EM2, EM3, Europa, Cargo missions with Heritage and New Production RD-25 engines.

Partials
Individually applies a variety of manufacturing uncertainties to the nominal trajectory to determine effects on certain performance parameters.

Off Nominal Studies
A variety of studies that determines the effects of failures, like an engine out, during flight

Trajectory Dispersion (TD) Vehicles
Apply multiple manufacturing uncertainties to nominal trajectories to determine individual responses of a variety of focus parameters

All trajectories run in Program to Optimize Simulated Trajectories (POST), a 3 degree of freedom (3-DOF) ascent simulator

TD Vehicle Background: Why TD Vehicles are necessary

- **Manufacturing uncertainties affect a variety of response parameters.**
- **These parameters can vary with each DAC depending on vehicle sensitivities. DAC2 Block 1B response parameters are:**

Key Response parameters

- Payload Mass
- Lift-Off-Thrust-To-Weight
- Max Dynamic Pressure (Q)
- Max Heat Rate
- Max Compression Load
- Max Axial Acceleration

- **A TD Vehicle is the configuration that is most likely to generate these extreme responses.**

If these response parameters are not accounted for in the design process, extreme cases could develop that lead to loss of mission, vehicle, or crew.

TD Vehicle Background: Case Matrix

- **Bounding missions and RS-25 power levels are determined to identify extreme cases and assembled into a case matrix. There were 9 TD vehicles made in total.**

- **Heavy Slow:**
  - Minimizes payload and lift-off-thrust-to-weight
- **Light Fast:**
  - Maximizes lift-off-thrust-to-weight, axial acceleration, heat rate, dynamic pressure
- **Hybrid:**
  - Minimizes payload
  - Maximizes acceleration, heat rate, dynamic pressure

Vehicle Type	RS-25 Power Level	Missions			
		EM-2	EM-3	Europa	Cargo
Heavy / Slow	109	x	x	x	
	111				x
Light / Fast	109				
	111	x		x	
Hybrid	109				x
	111		x	x	

EM-2: Exploration Mission 2 (crewed)
EM-3: Exploration Mission 3 (crewed)
Europa/Cargo: Unmanned

TD Vehicle Process Overview

Gather the required uncertainties from the Mass statements, Booster, and LEO
Apply to POST.

→

Design the search space
- Latin Hypercube
- Central Composite Design

→

Produce second order polynomial fit and analyze residuals.

→

Using 90th or 10th percentile variations as targets (vehicle dependent). Determine the Maximum Likelihood offsets for the TD vehicle.

Gather Uncertainties

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Gather Uncertainties

- **Manufacturing uncertainties are gathered from the SLS team and applied to the POST input assuming normal distribution.**

Key Manufacturing Uncertainties

- SRB Burn Rate
- SRB Dry Mass
- RS-25 Thrust & ISP
- Core Dry Mass
- Launch Abort System (LAS)/Shroud Mass
- RL-10 Thrust & ISP
- EUS Dry Mass

- **Ideally, as the SLS vehicle is developed, these uncertainties will decrease. In future DACs we intended to reduce these parameters as their uncertainties diminish.**

Design Search Space

Gather the required uncertainties from the Mass statements, Booster, and LEO
Apply to POST.

→

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- Latin Hypercube
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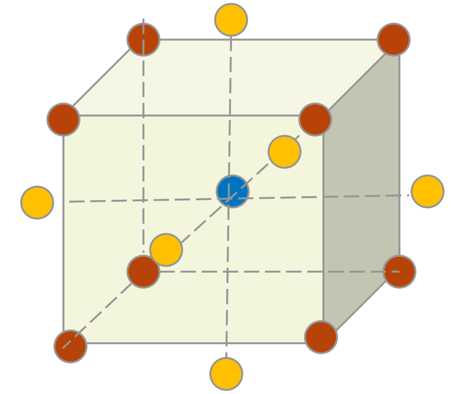
Central Composite Design vs. Latin Hypercube

- **Central Composite Design**
  - Captures the corner points of the design space
  - Captures the centers of the face (3-sigma)
  - No interior points other than the cube center are captured

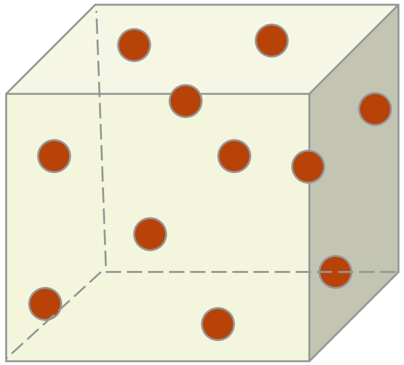
- **Latin Hypercube**
  - Captures more of the interior space
  - Fills in more central points on the Response Surface
  - Lacks complete edges and may under perform at those regions

- **Both options have merits and demerits**
  - Both grids were used in the TD vehicle process
  - In some cases they were merged together

Central Composite Design



Latin Hypercube



Polynomial Fit

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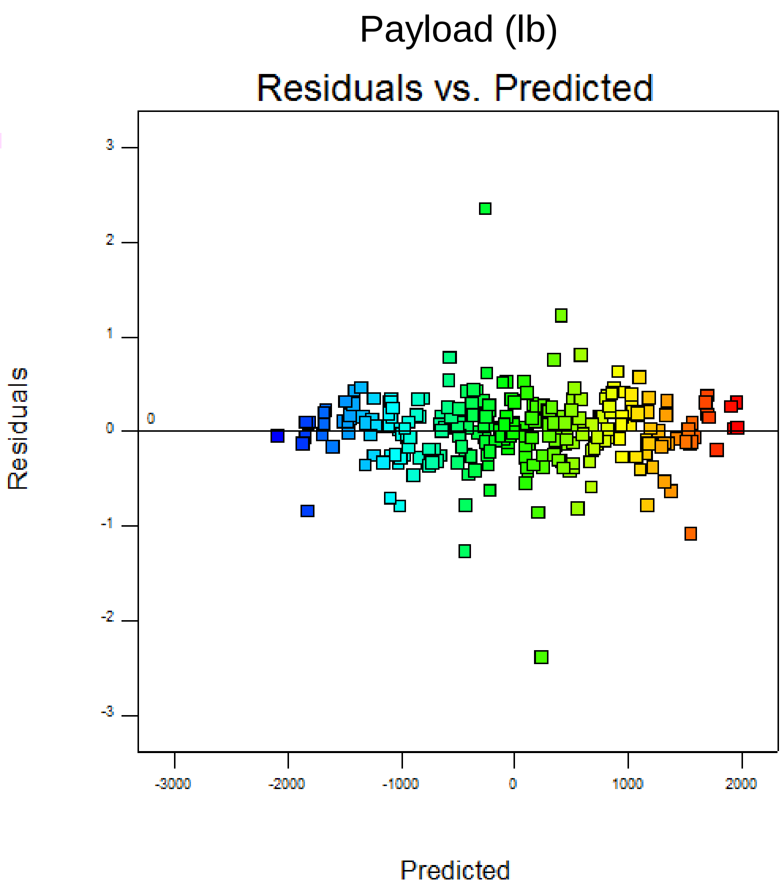
Polynomial Fit

- **Once the design space is run, a polynomial of the lowest sensible order is fit to the data using ordinary least squares as the fitting procedure**
  – This equation acts as a predictor for the response parameters allowing for a simplified optimization over the surface

- **TD vehicles uses a second order polynomial surface for each response parameter**
  – $f(x, y, z) = ax^2 + by^2 + cz^2 + dxy + exz + gyz + hx + iy + jz + Const$
    - x, y, & z represent manufacturing uncertainties
    - In the TD process our surface is a function of 10 independent variables
  – Coefficients *a, b, c, … j* yield clues to the importance of each term

- **Residuals of the surface are analyzed and determined if they meet a set tolerance. As an example 5 pounds for payload mass.**



Example of EM3 Payload Mass Residuals from Design Expert.

Maximum Likelihood Vehicle

Gather the required uncertainties from the Mass statements, Booster, and LEO
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Maximum Likelihood Vehicle

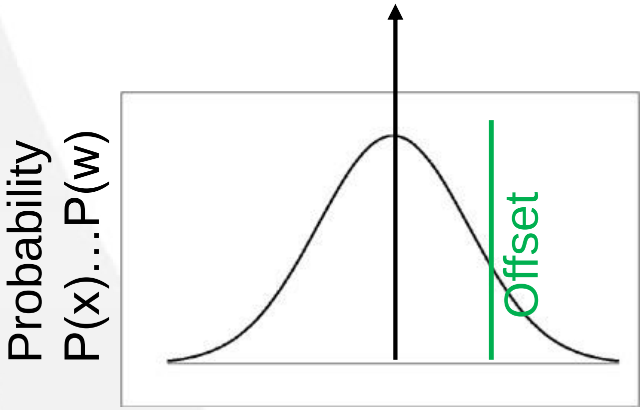
- **To build a TD vehicle we optimize the likelihood of each manufacturing parameter while targeting a specific set of responses (such as the 10^{th} percentile payload & 10^{th} percentile Lift Off Thrust to Weight)**
  - We are seeking to minimize the distance an uncertainty parameter is from the mean (maximize its probability of occurrence) while achieving the targeted response parameters predicted by the response surfaces
  - We must remain within the limits of each response surface

- $\boldsymbol{Cost} = \max\{\ln(P_1(x)) + \ln(P_2(y)) + \ln(P_3(z)) + \ldots + \ln(P_n(w))\}$
  - where $P_i(x)$ is the probability function of a manufacturing parameter and x is the uncertainty value (distance from mean)

Response Surface Optimization

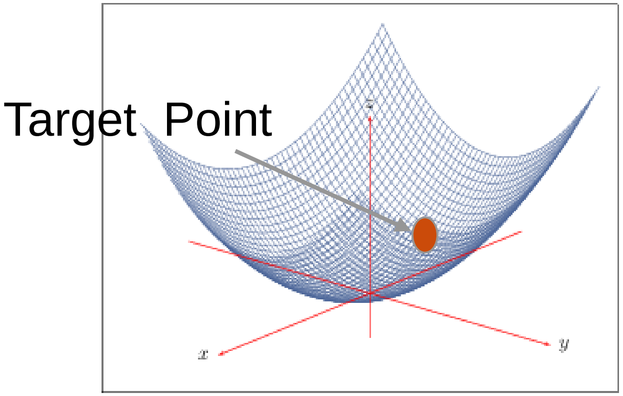
- **By ensuring the uncertainty of each manufacturing value is close to its mean we are maximizing the likelihood of each offset (x, y, z … w) while achieving the desired target parameter for each response**
  - The log summation is a traditional way of approaching this problem
    - could use the product of the probabilities and get the same result
  - Each x, y, z … w becomes the offset for a specified TD vehicle

Manufacturing Uncertainty



Uncertainty Value
(x, y, z, …w)

Response Surface



Figures are representative of all manufacturing uncertainties and responses

Verifying TD vehicles

- **After the Offsets are determined we do a POST run with those offsets**
- **The residual (difference between the POST run with the response surface) are compared**
  - If the residual is small the TD vehicle and response surface are in agreement and we consider the offsets to be accurate
- **TD vehicles residuals we are looking to be within**
  - Payload 5 lbm
  - Lift off Thrust to Weight 0.001
  - Max Q 1 psf
  - Max G 0.001 g
  - Max HR 0.001 $\mathrm{Btu\ ft^2/s}$
  - Compression load 500-1000 lbf
- **The residuals should be evaluated for each vehicles as design changes could add complexity to deck.**

Conclusion

- **Our TD Vehicle process allows the extreme SLS cases (Heavy/Slow, Light/Fast, Hybrid) to be identified from a response surface.**
  - This will be analyzed in the design process to ensure there will not be a loss of mission, vehicle, or crew.
- **The most likely estimate vehicle allows the most probable configuration to be used in these analyses.**
- **The uncertainties, responses, and acceptable residual tolerances will need to be reevaluated with each DAC cycle.**