National Aeronautics and Space Administration

SPACE LAUNCH SYSTEM

SLS Vehicle Modeling and Simulation

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Presentation to Boeing

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Outline

- **SLS introduction**
- **Early risk reduction obtained through use of M&S**
- **Use of design models in SLS**
  - Design models and requirements: reducing cost
  - Use of M&S to reduce conservatism and enhance launch vehicle knowledge

THE WORLD'S MOST POWERFUL ROCKET

Orion:
Carries astronauts into deep space

Stage Adapters:
The Orion stage adapter was the first new SLS hardware to fly.

Interim Cryogenic Propulsion Stage:
Based on the Delta IV Heavy upper stage; the power to leave Earth

Core Stage:
Newly developed for SLS, the Core Stage towers more than 200 feet tall

Solid Rocket Boosters:
Built on Space Shuttle hardware; more powerful for a new era of exploration

RS-25 Engines:
Space Shuttle engines for the first four flights are already in inventory

THE ROCKETS, THE MISSIONS

Capability to Low-Earth Orbit (LEO):
26 metric tons

Payload:
Critical crew module systems and Basic LAS/SM structure

Capability to Low-Earth Orbit (LE
70 metric tons

Payload:
Full Orion (Unmanned)

DELTA IV HEAVY

SPACE LAUNCH SYSTEM (SLS)

ORION'S FLIGHT TEST

OBJECTIVE:
Acquire data at beyond-Earth orbit reentry velocities

DISTANCE FROM EARTH:
3,600 miles

DURATION:
5 Hours

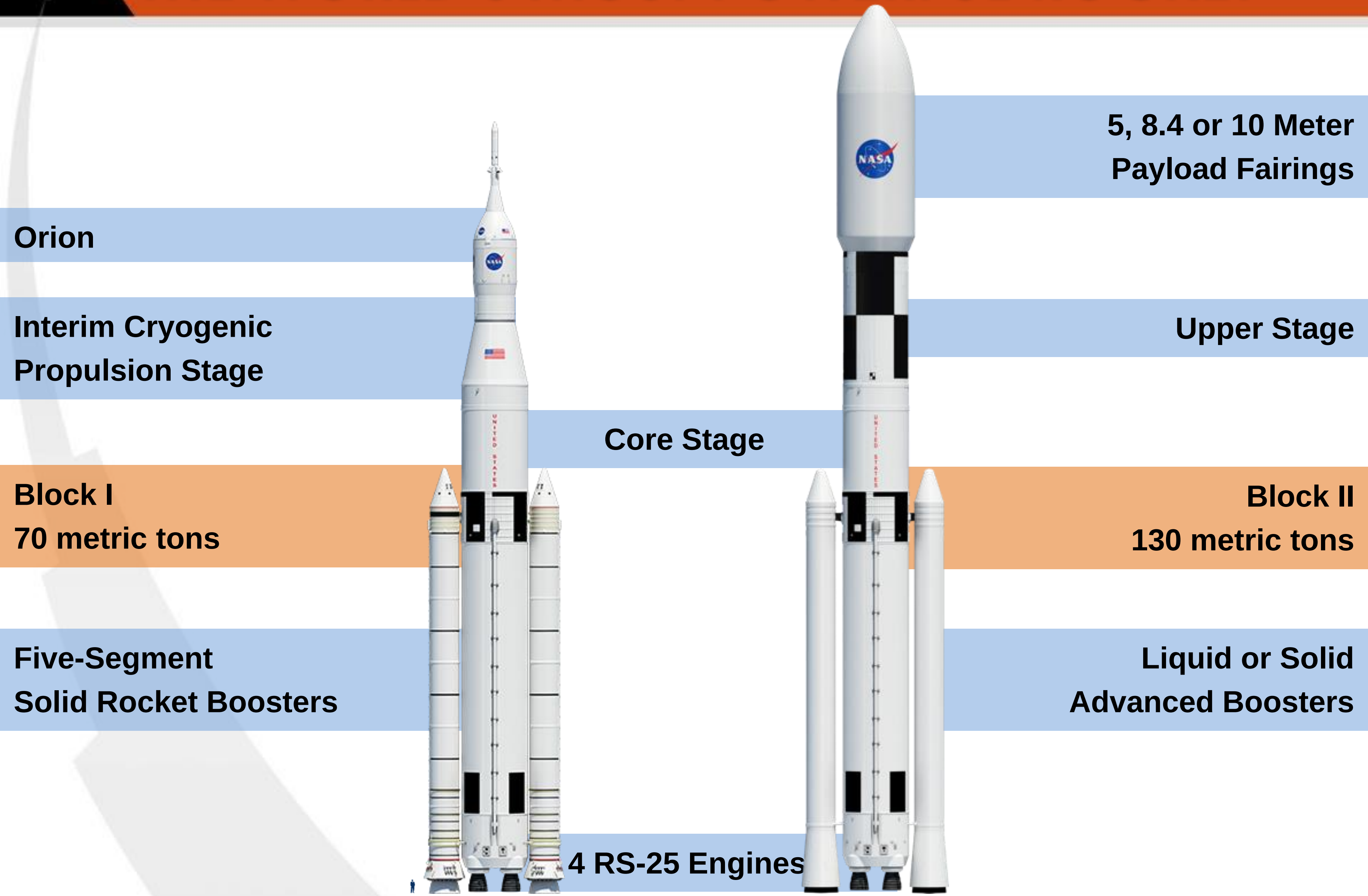
EXPLORATION MISSION ONE (EM-1)

OBJECTIVE:
System readiness for astronauts to travel farther than humans have ever gone before

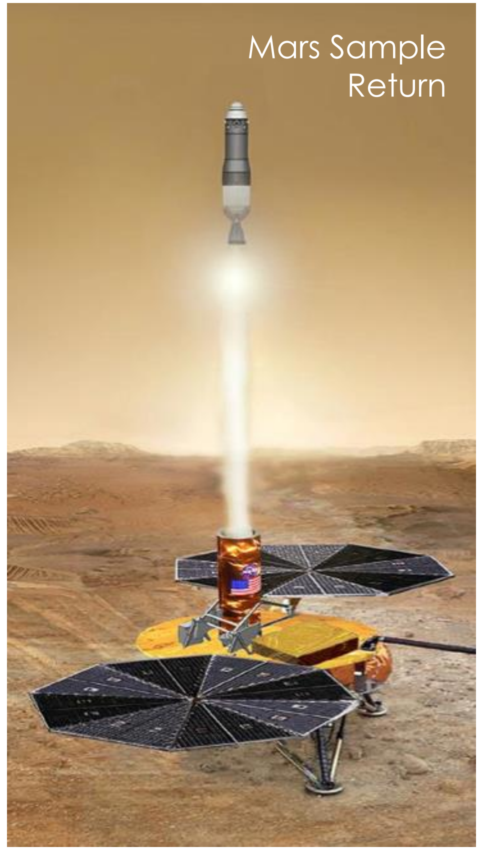
DISTANCE FROM EARTH:
Will break the distance record reached by the most remote Apollo spacecraft, and then ***30,000 miles farther out (275,000 total miles)***

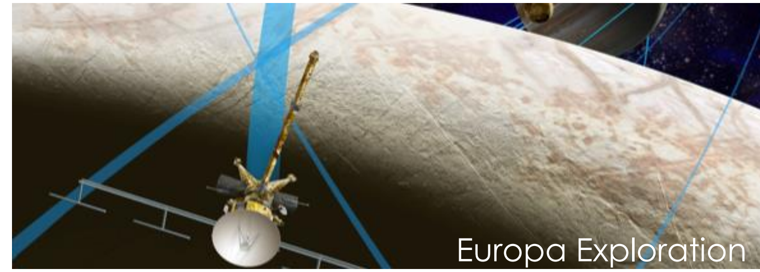
DURATION:
22 days

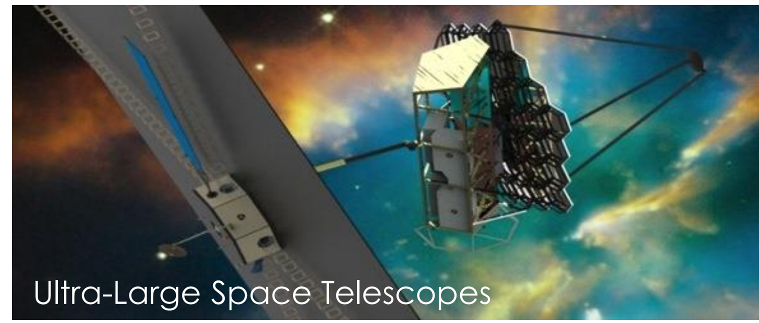
THE WORLD’S MOST POWERFUL ROCKET

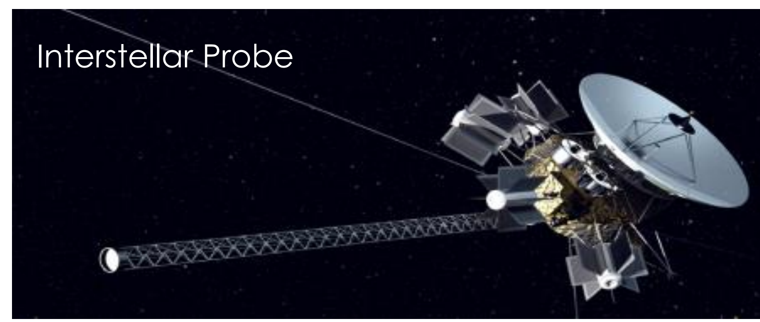


GAME-CHANGING POWER FOR EXPLORATION

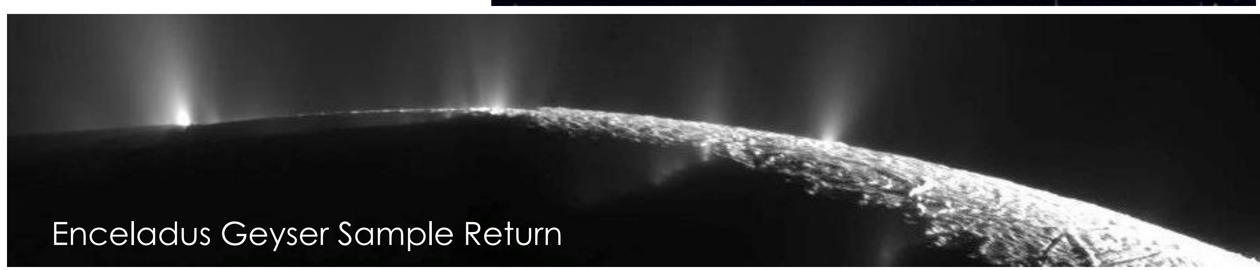




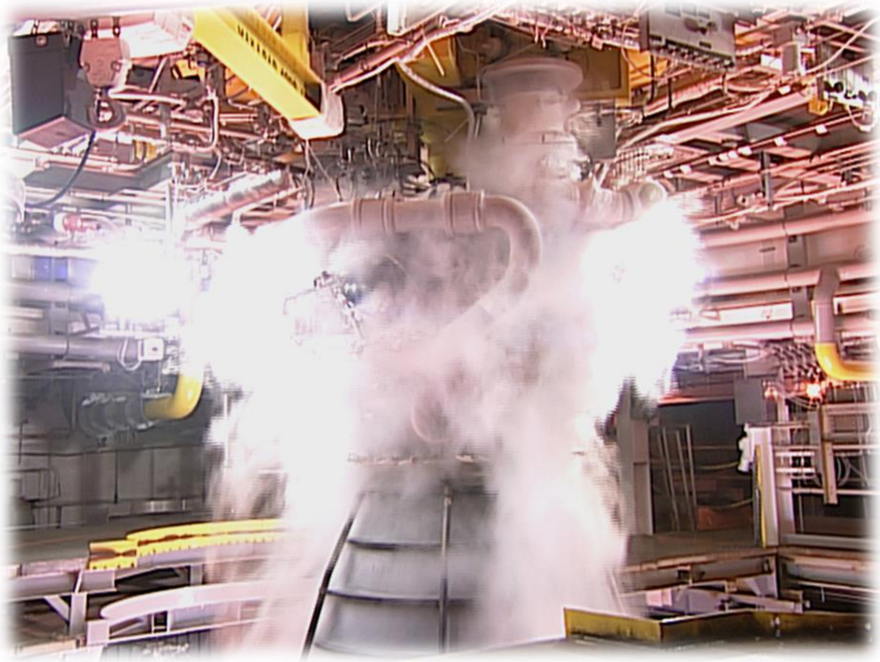




NASA's Space Launch System



FIRST RS-25 ENGINE FIRING

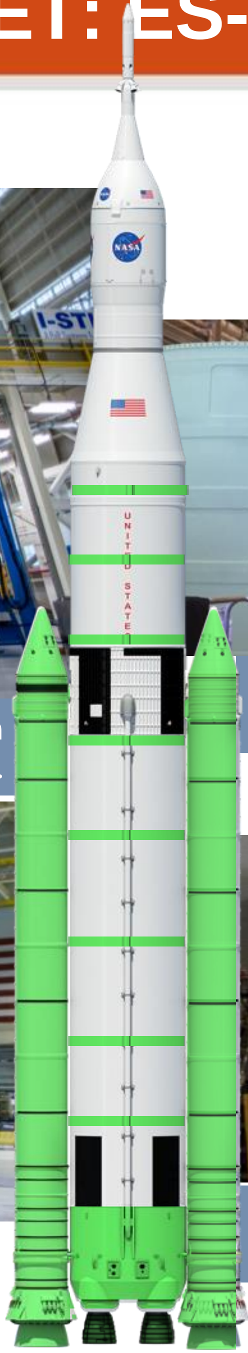


- New engine controller
- SLS inlet pressures

BOOSTER'S FIRST FIRING

THE FIRST ROCKET: ES-10000-001

Core Stage: Initial flight barrels and rings now in inventory at Michoud Assembly Facility.



Boosters: Initial flight hardware in inventory at Kennedy Space Center.

Engines: Sixteen engines currently in inventory at Stennis Space Center.

How Has Use of M&S Helped SLS Early?

Advanced Concepts

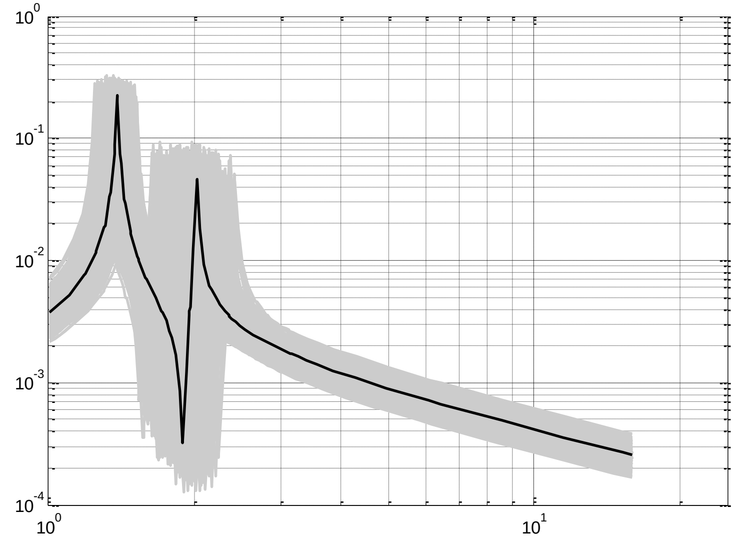
- **INTROS is a MSFC-developed tool that does conceptual launch vehicle design and sizing based on stage geometry and mass properties.**
  - Mass properties are established for selections from a large master list of launch vehicle systems, subsystems, propellants and fluids.
  - Mass calculations are based on mass estimating relationships (MERs) that are automatically generated from a large database of MERs that is built into the program.
  - Program mass calculation accuracy for existing and historical launch vehicles has been verified to be well within 5%.
- **LVA is a MSFC-developed tool that provides fast launch vehicle structural design and analysis.**
  - It supplies detailed analysis by using time proven engineering methods based on material properties, load factors, aerodynamic loads, stress, elastic stability, deflection, etc.
  - This tool and its predecessors have been in use at MSFC for over 25 years.
- **POST is an industry-standard trajectory optimization tool.**
- **Once a candidate configuration is developed in INTROS, these tools are used iteratively to converge on viable design solutions.**

How Has Use of M&S Helped SLS Early?

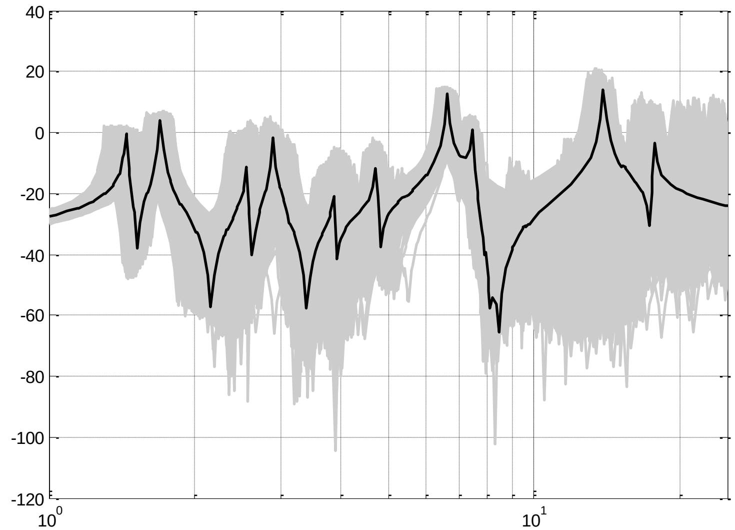
- Prior to SRR/SDR, analyzed items such as these using models
  - Engine out capability
  - RGA number and location
  - Vehicle sizing trade
  - Attitude control (P/Y/R) need for CS/US rate at Payload Separation
  - T-0 stay need, do we need it, where, active damping?
  - Core Stage Engine throttling needs (max dynamic pressure, inlet pressure, separation bolts, max accel)
  - Determined the necessary number of engines for all evolved versions
  - Trajectory runs with CFD-generated line loads
  - Used models for loads generation and aerothermal conditions
  - 6DOF dispersed analysis for insertion accuracy, performance, impact footprint, attitude rates for separation events, trajectories for loads & induced environments, separation clearance analyses
  - Early estimates of Flight Performance Reserve needed without extra conservatism
  - Modeling of heavy/slow and light/fast vehicles

Flex Mode Dispersions vs Finite Element Model Dispersions

- **Traditional techniques for dispersing flex modes**
  - Independent dispersions
    - No correlation between shape and frequency
  - Non-physical responses requires minimal set of modes to be used (~10)
  - Limits spectrum for analysis

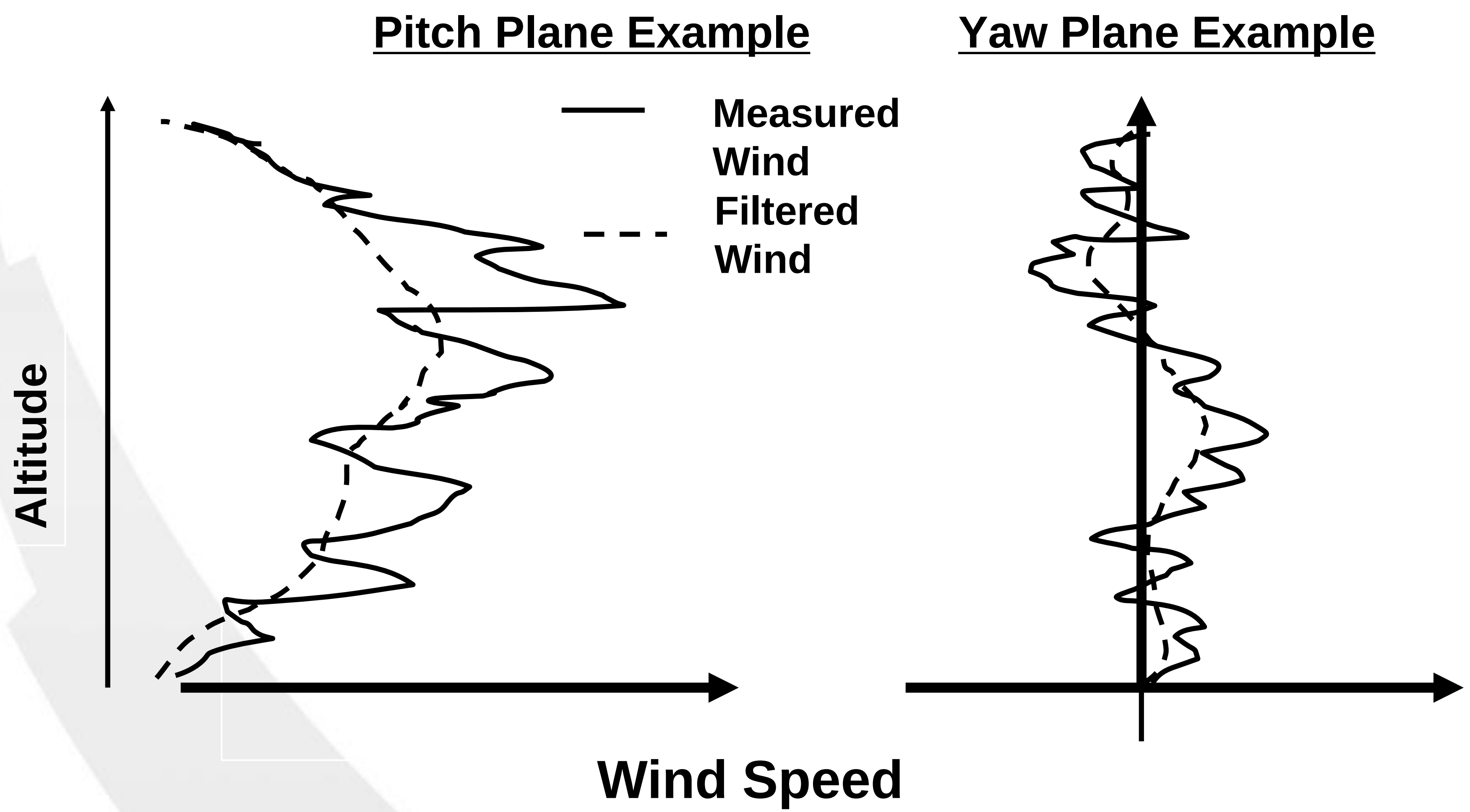


- **Dispersed FEM**
  - Randomly disperse FEM based on input uncertainties
  - Shape and frequency correlated
  - Responses are all physically realizable
  - Significant increase in analyzed spectrum (~200 modes)

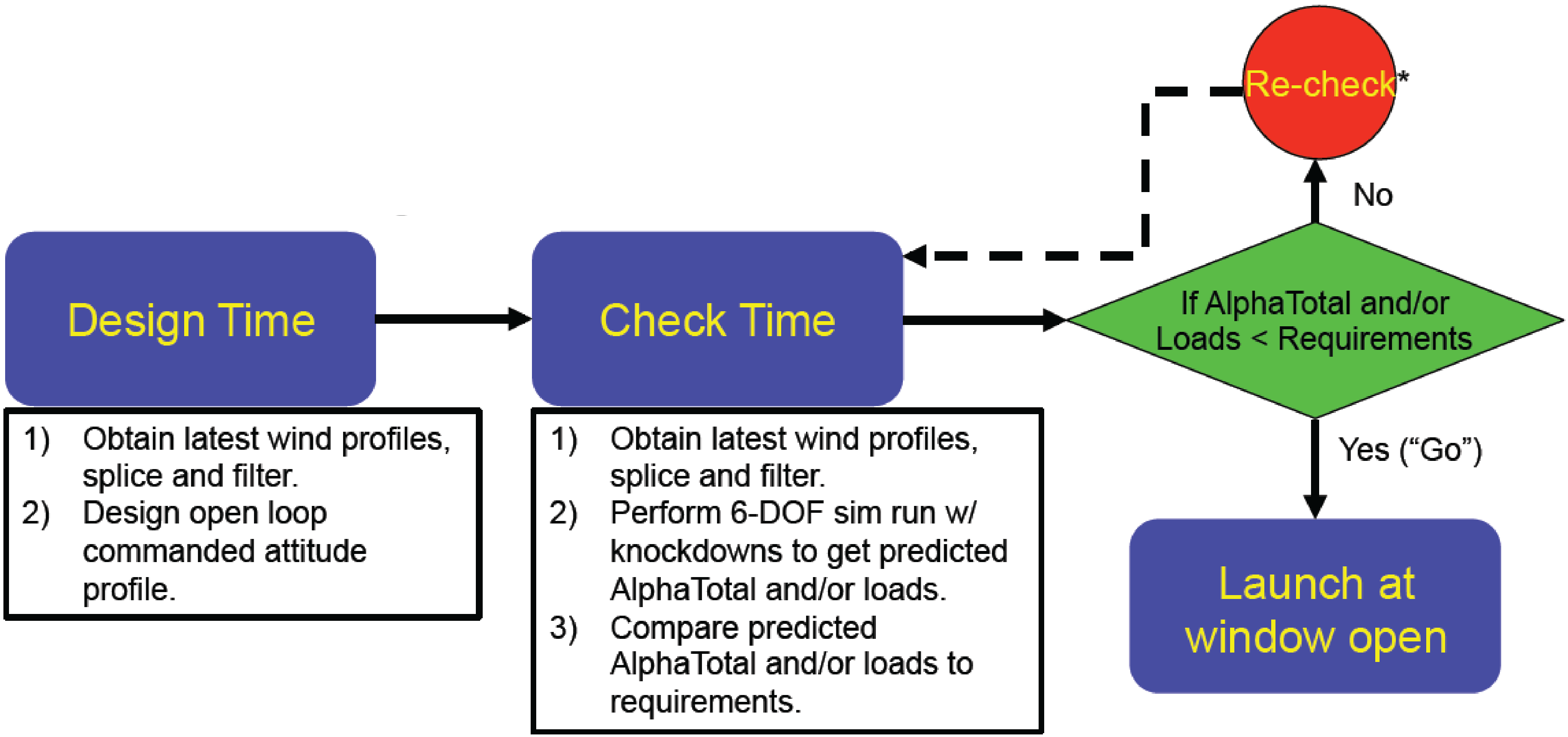


Day of Launch Wind Biasing

- **PDR Time Frame**
  - Day of launch wind biasing to reduce buffet loads by reducing maximum total angle of attack



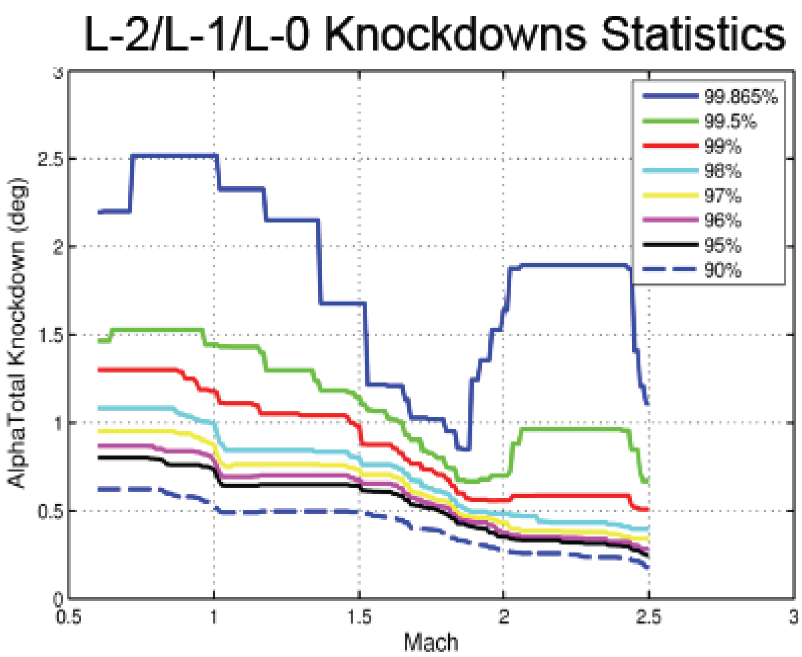
Day of Launch Wind Biasing Process

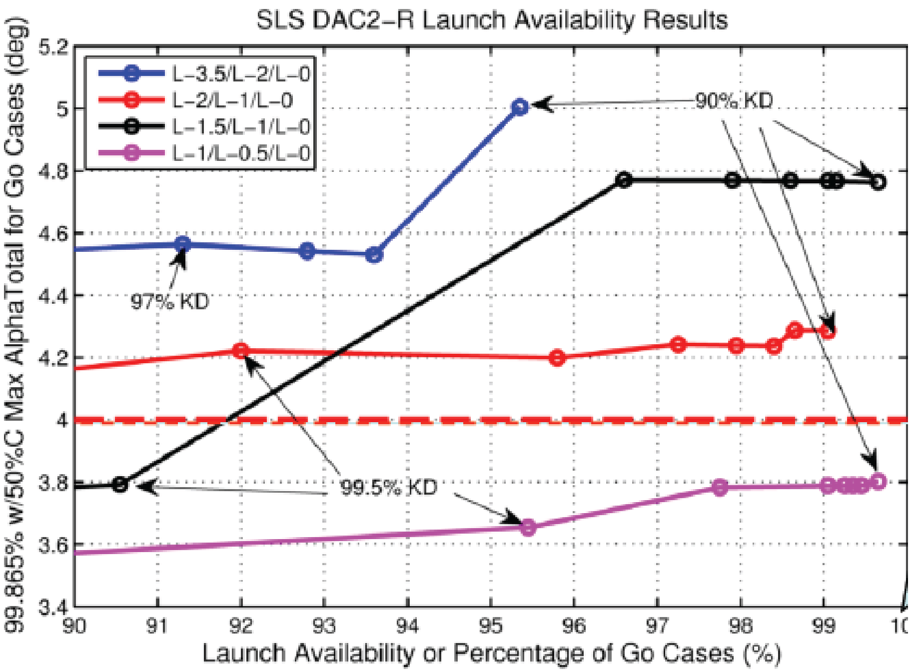


Day of Launch Wind Biasing Process

Examples of Day of Launch Process Results

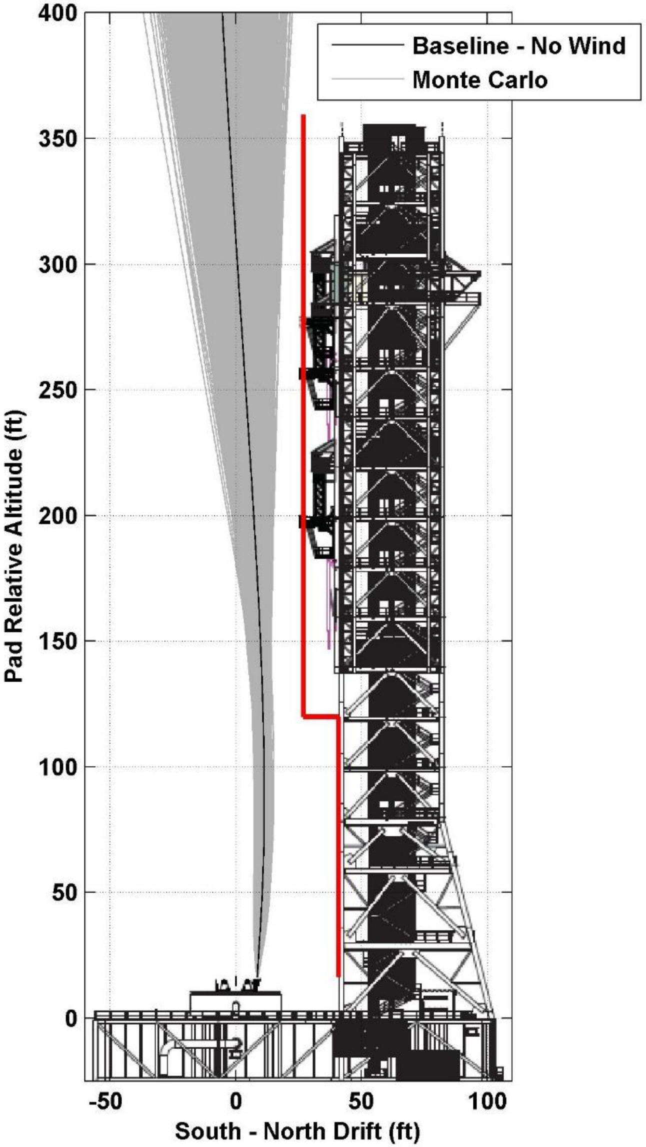
- Enhanced knowledge of correct knockdowns to use
- Enhanced knowledge of launch availability
- Ability to trade parameters, for example wind filtering frequency and wind measurement timeline





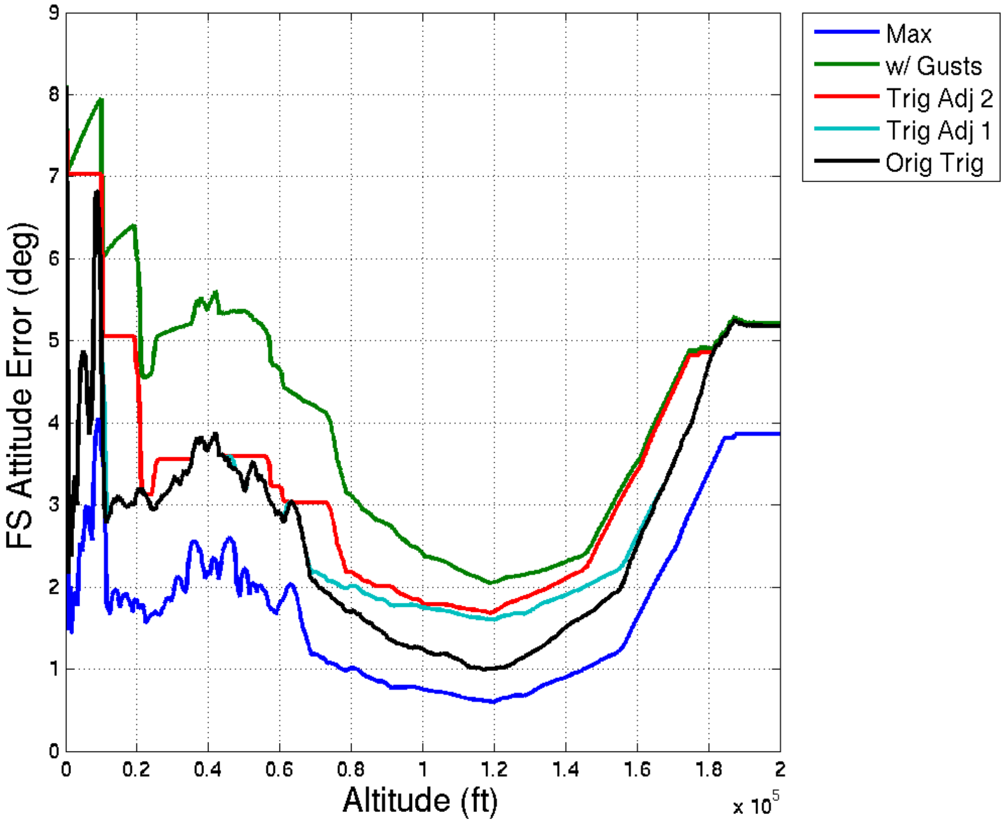
Led to Answers/Design Solutions Early?

- **PDR Time Frame**
  - Designed a good Design Reference Mission for ICPS contractor.
    - –Result of 6DOF Monte Carlo dispersion studies
  - Forward attach bolt adjust and throttle down to relieve excess bolt loads
  - No tower flyaway maneuver and wind placard to relieve acoustic loads
  - Identified inlet pressure concern for stuck throttle cases
  - Resolved controllability concern related to vehicle aft structure flexibility and aft RGA
  - ICPS tank stretch from simulation work
  - Navigation state vector update
- **CDR Time Frame**
  - Aerothermal exceedances for certain engine out cases due to increased angle of attack
    - – Might not have found these previously, or might have needed a lot more work to find them. Simple MC runs overnight, with computer compilation of the results. Found just before CDR. Using simulation to mitigate.



Improved Analysis of Failure Cases

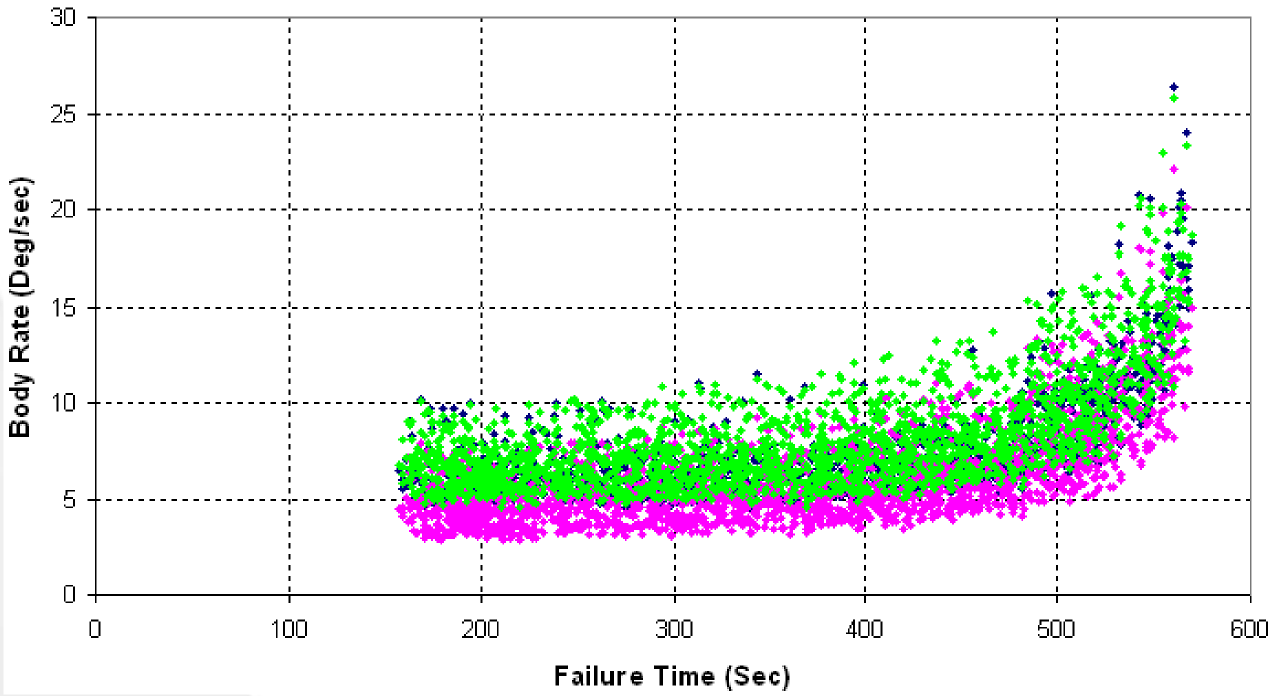
- Failure and abort cases, Monte Carlo nominal and failure runs done early.
- More sophisticated abort triggers improves crew safety.
- Saturn V had a fixed value for a bad case.



Abort Trigger Setting

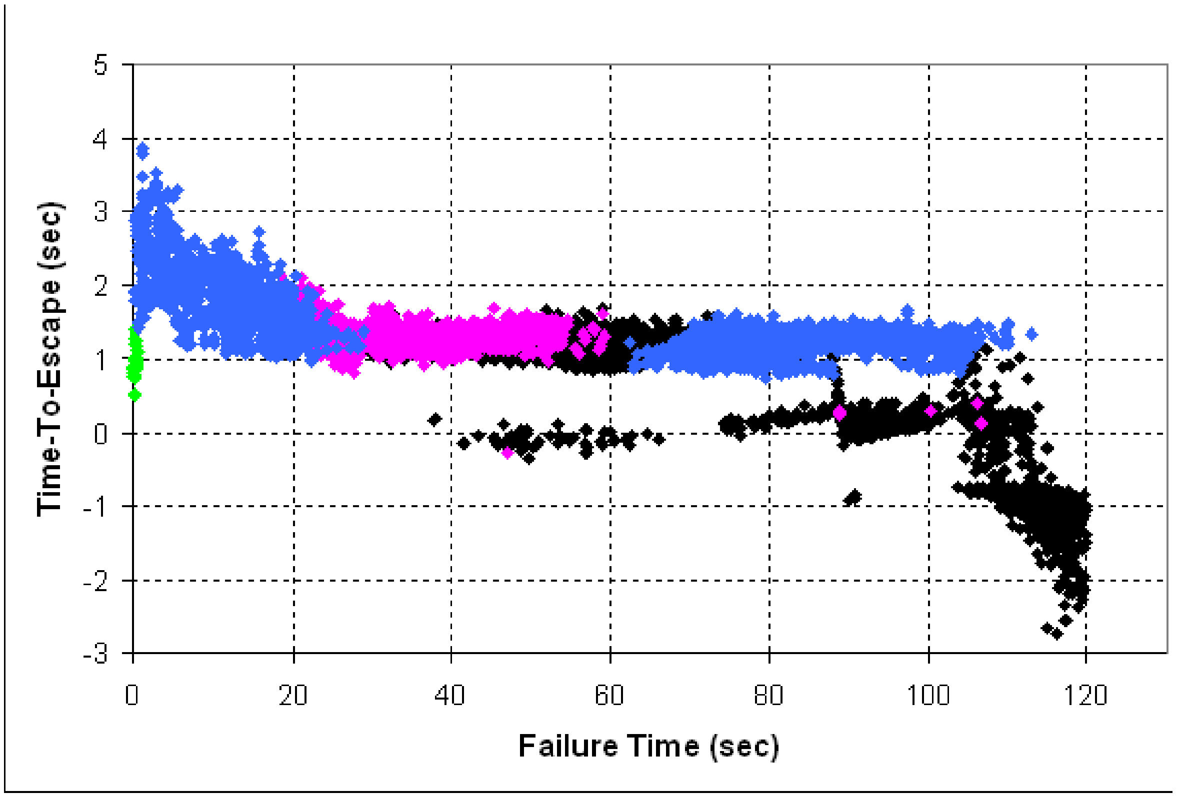
Improved Analysis of Failure Cases

- Actuator hard over in Upper Stage flight after LAS jettison
- Shut engine down as soon as triggers detect the problem
- Different colors are for different trigger combinations



Improved Analysis of Failure Cases

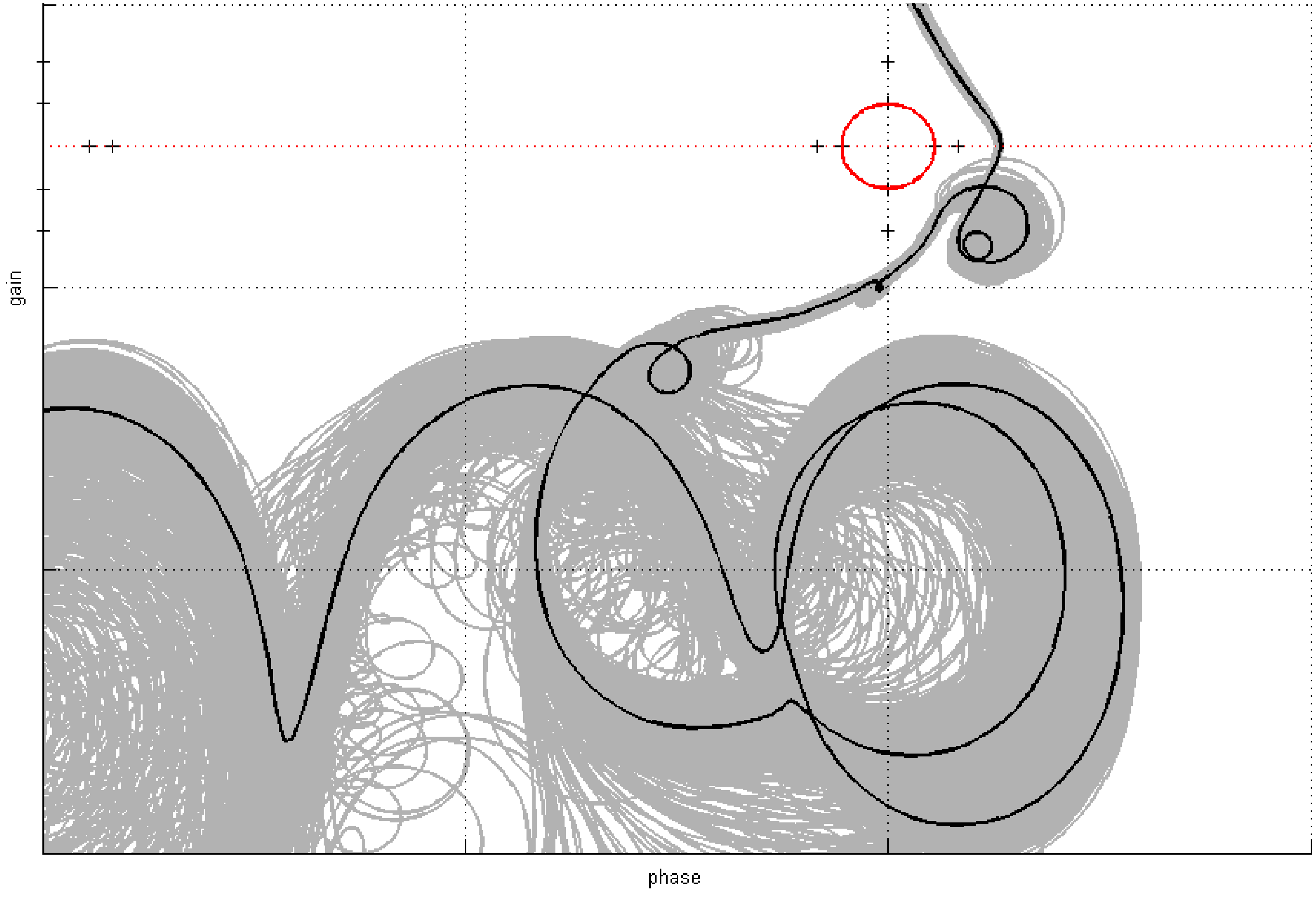
- Excess time (after detecting the failure and departing) available for escape
- Color indicates the first vehicle limit that was exceeded
- Could point to an issue that needs to be worked further



Monte Carlo Stability Analysis

PDR Time Frame

- Monte Carlo analysis of stability margins, allows for reduced conservatism.
- This is a gain in many design areas: instead of piling worst on worst, or bad on bad, Monte Carlo results are statistical.

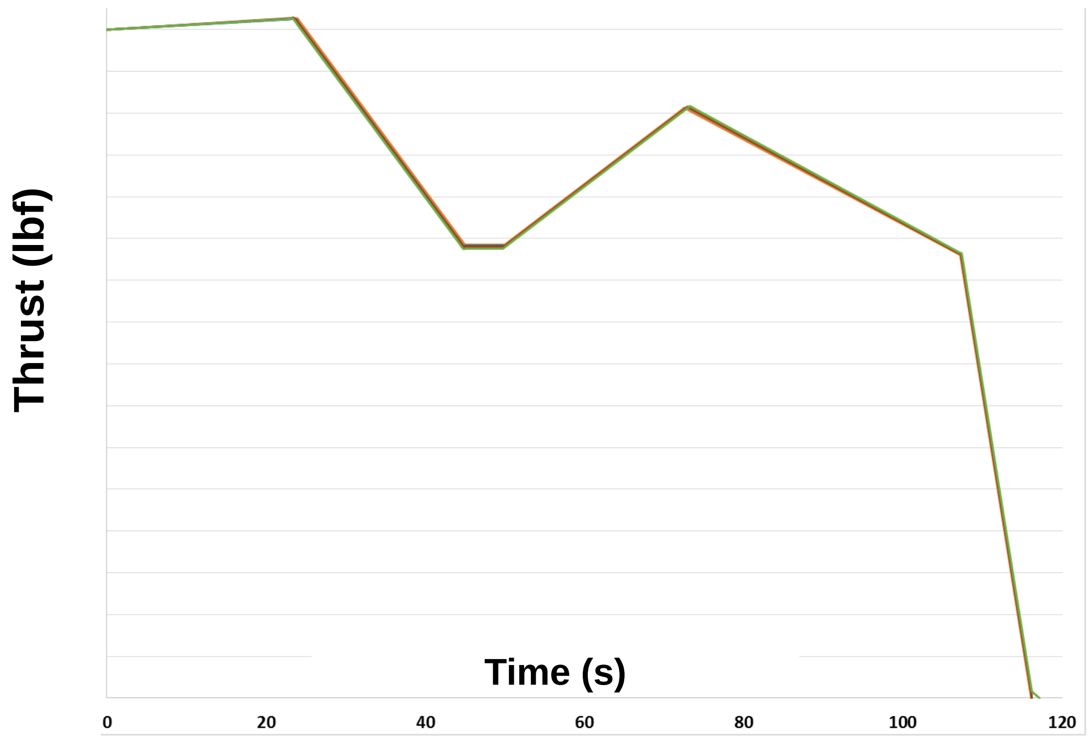


Some Other Uses of Models in SLS

- Using discrete event simulation to model the operations process, assembly, test, etc. To optimize the flow, understand the long poles in the tent, and understand how long each operation will take.

- Modeling of solid rocket booster options using stick traces and rules from Booster Element, to optimize Booster along with resizing of a stage or other trade parameters.

Stick traces with constraints defined by Booster personnel, used by trajectory/sizing personnel



Use of Design Models in SLS

Requirements Goal with Use of M&S

- **Goal - Define a process to employ on SLS to minimize requirements and attendant verification using engineering models.**
- **Why?**
  - Reduce the verification effort necessary for the Elements to satisfy vehicle-level requirements specifying the details of the system design
  - Reduce the verification effort necessary at the integrated vehicle level to track and roll up verification of all the detailed requirements
  - Allow the Elements the flexibility to adjust the detailed subsystem values to Element benefit without requesting approval for each detailed change
    - Don’t specify each detail, only control the output of the system model
  - Use of a single model for a system guarantees that the system-level impacts of changes will be visible, whereas specifying the detailed individual values does not. The model is needed anyway; the requirements are not.
  - Avoids the experience of having a system design that works, models that accurately show its behavior, but having to negotiate what the detailed requirements should be and how to verify them.
    - e.g. TVC model works, but in standard approach would negotiate detailed TVC requirements.
  - Reduces resulting conservatism

Key Points used in determining which Parameters to Elevate to a Requirement

- **If the System is Sensitive to the Model Parameter Limits and the Limits are a design driver, ELEVATE**

- **Not elevating a Model Parameter saves resources**
  - Determining the ‘hard’ limits for parameters can be an intensive analytical effort
  - Debates on adequate margin included in a requirement can be prolonged
  - Each additional requirement adds documentation and tracking

- **The program accepts the additional Risk when a requirement is not elevated**
  - Cost/Schedule Risk if we have to set a new requirement to get a model parameter “back in the box”
  - Or technical risk of accepting the model parameter as is

Examples of which model parameters are elevated to requirements

	Elevated to Requirements	Model Output Parameters
Mass Properties	Dry Mass, Prop Load Limits *-Rationale: directly affects SLS requirements, clear limits known*	Time dependent Cg *Rationale: Vehicle can accommodate multiple solutions, just needs to know the correct values*
Thrust Vector Control	Core Stage Gimbal range and rate *Rationale: Limits are significant driver in Core Stage design and limits are needed for design to proceed*	Booster Gimbal range and rate: *Rationale: Parameters are based on heritage and little risk that model outputs will become unacceptable.*
Inertial Navigation System	Vehicle Position Accuracy *Rationale: INS design and the navigation accuracy are highly sensitive to this parameter and limits are needed for design to proceed.*	Vehicle Position *Rationale: Producing this output is part of the functional design definition of the INS and an auditable parameter*

Inertial Navigation System Example

Traditional Requirements for INS System could result in <u>230 Shall Statements</u>

◆Requirements for anti-aliasing portion:

- The inertial measurements shall be anti-aliased
- Anti-alias filter shall have a bandwidth of 29.5 Hz
- Anti-alias filter shall execute at a minimum sample frequency of 250 Hz
- Anti-alias filter shall have a maximum phase lag of 5 degrees at 1 Hz.
- Anti-alias filter shall have a maximum gain of +/- 2e-3 dB at 1 Hz
- Anti-alias filter shall have a minimum attenuation of 6 dB at 20 Hz

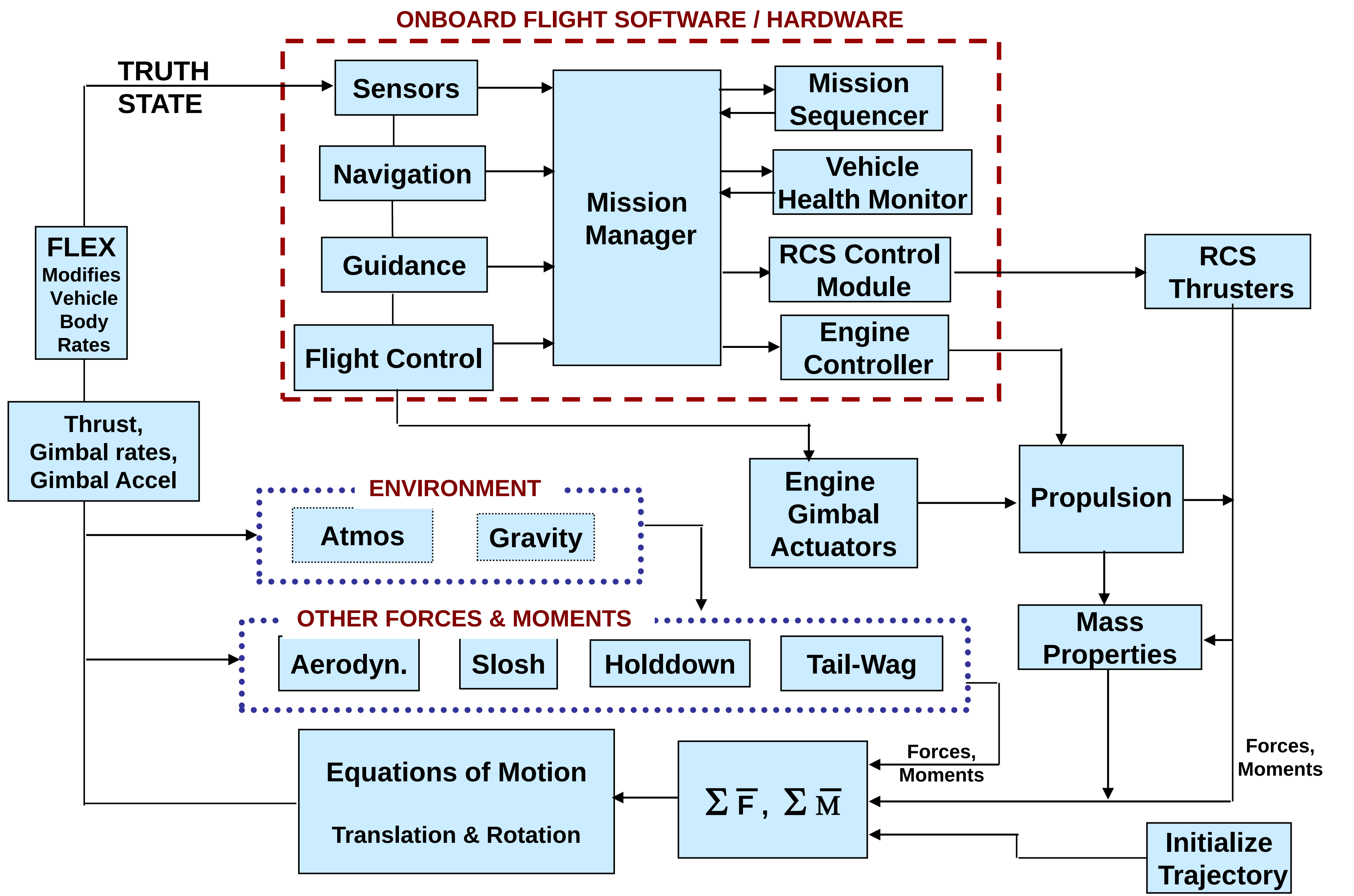
◆Anti-Aliasing Filter Implementation Model in Code

Model Input Data:

```
TF_method       3       # 2nd order TF method:
                        #   1) continuous with Euler integration,
                        #   2) continuous using MAVERIC integration,
                        #   3) discrete with Tustin transform
enableTFdyn_w   1       # enable 2nd order transfer function
omega_w_hz      29.5    # Gyro bandwidth frequency (Hs)
zeta_w          0.6     # second order damping factor
TF_T_w_hz       250.0   # Sampling freq for discrete filter (Hz)
enableTFdyn_a   1       # enable 2nd order transfer function
omega_a_hz      26.5    # Accel bandwidth frequency (Hz)
zeta_a          0.6     # second order damping factor
TF_T_a_hz       250.0   # sampling frequency for discrete filter (Hz)
```

- ◆ **Implementation in Code – little ambiguity in intent or assumptions**
- ◆ **Alternate implementations are available. If coefficients are specified, they would be dependent upon a fixed execution rate, and therefore could be constrained.**
- ◆ **Alternate designs are possible. As long as the vehicle-level needs are satisfied, these can be explored without detailed requirements revision.**
- ◆ **Customer works directly with the subsystem folks to agree on the model that meets the integrated vehicle needs and works best for the Element**

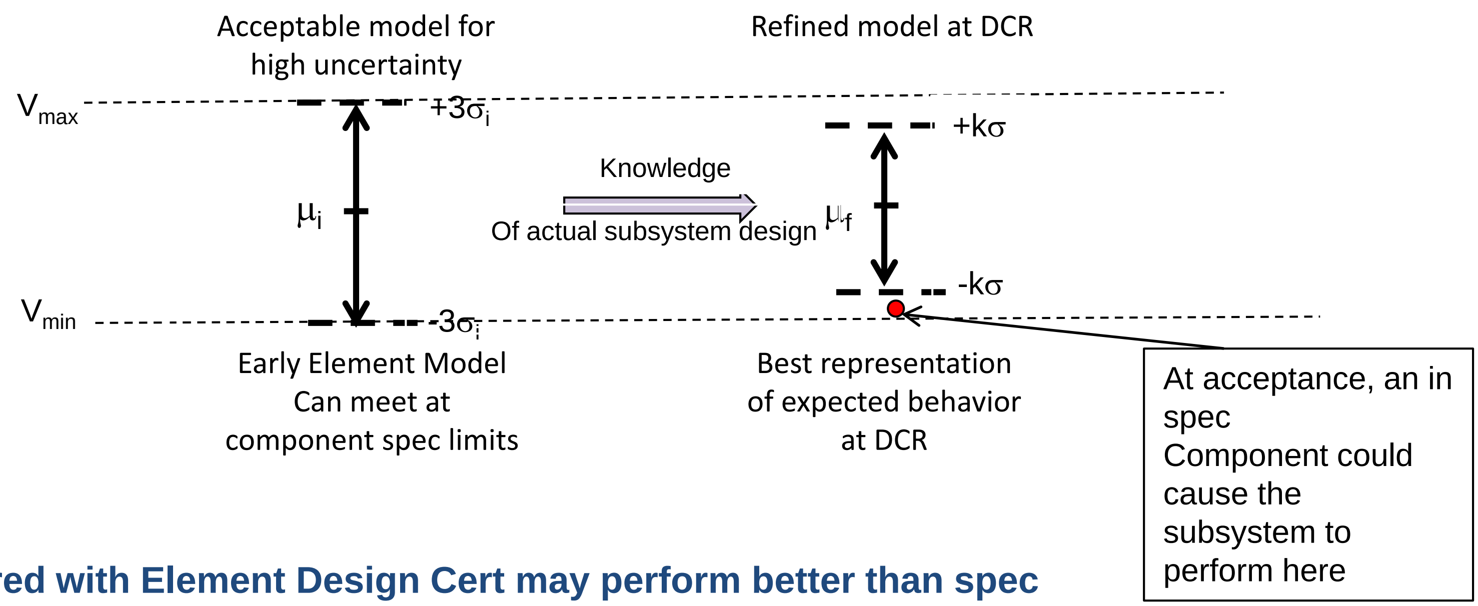
Model Used for Requirements Compliance



Types of Models Used for SLS at the Vehicle Level

- Element system models (propulsion, finite element, mass properties, TVC, navigation, …)
- Avionics box models
- Vehicle models (aerodynamics--16, finite element, mass properties, MPS, …)
- Integrated simulations (MAVERIC, CLVTOPS, ML_Pogo, …)
- Requirements definition (aerothermal, venting, loads, debris, …)
- Guidance, Navigation, and Control (GN&C) model
- Mission and Fault Manager
- Probabilistic Risk Assessment
- Discrete Event Simulation for operations planning

Design Model Verification



- **Models delivered with Element Design Cert may perform better than spec limits**
- **If acceptance data is outside the performance of DCR models, the models will be updated and flight performance will be reassessed as part of system acceptance**

Element model delivery:

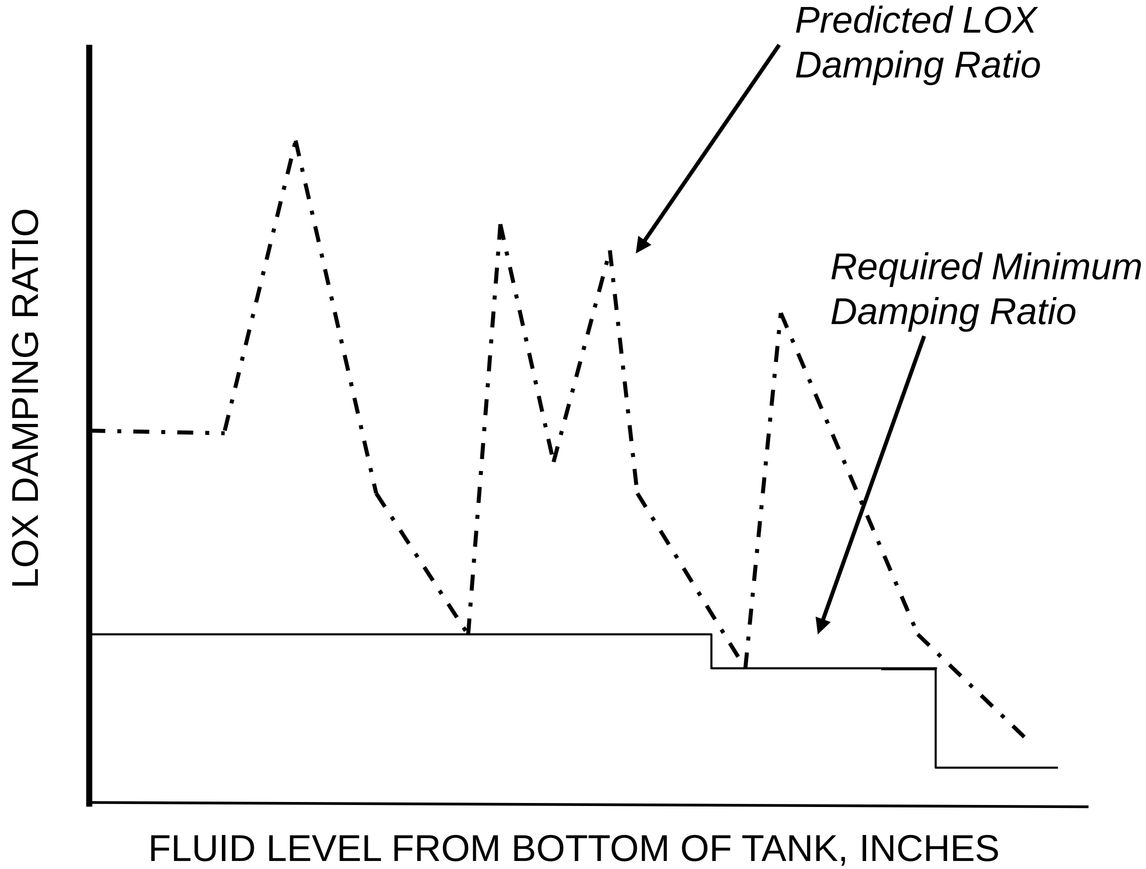
- **Models are developed in accordance with *SLS-PLAN-173, SLSP Modeling and Simulation Plan***
- **Design models used at the System Level are maintained in the *SLS-RPT-105, SLSP Design Model Log***
- **Models are delivered in accordance with *SLS-STD-038, SLSP Design Model Delivery Standard***

Some Advantages of Using Models

- Vehicle level doesn't need to see the verification of each detail, just that the model matches the hardware and meets the top-level vehicle needs
- If the contractor wanted to propose a completely new system, e.g. GPS/INS, it would be reflected by a completely different model. Using the approach of many detailed requirements, the contractor is led to a specific INS solution or has to change many requirements in order to change the system. With the model-based approach, if the new model meets the vehicle needs, changing to the new system is much easier.

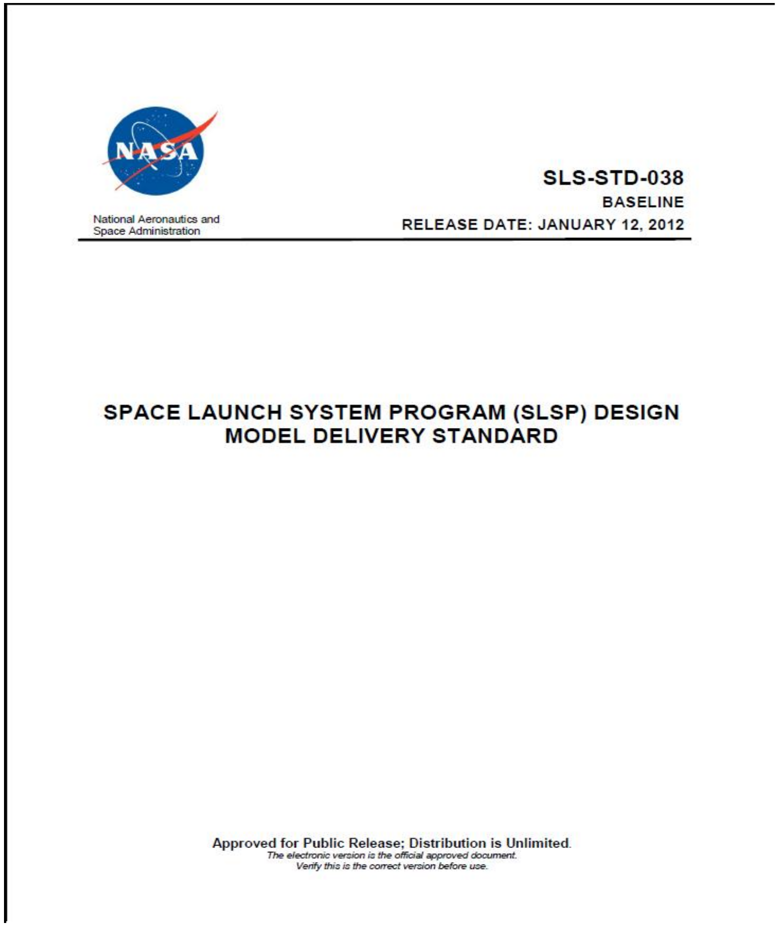
Models May Not Work Best in All Cases

- **For example, slosh damping requirements**
  - Model is a complicated characterization of slosh behavior
  - Requirement characterization is simple, and exceeding the required value is all that is needed (see figure)
  - A model is still necessary



The Design Model Delivery Standard

- SLS-STD-038 uses a streamlined subset of the Credibility Assessment Factors defined in the NASA Modeling and Simulation Standard (NASA-STD-7009)
- Model verification and validation, for this specific use, are thus established and uncertainties reported before a model is baselined
- Reassessed with each model delivery or update



National Aeronautics and Space Administration

SLS-STD-038
BASELINE
RELEASE DATE: JANUARY 12, 2012

SPACE LAUNCH SYSTEM PROGRAM (SLSP) DESIGN MODEL DELIVERY STANDARD

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The electronic version is the official approved document.
Verify this is the correct version before use.

Design Models Meta Data

- **The meta data controlled with the design models**
  - Bookkeeping (Identifier, Version, Release Date, Model Name, SLS Element/Subsystem, Dependencies on other models, Milestone applicability)
  - Statement of Intended Use
  - Technical Description of Model *spells out the required system inputs, outputs, test cases*
  - Assumptions
  - Operational Phase *(applicability)*
  - Verification
  - Validation
  - Results Uncertainty *(identifies and quantifies uncertainty of model output)*
  - Results Robustness
  - Limitations *(provides boundaries on the set of parameters for which a model result is valid)*
  - Input Pedigree *(includes the uncertainty of input data)*
  - Use History
  - Conservatism
    - So that an evaluation can be performed when the design is sensitive to the model, and so that conservatism doesn't get piled on top of conservatism.

Conclusion

- Modeling and Simulation has enabled SLS to
  - Reduce cost
  - Find issues sooner
  - Provide higher fidelity results
  - Allow more design flexibility
  - Reduce excess conservatism
  - Provide for increased mission success and crew safety