National Aeronautics and Space Administration

FY23 Strategic University Research Partnership (SURP)

Integrating Uncertainty Quantification with Traditional Systems Engineering Practices

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Objectives:
The research effort seeks to advance and integrate state-of-the-art uncertainty quantification and propagation methods with traditional systems engineering practices. There currently exists no formal methodology that optimizes the design of integration and test (I&T) and verification and validation (V&V) sequences with respect to cost, duration and instrument performance. This research will benefit JPL by providing a methodology for designing lower cost, lesser duration and more informative level three (L3) instrument V&V campaigns, through enhanced understanding of uncertainty.

The framework 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 instrument performance optimization and agile risk posturing. Further, Bayesian experimental design methods will be used to optimize resource allocation during integration and testing. The framework is demonstrated and scoped for MIT's Large Lenslet Array Magellan Spectrograph (LLAMAS).

Background:
As space missions grow in ambition and complexity, we will need better practices and methods for understanding uncertainty in complex systems in order to verify performance requirements and satisfy science goals. JPL is making advances in incorporating uncertainty into systems engineering high-level decision-making, and the Space Systems Lab at MIT has used Bayesian techniques to optimize some aspects of systems engineering. These advances have not yet fully linked experimental design, model fidelity, instrument performance metrics, and top-level science objectives with the overall I&T process.

Approach and Results:
This work is aimed at planning and carrying out verification in order to ensure an appropriate level of certainty on a system-level quantity of interest (QoI) for the minimum cost, prior to high-level validation. Figure 1 shows a generic system verification flowdown; for the CCD system, the verification activities are considered to be laboratory experiments that constrain quantities such as read noise and dark current, and the QoI is the total noise of the CCD. Figure 2 elaborates on how we will integrate uncertainty quantification and Bayesian experimental design methods with the existing I&T and V&V processes. Generally, once the V&V scope has been defined and the verification flowdown has been outlined, it remains to generate optimized V&V plans. To this end, 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 relates the uncertainty of a test result with the time and cost of the test.

For the CCD problem, system and experiment models were created, and uncertainty quantification was performed with the Kennedy-O'Hagan framework. In this analysis, parameter priors were defined based on historical data, and sensitivity analysis was used in order to scope the verification problem. The UQ analysis showed that, before any testing is done, there is only a 56% probability a priori that the system meets the requirement on the QoI, as seen in Figure 3. Optimal Bayesian experimental design (OBED) methods were used to calculate the utility of the historical design, with a utility function that minimizes the variance in the QoI and the total cost of verification.

Significance/Benefits to JPL and NASA:
In recent years, JPL has increasingly identified the importance of instrument systems engineering (SE), and the need for integrating uncertainty quantification efforts with the V&V process. UQ communities of practice are forming within the ESD to try to cultivate the skills needed to perform effective UQ for instrument SE. JPL efforts have, thus far, focused on UQ for (L1) science conclusions in-flight. Funding research into the proposed systems engineering framework development, especially as it relates to connecting measurement and model uncertainties with system-level instrument performance metrics and a broader assessment of the design of V&V sequences, will benefit a myriad of JPL flight projects as well as inform early design phase error propagation, and instrument performance evaluation. The V&V optimization methodology proposed in this research can reduce overruns of cost and schedule for V&V at JPL.

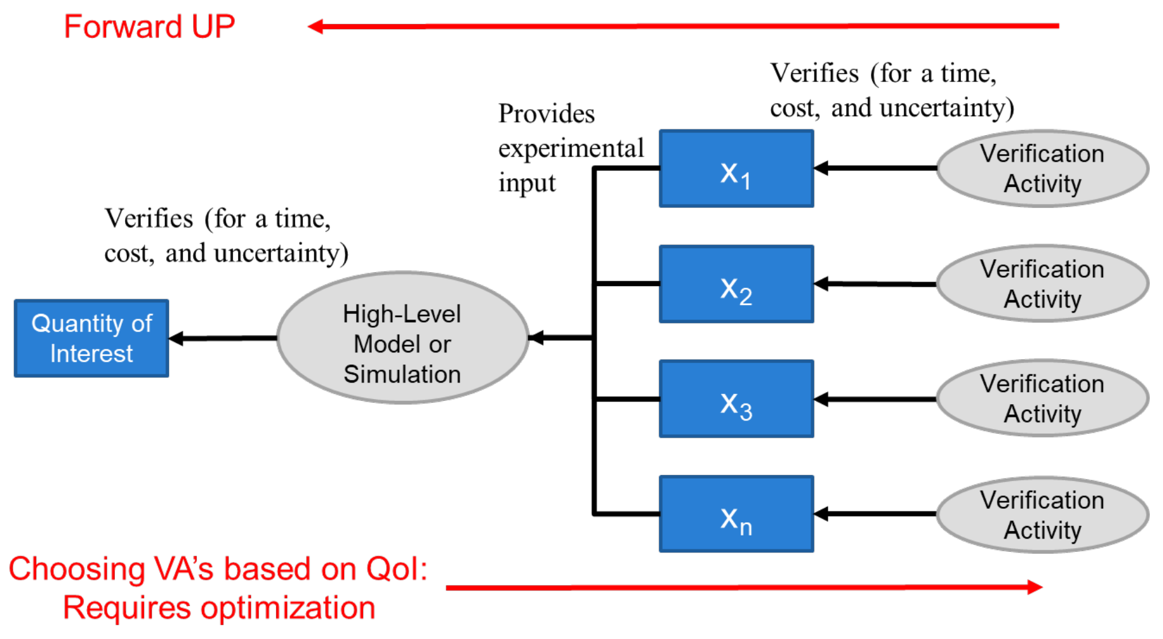

Figure 1. This is a diagram of a generic verification flowdown. This model takes in values for parameters of the system, which are the result of measurements or estimates from verification activities.

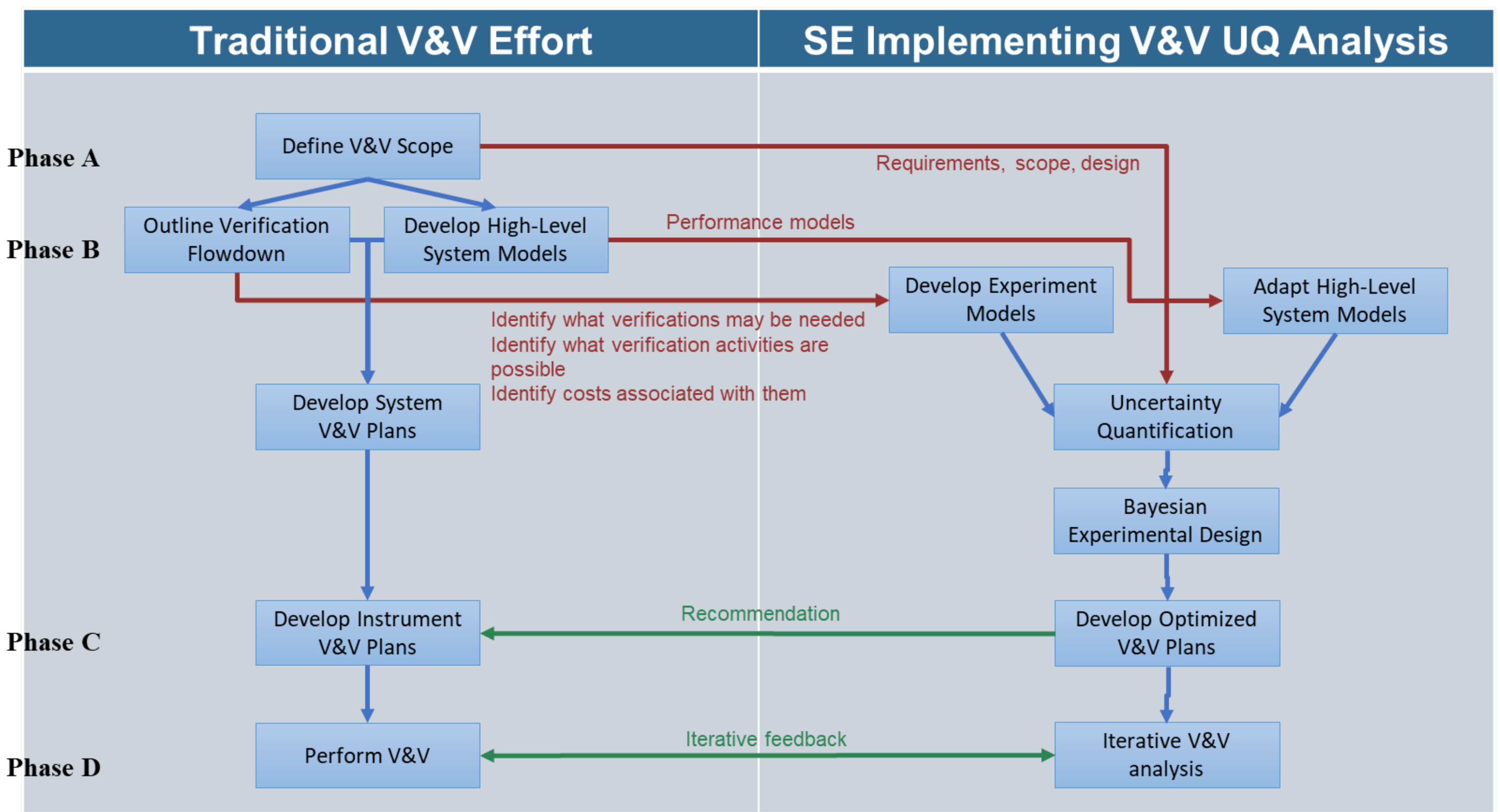

Figure 2. This is a flowchart showing how the verification optimization framework, including uncertainty quantification and Bayesian methods, can be integrated with a traditional V&V effort for a science instrument. For this method, the key up-front implementation costs are in developing experiment models and adapting the system model for use in the OBED algorithm.

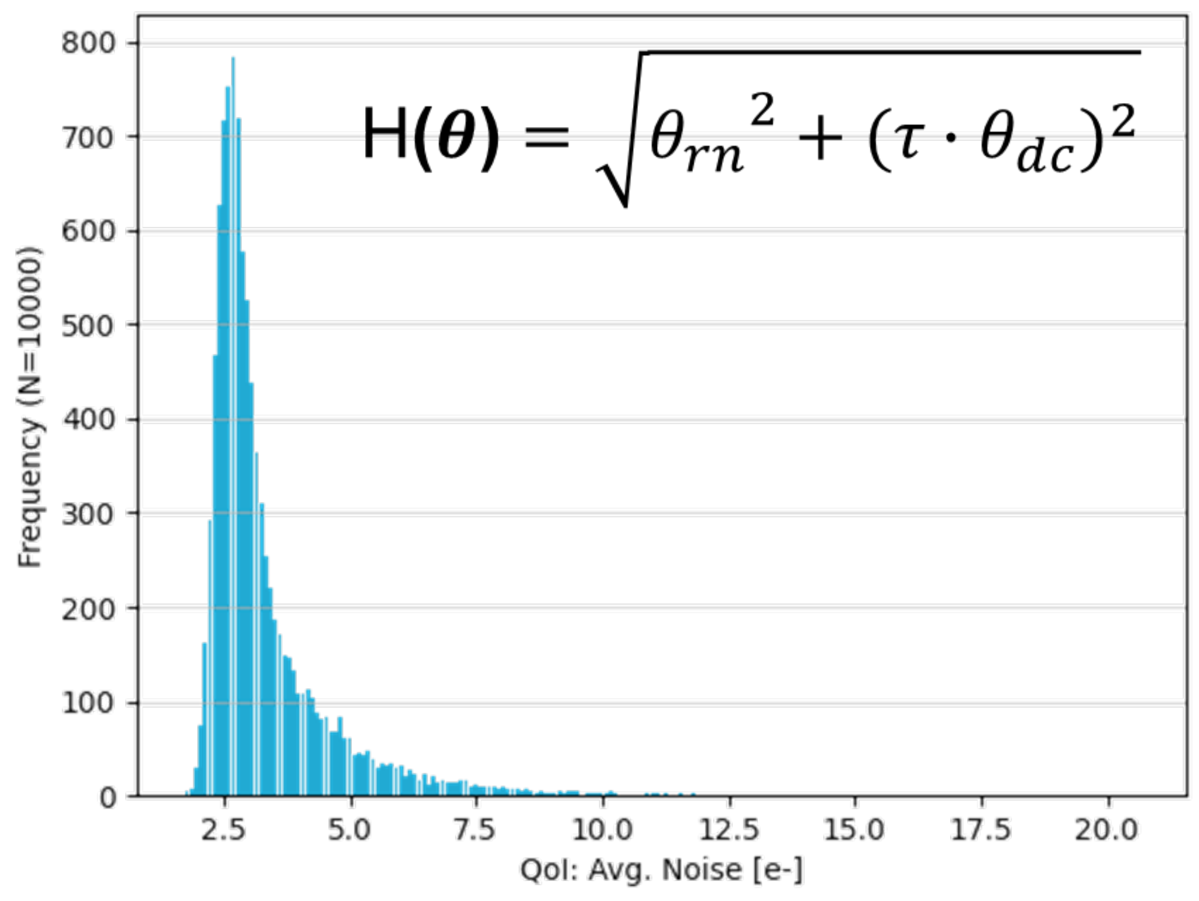

Figure 3. This figure shows the result of an a priori uncertainty propagation for the performance of the CCD. The system model is shown in the upper right; total intrinsic noise is the QoI, and in this model, read noise and dark current are the key contributors.

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Clearance Number: CL#00-0000
Poster Number: RPC#

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