Infusing Statistical Engineering at NASA

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National Aeronautics and Space Administration

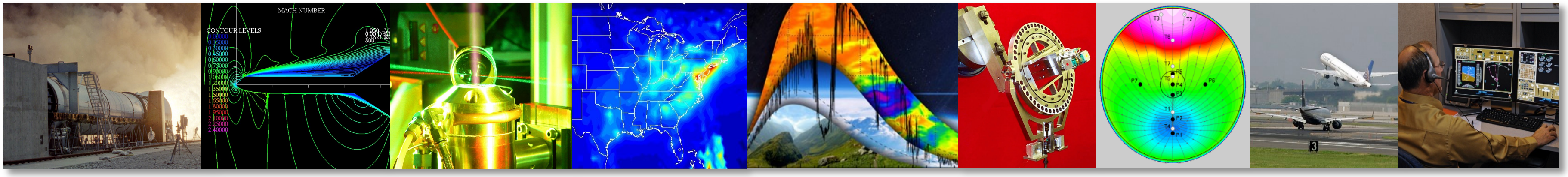
Langley Research Center

Hampton, Virginia

September 13th, 2021

European Network for Business and Industrial Statistics (ENBIS)

ENBIS-21 Annual Online Conference



NASA Langley Research Center

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

Today, we focus our research on technical challenges in:

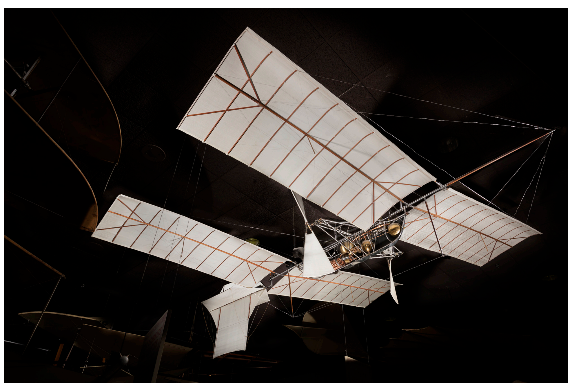
- Space Exploration
- Aeronautics and Air Transportation
- Earth and Planetary Science

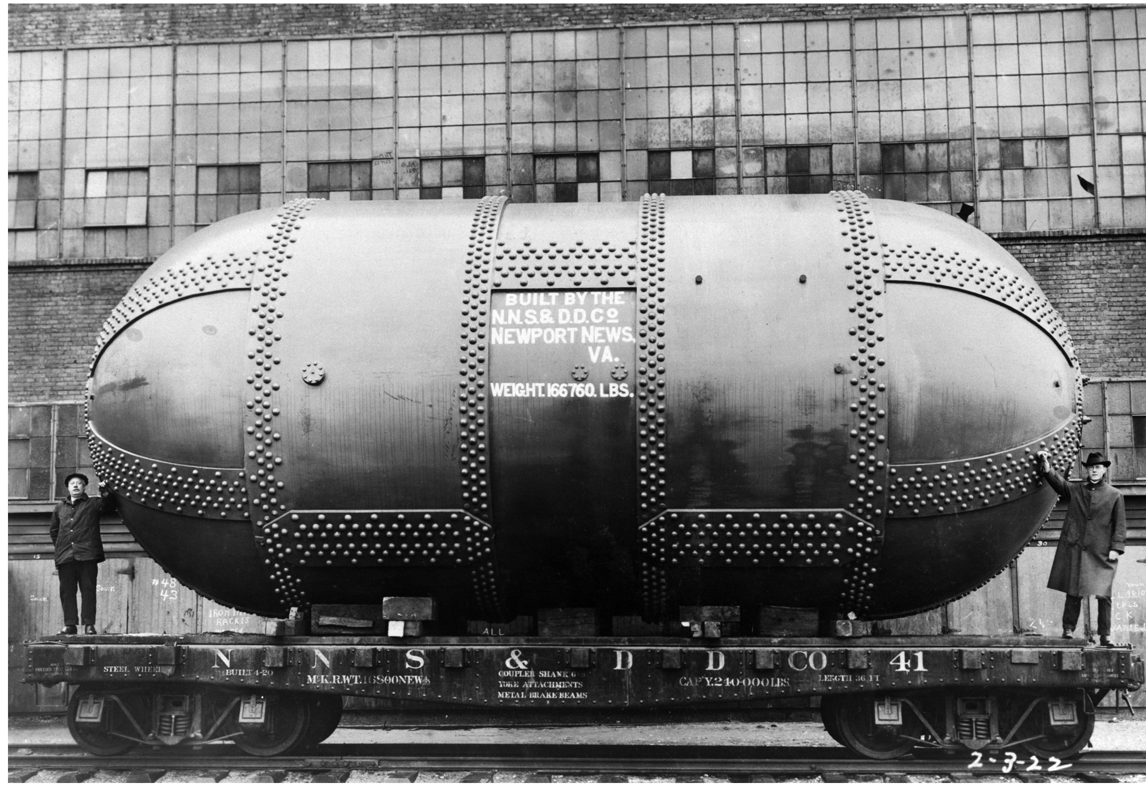
Overview of Presentation

- Applied statistics and quality engineering methods have played a role in NASA's development of technologically unique, complex, and astounding systems in history
- Awareness and acceptance of statistical thinking and methods in aerospace research and development is relatively new and growing
- Infusing an application-focused statistical engineering perspective over the past 20 years has contributed to NASA's broader adoption
  - Milestones in technical and organizational impact
  - Targeted educational resources
  - Methodological contributions

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

Early Experimentation in Aeronautics





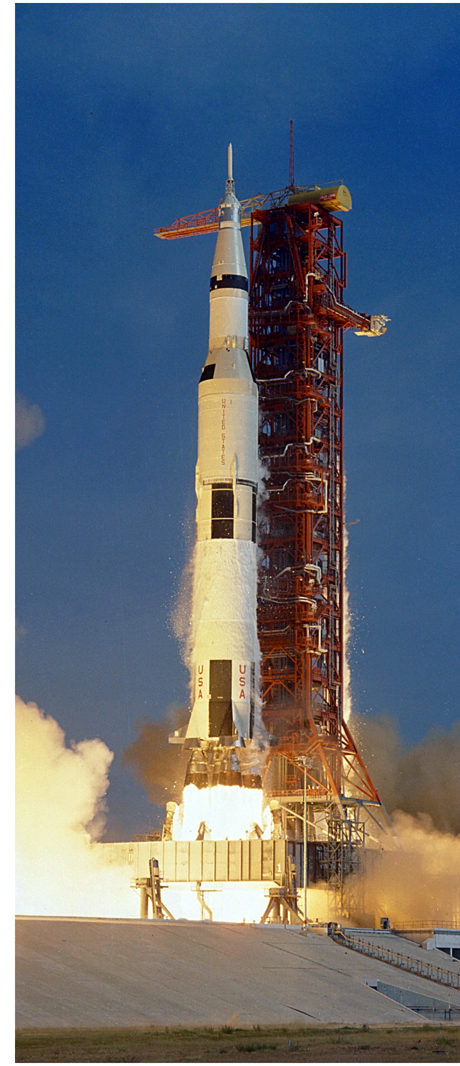
- Early 1900's, Aviation pioneers were "Edison-ian"
  - Wrights and Langley most likely used one-factor-at-a-time methods to discover first principles of aeronautics
- 1920's, Fisher's work in design of experiments occurred about the same time as the first production wind tunnels

From Aviation into the Space Era

1955, Conference on the Design of Experiments in Army Research, Development, and Testing

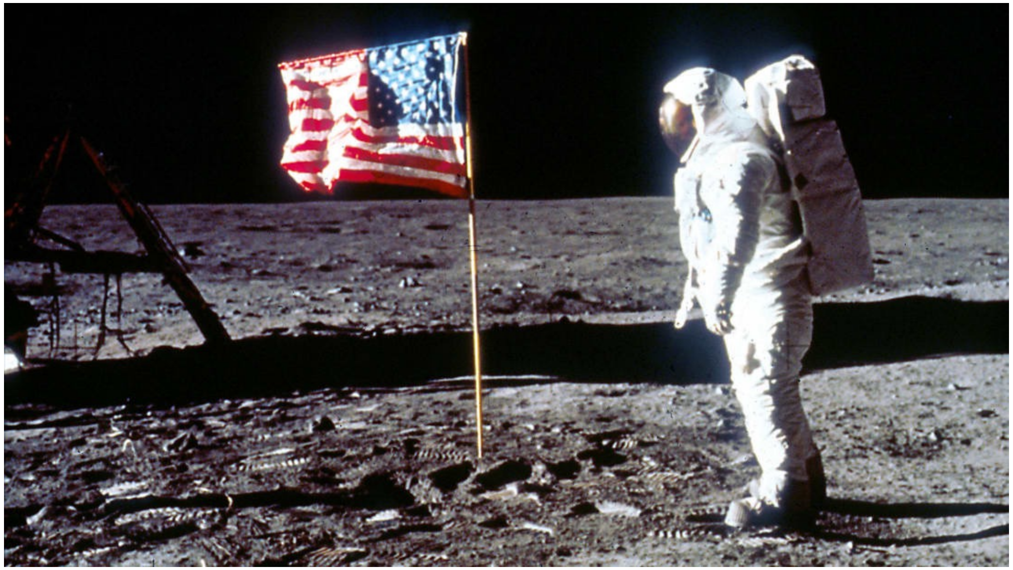
- **In 1954, the Army Mathematics Advisory Panel reported, "One of the most frequently mentioned needs expressed by the scientists and engineers .. was a greater knowledge and use of the modern statistical theory of the design and analysis of experiments…"**

Army Ballistic Missile Agency (ABMA) formed in 1956, Wernher von Braun as Technical Director. Launched Explorer, first US satellite, ABMA became part of NASA in 1960



Apollo Era

- **1962, Bellcomm is carved out Bell Labs, request of NASA**
  - **Systems engineering, analysis, quality management functions**
- **1966, “Some Statistical Applications in the Apollo Program,” The American Statistician.**
  - **“…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. … NASA job specifications show that no category of "Statistician" appears.”**



Experimental Testing Strategies

- **1966, "The Use of Statistically Designed Experiments in Wind Tunnel Test Programs," Pratt and Whitney**
  - **"A properly designed statistical experiment can effectively examine all combinations of the variables while greatly reducing the number of tests required."**
  - **2019 Parker, American Institute of Aeronautics and Astronautics, Invited talk entitled "A Survey of Statistical Methods in Aeronautical Ground Testing"**
- **1972, "Criteria for the Optimal Design of Experimental Tests," by Canavos, NASA Langley Research Center**
  - **"The purpose of this report is to unify some existing results of response-surface techniques… these techniques have the potential for reducing the amount of testing required in experimental investigations."**

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 and promised significant schedule and cost benefits.**

<u>A few "radical" statistical concepts</u>

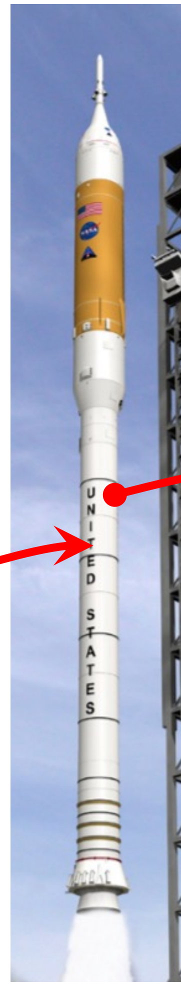
- **Experimental Design starts with questions, not data**
- **Factorial Experiments are efficient for learning, not chaotic**
- **Modeling is more than plotting to discern subtle differences**

Discovered "new" statistical techniques to efficiently learn and gain deeper insights

Capability Demonstration in 2006

Shuttle

Ares I



Full-Scale Static Firing

Flight Test

Contributors: Gentz, Roberts, Parker, Rhew, Jones, McLennan, Nester, Freeman, Vining

Statistical Engineering Motivation

- **A scalable, teachable, repeatable, approach to accelerate learning, ensure strategic resource investment, inform rigorous decision making, across NASA's missions.**

2008 White Paper

Infusing Statistical Engineering into Programs and Projects

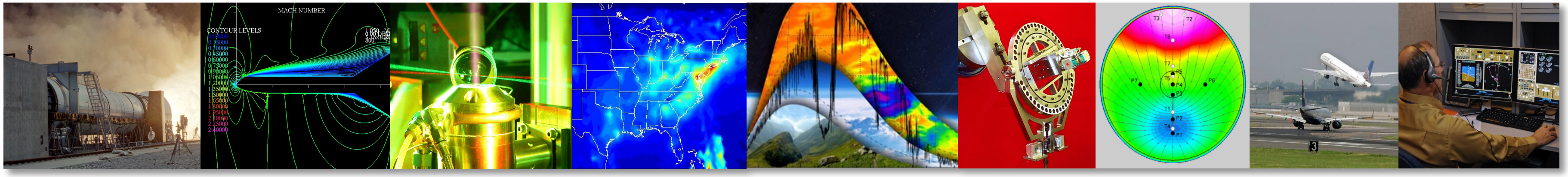
February 5, 2008

Prepared by Peter Parker for the Chief Engineer, Systems Engineering Directorate, NASA Langley Research Center

The purpose of this document is to provide a brief description of an SED-lead initiative to integrate statistical engineering into all levels of program and project management and to outline an implementation plan. Motivating this initiative is the requirement to systematically use the best tools and practices available to achieve the Agency's ambitious mission goals. Statistical engineering represents a mature discipline, used throughout industry for over 50 years, to improve competiveness and profitability. In other government research agencies, statistical engineering is used to ensure the veracity of national defense systems and international commerce. Currently across the Agency, statistical engineering utilization is sporadic rather than systematic. From years of demonstration projects within the Agency, statistical engineering has proven itself to be a scalable, teachable, and repeatable methodology. Therefore, strategically institutionalizing its practice will improve the Agency's ability to achieve their mission objectives.

Statistical Engineering Team Formed

- **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 in applications**
  - **Building external connections DoD and Academia**



NASA Statistical Engineering Symposium
May 2011

- Unique forum, with senior leaders, discipline experts and practitioners
- Keynotes by Director of Operational Test and Evaluation (DOT&E), and Roger Hoerl, GE Global Research
- 150 attendees, spanning NASA Centers, 4 other government agencies, 5 universities, and industry

Office of the Secretary of Defense	Virginia Tech
Los Alamos National Laboratory	Arizona State University
NIST	Old Dominion University
United States Air Force	University of Virginia
National Oceanic and Atmospheric Administration	General Electric
Naval Postgraduate School	Aerospace Corporation
	Pratt & Whitney

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

- **DoD and NASA develop, acquire, evaluate, and operate some of the world's most advanced and sophisticated systems.**
- **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.**

Key Elements

- **Deliberate leadership and tactical practitioner collaboration**
- **Annual meeting - DATAWorks**
  - **Defense and Aerospace Test and Analysis Workshop, 5th year**

Practice of Statistical Engineering Starts with Questions, not Data

- Heilmeier used 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 are the precise objectives?**
  - **What are we seeking to learn?**
  - **Are the objectives quantifiable, detectable, measurable?**
  - **What is the impact if you are successful?**

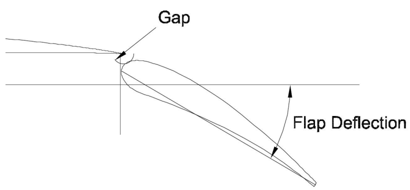
- **How well do we need to know the answers?**
  - **How much risk are we willing to accept in being wrong?**
  - **What are the consequences if we are wrong?**

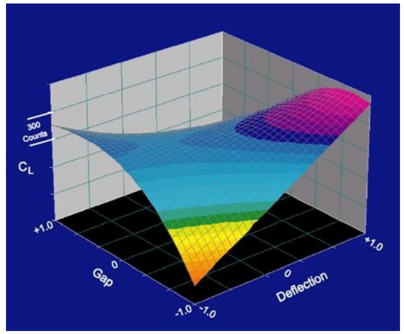
- **Do the methods rigorously link to the stated objectives and risk?**
  - **Are the resources justifiable and defendable?**

Questions apply recursively throughout project life-cycle

Shapiro (1994) "George H. Heilmeier," *IEEE Spectrum*

Aeroscience Wind Tunnel Testing





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English, et al. (2012), "An Efficient Split-Plot Approach for Modeling Nonlinear Aerodynamic Effects," *Quality Engineering*, 24: 522-530

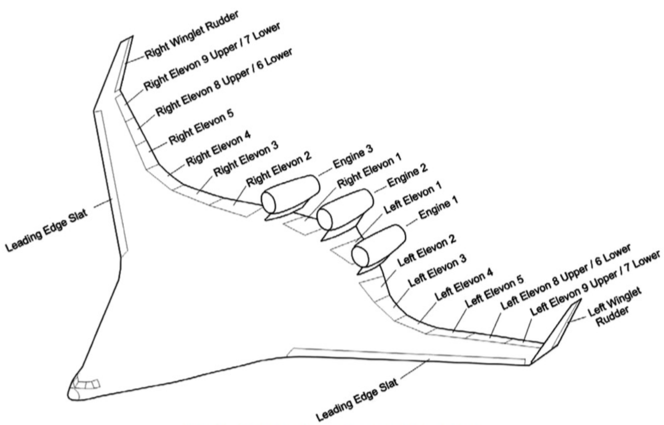

Fig. 2 BWB configuration control surfaces.

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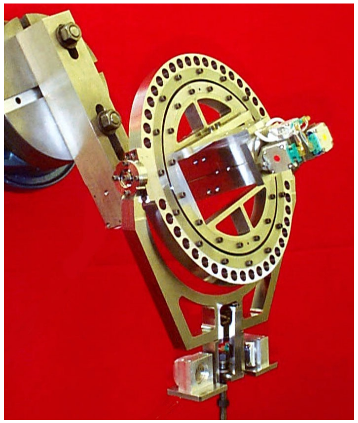
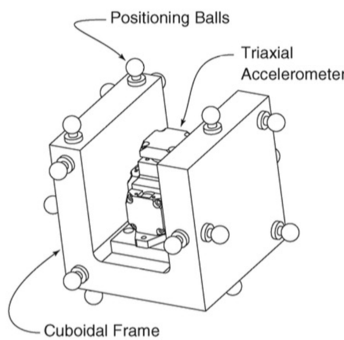
Overmeyer, et al. (2015), "Case Studies for the Statistical Design of Experiments Applied to Powered Rotor Wind Tunnel Tests," AIAA 2015-2713

Measurement System Characterization





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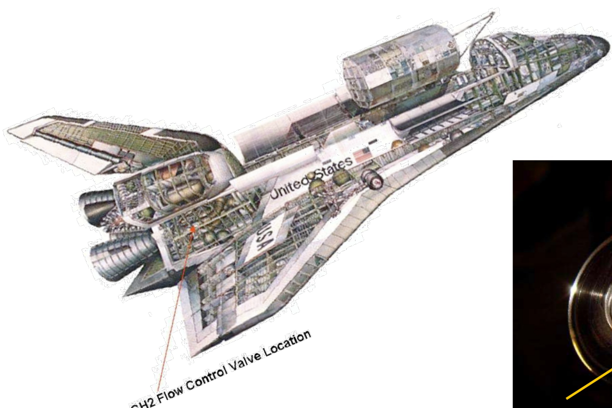
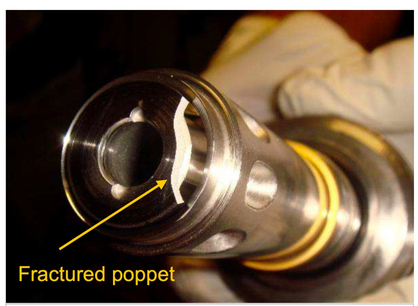
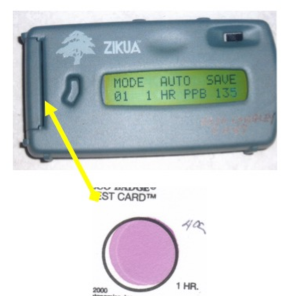
Gentz, Parker, Rhew, Roberts (2006), “Solid Rocket Motor Characterization of Ares I.” NASA TM

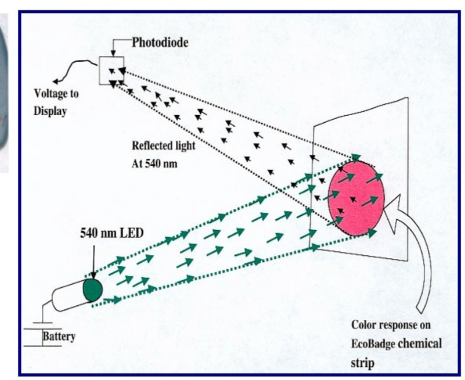




STS-126 Valve Poppet Following Removal

(2009), “Gaseous Hydrogen Flow Control Valves,” *NASA Fact Sheet (www.nasa.gov/pdf/313985main_Flow_Valve_Fact.pdf)*





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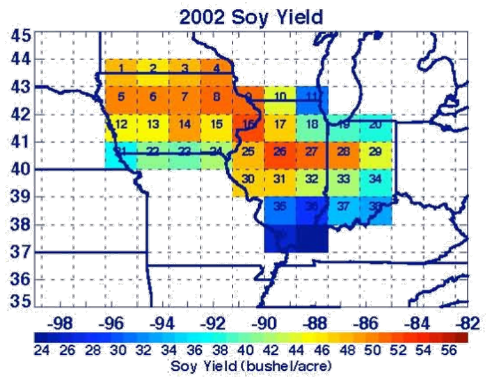
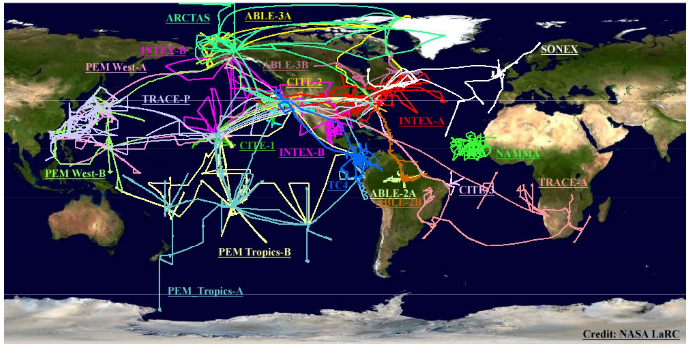
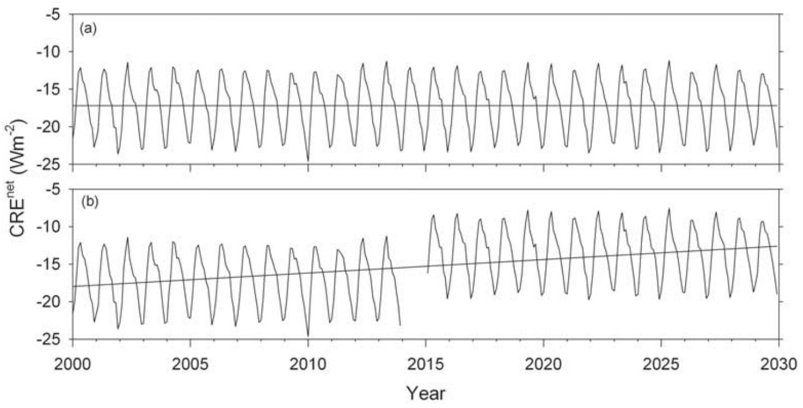
Atmospheric Sciences



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.



Kleb, et al. (2008), "Creating Airborne ESDR Products for Global and Regional Model Assessment," *American Geophysical Union Annual Conference*.



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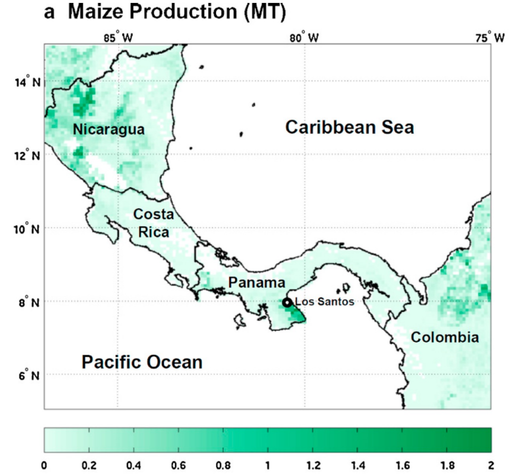

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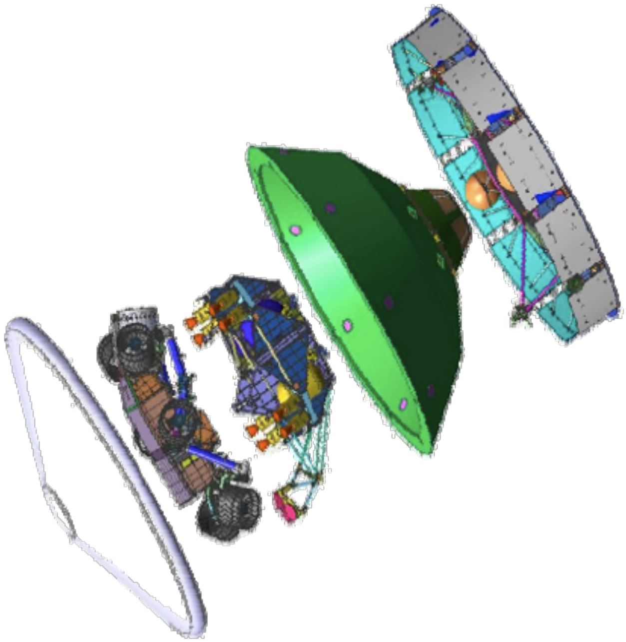
Planetary Entry, Descent, and Landing

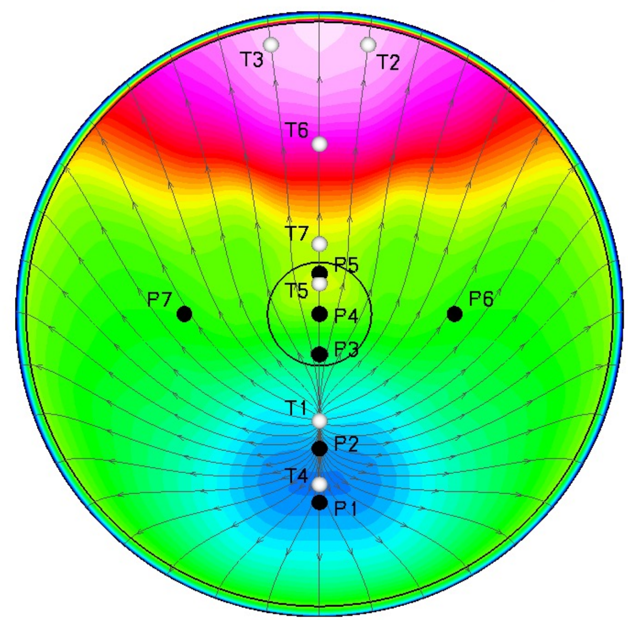


Objective

- **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**

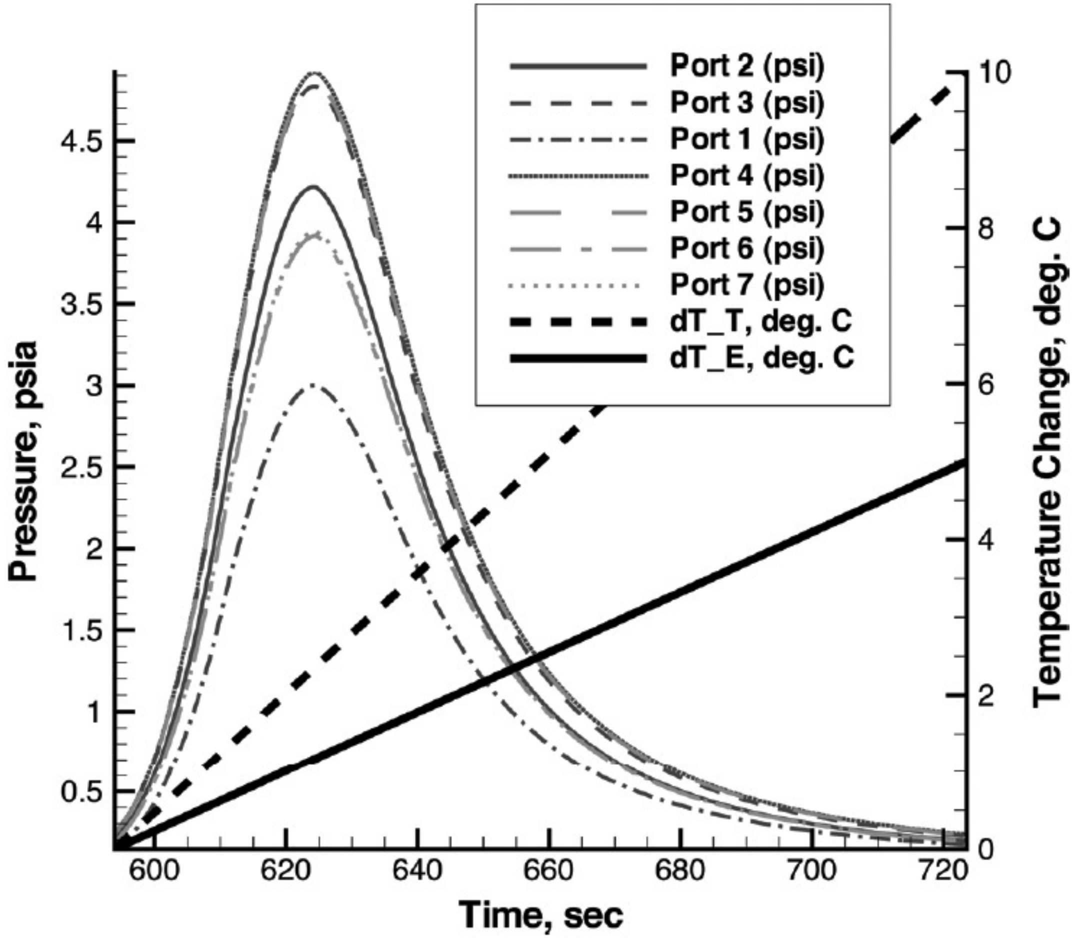


Commo and Parker (2012), “Statistical engineering perspective on planetary entry, descent, and landing research,” *Quality Engineering*

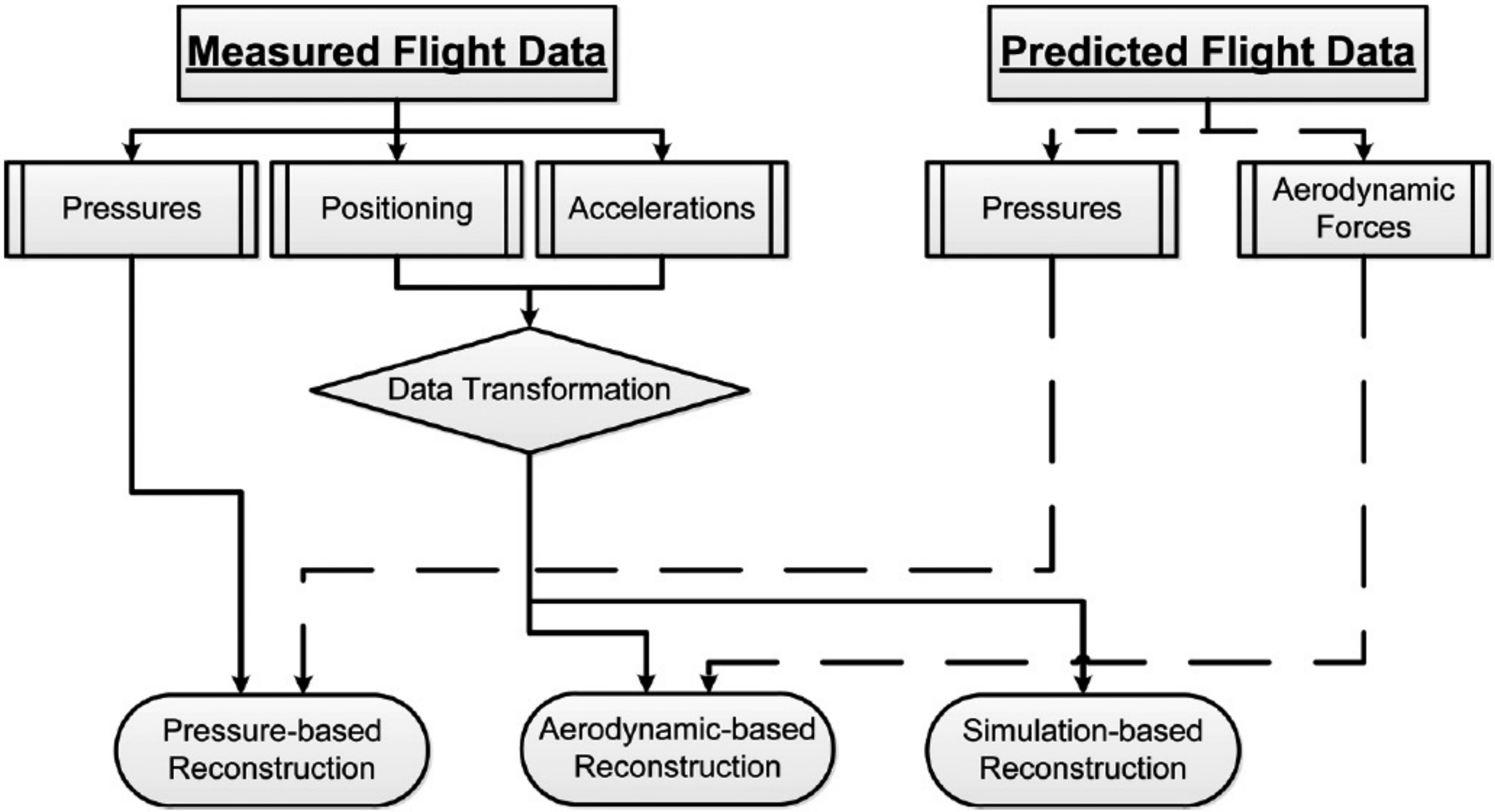
Flight Design Space Challenges

Characterization Space

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



Understanding the Integration of the Response Surface Models



Mathematical Model

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)

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

second-order effects of temperature on intercept

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

sensitivity adjustments as a function of temperature

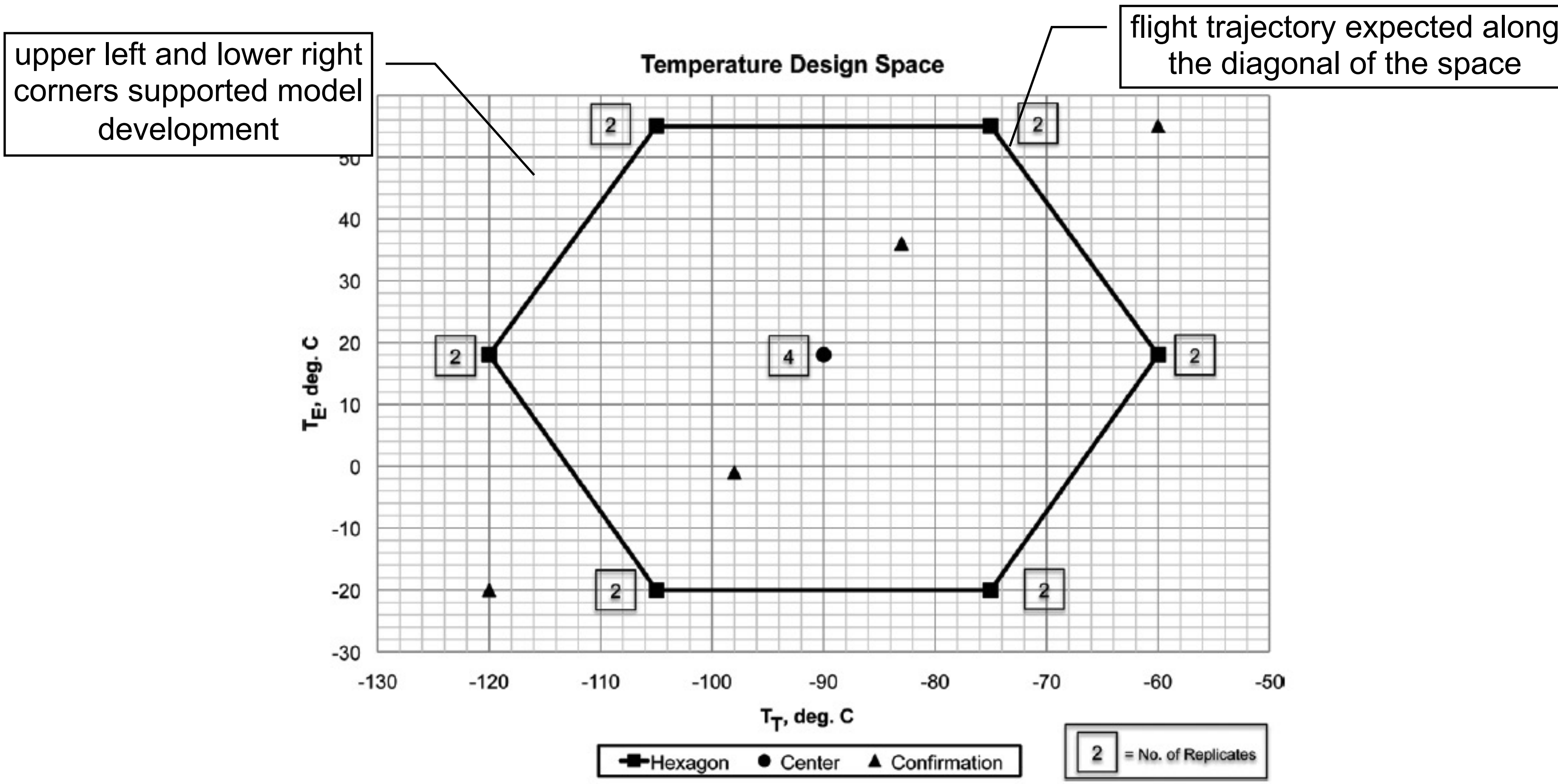
$$+ \beta_{23} T_{sensor} x T_{SSE} + \varepsilon$$

assumed negligible based on system knowledge

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

Experimental Design

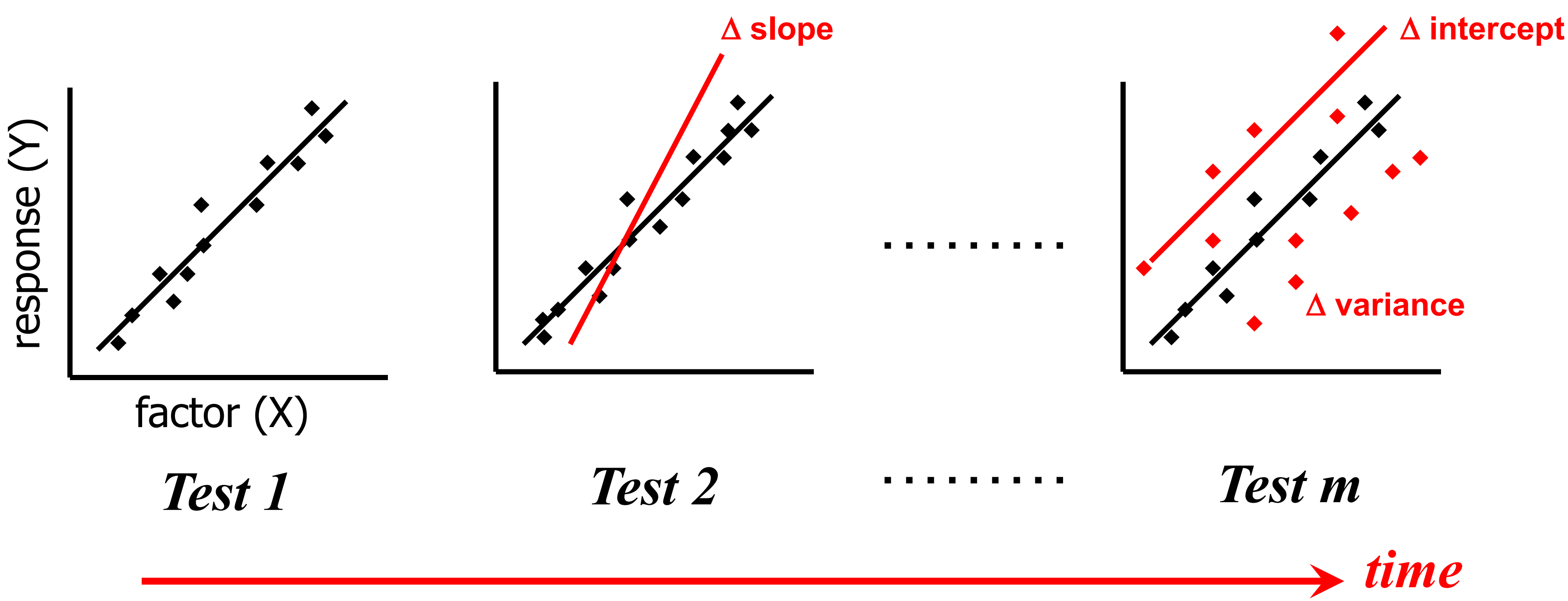
- **Superimposed designs to support multiple objectives**
  - **Model estimation, Confirmation, and Flight Trajectory**
- **Comprehensive assessment of the measurement system performance over predicted trajectories**



Characterization Stability Monitoring

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

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



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

Embedded Academic Collaboration

Virginia Tech – Geoff Vining, since 2009

Expected Reliability of Carbon Overwrapped Pressure Vessels at Use Conditions over Expected Mission Life

- **DOE for Reliability, with Anne Driscoll**

Virginia Commonwealth – David Edwards, since 2012

Next Generation Air Transportation Systems

- **Model specification and confidence intervals for complex voice clearance communication during approach to an airport**
- **Improving the realism of computer-simulated experiments with aircraft trajectory clustering in fast-time computer simulations**
- **Space-filling designs for multi-layer nested factors, where the level of one factor affects the range of possible levels for the nested factor.**

35 interns over ~15 years

Aerospace Educational Resources

Old Dominion University - Center for Experimental Aeronautics

- Drew Landman and Colin Britcher, established in 2000, in collaboration with Florida State, Jim Simpson
  - Graduate level, 2-course sequence
    - Design of Experiments and Response Surface Methodology
  - DOE is now a M.S. core course in Mechanical and Aerospace Eng.

American Institute of Aeronautics and Astronautics Short-Courses

- Drew Landman
  - Design of Experiments and Response Surface Methods

NASA Engineering and Safety Center Academy

- Geoff Vining
  - Design of Experiments and Regression short-courses

Motivated 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 experiments 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

Check for updates

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

External Collaboration is Critical

- International Statistical Engineering Association (ISEA)

  isea-change.org

  - Mission: To be the voice for statistical engineering, serving as a catalyst to drive sustainable results and impact by integrating multiple disciplines through the scientific method
- ASA Section in Defense and National Security (SDNS)
  - Sponsor of DATAWorks
  - Explore opportunities to more formally include aerospace
- Other government entities, leveraging and benchmarking their journey
  - Institute for Defense Analyses, Test Science Team
  - Director, Operational Test and Evaluation, Interagency Agreement
  - National Institute of Standards and Technology (NIST)
  - Statistical Sciences Group at the US Army Combat Capabilities Development Armaments Center at Picatinny Arsenal, NJ

Concluding Remarks

- **NASA enjoys a heritage of the impact of statistical methods in aerospace research and development**
- **Infusing a statistical engineering perspective has demonstrated impact and motivated institutionalization over the past 20 years**
- **NASA Langley has been an Agency leader in introducing the discipline, building academic relationships and external collaboration**
- **Growing from a few highly-skilled practitioners to broader workforce practice, going from limited applications to ubiquitous implementation**
- **State of the discipline within NASA is strong and continues growing**

Aspire to see NASA infusing statistical engineering as a routine part of aerospace research and mission execution