# Space Launch System Design: A Statistical Engineering Case Study

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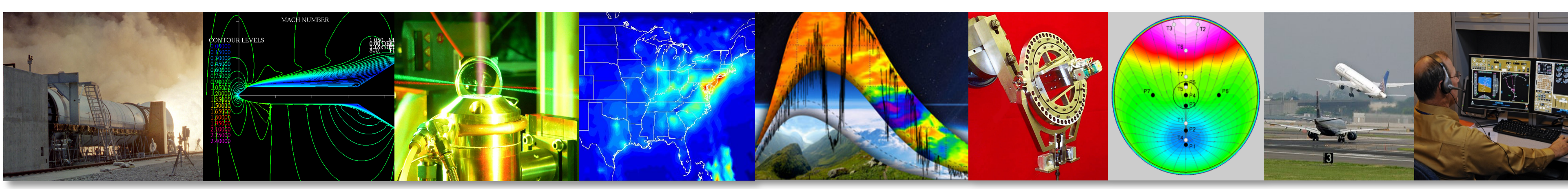
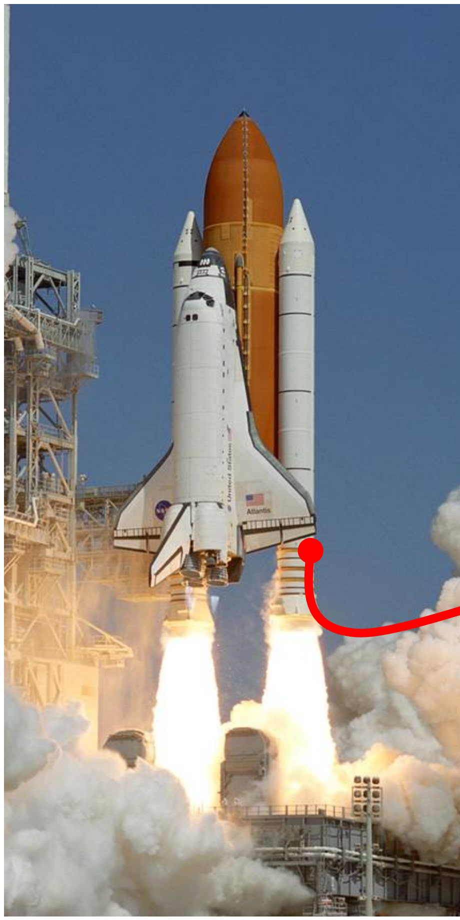
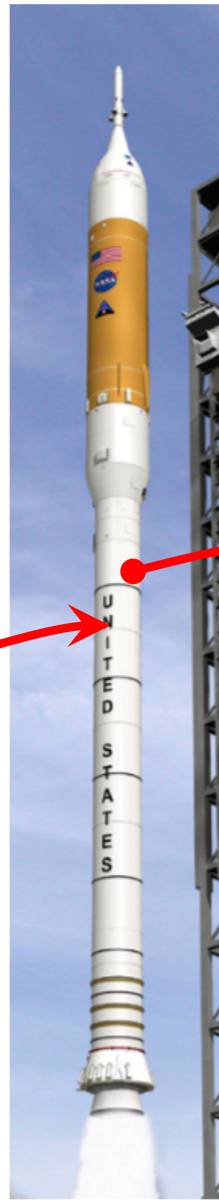


# *Case Study Overview*

## Shuttle

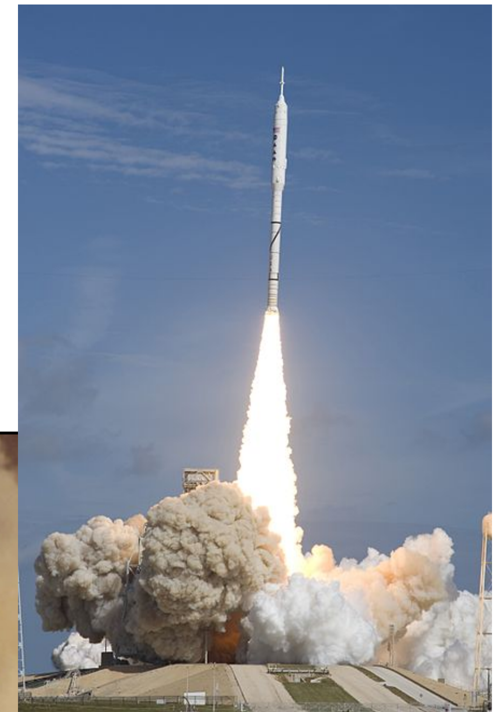


## Ares I




## Full Scale Static Firing

## Flight Test



# *Background and Motivation*

- NASA was leveraging heritage architecture for a new space launch system to minimize technical risk, cost, and schedule
- Heritage components subjected to new requirements, beyond the original design and test capabilities, requiring new sub-systems
- New vehicle design predicted to be overweight, and the program needed to find ways to reduce mass
- All system components scrutinized for potential weight savings by identifying those with the largest uncertainty and/or design margin
- The roll torque reaction control system of the reusable solid rocket motor was identified as having a high uncertainty in its requirements, lacking adequate test data, and physical understanding and therefore potentially being overdesigned resulting in excess weight

***How large does the reaction control system need to be?***

# *Consequences of Results*

- Mass is "king" in launch systems, it drives rocket performance, and influences mission payload capability
- Impact of excess mass is lifecycle cost on every subsequent launch, not a one-off test, sets a design for decades. Once a system gets onboard, it's hard to get it back off.
- Insufficient roll control authority is unstable flight, potential loss of test vehicle, collateral damage on the ground, and ultimately, in the production vehicle, loss of payload (if unmanned), loss of crew if astronauts are onboard.

# *Data, Champions, Stakeholders*

- Testing initiated, however two previous firings were unsuccessful in obtaining "high confidence," adequate measurements
- No clear understanding of what could or should be done to improve the measurements and report uncertainty within the time constraints
  - Options : (1) Increase confidence in existing experimental and theoretical data or (2) Develop a new strategy for testing
- NASA's independent technical authority engaged, critical leadership buy-in, Agency level impact, reporting to NASA's Chief Engineer
  - Culturally, little experience and comfort with design of experiments
- Organizational challenges with competing motivations and metrics (1) Program, (2) Independent technical authority, (3) Contractors.
- Safety critical: personnel, facility, test article are all high-value assets

***Large, Complex Challenge …***
***on the most powerful solid rocket motor in the world.***

# *Interdisciplinary Team*

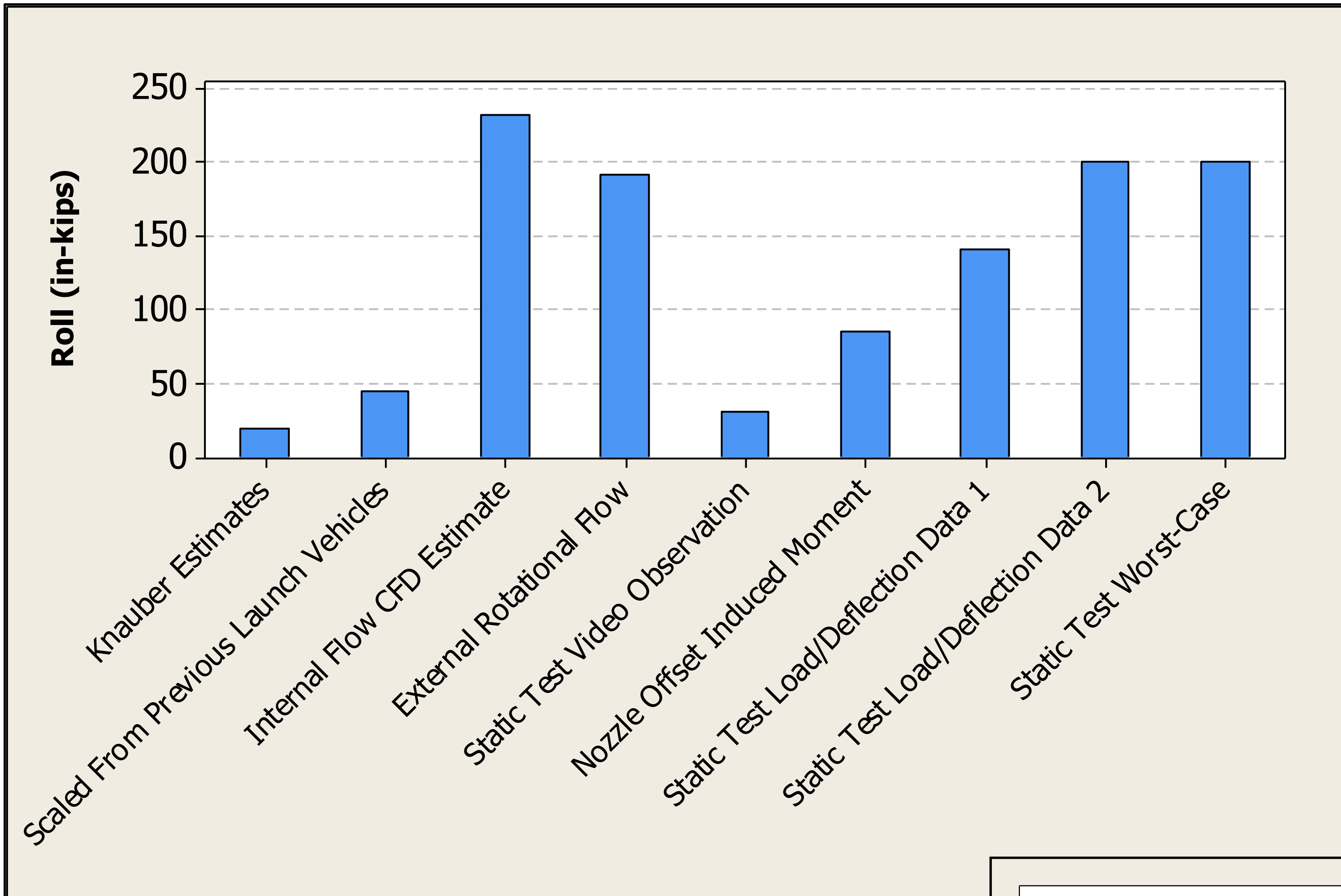
- **Weak corporate knowledge existed on original system design**
  - **No single expert to ask, and current discipline experts disagreed**
- **Interdisciplinary team was formed, cross-cutting organizations**
  - **System Engineers**
  - **Rocket Propulsion Scientists**
  - **Guidance, Navigation, and Controls**
  - **Test Facility Operators**
  - **Safety and Mission Assurance Specialists**
  - **Software Engineers**
  - **Mechanical Engineers**
  - **Measurement System Design and Calibration Engineers**
  - **Statisticians**

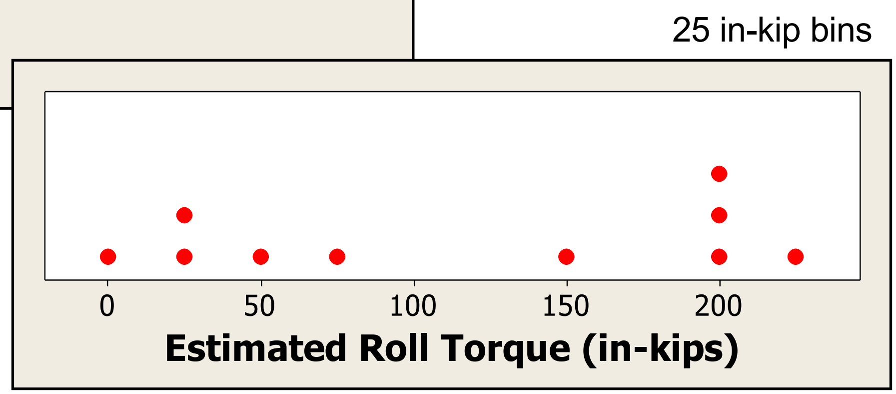
**How did a statistician get invited?**

# *Initial Problem Definition*

- **Measure internal roll torque of the reusable solid rocket motor during firing to provide design requirements for the reaction control system.**
- **When we started, with this broad requirement "measure roll torque" was accepted and most of the focus was on getting the measurement.**
- **Precise problem definition and the utilization of the measurement in the system analysis was not an initial focus.**
- **As it turned out, we measured roll torque well, but not under the most relevant test conditions.**
- **Lesson learned: #1**
  - **Should have pressed for a clearer understanding of how the measurement would be used in the system analysis.**
- **We felt that "they knew what they wanted", so we worked hard at the problem element "we knew how to solve best" rather than pressing into other's backyards to define the right question.**

# *Starting Estimates of Internal Roll Torque*



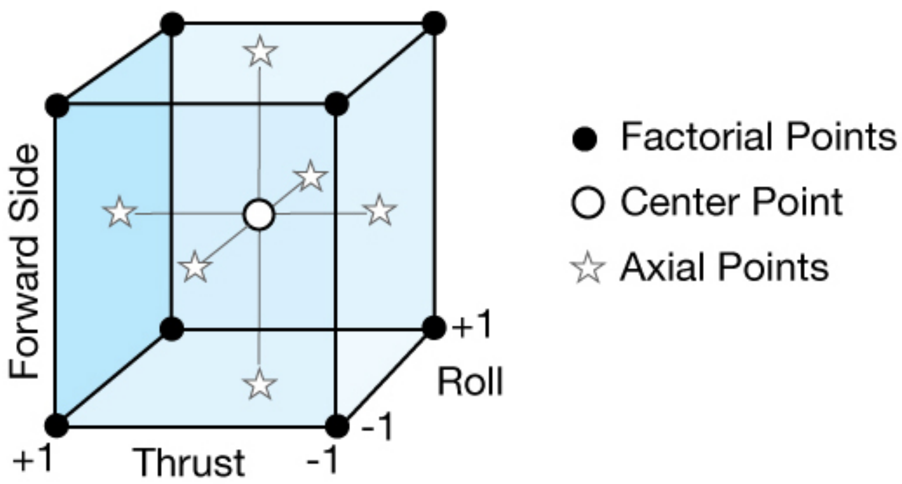

- **Discipline-centric estimates, no consensus**
- **No uncertainties on estimates**
- **Design Requirement set at 200 in-kips**

# *Experimental Campaign*

**Develop a strategy of nesting and sequencing of multiple experimental design and analysis phases, feeding into each other to provide the high-level "answers" needed for decision makers**

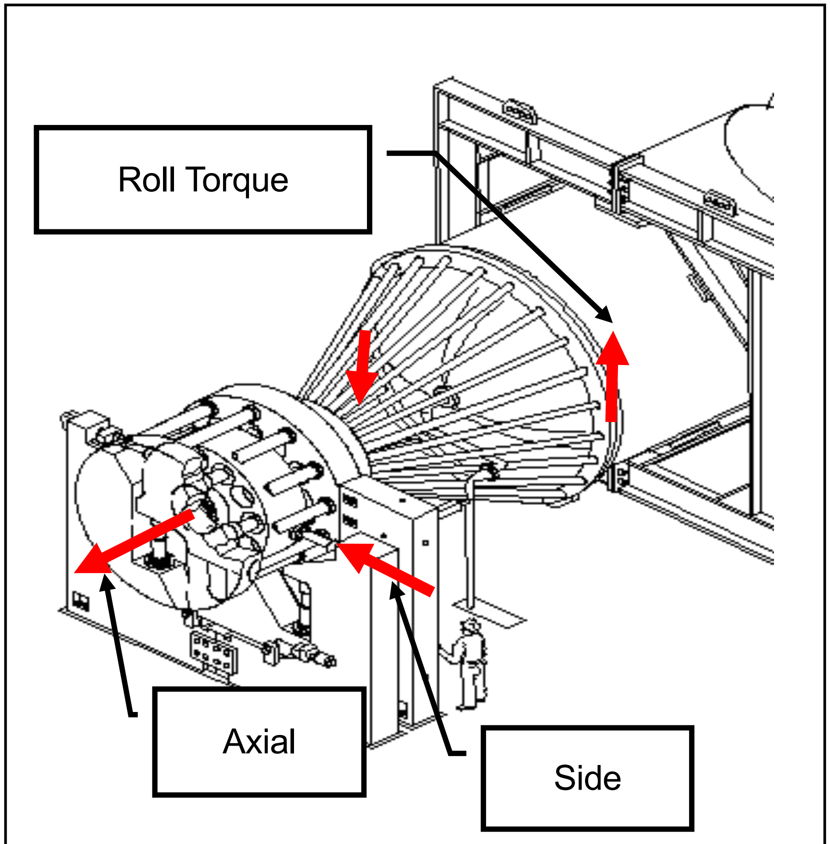
1. **Facility Characterization/Calibration Experiment Design**
   - **Before and after the firing to characterize the measurement system**
2. **Rocket Firing Design – Test Article Characterization, Flight Simulation**
   - **Strategically plan the 120 seconds of firing time**
3. **Combine the Facility and Test Article Characterization Models**
4. **Uncertainty Characterization and Communication of Responses**
5. **Iterative, continuous interpretation of the results with the subject-matter experts of both the test article and the test facility to reach consensus**
6. **Deliverables are input parameters in the GNC simulations of flight**

# *Facility Characterization Design*




**Face-Centered Central Composite**

- **Factorial combination limits**
- **Pseudo, Near replicates**
- **Restricted randomization**
- **Non-replicated whole-plots**




- **Adapted response surface approach**
- **Five-dimensional, second-order response surface for 5 responses**
- **Inverse prediction with estimated uncertainty**

# *Response Surface for Characterization*

- Response Surface Methods adapted for a nontraditional application
  - Characterization, not optimization
  - Mathematical model is the product, not optimized factor settings
  - Confirmation points over the entire design space, not sensitivity to the location of optimum performance
- Inverse Prediction of Second-Order Response Surface

$$\left[\hat{x}_1 \cdots \hat{x}_5\right] = \hat{F}\left(\left[y_1 \cdots y_5\right]\right)$$

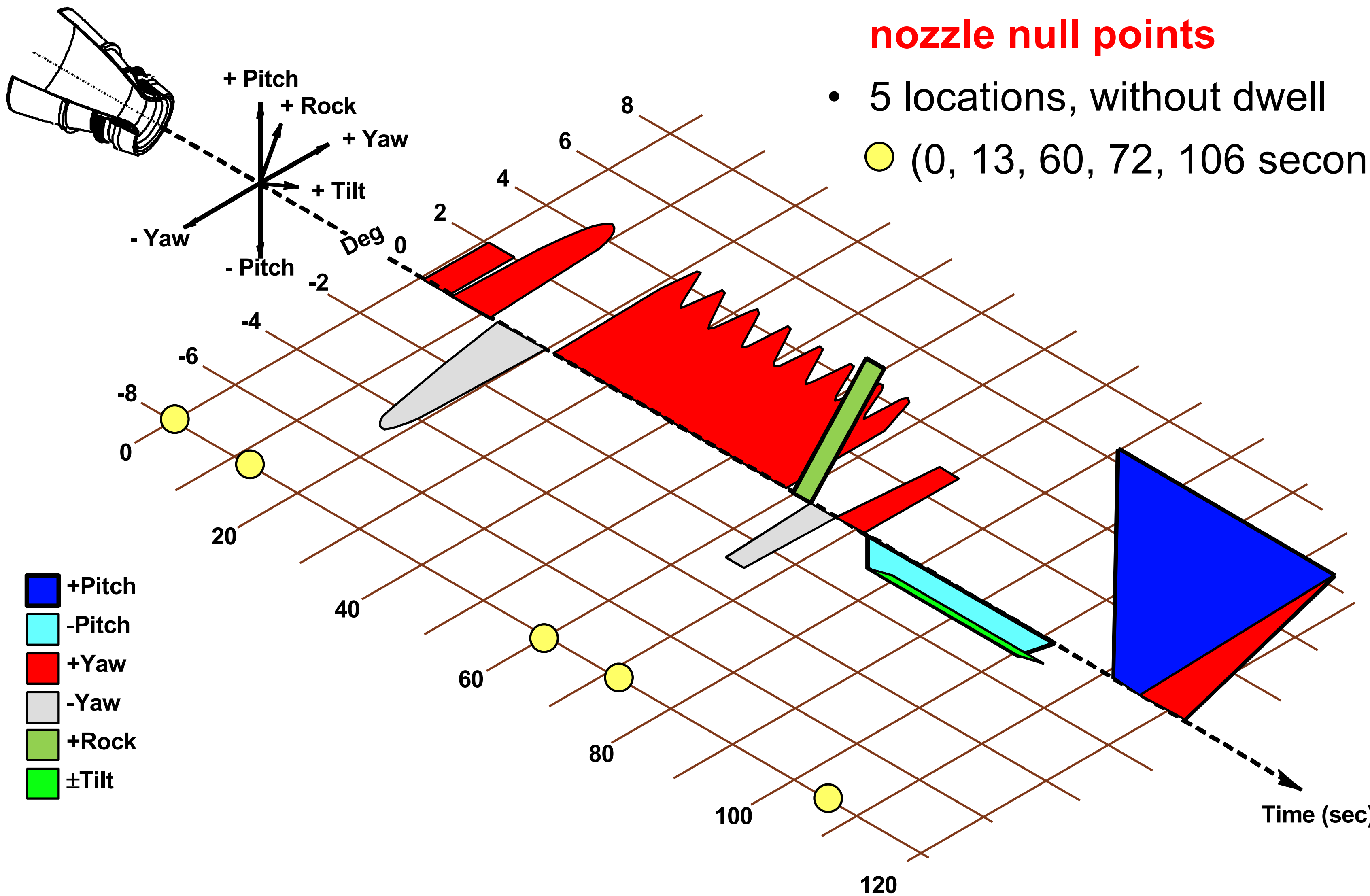
- Inverse prediction intervals were approximated through a localized mapping from classical forward regression intervals to the inverse space

Parker, Vining, Wilson, et al. (2010) "The Prediction Properties of Classical and Inverse Regression for the Simple Linear Calibration Problem," JQT

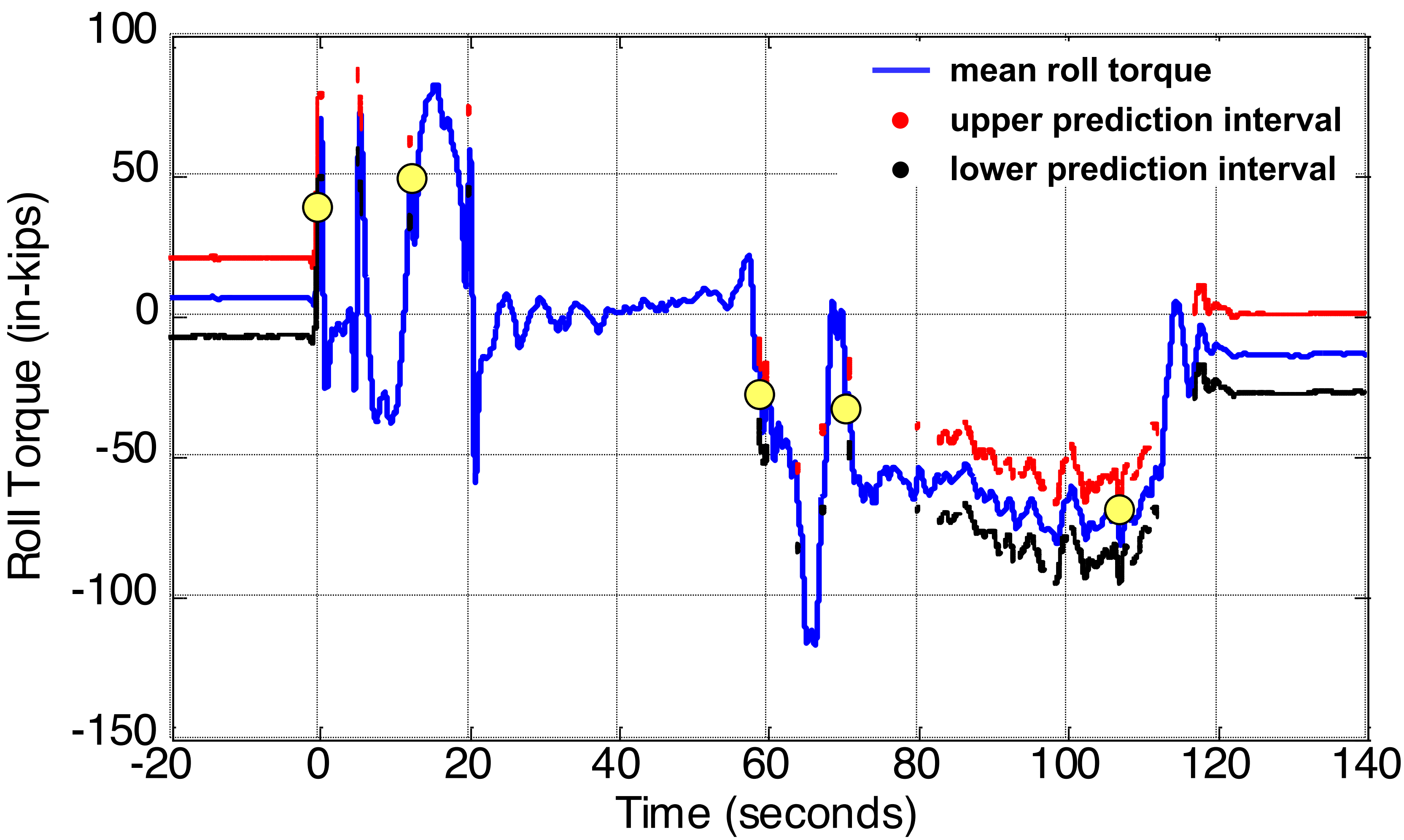
Parker and Finley (2010) "Advancements in Aircraft Model Force and Attitude Instrumentation by Integrating Statistical Methods," *AIAA Journal of Aircraft*

# *Rocket Nozzle Duty Cycle*

- **Interest: Measure roll at nozzle null points**
- 5 locations, without dwell
  - (0, 13, 60, 72, 106 seconds)



# *Full-Scale Motor Firing Results*



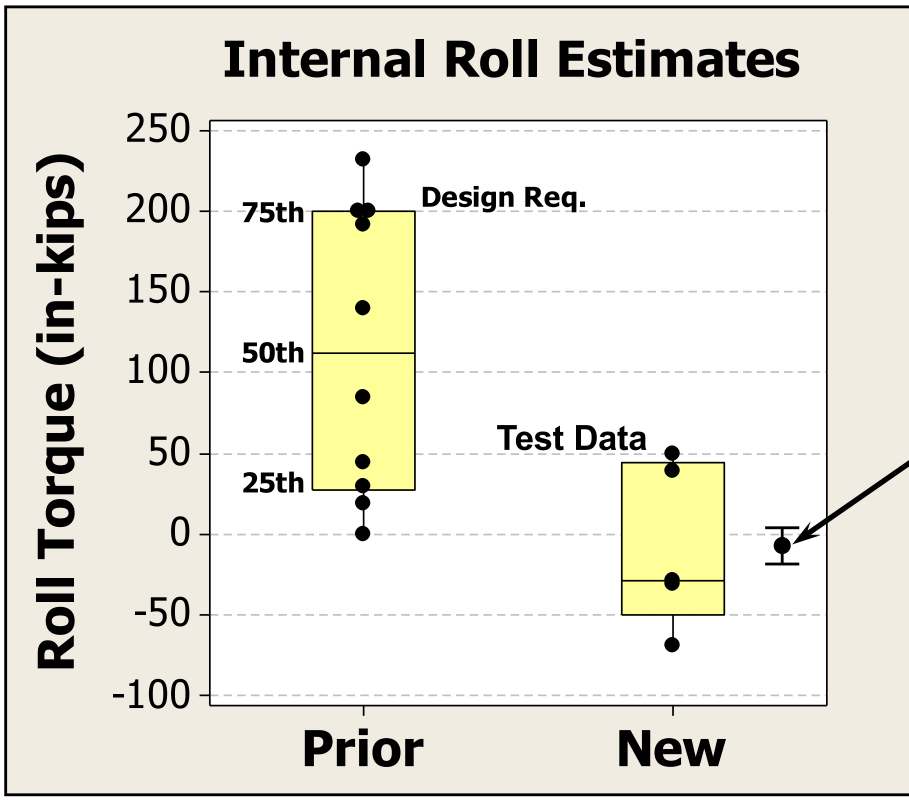

**Quantified intervals where defendable, not extrapolated**

Nozzle null points

(0, 13, 60, 72, 106 sec.)

# *Static Rocket Firing Data Interpretation*

**Developed a defendable, consensus methodology to estimate roll torque in collaboration with subject matter experts**




## Results

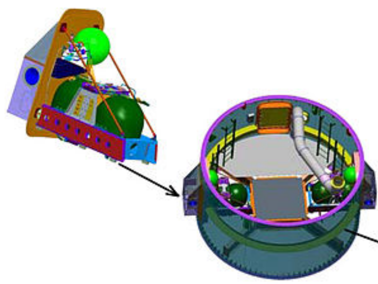
**Consensus estimate incorporating subject-matter knowledge:**

**-8 ± 13 in-kips**

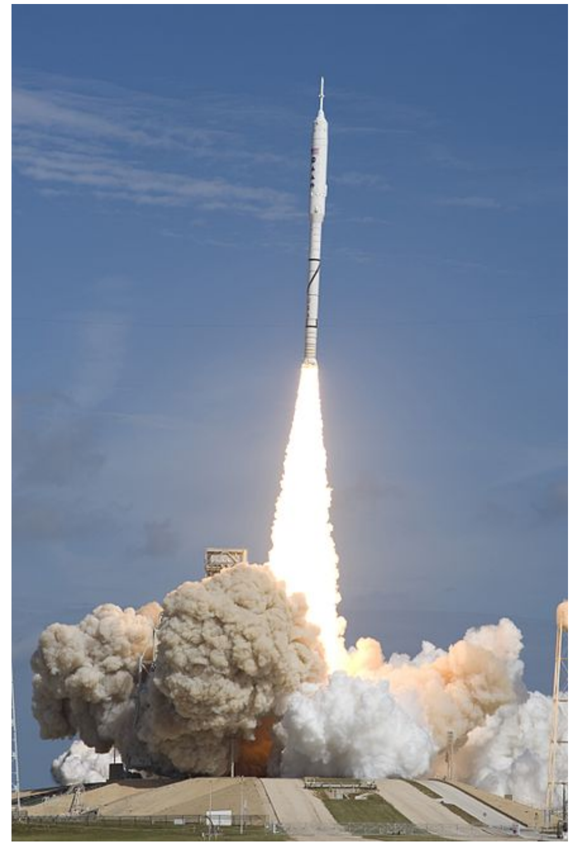
**Original requirement of 200 was reduced to near zero, with quantified uncertainty**

# *Flight Test Validation*

- **Flight test validation of ground test experimental campaign**
- **Ares IX launched on Oct. 28, 2009**
- **Successful flight**



Roll Reaction Control System



- **Reaction control system was active in the flight test**
- **Flight data reconstruction confirmed low roll torque as predicted from ground testing**

# *Challenging Statistical Techniques*

- Restricted randomization in a destructive (irreversible) test presented challenges for rigorous inference
- No pure replicates for experimental error, pseudo and near-replicates
- Restricted factor combinations due to infrastructure and safety issues
- Experimental inscribed resulting in restricted predictive model
- Inverse prediction of a five factor, second order response surface for five responses
- Interval estimation of the inverse regression
- Interpreting interactions, previously assumed to be zero, was critical in estimating roll torque and communicating value
- Building a consensus estimate with statistical rigor

# *Statistical Engineering Lessons Learned*

- Precise objectives were not defined until after the first test was completed - earlier, strategic involvement would have accelerated the learning process

- Success was not based on a single statistical tool, rather it was based on defining the right questions and integrating and extending multiple methods

- Changes to a complex and expensive process, embedded for decades takes leadership and demonstrated benefits

- Significant impact requires changing the normal operating process, rather than a one-time solution

# *Case Study Summary*

- Critical Features
  - Collaboration with other science and engineering disciplines
  - Synergistic combination and extension of statistical methods
  - Embedded into standard work processes
- Outcomes
  - Defined the right questions
  - Guided strategic resource investment
  - Efficiently generated knowledge and stimulated insights
  - Accelerated research and development

**Statistical Engineering was application focused and impact driven, and broadened the influence of statistical thinking and methods**

# *Case Study Impact and Insights*

- Project: Significant reduction in roll reaction control system design requirement uncertainty that allowed for mass reduction
- Discipline: Recognition of a statistician's value at the leadership level
  - Agency level team awards from the NASA Administrator
  - Pivotal demonstration motivated organizational changes within NASA to establish Statistical Engineering teams
  - Resulted in follow-on work for 5+ years in defining additional rocket motor performance requirements

**<u>Statistical Engineering Discipline Insights</u>**

- How would I teach someone how to attack this problem?
  - Knowing DOE/RSM was necessary, but not sufficient
- What were the critical skill sets necessary to be successful?
- Where do you find people with these skill sets?

# *Acknowledge Collaborators*

- Steve Gentz (NASA)
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