6DOF TESTING OF THE SLS INERTIAL NAVIGATION UNIT

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The Navigation System on the NASA Space Launch System (SLS) Block 1 vehicle performs initial alignment of the Inertial Navigation System (INS) navigation frame through gyrocompass alignment (GCA). In lieu of direct testing of GCA accuracy in support of requirement verification, the SLS Navigation Team proposed and conducted an engineering test to, among other things, validate the GCA performance and overall behavior of the SLS INS model through comparison with test data.

This paper will detail dynamic hardware testing of the SLS INS, conducted by the SLS Navigation Team at Marshall Space Flight Center's 6DOF Table Facility, in support of GCA performance characterization and INS model validation. A 6-DOF motion platform was used to produce 6DOF pad twist and sway dynamics while a simulated SLS flight computer communicated with the INS. Tests conducted include an evaluation of GCA algorithm robustness to increasingly dynamic pad environments, an examination of GCA algorithm stability and accuracy over long durations, and a long-duration static test to gather enough data for Allan Variance analysis. Test setup, execution, and data analysis will be discussed, including analysis performed in support of SLS INS model validation.

INTRODUCTION

The RINU is an internally-redundant strapdown inertial navigation unit. Its design is a derivative of the Fault-Tolerant Inertial Navigation Unit (FTINU) used on the Atlas family of launch vehicles. It is equipped with 5 accelerometers and 5 ring-laser gyros whose sense axes mutually overlap to provide redundancy. In addition to inertial navigation, the RINU performs on-board coning and sculling compensation; bias/scale factor compensation; size-effect compensation; anti-aliasing; fault detection, isolation, and recovery (FDIR); and gyrocompass alignment (GCA).

A test was planned and developed to provide insight into RINU GCA performance, both for model validation purposes and to increase confidence in and knowledge of RINU GCA capability. The objectives of the test were: (1) to gain insight into gyrocompassing performance of a flight-like RINU under representative SLS on-pad dynamics, (2) to provide gyrocompassing test

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data for validation of the RINU performance model, (3) to assess feasibility of planned pre-launch RINU operational procedures, and (4) to assess the robustness of the RINU GCA algorithm to larger-than-predicted SLS on-pad dynamic environments.

While the RINU 6-DOF test provides opportunities to analyze the execution of each of the RINU's operational functions, inertial navigation and gyrocompass alignment (GCA) are of specific interest due to their direct impact on SLS program requirements. Gyrocompass alignment (GCA) is the process of aligning the navigation frame with the Earth by sensing the directions of the gravity vector and the Earth's rotation rate. In a pure inertial navigation system, the initial attitude error is a major contributor to navigation error—for the SLS Block 1 vehicle, this is the primary contributor to orbital insertion error. Objective 1 above reflects the desire to have a test-based confidence that RINU GCA performance meets requirements. Objective 4 reflects the further desire to ensure that RINU GCA capability is robust to potential unknowns in the SLS on-pad dynamic environment.

A key component of the Design-Analysis Cycle (DAC) and Verification-Analysis Cycle (VAC) processes by which the SLS GN&C design is evaluated relative to requirements is a SLS Stages-developed RINU performance model (DMM-CS-0411). DMM-CS-0411 must be declared a verified and validated model for use in analysis to close SLS Program Design Verification Objectives (DVOs)—herein, it shall be referred to as simply the RINU performance model or RINU model. The "validated" designation requires comparison with test data produced by the actual hardware—RINU 6-DOF test objective 2 above reflects the test's focus on producing the required data. Objective 3 above refers to gathering test-based insight into RINU operational procedures as well as performing operational testing of flight software (FSW) algorithms to the extent possible. Objective 4 reflects the desire for a GCA solution robust to unexpectedly large pad dynamics, and ultimately, the desire to test and characterize the limitations of the RINU's GCA capabilities.

TEST FACILITY, EQUIPMENT, AND TEST CASE DEFINITION

RINU 6-DOF test planning and facility preparation was conducted over a period of 2 years. Test activity was planned to consist of GCA and navigation through various flight-like as well as notional stressing pad dynamics environments. The test article was a flight equivalent unit (FEU), meaning its hardware is identical to the flight units but that it does not undergo full acceptance testing (shock, thermal, and vibration testing are omitted). This unit is program-critical hardware.

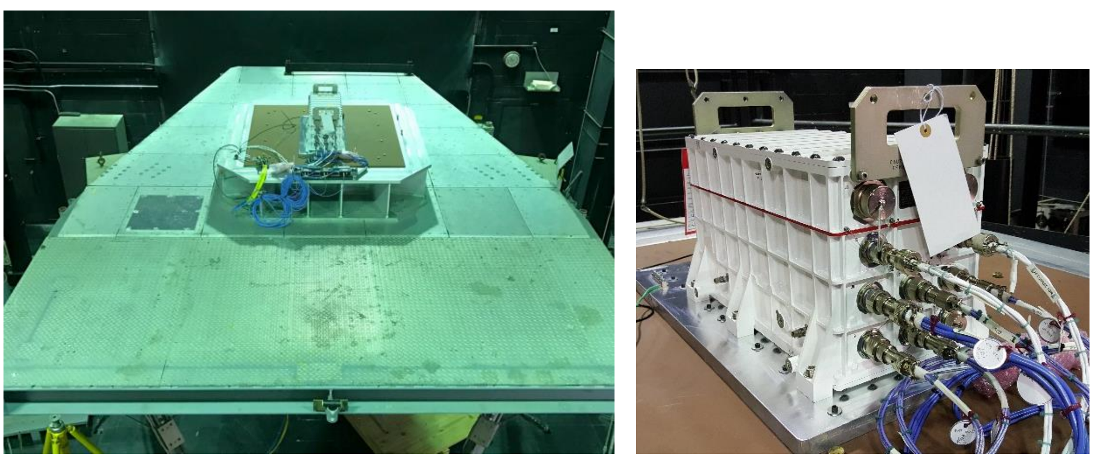

Figure 1. RINU and 6DOF Table (Left), Closeup View of Integrated RINU (Right)

The test was performed in the Marshall Space Flight Center Six Degree-of-Freedom (6-DOF) Table Facility in building 4663. The facility consists of a control room, 6-DOF table room and hydraulics room. The facility includes:

Table 1. Test Facility Equipment

1.	A six degree-of-freedom table with associated hydraulics system
2.	A table control cabinet that allows interfacing for control of the 6-DOF table, reading of its motion measurements, and monitoring of its safety discrete
3.	A monitoring system for the status of the table hydraulics
4.	Cameras, camera controllers, and displays for viewing in the control room of the test article on the 6-DOF table from the control room
5.	Uninterruptible power supplies for test equipment

A generalized concept of operation for a given test case is as follows:

Table 2. Test Operational Flow

1.	HWIL software, table control/hydraulics, data recorder and monitoring devices are powered on and confirmed to be operating normally.
2.	The RINU is powered on (and allowed to come to thermal equilibrium).
3.	The RINU is initialized.
4.	Table dynamics are initiated.
5.	The RINU is moded to GCA and allowed to gyrocompass for 60 minutes.
6.	The RINU is moded to navigation mode.
7.	Table dynamics end, the table is lowered and powered off.
8.	The RINU attitude is measured via theodolite.
9.	The RINU is powered off, the test ends.

Test cases were developed to address the aforementioned objectives of the test. These are detailed in Table 3 below.

Table 3. Test Case Descriptions

Number	Name	Description
1	Preliminary Testing	Static GCA only; no nav
2	Baseline GCA	Static GCA with nav
3	Dispersed Twist & Sway	3 dynamic twist & sway models: 1. SLS VAC-1 (latest model) 2. SLS DAC-2 (RINU vendor baseline) 3. RINU vendor heritage software-test profile
4	GCA Robustness Testing	5 dynamic test cases derived from SLS VAC-1 model—scaled up by: 1. 4X 2. 8X 3. 16X 4. 32X 5. 64X
5	24-Hour Static	24-hour static GCA
6	7-Hour GCA	7-hour dynamic GCA with SLS VAC-1 twist & sway model

The vendor-heritage profile listed as twist and sway model 3 under test case 3 is detailed in Reference 1—it is used to verify GCA performance in RINU software qualification. Like the others, it was included to provide a hardware-tested comparison against modeled GCA performance under modeled environments. The 24-hour static case, listed as test case number 5, was included to enable a noise-characterization analysis to be performed. The 7-hour case, listed as test case number 6, was included to verify that the RINU GCA algorithm stability over a large time period; the duration was determined by an operational limit. The tests listed in Table 3 were executed over the course of 23 days from March 21, 2017 to April 12, 2017.

TEST DATA ANALYSIS

To achieve the aforementioned test objectives, 3 analyses were performed using the resulting data. These are as follows:

1. Sensor bypass – an analysis was conducted in which the delta-Theta and delta-Velocity measurements going to the RINU GCA algorithm were input into the corresponding portion of the RINU performance model. The resulting attitude was compared to that reported by RINU during the test.
2. GCA robustness – a robustness study was conducted in which the different twist & sway models from test case number 3 and scaled-pad-dynamics cases from test case number 4

were simulated in a Monte Carlo analysis, and compared to the as-tested resulting azimuthal errors.

3. Noise characterization – an analysis was conducted to examine the RINU's instrument noise characteristics. This was performed as a part of the effort to validate the RINU performance model.

Sensor Bypass Analysis

Due to the lack of a reliable source of truth dynamics data (and limited insight into the RINU internal sensor errors), an analysis was conceived by which the inertial sensing portion of the RINU hardware could be bypassed, allowing comparisons between the navigation and GCA portion and the corresponding RINU performance model components. The purpose of this approach is to provide specific validation insight for the gyrocompass alignment and navigation algorithm portions of the RINU model.

This analysis depends upon the RINU-reported coning/sculling/size-effect–compensated delta-Velocity and delta-Theta inputs to RINU's on-board gyrocompass alignment and navigation algorithms. The RINU messages on which these are reported each contain a current 100 Hz sample and a buffered previous 100 Hz sample, such that collecting them at 50 Hz will nominally produce a full record of the 100 Hz data input to the RINU GCA algorithm. However, because of the lack of synchronization between the RINU and the SLS flight computer/flight software model commanding RINU data transmission, some asynchronous polling effects (missed/duplicate samples) were unfortunately present in the data. Upon direct analysis of the frame counter values, it became apparent that the RINU was being polled more slowly than would have been necessary to avoid missed samples. Figure 2 shows the discrepancy between observed and expected frame count.

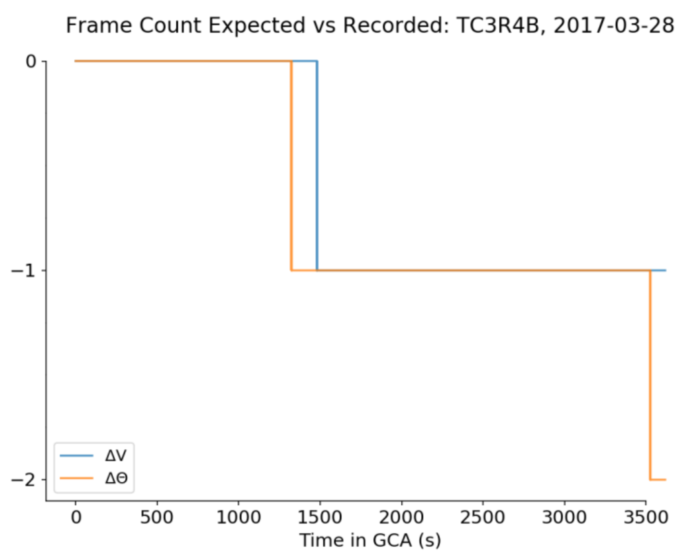

Figure 2. Example of Frame Loss Over 1 Hour Due to Asynchronous Polling

Over the course of execution of the test case depicted, the expected frame count outpaces the observed frame count by a total of 1-2 frames. Roughly the same missing-frame effect and general spacing (1 frame lost over ~2000 seconds) was observed in all test cases, though the timing of when the transitions occurred was observed to be variable.

The recorded delta-Theta and delta-Velocity data were input to the RINU model as recorded, bypassing the sensor model and coning/sculling compensation. To assess gyrocompassing behavior of the RINU model, the RINU model outputs were compared to the recorded navigation output data. Figure 3 shows the result of the attitude comparison.

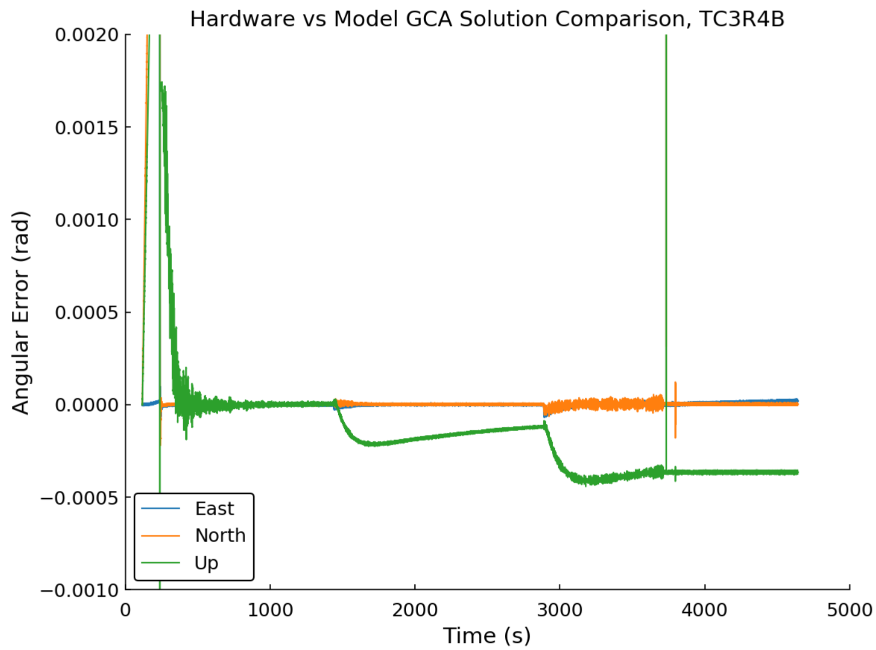

Figure 3. Example of GCA Solution Comparison

Note the divergences about the Up axis beginning about ~1400 s and again around ~2900 s. It was believed that this was occurring due to missing the information contained in the delta-Theta and delta-Velocity frames which were lost over the course of the run. Figure 4 below shows the frame drops overlaid on the attitude solution comparison.

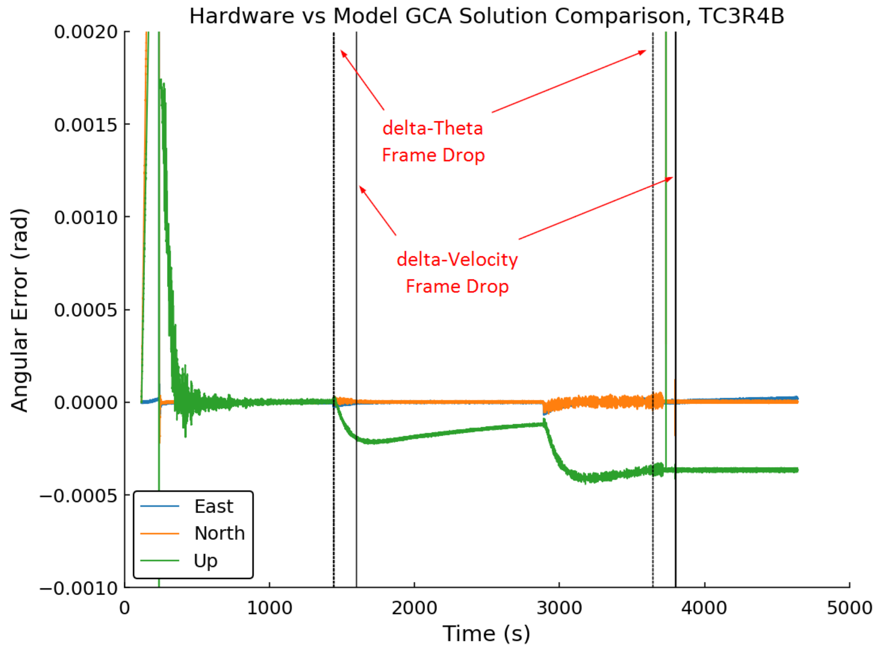

Figure 4. GCA Attitude Comparison with Frame Drops

Note that the first divergence is correlated with the first frame drop event. In an effort to minimize this effect, the test data was processed to replace the missing samples with interpolated data. An example of this is shown in Figure 5.

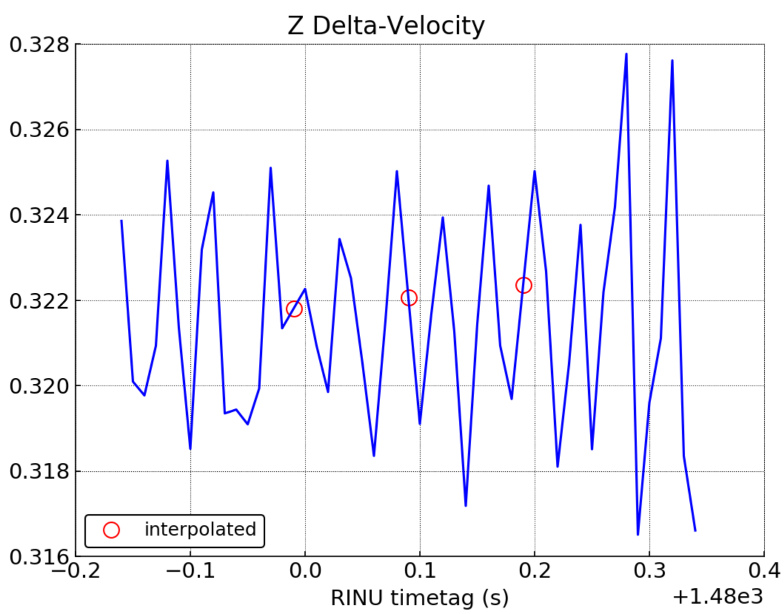

Figure 5. Example Missed-Sample Reconstruction by Interpolation

When the reconstructed delta-Theta and delta-Velocity data were used in the comparison, results were generally improved. Figure 6 shows an example of the comparison results with the data reconstruction technique.

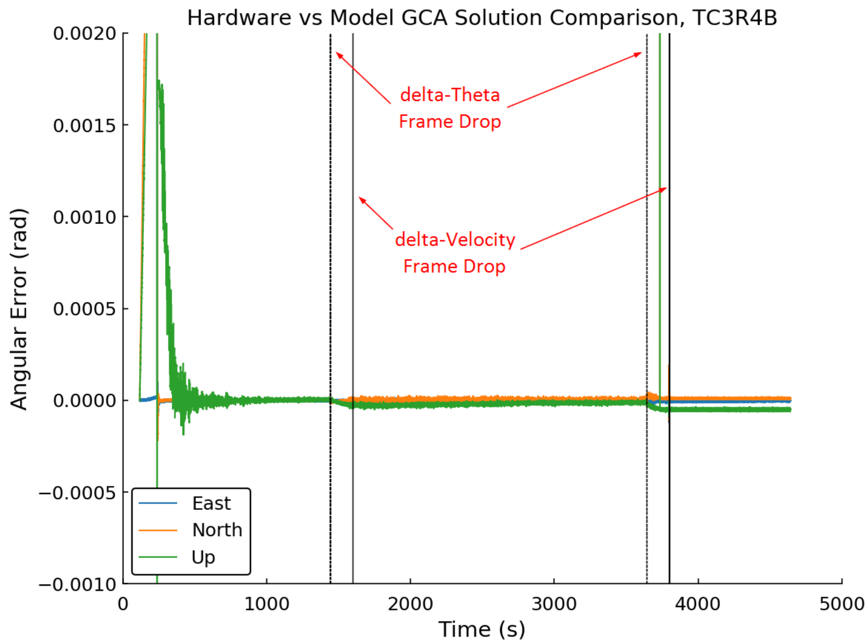

Figure 6. Example Comparison Results after Data Reconstruction by Interpolation

Overall, the model's predictions of the RINU's azimuth solution were quite accurate. Model and hardware were shown to be in close agreement when operating on the same sensor data, despite the aforementioned data-availability and data-collection issues. These results are shown in Table 4.

Table 4. Model-Hardware GCA Comparisons

Run ID	Azimuth Error (Model vs. Hardware), radians
TC3R2A	-0.000123
TC3R3A	0.000128
TC3R4B	-0.000054
TC3R5A	0.000162
TC3R6A	0.000048
TC4R1A	0.000026
TC4R2A	-0.000078
TC4R3A	-0.000199
TC4R4A	-0.000316
TC4R5A	-0.000339

GCA Robustness Analysis

The runs in test cases 3 and 4 consisted of various dynamic pad environments. In order to evaluate the RINU's performance, Monte Carlo simulations were run to provide an envelope for comparison purposes. Test case 3 consisted of runs with the SLS DAC2 and VAC1 twist & sway environments and the RINU vendor-heritage software testing profile—labeled below as "Heritage".

The Monte Carlo simulations were run using the RINU performance model, simulating the exact case run for each test run. Since the start of GCA mode was not fixed relative to the table's dynamic profile during testing, the start time of GCA was randomized for this Monte Carlo. The baseline error budget for the Monte Carlo simulations was that given by the vendor's capability estimate (labeled "NEB"). Additionally, an attempt was made to reduce the comparison envelope somewhat by using a reduced error budget derived from the Acceptance Test Procedure (ATP) for the specific test article RINU, which documents the thresholds on various error characteristics. Both the NEB and ATP error budgets were run, with 500 Monte Carlo simulations each, for each pad environment model.

The resulting comparison for test case 3 can be seen in Figure 7.

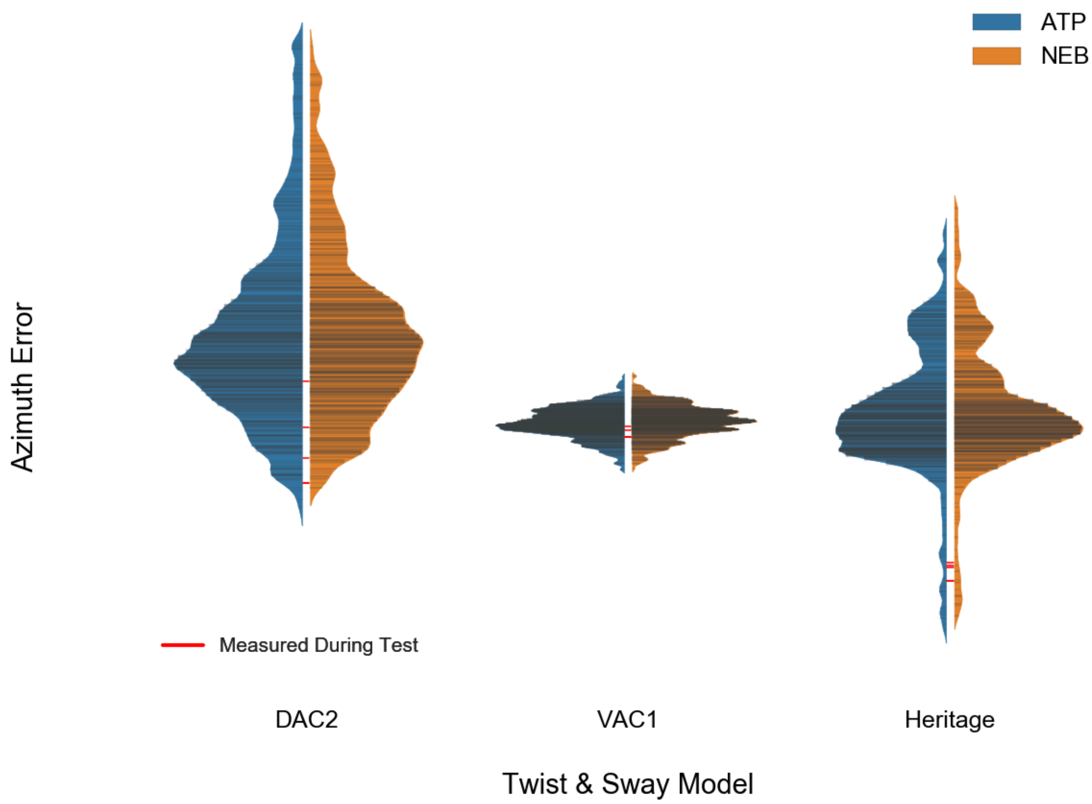

Figure 7. Monte Carlo Simulation Results vs Test Data, Test Case 3

It can be seen in Figure 7 that the test data does fit within the simulated envelope, although narrowly in some cases. The instance in which this is most evident is in the Heritage runs—even given only 4 test runs, the expectation would have been to have the test results more near the center of the distribution, rather than so tightly grouped at the edge. This could imply that there is some sensitivity in the real dynamics of the Heritage run that is not exercised in simulation—if true, this could imply that the Heritage profile is an inappropriate environment for the qualification or acceptance of GCA software (because the simulation seems to demonstrate better performance than the hardware). Another potential source for this discrepancy is a difference between the simulated and tested dynamics; the Heritage case was one of the most dynamic cases tested, and thus potentially more susceptible to excitation of the 6DOF table's structural modes or reaching controllability limits. Unfortunately, no truth data is available to allow further investigation. In addition to the Heritage case comparison, the mean bias and asymmetry of the DAC2 envelope is also unexpected—these are pending further investigation.

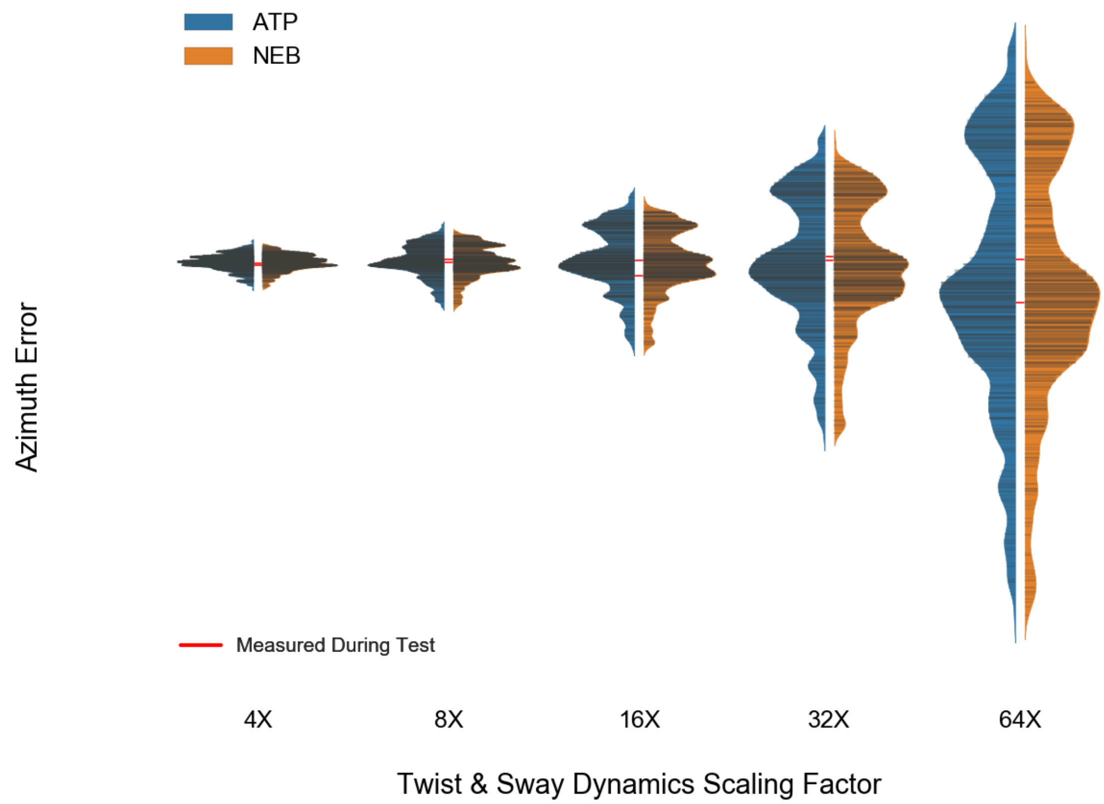

Figure 8. Monte Carlo Simulation Results vs Test Data, Test Case 4

As shown in the test case 4 comparisons in Figure 8, the GCA solutions recorded during the test fall neatly within the simulated envelopes. Note that the distributions start to become bimodal at around the 8X scaling level. This could indicate that the GCA algorithm as simulated by the RINU performance model is starting to lose effectiveness. Unfortunately, insufficient hardware test data was available to definitively confirm the simulated result.

Overall, the model performance in test case 3 and test case 4 comparison runs demonstrated that the simulated performance bounds the actual performance in all cases. Further, the simulation of each test case with both the NEB and ATP error budgets showed that the choice of instrument error budget had a near-negligible effect on attitude error resulting from GCA. This demonstrates that the dynamic environment is by far the dominant contributor to GCA error.

Additional Analysis

In addition to the analysis discussed above, Allan Deviation and spectral analyses were conducted using data collected during the 24-hour test (test case 5 in Table 3). Spectrograms produced of the test data have identified unexpected phenomena which are currently being investigated with the RINU vendor, as well as influencing future test actions. Allan Deviation analysis uncovered some differences between the hardware performance and the RINU performance model, specifically in the area of bias instability; these are currently being addressed in the model validation process.

CONCLUSION

A few lessons could be taken from the experience of planning and conducting the test. First, the potential for missing samples cannot be tolerated—the polling rate should have been increased so as to remove this source of error. Second, having a high-fidelity source for truth dynamics would have been very helpful—high quality 3-axis accelerometers at 3+ locations could have provided crucial insight. Third, not controlling the start time of GCA mode with respect to the table dynamics was an oversight—this would have enabled far more precision in the generation of the simulated envelopes in the robustness study.

Despite the above shortcomings, the RINU 6DOF test nonetheless achieved each of the stated test objectives. It succeeded in providing insight into gyrocompassing performance of a flight-like RINU under representative SLS on-pad dynamics, as well as testing the RINU's robustness to larger-than predicted on-pad dynamics; GCA performance is demonstrated in the Sensor Bypass study and robustness is explored in the GCA Robustness study. The test also provided gyrocompassing test data for use in validation of the RINU performance model—each analysis conducted (and described herein) as a result of this test provides validation evidence. Finally, it also allowed the SLS navigation team to assess the feasibility of planned pre-launch RINU operational procedures. This was achieved through modeling of the SLS Flight Computer running the SLS Flight Software in the HWIL environment in which the test was conducted.

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