National Aeronautics and Space Administration


# SPACE LAUNCH SYSTEM

# Post Flight Clearance Analysis by Photogrammetric Reconstruction

Aerospace Control and Guidance Systems Committee Meeting #127
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# Outline

I. **Background on Team & Task**

II. **Reconstruction Problem Setup**

III. **Requirements & Verification**
   I. ICPS (payload) Separation
   II. Booster Separation
   III. Liftoff Tower Clear

IV. **Closing Remarks**

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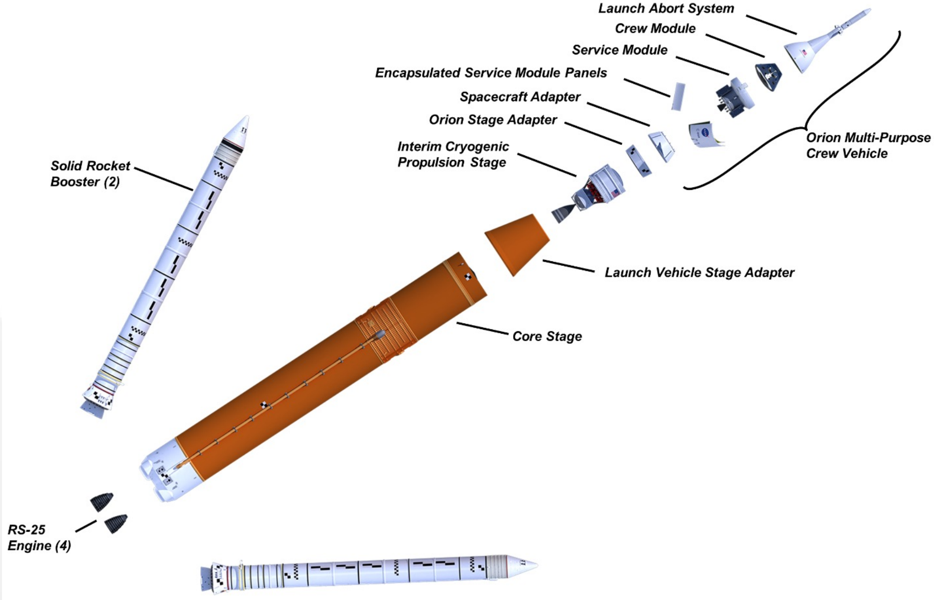
# Introduction

- **Space Launch System (SLS)**
  - NASA-developed, human-rated launch vehicle for large-scale (exploration-class) crew and cargo access
  - LEO: 95 t [~209 klbm] (Block I) / 130 t [~290 lbm] (Block II)
  - TLI:  26 t [~57 klbm] (Block I) / 37 t [~80 klbm] (Block II)
  - First uncrewed test flight: Artemis I (lunar)
  - First crewed test flight: Artemis II (lunar)

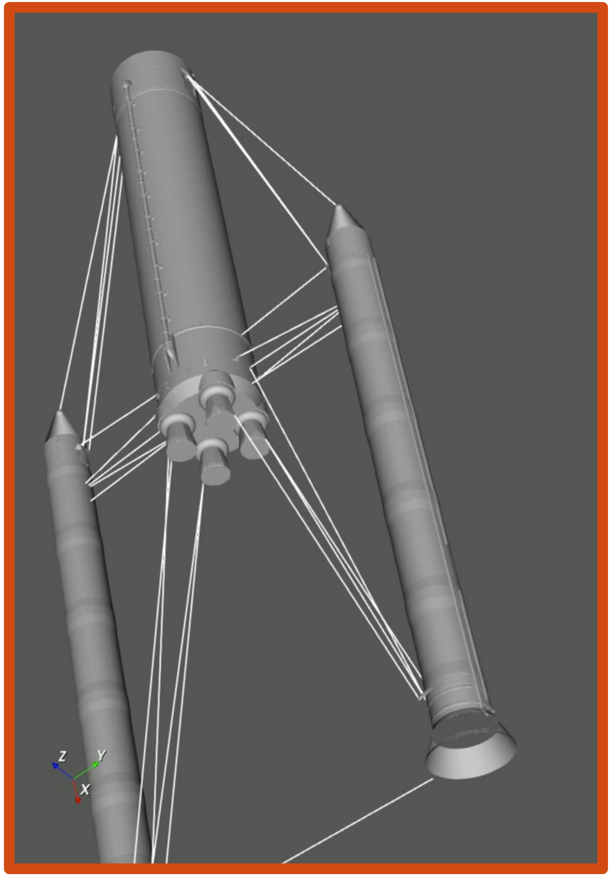



# MSFC Liftoff and Separation Analysis Group

- **Working group at NASA MSFC tasked with SLS liftoff and separation analysis**

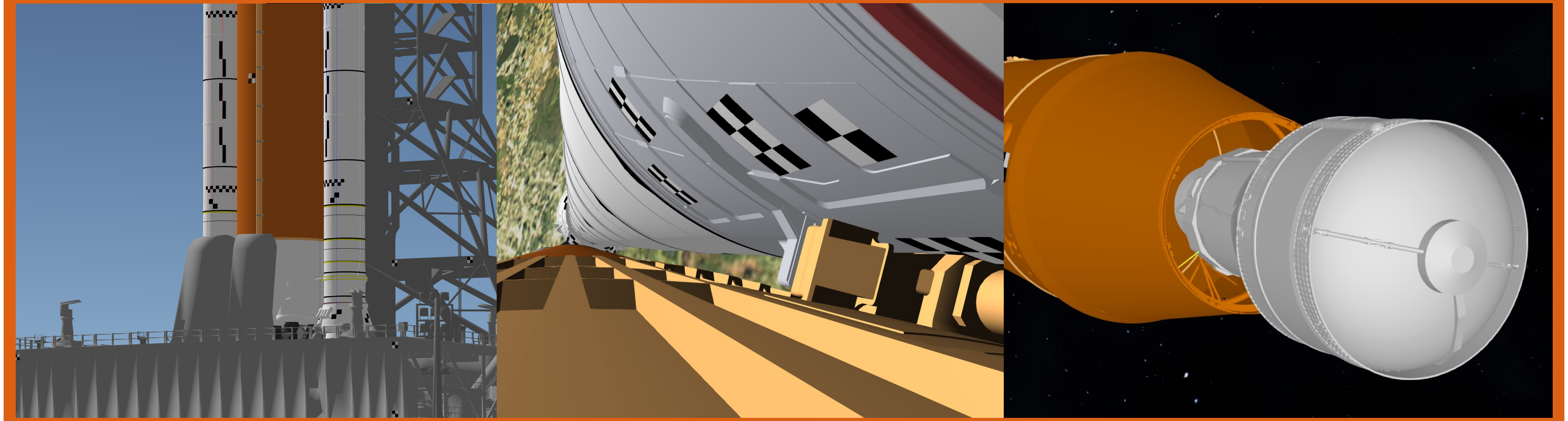
- **Main analysis tool is CLVTOPS, a hi-fidelity multi-body dynamics simulator, various analysis scripts, minimum distance algorithms, animation tools**

- **Main analysis product includes a cyclical report on separation event clearances**
  - Launch tower separation, booster separation, payload separation



# SLS Post Flight Clearance Analysis

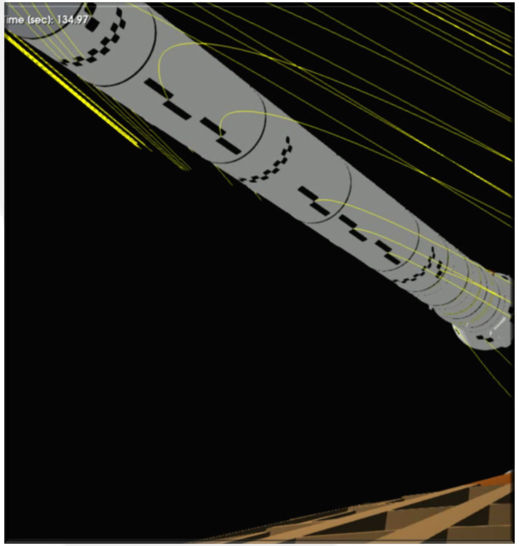
- **Task is to assess separation clearances at liftoff, booster-sep, and payload-sep to support verification & validation of SLS program analysis procedures and tools**
- **Photogrammetry and rigid body kinematics used for trajectory estimation***
  - Cameras capture images of a reference marked body
  - Photogrammetry process calculates reference marker trajectories
  - Vehicle states may be estimated by mapping the known marker points to their trajectories



*In addition to Day-of-Launch simulations

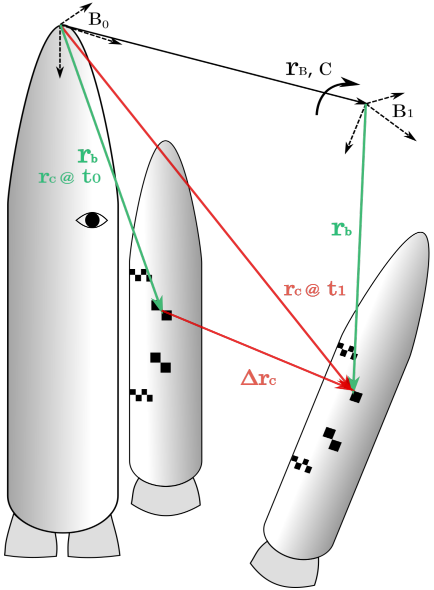
# Task Separation

- **Imagery Group**

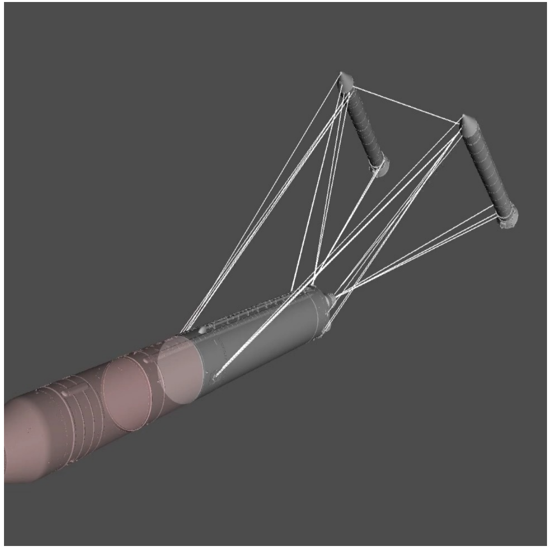



Photogrammetry

- **Liftoff and Separation Group**




Reconstruction



Clearance Analysis

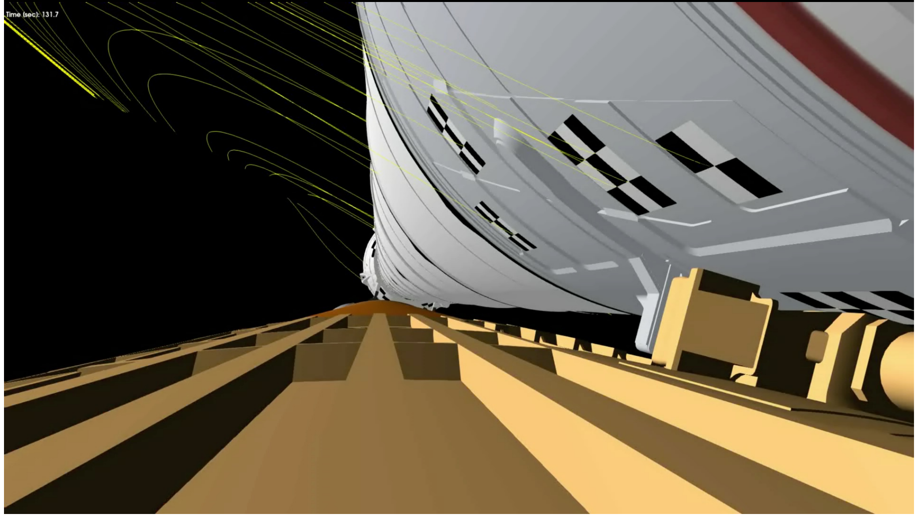


Approved for public release – NASA DAA XXXXXXX

# Photogrammetry Summary

- **Cameras are used to capture separation event**
- **High contrast photo-targets are tracked in 2D**
  - Markings are placed such that a minimum quantity subset is always visible
- **2D image coordinates are transformed to 3D world space**
  - Single Camera Setup
    - Use of collinearity equations and distance constraints
    - Solved by non-linear least squares
  - Multiple Camera Setup
    - Solved using triangulation

- **Yellow lines below are the tracked 3-DOF positions of the checkerboard corners as the booster falls away**



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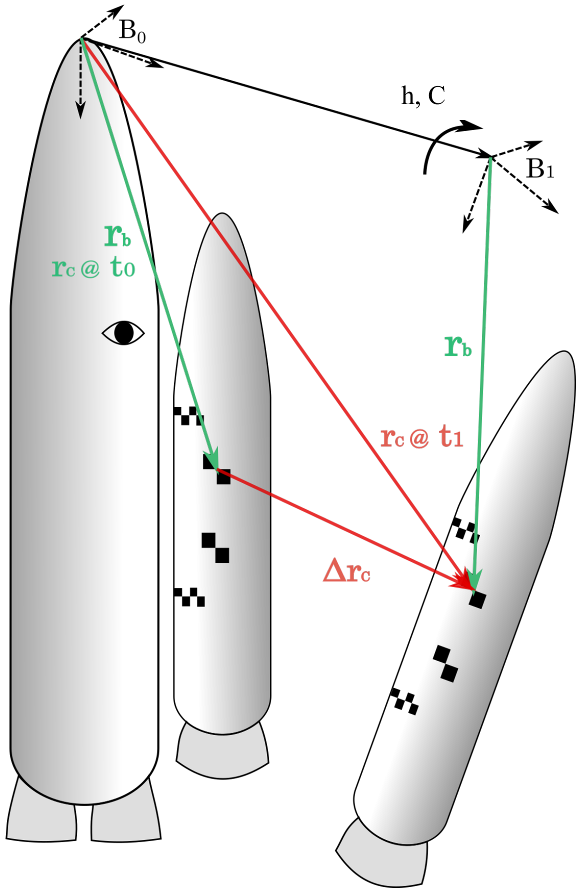
# Reconstruction Setup

- **Vehicle states can be estimated if the location of a sufficient number of points on the body are known**

- **Simplified diagram reveals main components necessary for state estimation**

$$\mathbf{r}_C = \mathbf{r}_B + \Delta\mathbf{r}_C = \mathbf{C}\mathbf{r}_B + \mathbf{h}$$



# Rigid Body State Equations

The location of a point on the booster represented in the core frame is as follows

$$\mathbf{r}_C = \mathbf{r}_B + \Delta\mathbf{r}_C = \mathbf{C}\mathbf{r}_B + \mathbf{h}$$

Where $\mathbf{r}_C$ and $\mathbf{r}_B$ are the vector to the point in the core and booster frame, $\mathbf{h}$ is the vector to the booster origin in core frame, $\mathbf{C}$ is the transformation from booster to core. $\mathbf{r}_B$ is statically known, $\mathbf{r}_C$ is generated by the photogrammetry.

A general system can be constructed per the following

$$\begin{bmatrix} \mathbf{r}_{C1} & \mathbf{r}_{C2} & \dots & \mathbf{r}_{Cn} \end{bmatrix} = \mathbf{C} \begin{bmatrix} \mathbf{r}_{B1} & \mathbf{r}_{B2} & \dots & \mathbf{r}_{Bn} \end{bmatrix} + \mathbf{h},$$

$$\mathbf{P}_C = \mathbf{C}\mathbf{P}_B + \mathbf{h}$$

# Algorithm Selection

- **A 1997 paper by Eggert *et al.***, conducts a survey of four major rigid body transformation algorithms**
  - SVD, orthonormal matrices, unit quaternions, dual quaternions
  - All manipulate eigensystem of a derived matrix
  - All solve for an optimal rotation before calculating translation
  - All minimize a similar cost function

$$\Sigma^2 = \sum_{i=1}^{n} \|d_i - \mathbf{R}m_i - \mathbf{T}\|^2$$

- **Result of survey is that there is no superior algorithm, differences come out in edge cases and high compute environments**

- **If all are similarly effective, choose the simplest to implement**
  - The SVD algorithm, which also happens to be marginally more accurate than the others

* Eggert, D. W., Lorusso, A., & Fisher, R. B. (1997). Estimating 3-D rigid BODY transformations: A comparison of four major algorithms. *Machine Vision and Applications*, 9(5-6), 272–290.

# Reconstruction Algorithm

- **Initial and final coordinates have the same centroid**
  - Relocate centroids to origin to isolate the rotation (i.e. subtract the means), $\mathbf{P}_B^* = \mathbf{P}_B - \overline{\mathbf{P}}_B$, $\mathbf{P}_C^* = \mathbf{P}_C - \overline{\mathbf{P}}_C$

- **$\mathbf{A}$ is a correlation matrix defined by the product of the relocated initial and final coordinates**
  - $\mathbf{A} = \mathbf{P}_B^* \mathbf{P}_C^{*T}$

- **Let** $\mathbf{U}, \mathbf{S}, \mathbf{V} = svd(\mathbf{A})$
  - The optimal rotation, $\mathbf{C} = \mathbf{V}\mathbf{U}^T$
  - If the determinant of $\mathbf{C}$ is -1, $\mathbf{C} = \mathbf{V}^*\mathbf{U}^T$, where $\mathbf{V}^* = [\mathbf{v}_1, \mathbf{v}_2, -\mathbf{v}_3]$

- **Once the rotation is found,** $\mathbf{h} = \overline{\mathbf{P}}_C - \mathbf{C}\overline{\mathbf{P}}_B$




Methodology from ref 1 – Eggert, et. al

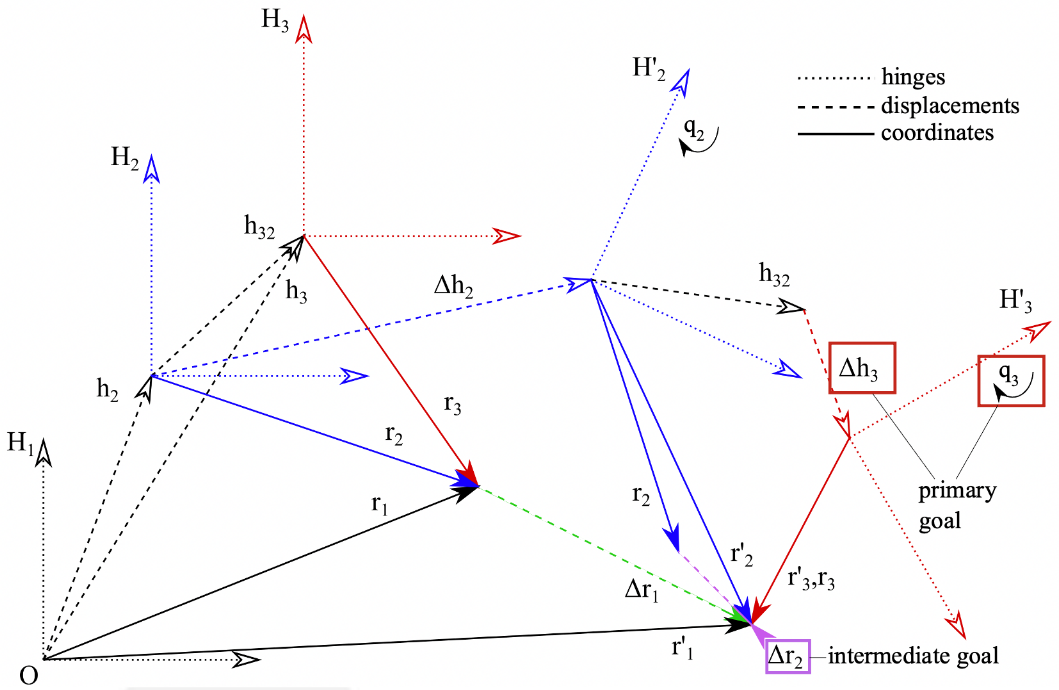
# N-Body State Estimation

- **The preceding was an explanation of the simplified procedure, where the camera and tracked body frames are directly connected (booster sep, ICPS sep)**
  - All that needs to be known is the initial location in both frames and the displacement in the observing

    $$r_1' = r_1 + \Delta r_1 = \mathbf{C} r_2 + \mathbf{h}$$

- **Reconstruction of the SLS liftoff case is more complex because we have a camera (on the ground) tracking points on bodies that are more than one frame separated from the camera frame (ground->core->SRBs->SRB nozzles)**
  - Now must account for frames moving within frames

# N-Body Accounting

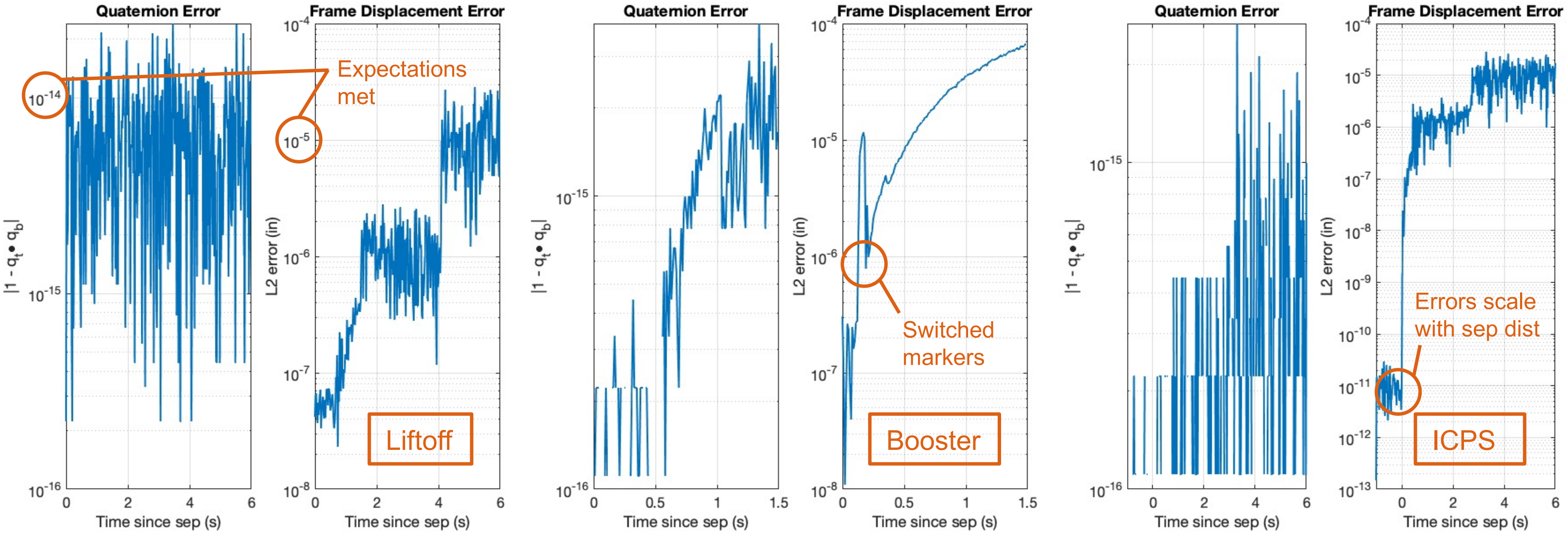



$$\Delta r_2 = C_2^T\left[(r_1 + \Delta r_1) - (h_2 + \Delta h_2)\right] - (r_1 - h_2)$$

- **Need to turn the N body problem into a series of 2 body problems**
- **Each frame observes the point with a different displacement**
- **Find the next frame's displacement, and you have the 2 body problem**

# Algorithm Verification

- **Using raw simulation output marker trajectories, we test the algorithm to see if it can perform a perfect reconstruction**



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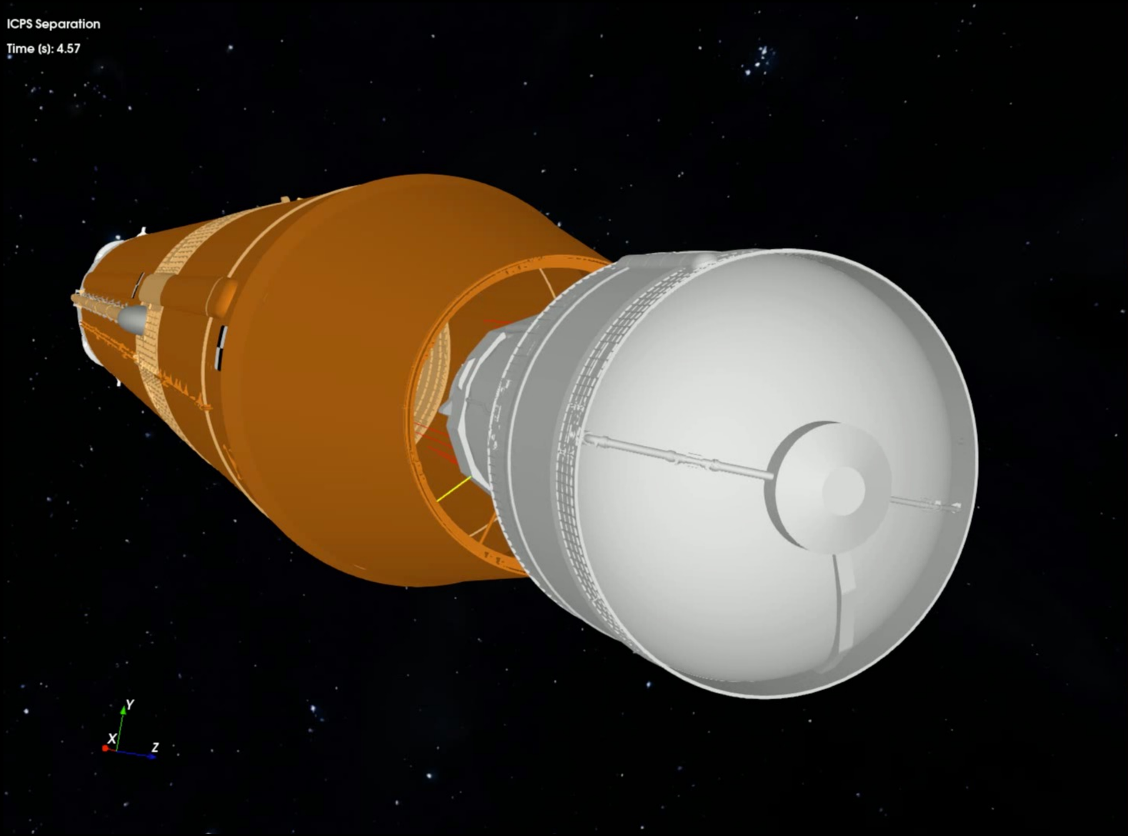
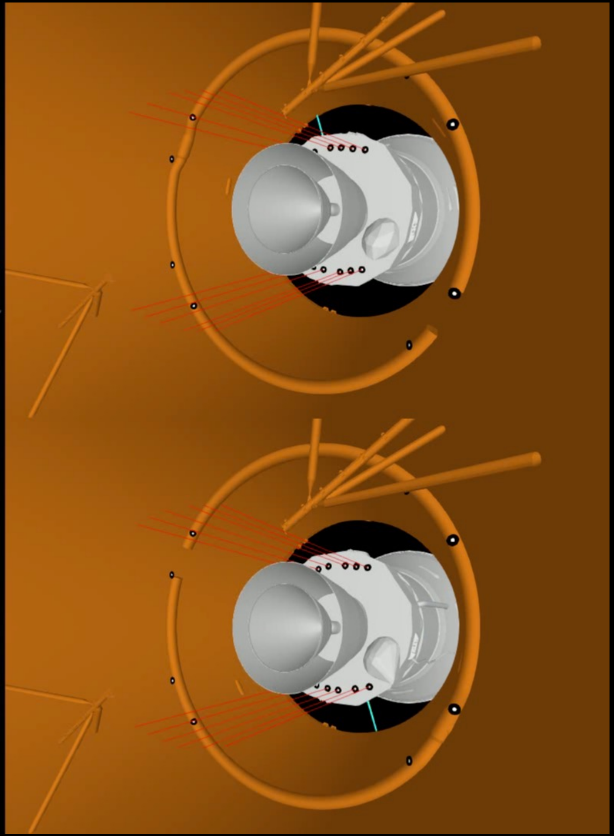
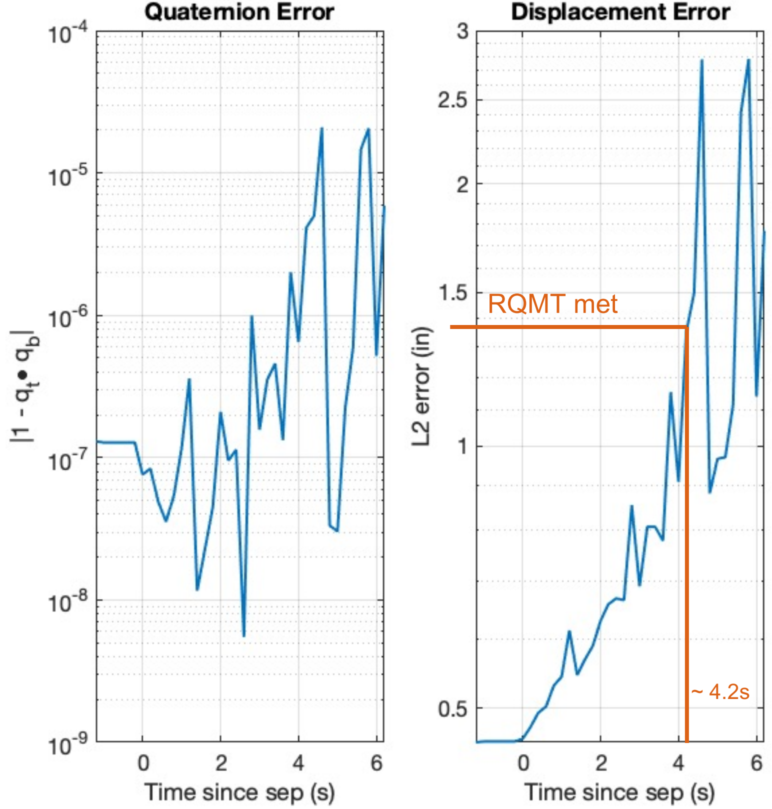

ICPS Separation
Time (s): 4.57
Y
X
Z

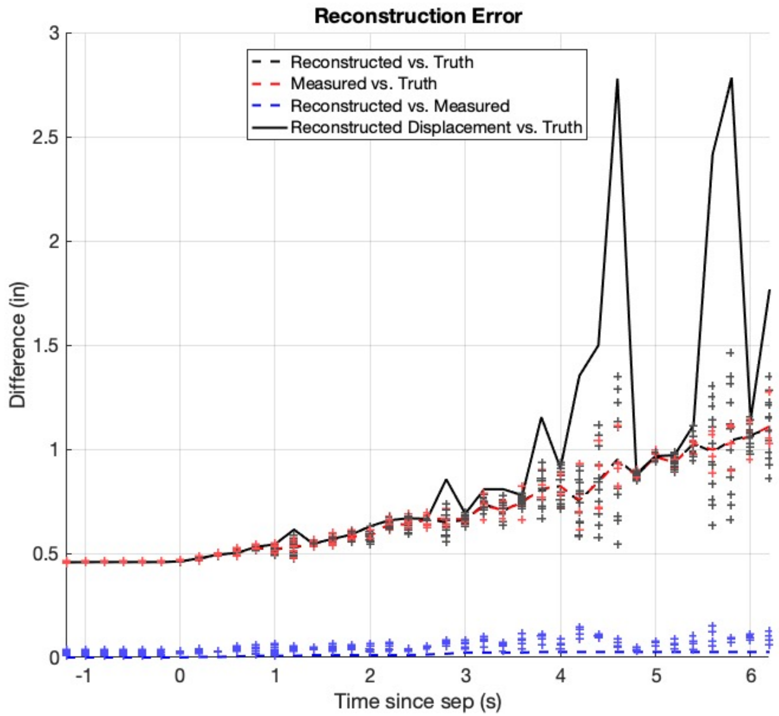


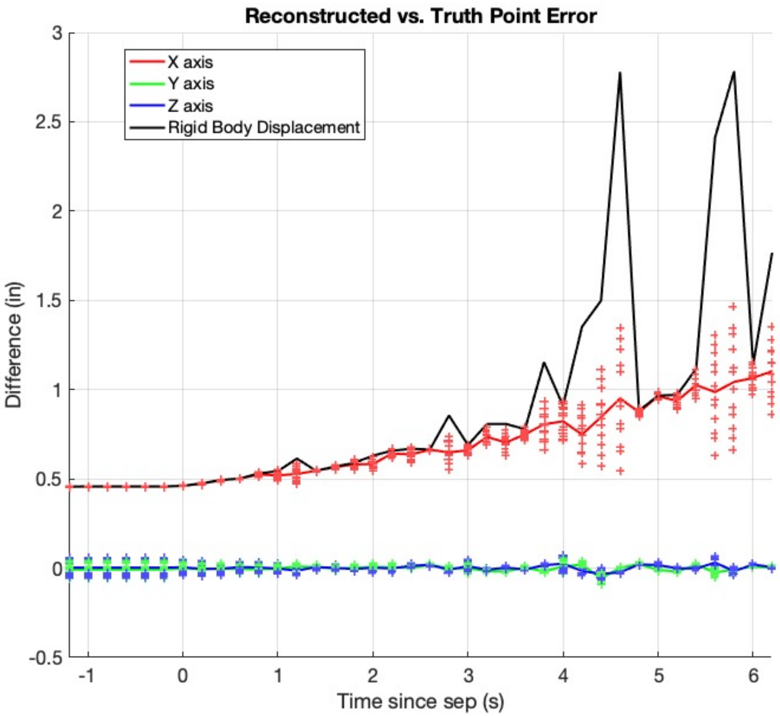
# ICPS Separation – Reconstruction

- **Accuracy Requirements**
  - Predict 6-DOF to within 2” when avionics shelf at exit plane ~4.2s after sep
- **Challenges**
  - Special case of planar coordinates
  - Depth measurement skew can lead to increased jitter
  - High measurement errors due to camera survey mismatch

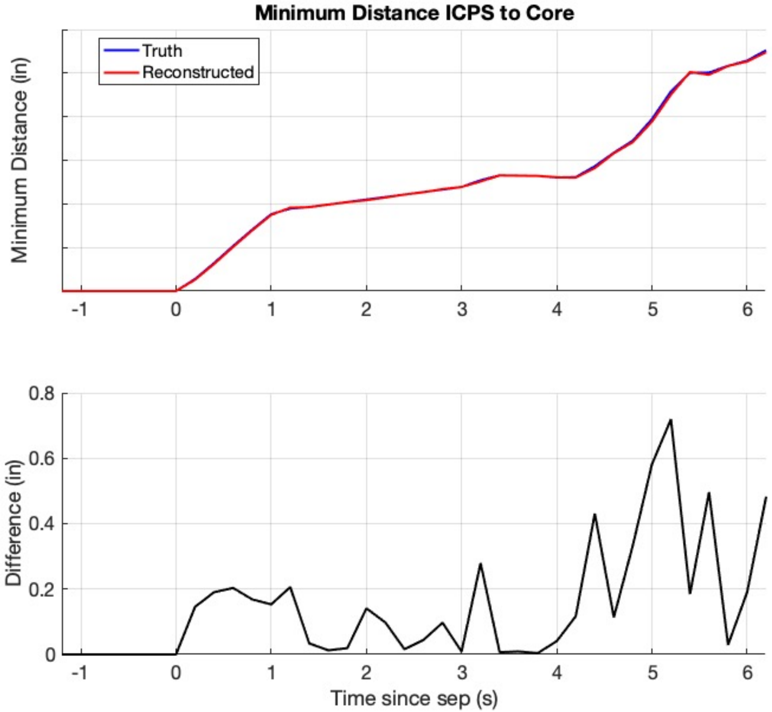


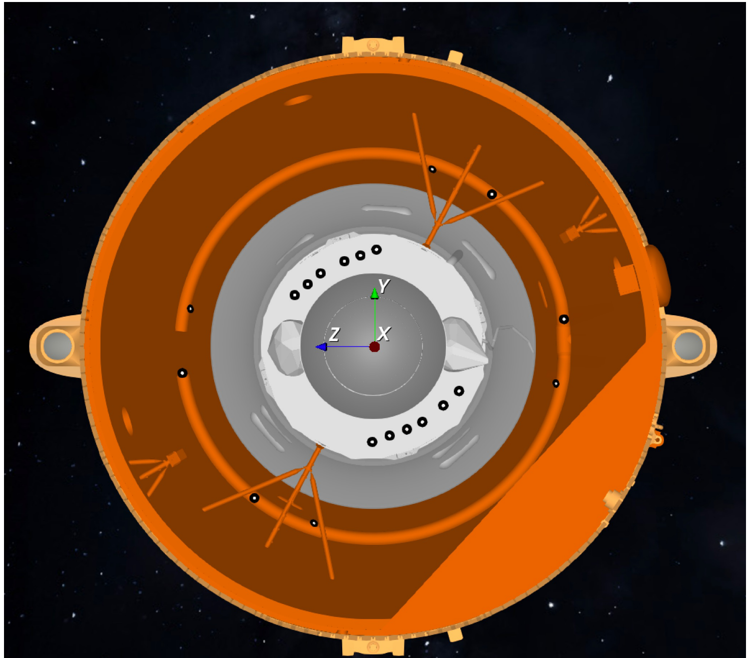
# ICPS Separation – Reconstruction Errors



# ICPS Separation - Minimum Distance



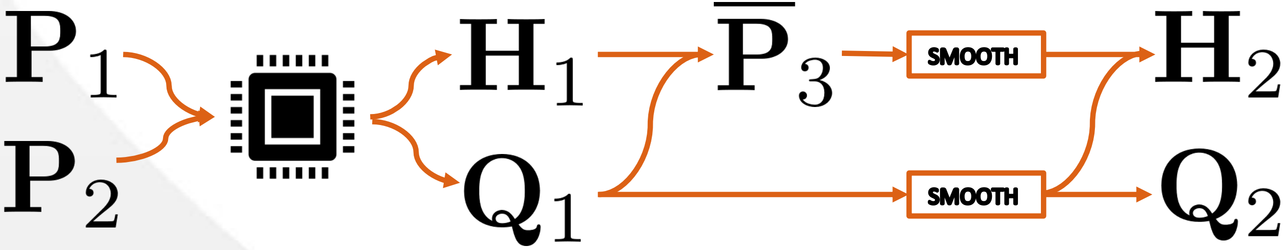




SLS forward looking cross section

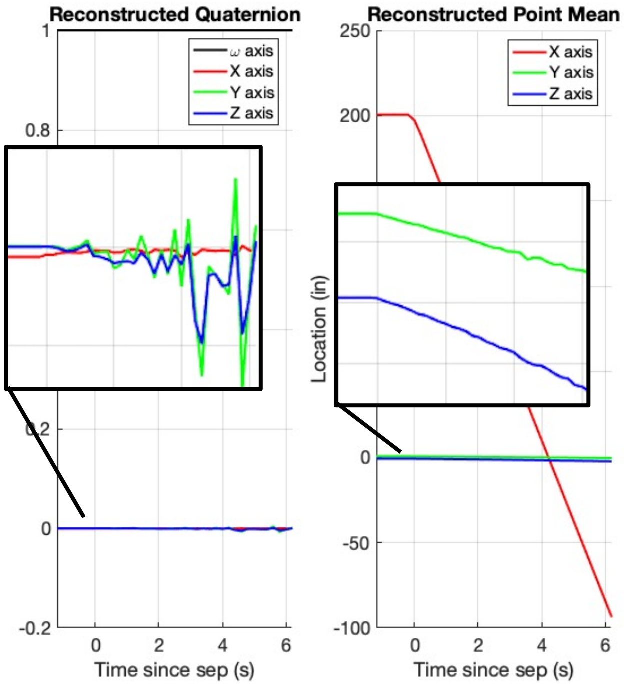
# ICPS Separation - Trajectory Smoothing

- **Kinematics occur continuously, unordered jitter is not desired**
  - Smoothing can help reduce variance in reconstruction errors and add to clearance fidelity
  - It can also introduce more error if done incorrectly

- **Method**
  - Generate mean of entire point trajectory using noisy 6DOF ($\overline{\mathbf{P}}_3$)
  - Apply smoothing filter to quaternion and and mean trajectory
  - Generate a smooth frame displacement using previous equation

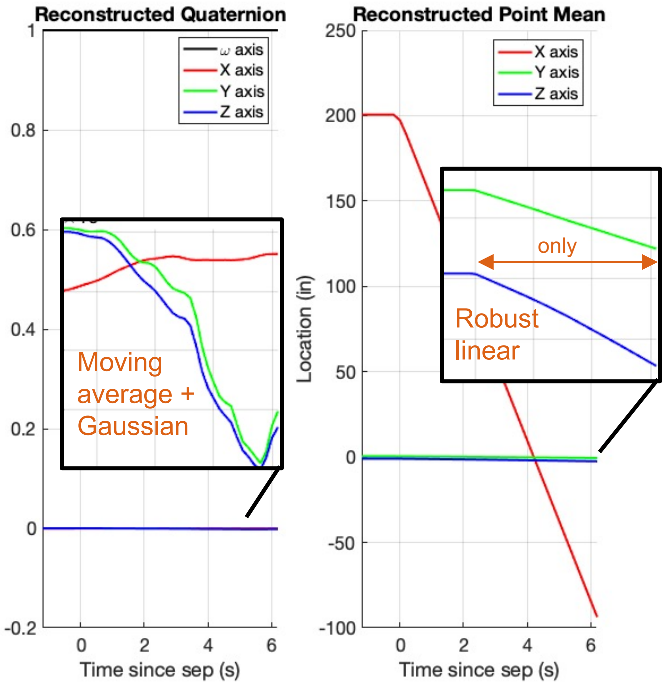


# ICPS Separation – Smoothing Philosophy

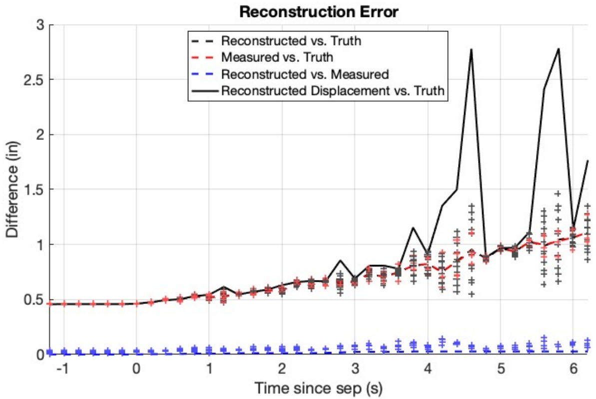


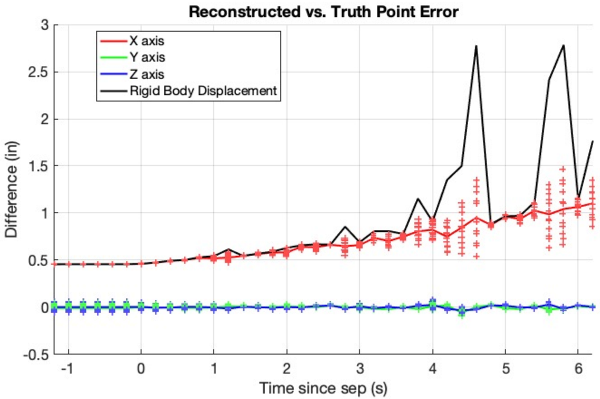

- Without access to truth data, smoothing can be somewhat arbitrary
- Bias filtering to curves with instability
- Infer trends from the curve/know what you're modeling
- Avoid blanketing the whole curve in one filter due to varying trends

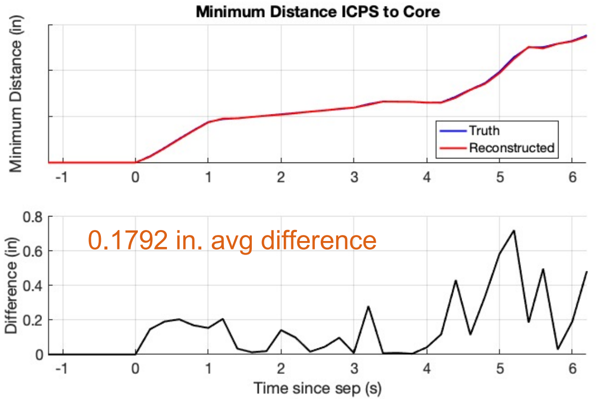
**SMOOTH**



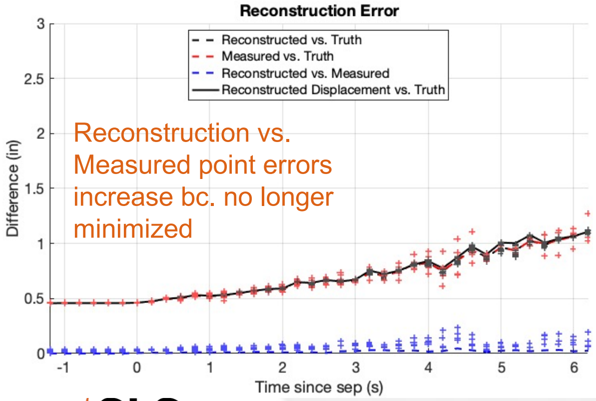
# ICPS Separation – Smoothing Results

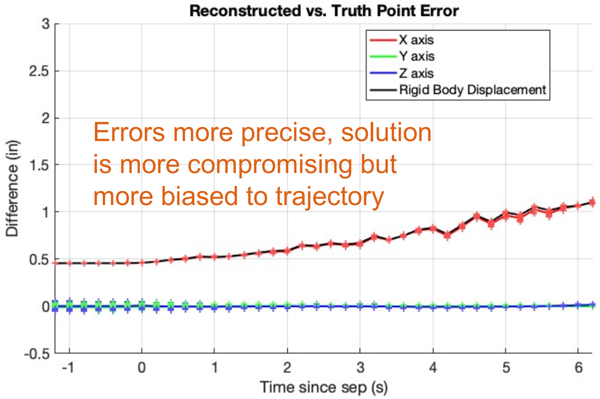


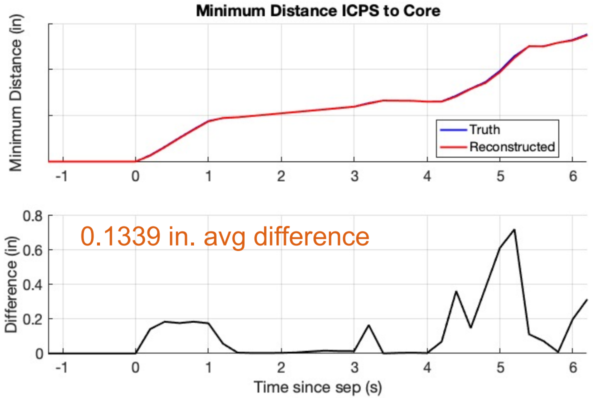



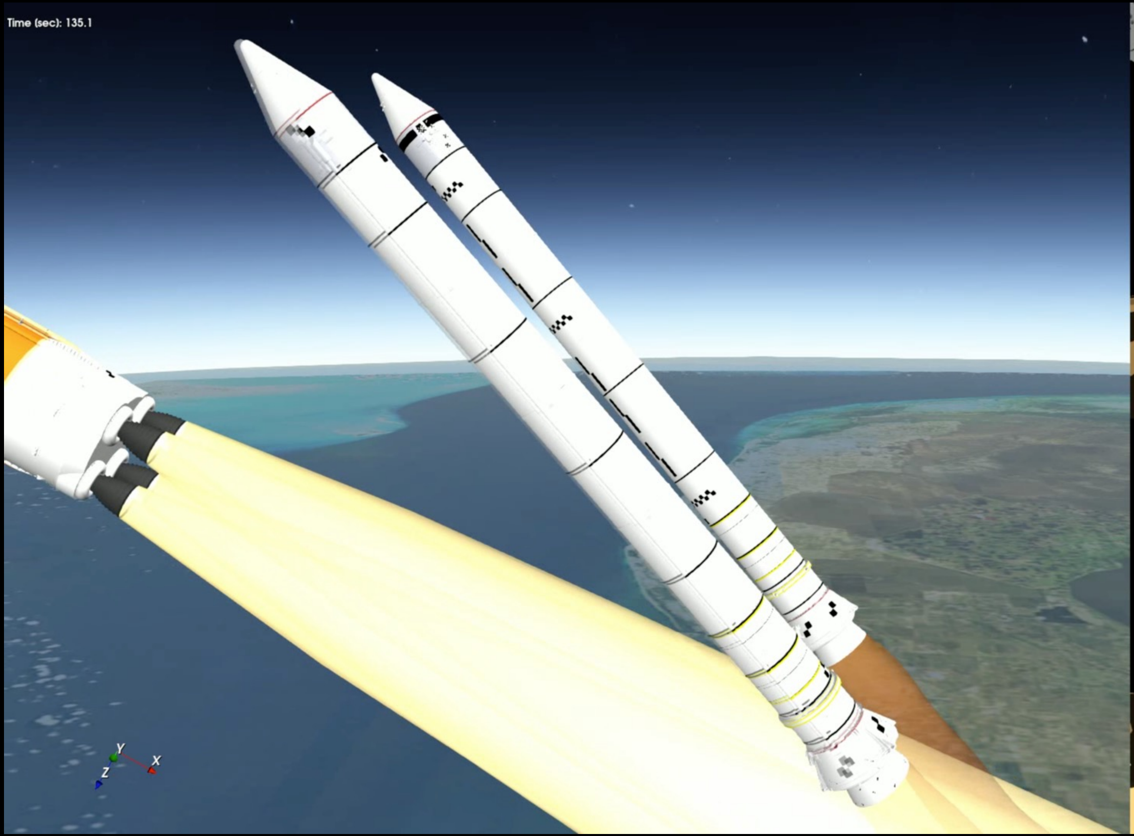




**SMOOTH**

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X
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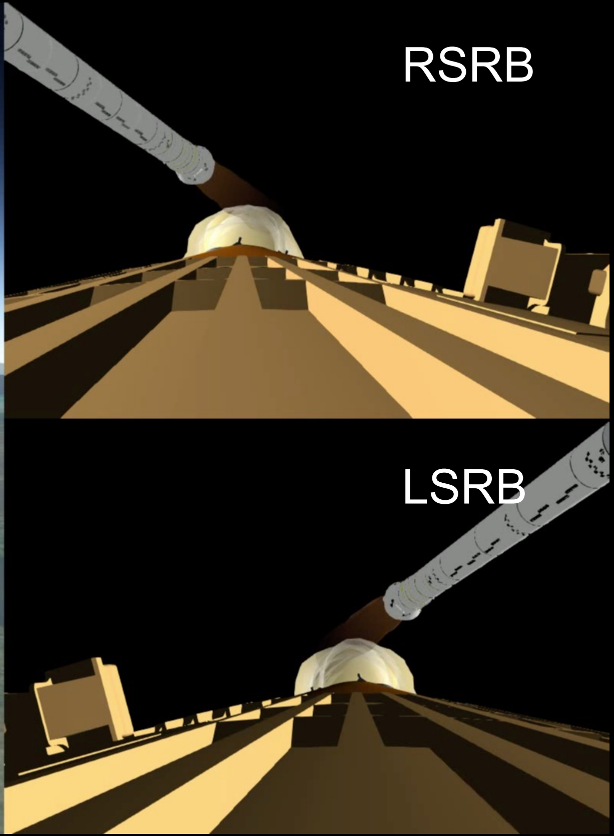
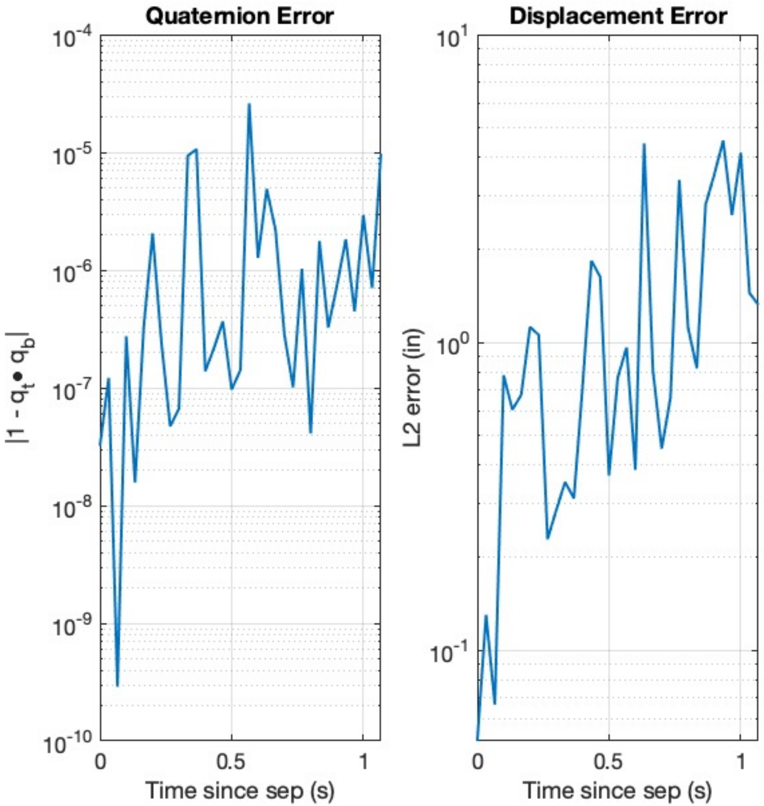

RSRB
LSRB

# Booster Separation – Reconstruction

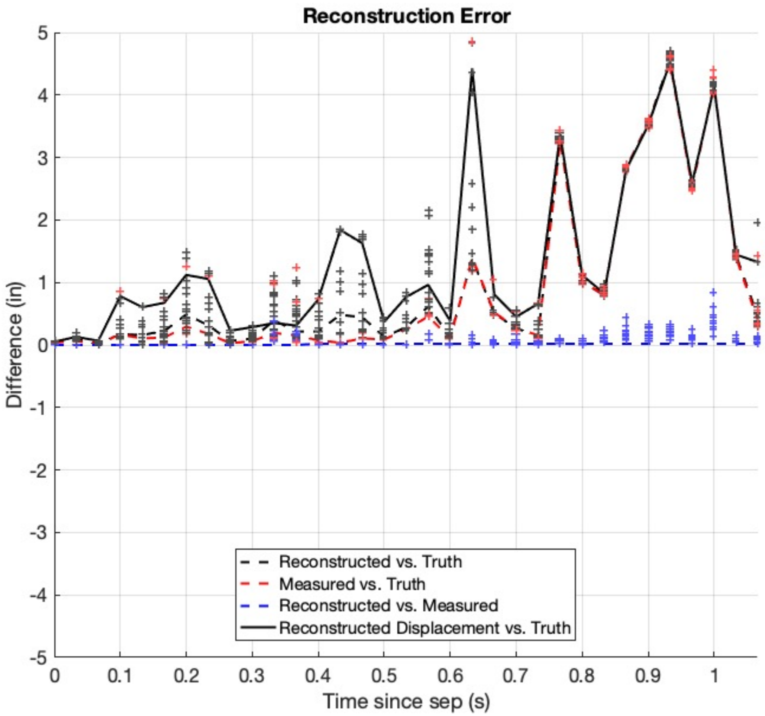
- **Accuracy Requirements**
  - Predict forward attach clearance to within 0.25" 0.8s after sep
  - Predict aft attach *SLS-Y/Z plane clearance to within 0.75" 0.8s after sep

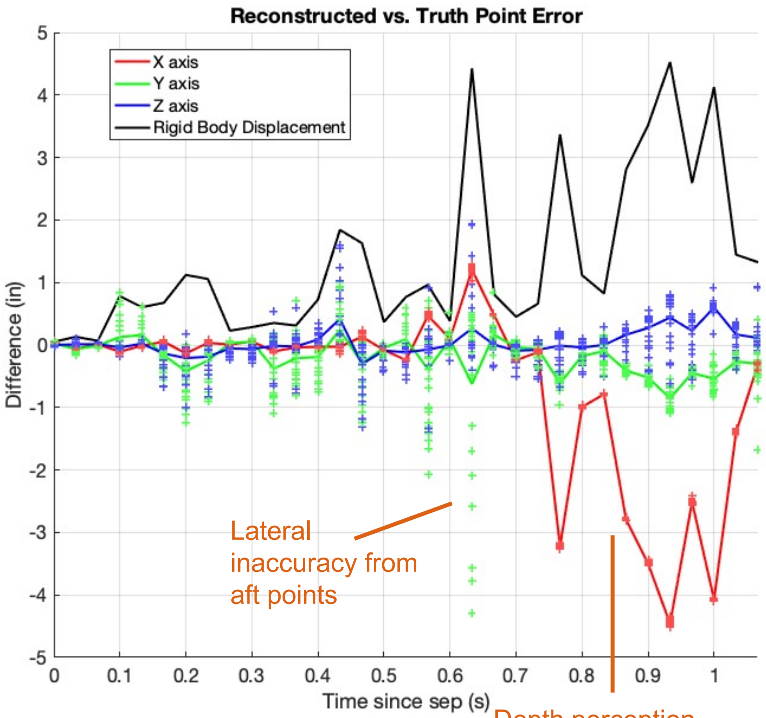
- **Challenges**
  - Single camera photo-grammetry not suited for depth perception
  - Tracked markers change frequently, causing jitter




*Interpret as using truth X

# Booster Separation – Reconstruction Errors

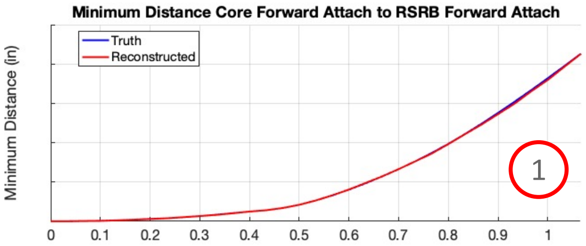


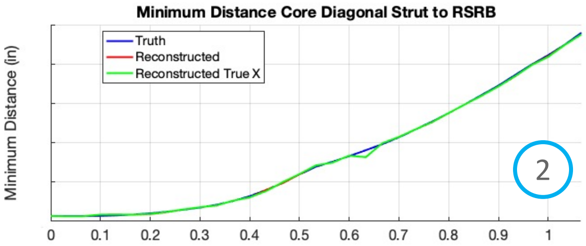



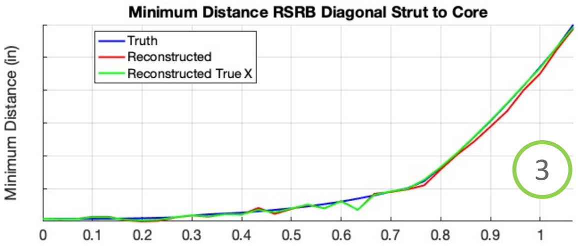

Lateral inaccuracy from aft points

Depth perception breaks down

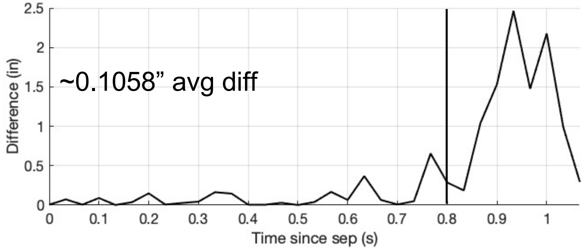
# Booster Separation - Clearance



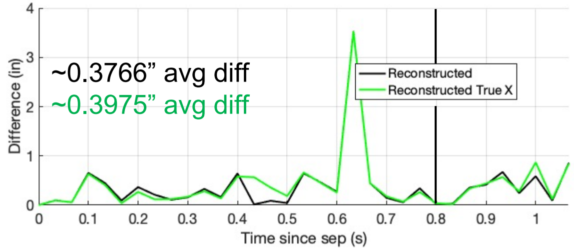



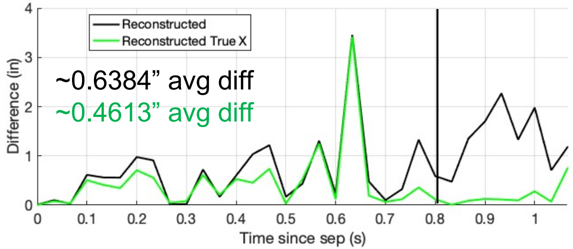

RQMT: 0.25”

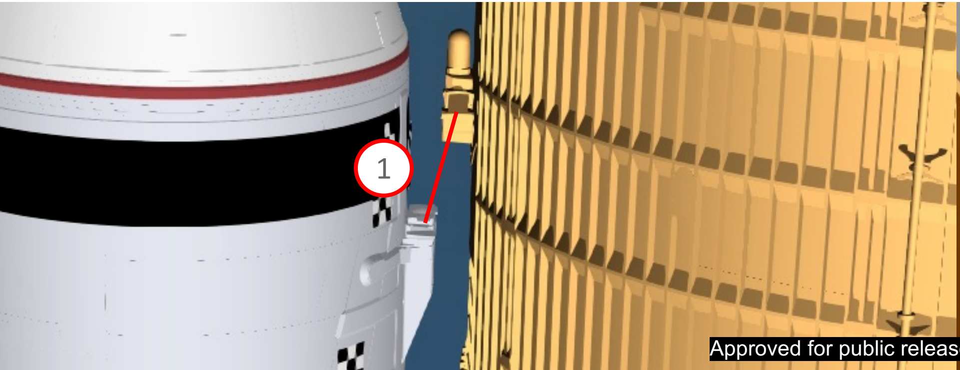


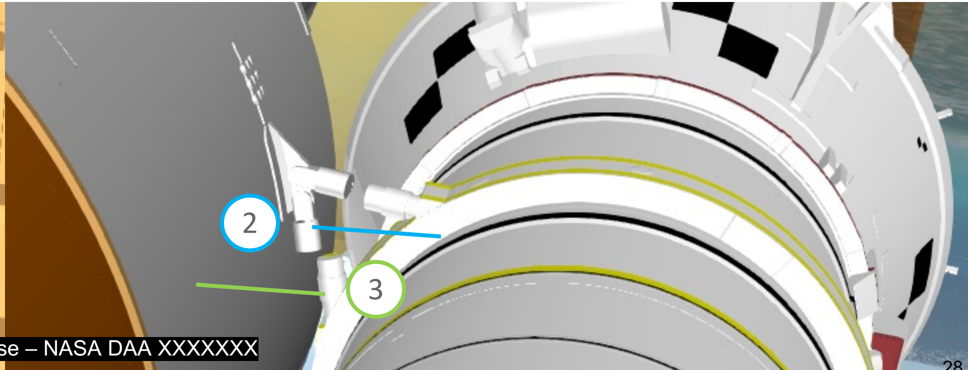

RQMT: 0.75”

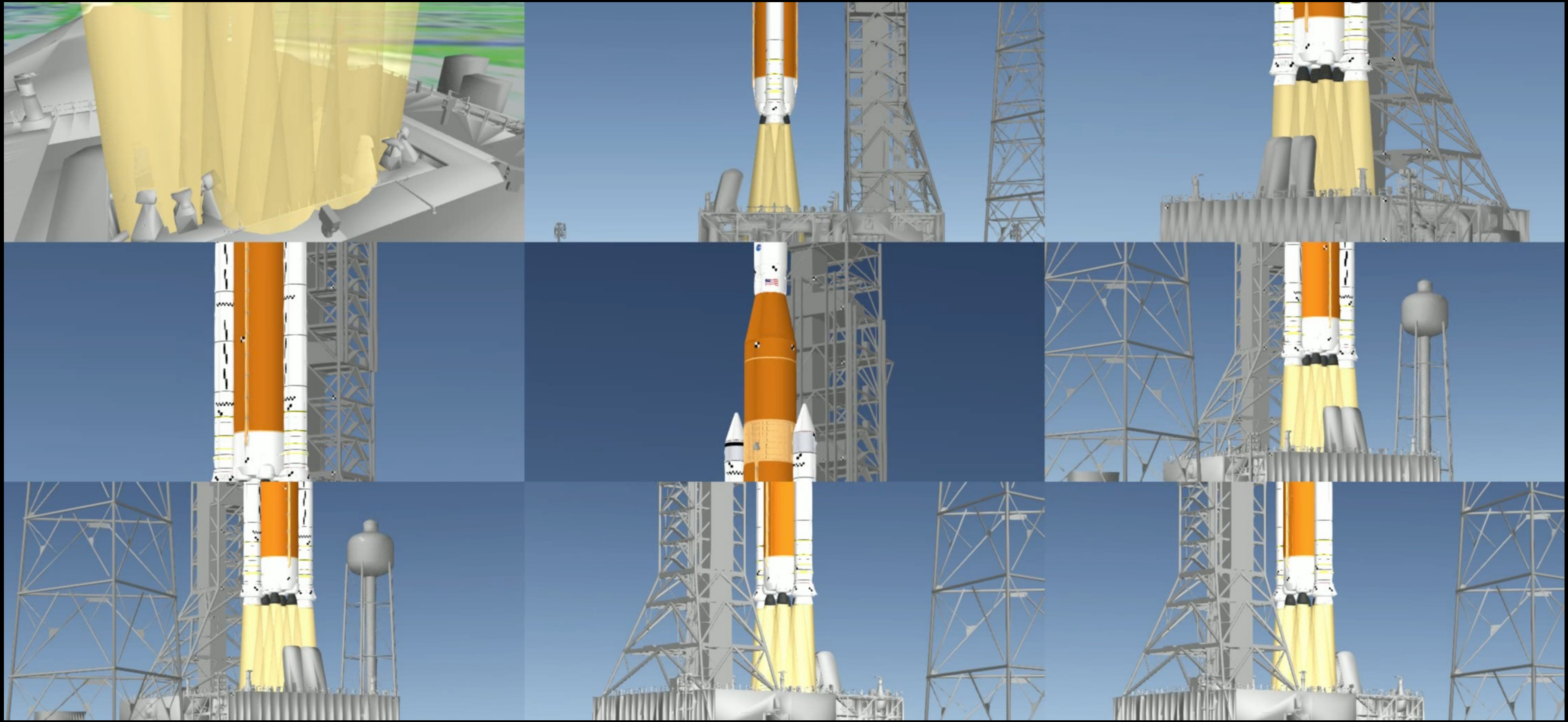



RQMT: 0.75”



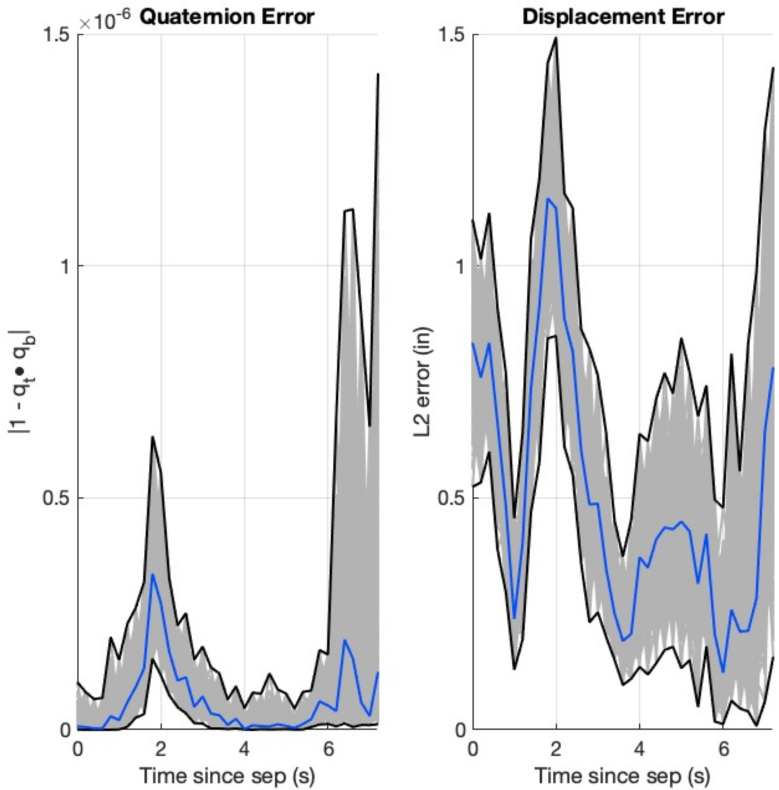





# Liftoff – Reconstruction Monte Carlo

- **Accuracy Requirements**
  - Predict 6-DOF to within 6” through tower clear
- **Challenges**
  - One of the simpler cases due to attitude hold
- **Monte Carlo**
  - Introduces camera error model, e.g. misalignment, noise
  - 1000 cases



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# Closing Remarks

- **In addition to day of launch simulations, photogrammetry appears to be a viable analysis tool for determining clearance**
  - Photogrammetry will likely be used to verify simulations are in the ballpark of observed trends

- **Camera footage quality is subject to environmental uncertainty**
  - Liftoff acoustics environment is not conducive to steady recording
  - Engine plumes or surrounding particulate could obscure cameras
  - No ambient lighting in payload deployment stage
  - Night launches make footage effectively unusable

# References


- Eggert, D. W., Lorusso, A., & Fisher, R. B. (1997). Estimating 3-D rigid body transformations: A comparison of four major algorithms. *Machine Vision and Applications*, *9*(5-6), 272–290. https://doi.org/10.1007/s001380050048



- Special thanks to photogrammetrists Bo Parker and Danny Osbourne for performing the imagery analysis.