Design for Reliability using Response Surface Methodology

Peter A. Parker, Ph.D., P.E.

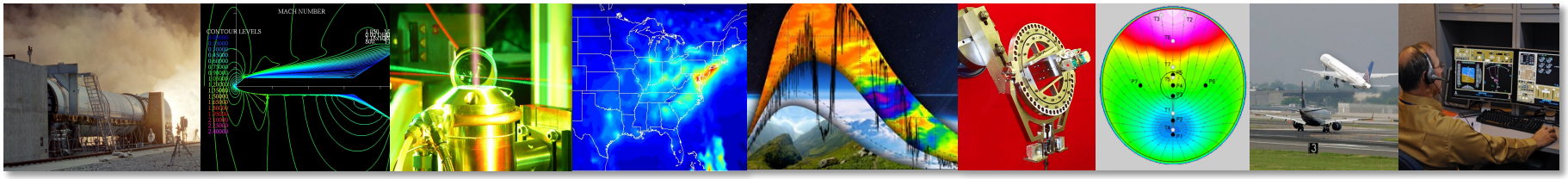
National Aeronautics and Space Administration

Langley Research Center

Hampton, Virginia

July 30th, 2021

Amazon Reliability Engineering Team



NASA Langley Research Center



- **One of 10 NASA Centers, located in Southeast Virginia**
- **Established in 1917, first civilian aeronautics laboratory in United States**
- **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**

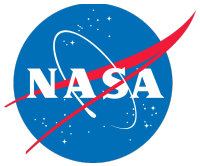


Reliability Perspectives

- **Probability that a system, vehicle, machine, device will perform its intended function under encountered operating conditions, for a specified period of time (Meeker and Escobar 1998)**
  - Engineering discipline based on statistical and probabilistic analyses
  - Reliability techniques apply throughout the concept to operation life-cycle of a component or system
- **NASA's Reliability and Maintainability (R&M) program ensures that the systems within NASA's spaceflight programs and projects perform as required throughout their life cycles to satisfy mission objectives. Mission objectives include safety, mission success and sustainability criteria. (https://sma.nasa.gov/sma-disciplines/reliability-and-maintainability, https://extapps.ksc.nasa.gov/Reliability/)**
- **In this presentation, we focus on the design aspects of reliability based on the "predictability" of systems performance**

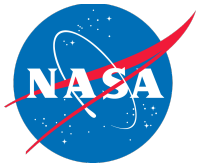
Meeker, Escobar (1998) Statistical Methods for Reliability Data

Presentation Overview



- **Introduce response surface methodology (RSM)**
- **Provide a sampling of RSM applications at NASA used during design and development stages to predict performance**
- **Present two in depth case studies**
  - **Computational fluid dynamics simulation**
  - **Planetary entry, descent, and landing improvements**

Response Surface Methodology (RSM)



- **Literally: A methodology to build and explore response surfaces for the purpose of learning and optimization with application to design and performance assessment**

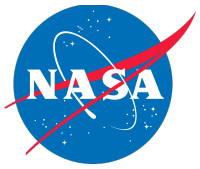
- "An ingenious common sense approach to problem solving, coupled with the use of reasonably well-known statistical and mathematical methods" (Myers RSM book, 1976)

- "Response surface methods are a group of statistical techniques specifically designed to catalyze scientific learning through -- a scientific paradigm in which data drives an alternation of induction and deduction" (Box, JQT, 1999)

- **A response surface is a mathematical Model of the relationship between Factors and Responses from a Designed Experiment**

Myers (1976) Response Surface Methodology
Box (1999) "Statistics as a Catalyst to Learning by Scientific Method," *Journal of Quality Technology*
Myers, Montgomery, Anderson-Cook (2016) Response Surface Methodology: Product and Process Optimization using Designed Experiments

Design of Experiments (DOE)

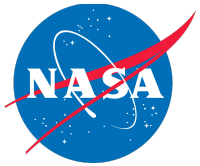


- **Designed Experiment - Purposeful control of the inputs (factors) in such a way as to deduce their relationships (if any) with the output (responses).**

- **Design – matrix of factor settings to execute to obtain a response**
  - **Factors represent axes in multidimensional design space**
  - **Design points are locations (coordinates) within the design space**
  - **Geometric interpretation of a design, a collection of points**
  - **Every design point has an associated cost-benefit tradeoff**

- **Design Questions**
  - **How many design points are required (factor combinations)?**
  - **How to select the location of the design points?**
  - **What order do we execute the design points?**

Origin and Background of DOE



"In 1919, Ronald Fisher was offered the post of statistician at the Rothamsted Agricultural Experiment Station. This was the oldest agricultural research institute in the United Kingdom, established in 1837 to study the effects of nutrition and soil types on plant fertility, and it appealed to Fisher's interest in farming. He accepted the post at Rothamsted where he made many contributions both to statistics, in particular the design and analysis of experiments, and to genetics."

Design of Experiments developed largely by Fisher, starting in 1920's

- **Agricultural context**
- **Experimental characteristics:**
  - **Categorical factors (fertilizer type, seed type, soil type)**
  - **Long response time (a growing season)**
  - **First-order models with interactions**

Motivation for RSM



George Box, originally trained as a Chemist, founder of RSM, 1951

In early days of his career, Box encountered resistance from chemists and engineers to the use of designed experiments. He concluded that methods originally developed for agricultural experiments were not properly adapted to industrial experimentation. (Box JQT 1999)

In the physical and engineering sciences data usually become available within hours, days, and sometimes even minutes; A situation he called immediacy that makes it necessary for investigators to look at what they have just done, and immediately ask the question "so what should we do now?" **They are involved not so much in testing, but in the process of sequential learning**." (Box, UoW, 2000)

Sought ways of using statistics to catalyze a process of investigation that was not static, but dynamic. Clearly, the investigation of a system that is not well understood is dynamic, and RSM was developed to provide a systematic approach using statistical methods to meet this need. (Box, JQT 1999)

Industrial and Scientific Experimental Characteristics:

- **Continuous factors, Quick response times**
- **Second-order regions with an optimum/robust combination of factors**

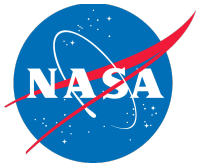
Box and Wilson (1951) "On the Experimental Attainment of Optimum Conditions," *Journal of Royal Statistical Society, Series B*

RSM Adoption at NASA

- **While RSM was introduced in 1951 and was in wide spread industry usage by the 1980's in the U.S., it was not as common in aerospace**
  - **RSM application in aerospace research and development at NASA is relatively new (last ~20 years) and still growing – Why?**
- **Traditional academic training of engineers lacked relevant, applicable, and implementable statistical courses**
- **Engineers are often trained to "fear" uncertainty**
  - **Uncertainty is a problem, a nuisance to be avoided**
  - **"Never replicate an experiment, because it causes error."**
- **Over last 15 years, there are better educational resources, accessible software, and an increasing appreciation for the role of statistical methods in aerospace research**

RSM offers an efficient, insightful, data-driven approach to make decisions in the presence of uncertainty

RSM 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?**

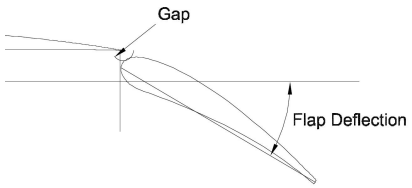
- **How well do we need to know the answers?**
  - **How much risk are we willing to accept in being wrong?**
  - **What are the consequences if we are wrong?**

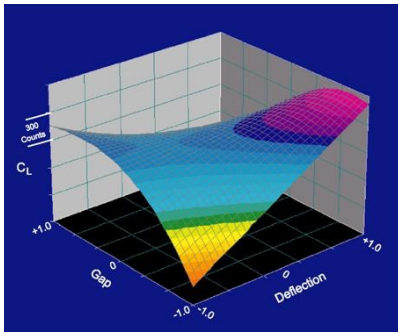
- **Do the methods rigorously link to the stated objectives and risk?**
  - **Are the resources justifiable and defendable?**

Questions apply recursively throughout project life-cycle

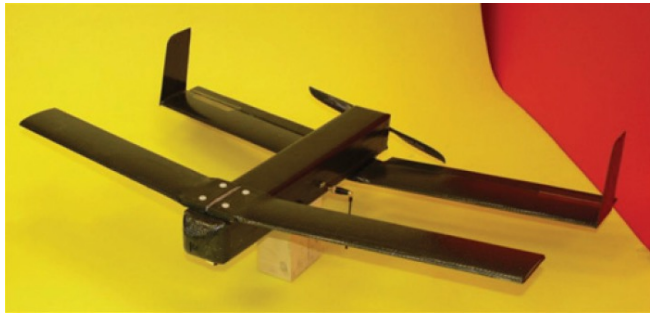
Shapiro (1994) "George H. Heilmeier," *IEEE Spectrum*

Aeroscience Wind Tunnel Testing





DeLoach, et al. (2001), "Practical Applications of Response Surface Methods in the NTF," AIAA 2001-0167



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

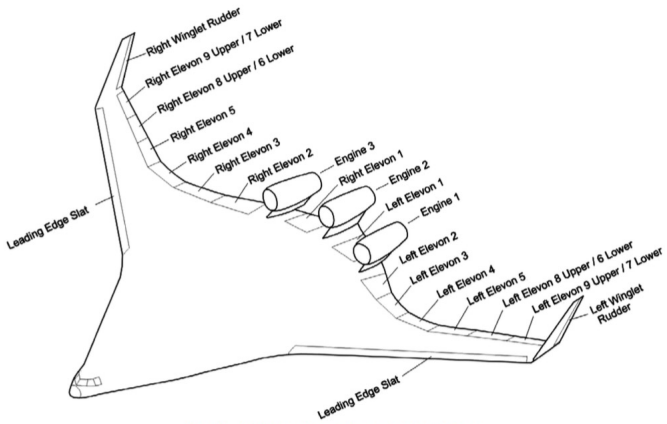


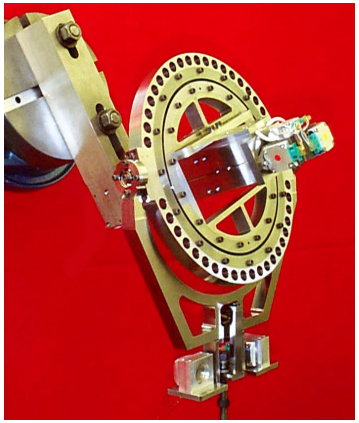
Fig. 2 BWB configuration control surfaces.

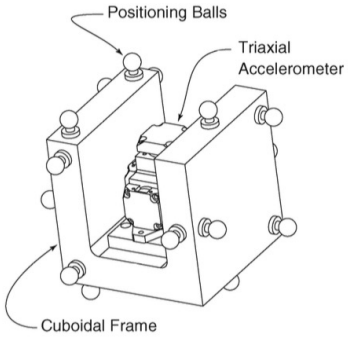
Landman, et al. (2007), "Response Surface Methods for Efficient Complex Aircraft Configuration Aerodynamic Characterization," *Journal of Aircraft*, 44, (4)



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

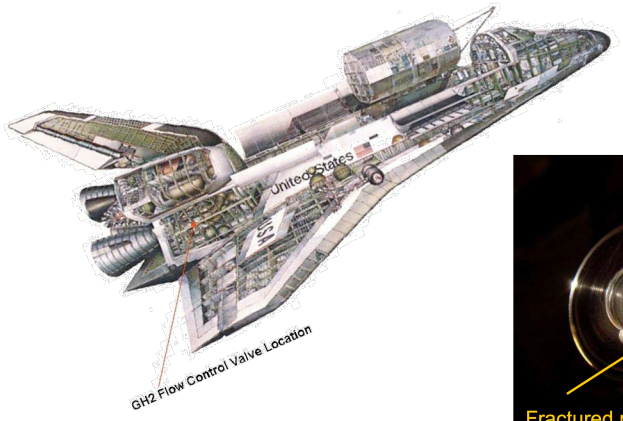


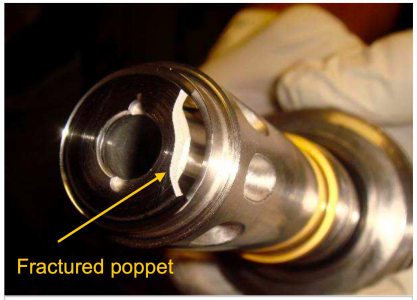


Parker, et al. (2001), "A Single-Vector Force Calibration Method Featuring the Modern Design of Experiments," AIAA 2001-0170



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

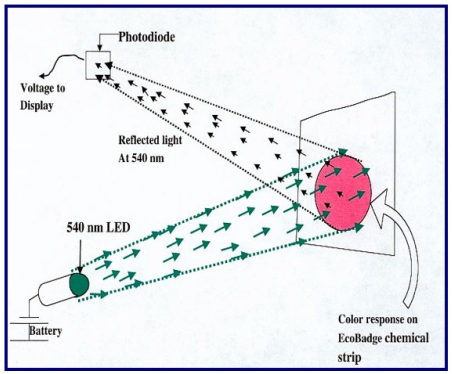




STS-126 Valve Poppet Following Removal

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

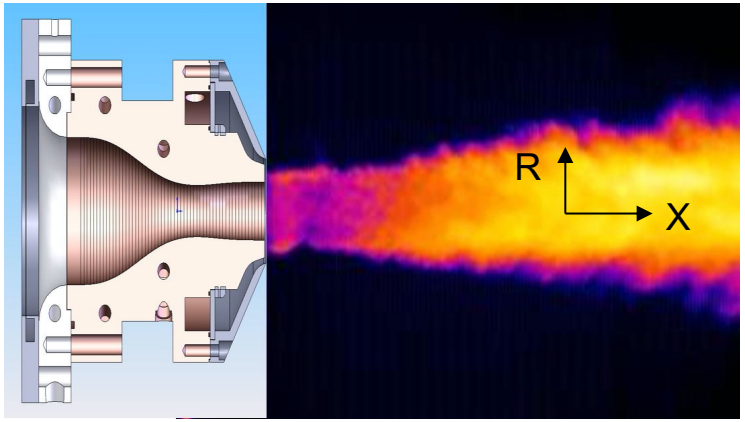




Pippin, et al. (2007), "Improvements to the Passive Ozone Measurement System Used by GLOBE Schools," *American Geophysical Union Annual Conference.*

Coaxial Free Jet Experiment

Objective: **Characterize coaxial flow mixing with quantified uncertainty of experimental flow-field parameters for computational code development and validation**



Factors

- X - axial distance
- R - radial distance

Responses

- T - temperature
- u – axis velocity
- v – axis velocity
- N_2 Nitrogen (%)
- H_2 Hydrogen (%)
- O_2 Oxygen (%)
- Variances of above variables
- Pair-wise Covariance

Systematic Sources of Variation

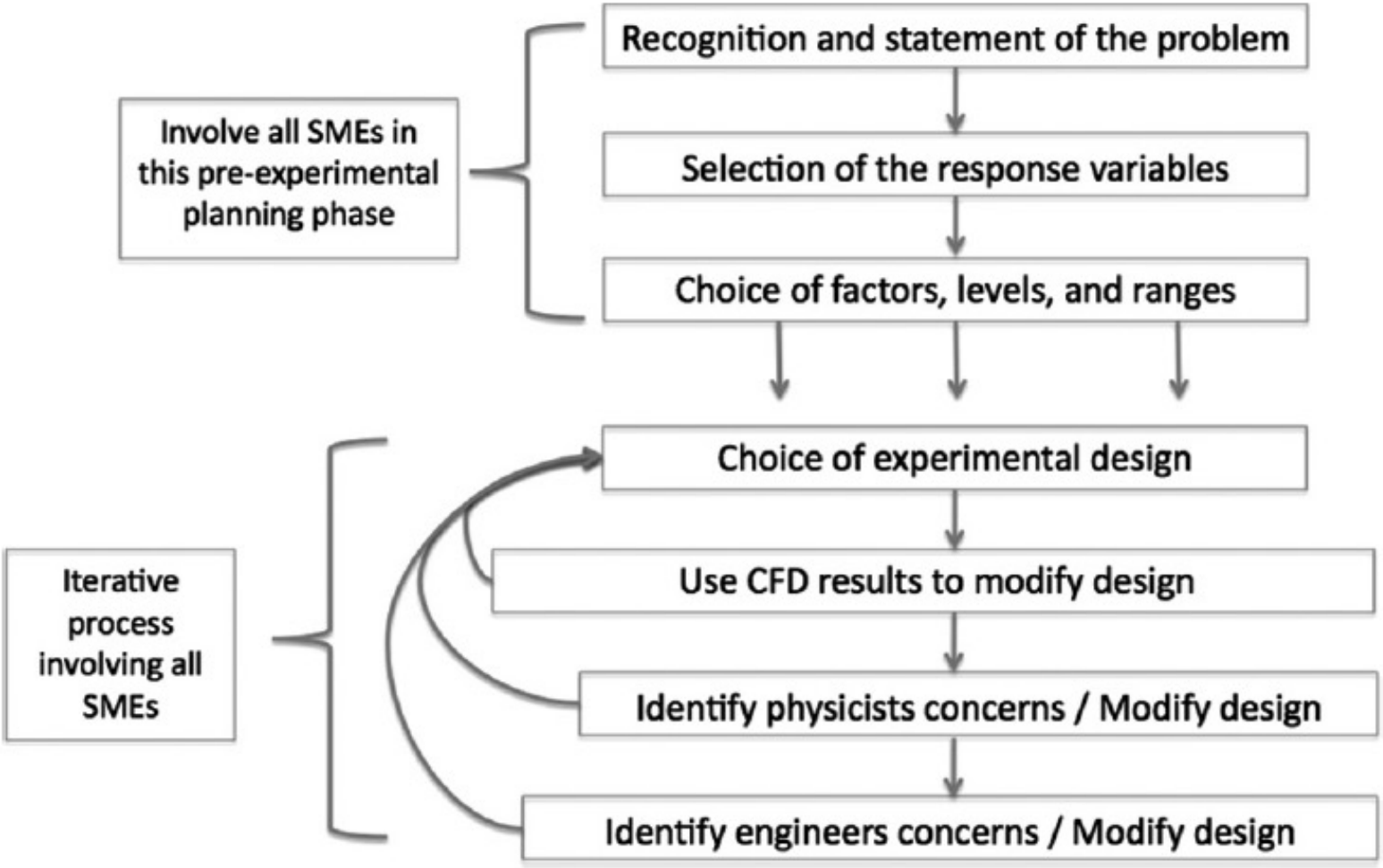
- Nozzle Geometry
- Boundary Conditions
- Measurement bias

Random Experimental Variation

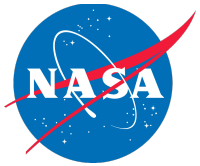
- Flow-field control
- Measurement precision
- Facility repeatability

Silvestrini and Parker (2012), “Aerospace Research through Statistical Engineering,” *Quality Engineering*

Collaboration to Define the Right Questions

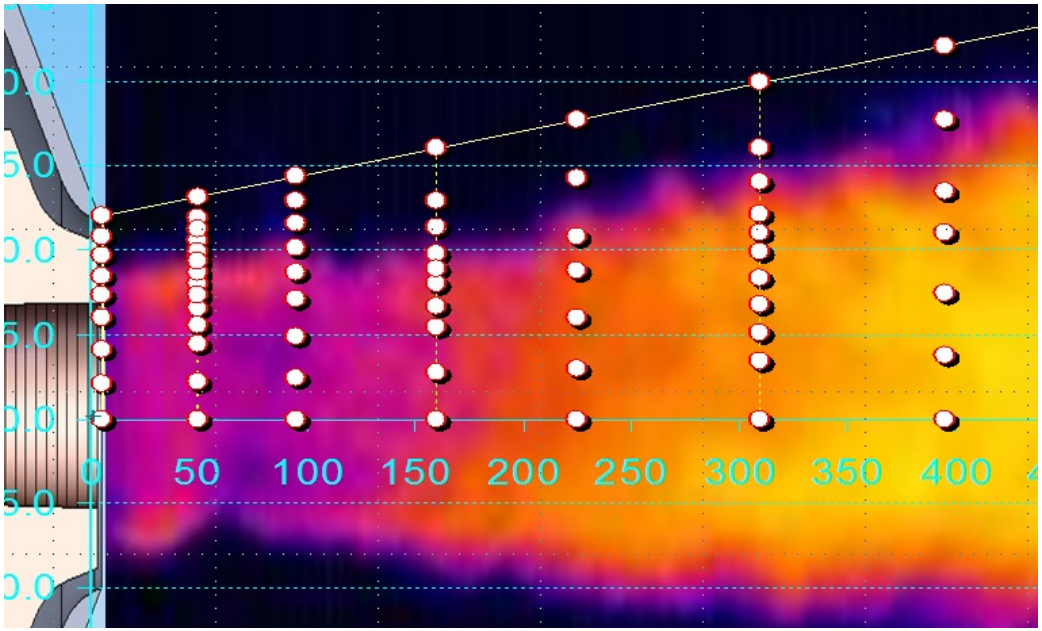


Experimental Design Challenges



- **Modeling Mean and Variance Responses**
  - Analogous to robust product design, with different objectives
  - Variability is intentional due to turbulent flow
  - Model is the product, rather than the optimum factor settings
- **Innovative Design and Modeling Approach**
  - Combined classical and space-filling design concepts
  - Design points are informed by computational simulation
- **Extreme Experimental Resource Constraints**
  - Time constrained to one-minute test
  - Execution ordering affects data volume and acquisition rate
  - Non-stationary in time, non-homogenous spatial variability

Experimental Design and Execution



- **Nested, overlapping face-centered central composite designs in partitioned subspaces with point density based on surface gradient**
- **Replication of design points (locations), and sub-sampling specified to meet absolute prediction variance requirements**
- **Subspace randomization and blocking of design points ordering to optimize execution efficiency and based on prior knowledge of flow field variability**

Hybrid Response Surface Modeling

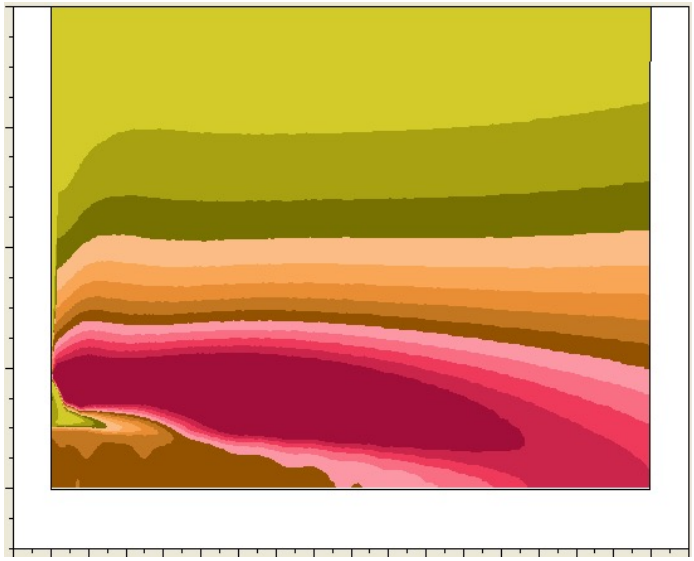
Seek parsimonious, empirical models of the flow-field parameters within the experimental error and quantify uncertainty

<u>Partition into near-field and far-field</u>

- **further partitioned into 1-D along radial trace and 2-D surface as *f(x,r)***

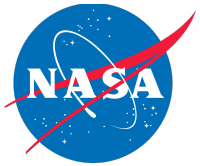
<u>Modeling methods supported</u>

- **Parametric models (polynomials)**
  - **easy to interpret**
  - **requires high-order for steep gradients**
- **Non-parametric (Gaussian process models)**
  - **excellent fit by interpolation**
  - **over-fitting is a concern**



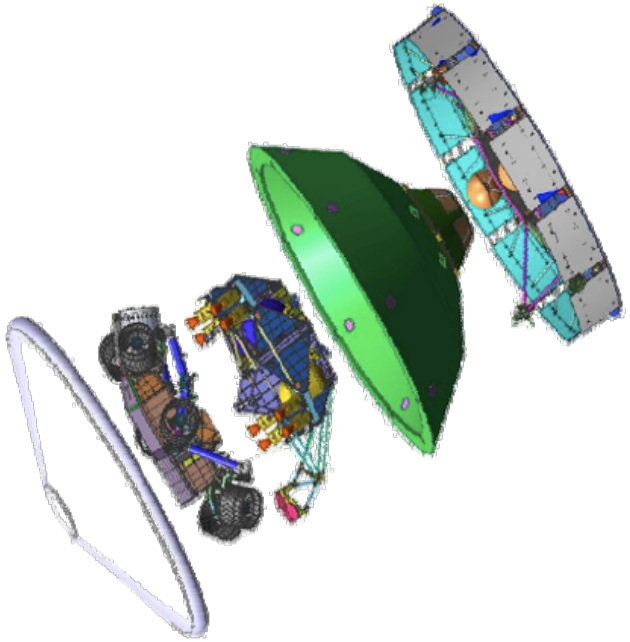
Predicted Response Surface of Temperature with Steep Gradients

Computational Case Study Success Factors



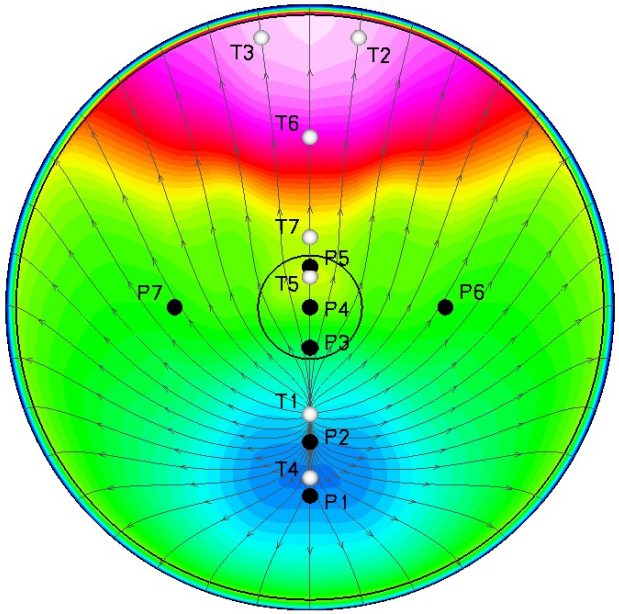
- Intensive Collaboration with subject matter experts is essential
  - Involved education and tutorials to obtain SME buy-in
  - Collaboration is successful when it becomes the SME's approach, not the statisticians suggestion
- Requires the innovative integration of multiple statistical methods and approaches to experimental design
  - Synergistic extension, adaption, and combination of methods
- Incorporates all available prior knowledge of response surface and facility and experimental constraints
- The solution approach did not exist in a textbook, it required a statistical library – along with essential non-statistical skills

Planetary Entry, Descent, and Landing



Objective

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



Measurement System Components

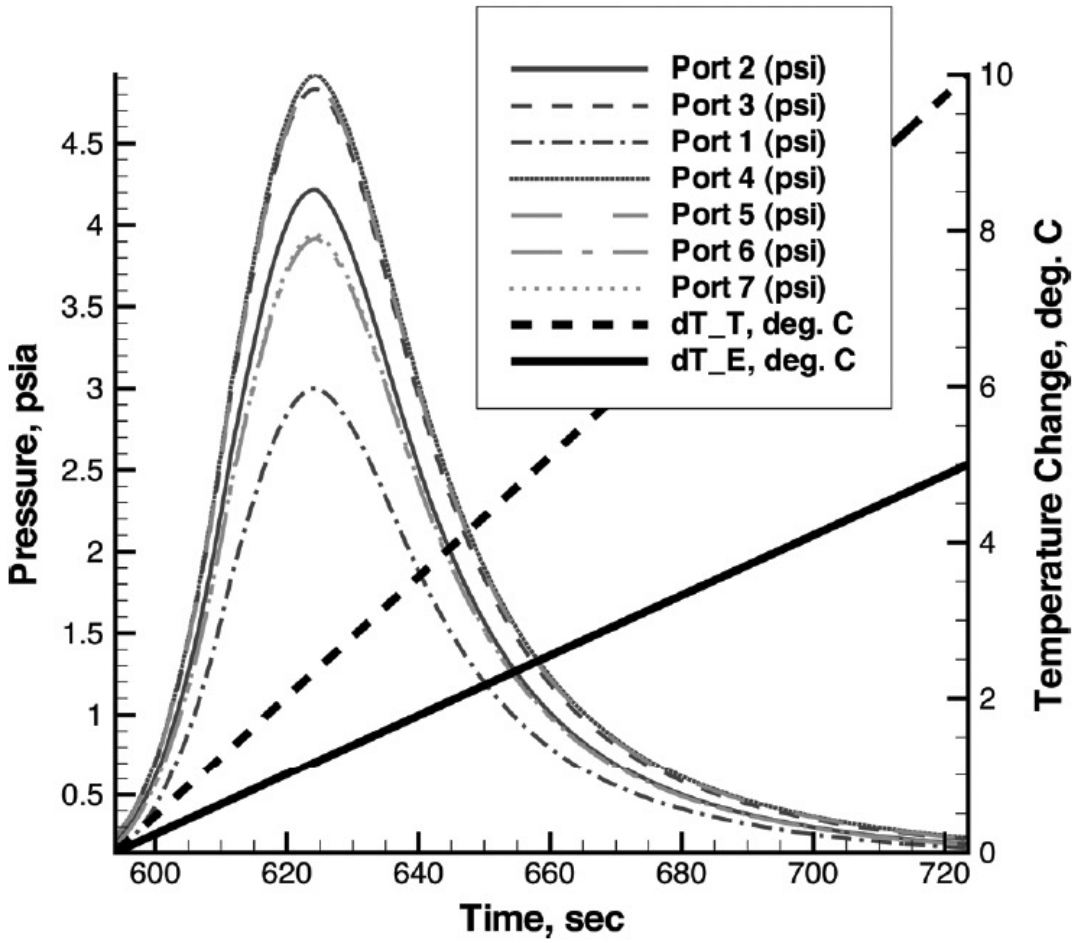
- **7 pressure transducers (sensors)**
- **Signal support electronics (SSE)**
- **Temperatures conditions at entry and across the heatshield vary**
- **Pressure varies across port locations**

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

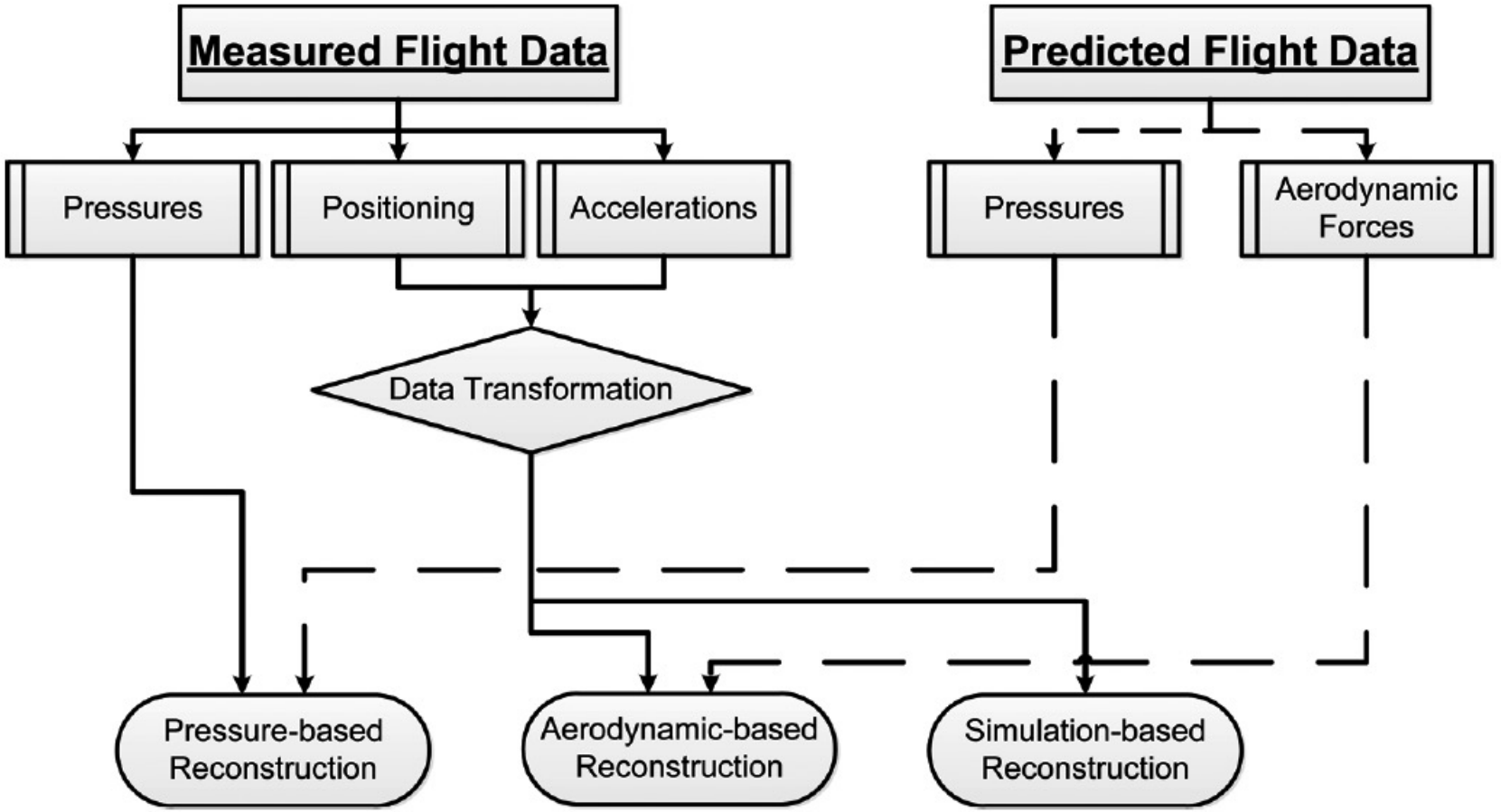
Flight Design Space Challenges

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

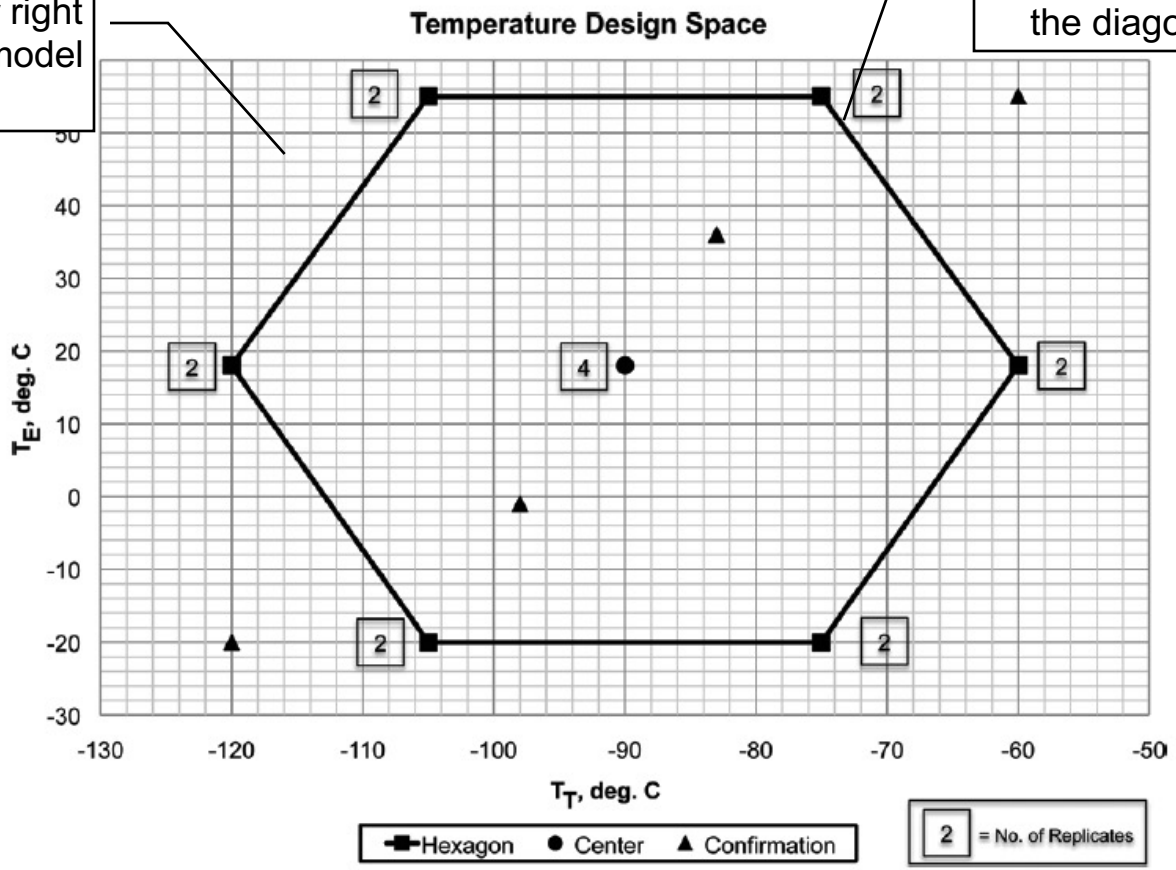
Interpretation and Translation into the Subject-Matter Experts' Nomenclature is Vital

Experimental Design

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

upper left and lower right corners supported model development

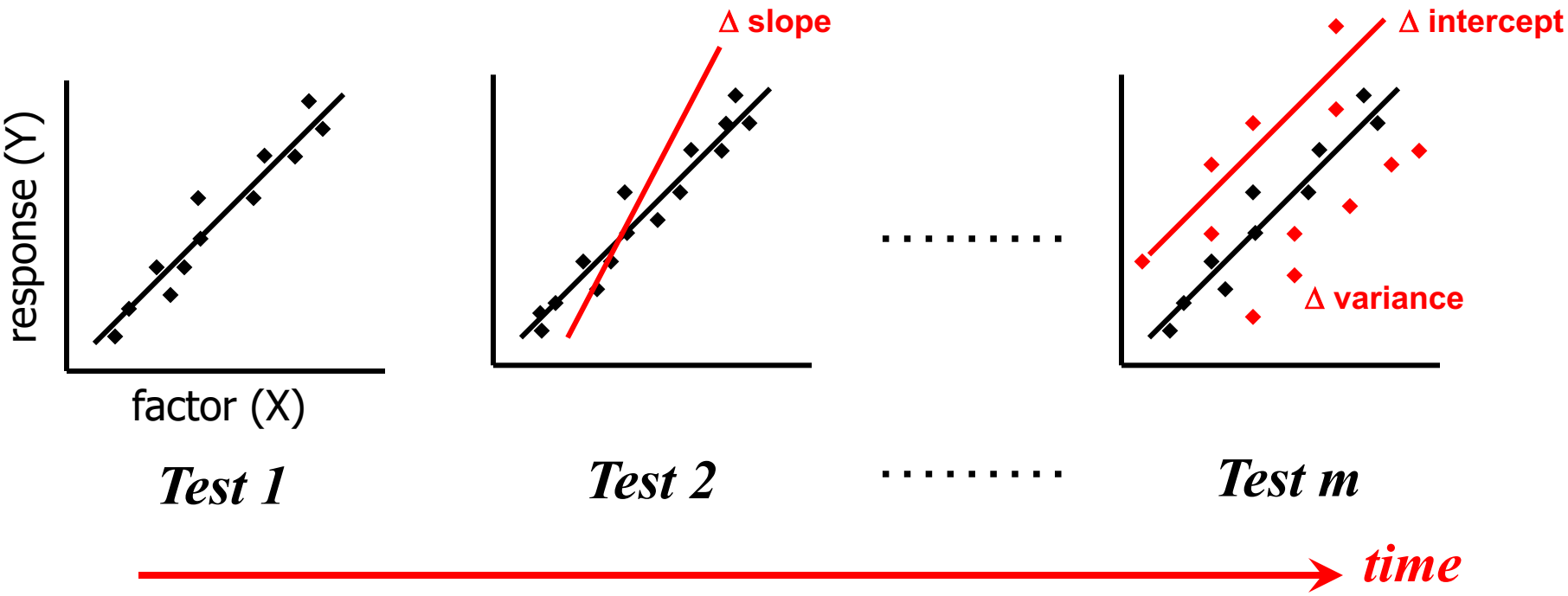
flight trajectory expected along the diagonal of the space



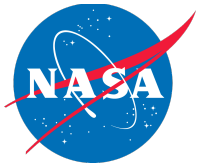
Characterization Stability Monitoring

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

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

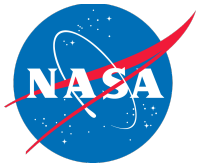


Entry, Descent, and Landing Case Study Summary



- **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**

Concluding Remarks



- **Reliability engineering applies throughout the system life-cycle**
- **Design predictions of system performance inform reliability**
- **Response surface methodology offers a powerful, strategic framework for understanding factor-response relationships**
- **RSM is broadly applicable to industrial product and process optimization throughout development and production**

RSM offers an efficient, insightful, data-driven approach to make decisions in the presence of uncertainty that inform reliability

Thank you for the invitation and opportunity to present to your team.