FY25 Strategic University Research Partnership (SURP)

Integrating Uncertainty Quantification with Traditional Systems Engineering Practices

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Objectives:

- Develop the Uncertainty Quantification Verification Methodology (UQVM) methodology that optimizes the design of integration and test (I&T) and verification and validation (V&V) sequences with respect to cost, duration and performance, through enhanced understanding of uncertainty.

Background:

- Modern systems engineering ontologies, processes, and integrated analysis tools now influence many aspects of flight project development, for example, trajectory analysis, and probabilistic reliability analyses.
- These advances have not yet fully linked measurement quality, model fidelity, system performance metrics, and science objectives with the goal of optimizing the overall V&V process.

Approach:

- Our technical approach is to apply uncertainty quantification and Bayesian experimental design methods to optimize the V&V process for different utility functions (minimize cost, maximize insight into the system, etc.) by:
  - Reducing the scope of each test to achieve the necessary reduction in uncertainty for a system-level quantity of interest (QoI).
  - Reducing the number of tests and the number of data points collected in each test, therefore reducing V&V cost and duration.

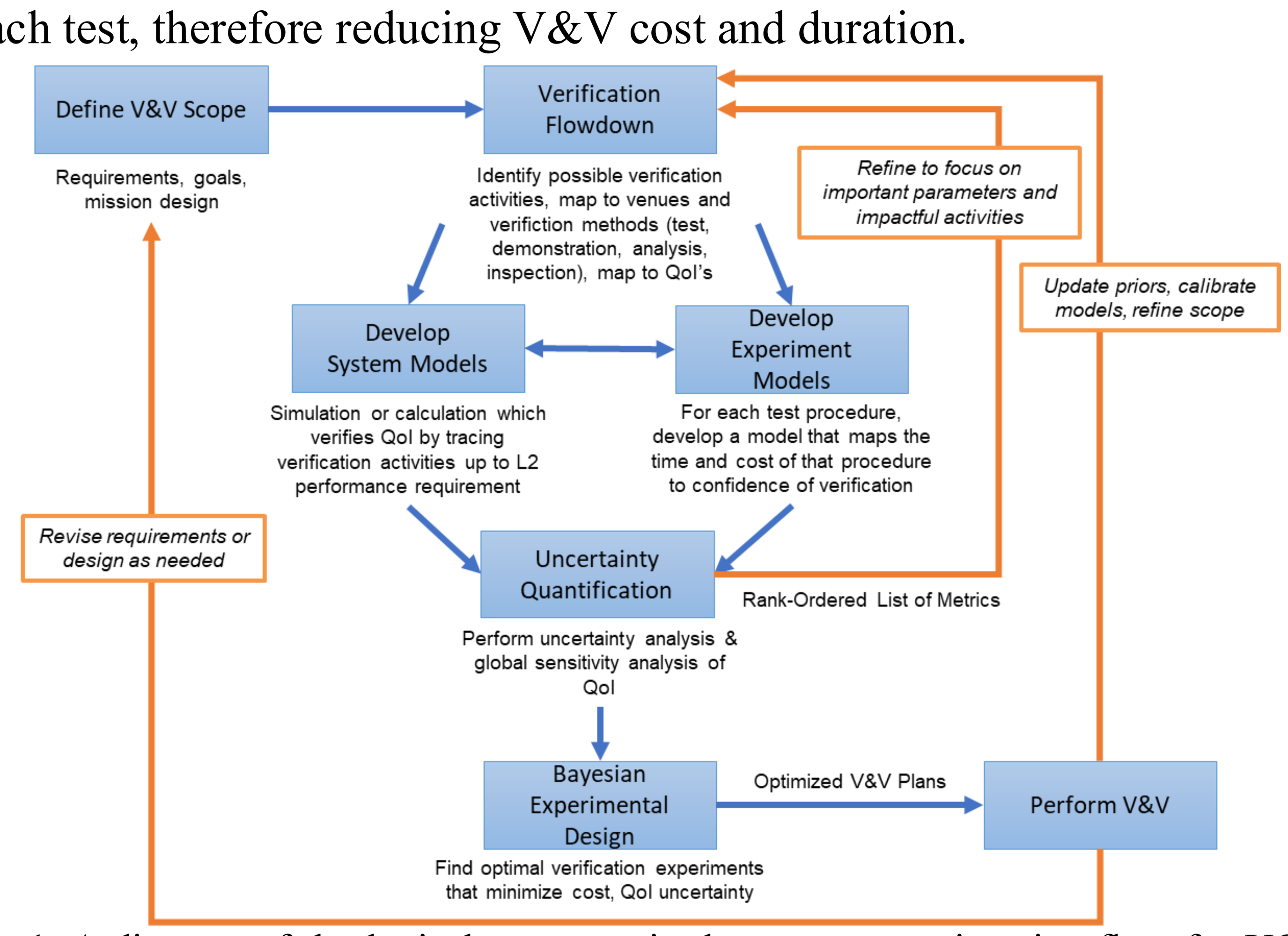

Figure 1. A diagram of the logical sequence in the systems engineering flow for UQVM. Experiment and system models are developed and are the basis for uncertainty quantification and verification optimization activities. The feedback mechanisms, indicated by orange arrows, enable iterative verification planning and optimized resource allocation, and are novel to this methodology.

- As proof of concept, UQVM was developed for the Large Lenslet Array Magellan Spectrograph (LLAMAS) instrument, a high-resolution integral field unit (IFU) instrument, designed to make spatially-resolved spectroscopic measurements of the sky.

Results:

- The key steps in this methodology are illustrated by results from the Performance Robustness Analysis (Figure 2) and Uncertainty Quantification implemented with the Kennedy-O'Hagan framework (Figure 3).

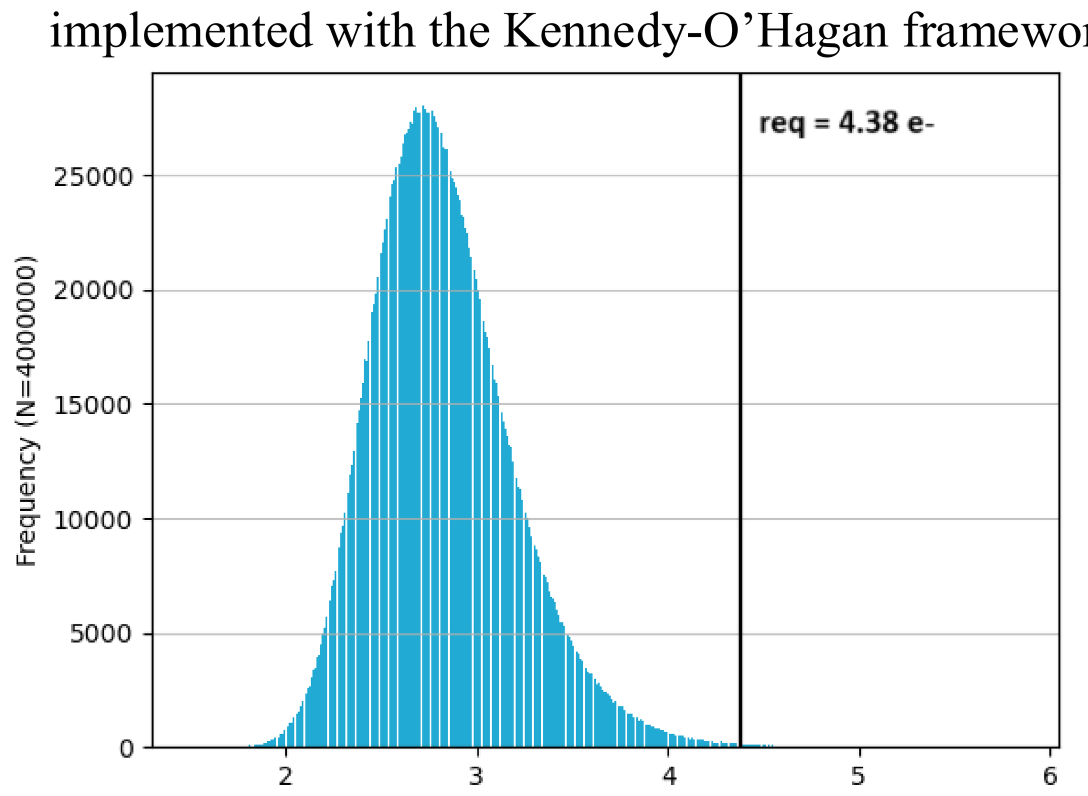

Figure 2. A diagram of performance robustness analysis for the LLAMAS case study. We define priors for the read noise, dark current, and gain, as Gamma distributions. Propagating this through system model gives us the prior probability of meeting the requirement $p(Q|\theta)$ = 99%. Through verification planning, the goal is to achieve lower variance in the QoI (average noise).

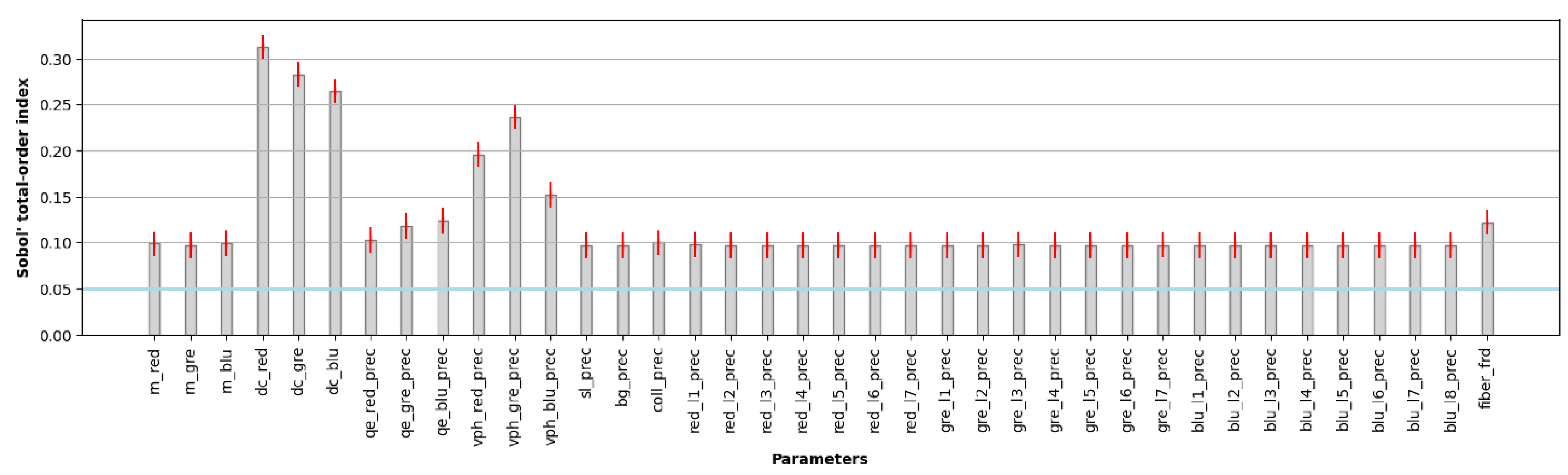

Figure 3. A diagram of global sensitivity analysis for the LLAMAS full-instrument study. Global sensitivity analysis measures how parameter uncertainty causes uncertainty in system performance, provides a qualitative assessment on prioritization of tests and enables us to reduce scope on the verification analysis to testing the most impactful parameters.

- The design space was defined, and optimal Bayesian experimental design (OBED) analysis was performed resulting in the Pareto front (Figure 4).
- The plot shows a range of potential verification plans which minimize both the cost of verification and the uncertainty of the estimated system performance. Here, we identify a design that is effectively globally optimal.
- If this optimal test plan had been used for LLAMAS instead of the historical plan, then 90% of testbed time could have been saved across the verification of all 24 focal plane units.

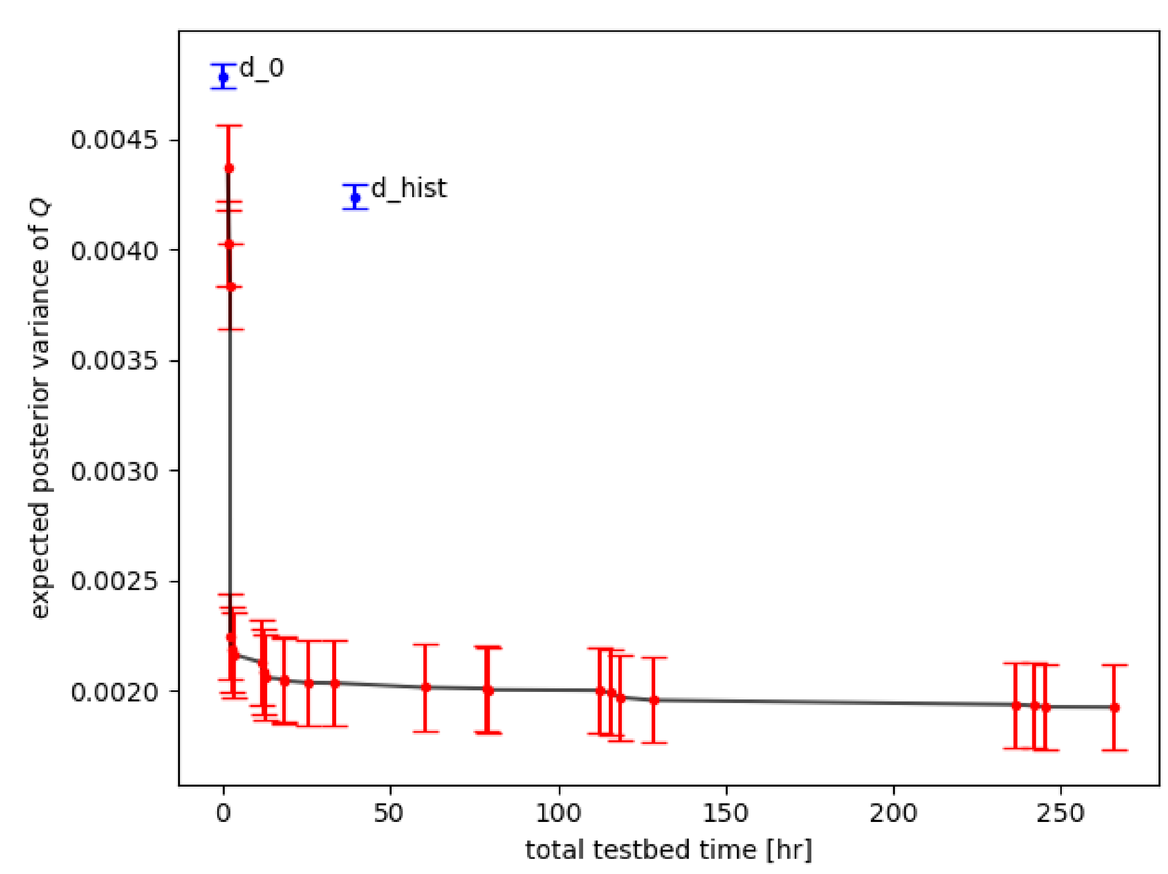

Figure 4. A diagram of pareto-optimal verification designs for the LLAMAS verification problem are plotted in red, with the optimal design noted in green. The historical verification plan is labeled with "d_hist" and several optimal plans achieve higher confidence in system performance while using less testbed time than the historical verification plan.

Significance to JPL and NASA:

This work is a significant milestone towards formalizing the use of integrated analysis tools for optimizing the I&T and V&V processes.

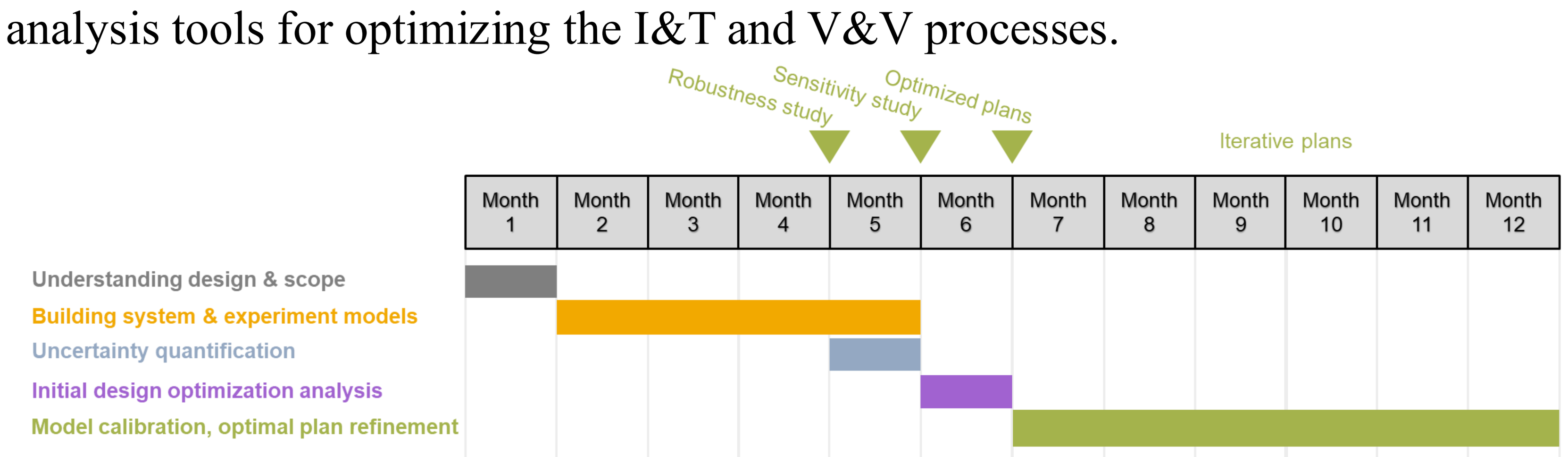

Figure 5. A Gantt chart showing what the first 12 months of applying UQVM to a flight project. UQVM can be implemented with 0.5 FTE building models and performing analysis in parallel with the project V&V effort. The duration of model development and initial analysis is estimated. Above the timeline are estimates of UQVM deliverables.

- The methodology connects measurement and model uncertainties with system-level metrics and provides a broader assessment of the design of V&V sequences, which will benefit a myriad of JPL flight projects by:
  - reducing cost and schedule overruns
  - informing early design phase error propagation, and science performance evaluation.

Publications:

J. Stenzel, R. Masterson, Y. Marzouk, A. Krishnamurthy, and M. Chodas, "Optimizing verification planning for uncertainty reduction using Bayesian design of experiments," in AIAA SCITECH 2024 Forum, American Institute of Aeronautics and Astronautics, 2024. doi: 10.2514/6.2024-1852.

J. Stenzel, "Verification Planning for Efficient Uncertainty Reduction of Space Science Systems," PhD Thesis, Massachusetts Institute of Technology, 2025.

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