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SENSOR DATA QUALITY AND ANGULAR RATE DOWN-SELECTION ALGORITHMS ON SLS EM-1

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The NASA Space Launch System Block 1 launch vehicle is equipped with an Inertial Navigation System (INS) and multiple Rate Gyro Assemblies (RGA) that are used in the Guidance, Navigation, and Control (GN&C) algorithms. The INS provides the inertial position, velocity, and attitude of the vehicle along with both angular rate and specific force measurements. Additionally, multiple sets of co-located rate gyros supply angular rate data. The collection of angular rate data, taken along the launch vehicle, is used to separate out vehicle motion from flexible body dynamics. Since the system architecture uses redundant sensors, the capability was developed to evaluate the health (or validity) of the independent measurements. A suite of Sensor Data Quality (SDQ) algorithms is responsible for assessing the angular rate data from the redundant sensors. When failures are detected, SDQ will take the appropriate action and disqualify or remove faulted sensors from forward processing. Additionally, the SDQ algorithms contain logic for down-selecting the angular rate data used by the GN&C software from the set of healthy measurements. This paper provides an overview of the algorithms used for both fault-detection and measurement down selection.

INTRODUCTION

The Space Launch System (SLS) is equipped with multiple Rate Gyro Assemblies (RGAs) along the body of the space vehicle. Each RGA consists of two orthogonal gyroscopes as well as supporting electronics. Three such pairs of RGAs are co-located on a common isolated member at two locations in the SLS vehicle. The responsibility of checking the health of the three independent measurements as well as consolidating, or down-selecting, a single rate measurement lies within a suite of Sensor Data Quality (SDQ) algorithms hosted in the navigation module of the SLS Flight Software. The suite of SDQ algorithms validates the angular rate data from the RGAs by analyzing the measured angular rate data from the respective gyros as well as data from the internally redundant Inertial Navigation System (INS), the corresponding timetags of the RGA and INS measurements, as well as the Data Quality Indicators (DQI) derived from the self-reported health and status messages from the inertial sensor hardware.

The algorithms that comprise SDQ can be grouped into two broad categories: functions that detect failures and those functions that respond to failures. The SDQ algorithms responsible for failure detection are the DQI check, the Timetag Check (TC), the Redundancy Check (RC) and the Box Comparison Check (BCC). The response to any detected failures occurs in the SDQ Decision

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Manager (DM). The DM uses the strike counters from the detection functions in order to set internal DQI values based on configurable persistence limits. Lastly, the Selection Filter (SF) nominally consolidates the angular rate data from the three co-located RGAs into a single set of body-pitch and body-yaw angular rate measurements using a modified mid-value selection scheme. Additionally, the SDQ is responsible for setting sensor failure indicators for Guidance, Controls, and other redundancy management modules in SLS Flight Software. The flow through each of the SDQ modules is shown in Figure 1.

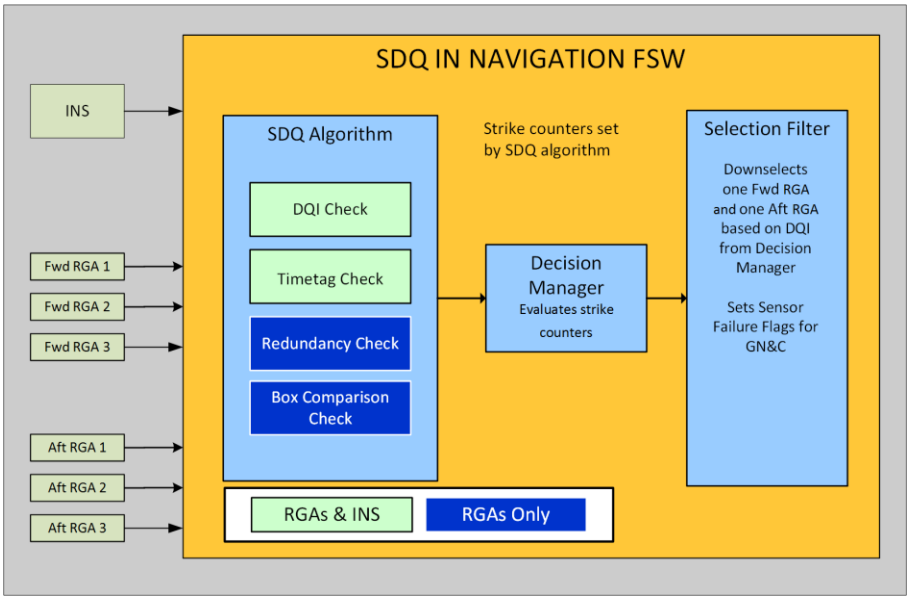


Figure 1- Data flow through navigation SDQ.

Each of the SDQ checks is configurable using software-loadable thresholds to denote the failure of a check, and communicates any detected failures to the DM by incrementing check-specific error/strike counters. The DM checks each of the strike counters against a software-loadable persistency value---an RGA must fail a check for a specified number of consecutive frames before any action is taken.

These configurable parameters are further discretized into flight phases: a different set of detection thresholds are used during each phase. Each SDQ flight phase (not to be confused with mission phase or software mode) is scheduled based on navigated altitude---analysis during the SLS design and verification cycles has shown that altitude is more correlated to changes in dynamics than other potential scheduling variables, e.g., time. In contrast to the SDQ thresholds, the persistency values are not phase dependent; the same persistency configuration for each check remains in effect for the duration of flight. In addition to altitude-based scheduling, the SDQ thresholds are altered when SDQ enters a safing mode. This SDQ safing mode is designed to allow a set of relaxed thresholds to be activated in the event of a Core Stage engine failure and during planned engine shutdown events.

The next several sections describe the various SDQ failure detection algorithms and the corresponding thresholds. Next, details of the DM and RGA selection algorithm are provided. A discussion follows of the methodology for determining the SDQ flight phases and the thresholds used in each phase. The current work concludes with a brief overview of a lesson-learned from early hardware-in-the-loop testing, specifically as it relates to timetags in an asynchronous system.

DQI CHECK

The RGAs perform a robust set of Built-In Tests (BIT) on the gyros, as well as on the sensor processing electronics. BIT failure indicators from each RGA are consolidated by input data handlers in the SLS Flight Software. Additionally, the INS provides indication of failures from its own internal redundancy management software. These data handlers also assess the message integrity of each message, checking for both valid messages and stale data. Based on the consolidated BIT data and 1553 communications check, each RGA is marked as having a valid or an invalid DQI. The SDQ DQI check marks any RGA with an invalid DQI and increments the appropriate strike counter associated with the failed RGA.

The INS contains sufficient redundant management provisions—both in hardware and software—to allow the SLS vehicle to complete its mission even after failure of one accelerometer and one gyro in the INS. While fault management algorithms in SLS Flight Software monitor for single failures of the INS—and report on failures in telemetry—the GNC is only notified once the INS has failed sufficiently—loss of required function—to affect mission. The input data handlers monitor the INS for multiple-failure events and set an invalid DQI on the INS measurements. When the INS DQI is invalid, the DQI check increments the corresponding strike counter. In this case, the navigation software will publish an indication that the INS has failed so that guidance and controls can take appropriate action.

TIMETAG CHECK

The SDQ Timetag Check (TC) determines whether the timetags reported from the RGAs and the INS are within expected bounds, i.e., that the timetags are not duplicated (stale data) from one minor frame to the next and that the timetags vary from minor frame to minor frame within configurable limits. It is not unexpected for the RINU and RGA to have stale data periodically in flight due to the asynchronous nature of communication between the Flight Computers and the avionics boxes with independent clocks. Separate strike counters are maintained for each RGA.

REDUNDANCY CHECK

For a given mounting location, the three co-located RGAs will experience the same vehicle dynamics. Therefore, any difference in measured angular rates for each axis should be bounded by the gyro instrument error specification. To mitigate the effects of output noise in the comparisons, the angular rates are first filtered with a critically damped 4 Hz filter. This 4 Hz filter eliminates any unmodeled effects from high frequency dynamics or from simulation artifacts in the modeling of flexible body dynamics and focuses the comparison on a frequency band in which the dynamics are well characterized.

For each RGA mounting location, the filtered rates are differenced to form three pairs of rate differences per axis. For either input axis of an RGA, the two pair-wise differences (between it and the other two co-located RGAs) for two healthy gyro should be bounded by a pre-determined threshold. If either of the differences are above the threshold, an error is detected on that axis of the RGA. The RC increments an internal strike counter if a fault is detected on either axis. Due to the nature of the comparison logic, faults can be detected on only one or all three RGAs in a particular mounting location.

BOX COMPARISON CHECK

Whereas the Redundancy Check assesses the consistency of the angular rates at a specific location on the vehicle, the Box Comparison Check (BCC) compares rate data across all three sensor locations at which inertial measurements are available, i.e., at the two RGA locations and at the

INS location. The BCC operates on angular rates from each of the two down-selected RGAs (selection from the previous computational frame) as well as from the INS.

The angular rates from the three sources are first filtered with a critically damped 1 Hz filter. This 1 Hz filter was chosen for the BCC to dampen out all flexible body dynamics. According to the Space Launch System Program Integrated Guidance, Navigation, and Control Performance Assessment[1], the first bending mode is around 1.4-1.5 Hz. Thus, a 1 Hz filter should attenuate flex transients, flexible body dynamics, and all other high frequency content. The only content left that can lead to an error detection in the angular rate measurements are quasi-static instrument errors and low frequency errors like random walk and gyro bias.

The filtered rates are then differenced to form three pairs of rate differences (per axis and per sensor location). For each sensor axis measurement, the differences between it and that of the other two sensors are compared against a pre-determined threshold. For an RGA (location), if these filtered rate differences exceed this threshold, the BCC increments the strike counter for that RGA location. If the rate differences exceed the thresholds for both RGAs, the results of the BCC are invalidated by marking all sensors as passing the BCC. In this case, the reduced redundancy of the measurements directly impacts the observability of failures. Also, since the INS is considered a trusted source—owing to the hardware and software redundancy provisions internal to the box—if the rate differences associated with the INS exceed the detection thresholds, the results of the BCC are invalidated by marking all sensors as passing the BCC.

DECISION MANAGER

The Decision Manager (DM) is responsible for assessing the strike counters from each of the SDQ detection algorithms—the Data Quality Check, the Timetag Check, the Redundancy Check, and the Box Comparison Check. Each of the SDQ strike counters have two associated persistency limits that determine (a) the minimum number of strikes/frames that must occur before a temporary failure is declared and (b) the maximum number of strikes/frames before which a permanent failure is declared for a given RGA or the INS.

Depending on the individual strike counters the DM can be configured to either (a) permanently fail sensors on detection of any error, (b) to temporarily fail a sensor with the possibility of recovery in a subsequent computational frame, or (c) temporarily fail a sensor with the possibility of recovery but also allowing for permanent failure based on a secondary (configurable) persistence value. Depending on configuration, the DM can allow recovery of a sensor by clearing that sensor's failure status if no faults have been detected by the checks for a configurable amount of time.

The result of the DM is that any sensor with error counters in excess of the persistence limits are marked as disqualified/failed. These screened failure indicators are used in the Selection Filter.

RGA DOWN SELECTION

The RGA Selection Filter (SF) is responsible for selecting an (un-failed) RGA to use for the angular rate measurements at that location in the vehicle. The SF uses the indicators from Decision Manager, along with the angular rate data from the non-failed RGAs at each location to perform this selection.

When no RGA (at a location) is marked as failed, a modified Mean-Value Selection algorithm is used. The selection filter computes the squares of the pair-wise differences between the angular rates from each RGA and chooses the channel whose measurements lie between the other two. Defining the rate differences as,

$$\Delta_{0,1} = \vec{\omega}_{RGA0} - \vec{\omega}_{RGA1}$$
$$\Delta_{0,2} = \vec{\omega}_{RGA0} - \vec{\omega}_{RGA2}$$
$$\Delta_{1,2} = \vec{\omega}_{RGA1} - \vec{\omega}_{RGA2}$$

The corresponding square magnitudes are then,

$$\begin{aligned} \|\Delta_{0,1}\|^2 &= ([\Delta_{0,1}]_x^2 + [\Delta_{0,1}]_y^2 + [\Delta_{0,1}]_z^2) \\ \|\Delta_{0,2}\|^2 &= \left([\Delta_{0,2}]_x^2 + [\Delta_{0,2}]_y^2 + [\Delta_{0,2}]_z^2\right) \\ \|\Delta_{12}\|^2 &= ([\Delta_{1,2}]_x^2 + [\Delta_{1,2}]_y^2 + [\Delta_{1,2}]_z^2) \end{aligned} \quad (1)$$

These squared magnitudes in Equation (1) are used by the SF to select the RGA whose pair-wise differences are the smallest. The full logic is detailed in Table 1.

Table 1 Selection scheme for the no RGA failure case. The square-magnitudes are compared pair-wise in a modified Mean Value Selection.

IF	AND	IF	SELECT
$\|\Delta_{0,1}\|^2 \leq \|\Delta_{1,2}\|^2$		$\|\Delta_{0,2}\|^2 \leq \|\Delta_{1,2}\|^2$	0
$\|\Delta_{0,1}\|^2 \leq \|\Delta_{0,2}\|^2$		$\|\Delta_{1,2}\|^2 \leq \|\Delta_{0,2}\|^2$	1
$\|\Delta_{0,2}\|^2 \leq \|\Delta_{0,1}\|^2$		$\|\Delta_{1,2}\|^2 \leq \|\Delta_{0,1}\|^2$	2

This selection logic is also used in the unlikely event that all RGAs are marked as failed. This event will also cause the navigation software to assert a failure condition signifying that no reliable rate data is available for that RGA location. The vehicle controller will re-configure any rate blending scheme to de-emphasize the affected rate measurements. Additionally, fault management processing in other partitions of SLS Flight Software will issue appropriate caution or warning messages. This indication of all RGA failure may be removed provided that at least one RGA is re-admitted on a subsequent frame.

If only one or two RGAs have failed, the Selection Filter will use a sensor priority system. Each RGA is assigned an arbitrary and configurable priority index as a part of the software-configurable parameters. The SF will select the un-failed RGA with highest priority index. This way, the SF remains deterministic software and will never chose a random RGA's angular rate data.

SDQ PHASE DETERMINATION

Because the vehicle's flexible body and trajectory dynamics vary over the course of flight, the SDQ error detection thresholds should change accordingly. Analysis during the SLS design and verification cycles has shown that altitude is more correlated to changes in dynamics than other potential scheduling variables, e.g., time. This ability to change thresholds as a function of vehicle altitude allows for a more robust detection capability by using looser detection thresholds during more dynamic flight phases, e.g., at liftoff and max-Q, while using tighter thresholds during less volatile times of flight.

The SDQ threshold phases are set based upon similar flight phases as determined by bounding cases of the vehicle pitch profile. A notional profile of the min/max pitch rate versus altitude is illustrated in Figure 2. The altitude-based phases are determined by first enveloping the pitch rates on each of ten subintervals. The bounds of the subintervals are adjusted so that the total area enclosed is minimized. Additionally, for the case illustrated in Figure 2, the two altitude bands indicated with green arrows shown were combined into one single phase due to the much larger rate bounding box to the right of the combined altitude phases. Combining these two altitude phases allows for a decrease in the chance for false positives.

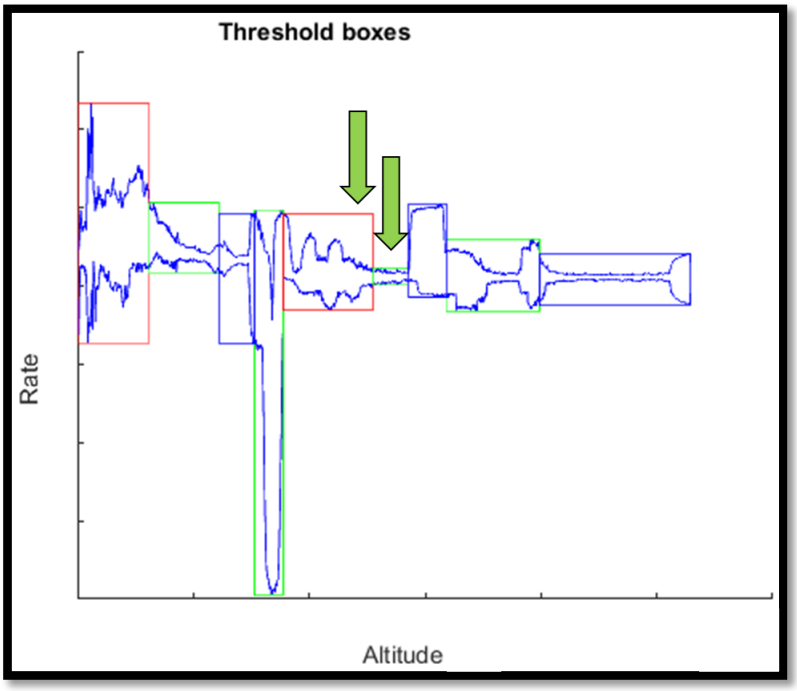


Figure 2 The minimum and maximum pitch rate versus altitude data along with the altitude-based SDQ flight phases. The two indicated phases were merged using the min/max rates across the union of the two sub-intervals.

SDQ THRESHOLDS AND MARGIN

Eight separate SLS vehicle configurations were examined during the most recent Verification Analysis Cycle. For each configuration, a set of nominal (no failure) Monte Carlo runs were used to envelope the no-failure behavior of the angular rate data. An analysis was performed on these simulation results to determine the minimal SDQ error detection thresholds—the smallest possible threshold values the SDQ checks can have for a defined SLS vehicle before an error is detected incorrectly (zero-margin thresholds). The analysis revealed that the zero-margin thresholds for each of different configurations are not that different. The zero-margin thresholds across the different configurations are illustrated by the horizontal bars near the center of the SDQ altitude phases in Figure 3.

For the purpose of setting SDQ thresholds for this analysis cycle, the zero-margin thresholds for a specific configuration were scaled such that the resulting values enveloped the thresholds for all cases with significant margin. The resulting thresholds, with margin, are illustrated by the green bars in Figure 3.

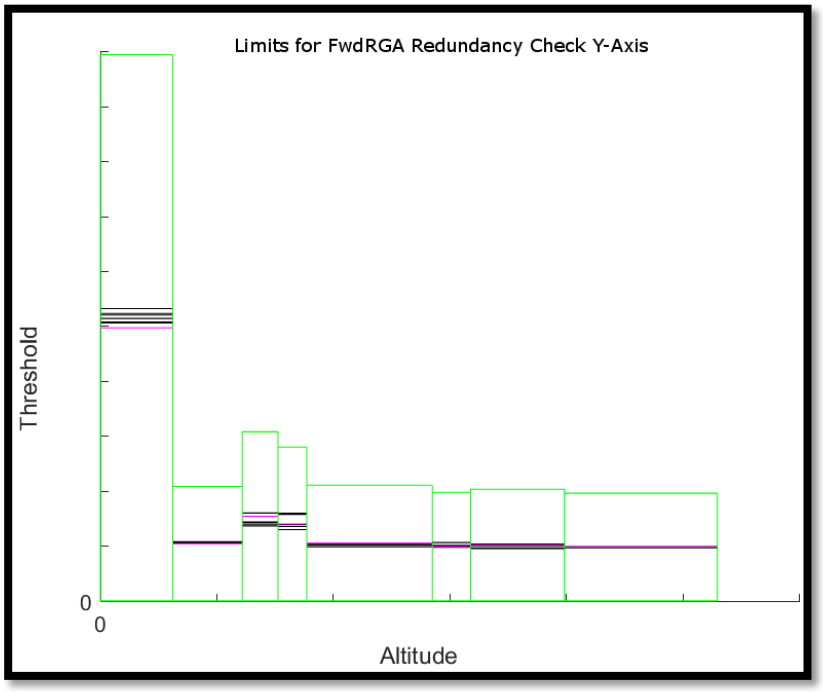


Figure 3 The zero-margin thresholds for each altitude phase along with the scaled thresholds used across all configurations.

The low-pass filters used in the Redundancy Check and in the Box Comparison Check, in addition to attenuating undesired frequency content, reduce the corresponding thresholds in each of the altitude-based phases. Figure 4 and Figure 5 illustrate this reduction in the thresholds. The thresholds generated without using any pre-filter are shown in blue. The corresponding thresholds when the angular rates are filtered with 4 Hz and 1 Hz filters are shown in green and cyan, respectively.

Even though the effects of both filters are shown in Figure 4 and Figure 5, the Redundancy Check only uses the 4 Hz filter, while the Box Comparison Check only uses the 1 Hz filter.

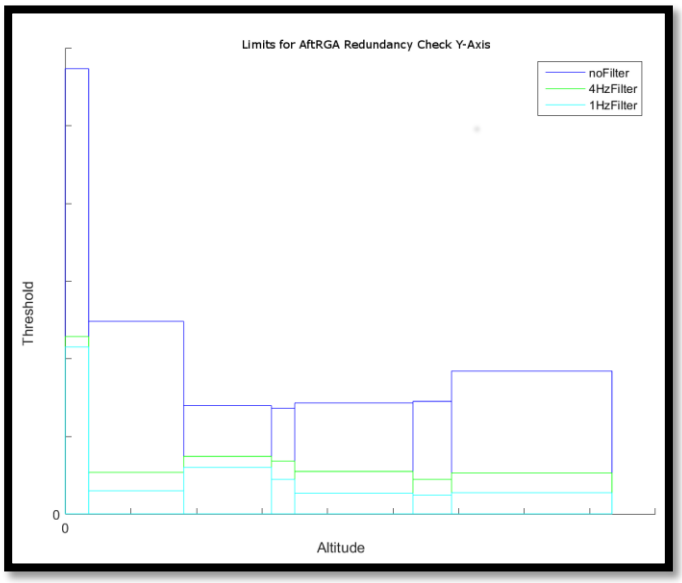


Figure 4 Effects of using a low-pass filter on the angular rate measurements in the Redundancy Check.

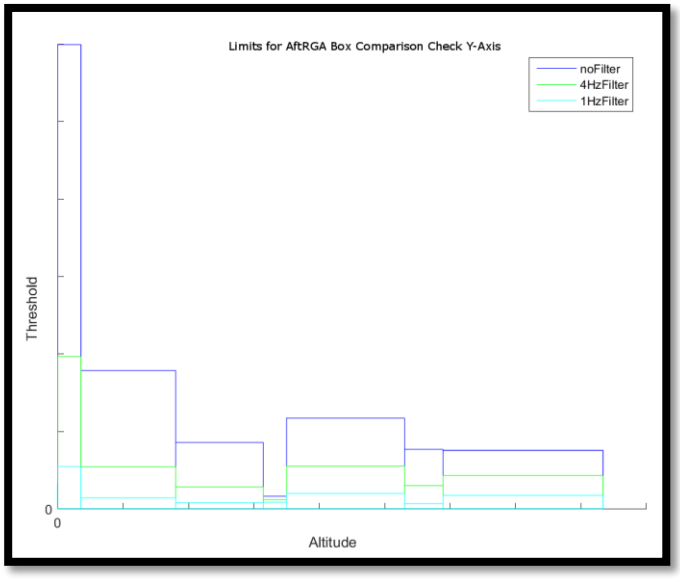


Figure 5 Effects of using a low-pass filter on the angular rate measurements in Box Comparison Check.

LESSON LEARNED FROM HARDWARE-IN-THE-LOOP-TESTING

During software integration testing with the INS engineering unit, the SDQ Timetag Check was erroneously disqualifying the INS. After carefully analyzing the buffered timetags of the INS compared to the INS timetags reported by the Flight Computer (FC), it was discovered that the FC was occasionally missing samples.

The SLS FC communicates with the INS over an asynchronous MIL-STD-1553B data bus. The FC is the master clock for the vehicle. While adjusting timetags based on the time broadcast message from the FC, the INS uses a free-running clock for inertial measurement processing. These independent clocks will drift pass one another. When the frame boundaries cross, the FC will either miss an INS sample or will pull an old/stale sample. When these clocks are not precisely the same the flight computer will either miss INS samples or report duplicated samples.

Figure 6 illustrates four scenarios involving clocks. At the top of the figure, the FC's and INS' clocks are synced resulting in the FC always receiving the most up-to-date data. The next scenario in Figure 6 is that of asynchronous but identically behaved clocks—there is a fixed offset between the INS updates and the FC polling for data. In this, nearly ideal, scenario, no samples are missed nor repeated. In practice, independent clocks in an asynchronous system will have different drift rates. The last two scenarios in Figure 6 illustrate the two cases resulting from the FC running faster than the INS—in this case samples will be repeated— and with the FC running slower than the INS—in this case new samples are missed.

The jitter in the clock signals compounds the problem of missing or repeating samples from the as the FC and INS frame boundaries close in on one another. If the drift rates of the clocks are very similar, the dwell time during a frame crossing can be significant. During this dwell time, the FC will bounce between missing and repeating the INS samples. This back-and-forth behavior is observed by examining the difference in the FC and INS timetags around a frame crossing. Figure 7 illustrates these timetag differences from a HWIL test. The slope of the difference gives a measure of the relative drift rates between the two clocks. The inset in Figure 7 highlights the effects of jitter in the two timetags.

A simulation model was created to assist in characterizing the uncertainty in the timetag increments from frame-to-frame. This model was used to adjust the thresholds and persistency limits in the Timetag Check. Using the navigated state from the INS—rather than integrating the incremental angles and incremental velocities in the SLS navigation software—reduces the sensitivity of missed or skipped INS data. However, for the Block 1B family of vehicles, the SLS navigation software integrates the dvs and $d\theta$s directly. This timing model allows for testing of the Block 1B integration algorithms when presented with skipped and duplicate samples.

CONCLUSION

The SLS Block-1 vehicle uses redundant rate gyroscopes in two different locations. The navigation team developed, implemented, and tested a suite of SDQ algorithms to detect and isolate sensor failures. These error detection algorithms are driven by software-configurable thresholds developed using Monte-Carlo simulations. When no failures are detected a modified mid-value selection algorithm selects the angular rates from an RGA at that location for forward processing.

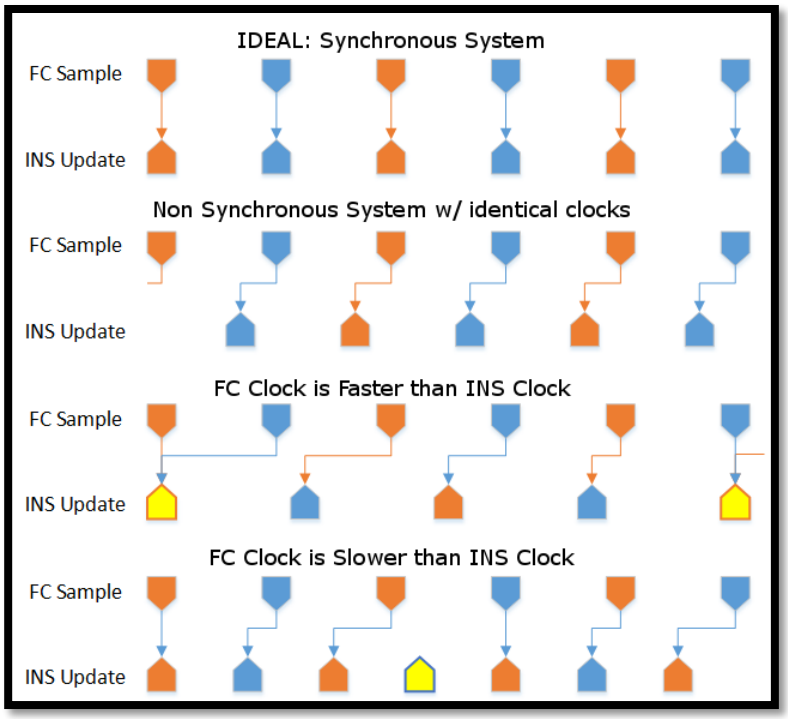


Figure 6 FC Perfect Sample INS

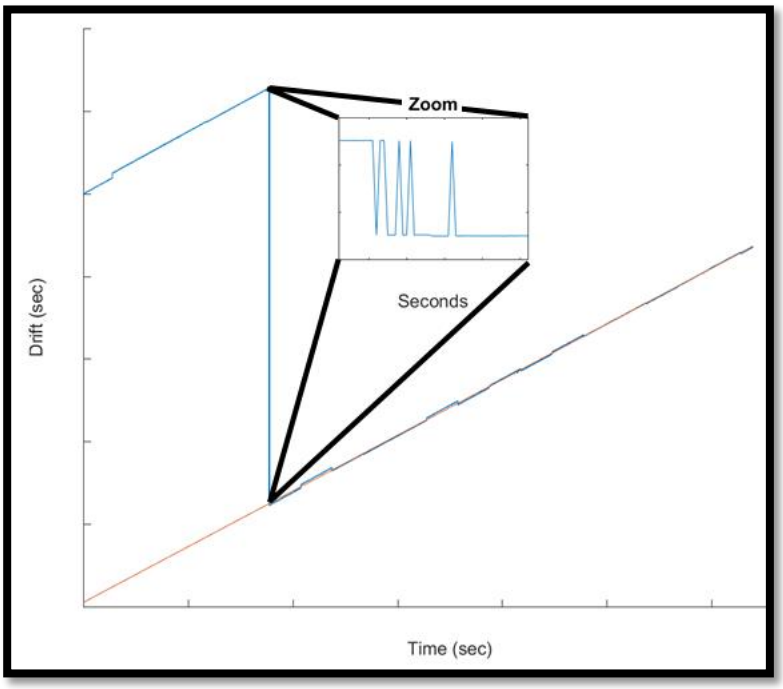


Figure 7 Example of FC and INS Async Event

REFERENCES

[1] SLS-RPT-080, Space Launch System Program Integrated Guidance, Navigation, and Control Performance Assessment.