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SPACE LAUNCH SYSTEM

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**HARDWARE VERIFICATION AND VALIDATION FOR A
NAVIGATION SENSOR SOFTWARE MODEL IN SUPPORT OF
FLIGHT VEHICLE PERFORMANCE ANALYSIS**

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- **SLS SE&I Model Based Design**

- building off of *SLS Model Based Design: A Navigation Perspective* (Oliver, Anzalone, Park, Geohagan, AAS 18-131)
- example: GN&C Model Development & Integration

- **Navigation Sensor Model Development & Verification**

- Input data sources
- Component sub-models
- Verification activities
- Interface-level requirements

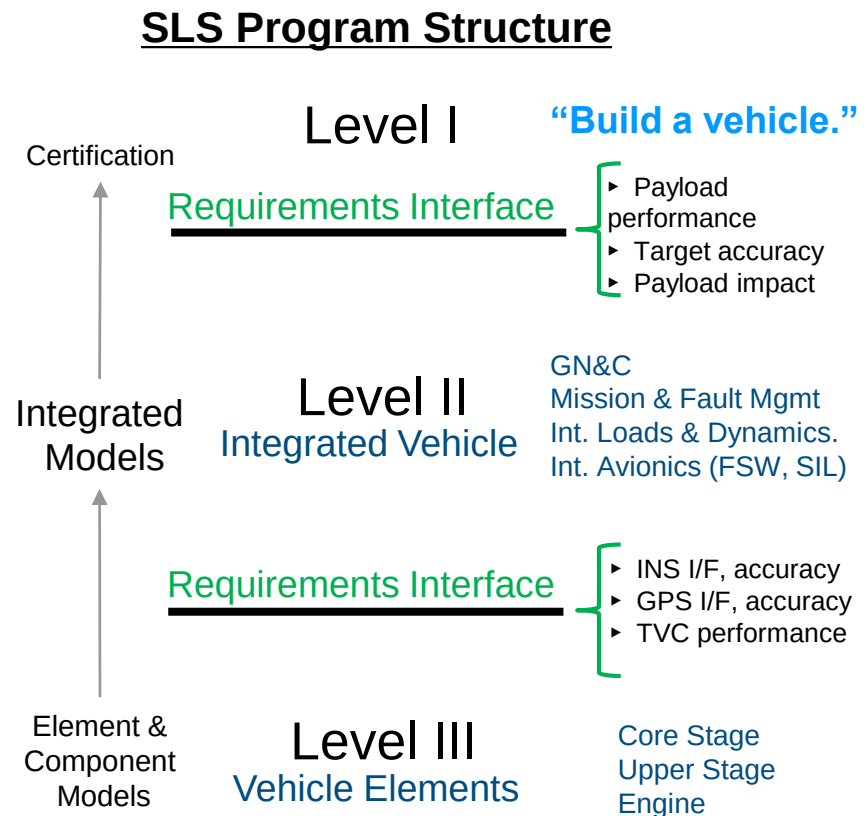
- **Model Validation Testing Highlights**

- Gyro-compassing
- Static Analysis
- Frequency Response
- Latency Testing
- Software- and Hardware-in-the-Loop Validation

- **Lessons Learned/Conclusions**

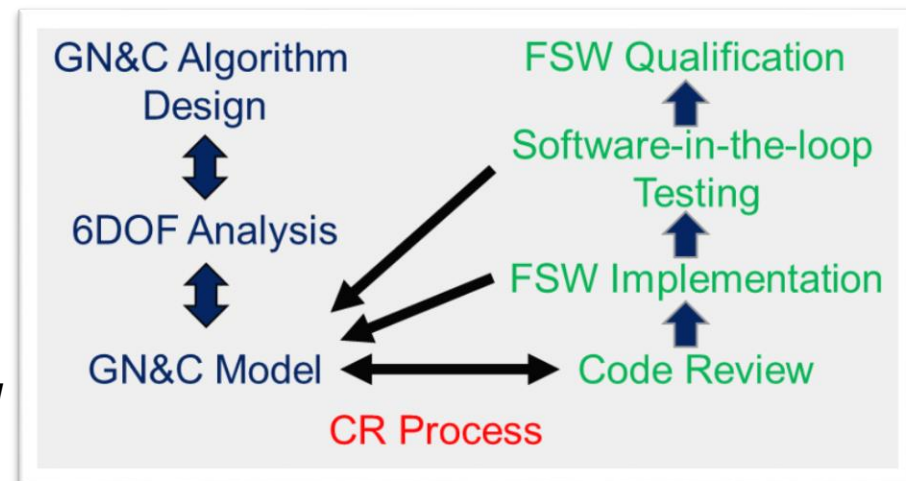
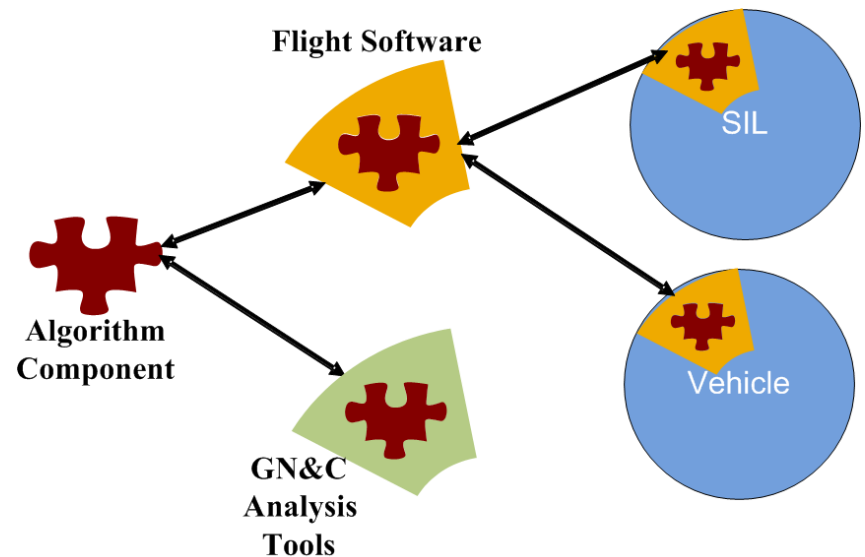
SLS SE&I Model Based Design

- **Reduce requirements management effort (decomposition & verification) when using heritage hardware**
 - Effort better spent on characterizing hardware
 - Specify requirements at the interface level
- **Design Math Models (DMM) convey the design of a sub-system/component:**
 - Captures the physics/logic of the component
 - Delivered with unit tests to ensure integration in desired framework
 - Controlled at the Program level
- **DMMs should be developed according to specific processes as well as:**
 - Verified---is the implementation correct?
 - Validated---does the model output correlate to hardware performance



Example: GN&C Implementation of MBD Processes

- **Heritage programs used documentation to describe GNC algorithms to FSW team**
 - Test cases included to verify functionality
- **MBD began as pilot program in 2010**
 - Working towards efficient GNC and FSW Process
- **DMM Contents**
 - Executable Algorithms
 - Parameter Definition
 - Technical Memorandum
 - Interface assumptions
 - Unit test cases
- **GNC Model**
 - Pulled directly from simulation architecture
 - Direct tie to performance results
 - Captures implementation of design
 - Includes unit test functionality and hardware testing
- **Detailed CR Process for integration with FSW and internal development**



Navigation Models and Initial Verification

- **Input Products from Supplier**

- Software Design Documentation
- Error Budgets / Capability Estimates
- Subsystem Requirements
- Minutes/Actions from TIMs
- Acceptance/Qual test data

- **Sub-models in INS Model:**

- Chassis & isolators
- Sensor error
- Latency/delay
- Dynamic compensation
- Anti-Aliasing Filter
- FDIR
- Inertial Navigation

- **Verification Activities**

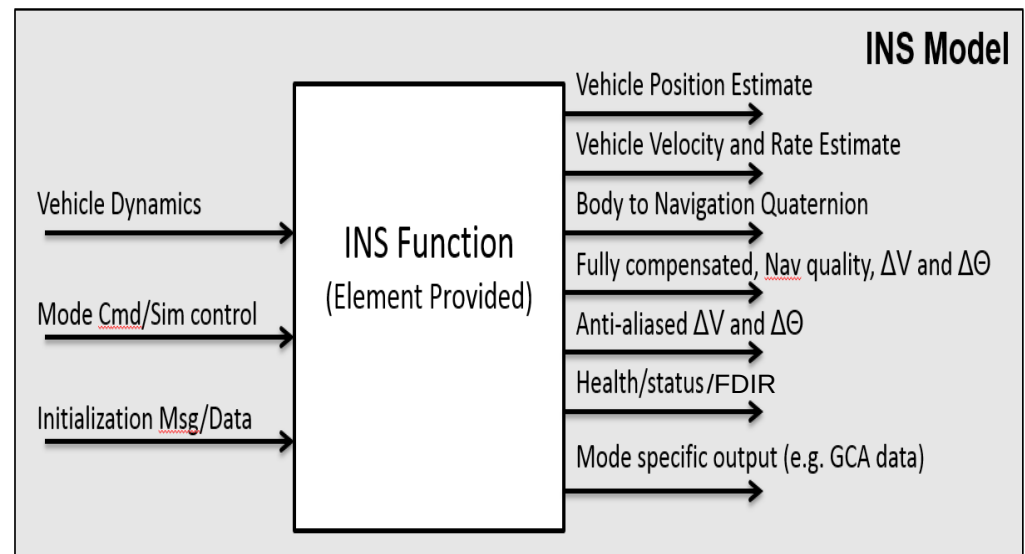
- Code review and Inspection
- Shoot-outs using vendor data
- Sensitivity analysis
- Monte Carlo analysis
- Schuler test

- **Requirements on RINU model**

- Measurement frequency (output rates)
- GCA accuracy w/prescribed Pad dynamics
- Navigation accuracy over a reference trajectory
- Frequency response of ΔV & $\Delta \theta$
- Latency of ΔV & $\Delta \theta$ as well as nav. state estimate
- Redundancy Management/Fault Tolerance

- **Requirements on RGA Model**

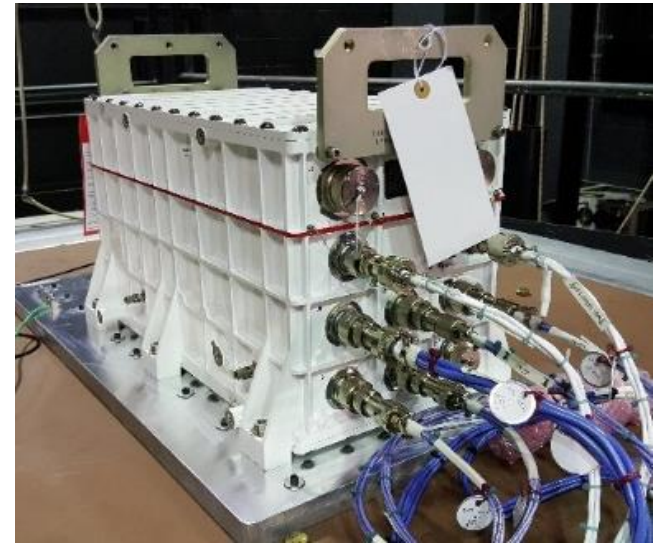
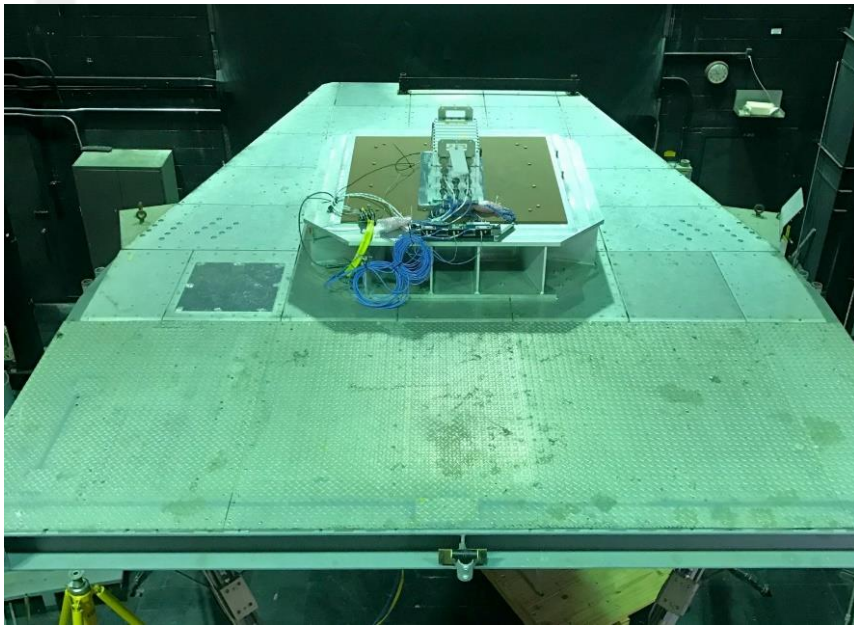
- Similar to RINU $\Delta \theta$ requirements



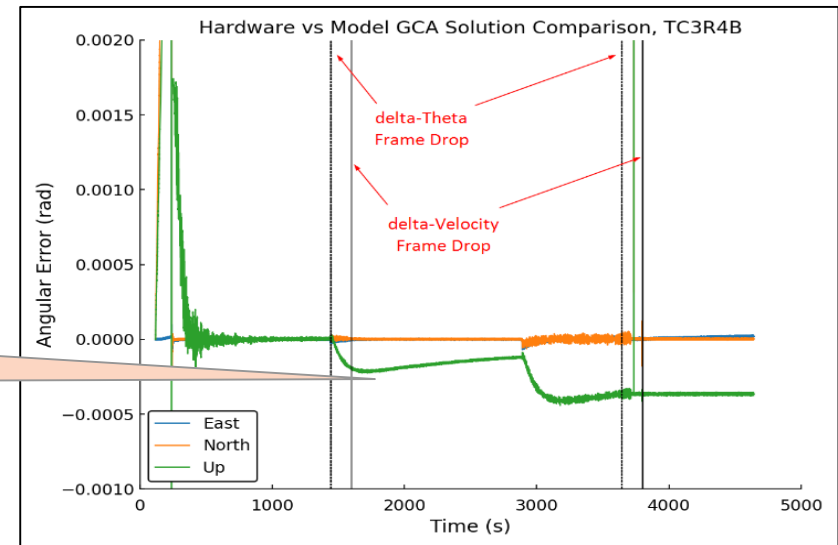
Model Validation with Hardware: Gyrocompassing Alignment

- **GCA Testing:**

- Simulated pad motion with 6-DOF table
- Validate GCA performance of model with same input dynamics
- Demonstrated robustness of GCA by increasing dynamic inputs



Effects with asynchronous sampling /
skipped samples when processing HW
output through model

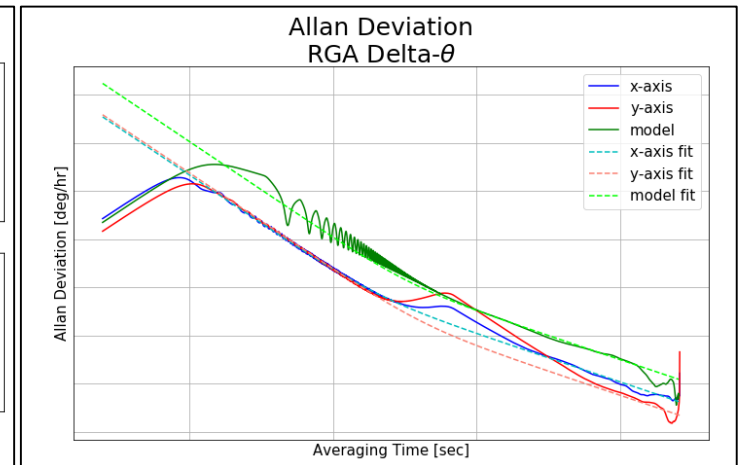
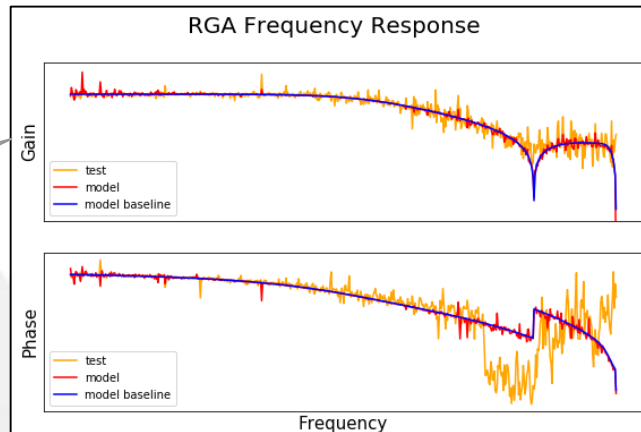


Model Validation with Hardware: Freq. Response & Static Testing

- **In-House Frequency Response Testing**
 - Linear shakers attached to mounting fixtures
 - “Truth” dynamics recorded by combination of LVDTs and accels
 - Recording HW output to validate FRF
 - Fed “truth” dynamics into models and compared frequency response to HW reconstruction
- **Noise Model Validation: Static Testing**
 - Performed static “flat floor” testing for ~ 48 hours
 - Characterized observed noise sources via Alan Variation
 - Validated model errors bounded HW performance



Difficulty in
reconstructing FRF for
low-frequency domain.

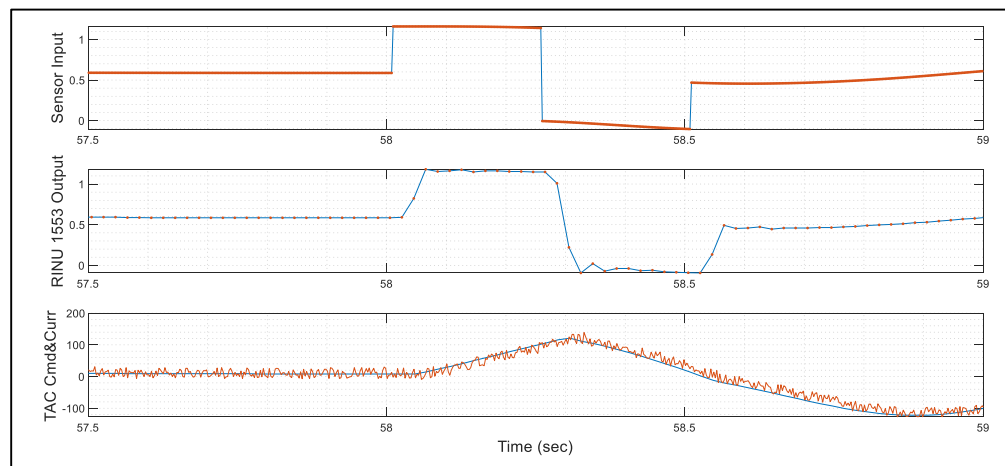


- **Modeled sensor quantization levels different than HW**
- **Developed additional noise models to account for residual dithering effects**
- **Hi-fidelity validation of performance model vs. hardware**

Latency & HWIL Testing Comparisons

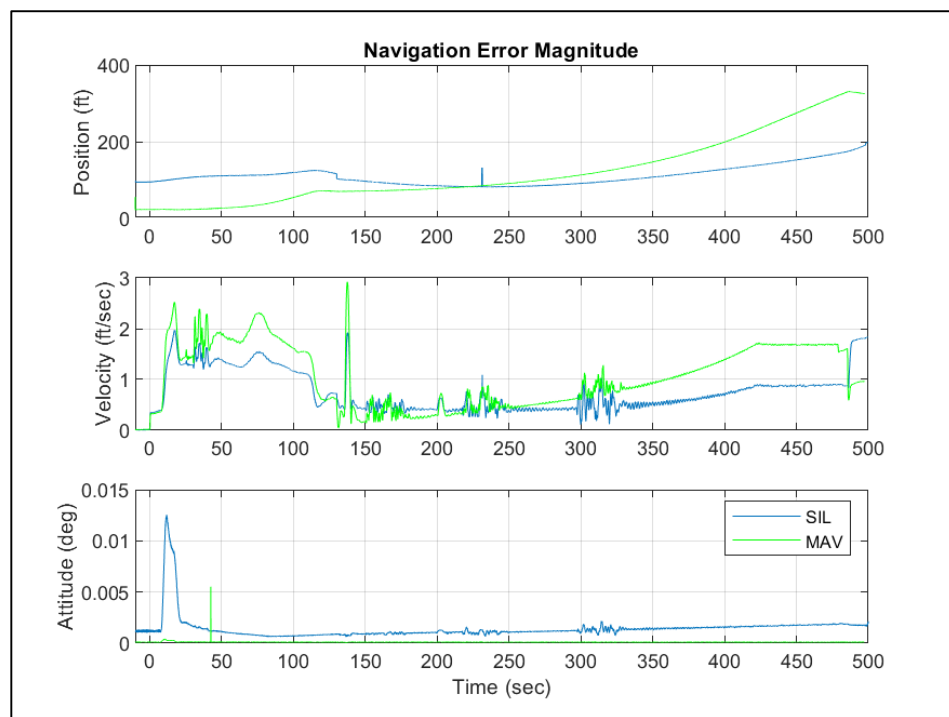
- **Latency Testing**

- Input known disturbances during nominal fly-out
- Measured time to response from sensors through avionics to actuators
- Validated models and predicted latencies



- **Software/Hardware-in-the-Loop comparisons**

- Assessed vehicle performance from integrated models & HW (SIL) vs. MAVERIC 6DOF results
- Utilized RINU EDU with simulated input data
- Characterized independent plant models and SW effects



- **Evaluation of actual sensor & avionics hardware resulted in understanding of time synchronization, asynchronous behavior, and latency/delay interactions.**
- **Interaction of HWIL simulation models, actual hardware, and Flight Software verified multiple layers of data interfaces.**
- **Validated latencies & delays that are critical for control stability and orbit insertion accuracy.**

Conclusions & Lessons Learned

- **Availability of vendor documentation enabled development of detailed nav sensor models and their verification**
 - Required programmatic support to integrate with suppliers
- **Process of validating model to hardware gave GN&C team high levels of insight:**
 - Sensor performance
 - Redundancy & fault management
 - Flight operations
- **Validation testing demonstrated model-to-hardware correlation in high interest areas critical to mission success:**
 - High sensitivity of insertion accuracy to gyro-compassing performance
 - Impacts of latency and frequency-based noise to actuator control
 - Impacts of sensor error characteristics on fault detection logic

The collection of high-fidelity validation activities has significantly increased our confidence in the expected performance of the SLS Vehicle for flight certification

THANK YOU!

