Statistical Calibration of the HIFiRE Flight 2 Combustion Model

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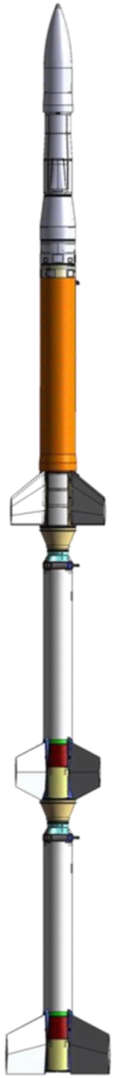
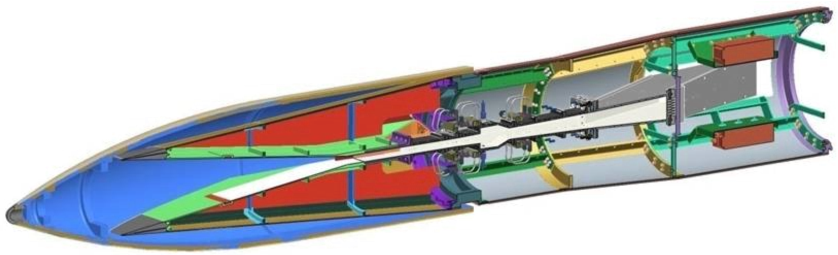
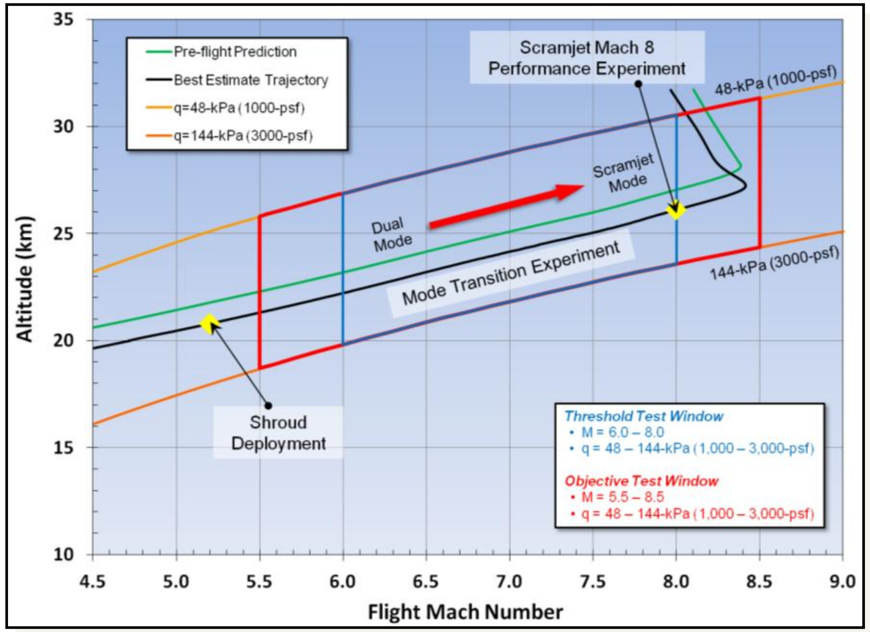
Motivation and Objective

- Air-breathing propulsion systems on hypersonic systems are some of the most complex technologies in flight vehicles
  - Complex physics with widely varying length and time scales
  - Highly sensitive to small perturbations
  - Ground testing limitations
  - Highly complex integration on vehicle platforms
- HIFiRE: Hypersonic International Flight Research Experimentation
  - Joint program between the US Air Force and the Australian Defence Science and Technology Organisation (DSTO)
  - HIFiRE Flight 2 supported by NASA
    - Suppressed trajectory sounding rocket flight test
    - Nearly constant dynamic pressure flight
    - Mach 6 to 8+ flight
    - Hydrocarbon fueled scramjet
    - Dual-mode ramjet (DMRJ) to scramjet transition
    - Successfully flown on May 1, 2012
- An accurate combustor model is critical predicting flight performance of air-breathing propulsion systems
- Objective: Statistically calibrate the HIFiRE 2 combustor model at DMRJ conditions







Uncertainty Quantification Process

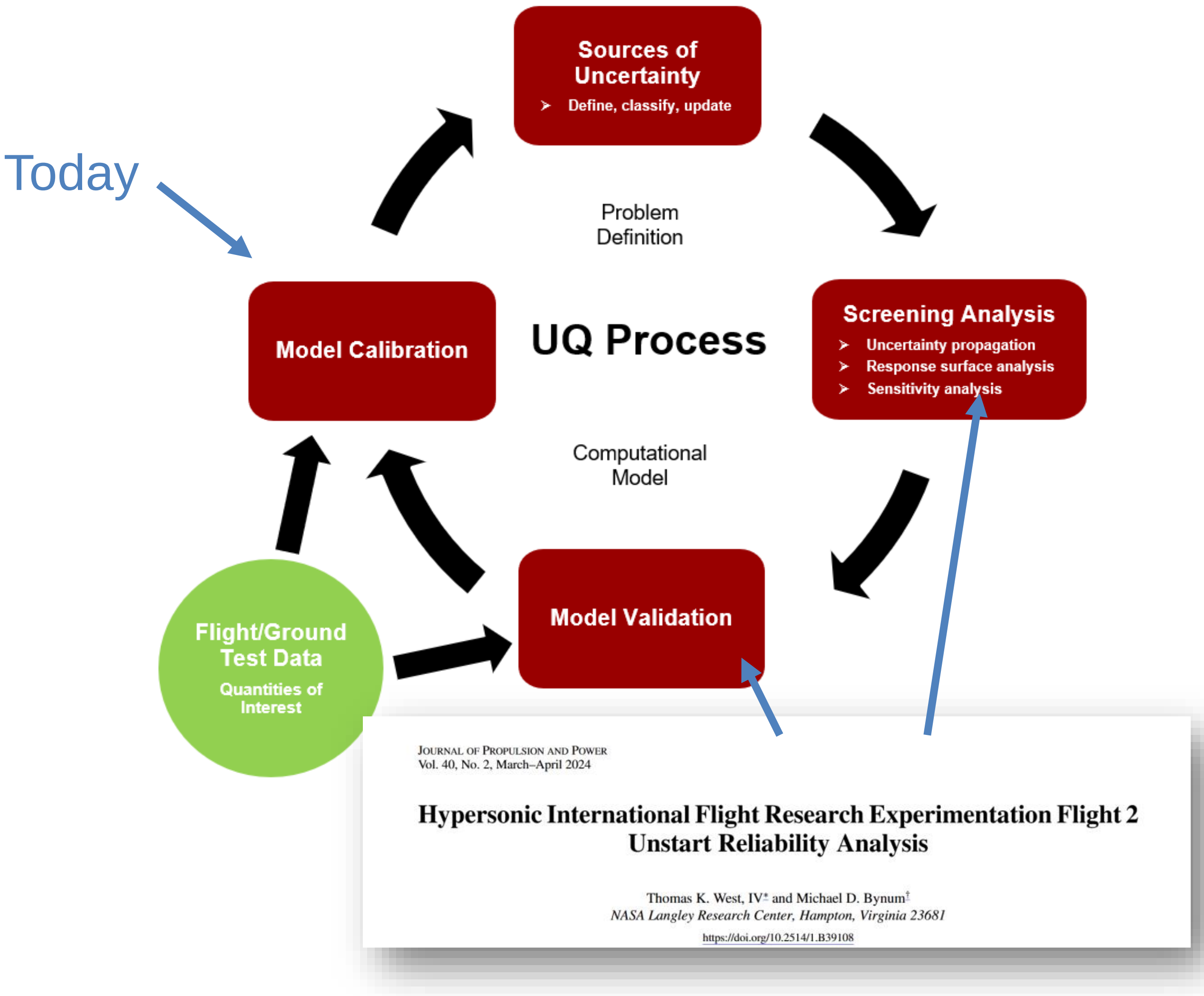
- Kennedy and O'Hagan framework
  - Describes the relationship between measurements and model predictions
  - Acknowledges presence of model-form uncertainty (i.e., model discrepancy)
  - Includes observation error
  - Basis for model calibration

Model Prediction | Model Discrepancy | Observation Error

$$y_{obs,i} = R(\mathbf{x}_i, \boldsymbol{\theta}) + \delta(\mathbf{x}_i) + e_i$$

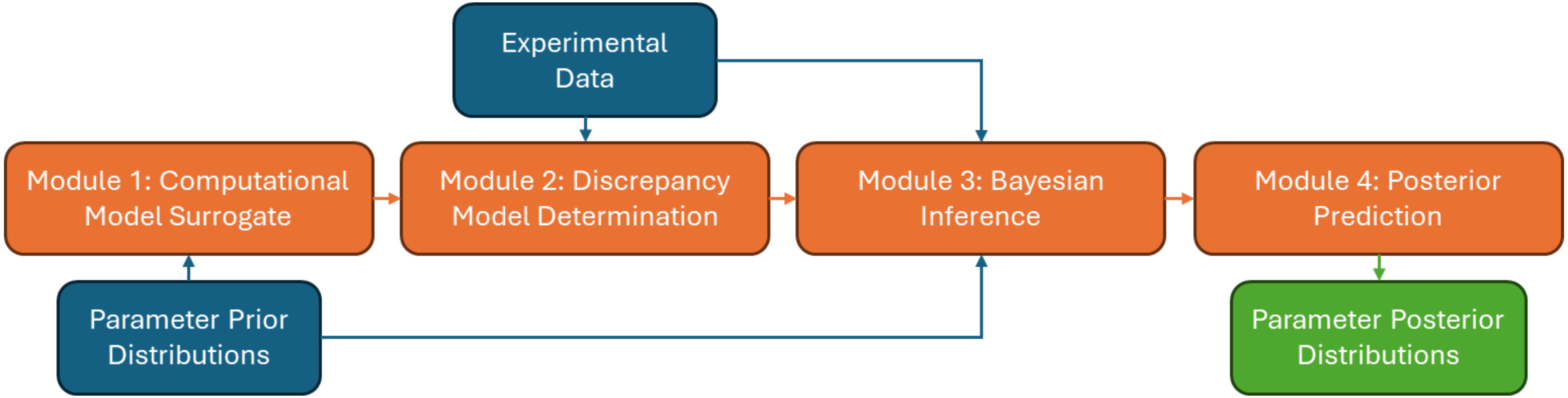
Calibration Parameters | Deterministic Parameters

- Bayesian inference used to calibrate model parameters
  - Based on Bayes theorem
  - Assume Gaussian likelihood
  - Uniform prior distributions (uninformative)
  - Adaptive Metropolis-Hastings



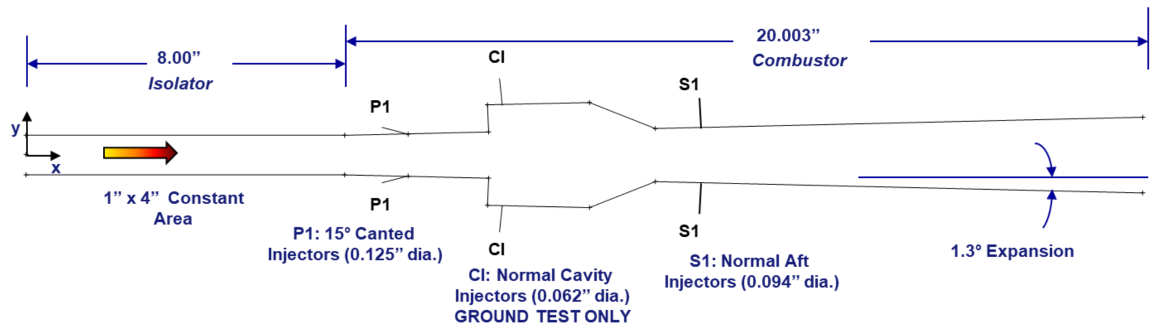
Modular Bayesian Framework

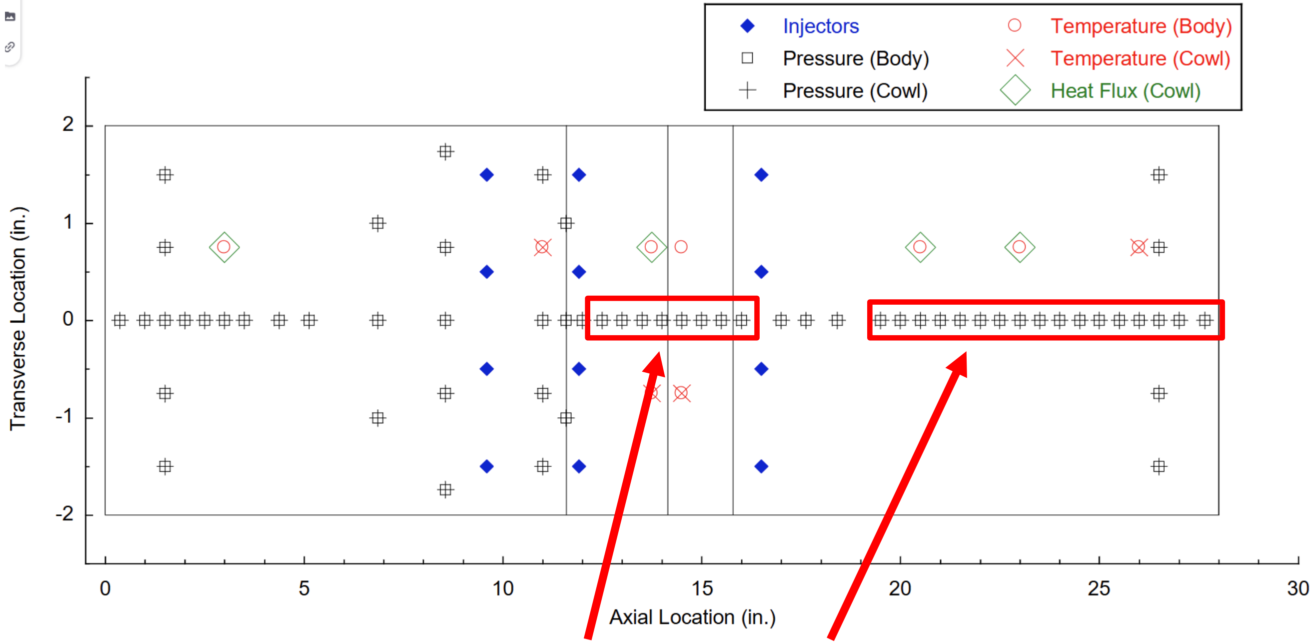
- Classical Kennedy and O'Hagan framework assumes model parameters, model discrepancy, and observation error can be calibrated simultaneously
  - Computationally expensive
  - Can lead to unidentifiability (mixing of where uncertainty is attributed)
- Modular framework separates model discrepancy estimation and parameter calibration
  - Surrogate model replaces computational model to reduce evaluation cost
  - Model discrepancy function determined using a maximum likelihood estimate
- Caveat: Posterior parameter distributions depend on model discrepancy



HIFiRE Direct Connect Rig (HDCR)

- Direct connect testing used to characterize combustor performance (no other propulsion system testing performed)
- Tested in the Arc-Heated Scramjet Test Facility at NASA Langley Research Center
- HDCR is a one-to-one scale model of the flight test article isolator and combustor
- Copper heat sink flowpath
  - Thermal barrier coated
  - Heavily instrumented (nearly identical to flight instrumentation)
    - 144 static pressure taps, 23 thermocouples, 4 heat flux gauges
- Calibration performed using wall pressure measurements from cavity and expansion regions – locations chosen to target combustion
- Calibrated to Mach 6.5 flow condition

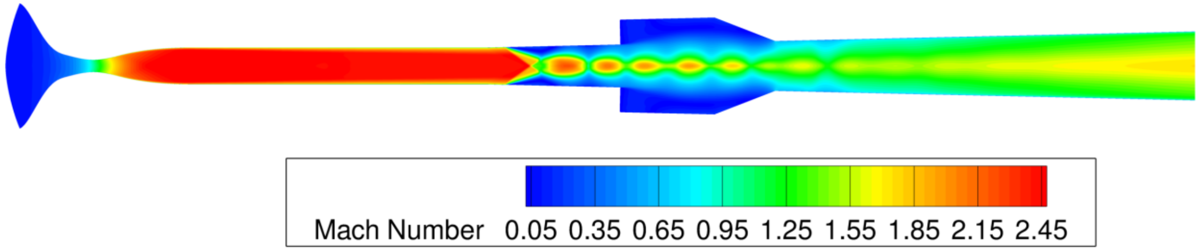


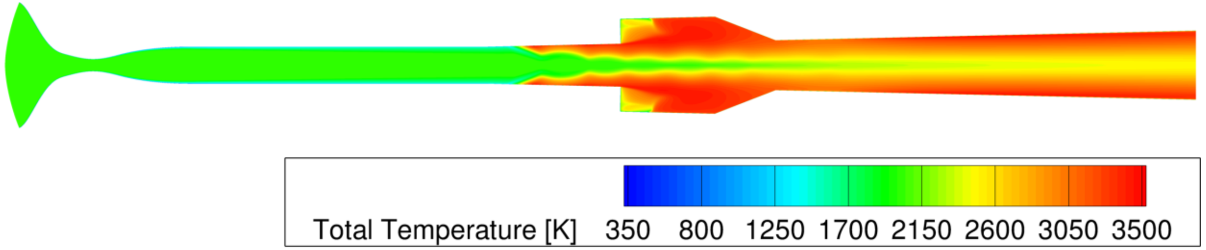


Used two regions of data to isolate combustion physics

Computational Model

- VULCAN-CFD 7.1
- Structured, three-dimensional, cell-centered, finite volume solver
- Assumed steady state, thermally perfect flow
- Flux Scheme: Edwards Low Dissipation Flux Split Scheme (LDFSS)
- Turbulence model: Menter blended k-ω / k-ε with wall matching functions of Wilcox
- One-dimensional, wall-normal heat transfer boundary condition using experimentally obtained back-side temperatures
- Combustion model: modified version of the Eddy Dissipation Concept (EDC) model of Magnussen and Hjertager
  - Significantly lower computational cost vs. a finite rate model
  - Valid for mixing limited and stable flows





Calibration Parameters

Parameter	Distribution	Min	Max
Sc_t	Uniform	0.2	0.7
A	Uniform	0.5	4.0

Uninformative Priors

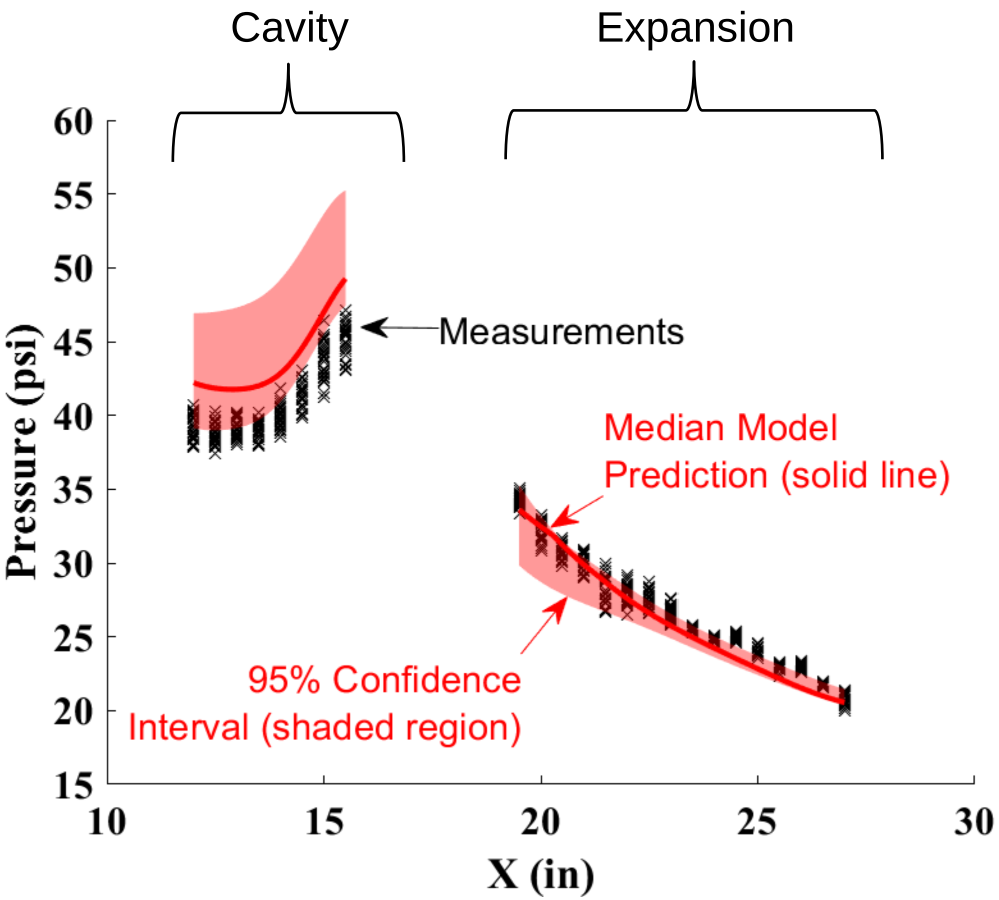
Uncalibrated Model Compared to Measurements

- Computational model surrogates were Gaussian Process models
  - Divided into two regions for improved accuracy
  - Models fit over full prior parameter domains

- Forward propagation of parameter uncertainties via Monte Carlo sampling

- Notice the scatter in the measurements
  - Variation observed even under “steady-state” test conditions (facility and fuel injection)
  - Measurement uncertainty known to have a standard deviation of ~0.1 psi

- Model prediction do not bound measurements – suggests model-form uncertainty exists

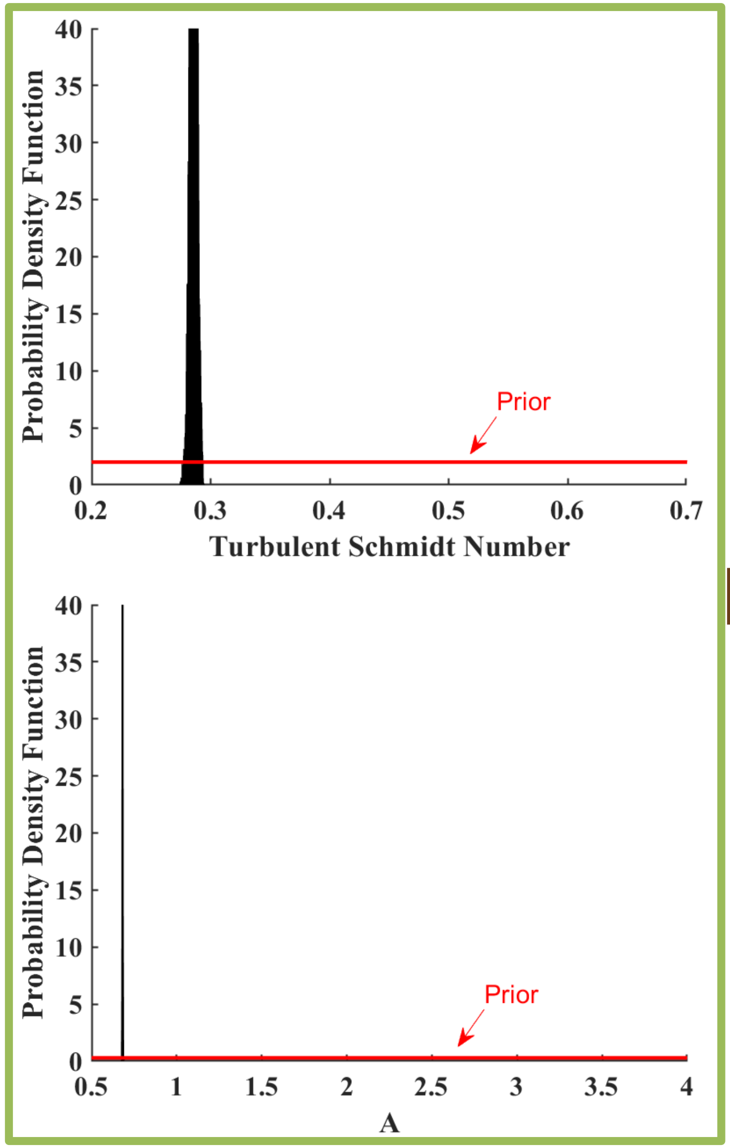


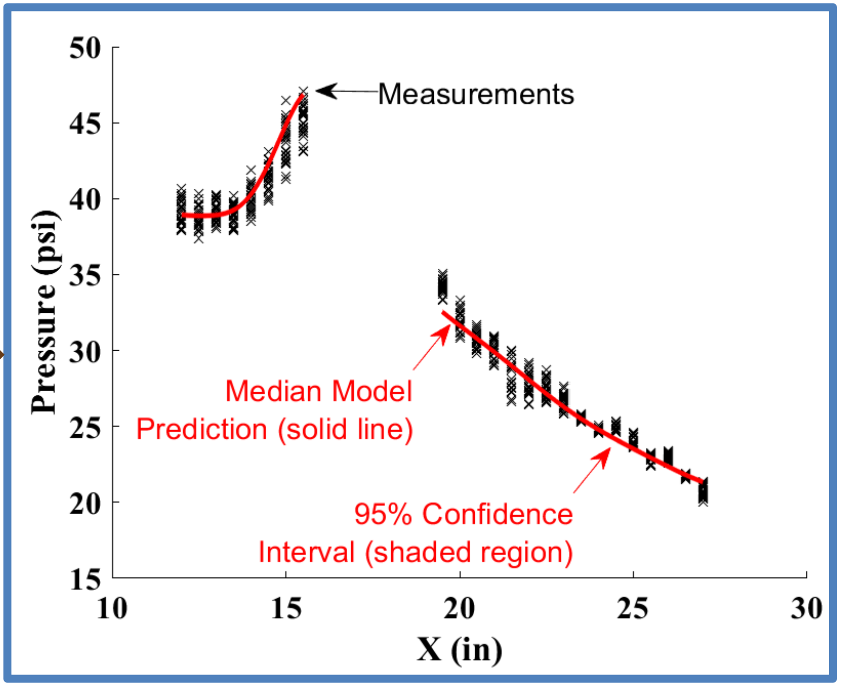
Calibration without Model Discrepancy and Fixed Observation Error

- Initial calibration done without including model discrepancy

$$y_{obs,i} = R(\mathbf{x}_i, \boldsymbol{\theta}) + \cancelto{0}{\delta(\mathbf{x}_i)} + e_i$$

- Observation error fixed at a standard deviation of 0.1 psi

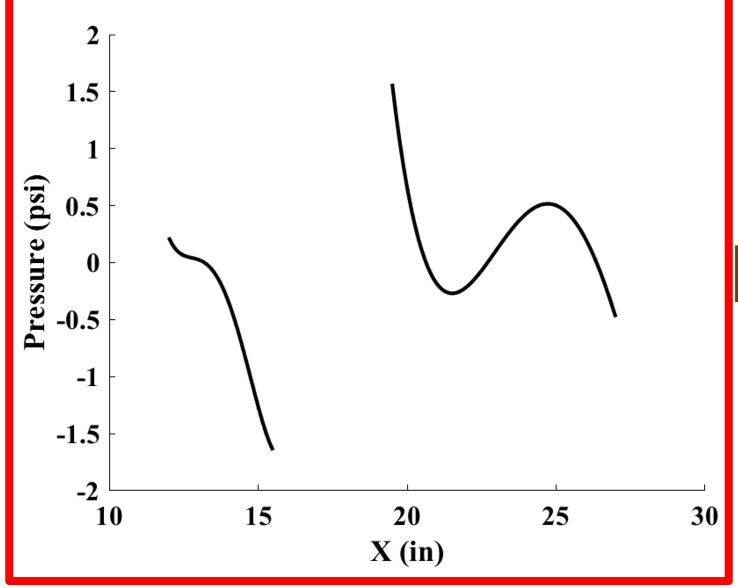




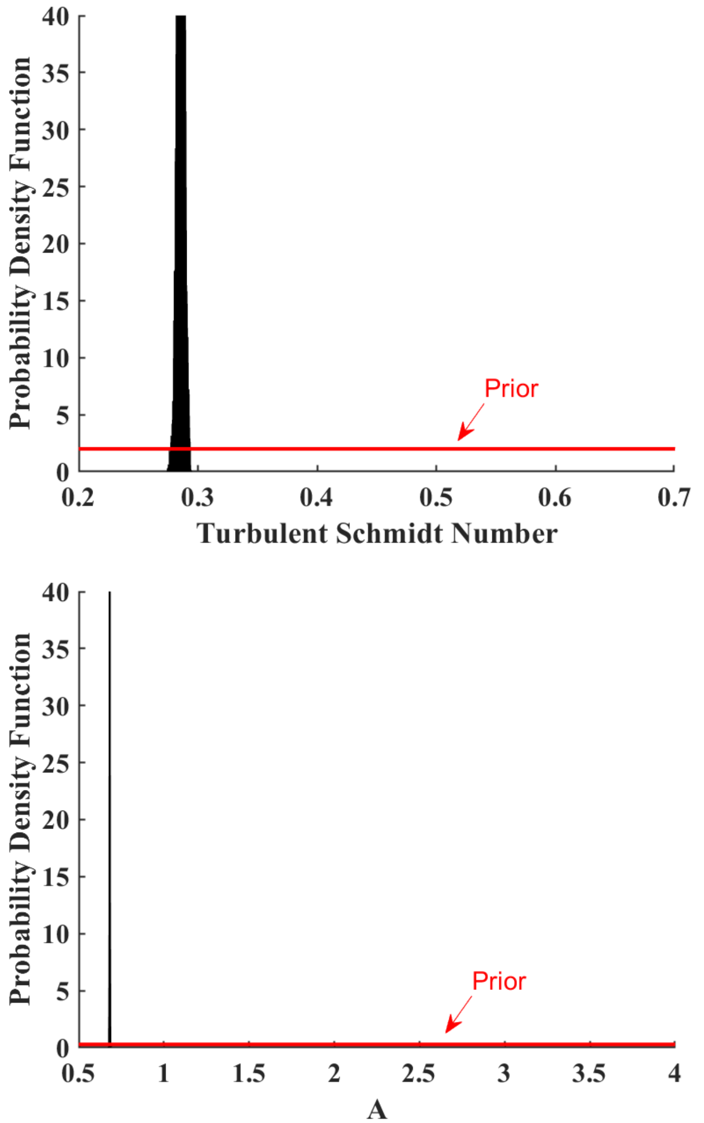
- Small confidence interval due to small parameter uncertainties
- Bias prediction compared to measurement distributions

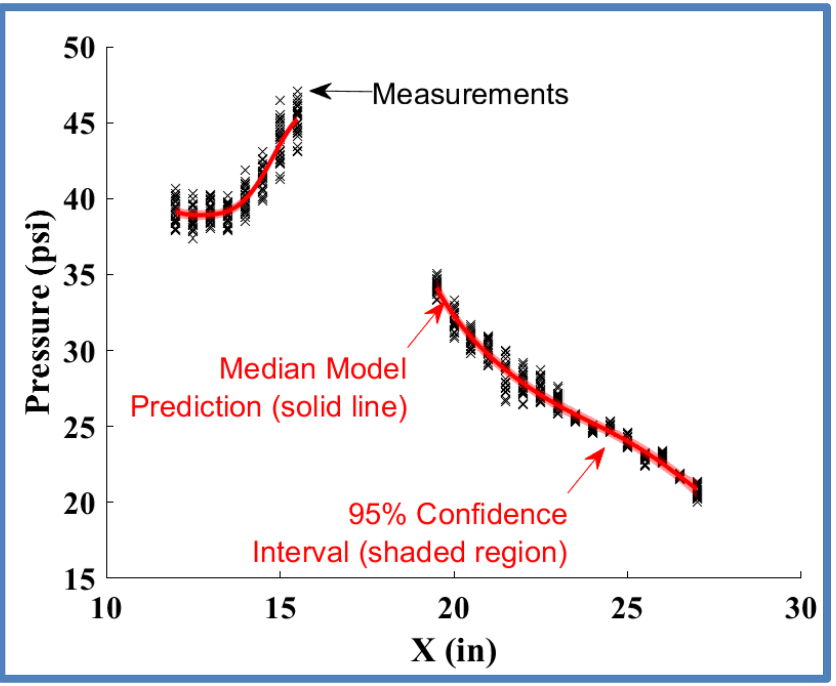
Calibration with Model Discrepancy and Fixed Observation Error

- Now include model discrepancy
- Observation error still fixed at a standard deviation of 0.1 psi



Model discrepancy described by polynomials (one for each region) fit based on a maximum likelihood estimate

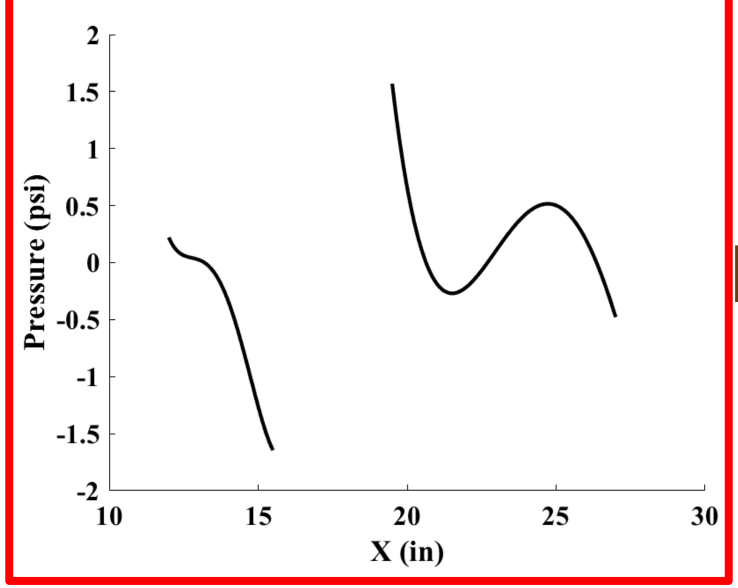




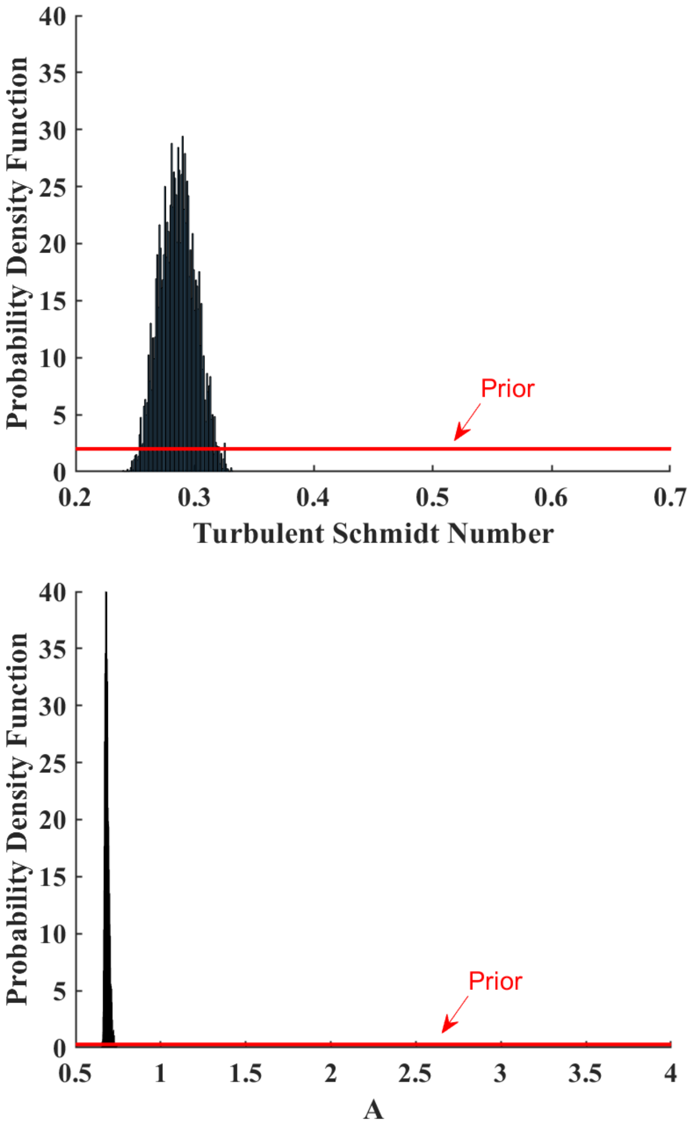
- Small confidence interval due to small parameter uncertainties
- Median prediction much closer to measurement medians

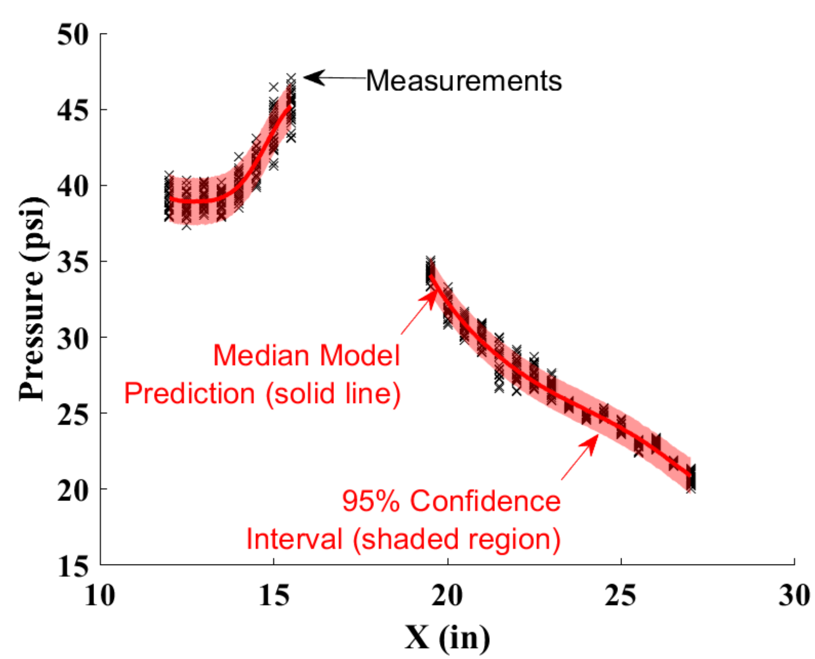
Calibration with Model Discrepancy and Calibrated Observation Error

- Now calibrate the observation error in each region along with model parameters – adds two calibration parameters



Same model discrepancy functions





- Model predictions now capture measurements
- Parameter distributions are physically more reasonable

Conclusions

- Calibration of accurate hypersonic air-breathing combustion models using available and relevant ground test data is critical to accurately predicting flight vehicle performance

- Complexity of both the physics models and ground testing make statistical calibration challenging

- Bayesian inference approach used in this work outline a computationally efficient approach to combustor model calibration

- Results from this study only valid at comparable operating conditions

- Important to capture model-form uncertainty and observation error to avoid misallocation of uncertainty

Questions?

Calibration with Model Discrepancy and Calibrated Observation Error