

Statistical Practice in Aerospace Research and Development at NASA

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National Aeronautics and Space Administration

Langley Research Center

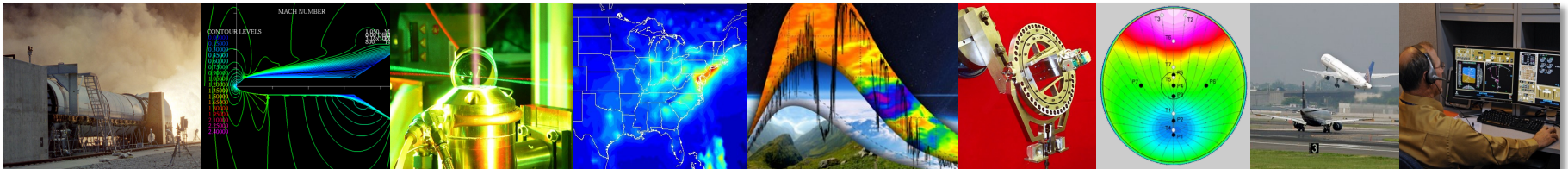
Hampton, Virginia

June 12, 2023

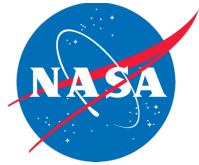
University of Naples

Department of Industrial Engineering

Virtual Seminar



NASA Langley Research Center

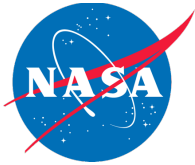


- **One of 10 NASA Centers located in Southeastern Virginia**
- **Established in 1917 as first civilian aeronautics laboratory in the U.S.**
- **Initial home of the first astronauts, Mercury 7**

Today, we focus our research on technical challenges in:

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



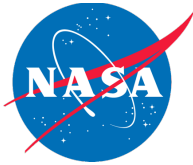


Introduction

- **Statistical methods played a role in NASA's development of some of the most unique, complex, and awe-inspiring systems in history**
- **Ubiquitous application of statistical thinking and methods is growing in aerospace research and development**
- **Infusing a statistical practice over the past 20 years has significantly contributed to broader acceptance and application**
 - **Technical and organizational impact**
 - **Targeted educational resources**
 - **Methodological contributions**

Aspire to see NASA infusing statistical thinking and methods routinely in aerospace research and mission execution

Aerospace and Statistical Development

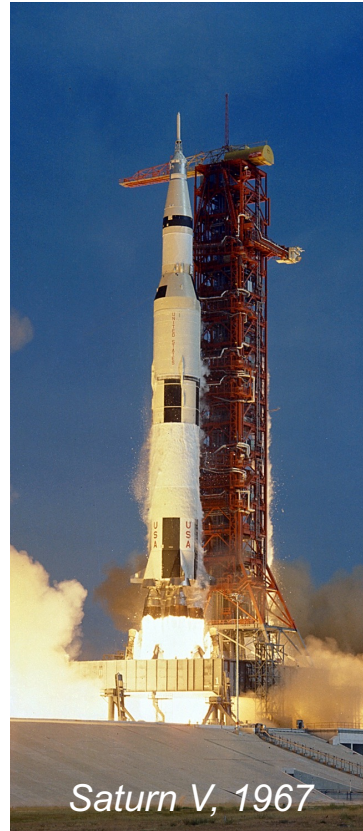


Wright Flyer, 1903

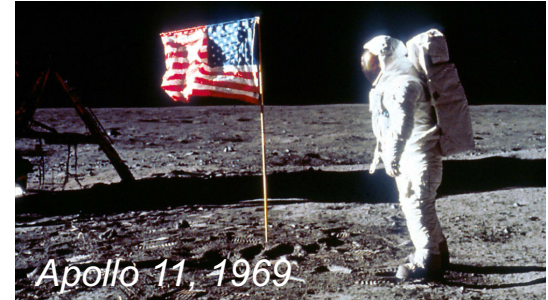


Variable Density Tunnel, 1921

NASA Formed, 1958

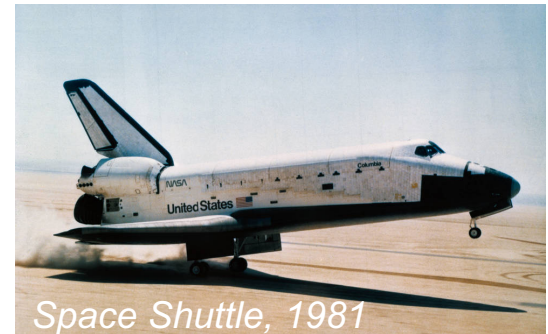


Saturn V, 1967



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



Space Shuttle, 1981

Fisher, DOE, 1920's



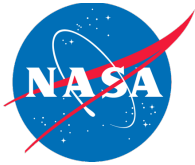
Box, RSM, 1951



Deming, Taguchi, Quality, 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's 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 that promised significant schedule and cost benefits.

A few “radical” statistical concepts

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

Discovered “new” powerful statistical techniques to efficiently learn and gain deeper insights

Demonstrated Statistical Engineering, 2006



Shuttle



Ares I



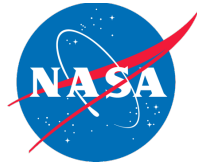
Flight Test



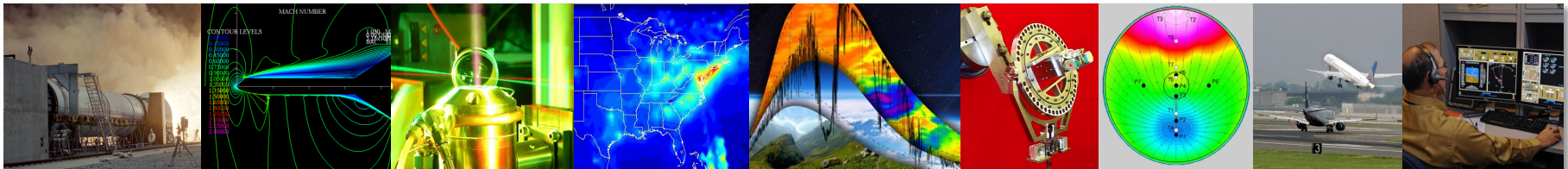
**Full-Scale
Static Firing**



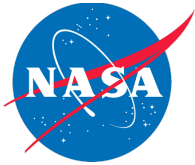
Statistical Engineering Discipline Team Formed at NASA Langley



- **Motivated by successful demonstrations with Agency-level recognition and impact**
- **Langley leadership proposed a group to be formed as an Agency-wide resource and established the first Statistical Engineering Team in NASA in 2008**
- **Crucial elements of successful team formation and growth**
 - **Visionary, multi-level leadership**
 - **Strategic hiring authority**
 - **Consistent demonstration of benefits**
 - **Building external collaborations**



Statistical Practice Starts with Questions, not Data

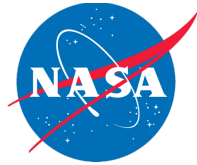


Heilmeier's preflight checklist for successfully launching a project
“to curb and clarify both the enthusiasm of the researchers and to evaluate the resource demands of the project managers”

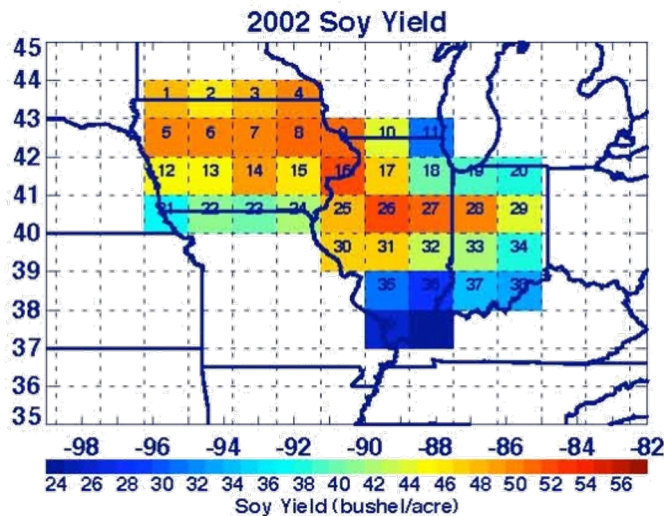
- **What are we seeking to learn?**
 - Are the objectives quantifiable, detectable, measurable?
 - What is the impact if you we successful?
- **How well do we need to know?**
 - How much risk are we willing to accept in being wrong?
 - What are the consequences if we are wrong?
- **Are the resource demands defensible to meet our objectives?**

Questions apply recursively throughout project life-cycle, and vertically from component testing up to vehicle design.

Atmospheric Sciences

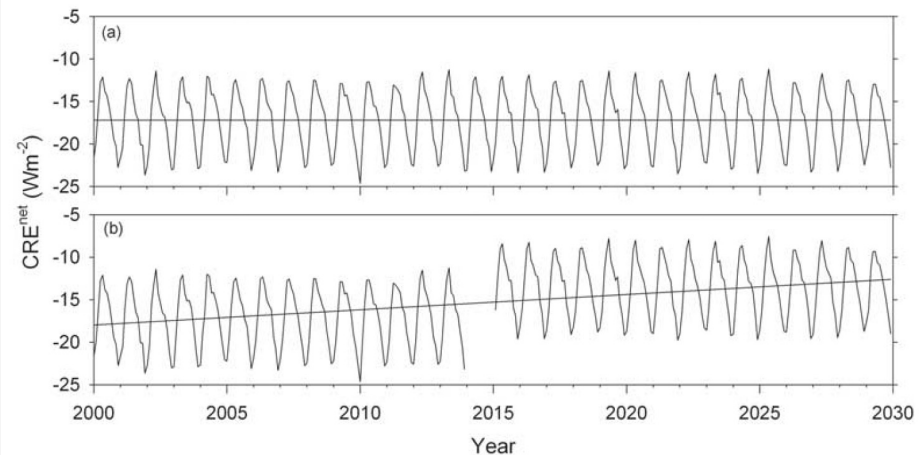


**Improving soybean yield
with satellite-based
measurements of ozone
to mitigate crop damage**



Fishman, et al. (2006), "An Investigation of Widespread Ozone Damage to the Soybean Crop in the Upper Midwest Determined from Ground-Based and Satellite Measurements," *Atmospheric Environment*, 44, pp. 2248-2256.

**Quantitatively advocating
for mission launch priority
to ensure continuous
climate record monitoring**



Loeb, et al. (2009), "Impact of Data Gaps on Satellite Broadband Radiation Records," *Journal of Geophysical Research*, 114.

Aerospace Wind Tunnel Testing

Characterizing aerodynamic performance of complex aircraft configurations

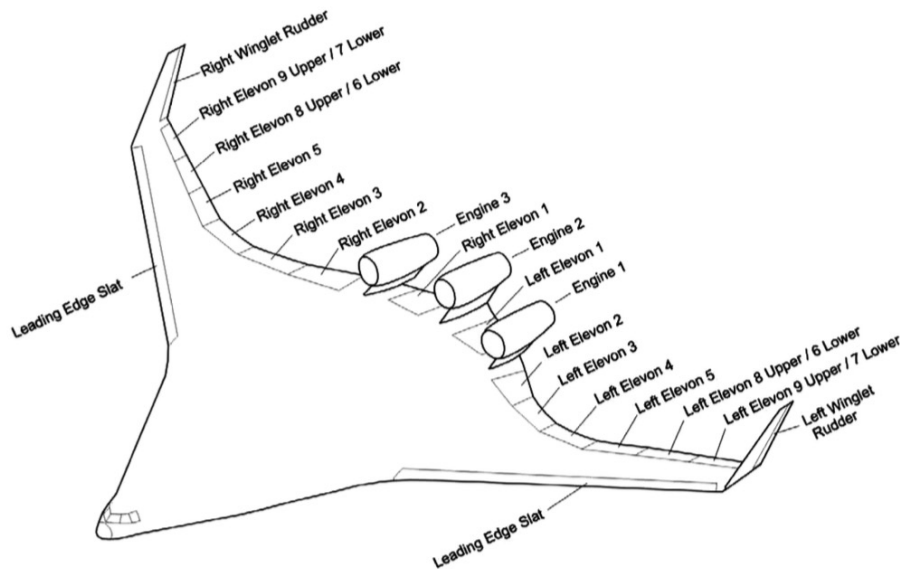


Fig. 2 BWB configuration control surfaces.

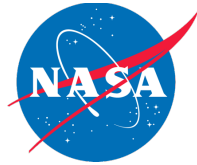
Landman, et al. (2007), "Response Surface Methods for Efficient Complex Aircraft Configuration Aerodynamic Characterization," *Journal of Aircraft*, 44, (4)

Powered test article of rotorcraft for computational model validation

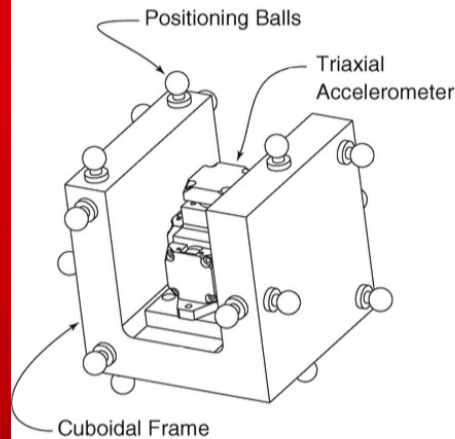
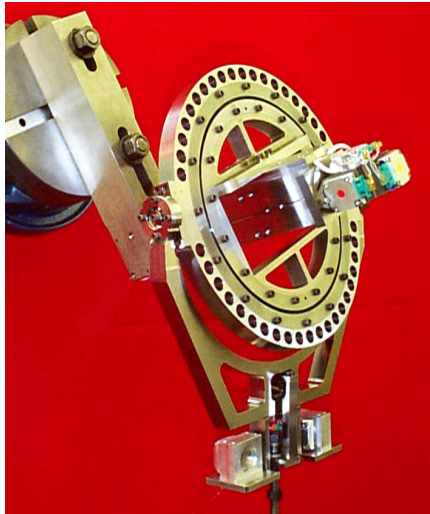


Overmeyer, et al. (2015), "Case Studies for the Statistical Design of Experiments Applied to Powered Rotor Wind Tunnel Tests," AIAA 2015-2713

Measurement System Characterization

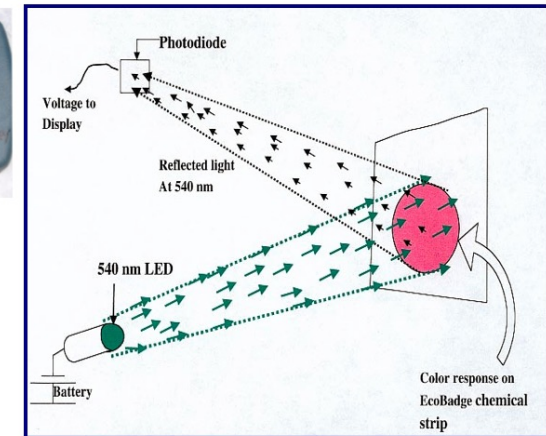
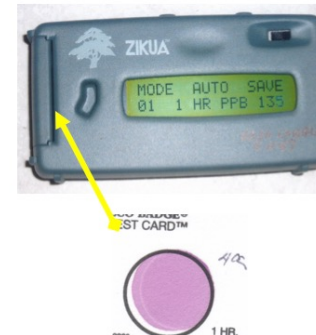


Improving aerospace research measurement systems quality

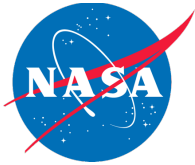


Parker and Finley (2007), "Advancements in Aircraft Model Force and Attitude Instrumentation by Integrating Statistical Methods," *AIAA Journal of Aircraft*.

Increasing accessibility and participation in climate monitoring education

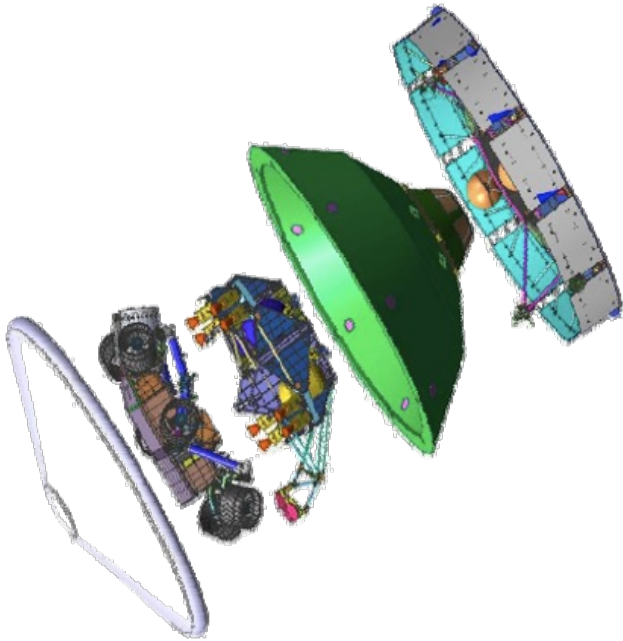
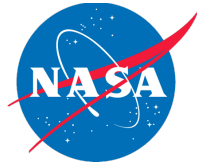


Pippin, et al. (2007), "Improvements to the Passive Ozone Measurement System Used by GLOBE Schools," *American Geophysical Union Annual Conference*.



A Space Exploration Case Study

Mars Planetary Entry, Descent, and Landing

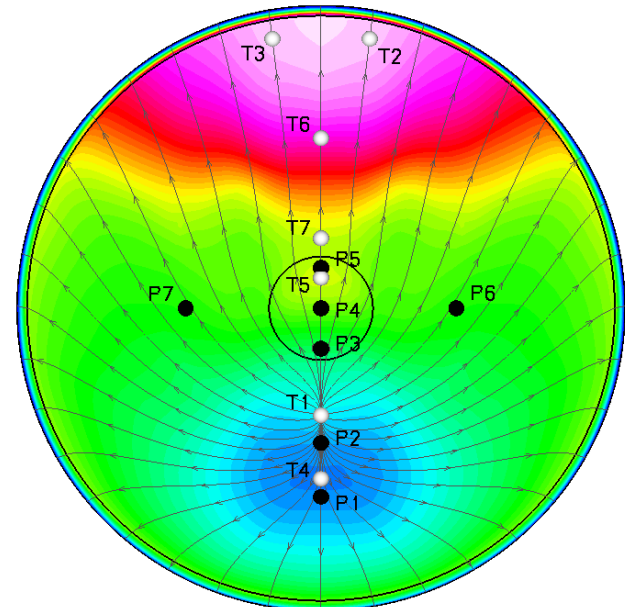


Objective

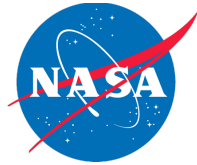
- Reduce uncertainty in pre-flight landing ellipse estimation through experimental measurements during actual Mars entry

Measurement System Components

- 7 pressure transducers (sensors)
- Signal support electronics (SSE)
- Temperatures conditions at entry and across the heatshield vary
- Pressure varies across port locations

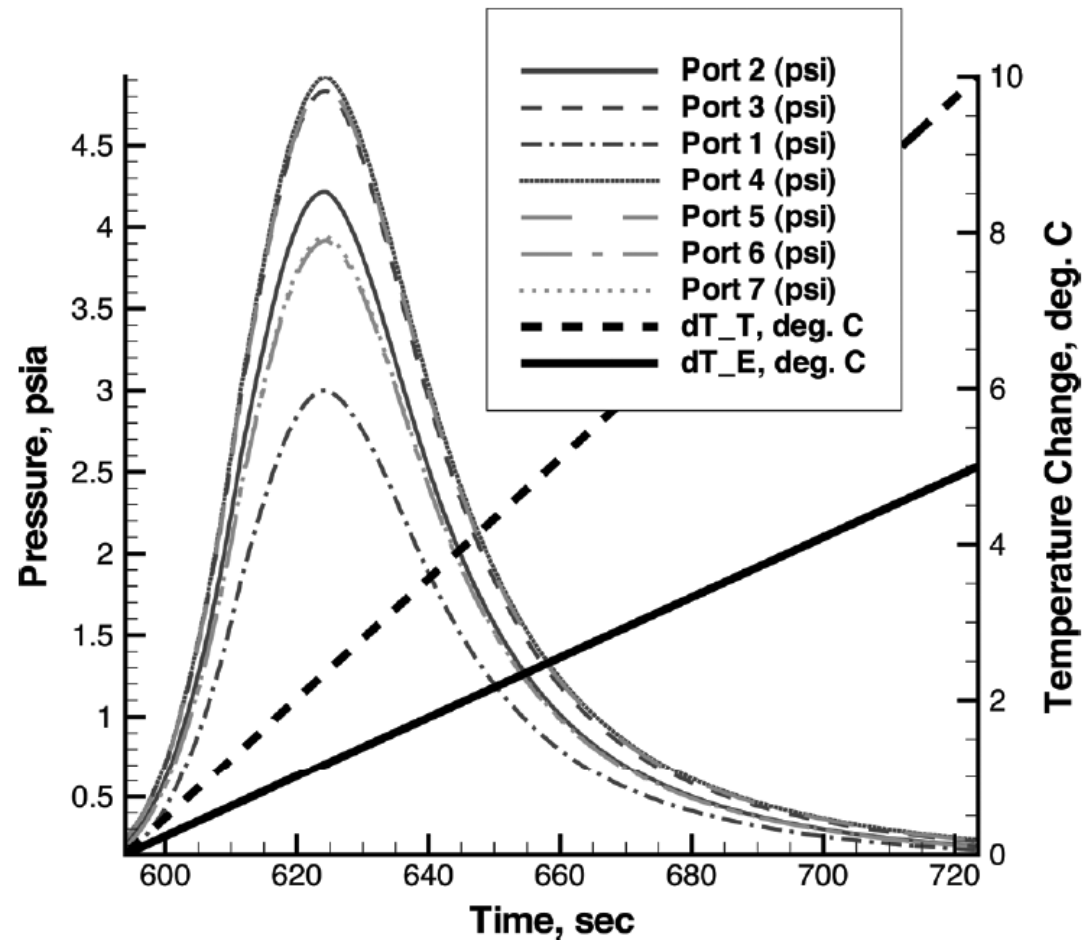


Flight Design Space Challenges

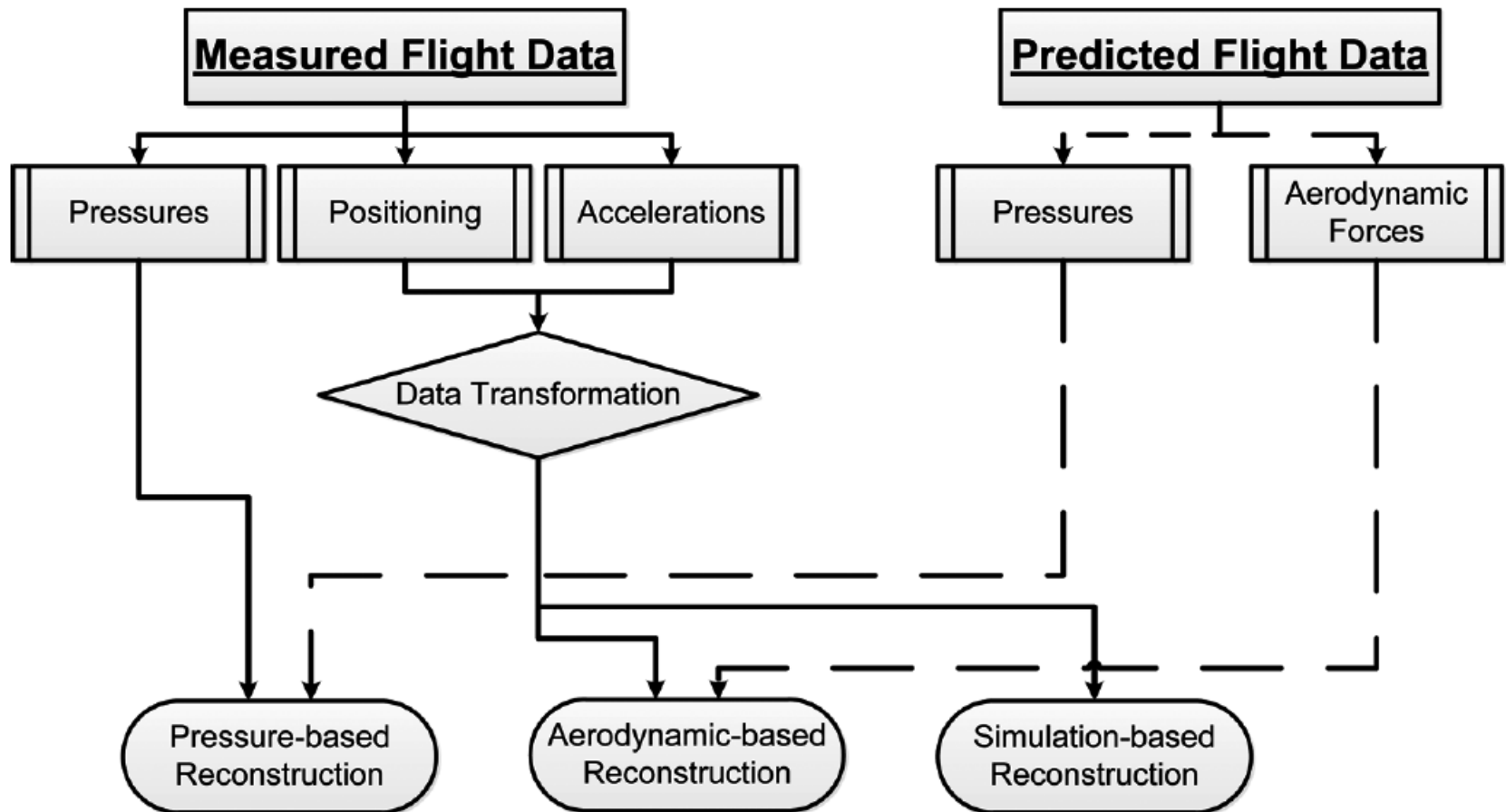
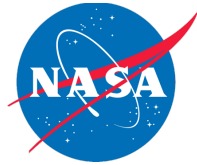


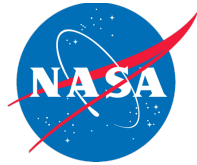
Characterization Space

Pressure	0 to 5 psia
Temp. Sensor	-120 to -60 deg.C
Temp. SSE	-20 to +55 deg.C



Integrating Experimental and Computational Models





Mathematical Model Insights

ability to update and estimate in flight

zero intercept adjustments as a function of temperature

$$V = \beta_0 + \beta_1 P + \beta_2 T_{sensor} + \beta_3 T_{SSE}$$

second-order effect of pressure (non-linearity)

$$+ \beta_{11} P^2 + \beta_{22} T_{sensor}^2 + \beta_{33} T_{SSE}^2$$

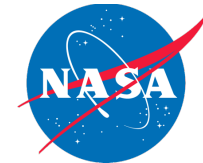
$$+ \beta_{12} P \times T_{sensor} + \beta_{13} P \times T_{SSE}$$

second-order effects of temperature on intercept

$$+ \beta_{23} T_{sensor} \times T_{SSE} + \varepsilon$$

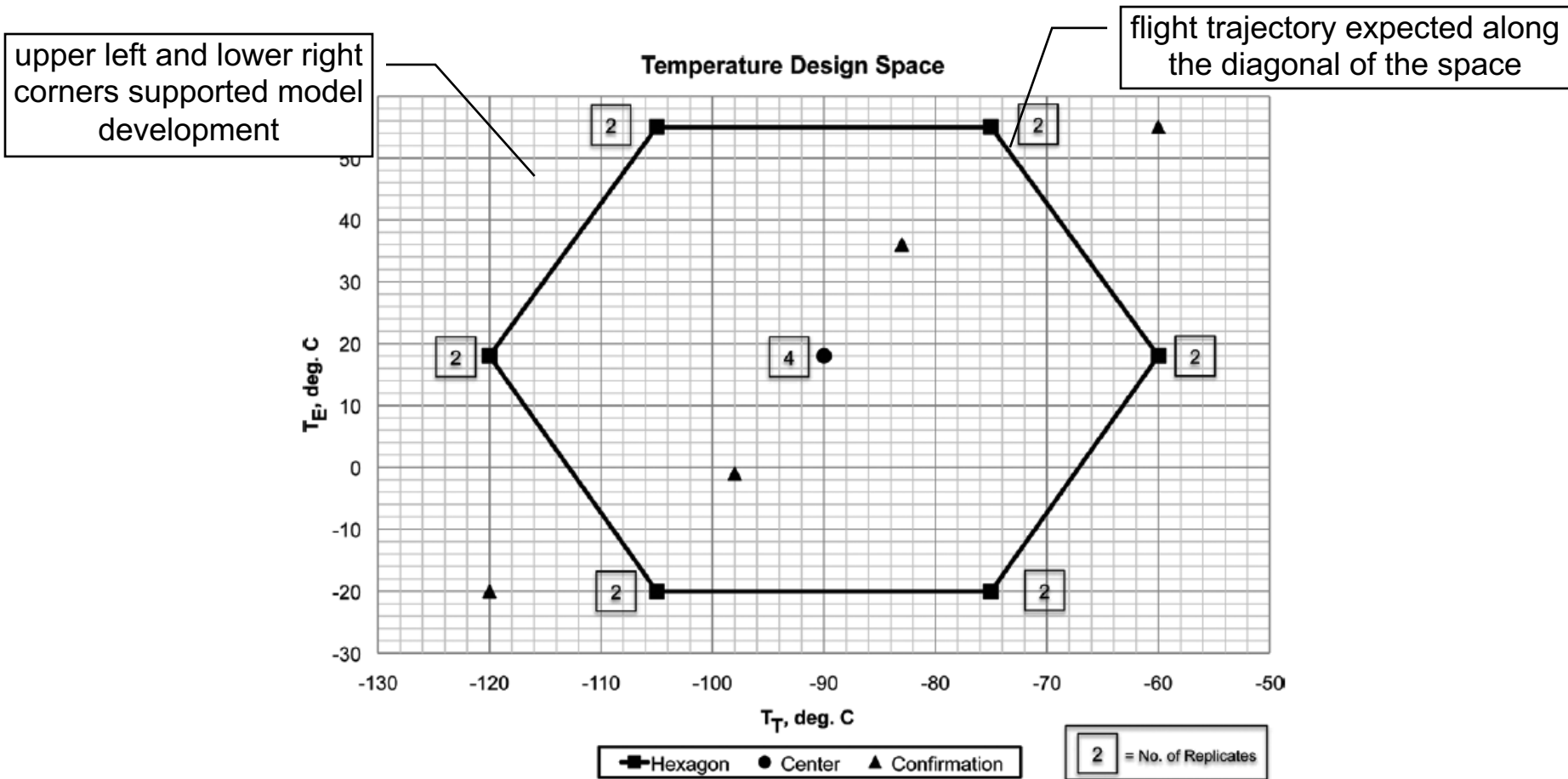
assumed negligible based on system knowledge

Interpretation and Translation into the Subject-Matter Experts' Nomenclature is Vital

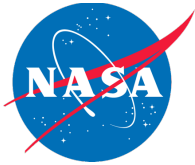


Experimental Design

- Superimposed designs to support multiple objectives
 - Model estimation, Confirmation, and Flight Trajectory
- Comprehensive assessment of the measurement system performance over predicted trajectories

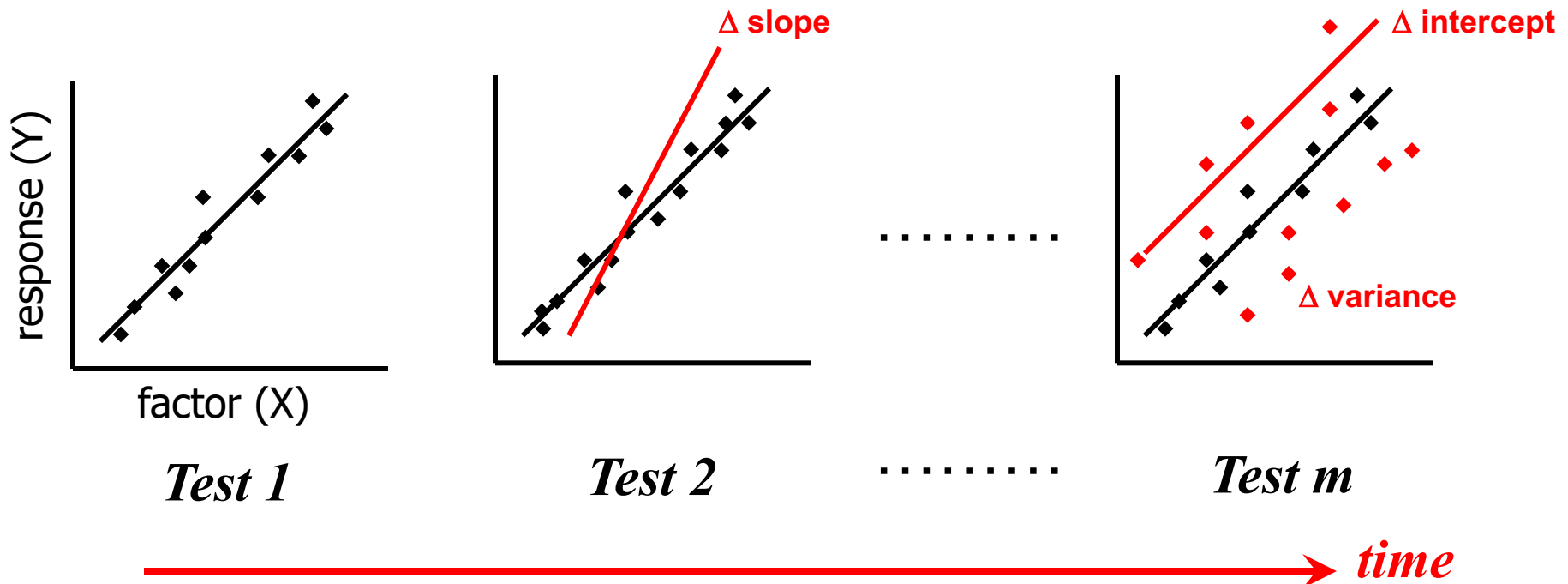


Characterization Stability Monitoring

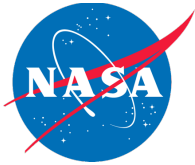


- Stability tests are performed periodically at room temperature to monitor the calibration model coefficients, not the raw data

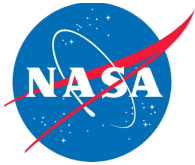
$$V = \beta_0 + \beta_1 P + \beta_2 T_{\text{sensor}} + \beta_3 T_{\text{SSE}} + \beta_{11} P^2 + \beta_{22} T_{\text{sensor}}^2 + \beta_{33} T_{\text{SSE}}^2 \\ + \beta_{12} P \times T_{\text{sensor}} + \beta_{13} P \times T_{\text{SSE}} + \beta_{23} T_{\text{sensor}} \times T_{\text{SSE}} + \varepsilon$$



Entry, Descent, and Landing Case Study Summary

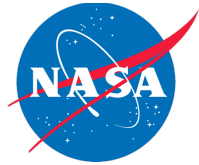


- Required significant **collaboration** to understand how the response surface models are used in the flight algorithm
- **Translation and interpretation** into the subject-matter experts' nomenclature is vital
- **Superimposing designs** overlays multiple objectives for efficiency
- **Inverse multidimensional prediction** models based on extensions of response surface methodology
- **Assess model stability** through profile monitoring that builds on the principles of statistical process control
- Methods are tightly, **synergistically integrated** to form an overall measurement system uncertainty quantification
- Resulted in **embedded changes** to the standard processes for planetary entry measurement systems



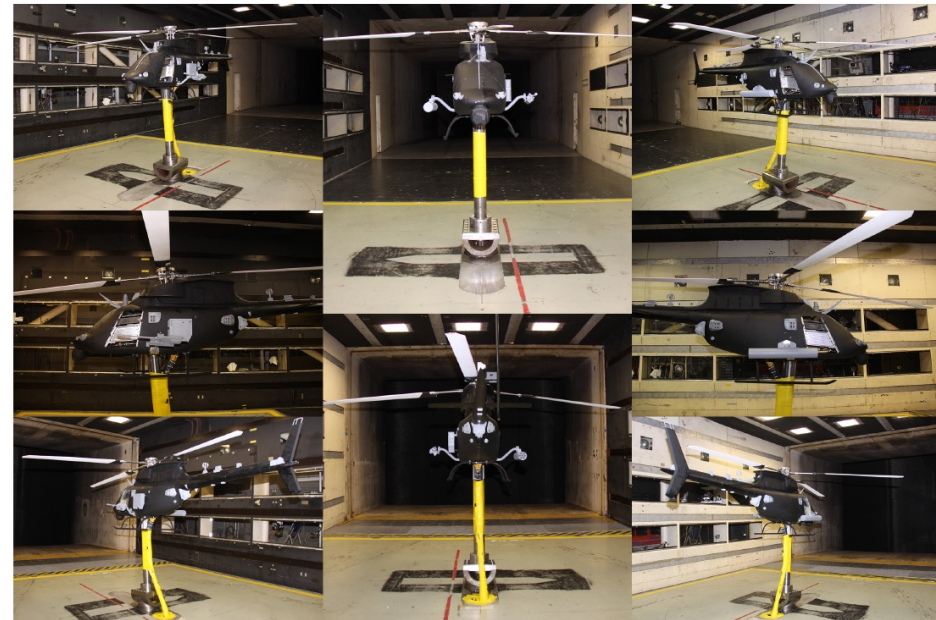
Aerodynamic Testing Case Study

Aerodynamic Characterization in Powered Helicopter Simulation

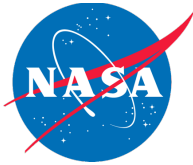


- **NASA Langley 14x22 Subsonic Wind Tunnel**
- **Closed circuit, single return, atmospheric wind tunnel**

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

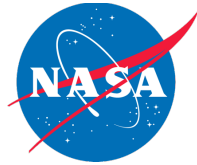


Helicopter Testing Case Study Overview



- **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

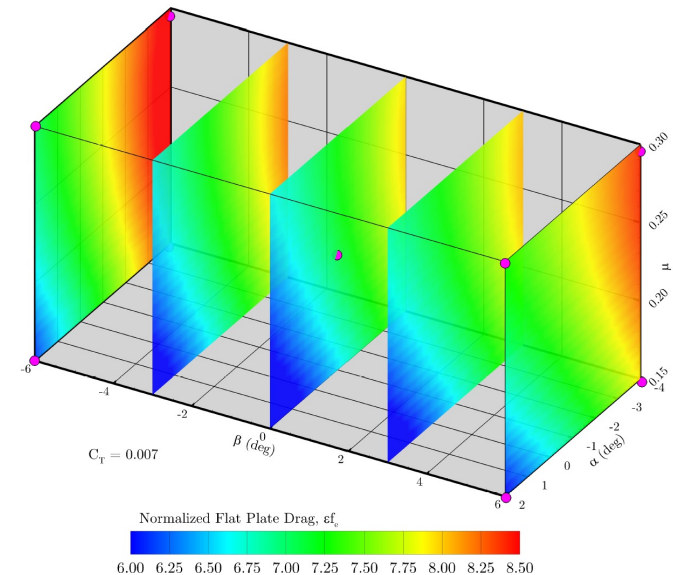
OH-58F Configuration Testing



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

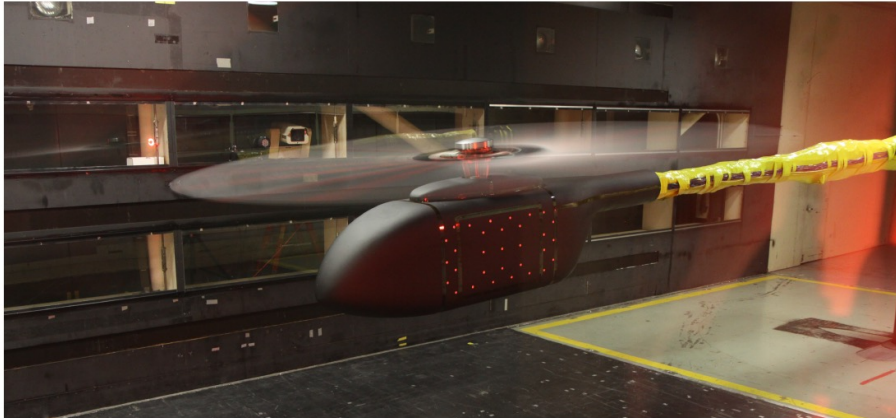
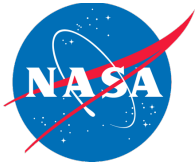
Demonstrated a statistical experiment design approach to improve test efficiency and reduce uncertainty in performance models.

- **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

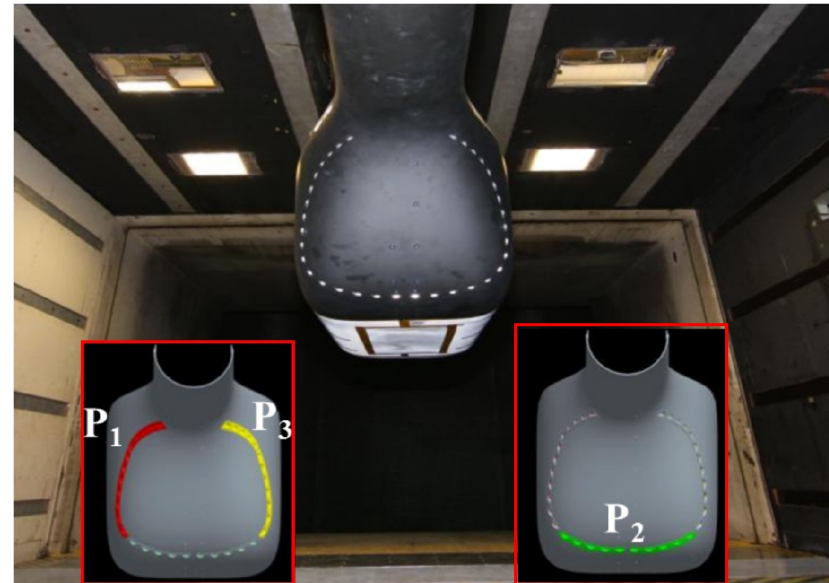
Active Flow Control (AFC) Investigation

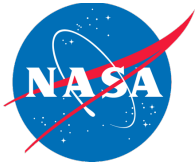


Test designed to explore the reduction of fuselage drag and download

- 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



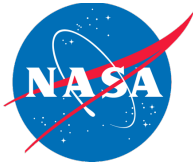


Testing Efficiency Improvement

- **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**

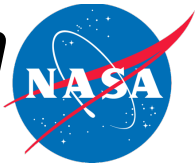
“The potential time savings of a design of experiments methodology, while maintaining accuracy, is too great to ignore.”

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**

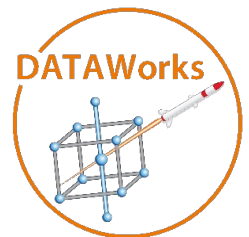
NASA's Statistical Engineering Symposium Williamsburg, Virginia, 2011

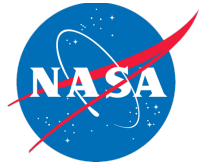


- Unique forum, senior leaders, discipline experts, practitioners
- Keynotes by the Director of Operational Test and Evaluation, Office of the Secretary of Defense, and Roger Hoerl, GE

DOT&E / NASA Statistical Engineering Interagency 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 – DATAWorks, now in 8th year
 - **Defense and Aerospace Test and Analysis Workshop**





Methodological Research

- **Restricted randomization in response surface methodology**
- **Advanced reliability engineering design and modeling**
- **Bayesian dose-response modeling for community noise**
- **Space-filling design for multi-layer nested factors**
- **Calibration with multi-dimensional response surfaces**
- **Collaboration, the art and the science**

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



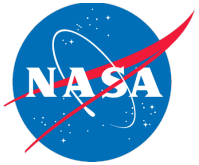
Taylor & Francis
Taylor & Francis Group



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



Concluding Remarks

- **NASA enjoys a rich heritage of the statistical methods utilized in aerospace research and development**
- **Infusing statistical engineering has impacted and motivated institutionalization over the past 20 years**
- **NASA Langley has been a leader in introducing the discipline, building academic relationships and external collaboration**
- **State of the discipline within NASA is strong and growing**

Aspire to see NASA infusing statistical thinking and methods routinely in aerospace research and mission execution