



Statistical Practice and Research at NASA

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National Aeronautics and Space Administration

Langley Research Center

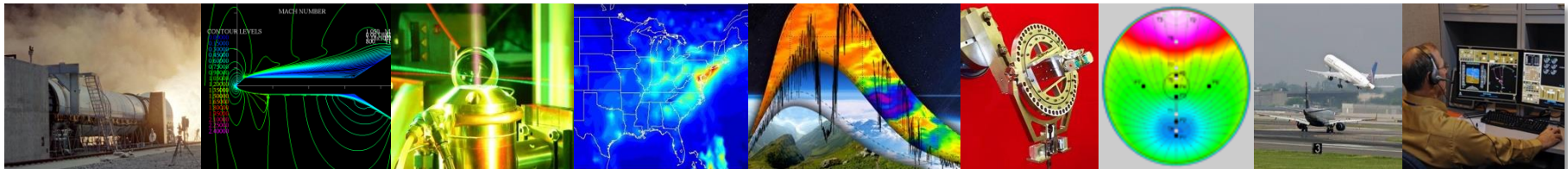
Hampton, Virginia

November 7, 2024

Air Force Institute of Technology

Department of Operational Sciences, Invited Seminar

Dayton, Ohio



NASA Langley Research Center



- One of 10 NASA Centers located in Southeastern Virginia
- Established in 1917 as first civilian aeronautics laboratory in the U.S.
- Initial home of the first astronauts, Mercury 7

Today, we focus our research on technical challenges in:

- Space Exploration
- Aeronautics and Air Transportation
- Earth and Planetary Science





Overview of Presentation

- **Aerospace and statistics parallel history, and my journey**
- **Statistical collaboration, influence, and recent impact at NASA**
- **Case studies to illustrate practice and motivate research**

Statistical and Aerospace Timeline



Wright Flyer, 1903

NASA Formed, 1958



Saturn V, 1967

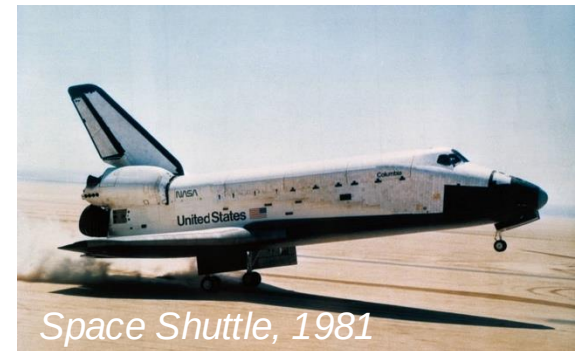


Apollo 11, 1969

“...most of the statistical work is performed by engineers and scientists, some well trained in statistics and others having only a passing acquaintance with the subject....”¹



Variable Density Tunnel, 1921



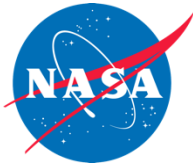
Space Shuttle, 1981

Statistical timeline

Fisher, DOE, 1920's → Box, RSM, 1951 → Deming, Taguchi, 1980's

¹ Rubin, E. (1966) “Some Statistical Applications in the Apollo Program.” *The American Statistician*, 20 (4), pp. 32-34.

An Engineer's Statistical Awakening



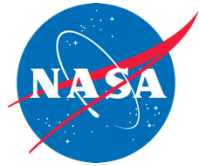
- Traditionally, academic training of engineers lacked relevant, applicable, practical courses in statistics (*that was me*).
 - Engineers are generally trained to “fear” uncertainty
- In 1999, I stumbled upon a 1980 NASA report written by a visiting statistics professor that proposed “radical” ideas promising significant schedule and cost benefits.

“Radical” statistical concepts

- Experimental design starts with questions, not data
- Factorial experiments are efficient, not chaotic
- Modeling involves inference, more than simply plotting data

Discovered “new” powerful statistical techniques to efficiently characterize system performance to support rigorous decisions.

Solid Rocket Motor Heritage System Leveraged for New Architecture



Shuttle



Ares I



Flight Test



**Full-Scale
Static Firing**



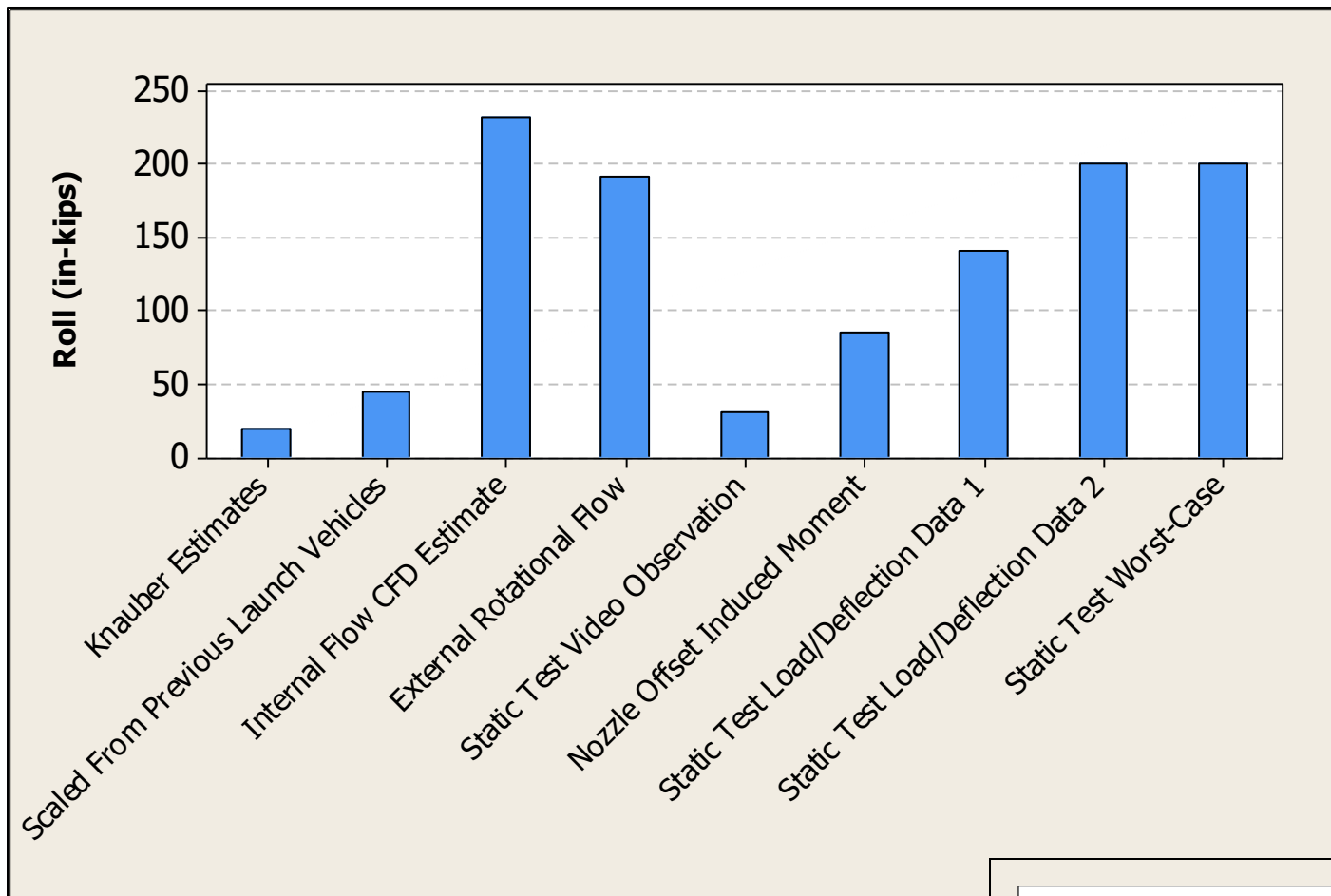
Rocket Motor Case Study Overview



- **Background/Context:** Leverage Shuttle reusable solid rocket motor design in a new configuration with new performance metrics and system requirements, previously unquantified for Shuttle.
- **Objective:** Estimate internal roll torque during static firing to support reaction control system requirements.
- **Consequences:** Uncertainty in control system requirements effect system reliability and operational capability, over vehicle's life-cycle.
- **Features of Solution Approach:**
 - Independent engineering assessment
 - Solicited and coalesced available information and data
 - Collaborative, systems perspective
 - Analytical tools were central in solution, requiring extension
 - Delivered a consensus estimate combining the measurements, mathematical models, and engineering knowledge of the system

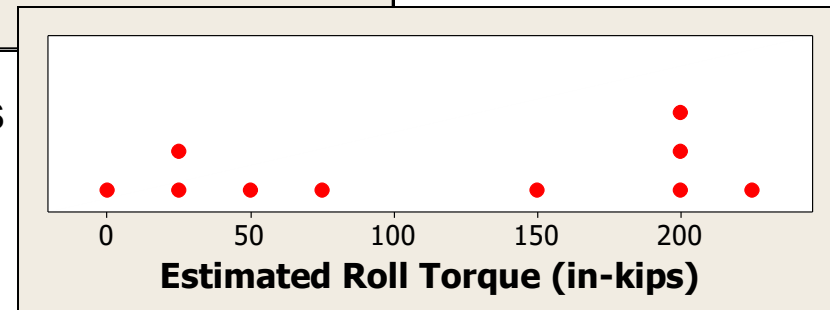


Initial Estimates of Roll Torque

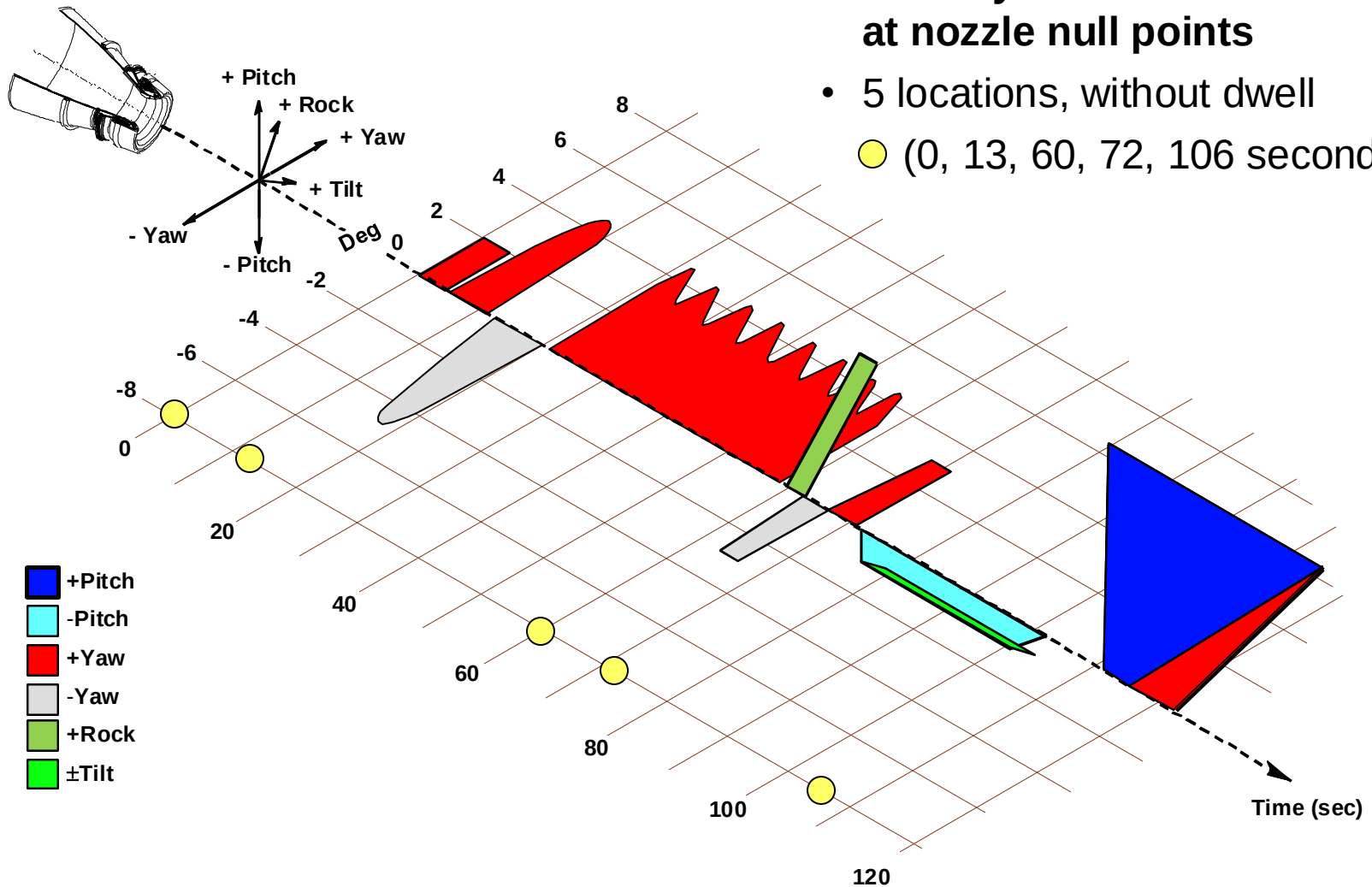
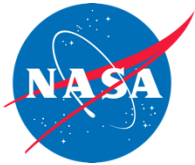


25 in-kip bins

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



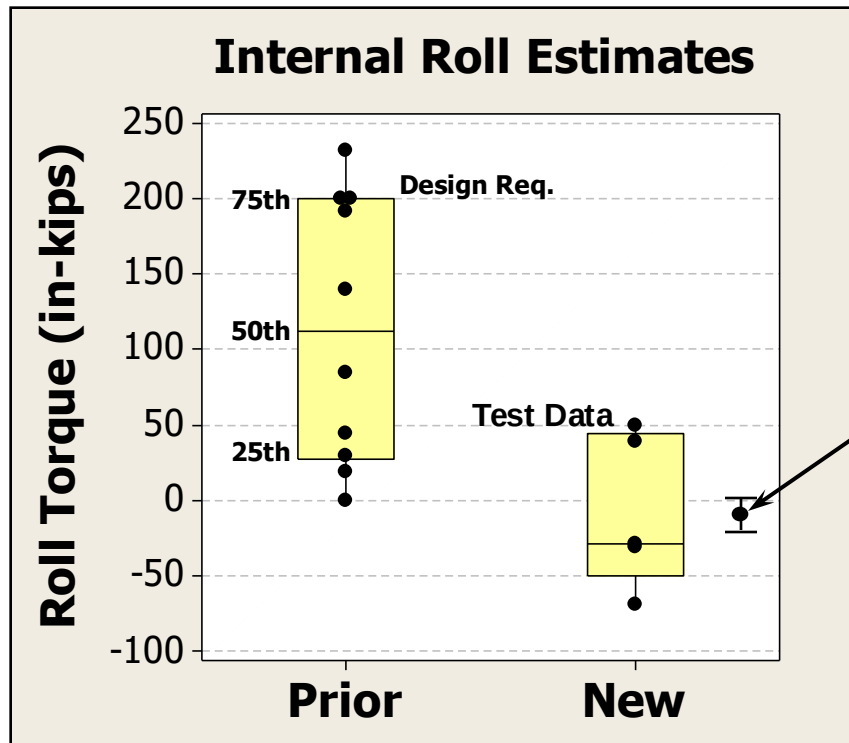
Rocket Nozzle Static Firing Duty Cycle





Roll Torque Consensus Estimate

Developed a defensible, consensus methodology to estimate roll torque in collaboration with test facility and subject matter experts



Consensus Estimate

- 8 ± 13 in-kips

Resulted in a significant reduction in roll torque uncertainty for the reaction control system design

Flight Test Validation

- **Flight test validation of static firing**
- **Ares IX launched on Oct. 28, 2009**

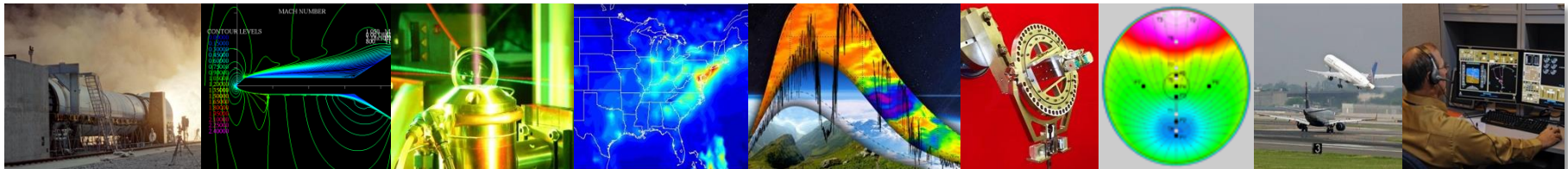


Flight data reconstruction supported low roll torque estimates predicted from static firing

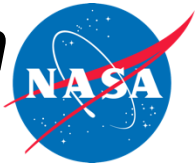
Statistical Discipline Team formed at NASA Langley in 2008



- **Motivated by successful demonstrations with Agency-level recognition and impact.**
- **Langley leadership envisioned team as an Agency-wide resource, a first of its kind.**
- **Crucial elements of successful team formation and growth**
 - **Visionary, multi-level leadership**
 - **Strategic hiring authority**
 - **Consistent demonstration of benefits**
 - **Building external collaborations**



NASA Statistical Engineering Symposium Williamsburg, Virginia 2011



- Unique forum: senior leaders, discipline experts and practitioners.
- Keynotes by the Dr. Michael Gilmore, OSD, Director of Operational Test and Evaluation (DOT&E), and Roger Hoerl, GE Global Research
- 150 attendees, across NASA Centers, other government agencies, academia, and industry.

Office of the Secretary of Defense
Los Alamos National Laboratory
NIST
United States Air Force
National Oceanic and
Atmospheric Administration
Naval Postgraduate School

Virginia Tech
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Old Dominion University
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Langley Research Center and Agency Sponsors



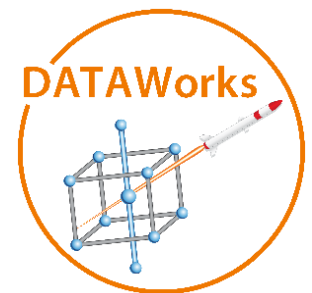
DOT&E / NASA Statistical Engineering Inter-Agency Agreement, est. 2014



- Partnership to advance and broaden statistical engineering practice, and a catalyst to engage the broader statistical engineering community in industry, academia, and other government agencies.

Annual Meeting is a Key Element of the IAA

- Defense and Aerospace Test and Analysis Workshop (**DATAWorks**).
 - Institute for Defense Analyses
 - American Statistical Association's Section on Defense and National Security (SDNS).
- Planning is in it's 10th year for April 22-24, 2025
<https://dataworks.testscience.org>



Statistical Collaboration and Influence



- Collaboration is multidisciplinary engagement from problem definition, solution development, and deployment with common goals.
 - It's more than *consultation* (advising others to help solve “their” problem) or *cooperation* (a team member assigned tasks).
- Collaboration leads to influence, a “power whose operation is invisible and known only by its effects¹ ...” on individuals, within organizations, and between organizations resulting in long-term impact.
 - Influence advances the practice of statistics and enhances an organization's ability to achieve their mission.

QUALITY ENGINEERING
<https://doi.org/10.1080/08982112.2018.1530357>



Taylor & Francis
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Effective interdisciplinary collaboration between statisticians and other subject matter experts

Christine M. Anderson-Cook^a, Lu Lu^b, and Peter A. Parker^c

with 6 Discussants: DeHart and White, Hoerl, Jensen, Litano, Slade, Typhina and Wilson

¹Webster, Noah (1828) American Dictionary of the English Language, United States, Editorium.



Strategic Collaborative Dialogue

- **Heilmeier questions were a preflight checklist for successfully launching a research project “to curb and clarify both the enthusiasm of the researchers and to evaluate the resource demands of the project managers”**
- **What do we need to know?**
 - **What are we seeking to confirm or discover?**
 - **What is quantifiable, detectable, measurable?**
 - **What is the impact if successful?**

Identifies candidate methods, factors, and responses

- **How well do we need to know?**
 - **What are the consequences of being wrong?**
 - **How much risk are we willing to accept in being wrong?**

Defines sample size, power, i.e., the scale/volume of required data



Case Study

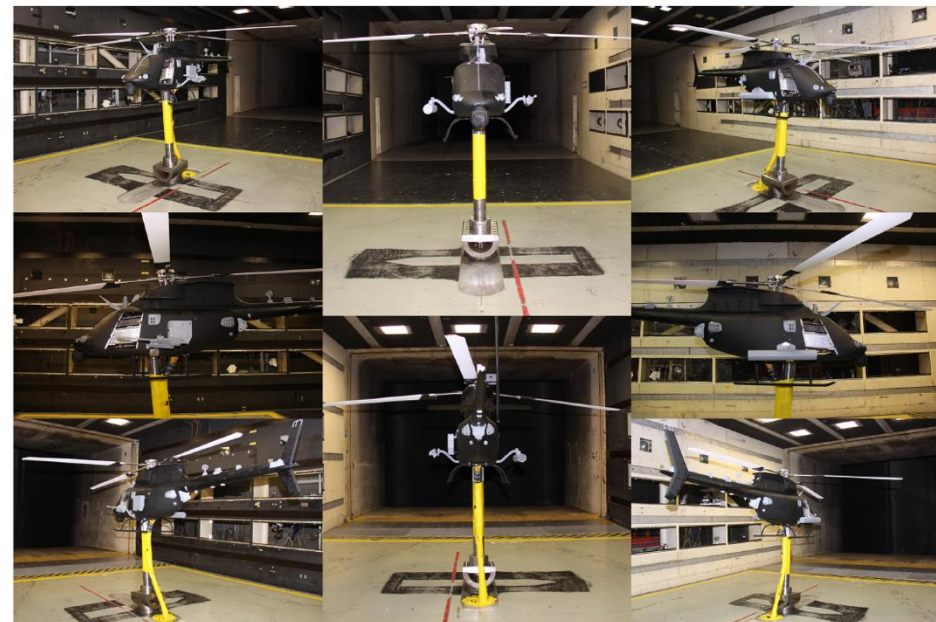
Aerodynamic Characterization in Powered Helicopter Simulation

Overview of Test Facility and Model

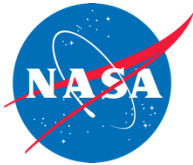


- **NASA Langley 14x22 Subsonic Wind Tunnel**
- **Closed circuit, single return, atmospheric wind tunnel**

- **Powered, helicopter testing on two vehicles**
- **U.S. Army Aviation Development Directorate, Joint Research Program Office**
- **NASA Rotary Wing Project Office**



Helicopter Testing Case Study Overview



- **Background/Context:** Conducted wind-tunnel testing of OH-58F configurations and Active Flow Control (AFC) concepts for computational fluid dynamics (CFD) validation and refinement.
- **Objective:** Develop mathematical predictive models of vehicle performance over a broad range of configurations with quantified uncertainty.
- **Consequences:** Improved CFD models provide better mission simulation capabilities and reduce wind tunnel testing.
- **Highlights of Solution Approach:**
 - Collaborative demonstration of alternative experimental strategy to improve efficiency and accelerate learning
 - Reduced tunnel testing time and provided enhanced information on vehicle performance
 - Developed trust among subject matter experts, changed testing philosophy impacting future tests

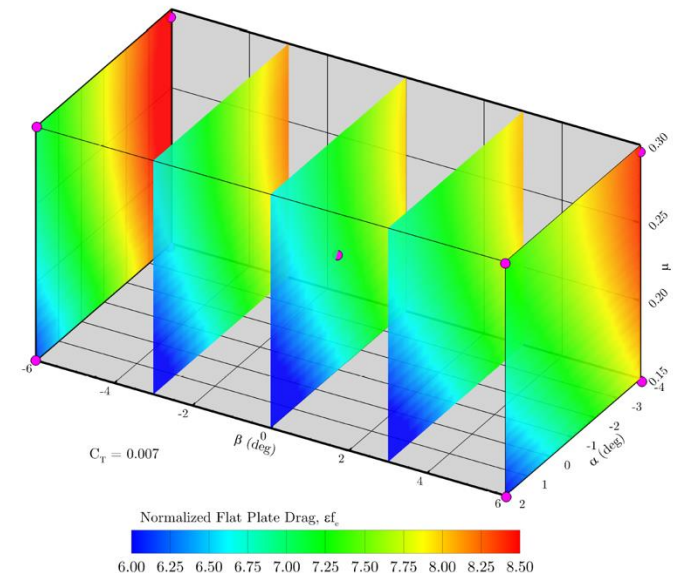


OH-58F Configuration Testing

Testing to update the flight performance models and investigate potential interactional aerodynamic issues for the F-model aircraft.

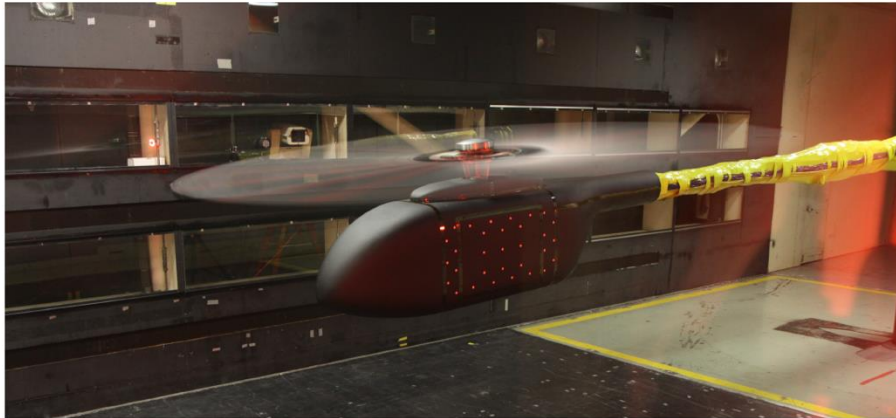
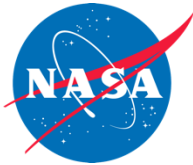
Demonstrated a statistical experiment design approach to improve test efficiency and reduce uncertainty in performance models.

- **Performance Metrics:**
 - Drag and Download
- **Factors of Interest (4):**
 - Angle of Attack and Sideslip, Advance Ratio, Rotor Thrust Coefficient



Drag as function of angle of attack and angle of sideslip at a constant thrust coefficient

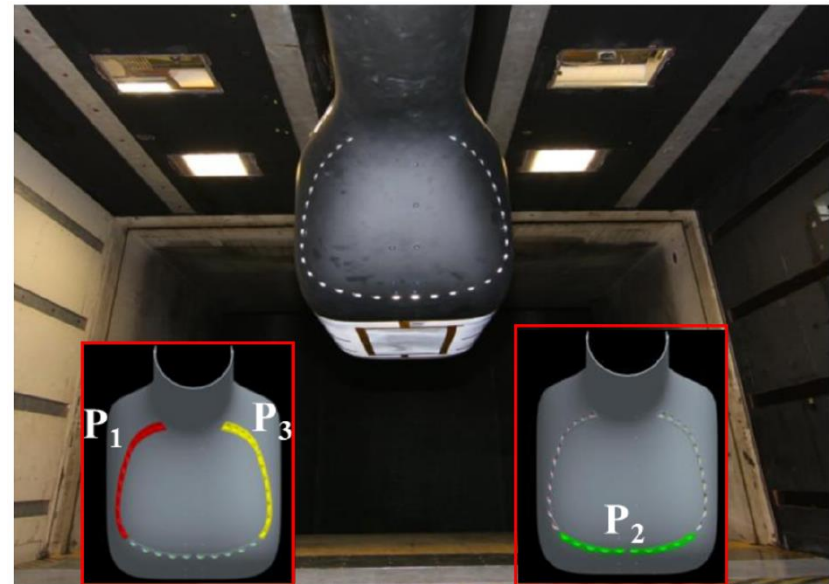
Active Flow Control (AFC) Investigation

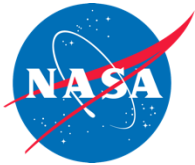


Test designed to explore the reduction of fuselage drag and download

- Aft ramp housing fluidic actuators on a generic fuselage
- Consisted of three independent actuator zones, with independent pressure control

- Performance Metric :
 - Drag change with actuators On & Off
- Factors of Interest (4):
 - Pressure of vertical zone (P1 and P3)
 - Pressure of horizontal zone (P2)
 - Fuselage pitch and advance ratio



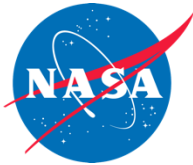


Testing Efficiency Improvement

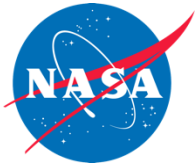
- Researchers prioritize test objectives to fit within resources (wind tunnel occupancy), therefore all possible combinations of factors usually cannot be tested within the allotted time.
- Due to the inherent complexity of powered rotor wind tunnel testing, the ratio of testing time to tunnel occupancy time (wind-on rates) is usually lower than fixed-wing testing.
- 14 x 22 wind tunnel typical wind-on rates
 - Fixed-wing: 50-70%
 - Powered rotor: 25%, 4 hours of occupancy = 1 hour of testing
- Time savings, reported by the test team
 - OH-58F: 47 times reduction in the number of data points
 - 2.5 hours of testing was estimated as equivalent to 117 hours
 - AFC: 16 times reduction in the number of data points

“The potential time savings of a design of experiments methodology, while maintaining accuracy, is too great to ignore.”

Improved Characterization and Insights



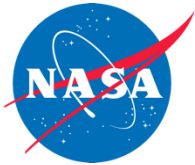
- **Predictive models derived from the wind tunnel testing provided an enhanced comparison with the computational models by including an assessment of experimental uncertainty**
- **OH-58F**
 - **Broader exploration of the factors and identified beneficial combinations**
 - **Discovered a low-drag condition, previously unexplored**
- **Active Flow Control**
 - **Ability to predict the optimal pressure actuator configuration as a function of flight conditions without running all of the possible configurations at each flight condition**



Case Study in Work

Modeling Psychoacoustic Annoyance due to Supersonic Overflights

Experimental Plan and Modeling Utility



- **Model the probability of human annoyance due to noise levels induced by a supersonic overflights to inform regulators and designers.**
- **Experiment is conducted by flying an experimental aircraft over communities with varying noise levels and surveying participants for their level of annoyance, highly-annoyed or not.**

X-59



Example Utility of Model

Predict the noise level that induces a given population proportion to be highly-annoyed, with 95% confidence.

Predict the population proportion that are highly-annoyed at a given noise level, with 95% confidence.



Statistical Design and Modeling

- **Estimate a dose-response model to predict high-annoyance (binary) as a function of the perceived noise level.**
- **Experiment design is the definition of levels and order of noise level to deduce its relationships, if any, with the responses.**
 - Constrained by physics, ethics, resources, cost, time, and capability that restrict sample size, factor range, and distribution of factor levels.
- **Generalized linear model (GLM) framework, e.g., logistic regression. Probability of a 1/0 as a function of the noise level (x).**

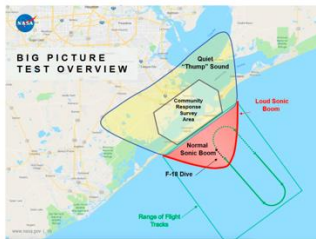
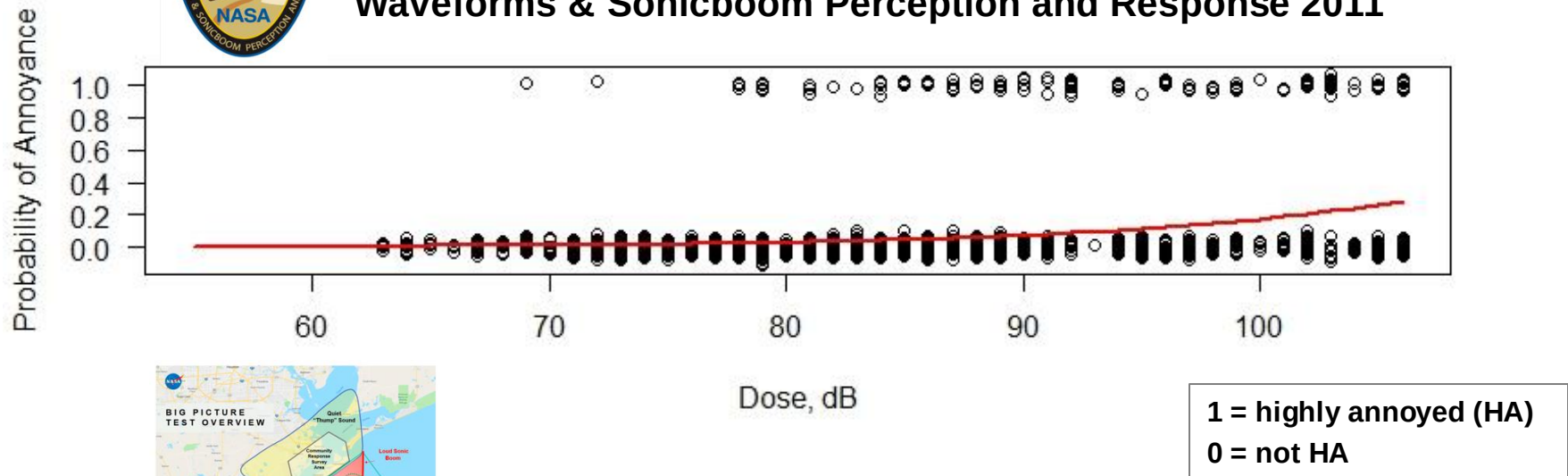
$$p(x) = \frac{1}{1 + e^{-(\beta_0 + \beta_1 x)}}$$

- **Participants are a random sample to infer the population, therefore, we estimate a Generalized linear mixed model (GLMM).**
- **Uncertainty in the noise level (x) delivered to participant leads to a Generalized Linear Mixed Measurement Error models (GLMMMe).**

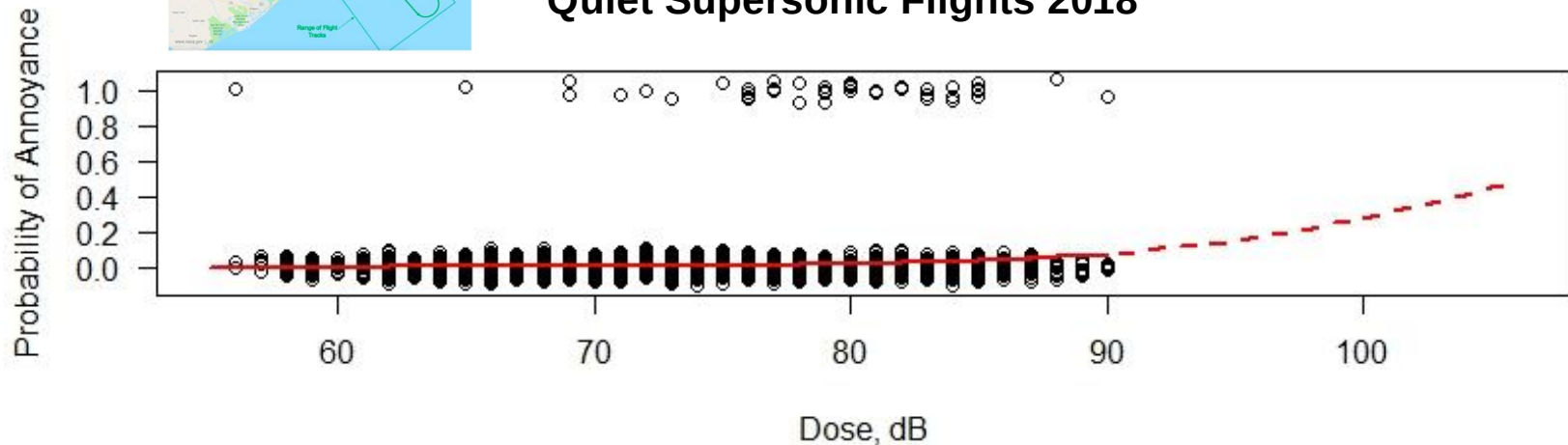
Previous Noise-Annoyance Studies



Waveforms & Sonicboom Perception and Response 2011



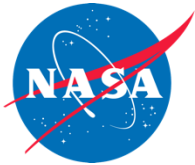
Quiet Supersonic Flights 2018



Lee, Rathsam, Wilson (2019) "Statistical Modeling of Quiet Sonic Boom Community Response Survey Data," NASA TM 2019-220427.

Lee, Rathsam, Wilson (2020), "Bayesian Statistical Models for Community Annoyance Survey Data," Journal of Acoustical Society of America.

Challenges in Design and Modeling



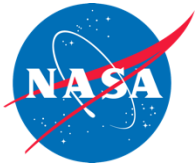
Experimental Design

- **Binary responses are common in aerospace and defense testing, and they always involve practical constraints, and design guidance is limited.**
- **Experimental design is often underappreciated for binary responses due to an over-emphasis on modeling.**

Modeling

- **Measurement error models are available, but they require reliable estimates of dose uncertainty and dependence on dose level.**
- **Distributional modeling of rare events with tolerance intervals, i.e., one-sided confidence bounds on a quantile.**
- **Modeling methods that incorporate responses from a control condition when no supersonic overflight occurred.**

Similar methodological challenges apply in material characterization (allowables), nondestructive testing, and structural health monitoring.



Concluding Remarks

- **NASA enjoys a rich heritage of applying statistical methods in aerospace research and development.**
- **Multidisciplinary statistical collaboration, leads to personal and organization influence.**
- **Challenging applications motivate statistical contributions and research opportunities.**
- **At NASA, statistical methods must be approachable and intuitive to engineering decision makers to be trusted and adopted**

NASA continues to develop the most unique, complex, and awe-inspiring systems in the world, and advances in statistical practice and methodology helps us achieve our missions.