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Independent Verification and Validation of Artemis I Ascent Integrated Flight Performance Simulations

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Artemis I Trajectory

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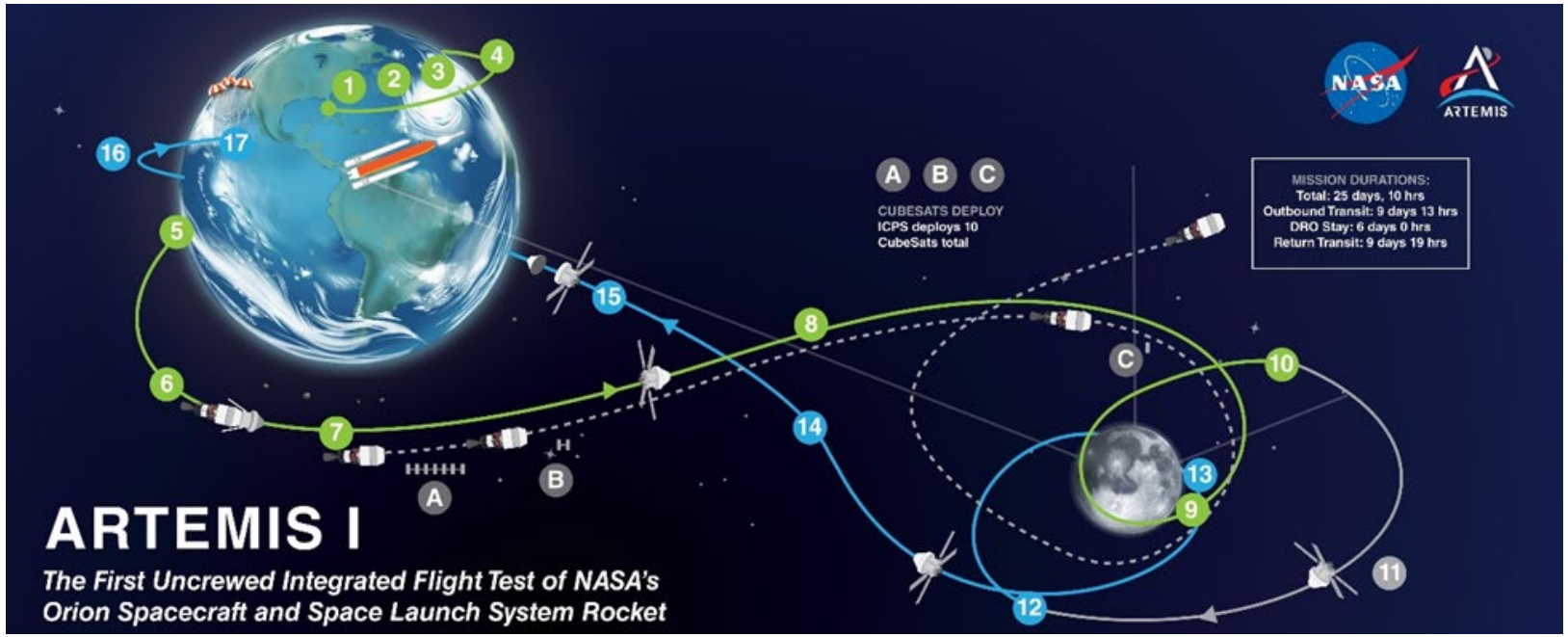
- **Outbound Transit (1 – 10)**
  - (1) Launched from Complex 39B at NASA's KSC (Nov. 16, 2022)
  - (2) Booster Jettison
  - (3) Core Stage Separation
  - (6) Trans Lunar Injection Burn
  - (10) Lunar Orbit Insertion
- **Distant Retrograde Orbit (DRO, 11)**
- **Return Transit (12 – 17)**
  - (12) DRO Departure
  - (14) Return Transit
  - (15) Orion & Crew Module Separation
  - (16) Orion Re-Entry
  - (17) Orion Splashdown (Dec. 11, 2022)



- SLS atmospheric ascent
- Postflight verification & validation of integrated flight performance simulation
  - Space Launch System (SLSP) Program & NASA Engineering and Safety Center (NESC) joint effort

Overview

Simulation Tools:
- Flight Performance Simulation Tools
- POST2

Postflight Analysis:
- Analysis Goals
- Postflight Simulation Updates

Results:
- Artemis I vs. Simulated Results
- Future Work (Artemis II)

SLS Launch (Artemis I) on Wednesday, November 16, 2022, from Launch Complex 39B at NASA's Kennedy Space Center in Florida at 1:47 a.m. EST
(Image Credit: NASA/Bill Ingalls)

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Simulation Tools

Flight Performance Simulation Tools

POST2

Flight Performance Simulation Tools

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Tool		NASA Center	Language	Postflight Analysis Data Product
Marshall Aerospace Vehicle Representation in C	**MAVERIC**	MSFC	C/C++	Nominal Trajectory
CLVTOPS (A TREETOPS derived tool)	**CLVTOPS**	MSFC	FORTRAN Python	Nominal Trajectory
SPACE Transportation & Aeronautics Research Simulation	**STARS**	LaRC	MATLAB Simulink	Nominal Trajectory
Program to Optimize Simulated Trajectories II	**POST2**	LaRC	C	Nominal Trajectory 2,000 Dispersed Trajectories

Flight Performance Tool: POST2

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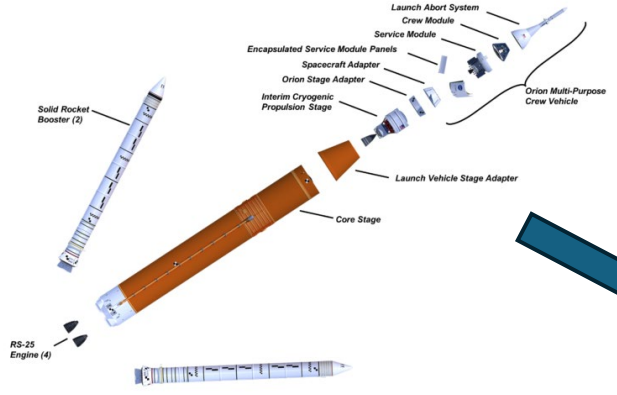
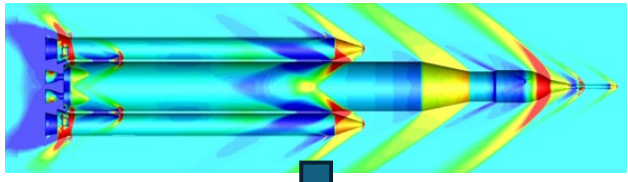
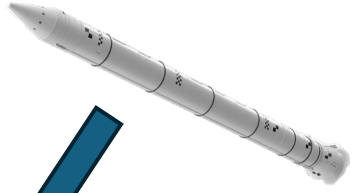
Component Mass Properties



Aerodynamics



Boosters

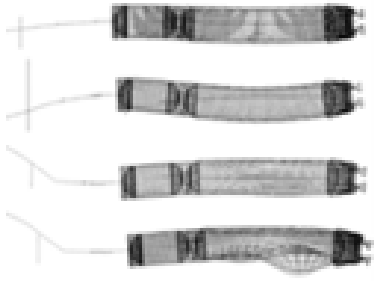


Thrust Performance
Actuators
Transients
Separation Motors

POST2

Integrated Performance
Trajectory Propagation
Multi-Body Dynamics
Monte Carlo

Flex & Fuel Slosh Models



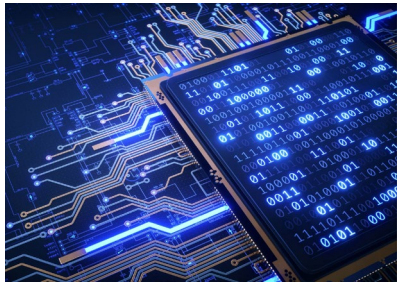
Core Engines

Thrust Performance
Actuators
Transients
Throttle

Ground Support

Launchpad Support
Launch Tower Support
Umbilical Separation

Flight Software



Planetary Conditions

Atmospheric Models
Gravitational Field
Ellipsoid Dimensions

Postflight Analysis

Analysis Goals

Postflight Simulation Updates

Postflight Analysis Goals: Reconstruction vs. Reconciliation

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Trajectory Reconstruction

Question:

- **What is the best estimate of the vehicle's trajectory?**

Process:

- Filter out noise from flight measurements
  - Kalman Filter
  - Utilizes as much data as possible (flight measurements, boundary conditions, etc.)
- Filtered results allow for computation of additional trajectory parameters

Product:

- Produce a Best Estimate of Trajectory (BET) dataset
- BET produced by SLS Program

Trajectory Reconciliation

Questions:

- **How well can our simulation match the BET?**
- **Do our dispersed results encompass the BET?**

Simulation Updates:

- Preflight simulations required of Day of Launch (DOL) conditions & performance

Simulation Results:

- Nominal simulation results compared against the BET
  - Error, percent difference, & qualitative comparisons
- Monte Carlo results bound the BET
  - Qualitative comparison
  - BET data outside Monte Carlo bounds was considered a flight scenario beyond simulation predictions

End Goals:

1. Refine flight simulation tools ***prior to***…
   a) Postflight Separation & Clearance Analyses
   b) Future SLS Analyses & Flights
2. Confirm that our simulations are "flight-validated"
3. Investigate areas for future model improvements

Postflight Simulation Updates

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Postflight Simulation Setup

- Sims updated with as much Day of Launch (DOL) data as possible
- Remaining models relied on pre-flight engineering estimates:
  - Flex
  - Fuel Slosh
  - Aerodynamics
  - Actuators
  - Monte Carlo Dispersions
  - Etc.

Analysis

- Simulated results were compared against the BET
- Simulations were compared against each other

Nominal Trajectory Model Updates	
Atmosphere & Winds	DOL Atmosphere & Wind Measurements
GN&C	DOL GN&C Inputs
Mass Properties	Reconstructed Initial Mass Properties
SRBs	Reconstructed SRB Performance
Core Engines	Reconstructed Core Engine Performance Adjustments
Aerodynamics	Reconstructed Base Force Profile

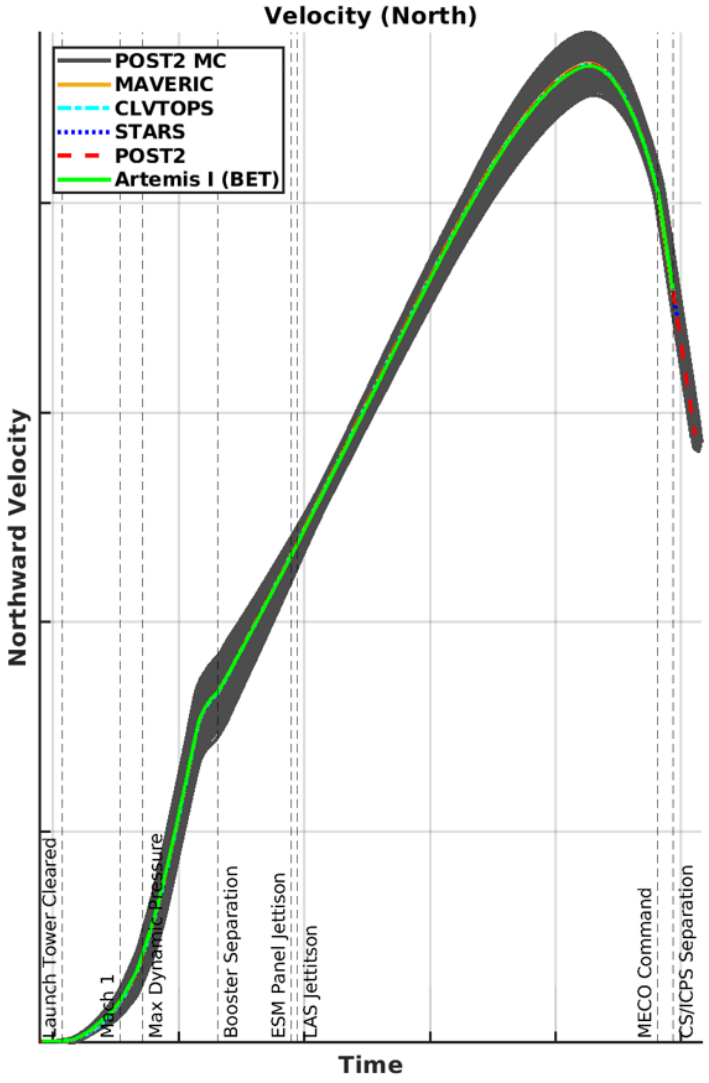
POST2 DOL Monte Carlo	
Atmosphere Winds	Undispersed
GN&C	Optimized steering inputs ***not*** generated for each dispersed trajectory

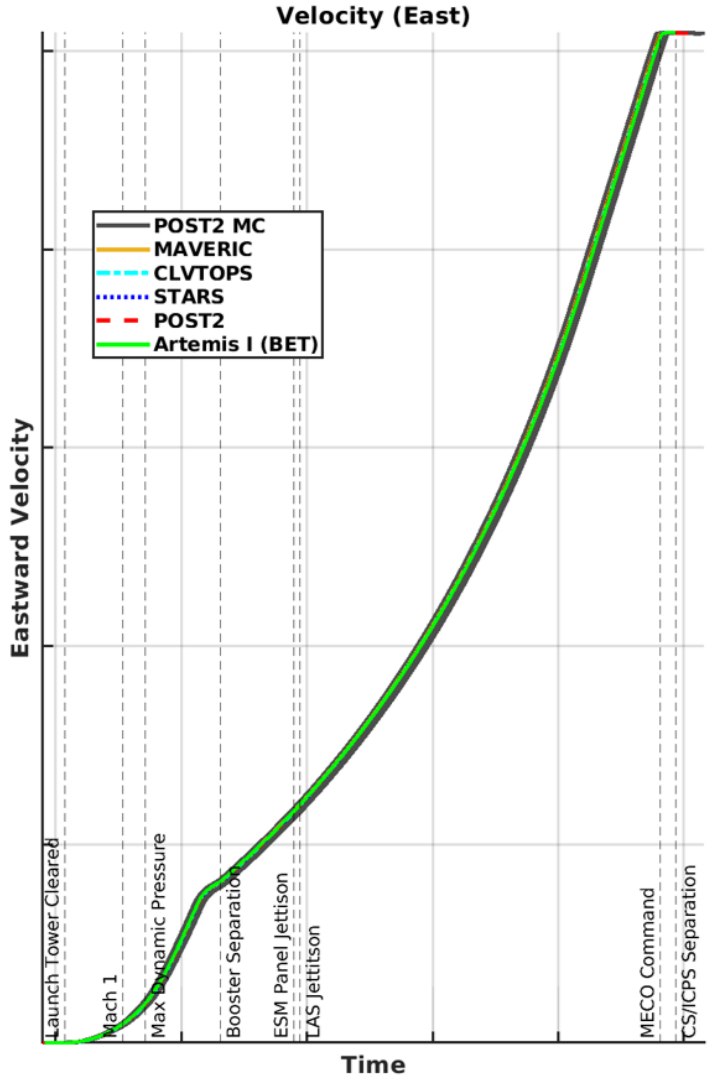
Results

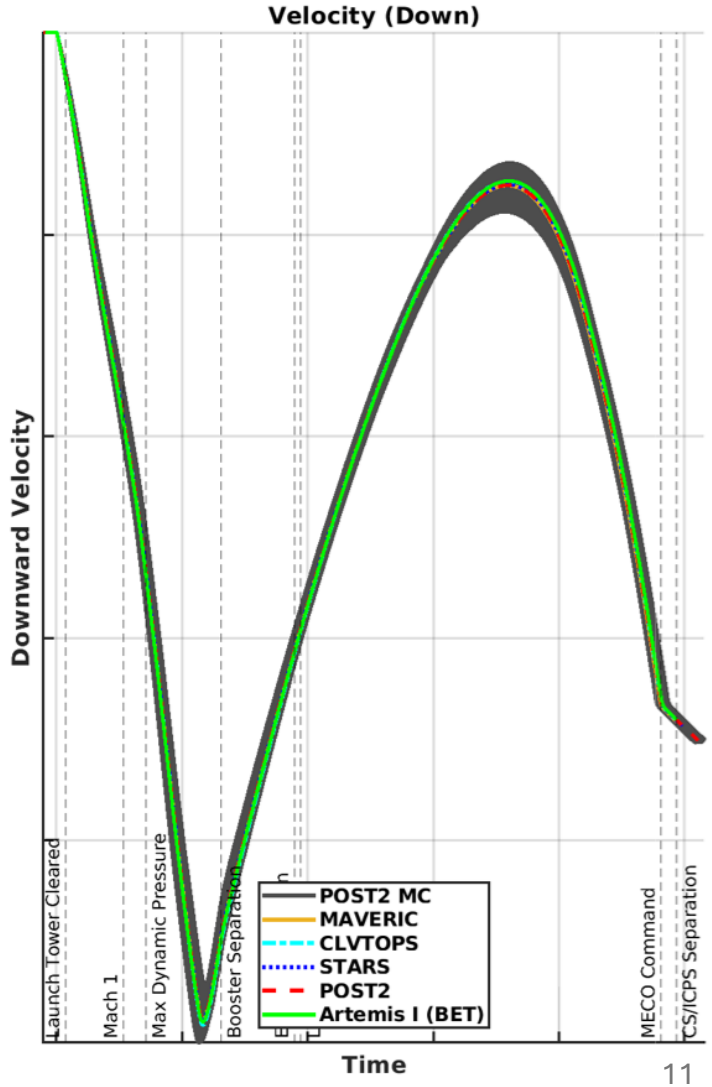
Artemis I BET vs. Simulated Results

Future Work (Artemis II)

Results: Vehicle Velocity







Results: Body Accelerations

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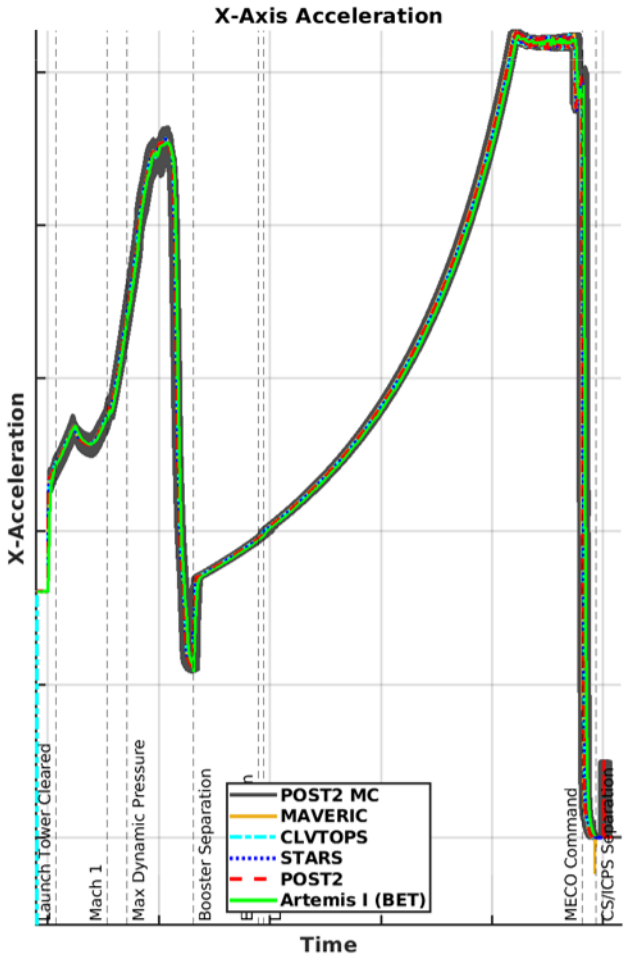
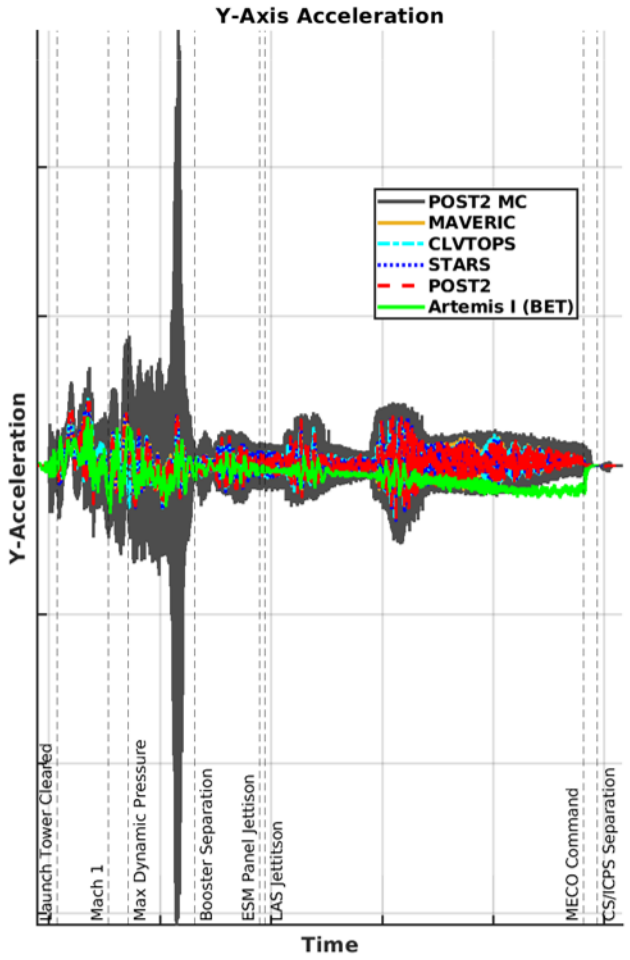
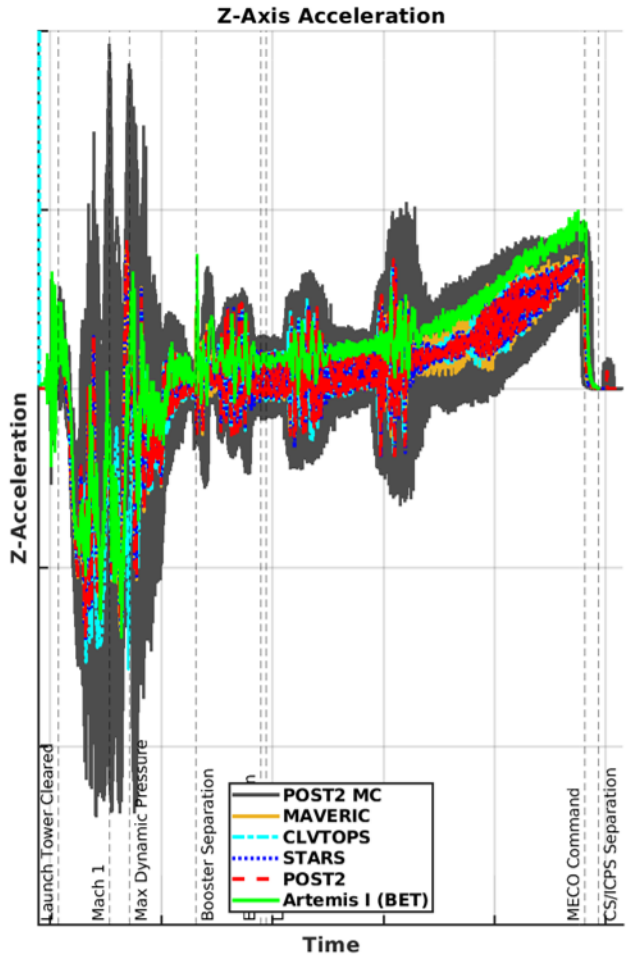
Proposed Explanations

- Accelerometer Bias:
  - Not sufficiently filtered
  - More biased than expected
- LAS Separation:
  - Hardware damage
  - Change in temp
- Mounting Misalignment
- Unmodeled Effects
  - Slosh
  - Flex
  - Aerodynamics







Simulated Roll Rate: Mid Trajectory

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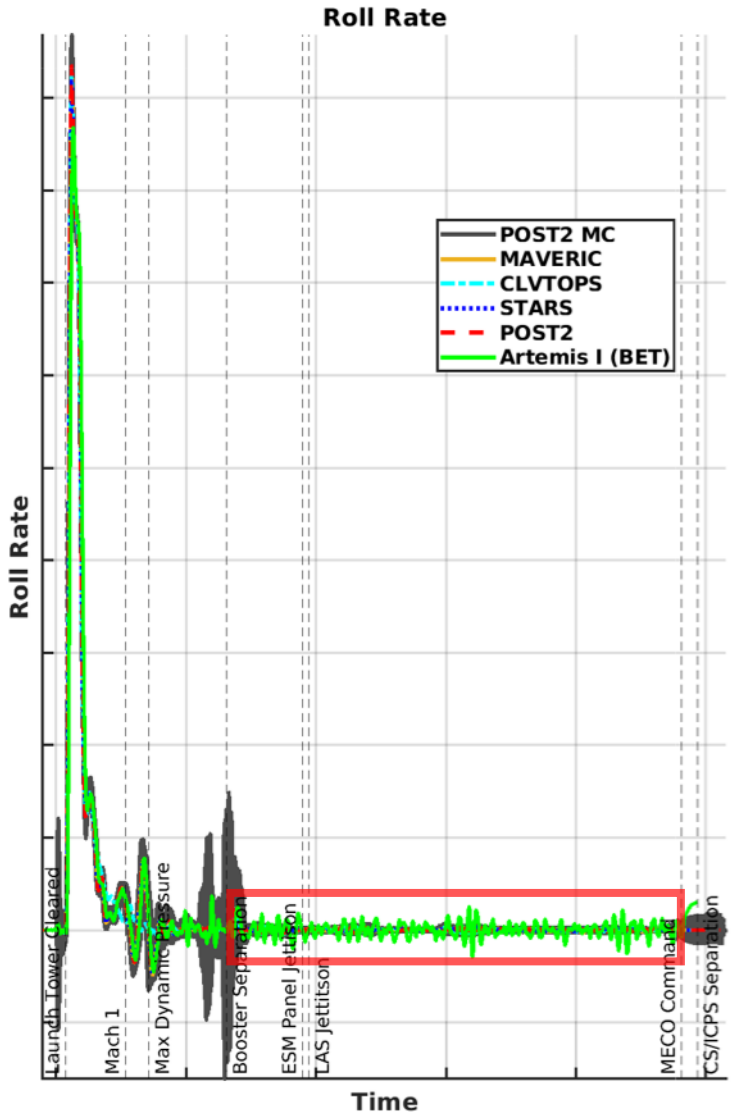
Roll Rate

- Core Stage Engine gimbal friction modeling did not fully capture the complexities of flight day performance

Expected that updates to this model will…

- More accurately match the BET by adequately capturing observed roll rate oscillations



Roll Performance: Tower Clearance Roll Maneuver

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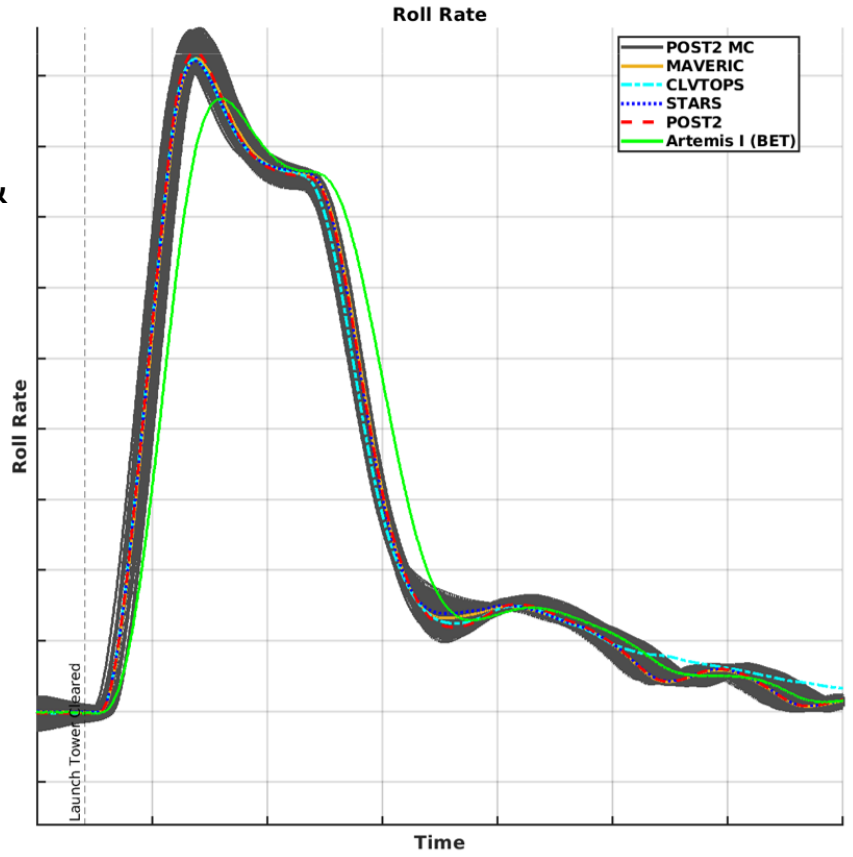
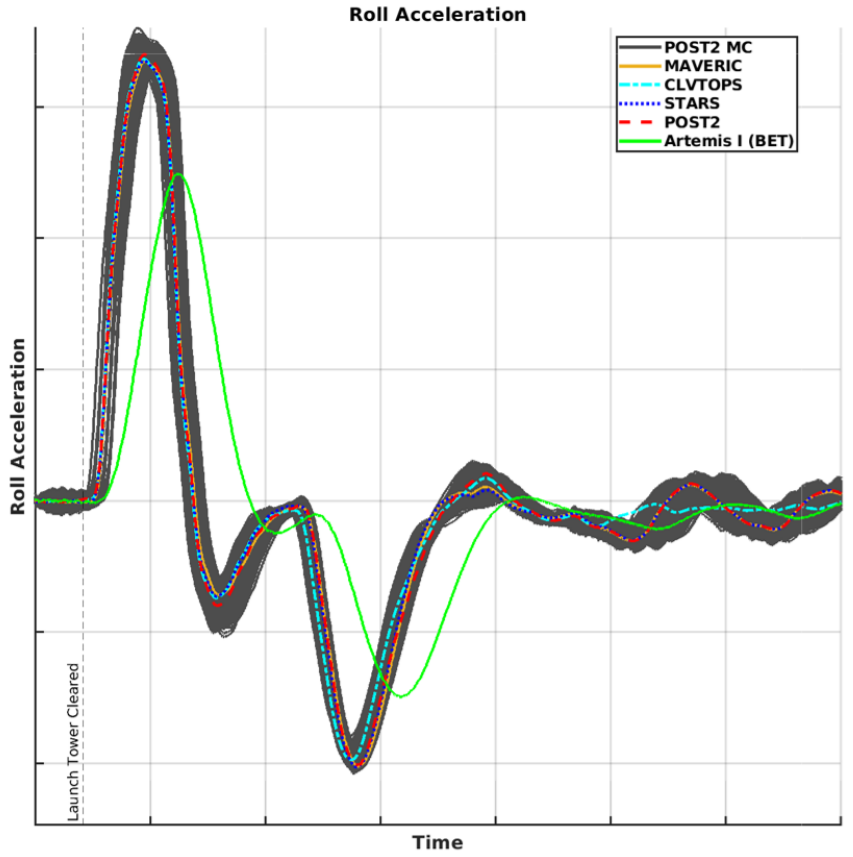
Observations

- Simulated peak Roll Rate & Roll Acceleration greater than BET
- Simulated Roll Rate & Acceleration is out phase with BET
- Simulation results overperform roll & pitch maneuver
- One of the most significant differences between BET & simulation results
  - Maximum Percent Error ≈ 10%

Explanation

- BET Artifact
- Noisy measurements collected during roll maneuver
- Low Pass filter used to evaluate flight measurements
- Signal Delay & reduction in max Roll Rate





Summary & Future Work

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Summary

- Artemis I simulations were updated and refined ***prior to***…
  - Postflight Separation & Clearance analyses
  - Future SLS analyses & flights
- Four independent simulations were compared against the BET results
  - Simulations were flight-validated
- Model limitations were identified & documented by the NESC and the SLS Program

Future Work (Artemis II & Beyond)

- Additional comparison of pre-flight predictions vs. BET:
  - **“How accurately can we *predict* SLS flight performance?”**
  - **“How much did DOL simulation inputs change?”**
- More quantitative comparisons rather than qualitative

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Acknowledgements

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- Ben Burger, Joey Harlin, Thomas Park, Frank Willis, Nick Hoen, and the rest of the SLSP for their collaboration and feedback involved with this analysis, for generating their respec-tive DOL simulations, and for generating the many postflight data products that collective-ly make up the BET for this postflight comparison effort that are listed in Table 2 and Appendix A.
- The NESC for supporting this work under NESC Assessment TI-12-00766, “Exploration Systems Independent Modeling and Simulation.”

Backup

Summary of Data Products

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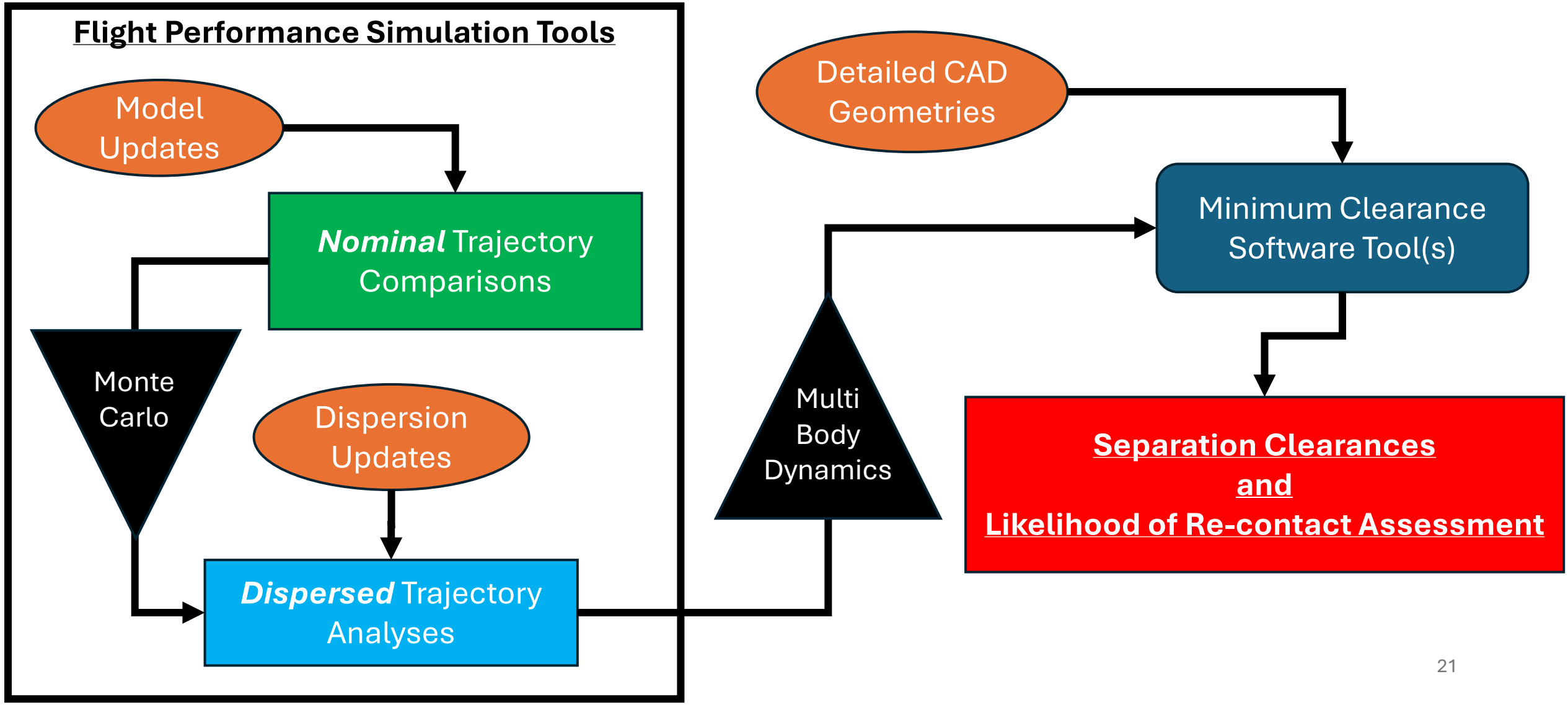
BET Data Products	
Trajectory Reconstruction	• Vehicle States • Trajectory Parameters
Aerodynamics	• Aerodynamic Coefficients • ***Base Force Profile****
Engine Performance	• ***SRB Thrust Profiles****
Atmosphere & Winds	• ***Temperature**** • ***Pressure**** • ***Density**** • ***Wind Speeds****
Mass Properties	• Mass • Center of Gravity • Inertias
Event Timing	• Time-Stamps of Major Trajectory Events
Telemetry	• Raw Flight Measurements

Simulation Data Products	
MAVERIC	• Nominal Trajectory
CLVTOPS	• Nominal Trajectory
STARS	• Nominal Trajectory
POST2	• Nominal Trajectory • 2,000 Dispersed Trajectories

**** Used as BET and simulation input***

Simulation Process



Mach Number & Dynamic Pressure

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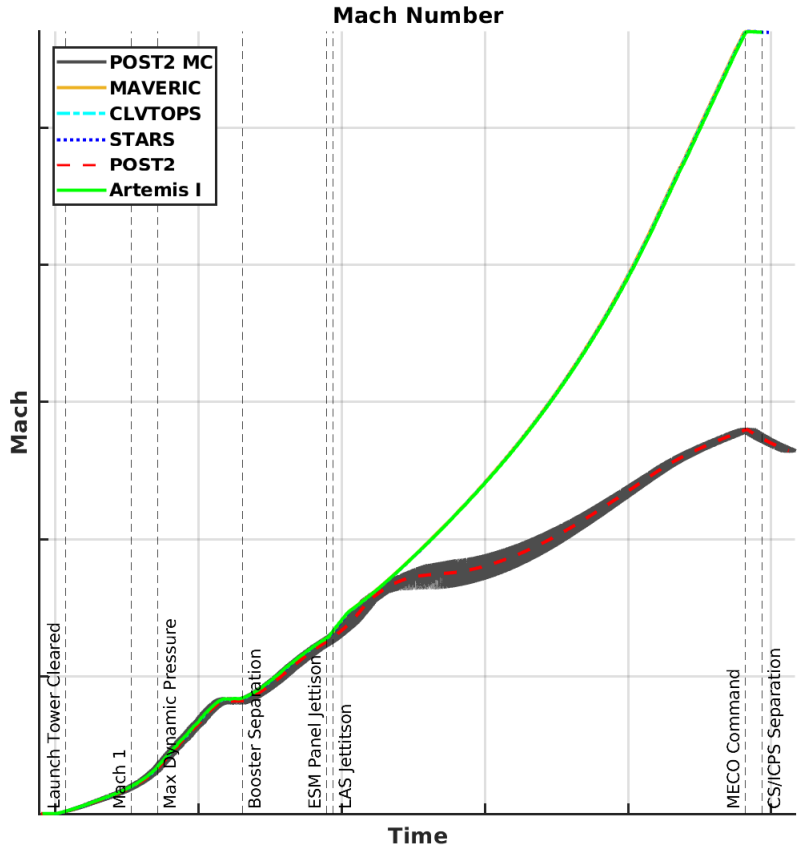
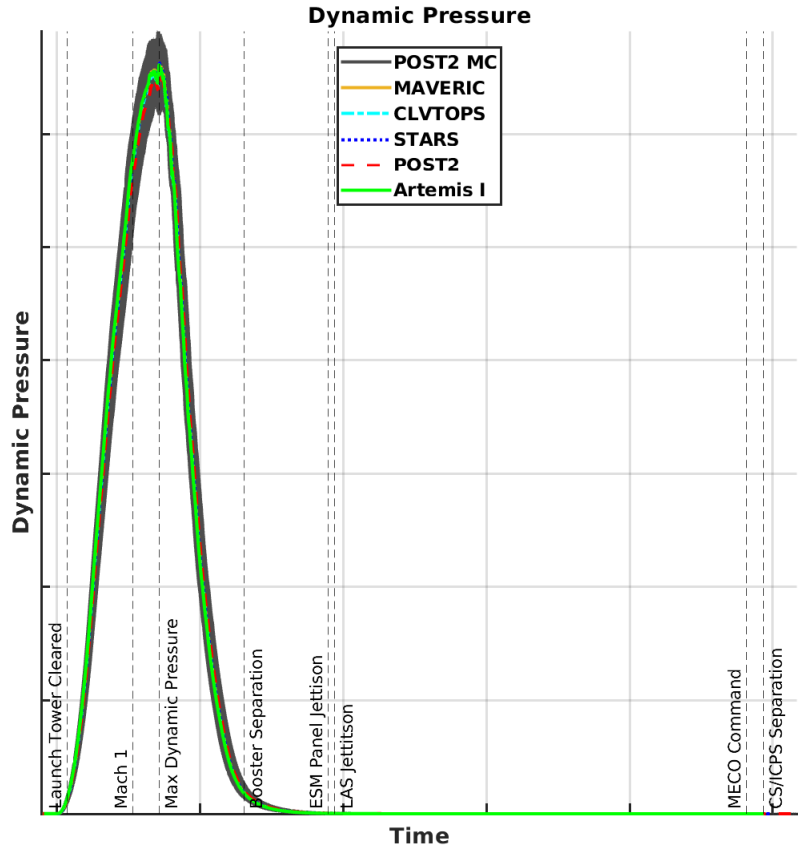
Mach Number

- POST2 calculated speed of sound directly at high altitudes
- Other sims & BET implemented a constant speed of sound assumption at high altitudes
- POST2 adjusted its simulation to implement this assumption

Dynamic Pressure

- Simulations & BET agreed on Max Dynamic Pressure timing





Estimated Mass Error

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Before Booster Separation

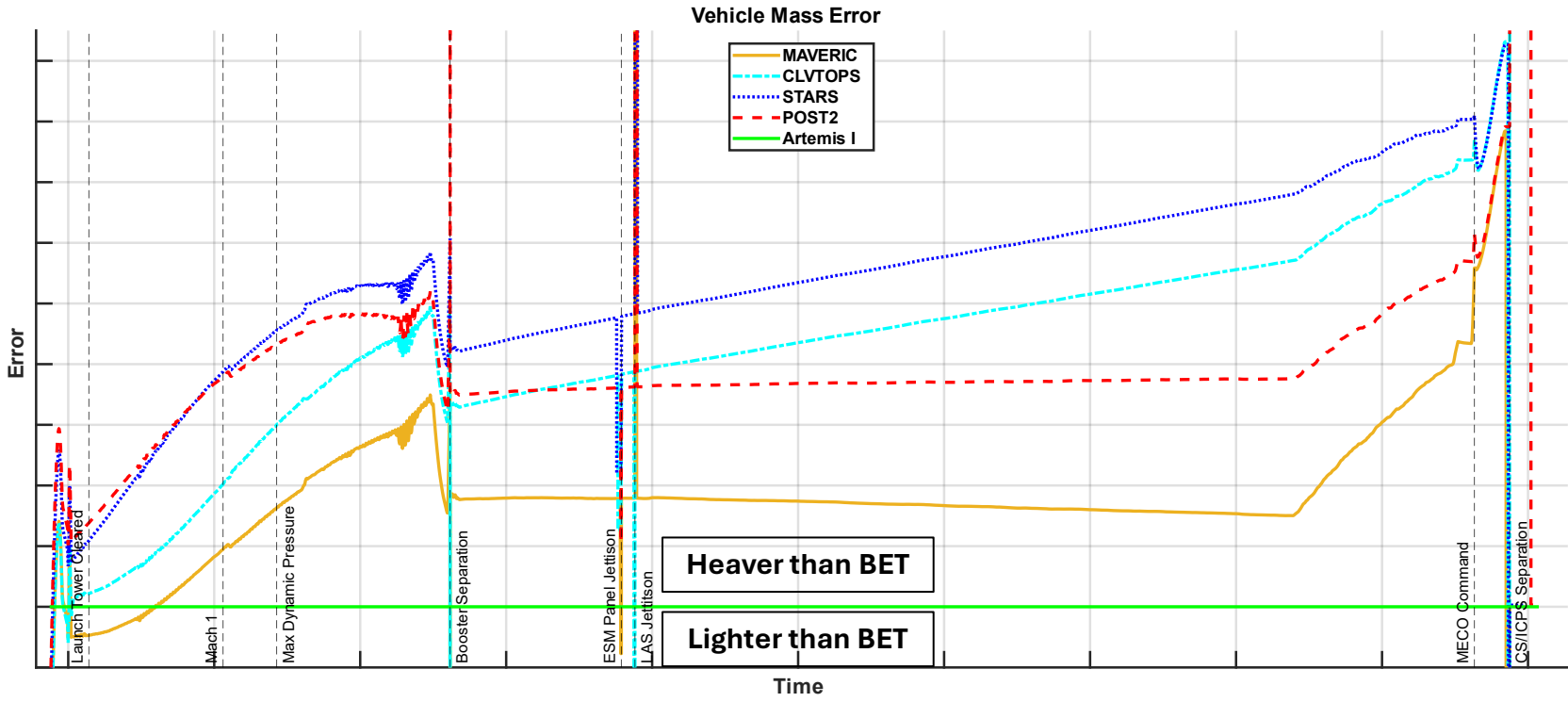
- All simulations expend propellant mass slower than BET
- MAVERIC is the only sim lighter than BET after Tower Clearance

After Booster Separation

- STARS & CLVTOPS expend propellant mass at roughly the same rate
- MAVERIC & POST2 expend propellant mass at roughly the same rate as BET
- Differences driven by postflight adjustments to Core Engine performance

Additional Observations

- Numerical differences present in postflight Mass Property Datasets
- Small differences observed in simulated initial vehicle masses



Challenges with Quantitative Comparisons

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Simulation Accuracy Requirement:

- No simulation accuracy requirement was provided
- Defining our own requirement was considered but disregarded:
  - Postflight simulation accuracy was highly dependent on the amount of DOL data available
  - Noisy measurements & filtering methods could sometimes drive mismatches between the BET & simulation results
  - Difficulty in determining a quantitative method of comparison that was sufficient for all simulation variables of interest
    - Number of simulation variables evaluated: **277**
  - Defining a requirement became subjective & didn't align well with goals

Challenges with Quantitative Comparisons

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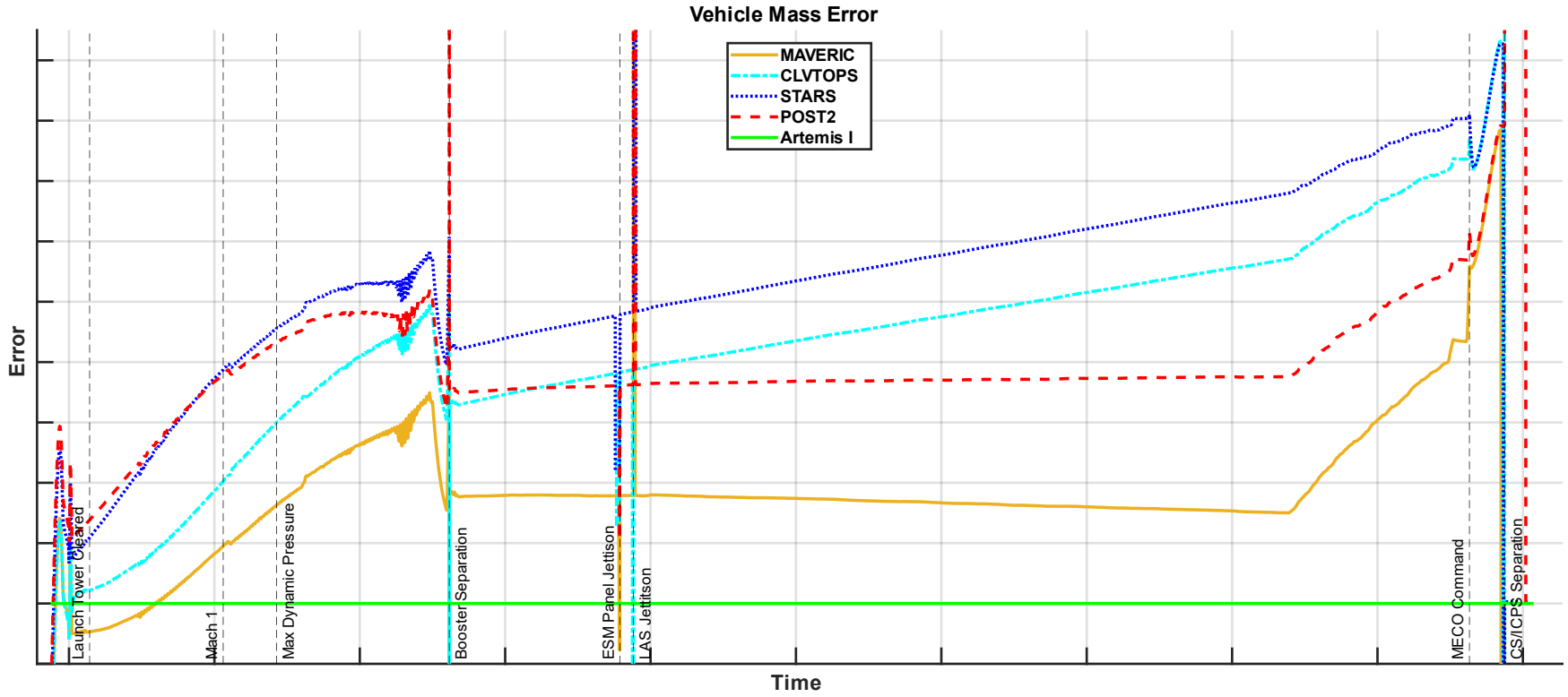
Error Computation Challenges

- Inconsistent Error magnitude across simulation variables
- Interpolation required for data-rate synchronization
  - Introduces additional error
- Significant error spikes at separation events (discontinuities)
  - Amplified by interpolation
  - Error spikes to be assessed & weeded out individually



Future Comparisons (Artemis II)

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Adjustments for Artemis II

- Postprocess (interpolate) simulated results only
- Disperse DOL atmosphere
- Quantify differences between preflight & postflight models:
  - Preflight vs. DOL simulation inputs
  - Preflight vs. DOL simulation performance
- Attempt to quantify "*boundedness*" of BET