Sensonor AS	TECHNICAL NOTE		
Distribution	**Prepared by** Hans Erik Mathisen		**Document No** TN 21070201
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Document Title TVAC testing of Sensonor Inertial Measurement Unit STIM377H			

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1 References

[1] SMC-S-016 standard

2 Abbreviations

IMU	Inertial Measurement Unit
MEMS	Micro-Electro-Mechanical System
UUT	Unit Under Test
TVAC testing	Thermal-Vacuum testing

3 Summary

This document describes the test procedure and results of TVAC testing performed on the Sensonor STIM377H IMU. The tests have been performed on 5 devices: 4 samples for TVAC test and 1 sample for reference. After the TVAC test, the units have undergone an analysis program with testing of several key parameters. These test results are then compared to original measurements done prior to TVAC. During TVAC test, the UUT's output was logged for investigation of behavior during TVAC.

STIM377H passed the TVAC test verifying that the product have a general robustness towards temperature and vacuum variation.

Acknowledgements: Sensonor wishes to extend its gratitude to the Norwegian Space Agency for their financial contribution.

Sensonor is thankful for generous contribution from several players in the New Space Community for open sharing of field experiences and ideas that have enabled a range of improvements and this work.

4 Introduction

STIM377H is a MEMS based IMU with a design based on the STIM300. The STIM377H is packaged in a hermetic enclosure and was used for all the tests reported in this document. Several market segments and in particular for the space segment it is important to investigate the performance of all components in an environment similar to what is represented in an actual space flight operation.

5 Objective

The objective is to document the results from the TVAC testing on the STIM377H including any failure analysis.

6 Test plan

6.1 Overall test plan

Figure 1 shows the test flow for the TVAC test.

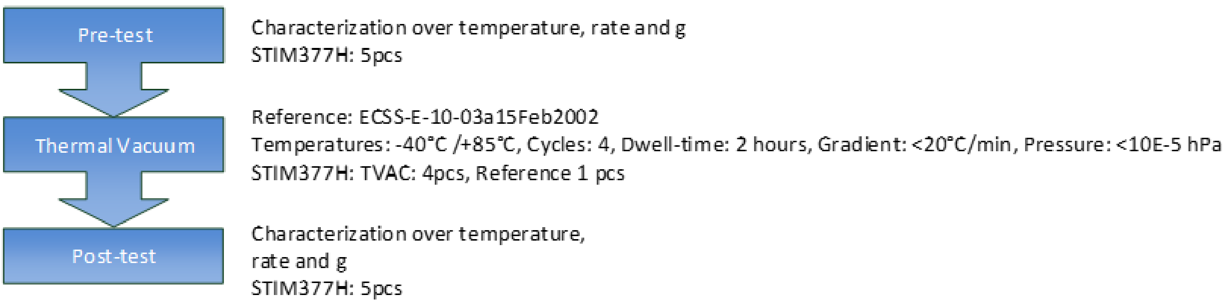

Figure 1 Test plan for the TVAC test

Prior to and after the TVAC tests, all UUTs were tested at Sensonor in a selected set of production test insertions. These Pre- and Post-tests are full product characterization tests done at various temperature levels, temperature gradients, rate and acceleration levels. Results from these tests are used for comparison of performance before and after the TVAC test.

6.2 TVAC test plan

Table 1 describes the performance criteria according to [1].

Table 1: TVAC compliance criteria

Req ID	Requirement	Compliance Criteria
1.0	Environment shall reach vacuum	*Chamber Pressure < 1.0 mPa*
1.1	Internal component vacuum equilibrium shall be achieved prior to thermal cycling	*Vacuum Dwell Time > 12 hr*
1.2	Minimum number of thermal vacuum cycles	*12*
1.3	Device under test shall be subjected to the thermal cycle temperature limits	*-40°C to 80°C*
1.4	Dwell temperature tolerance	*±3°C*
1.5	Temperature stability shall be achieved during thermal dwell	*Unit baseplate temperature change < 3.0°C per hour*
1.6	Minimum dwell time while component is thermally stable	*> 30 minutes*
1.7	Transitions between hot and cold shall be at an average rate greater than	*> 1°C/min*
2.0	Unit gyroscope biases shall be within operational limits	*<= ±250° per hour*
2.1	Unit shall remain operational throughout thermal vacuum test	*No data dropouts*
2.2	Device under test shall be power cycled at both the cold and hot dwell temperatures	*Unit Power Cycled*

The testing is based on [1] with the following deviations:

- Vacuum was achieved slower than what would normally be seen during a launch (several hours as opposed to several minutes)
- Soaking time at target temperatures was 0.5hr instead of 1hr+6hr for first and last cycle
- 12 TV cycles instead of 6 TV cycles was performed

- Low temperature and high temperature was -40°C and +80°C (the UUTs operational range)
- One hot start and cold start with performance testing in the middle cycle was performed instead of one hot start and cold start with performance testing on the first and last cycles

7 Test samples

STIM377H is a cluster of three high accuracy MEMS-based gyros, three high stability accelerometers and three high stability inclinometers, built into a small package. Each sensor cluster is factory-calibrated for bias, sensitivity, non-linearity and compensated for temperature effects to provide high accuracy measurements in the temperature range from -40 °C to +85 °C. The unit runs off a single 5 V supply. Ref. Figure 2 for a functional block schematic and a picture of a STIM377H.

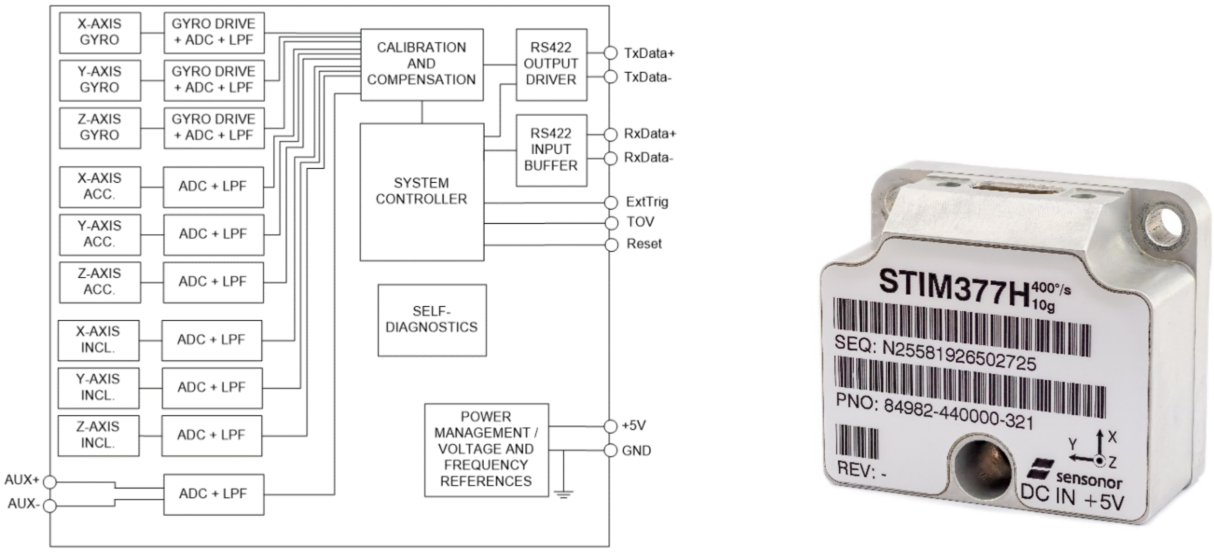

Figure 2: STIM377H functional blocks schematics (left) and the STIM377H IMU (right)

7.1 Sample selection

Sample selection for the complete test program was done according to Table 2.

Table 2: Samples used in test

TEST	ID	Design.
TVAC	N25582037623199	Reference
	N25582039682342	UUT1
	N25582032536730	UUT2
	N25582037623167	UUT3
	N25582037624299	UUT4

All UUTs are of the latest version and were tested and calibrated just prior to the start of the test program.

8 TVAC Test

This section features the description of the TVAC tests and the equipment used for the tests. The results are shown in 8.2.

8.1 Execution of test

8.1.1 Facility

The TVAC tests was performed at a business partner test laboratory.

1.1. Internal Thermal Chamber Setup

A thermal vacuum chamber is used to complete thermal vacuum testing on all STIM377H MEMS IMUs simultaneously. The thermal vacuum chamber can reach pressures below 1 millipascals, with thermal control of the test article(s) achieved via a heat exchanger, which is regulated using liquid nitrogen and an electrical heater.

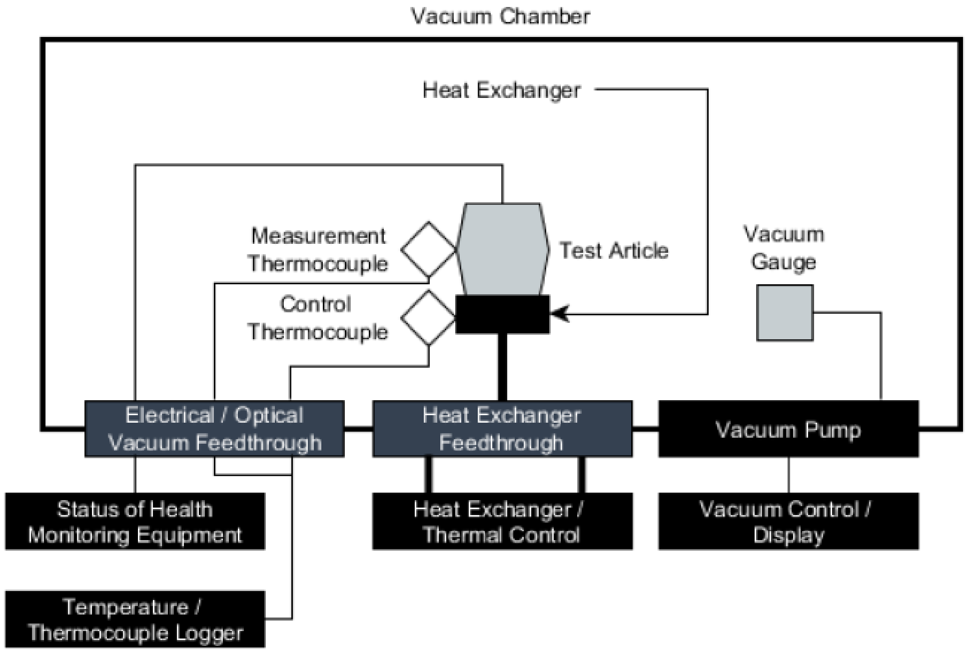

Figure 3: Thermal vacuum test system diagram.

The STIM377H MEMS IMUs are mounted in the thermal vacuum chamber to the heat exchanger plate via an adapter plate. Vacuum safe thermal paste is applied between surfaces to ensure good thermal conductivity between the units and the heat exchanger plate.

Table 3: TVAC chamber test setup

Test Setup Parameter	Mounting Information
STIM377H Fastener Torque	3.0 Nm
Measurement Thermocouple	Attached to STIM377H unit #5
Control Thermocouple	Attached to adapter plate
Devices Under Test	5 STIM377H MEMS IMUs

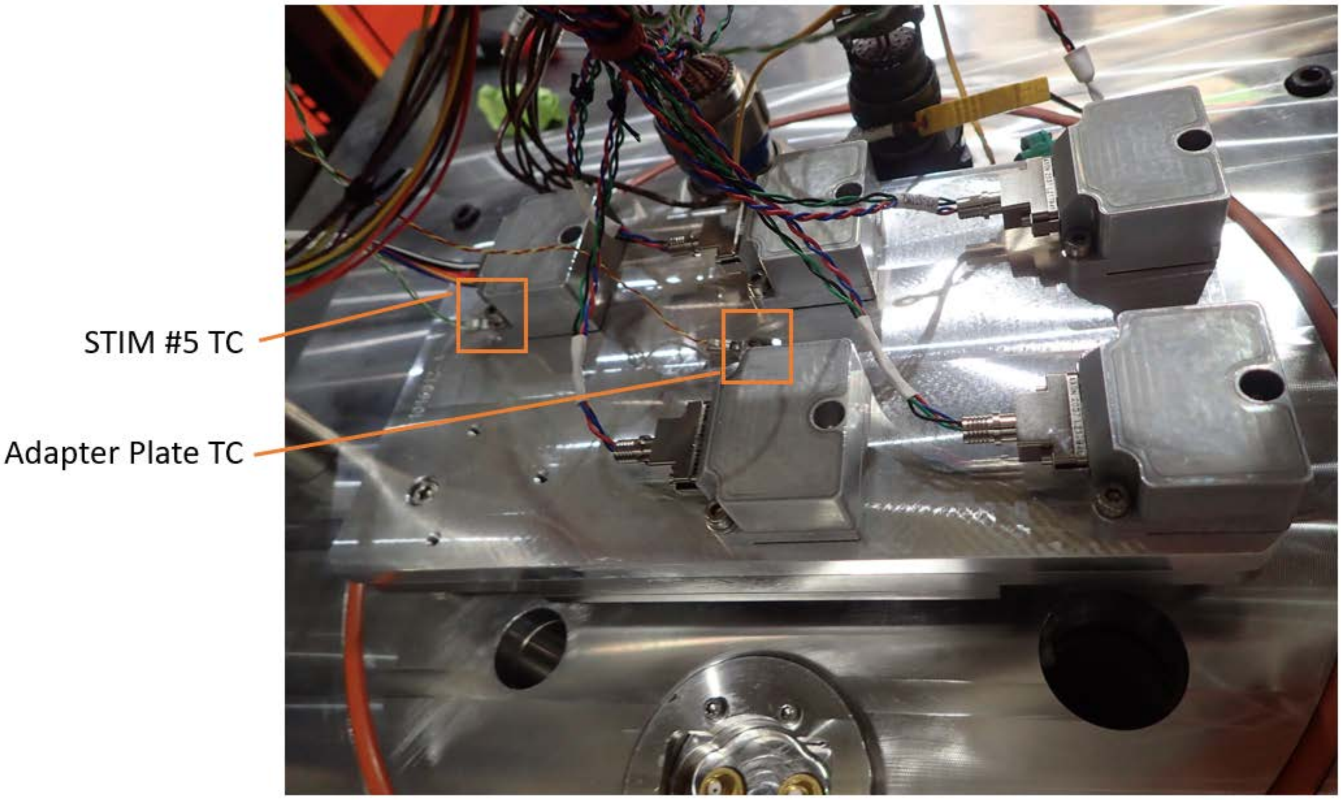

Figure 4: Chamber internal configuration.

In the thermal vacuum chamber, each STIM377H has a dedicated harness providing both power and RS-422 serial communication. Externally, these harnesses are connected to a 5.0V power supply and logging computer to monitor STIM377H telemetry.

8.1.2 Sample holder

A custom-built sample holder (Figure 5) was used to

- fix the samples inside the vacuum chamber
- dissipate heat from the UUT's

The sample holder is built as an attachment part to the vacuum chamber bottom plate, see Figure 6. The bottom plate also facilitates feed-through of power and communication cables used for powering and monitoring of the UUT's during test. Note that in the pictures there are 5 UUT's present as one additional UUT was included by business partner for product qualification. This device is not discussed further in this document.

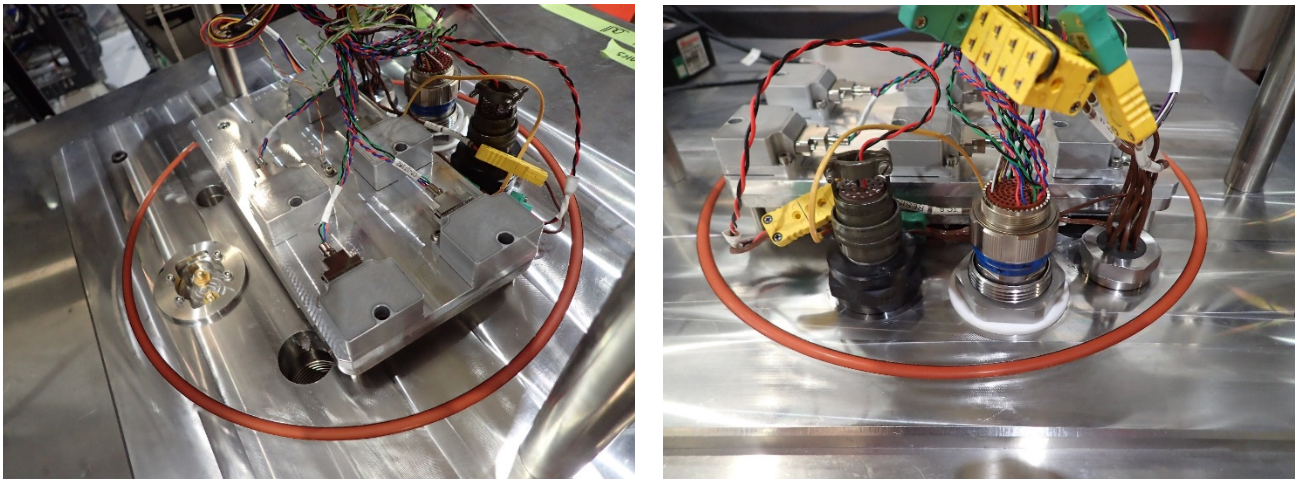

Figure 5: Bottom plate with sample holder and cable feedthrough

Figure 6: Left: Vacuum chamber, open position. Right: Chamber top with pressure gauge and relief valve

8.1.3 External Thermal Chamber Setup

IMU testing is sensitive to motion and mechanical vibration. Mitigations against all sources of mechanical interference are implemented to ensure a static test setup.

To achieve this, the thermal vacuum chamber was mounted to a stainless-steel table and cordoned off to minimize disturbances. The nature of thermal vacuum testing requires operation of a mechanical pump and solenoids that induce mechanical vibrations on the chamber and DUT. To mitigate against these disturbances, the mechanical pump was mounted on dampening foam to isolate the vibrations.

8.1.4 Performance Verification Testing

STIM377H telemetry was continuously measured throughout the thermal vacuum test to ascertain status of health, with complete coverage of operation across the full temperature range.

10-minute performance verification tests was performed throughout thermal vacuum testing to allow for performance comparison of gyroscope biases across different environmental conditions.

The performance verification tests are sensitive to motion and mechanical vibration. For this short duration test the vacuum pump and all solenoids and valves was turned off to minimize mechanical interference, such that Earth's rotation rate could be considered constant for the duration of the test. Prior to the test, the DUTs were power cycled to reset any accumulated drift from long-term operation. This approach ensures the collected data from the 10-minute performance verification tests are comparable.

8.1.5 Power conditioning and test setup

During the TVAC test, the UUTs were powered up and operating continuously. A Tenma power supply was used for powering the UUT's for the complete duration of the test. The equipment used is listed in Table 4.

Table 4: Test equipment

Equipment	Manufacturer	Model	Calibration
Power supply	Tenma	N/A	N/A
Thermocouple	National Instruments	NI9213	May 10/2022
Analog Input Module	National Instruments	NI9215	Apr 23/2022
Pressure Gauge	Edwards	Wide Range Gauge WRg-S 14.5-36V 2W	Jul 11/2021
Vacuum Pump	Edwards	N/A	N/A

8.1.6 Environmental variables and test procedure

All TVAC test steps were done in a temperature and pressure controlled environment except for the pre- and post TVAC baseline test which were done at ambient temperature and pressure. The environmental parameters and temperature profile throughout the test are given in Table 5 and Figure 7.

Table 5: Environmental variables during irradiation

Parameter	Value and Unit
Temperature range	–40°C to 80°C
Full cycles	12
Temperature tolerance	± 3 °C
Thermal stabilization criteria	± 3°C/h for 30 minutes
Transition rate	> 1°C/min
Dwell time at each plateau	60 min

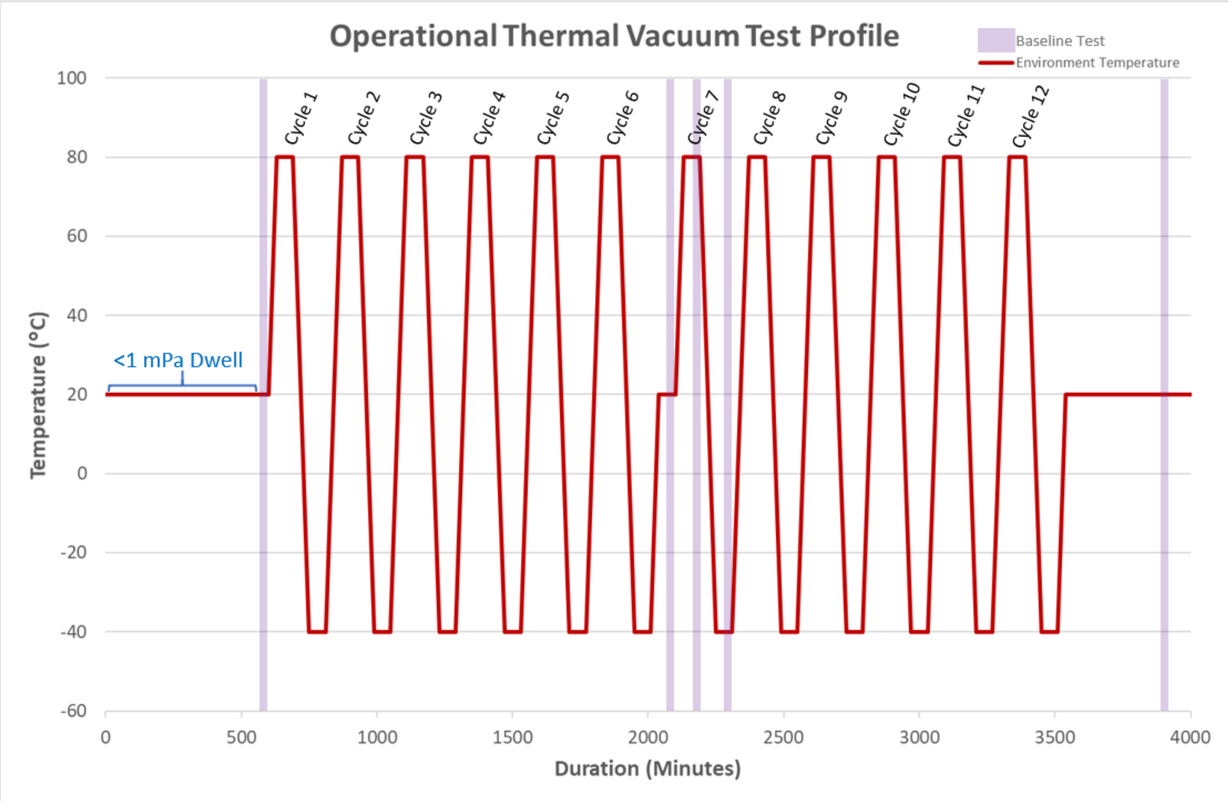

Figure 7: Operational thermal vacuum test profile

STIM377H MEMS IMUs reach thermal equilibrium within 30 minutes of operation after a temperature ramp. Therefore, the thermal dwell duration was set at 60 minutes, allowing a minimum of 30 minutes of steady-state operation.

Several “baseline” tests were performed at intervals during the test to allow performance comparisons across the test at different environmental states (see Figure 7). The vacuum pump was turned off for the duration of each of these tests to minimise noise.

Table 6: Gyroscope baseline testing events

Test Description	Environmental Temperature	Environmental Pressure	Test Sequence
Pre-TVAC Baseline	Ambient	Atmospheric	Before Vacuum
Pre-TVAC Vacuum Baseline	Ambient	< 1 mPa	End of 12-hour Vacuum Dwell
Mid-TVAC	Ambient	< 1 mPa	End of Cycle 6
Hot Mid-TVAC	80°C	< 1 mPa	Hot Dwell of Cycle 7
Cold Mid-TVAC	-40°C	< 1mPa	Cold Dwell of Cycle 7
Post-TVAC Vacuum	Ambient	< 1 mPa	End of Cycle 12
Post-TVAC	Ambient	Atmospheric	After Vacuum

8.2 Results

8.2.1 Test environment

The chamber and DUT’s was brought down to vacuum and underwent a <1 mPa dwell for >12 hours to achieve internal component vacuum equilibrium. See Figure 8 for details.

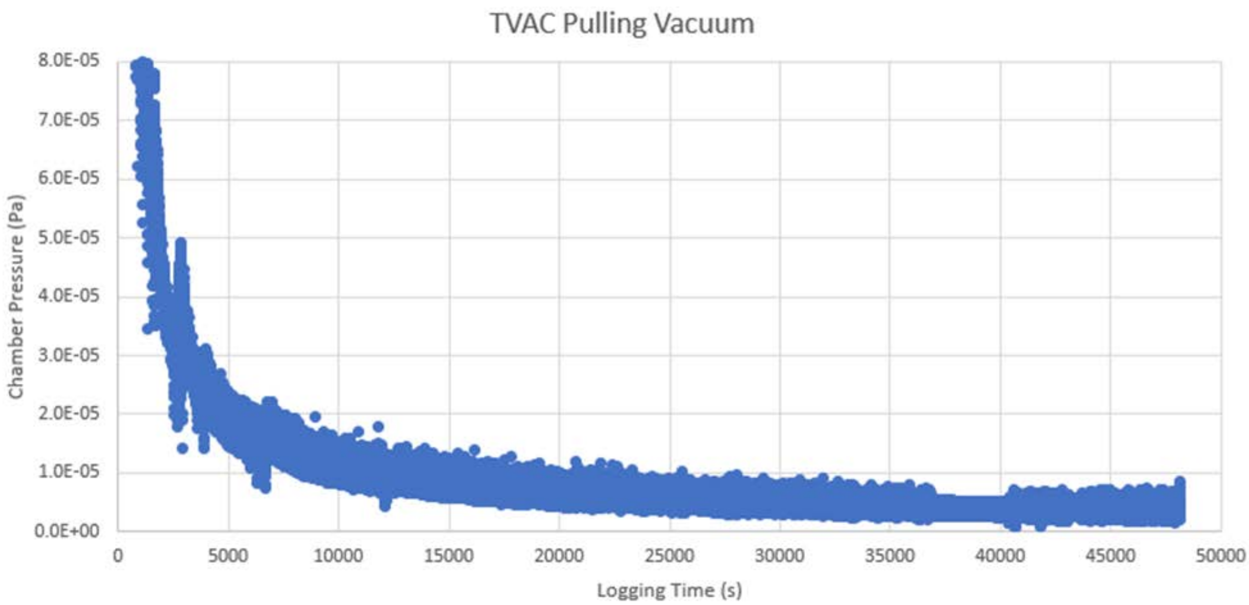

Figure 8: Environmental Pressure Vacuum Ramp

During thermal cycling, issues with the thermal vacuum control caused the first 6 thermal cycles to reach a cold dwell temperature of -37°C for a duration of 5 minutes (see Figure 9). The issue was resolved for the following 6 thermal cycles and the cold dwells reached a temperature of -40°C for a duration of 60 minutes (see Figure 10). This issue does not invalidate the thermal vacuum testing, as the cold ramp met the compliance criteria of > 1°C/min and the coldest recorded environmental temperature is –37°C and within the ±3°C bounds of the dwell temperature tolerance.

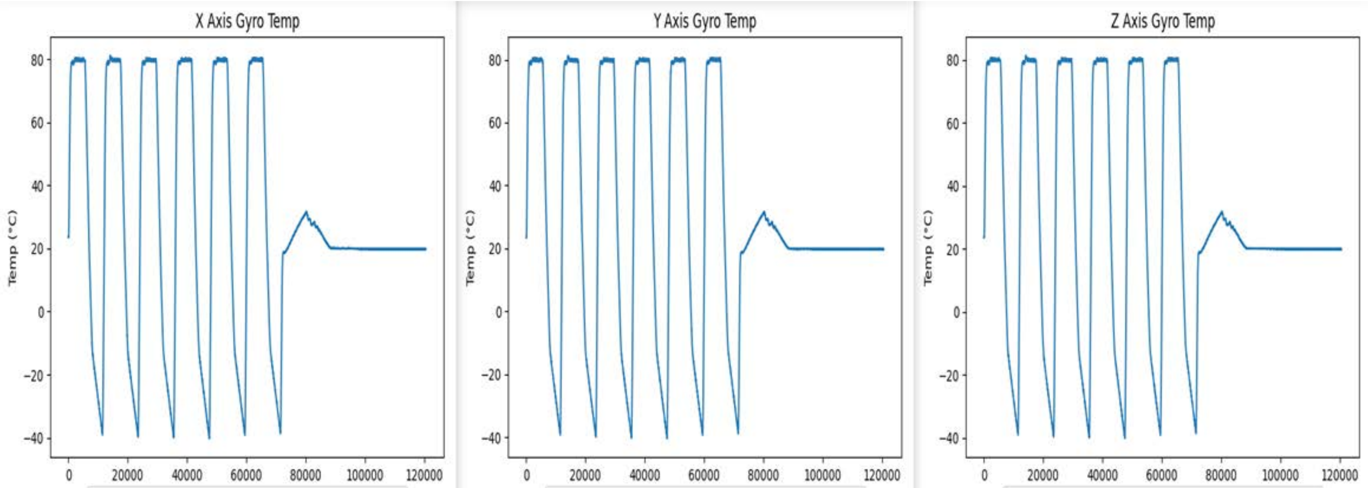

Figure 9: First 6 thermal cycles

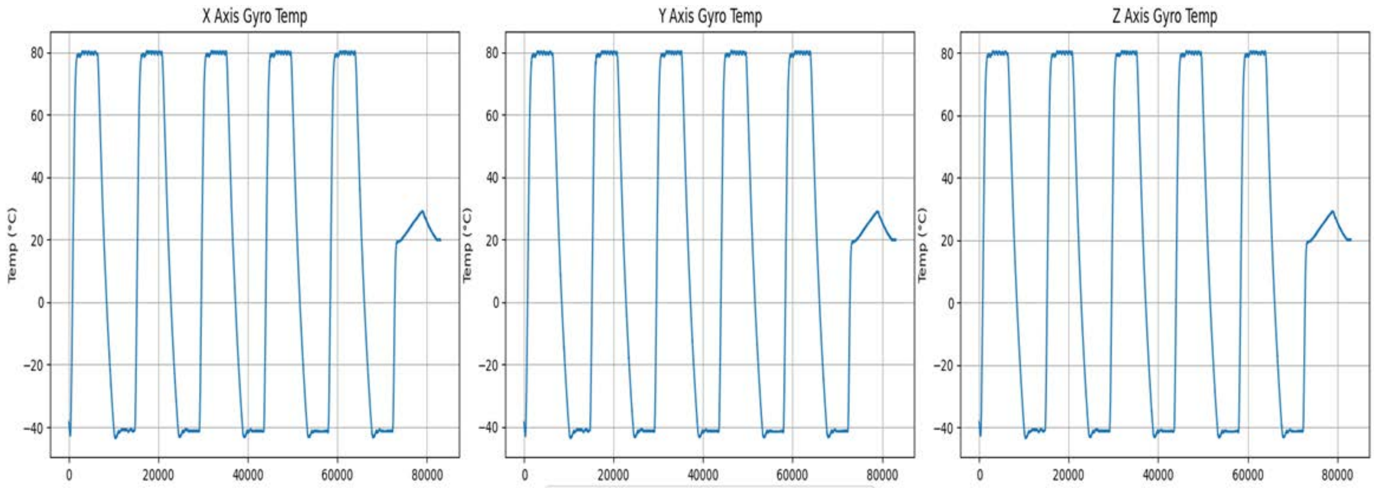

Figure 10: Last 6 thermal cycles

After the completion of thermal cycling, the chamber and DUT was ramped back to atmospheric pressure over a 5-minute duration.

8.2.2 TVAC Performance Results

The units remained operational, and no data dropouts were observed for the duration of the test. Performance comparison of gyroscope biases across different environmental conditions are presented in the following histograms. The biases were measured as part of the 10-minute performance verification tests performed throughout thermal vacuum testing. The summary of the tests is provided in Table 6.

All gyroscope bias change measurements are the absolute change relative to the Pre-TVAC Vacuum test.

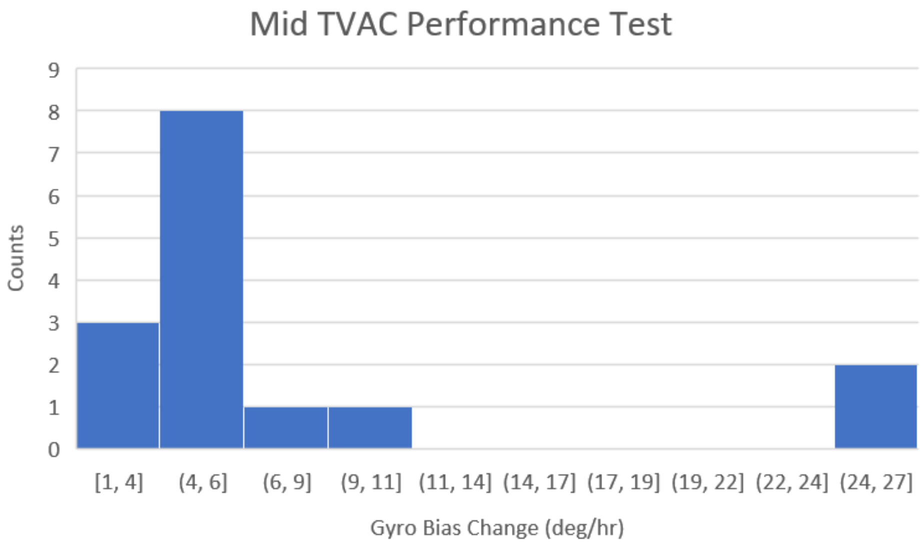

Figure 11: Absolute difference in gyro biases at 20°C between before Cycle 1 and after Cycle 6.

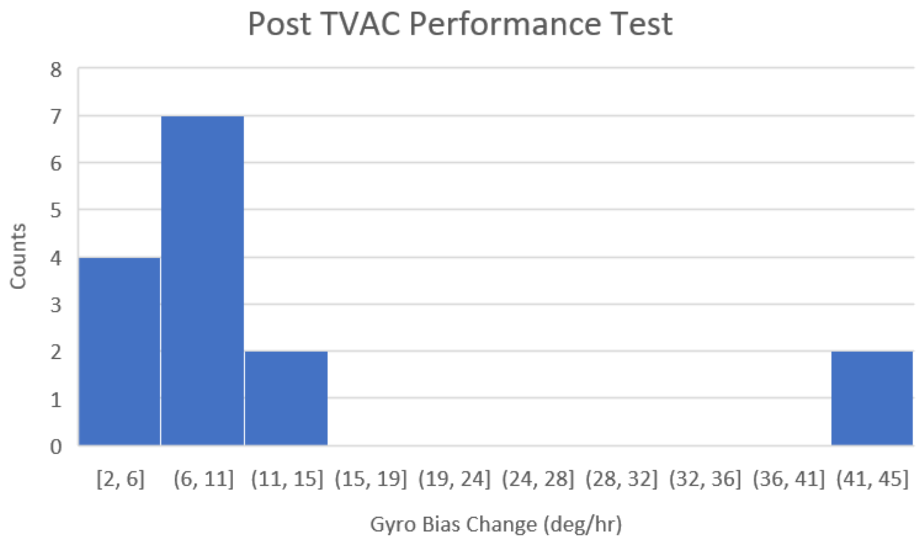

Figure 12: Absolute difference in gyro biases at 20°C between before Cycle 1 and after Cycle 12.

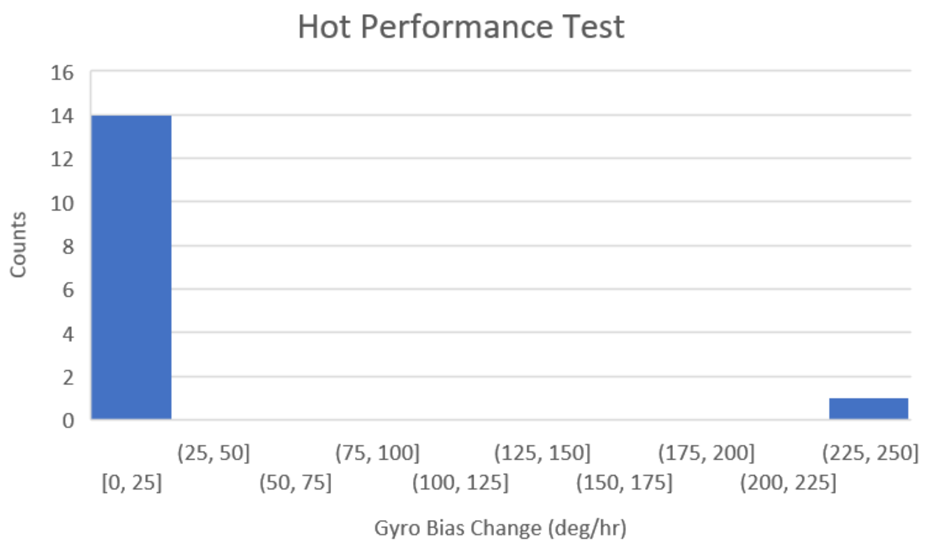

Figure 13: Absolute difference in gyro biases after Cycle 6 between 20°C and 80°C.

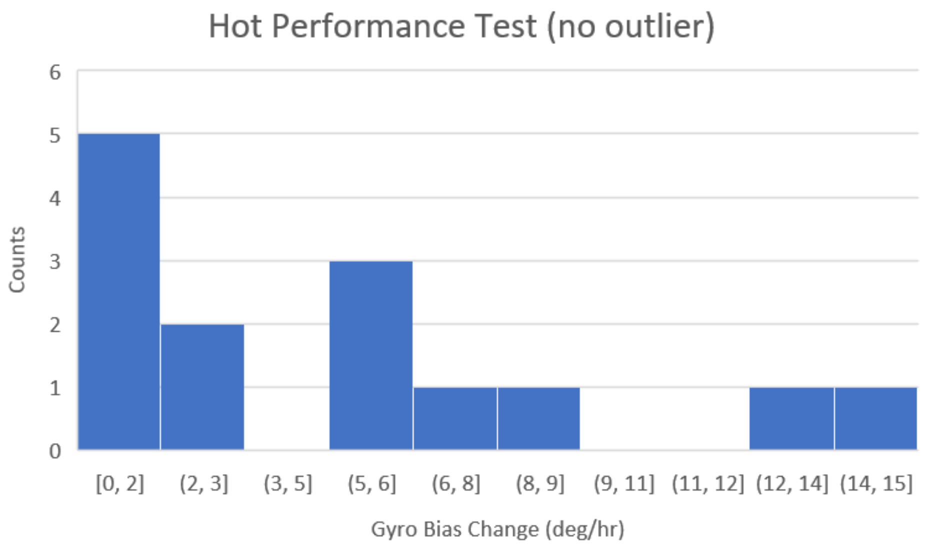

Figure 14: Absolute difference in gyro biases after Cycle 6 between 20°C and 80°C. The outlier around 250°/hr was removed here.

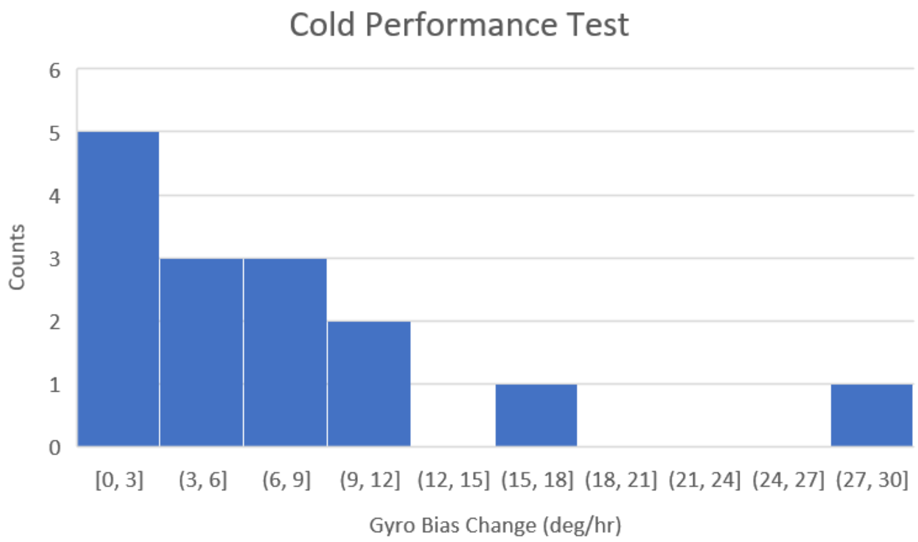

Figure 15: Absolute difference in gyro biases after Cycle 6 between 20°C and –40°C.

Table 7: Gyroscope bias change summary

Performance Verification Test	Bias change (°/h rms)
Mid-TVAC	10.9
Post-TVAC Vacuum	17.9
Hot Mid-TVAC	64.9
Hot Mid-TVAC (outlier removed)	6.6
Cold Mid-TVAC	11.7

A bias change of approximately 250°/hr is observed in the Z-axis gyroscope of UUT1 at an environmental temperature of 80°C. This bias change is present in comparison of the ambient Mid-TVAC and Post-TVAC performance verification results (see Figure 16). This unit's change in gyroscope bias is an outlier compared to the three other DUT's.

Apart from the outlier gyroscope, the rest of the data is comparable to operation in ambient conditions.

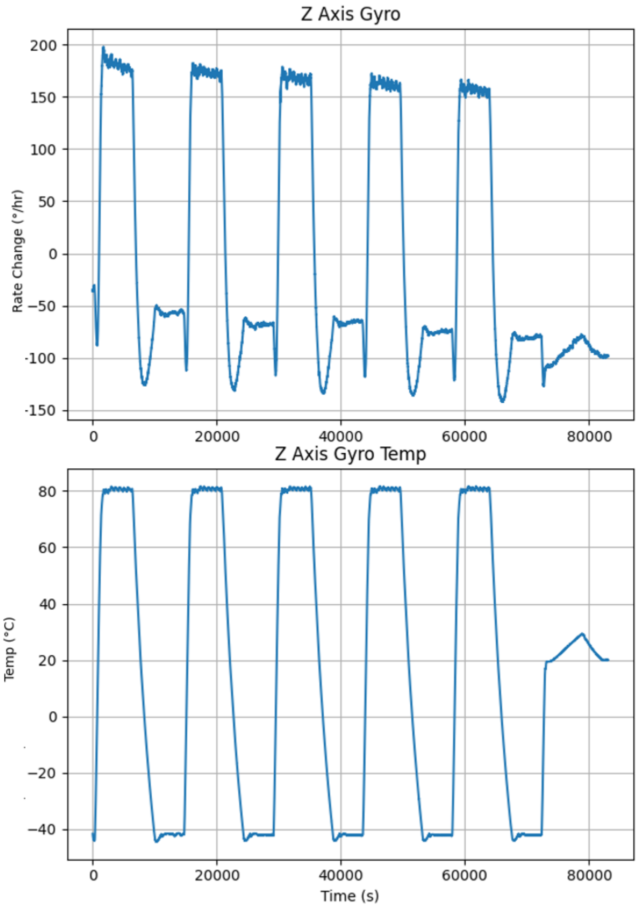

Figure 16: UUT1 Z-axis gyroscope bias change and temperature over last 5 cycles.

8.2.3 UUT failure classification

After return to Sensonor, an initial inspection was done to verify the hardware status of all irradiated units. No units indicate hardware errors.

8.2.4 Post TVAC test verification

Bias offset and Scale Factor were measured in the Sensonor production line. The results from these tests have been compared to the results of identical measurements made before the TVAC test. A summary can be found in Table 8.

Table 8: Summary of results of functional parts after TVAC-test

STIM377H, functional after TVAC	Parameter		
	Gyro	Acc	Inc
Result	FAIL	PASS	PASS

One gyro axis (Z-axis) in UUT1 showed a significant drift in gyro bias after TVAC testing, especially at high temperature (see Figure 26). The bias level after TVAC was measured to 728.9 °/h. Before TVAC test, the bias level at 85 °C was measured to 75.9 °/h. This results in a bias drift of approximately +653 °/h.

When observing the bias level development of this particular axis throughout the TVAC test cycles (see Figure 17), we see a decline in bias level of approximately -83.3 °/h. This does clearly indicate that the large bias drift is not induced by the TVAC test itself, but caused by an inherent weakness in the gyro itself.

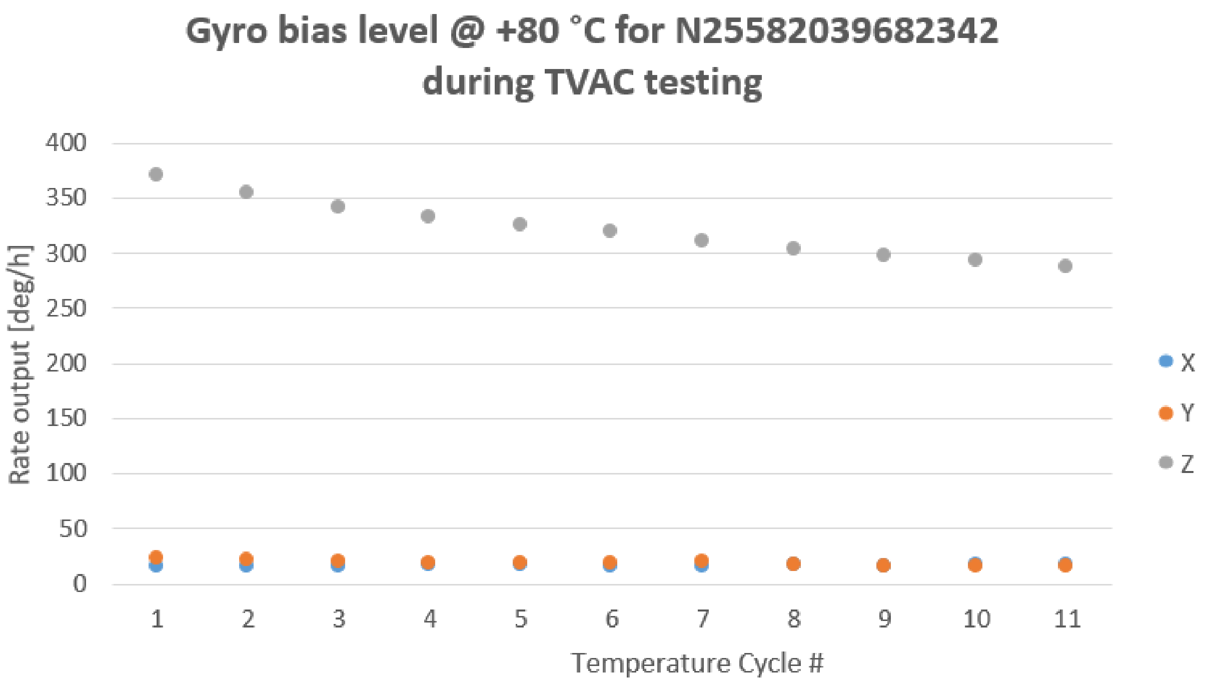

Figure 17: Bias level of gyros in UUT1 during TVAC test

The plots in Figure 18 to Figure 23 show the absolute value of the bias and scale factor change at 25 °C between pre- and post-tests. The boxplots represent the interquartile range with the middle line representing the median. The full comparison of test results can be found in Appendix A.

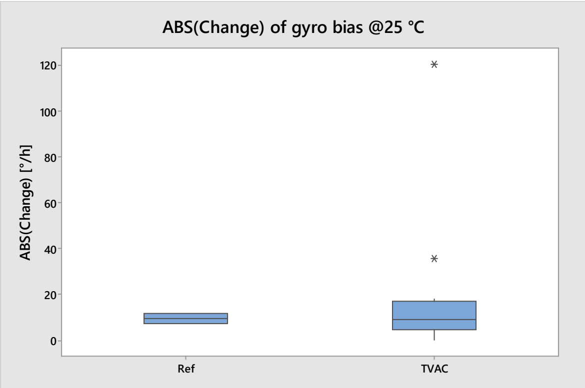

Figure 18 Change in gyro bias

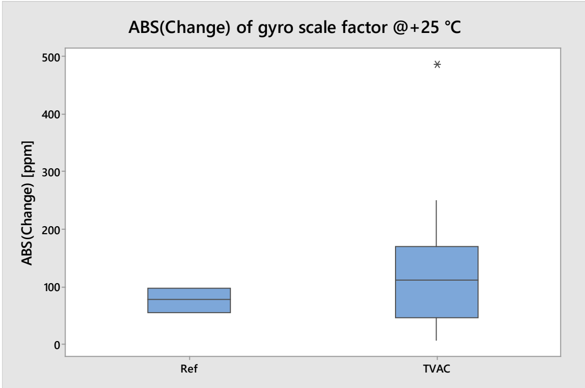

Figure 19 Change in gyro scale factor

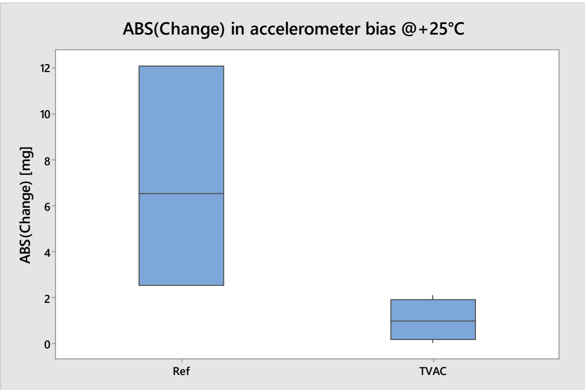

Figure 20 Change in accelerometer bias

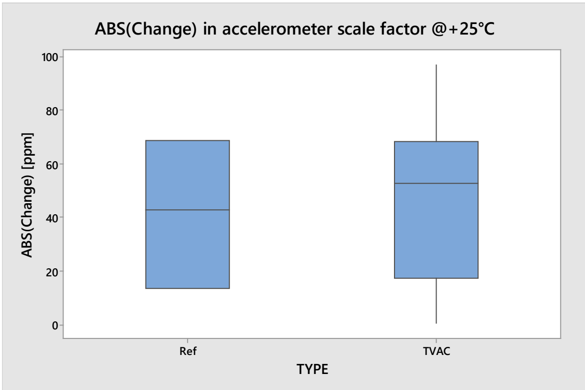

Figure 21 Change in accelerometer scale factor

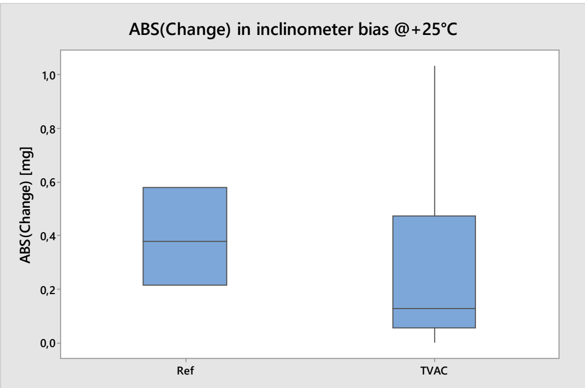

Figure 22 Change in inclinometer bias

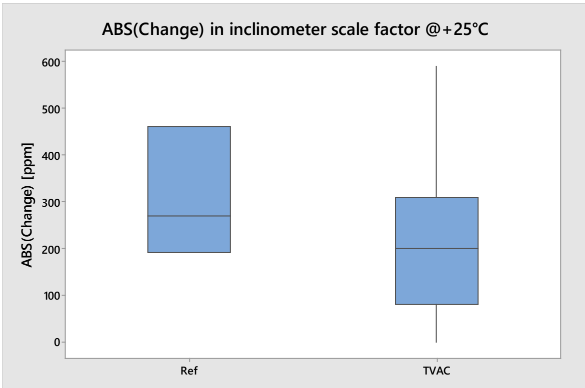

Figure 23 Change in inclinometer scale factor

9 Discussion of results

9.1 TVAC Test

With reference to the pre- and post-test comparison, ref. Appendix A, the following observations were made:

- The TVAC testing does not cause any significant change in performance of the STIM377H

The gyro bias for the Z-axis on UUT1 had a significant change. When examining the production test results for this particular axis before and after the TVAC test, it is clear that especially for elevated temperatures this change in bias is more distinct. A bias change of approximately 653°/h is measured at 80 °C. However, this particular axis had a distinct signature indicating it could be prone to display an abnormal behavior prior to TVAC testing. It is not likely this behavior was caused by the TVAC test itself.

10 Conclusions

Four STIM377H MEMS IMUs performance and functionality were fully characterized over the temperature range of -40 °C to 80 °C in a vacuum of < 1 mPa.

Table 9 provides the average change in gyroscope bias relative to the baseline test performed in ambient conditions prior to thermal vacuum testing.

Table 9: Results summary

Performance Test	Gyro Average Bias change (°/h rms)
Post-Thermal Vacuum Testing at 20°C in Vacuum	17.9
Cycle 7 Hot Dwell (80°C) in Vacuum	64.9
Cycle 7 Cold Dwell (-40°C) in Vacuum	11.7

Performance of the units remained within operational limits throughout testing. 1 of the 12 gyroscope axes exhibited a 250°/hour bias during hot dwells which was on the operational limit but was considered to remain a favorable result as this was within manufacturer performance specification.

Operation of STIM377H MEMS IMUs in thermal vacuum met all operational compliance criteria.

A Verification Test results comparisons before and after TVAC test

The following figures shows the performance before and after TVAC test on the key parameters; bias change and scale factor error

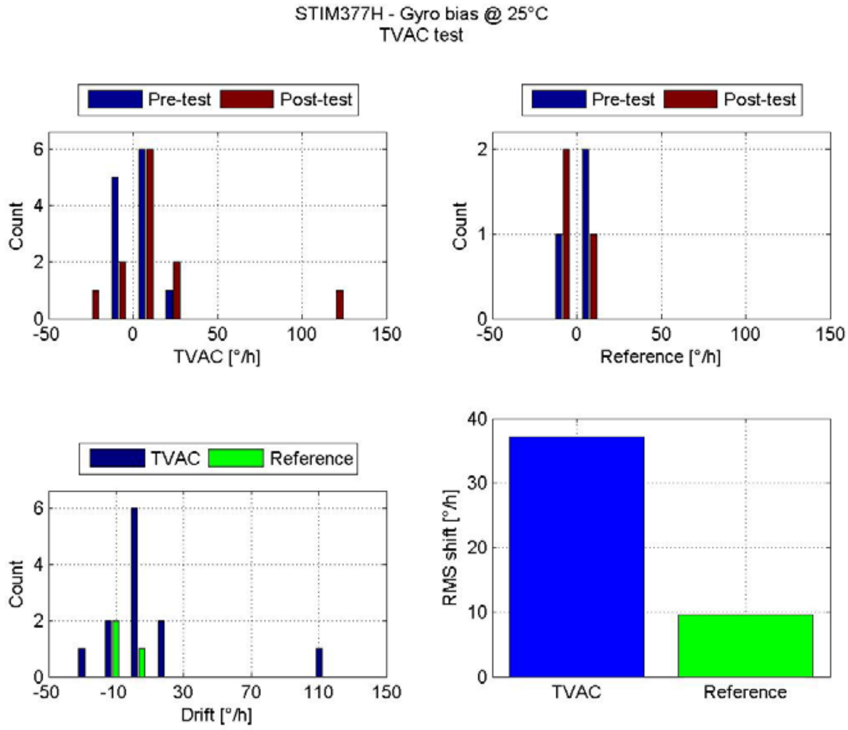

Figure 24 Gyro bias at +25 °C before and after TVAC test

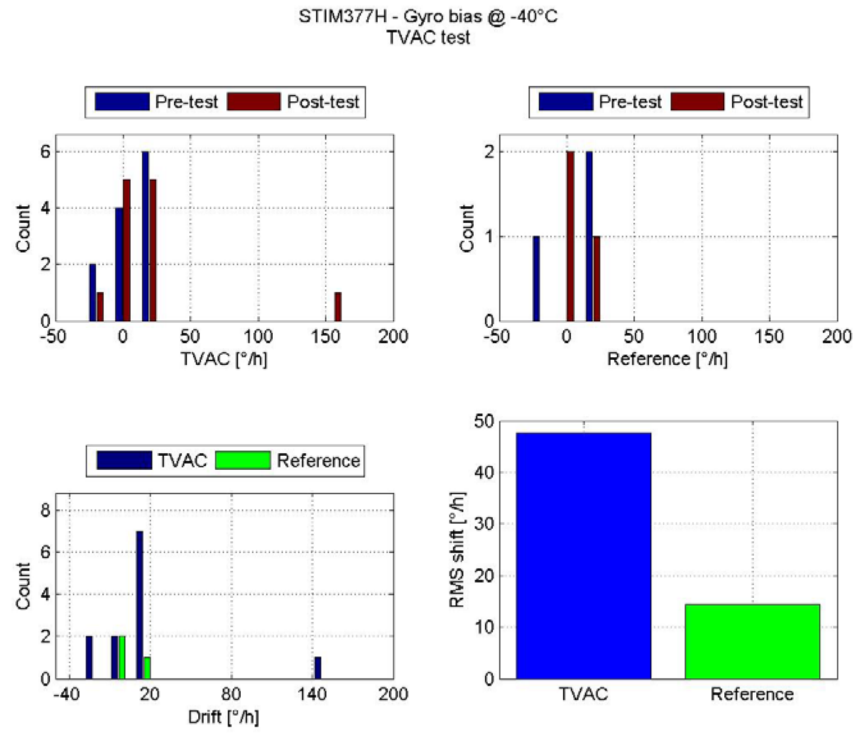

Figure 25 Gyro bias at -40°C before and after TVAC test

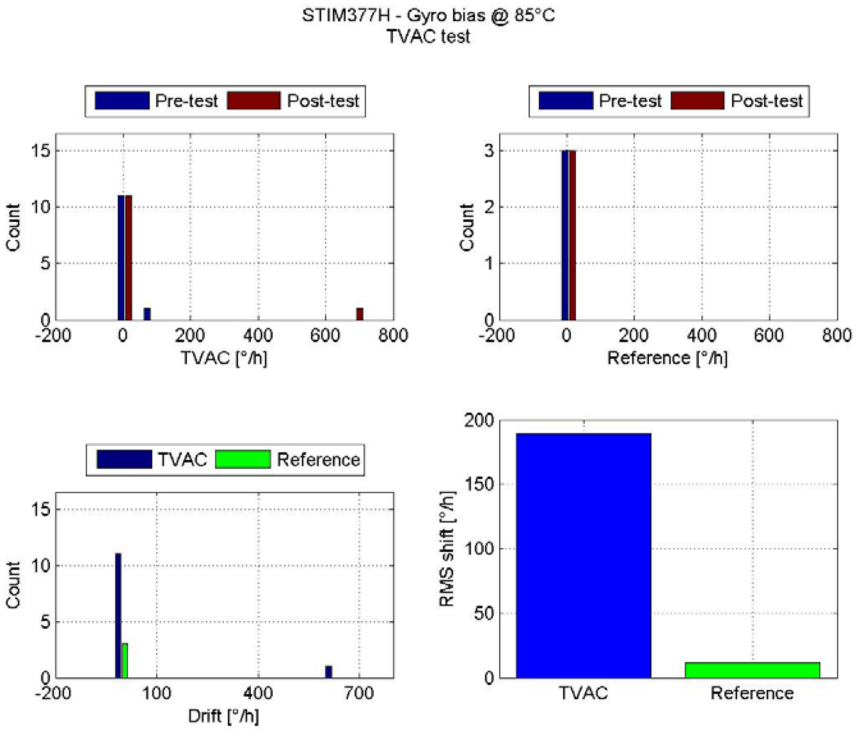

Figure 26 Gyro bias at +85 °C before and after TVAC test

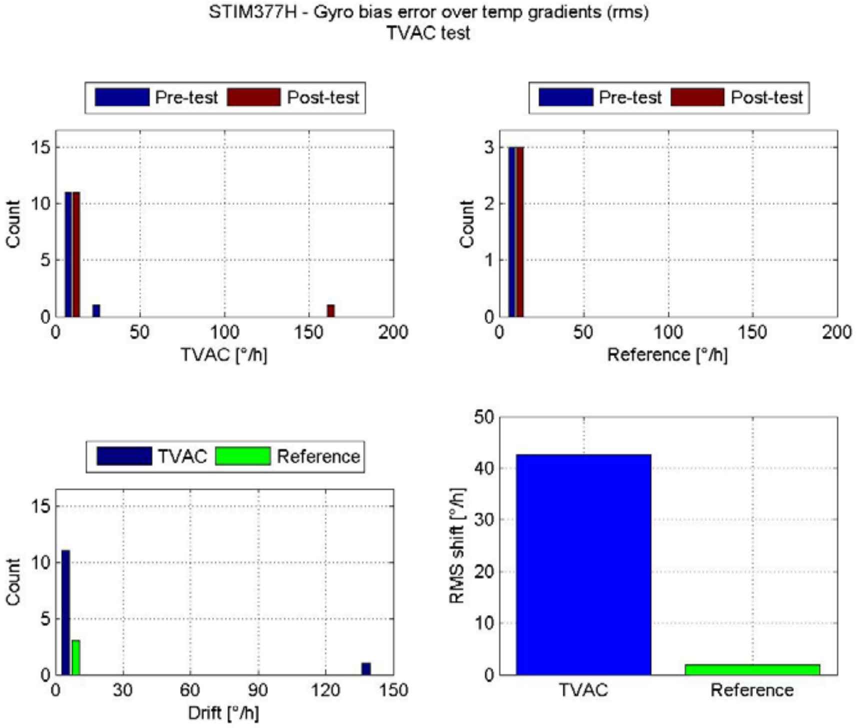

Figure 27 Gyro RMS bias error over temperature gradient before and after TVAC test

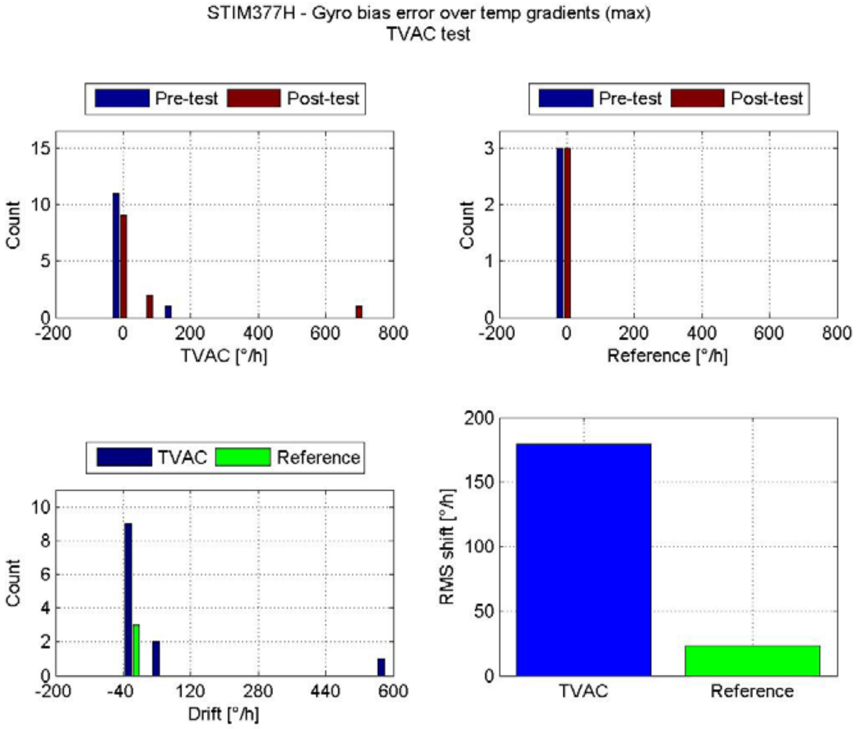

Figure 28 Gyro maximum bias error over temperature gradient before and after TVAC test

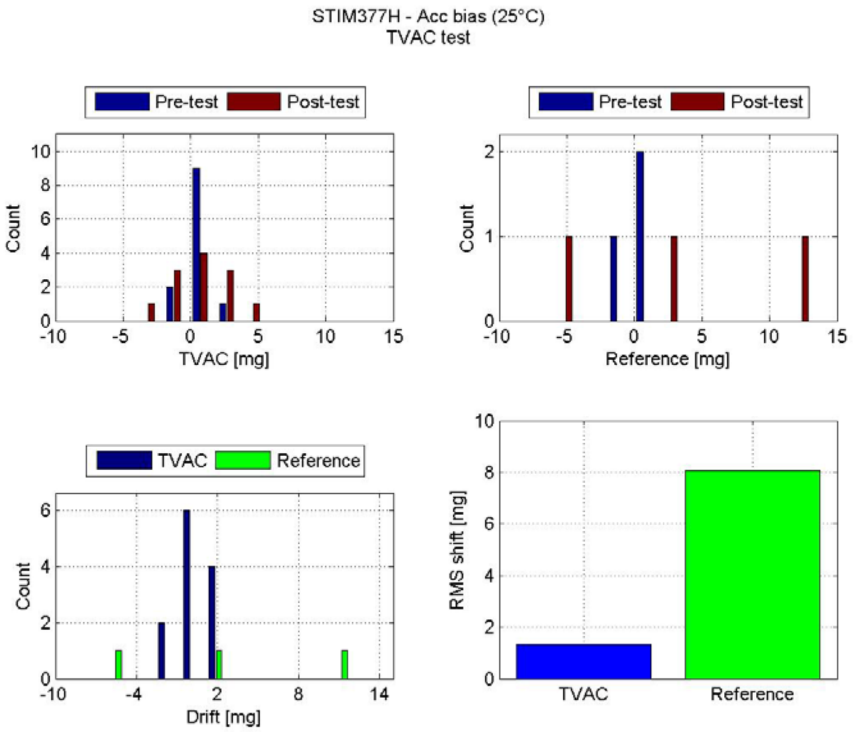

Figure 29 Accelerometer bias at +25 °C before and after TVAC test

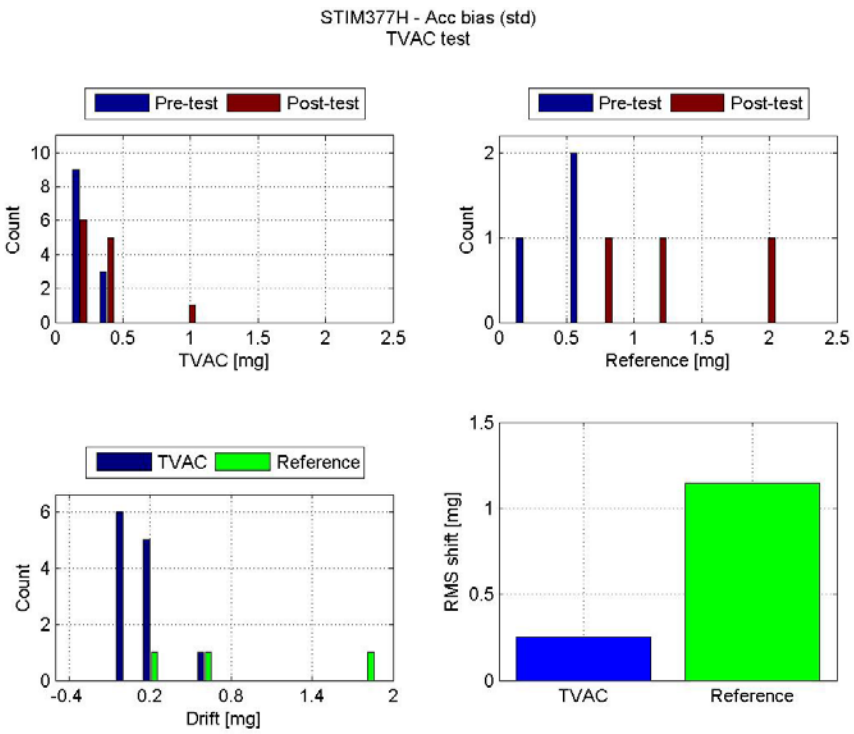

Figure 30 Accelerometer bias standard devation over temperature before and after TVAC test

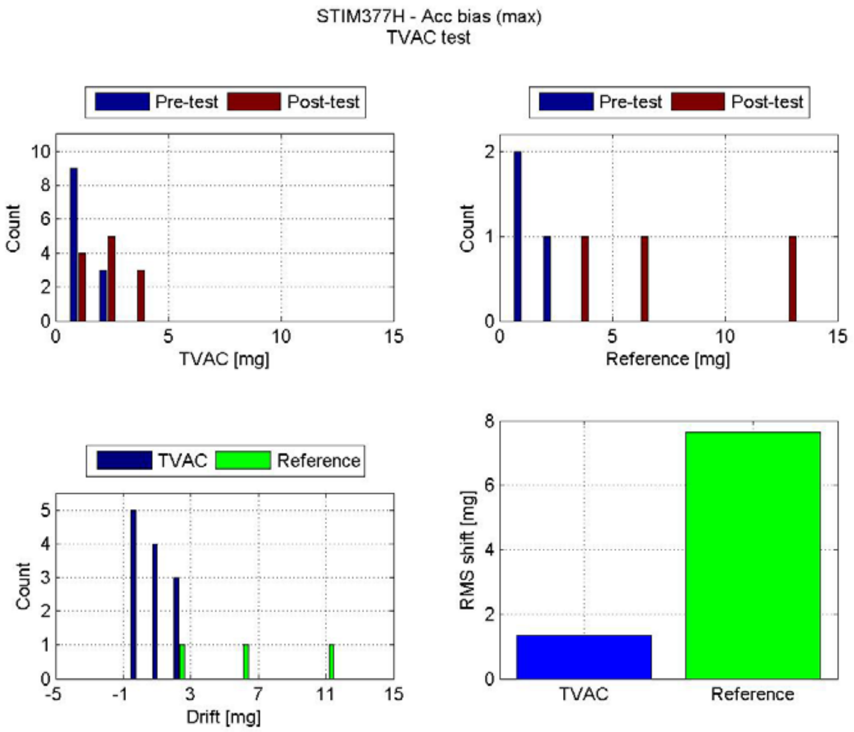

Figure 31 Accelerometer Max devation over temperature before and after TVAC test

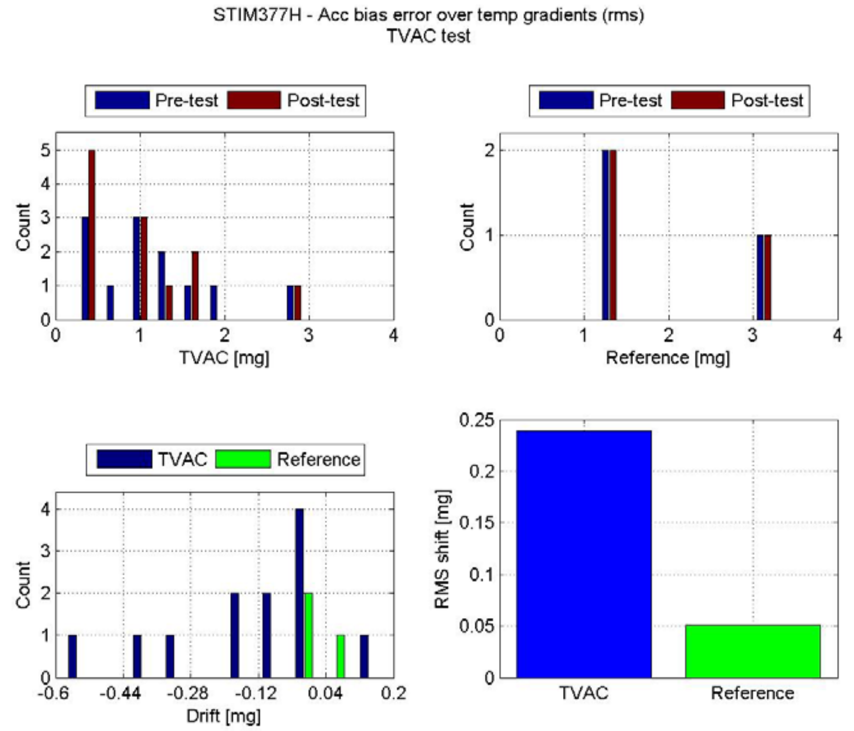

Figure 32 Accelerometer RMS bias error over temperature gradient before and after TVAC test

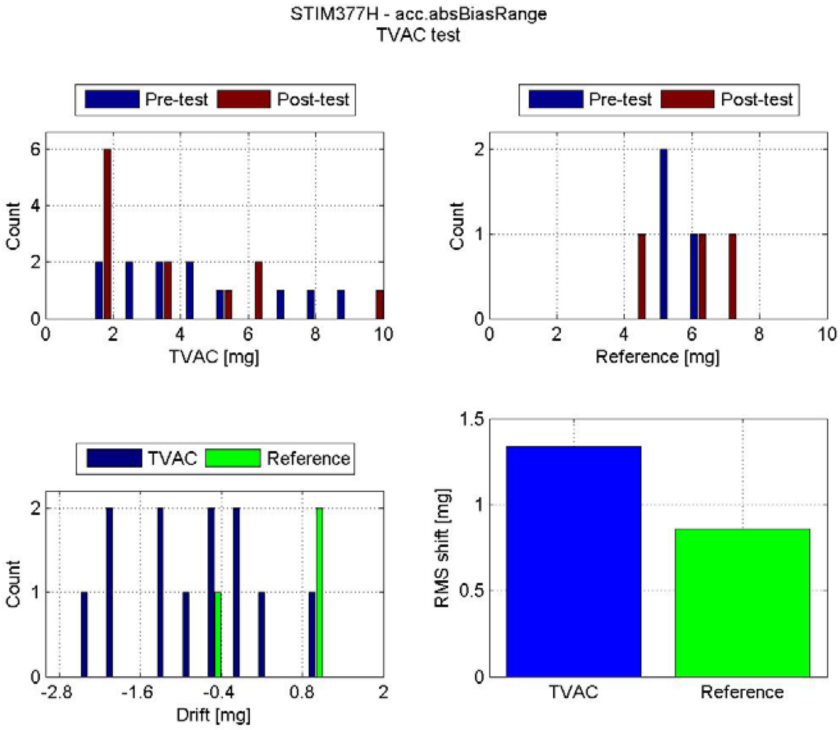

Figure 33 Accelerometer bias range over temperature gradient before and after TVAC test

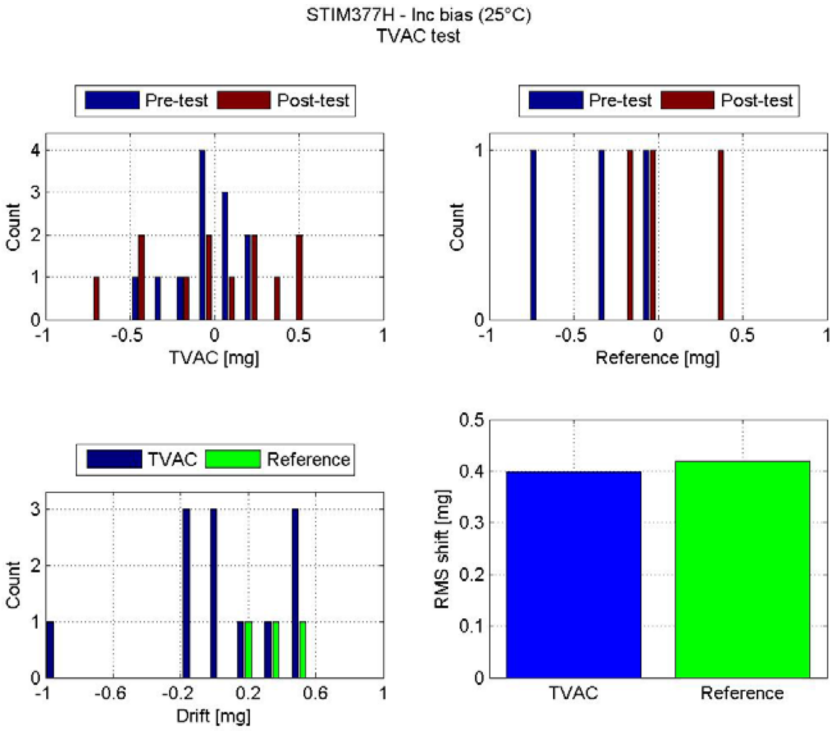

Figure 34 inclinometer bias at +25 °C after TVAC test

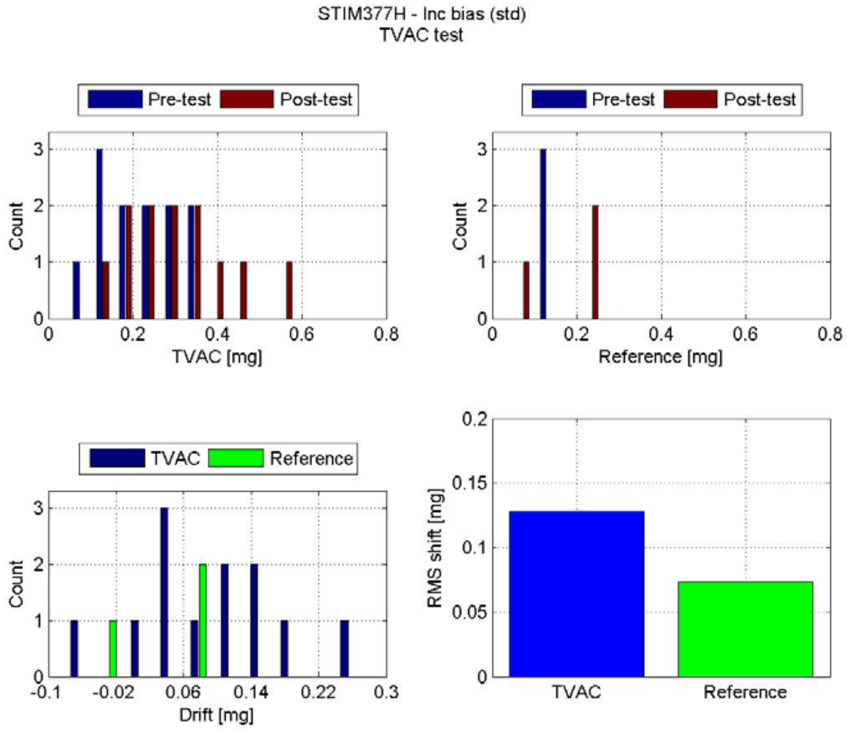

Figure 35 Inclinometer bias standard devation over temperature before and after TVAC test

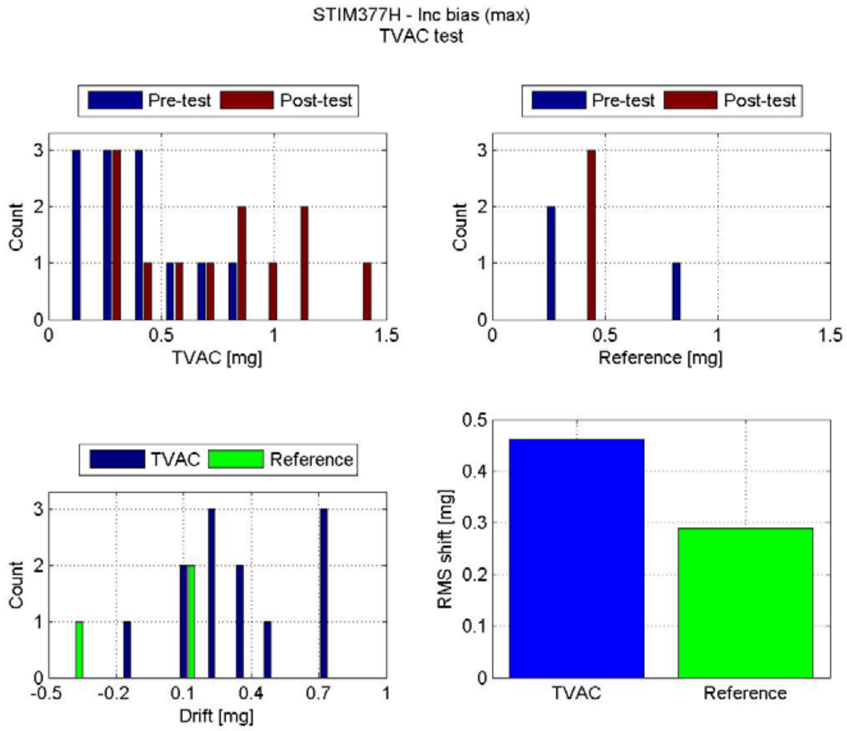

Figure 36 Inclinometer bias maximum devation over temperature before and after TVAC test

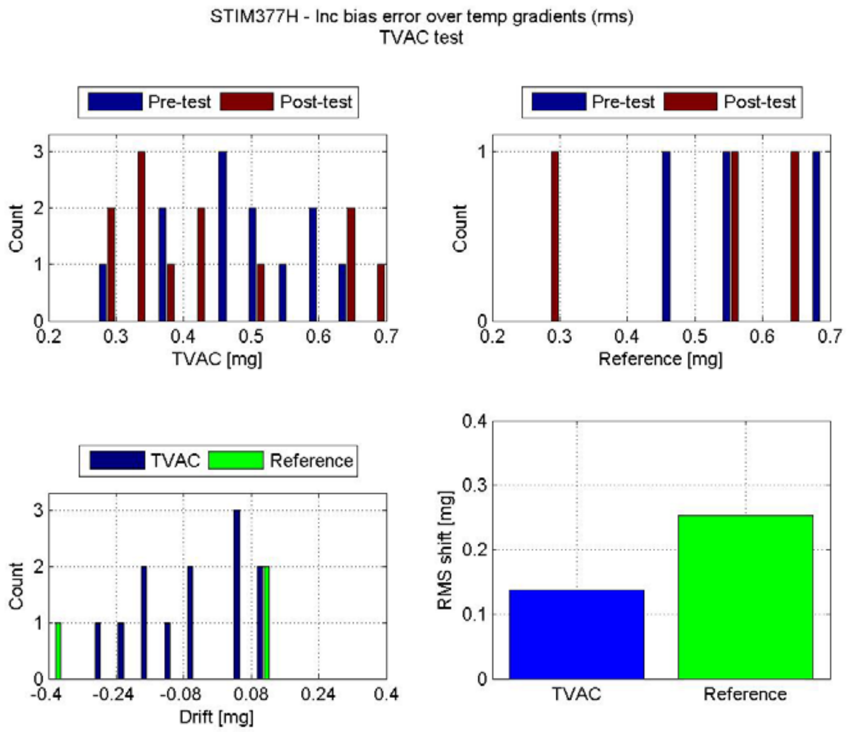

Figure 37 Inclinometer RMS bias error over temperature gradient before and after TVAC test

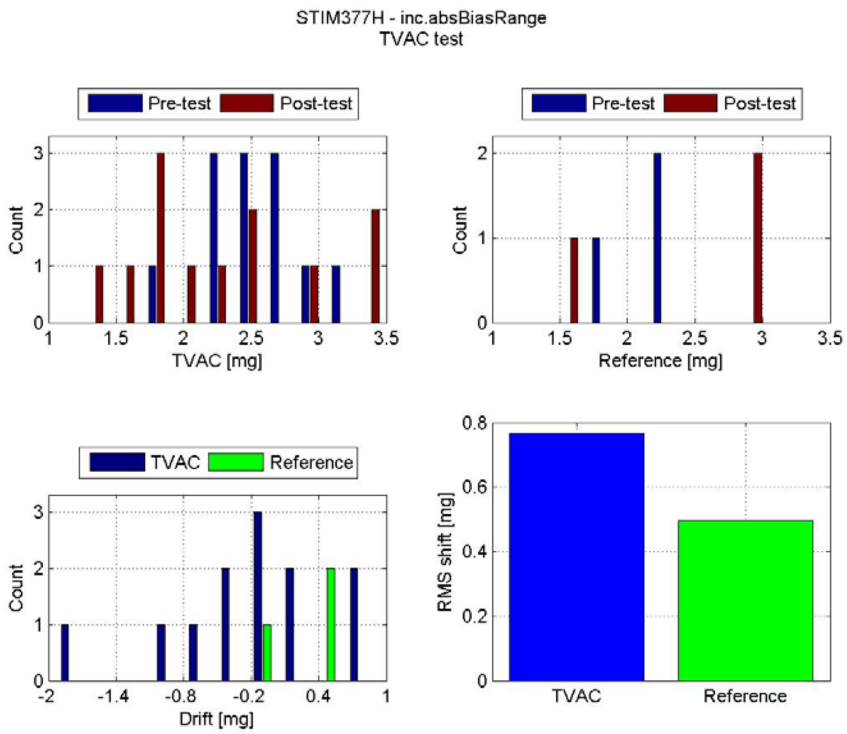

Figure 38 Inclinrometer bias range over temperature gradient before and after TVAC test

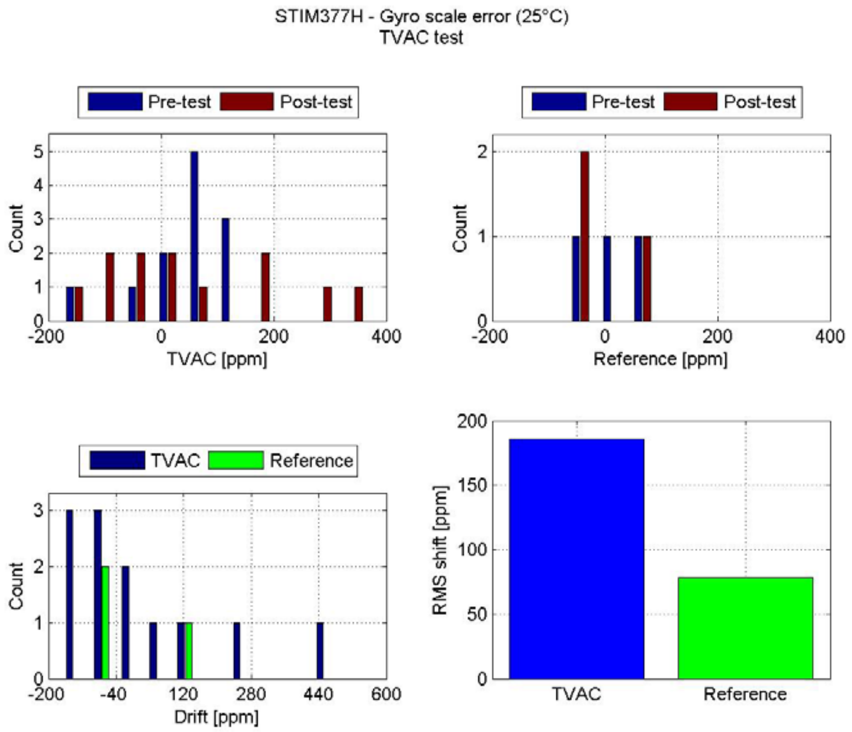

Figure 39 Gyro Scale factor error at +25 °C before and after TVAC test

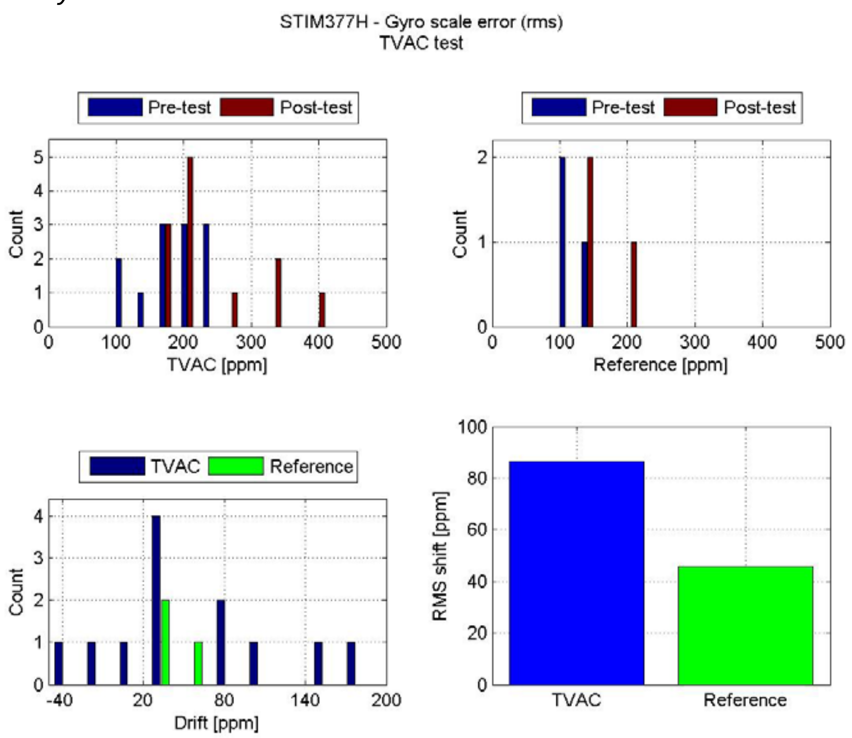

Figure 40 Gyro RMS Scale factor error over temperature before and after TVAC test

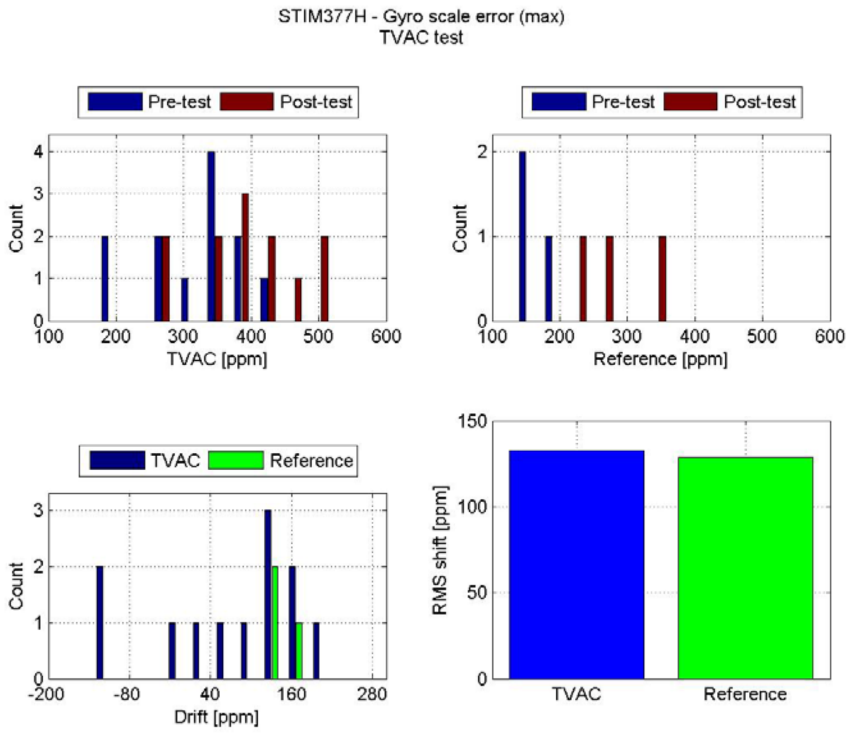

Figure 41 Gyro maximum Scale factor error over temperature before and after TVAC test

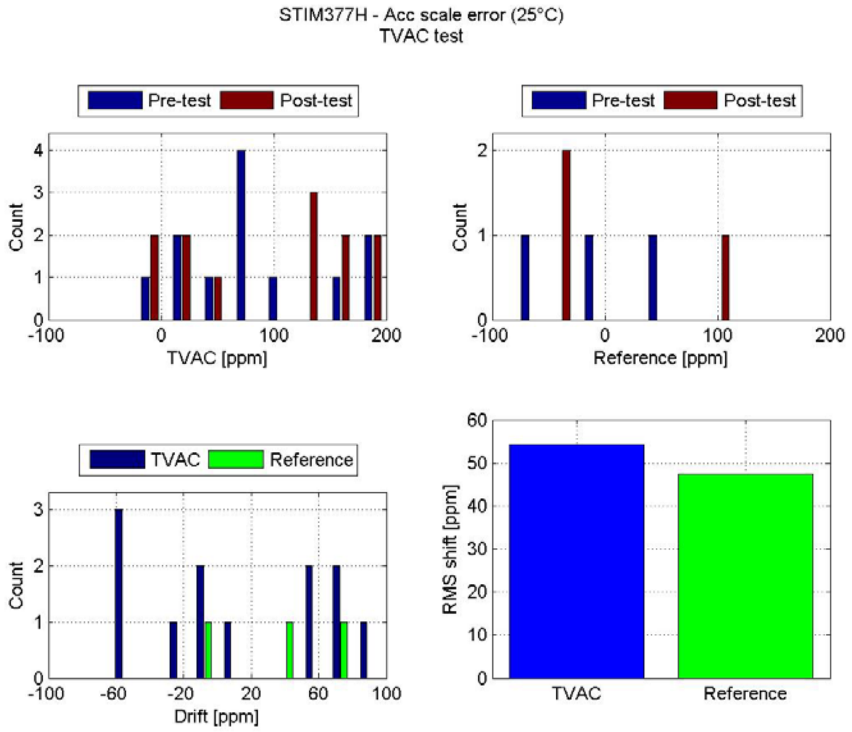

Figure 42 Accelerometer Scale factor error at +25 °C before and after TVAC test

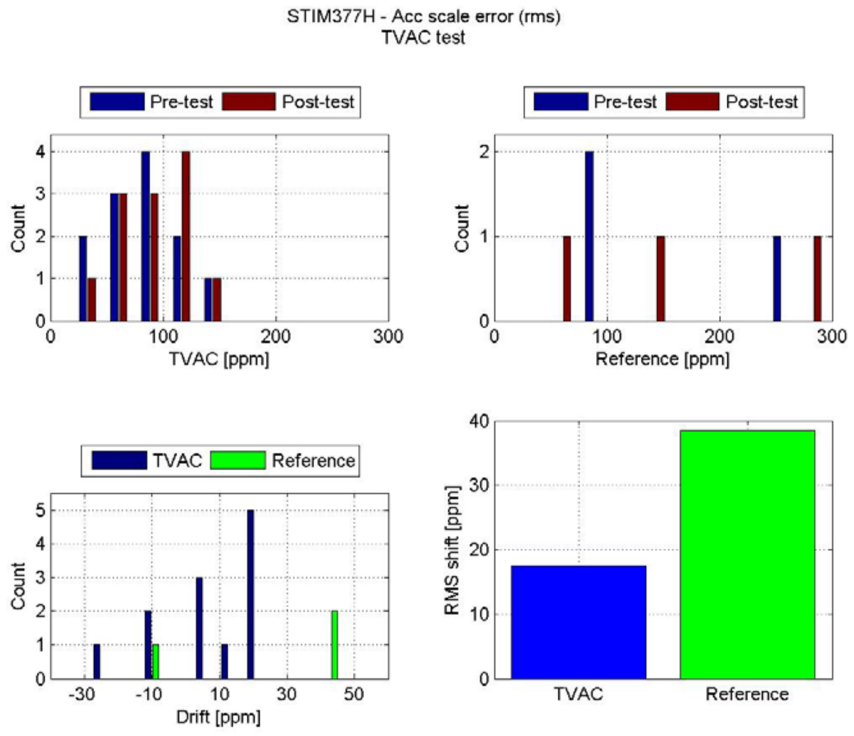

Figure 43 Accelerometer RMS Scale factor error over temperature before and after TVAC test

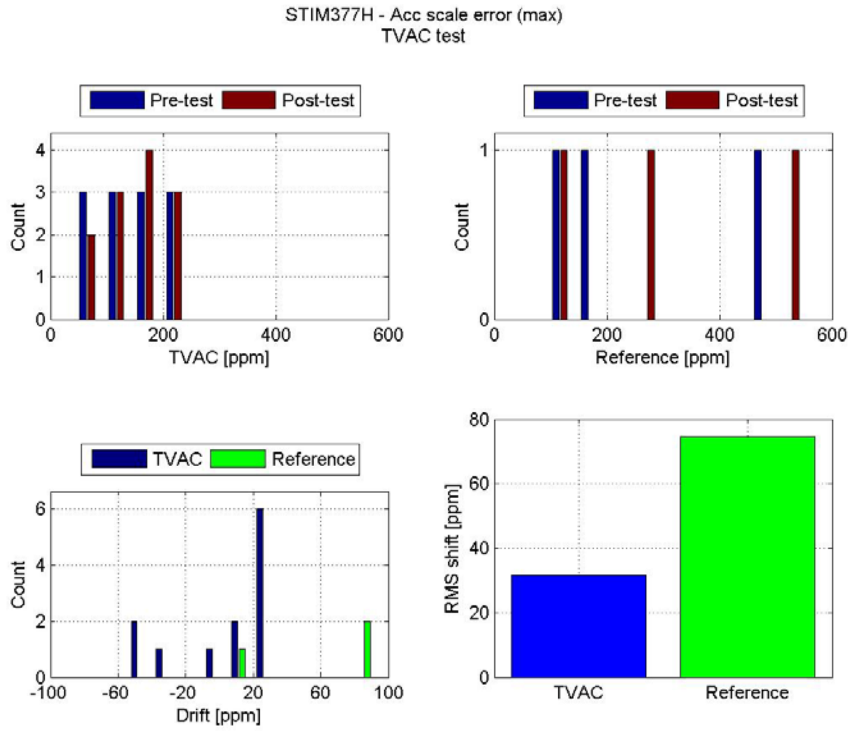

Figure 44 Accelerometer maximum Scale factor error over temperature before and after TVAC test

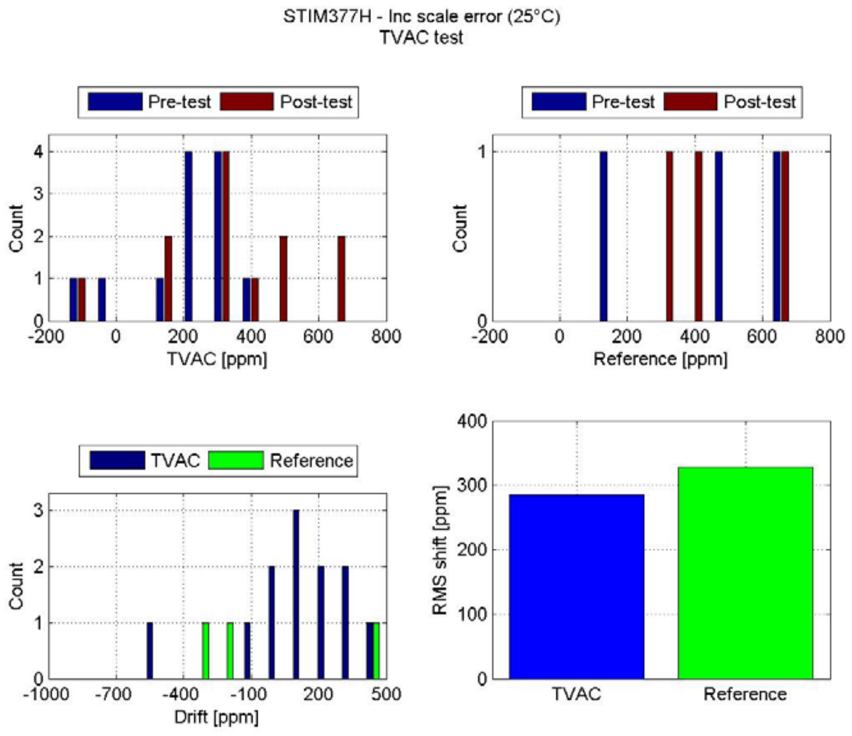

Figure 45 Inclinometer Scale factor error at +25 °C before and after TVAC test

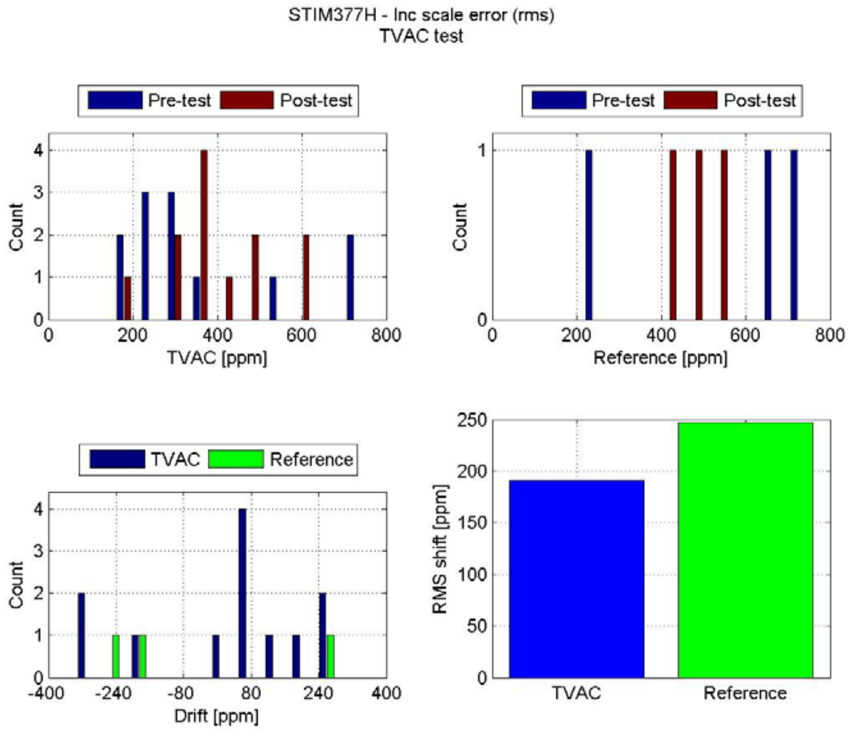

Figure 46 Inclinometer RMS Scale factor error over temperature before and after TVAC test

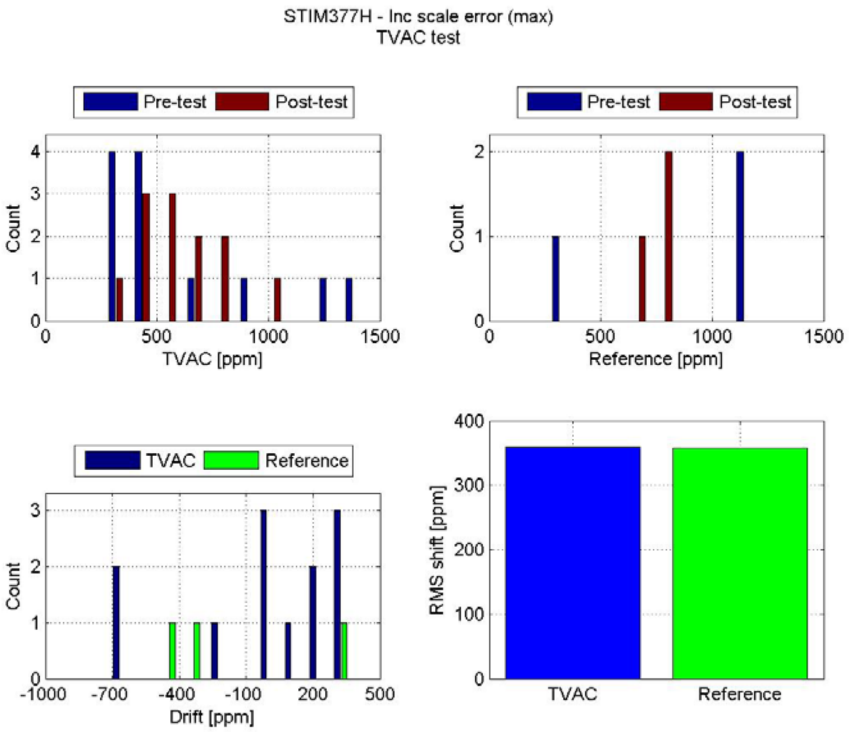

Figure 47 Inclinometer maximum Scale factor error over temperature before and after TVAC test

B Measurements during TVAC testing

The following figures shows the performance during TVAC test on gyro bias

UUT1 (N25582039682342)

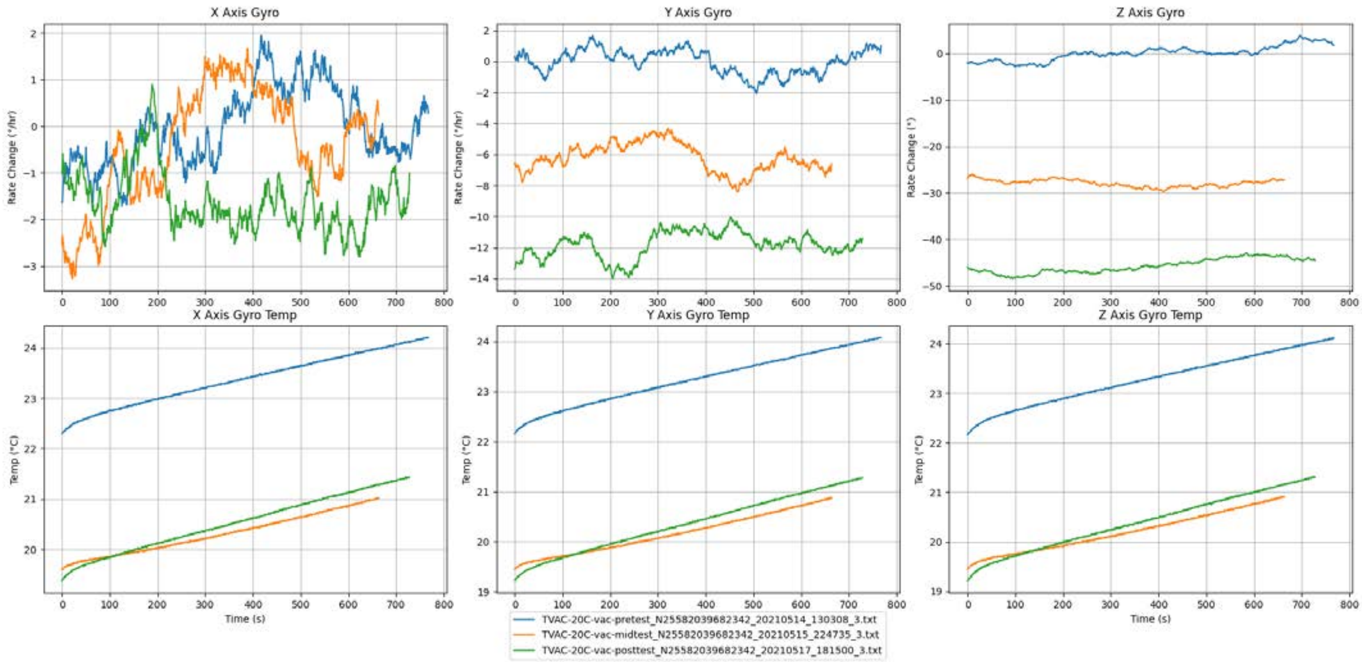

Figure 48: UUT1 gyroscope bias changes at ambient temperature under vacuum measured with vacuum pump off at start, mid and end of test

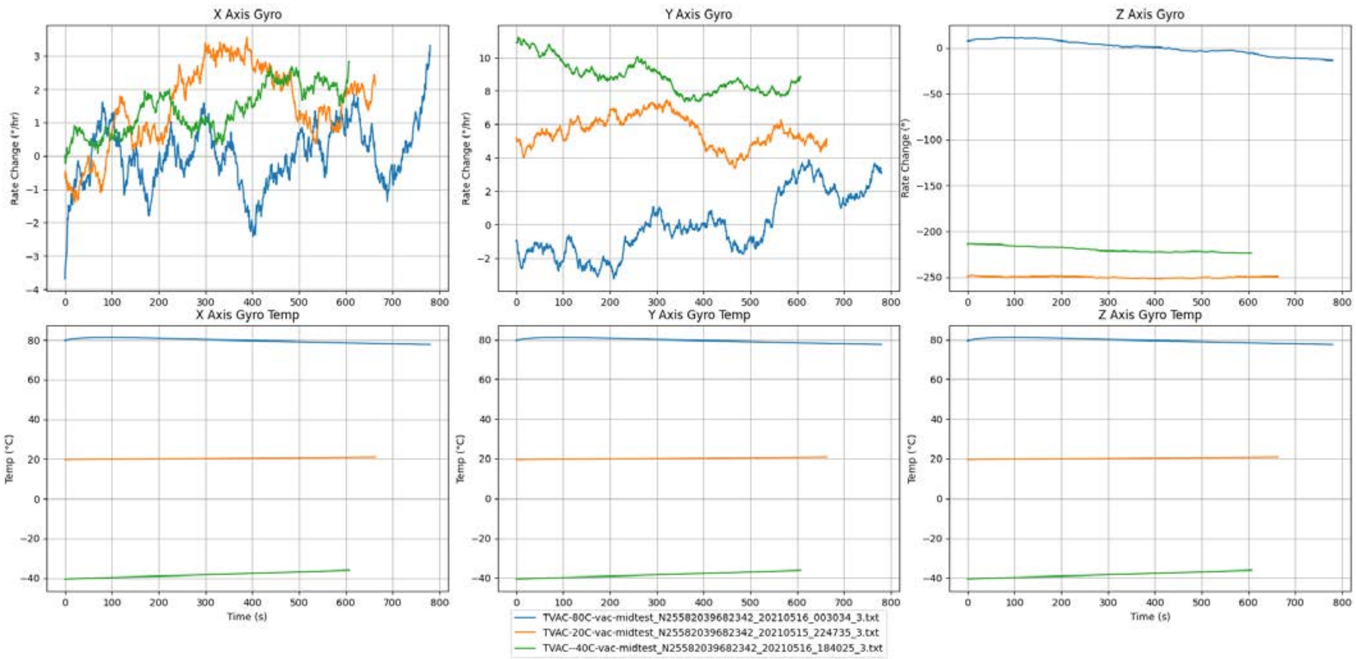

Figure 49: UUT1 gyroscope bias changes under vacuum measured with vacuum pump off at 20°C, 80°C and –40°C

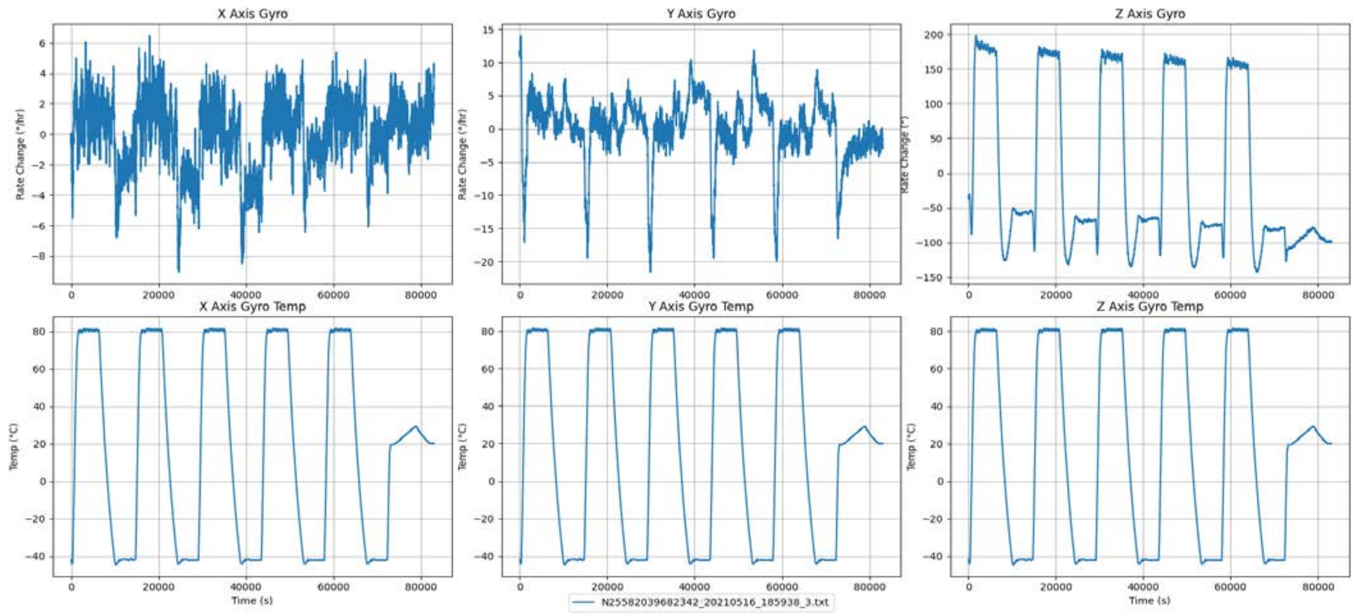

Figure 50: UUT1 gyroscope bias changes and temperature during last 5 cycles

UUT2 (N25582032536730)

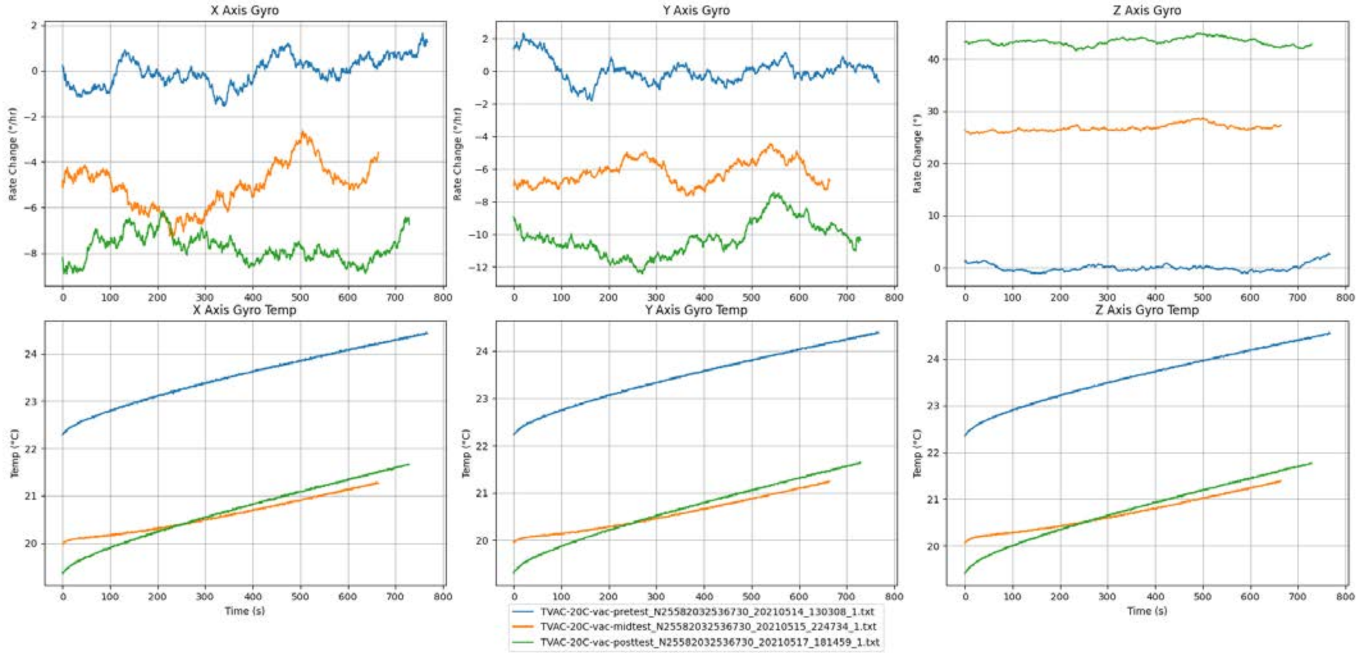

Figure 51: UUT2 gyroscope bias changes at ambient temperature under vacuum measured with vacuum pump off at start, mid and end of test

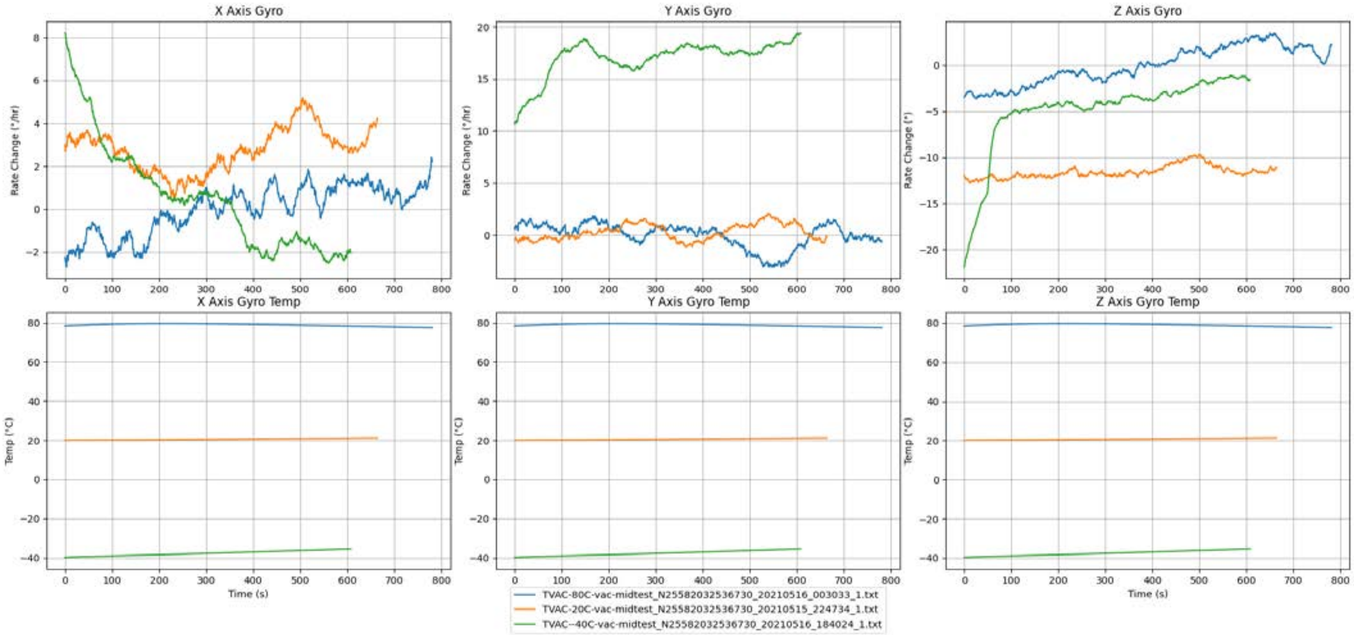

Figure 52: UUT2 gyroscope bias changes under vacuum measured with vacuum pump off at 20°C, 80°C and –40°C

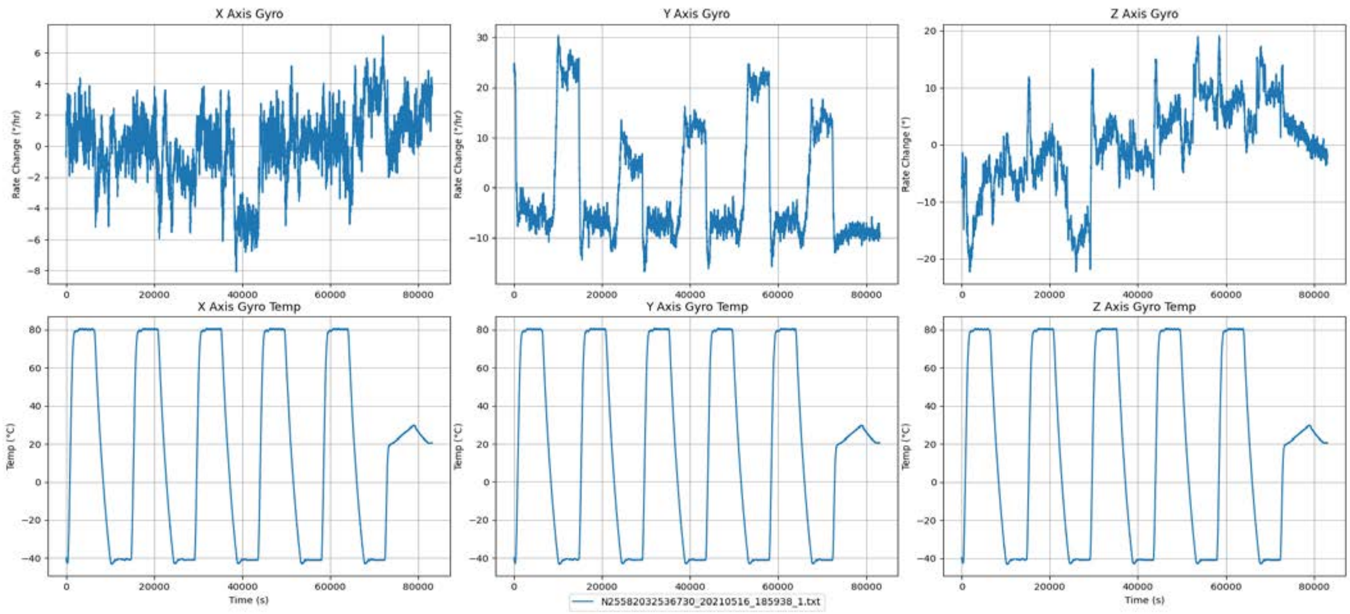

Figure 53: UUT2 gyroscope bias changes and temperature during last 5 cycles

UUT3 (N25582037623167)

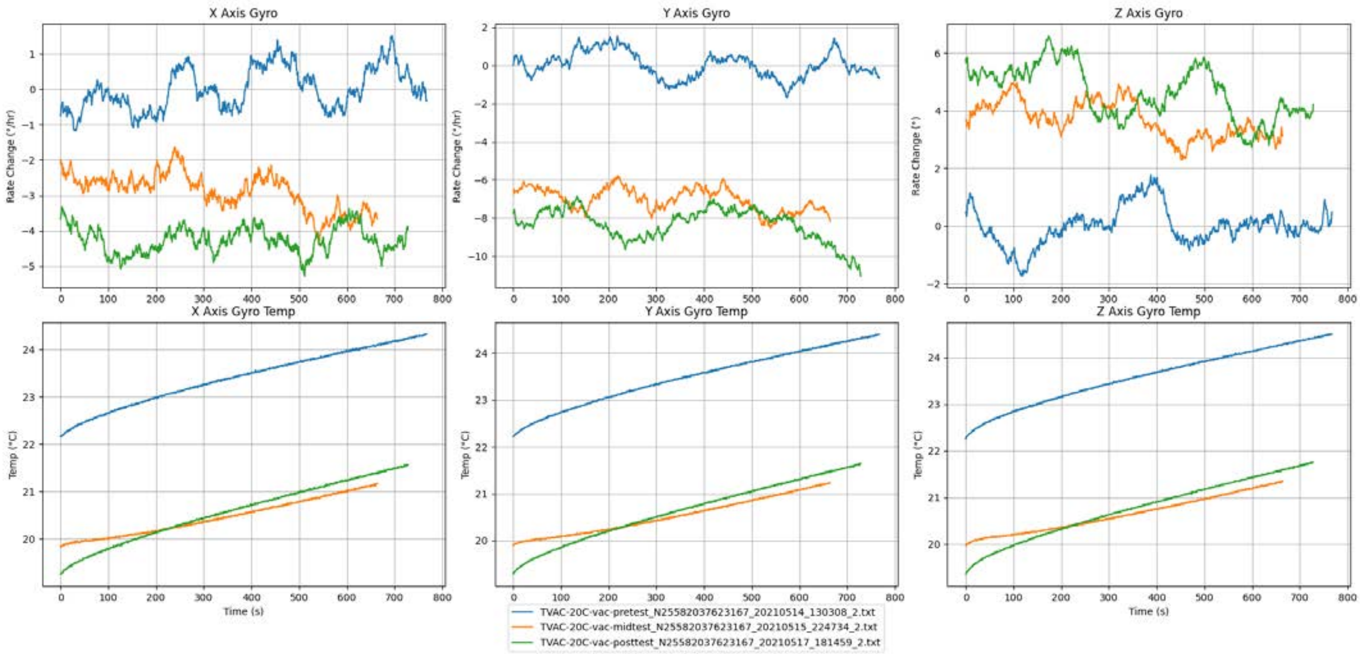

Figure 54: UUT3 gyroscope bias changes at ambient temperature under vacuum measured with vacuum pump off at start, mid and end of test

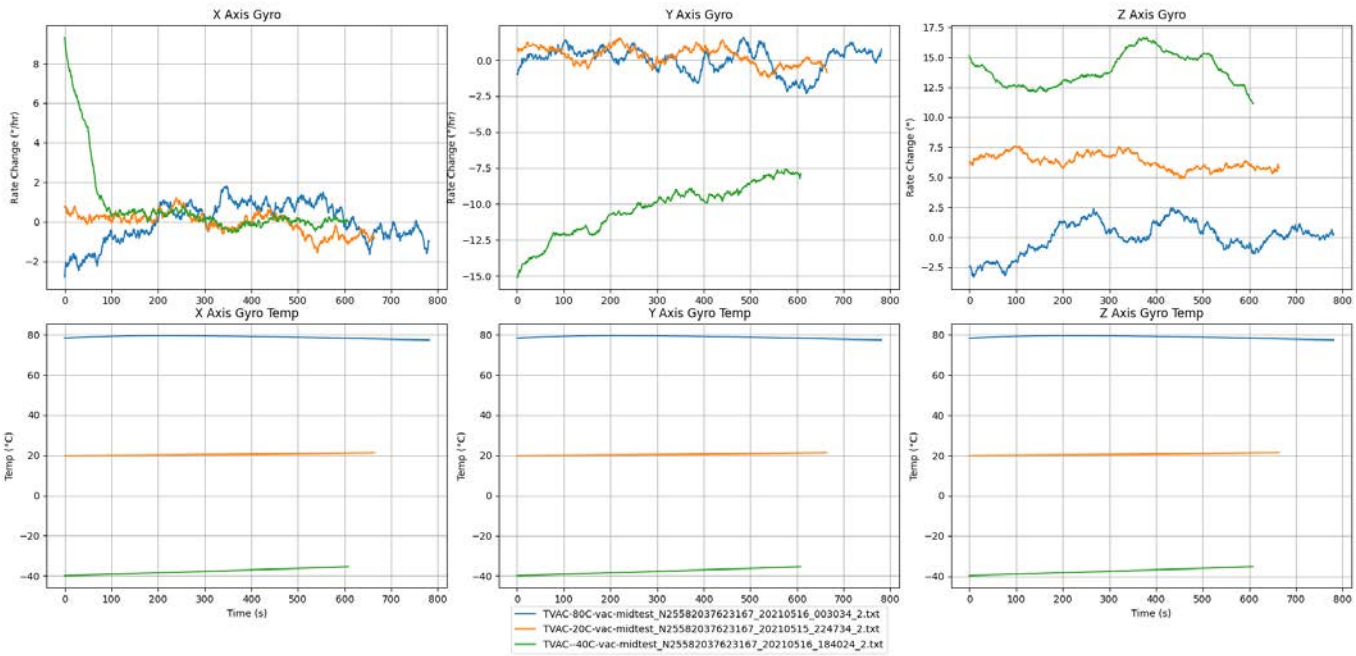

Figure 55: UUT3 gyroscope bias changes under vacuum measured with vacuum pump off at 20°C, 80°C and –40°C

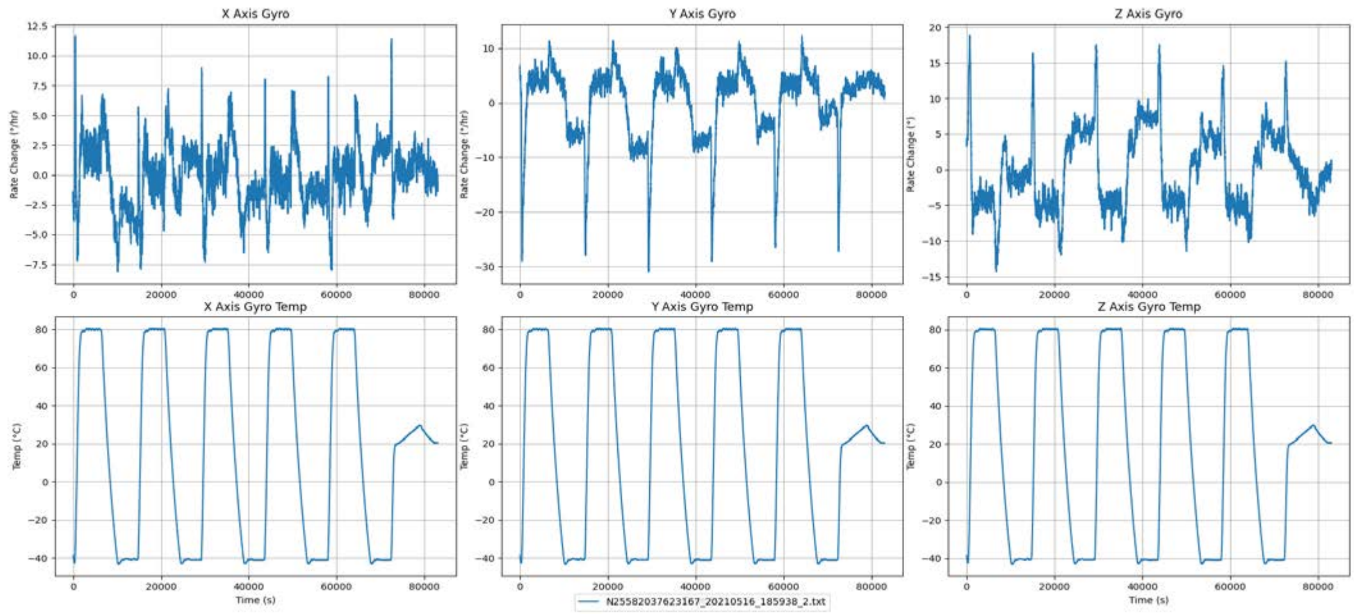

Figure 56: UUT3 gyroscope bias changes and temperature during last 5 cycles

UUT4 (N25582037624299)

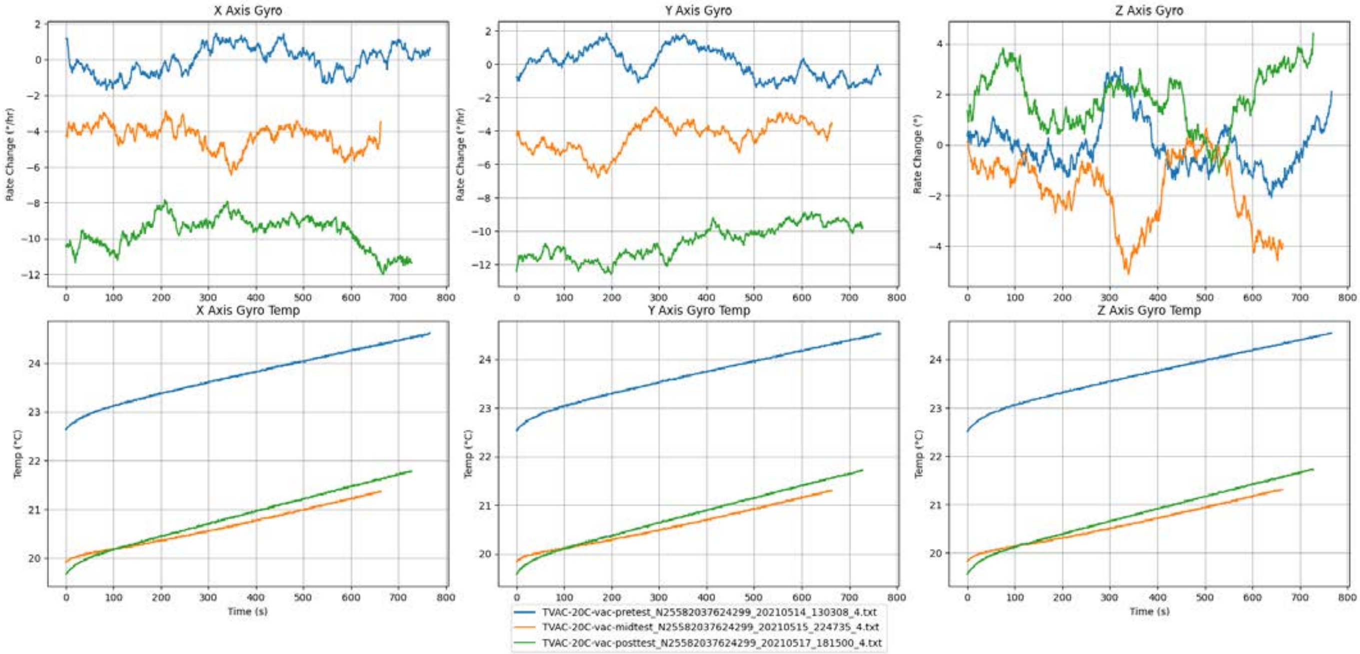

Figure 57: UUT4 gyroscope bias changes at ambient temperature under vacuum measured with vacuum pump off at start, mid and end of test

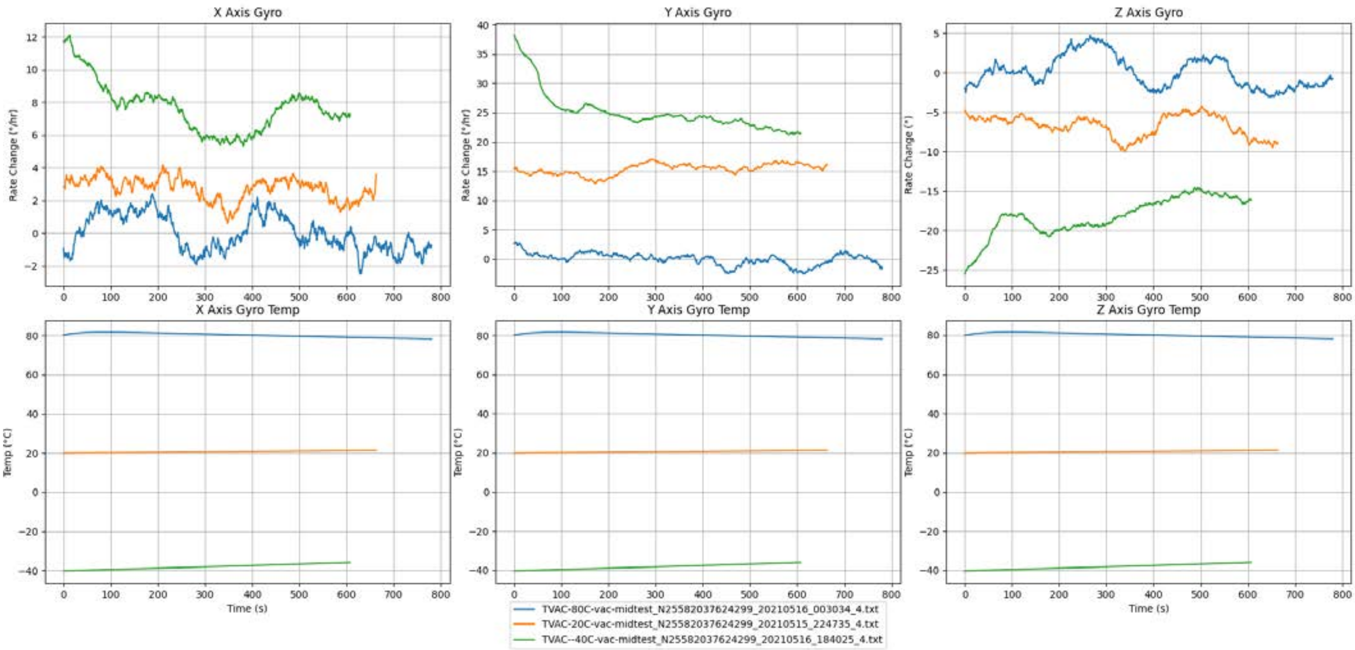

Figure 58: UUT4 gyroscope bias changes under vacuum measured with vacuum pump off at 20°C, 80°C and –40°C

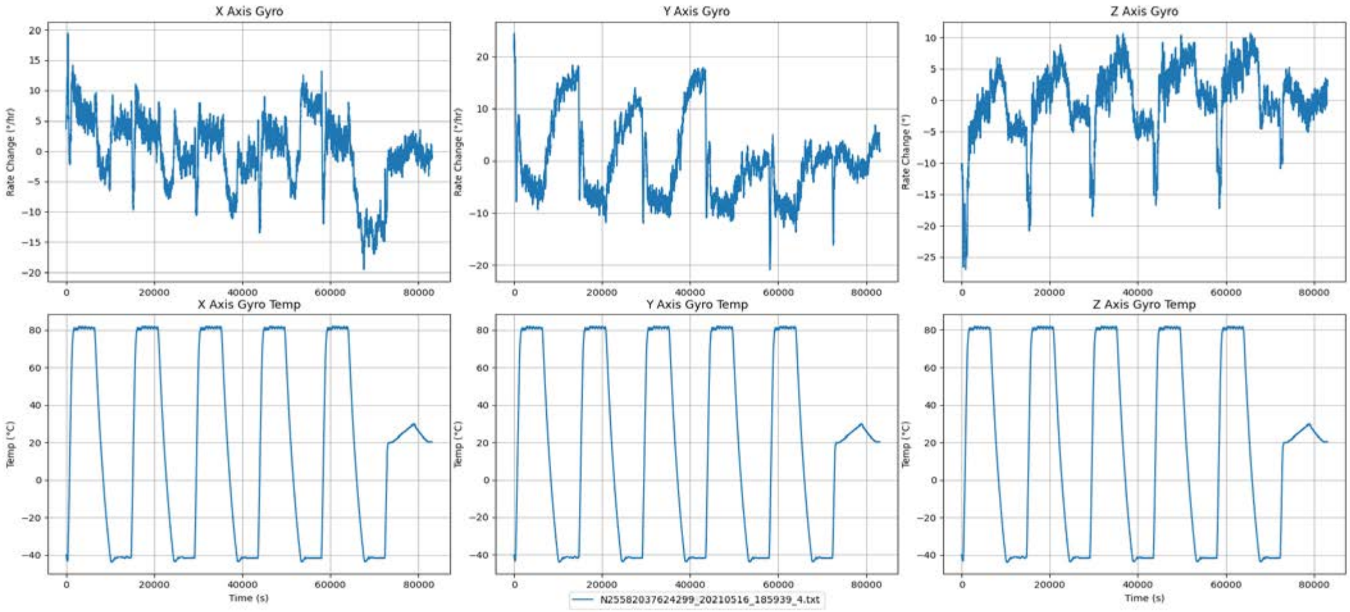

Figure 59: UUT4 gyroscope bias changes and temperature during last 5 cycles