

Unique Booster and Tower Force Measurements on NASA's Space Launch System (SLS)

Kenneth Toro and Peter A. Parker

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Acknowledging Collaborators



Sean Commo

Advanced Measurement and Data Systems Branch

Mark Cagle, Jared Fell, Sandy Webb, Chris Laws and Ray Rhew

Aeronautics Systems Engineering Branch

Dave Chan, Jeffery Flamm, and Jeremy Pinier

Configuration Aerodynamics Branch

Samantha Zauber

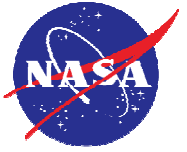
Subsonic /Transonic Testing Branch

Jacobs Technology, Inc.



- **Space Launch System Liftoff and Transition Test Objectives**
- **Isolated Booster Force Measurement Capability**
- **Isolated Tower Force Measurement Capability**
- **Calibration Strategy**
- **Concluding Remarks**

Space Launch System (SLS) Test Objectives



Langley's 14x22 Wind Tunnel

Evaluate Aerodynamic Forces and Moments

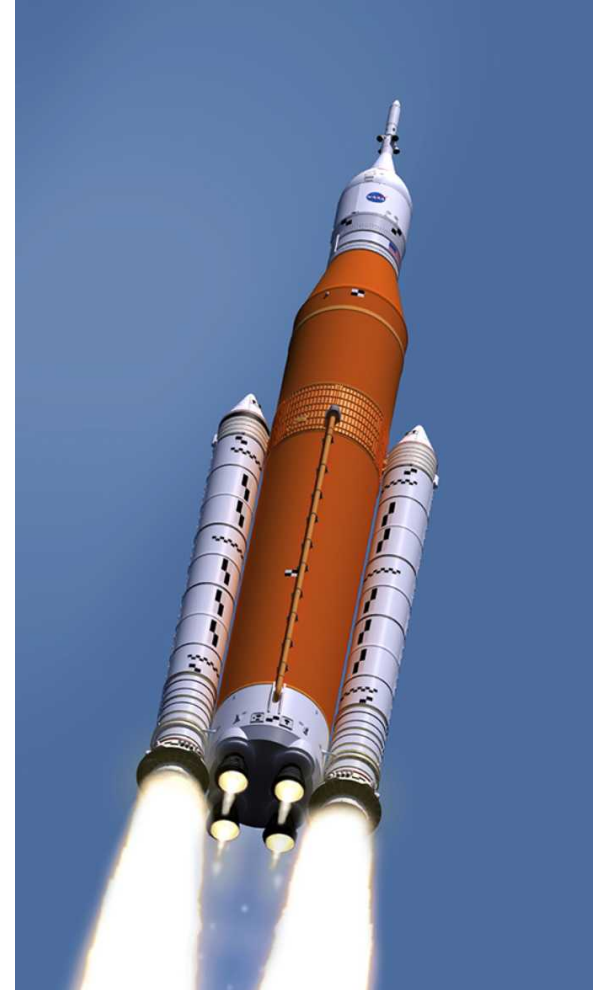
Liftoff Phase

- Interaction with the launch tower and mobile launch platform being subjected to ground winds while varying vehicle's height off of the launch pad

Transition Phase (from liftoff to ascent)

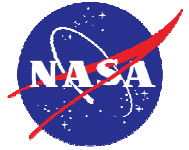
- Varied over a wide range of angles of attack and angles of sideslip

Data used to develop aerodynamic databases for the Guidance, Navigation, and Control

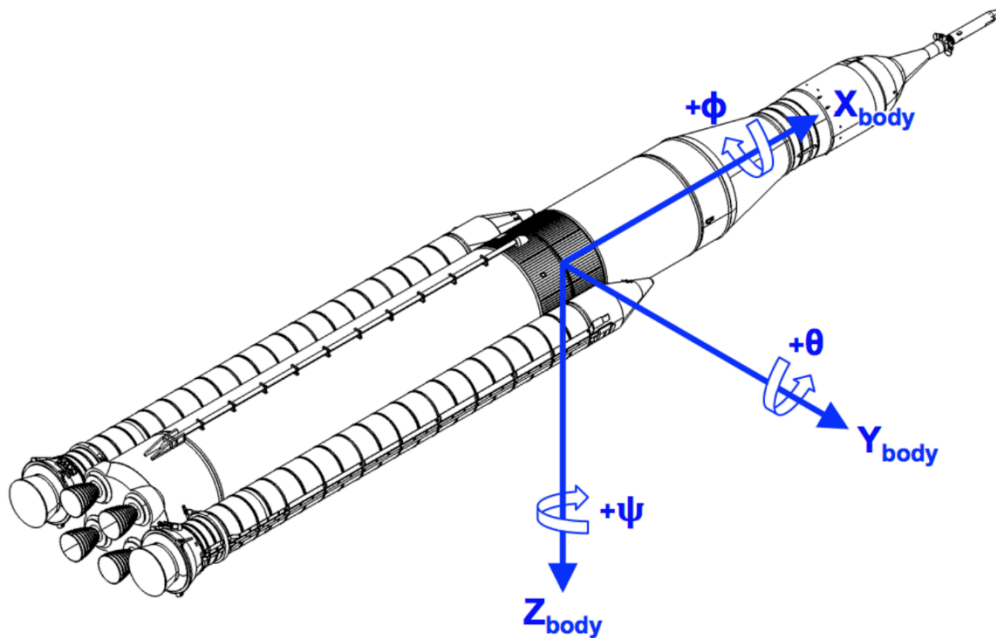


Booster Measurement Capability

Enhancing Measurement Capability by Isolating Booster Loads



- Isolate solid rocket boosters (SRB) from the overall vehicle loads
 - Force measurement accuracy of 5% desired
- No capability existed to directly measure forces and moments
- Testing schedule precluded fabrication of custom force balances



Measurement System Design Strategy

- Identified available load cells used in industrial robotics
- Compact design fit within the existing boosters
- Available in 4-week lead time, \$4K/each
 - Compared to custom design/fab of 4-month, \$50K/each
- Provided with six-component calibration
- Cost effective solution when combined with **in-situ system calibration**

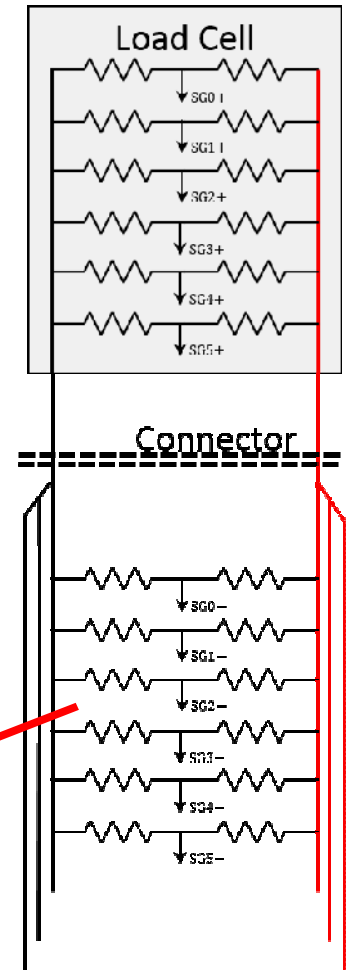


Specifications:

- 1.750 inch diameter
- 0.625 inch thickness
- 120-240 lb. forces

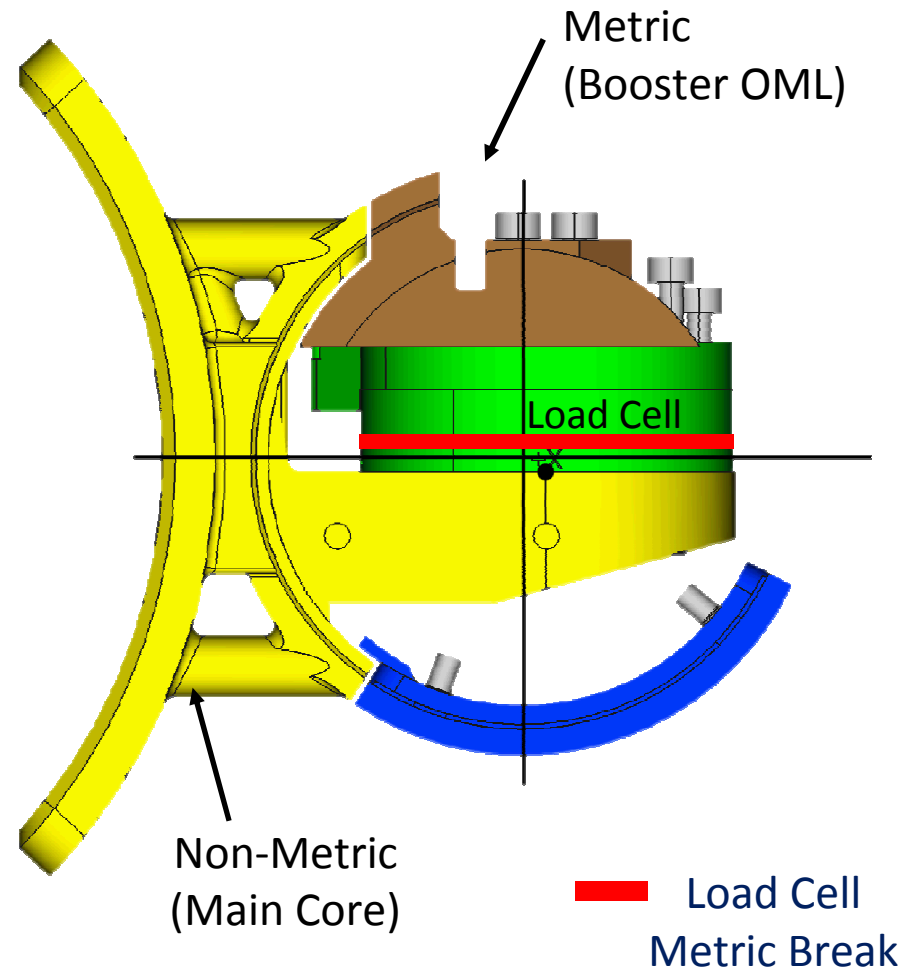
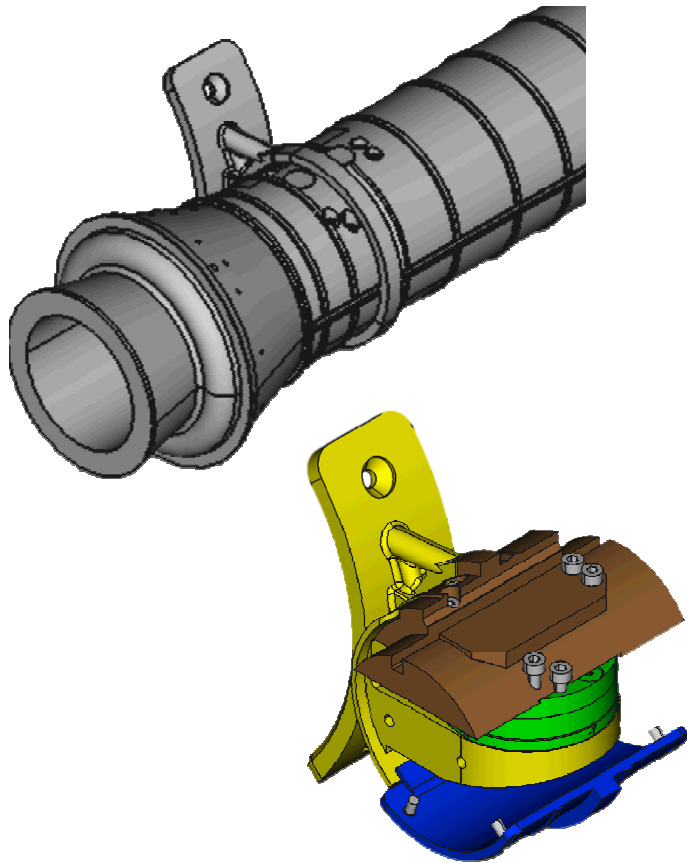
Special Implementation Considerations

- Load cells comprised of half-bridges circuits which can not be directly connected to nano-volt range meters
 - Cabling was produced to arrange half bridge completion circuits near the load cell connector
- Mitigation of undesired air currents over metric gap was accomplished with loose fitting Kapton rings

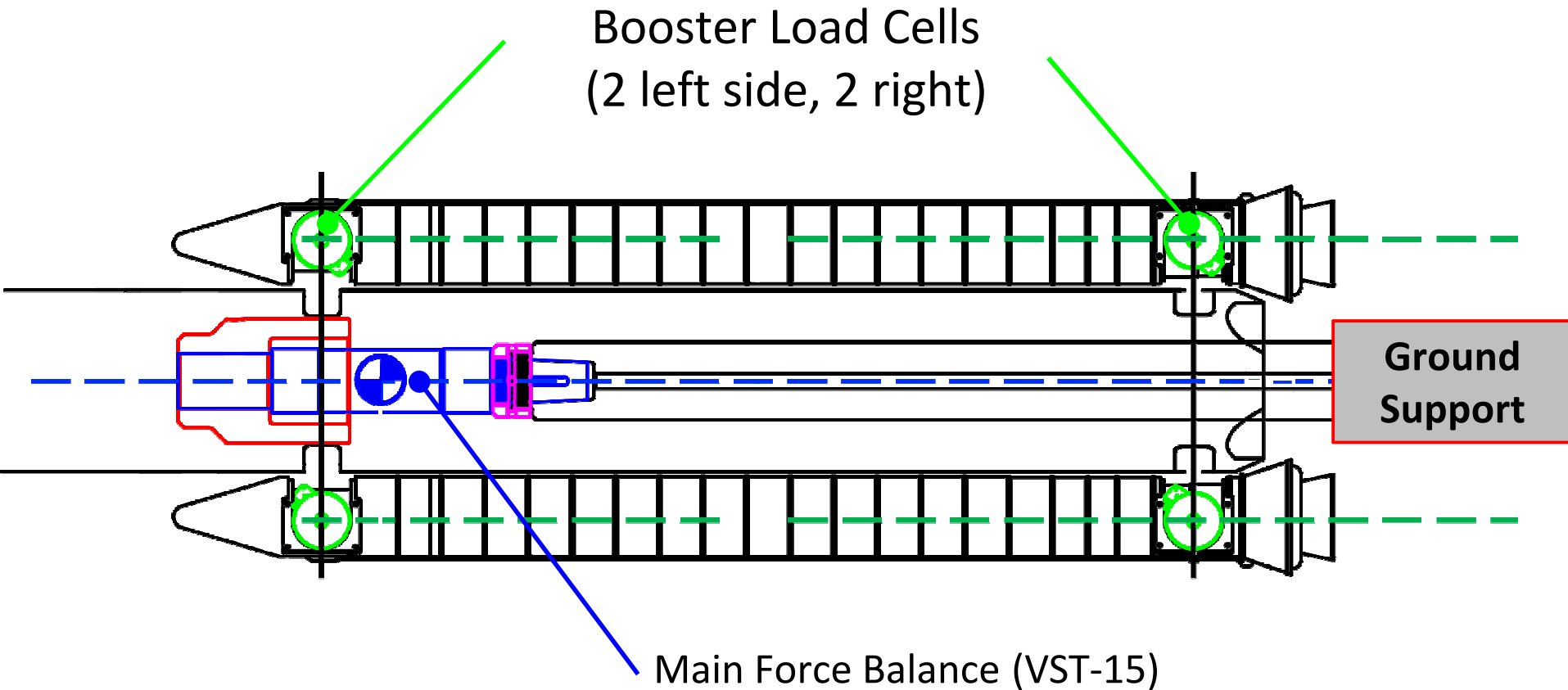


Integration of Load Cells into Test Article

Aft Booster
Bracket



Test Article Force Measurement System



5 six-component balances tested simultaneously

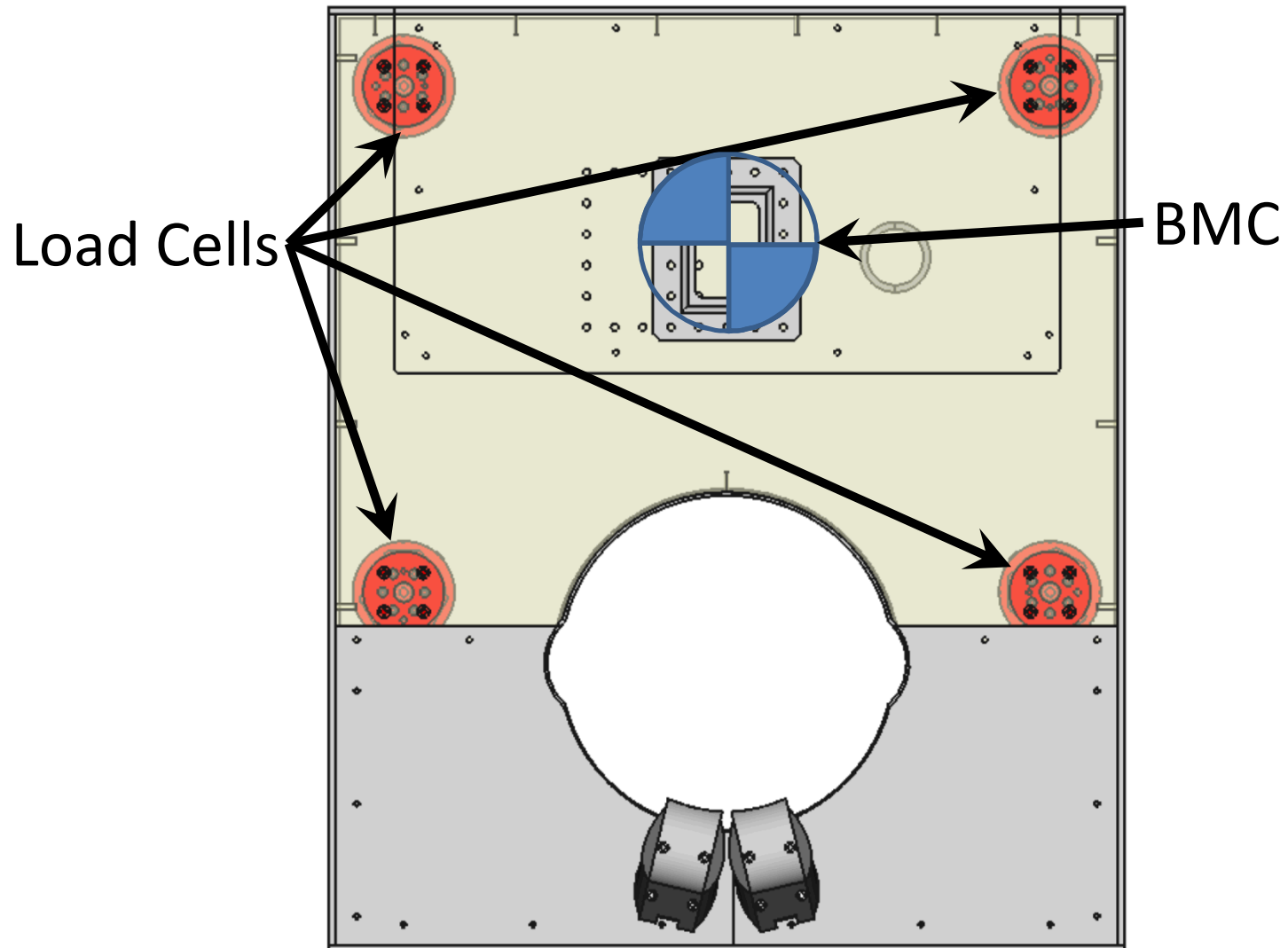
Tower Measurement Capability

Tower Load System

- **Unique to the 2019 entry, tower loads were desired to validate wind-load estimates**
- **Four off-the-shelf load cells were integrated into the tower model**
 - **Six-Component Load Cells**
 - **Sized at 150% expected loads**



Load Cell Positioning



Calibration Strategy



- **Factorial load schedule (design) featuring 1, 2, and 6 component loads**
- **Multicomponent loadings achieved by angular positioning of model support system, utilizing previous research and development**
 - Parker, P. A. (2003) “**Single vector calibration system for multi-axis load cells and method for calibrating a multi-axis load cell,**” US Patent 6629446.
 - Commo, S. A. and et. al (2016) “**In-situ load system for calibrating and validating aerodynamic properties of scaled aircraft in ground-based aerospace testing applications,**” US Patent 9354134.
- **Utilized main balance as reference for applied loads on boosters, increasing efficiency and reducing the need for precise fixture**
 - **Complete calibration of both boosters in about 2 days**
- **Data reduction algorithm for real-time force display during testing**

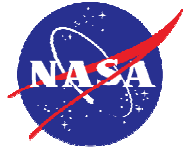


- Unique to this FMS, the load cell outputs are converted to forces/moments using factory provided calibrations.
- Corrections for assembly misalignments are provided by in-situ booster and tower calibrations:

$$NF_{UnCor} = \beta_0 + \beta_{NF} NF_{Cor} + \cdots \beta_{NF*RM} NF_{Cor} * RM_{Cor} + \cdots \beta_{SF^2} SF_{Cor}^2$$

- This model allows for the use of existing balance reduction algorithms implemented at the 14x22 facility
- 24 coefficients estimated in calibration

Booster Calibration



Booster Load Transfer

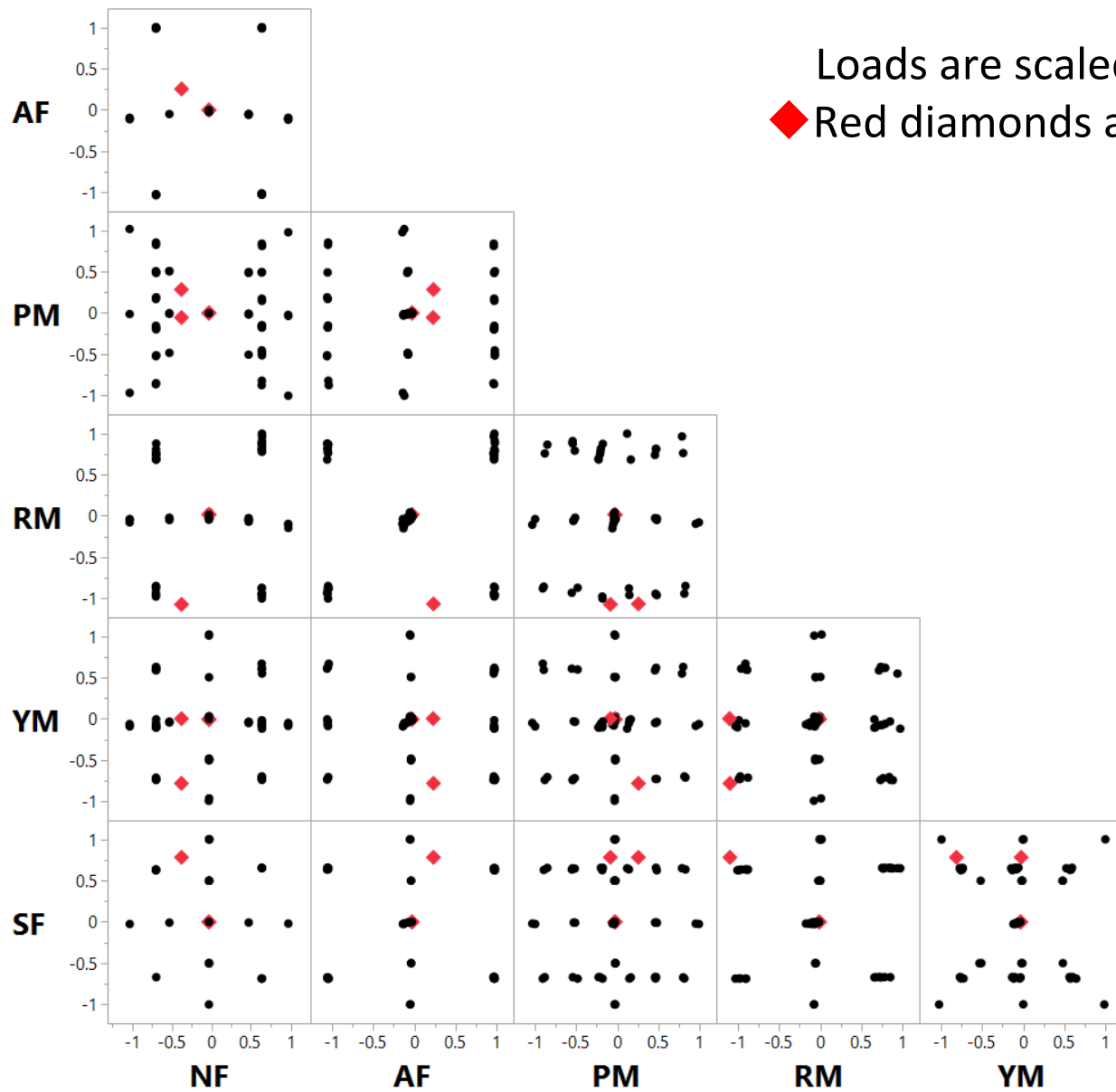
- Each pair of load cells are combined to a common moment center located at mid-distance between load cells:

$$\begin{bmatrix} NF \\ AF \\ SF \end{bmatrix}_{SRB(UnCor)} = \begin{bmatrix} NF \\ AF \\ SF \end{bmatrix}_{fwd} + \begin{bmatrix} NF \\ AF \\ SF \end{bmatrix}_{aft}$$

$$\begin{bmatrix} RM \\ PM \\ YM \end{bmatrix}_{SRB(UnCor)} = \left(\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} \times \begin{bmatrix} -AF \\ SF \\ -NF \end{bmatrix} + \begin{bmatrix} RM \\ PM \\ YM \end{bmatrix} \right)_{fwd} + \left(\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} \times \begin{bmatrix} -AF \\ SF \\ -NF \end{bmatrix} + \begin{bmatrix} RM \\ PM \\ YM \end{bmatrix} \right)_{aft}$$

- In-situ applied loads measured with the VST-15 are transferred to each SRB Balance Moment Center (BMC)

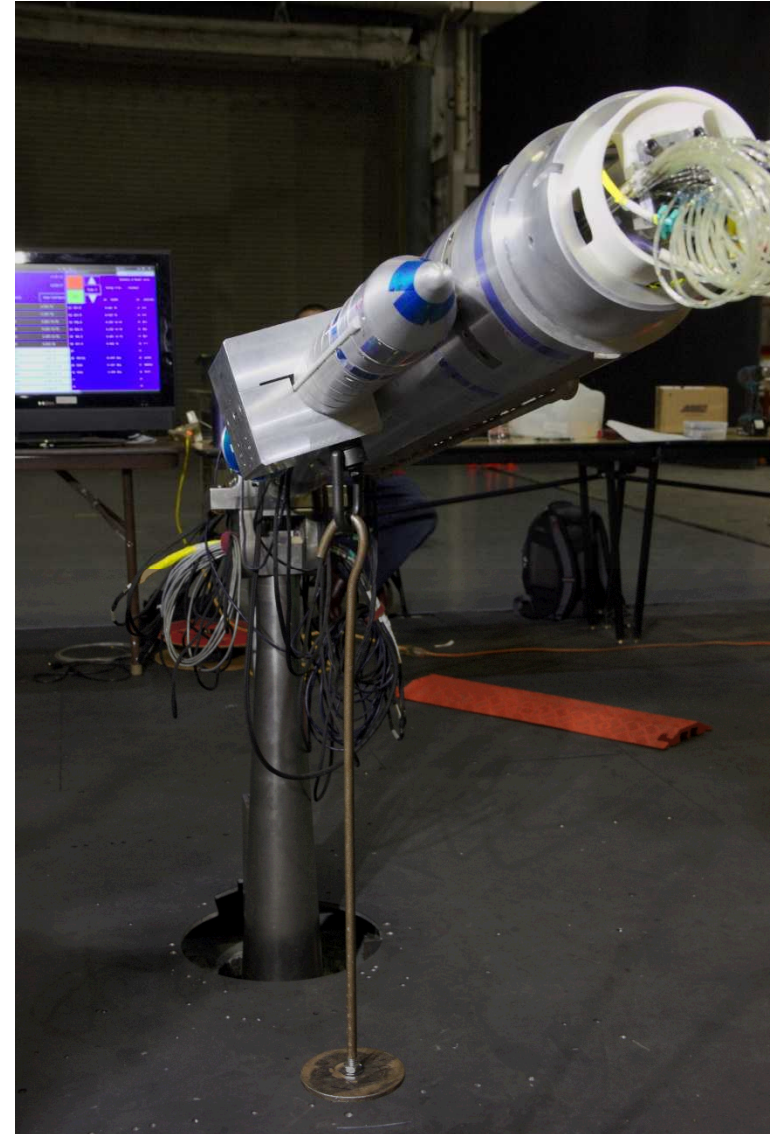
Booster Calibration Design



Loads are scaled to ± 1

Red diamonds are confirmation points

Assembled In-Situ System Calibration





Booster Calibration Accuracies

- Accuracies are based on two-sigma values of the back-computed corrected loads.
- Includes all points collected during calibration activity: preloaded, unpreloaded, and confirmation points.
- Values are in percent of full-scale

Left Booster

	NF	AF	PM	RM	YM	SF
Uncorrected	0.5	3.5	2.1	3.7	28.6	2.3
Corrected	0.2	0.8	1.0	1.2	2.7	0.4

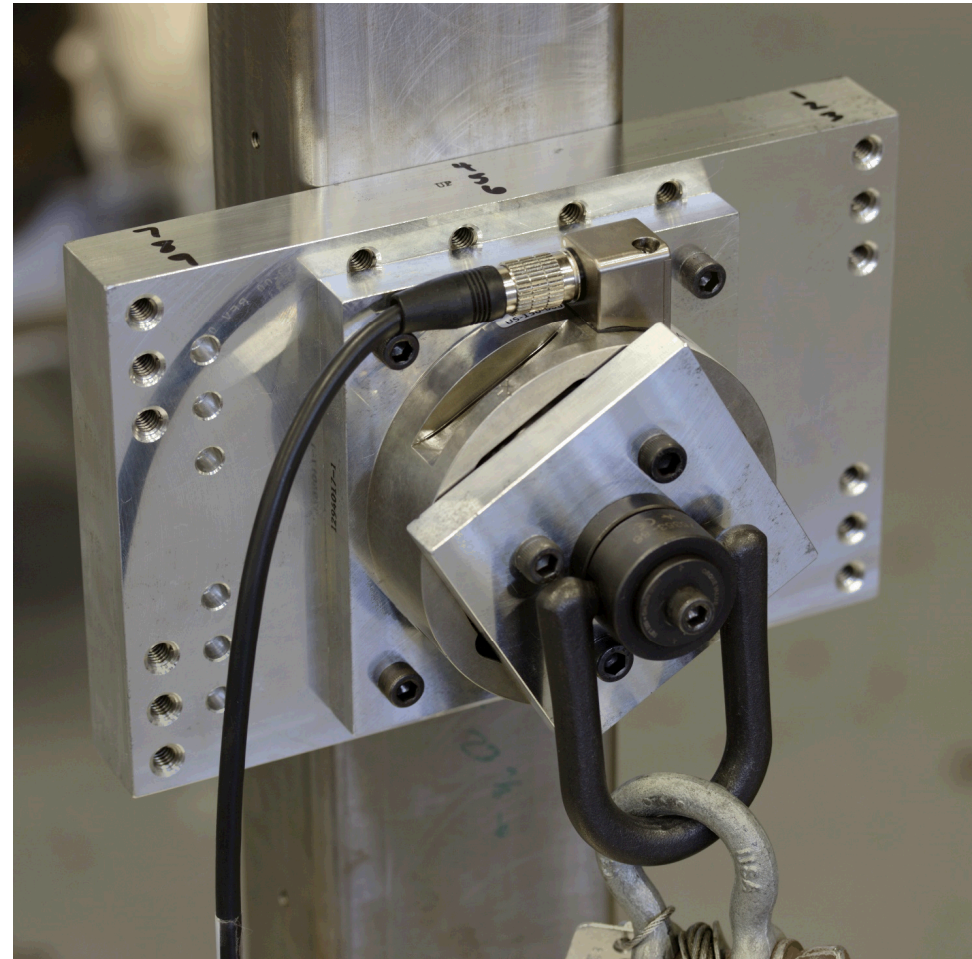
Right Booster

	NF	AF	PM	RM	YM	SF
Uncorrected	0.4	3.9	4.4	4.2	9.8	3.9
Corrected	0.3	0.7	1.2	1.3	3.5	0.5

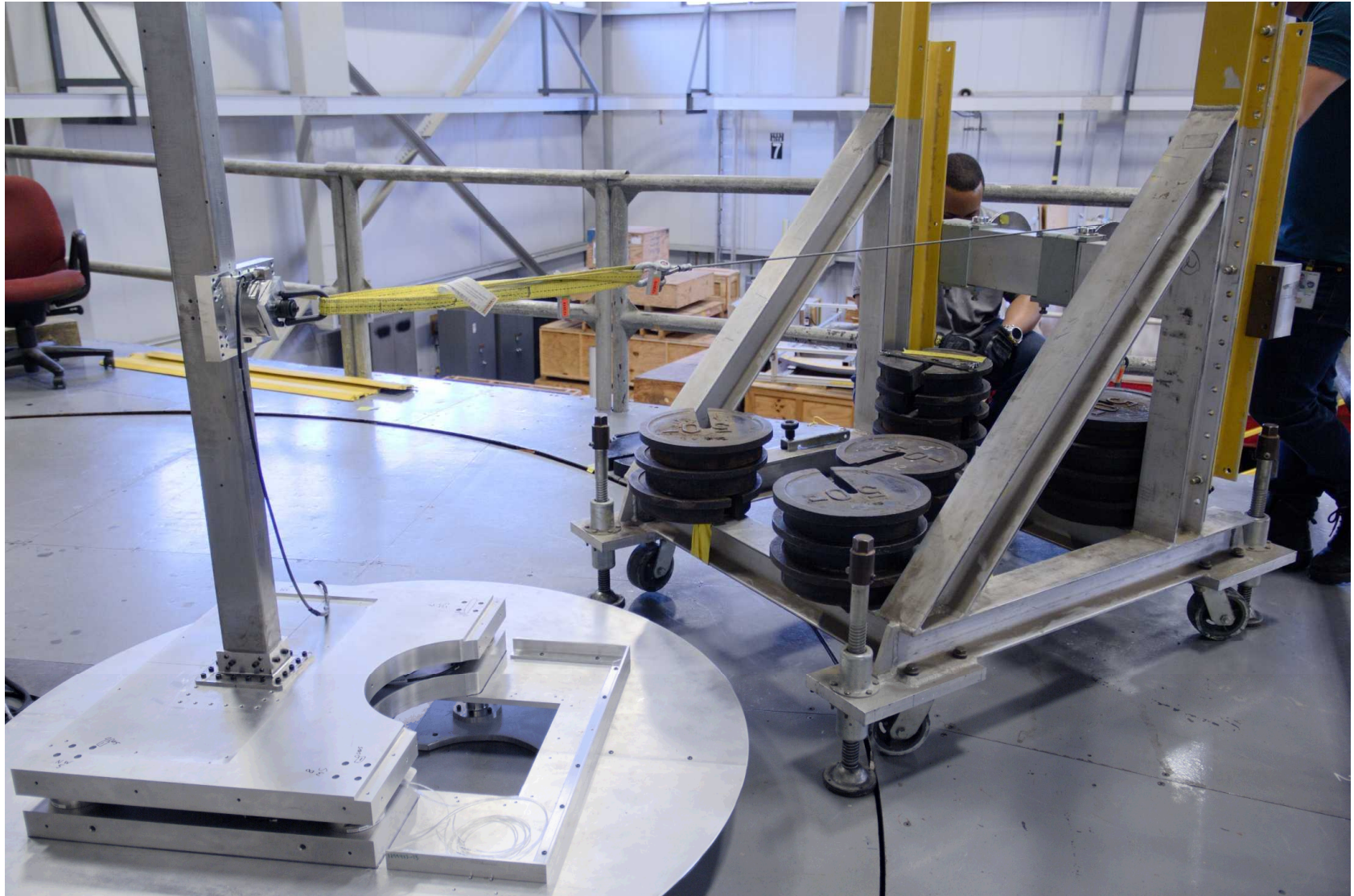
Tower Calibration

Tower Calibration Strategy

- The tower system lacked a precision force-balance for applied load
- A fifth load cell was used to provide loads applied via a cable
- Load cell mounting plate implemented DoE principles
 - 9 Locating Pins
 - Axial points
 - Factorial points



Tower Calibration Setup



Tower Load Transfer

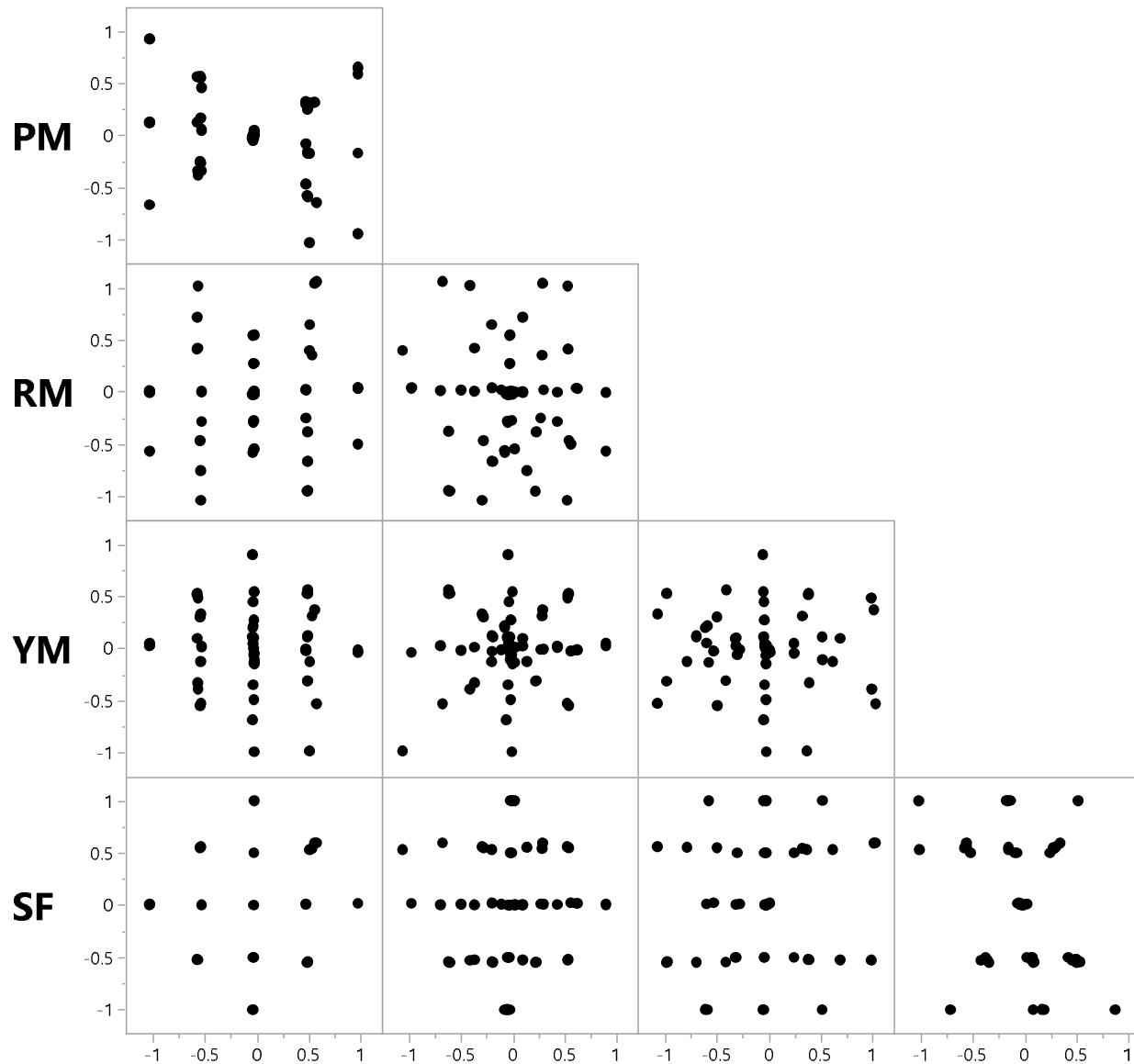
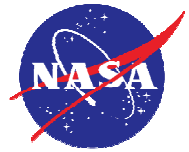
- Each pair of load cells are combined to a common moment center located at mid-distance between load cells:

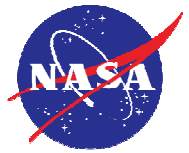
$$\begin{bmatrix} NF \\ AF \\ SF \end{bmatrix}_{Tower} = \sum \left(\begin{bmatrix} NF \\ AF \\ SF \end{bmatrix} \right)_i$$

$$\begin{bmatrix} RM \\ PM \\ YM \end{bmatrix}_{Tower} = \sum \left(\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} \times \begin{bmatrix} -AF \\ SF \\ -NF \end{bmatrix} + \begin{bmatrix} RM \\ PM \\ YM \end{bmatrix} \right)_i$$

- In-situ applied loads measured with fifth load cell transferred to the tower moment center

Tower Calibration Design





Tower Calibration Accuracies

- Accuracies are based on two-sigma values of the back-computed corrected loads.
- Calibration greatly reduce moments
- Values are in percent of full-scale

	NF	PM	RM	YM	SF
Uncorrected	0.32	13.63	5.03	36.33	0.31
Corrected	0.03	0.47	0.63	0.60	0.07

Concluding Remarks

Booster and Tower Force Measurement Results and Future Impact



- **Successfully measured booster and tower loads**
- **Integrated and adapted off-the-shelf force transducers**
 - **Significantly reduced cost and schedule for this class of test articles**
- **In-situ assembled system calibration was highly efficient**
- **Demonstrated an innovative force measurement capability enhancement for the class of test articles**
- **Methodology is being documented in an NASA Technical Memorandum**



- **Collaboration among researchers, force measurement experts, model designers, and facility test personnel was critical to the success of this experimental campaign**
 - **Begins with the research questions and article design stage**
 - **Requires participation through testing and post-test analyses**
- **To meet today's advanced measurement system demands, an integrated team paradigm is required**

