FY24 Strategic University Research Partnership (SURP)

Integrating Uncertainty Quantification with Traditional Systems Engineering Practices

Principal Investigator: Akshata Krishnamurthy (314);
Co-Investigators: Mark Chodas (312), Bogdan Oaida (382),
Prof. Olivier de Weck (Massachusetts Institute of Technology),
June Stenzel (Massachusetts Institute of Technology)

Objectives:

- Develop a formal methodology that optimizes verification and validation (V&V) test activities, with respect to cost, duration and performance, through enhanced understanding of uncertainty.
  - The Uncertainty Quantification Verification Methodology (UQVM) will quantify margins and sensitivities, and attribute performance uncertainties to a rank order list of measurement and test metrics that will enable systems engineers (SEs) to continuously evaluate sources of uncertainty (such as measurement, test, model discretization, etc.) that impact instrument performance requirements, and perform rapid trade-offs during I&T.
  - As measured values become available, model-validated data with error bars will allow for performance optimization and agile risk posturing.
  - Further, Optimal Bayesian Experimental Design (OBED) methods will be used to optimize resource allocation during integration and testing.

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.).
- The V&V process is optimized by reducing the scope of each test to only that which is needed to achieve the necessary reduction in uncertainty for a system-level quantity of interest.
- The number of tests and/or the number of data points collected in each test can be significantly reduced, therefore reducing V&V cost and duration.
- The goal is to achieve a high level of certainty on a system-level quantity of interest (QoI) for minimum cost. Figure 1 shows a diagram of the proposed methodology.

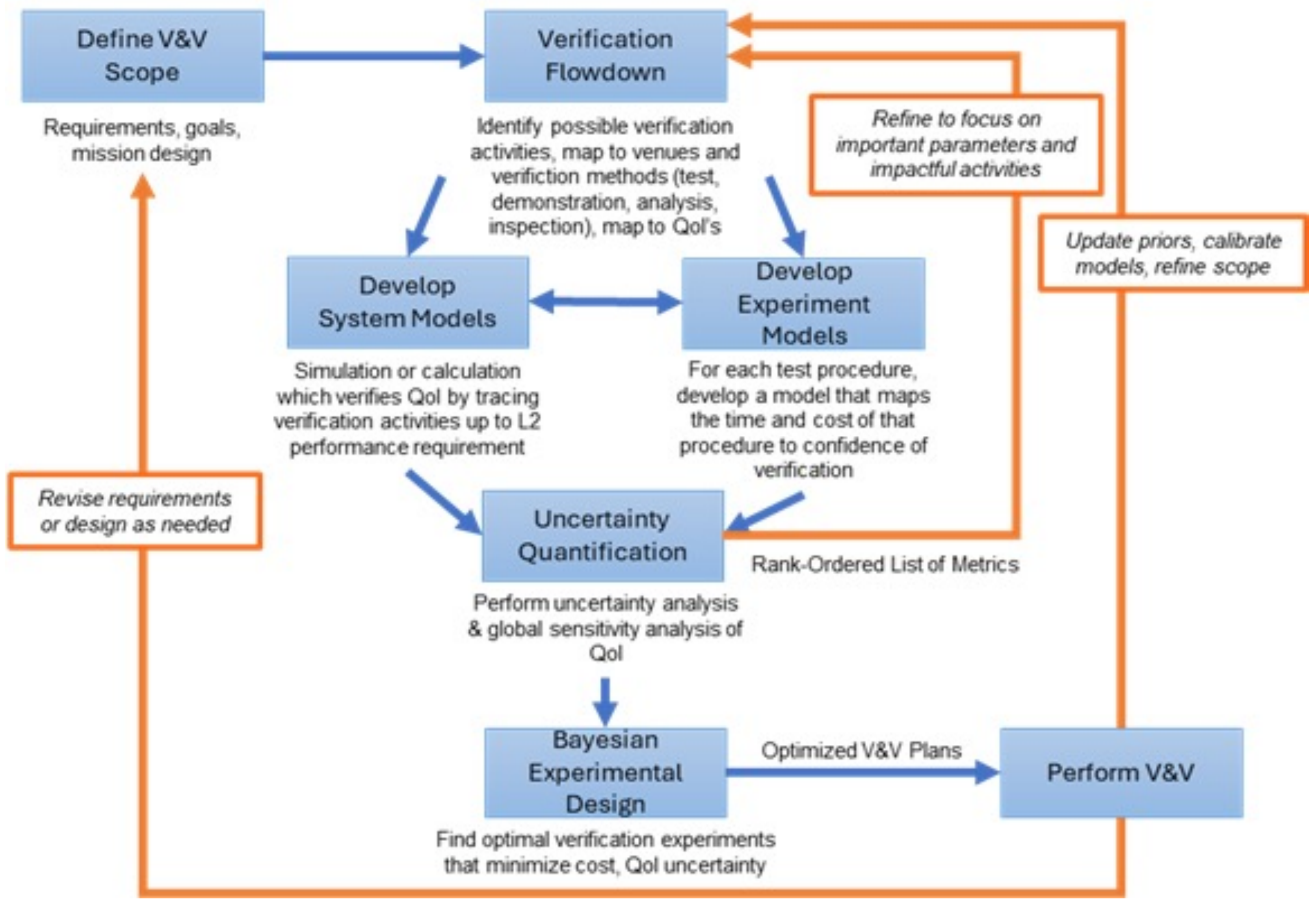

Figure 1. A diagram of the logical sequence in the systems engineering flow for UQVM. Experiment and system models are developed and are the basis for uncertainty quantification and verification optimization activities. The feedback mechanisms, indicated by orange arrows, enable iterative verification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

To determine and perform optimal verification plans under uncertainty, two kinds of data products must be generated: a "high-level system model" that determines how the results of lower-level verification activities provide knowledge about the QoI, and stochastic "experiment models" for each verification activity, which relate the uncertainty of a test result with the time and cost of the test.

Results:

Verification planning for the CCD components of the LLAMAS instrument serves as a proof of concept for the framework.

For the CCD problem, system and experiment models were created, and uncertainty quantification was performed with the Kennedy-O'Hagan framework The design space was defined and explored, and the OBED analysis resulted in the Pareto front in Figure 2.

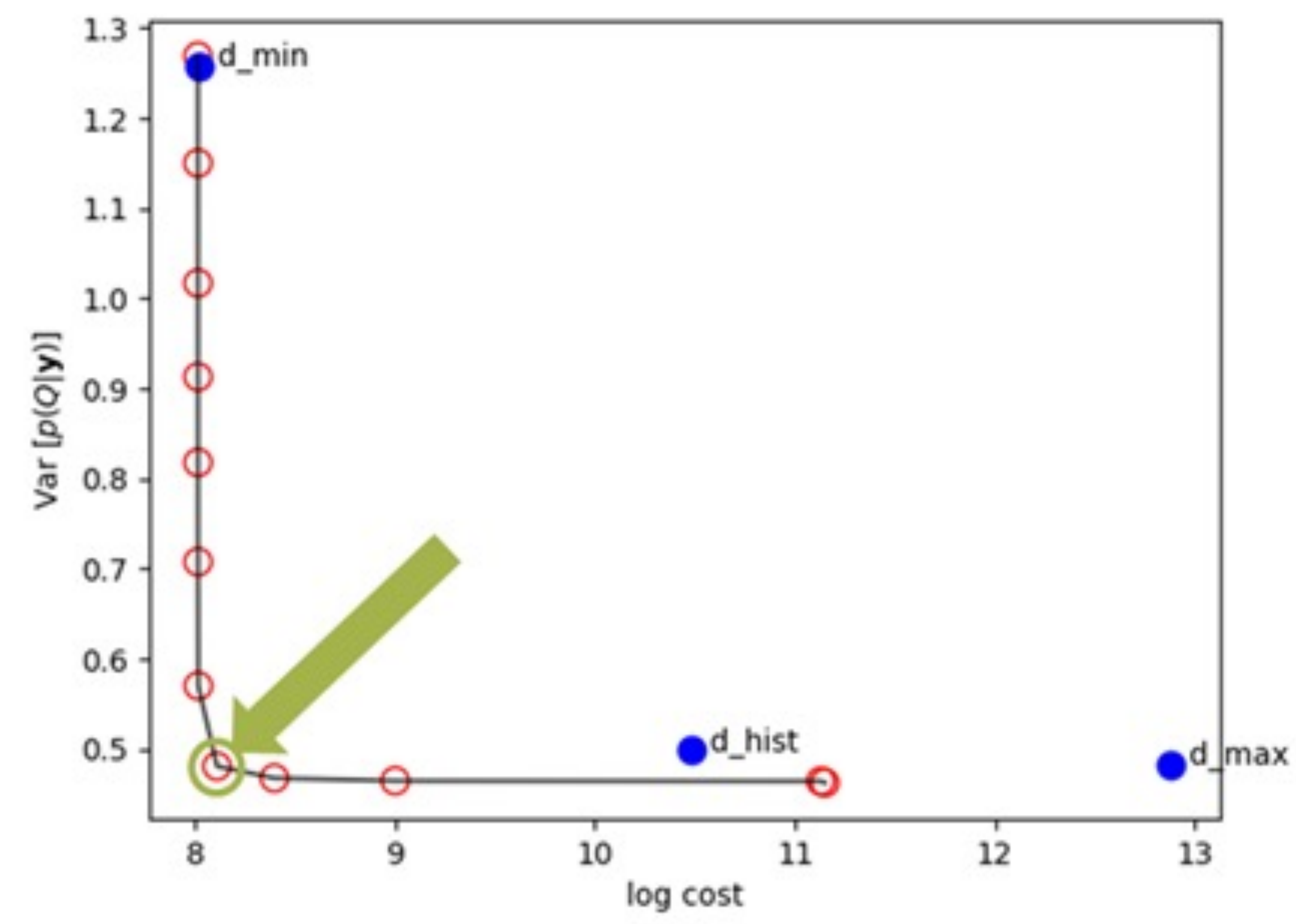

Figure 2. Pareto-optimal verification designs for the CCD toy problem are plotted in red, with the optimal design noted in green. The historical verification plan is labeled with "$\mathbf{d}_{hist}$" and is dominated by several of the optimal designs.

The plot shows a range of potential verification plans which minimize both the cost of verification and the uncertainty of the estimated system performance. In this set, we identify a design that is effectively globally optimal.

If the optimal test plan had been used for LLAMAS instead of the historical plan, then as much as **90% of testbed time** could have been saved across the verification of all 24 focal plane units, with less uncertainty.
Following the success of this work, the methodology is beginning to be implemented for the full LLAMAS system.

Significance to JPL and NASA:

The V&V optimization methodology proposed in this research can significantly reduce overruns of cost and schedule during I&T and V&V on flight projects at JPL.

A white paper exploring implementation of the verification planning methodology on JPL flight projects is now being developed.

- Several retrospective case studies are examined, based on existing UQ implementations at JPL and input from JPL experts.
- One case study shows how the verification planning methodology improves uncertainty models and L1 science estimation for Europa Clipper.
- Another case study shows how the methodology could integrate with and offer improvements on optical tolerancing methods for spectroscopy instruments such as EMIT.

National Aeronautics and Space Administration

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

www.nasa.gov

RPD-000 Clearance Number: CL#00-0000

Publications:

Stenzel, J., Masterson, R., Marzouk, Y., Krishnamurthy, A. and Chodas, M., 2024. Optimizing verification planning for uncertainty reduction using Bayesian design of experiments. In *AIAA SCITECH 2024 Forum* (p. 1852).

PI/Task Mgr. Contact Information:

akshata.krishnamurthy@jpl.nasa.gov
(818) 928-9881