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New Product Introduction (NPI) Steps of Navigation Grade Closed Loop MEMS Accelerometer MAXL-CL-3000

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Introduction

In 2020, Physical Logic introduced its 3rd generation Closed-Loop MEMS accelerometer product family composed of the MAXL-CL-3015 (15g sensing range) and MAXL-CL-3030 (30g sensing range). The main challenge in the development was to minimize charging effects on the MEMS device surfaces, and in turn to reduce short term and long term errors.

Charges build up on MEMS features surfaces and between interfaces such as Si/SiO_2, $Si/SiO_2/Metal$. Additionally, charge traps on the capacitor's sidewalls result in variations in electrical characteristics leading to measurement errors. The charge buildup is difficult to diagnose and to model. It can be associated with inherent characteristics and/or manufacturing variations of a given device and variations of temperature, aging and previous circuit conditions affect the magnitude of charge buildup in the device. High feedback voltage applied in closed loop accelerometers increases charge buildup and results in high scale factor (SF) and bias errors.

In 2019 our R&D team invested efforts on the optimization of MEMS device process parameters and in parallel introduced a new Charge Release Algorithm (CRA) module to the sensor's electronic circuit. The new CRA feature ensures a non-constant voltage and eliminates build-up of charges on both capacitors and other MEMS electrode surfaces.

In 2021 Physical Logic is expanding this product family by adding two new products, MAXL-CL-3050 (50g sensing range) and MAXL-CL-3070 (70g sensing range). The challenge in the development of these products was to maintain tactical and navigation sensor performance while requiring even higher feedback voltage to achieve the higher sensing range. Increasing feedback voltage naturally enhances charge accumulation on the electrode surfaces and thus the challenge of CRA optimization required new electronic features.

In this paper we present Physical Logic's methodology of 4 NPI (New Product Introduction) steps which are implemented after either product development or a major change in an existing product. We present test results from each NPI step that was performed during the last year while introducing our 3rd generation MAXL-CL-3030 Closed-Loop MEMS accelerometer. The NPI program was made possible after the successful development of new charge release features that minimized charging effects on MEMS device surfaces and enabled mass production of the Navigation Grade Closed Loop MEMS accelerometer. The accelerometer long term performance demonstrates bias repeatability of less than 500 μg and scale factor (SF) repeatability of less than 400 ppm.

4 NPI steps

We present the 4 NPI steps; each of which allows further progress in proving the maturity of the product and providing the opportunity to advance in its sale.

Step 1: accelerated environmental tests (Highly accelerated life test, i.e. HALT Oven)
✓ Offer customers first prototypes for evaluation.

Step 2: Product qualification Procedure (QTP):
✓ Sell prototypes from first assembly batches.

Step 3: Statistical Data on ≥ 100 sensors
✓ Production ramp-up readiness.

Step 4: Accelerated Lifetime testing
✓ Freeze product datasheet.

Step 1: Accelerated Environmental Tests (HALT Oven):

The objective of accelerated environmental tests was to get a fast (< 2 days) and reliable indication of product readiness prior to implementation of a long and expensive Qualification Test Procedure (QTP).
This test was performed using a HALT oven and included 4 environmental cycles:

1. Temperature steps from -60°C to 100°C including device turn off and on at each step.
2. Temperature cycles from -60°C to 100°C @ dT/dt = 40°C/min (described in Figure 1).
3. Vibration steps from 3gRMS to 20gRMS, 10 min. at each step.
4. Temperature combined with vibration cycles from -60°C to 100°C @ dT/dt = 40°C/min and vibrations between 10gRMS to 20gRMS.

The described environmental cycles verify survival of the new accelerometer revision subject to harsh conditions, beyond product specification.
Measurements of delta bias, scale factor and misalignment of the sensor before and after applying HALT procedure provide a good indication of long term repeatability errors of the product.

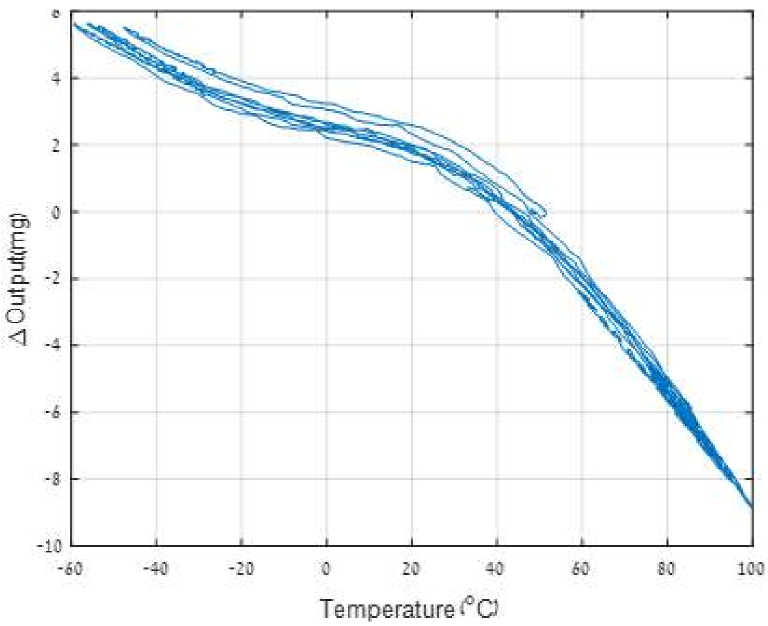


Figure 1: Accelerometer output (mg) at multiple temperature cycles from -60°C to 100°C @ dT/dt = 40°C/min

Step 2: Product Qualification Procedure (QTP)

The qualification program was performed, using Mil-Standard 810g specifications, on 16 MAXL-CL-3030 units (8 units on each Qualification Jig (QJ); each 8-unit batch from a different assembly batch and contains MEMS devices from at least from 2 different silicon wafers. The units chosen for the QTP were randomly chosen from the units that passed a successful Acceptance Test Procedure (ATP).

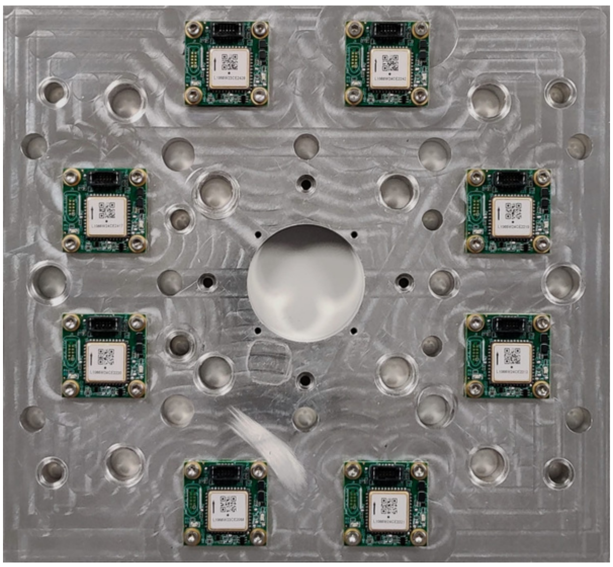


Figure 2: Qualification Jig (QJ)

During the QTP, 4-point tests are performed at 20°C inside a temperature chamber to track Bias, SF and Misalignment (MA) changes after each environmental exposure. Summary of these tests is presented in Figure 4.

To avoid reproducibility errors, it is most important to ensure no sensors are disassembled from the QJ during the qualification program.

QTP includes various temperature, vibration, and shock conditions described in Figure 3.

Success criteria of the qualification was defined for each step, for the overall shifts before and after qualification, and for shifts between each qualification step.

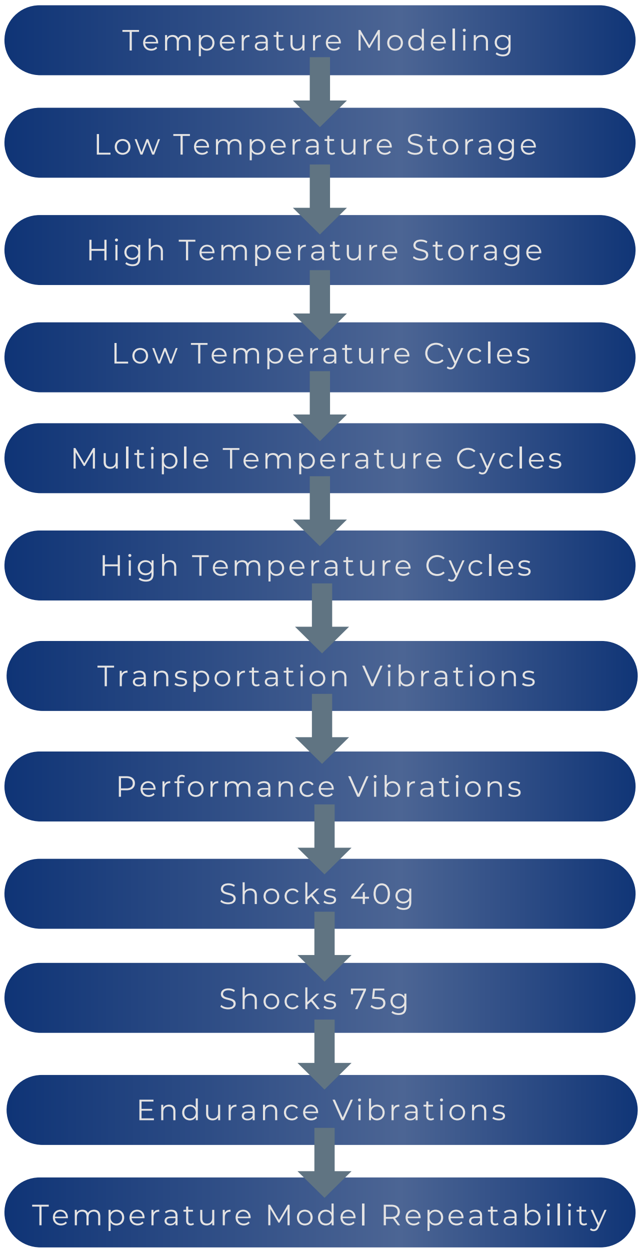


Figure 3: Qualification Test Procedure (QTP)

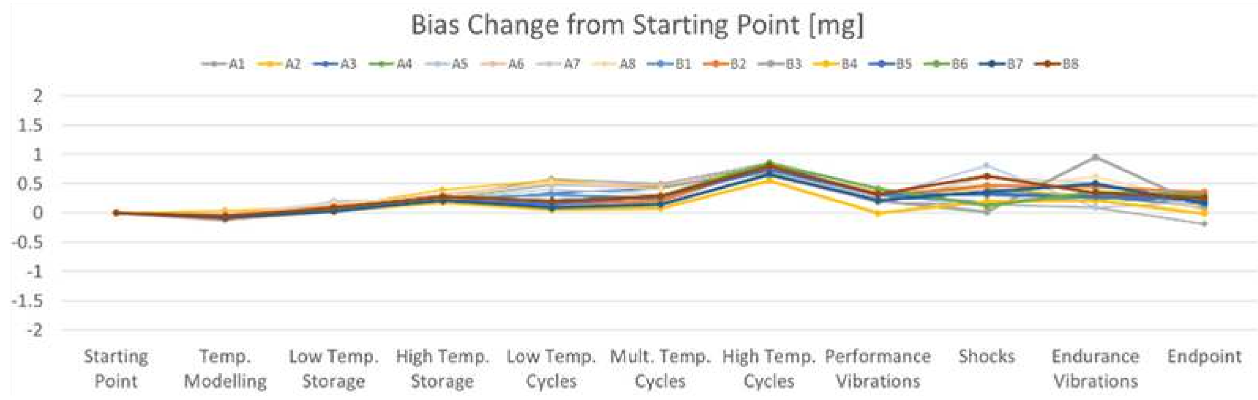


Figure 4a: Bias over QTP monitor

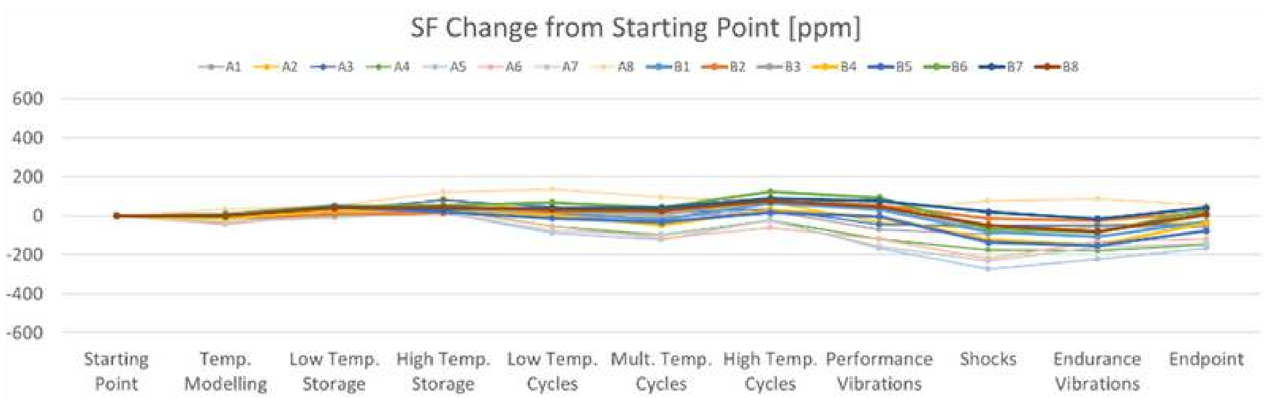


Figure 4b: Scale Factor over QTP monitor

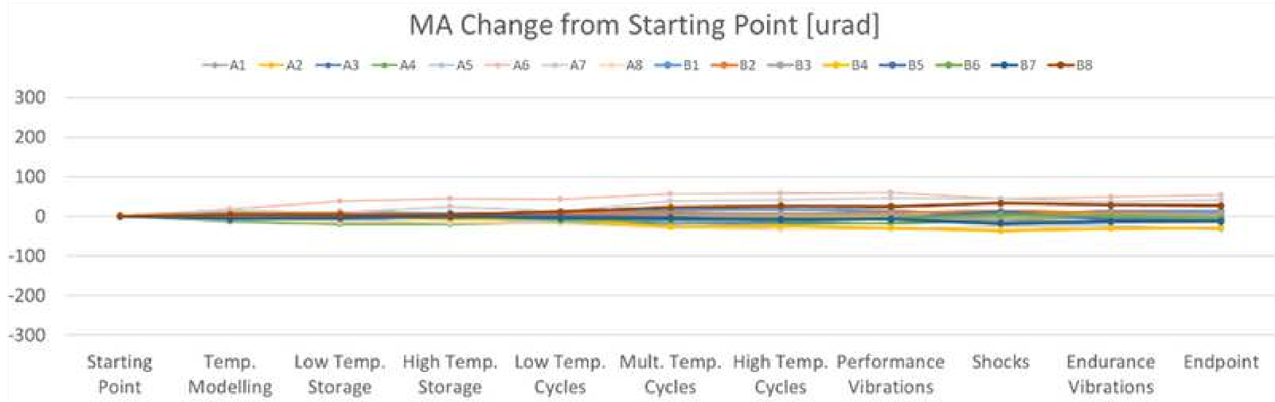


Figure 4c: Misalignment over QTP monitor

Step 3: Statistical Data

Statistical data on ≥100 assembled sensors manufactured from at least 3 MEMS wafers and 2 assembly batches was collected and analyzed to apply production ramp-up and to commit deliveries to customers. Figures 5 shows the improved performance when minimizing charging effects on the MEMS device' surfaces, improvement which enabled customers to integrate Physical Logic's accelerometers in inertial grade IMUs.

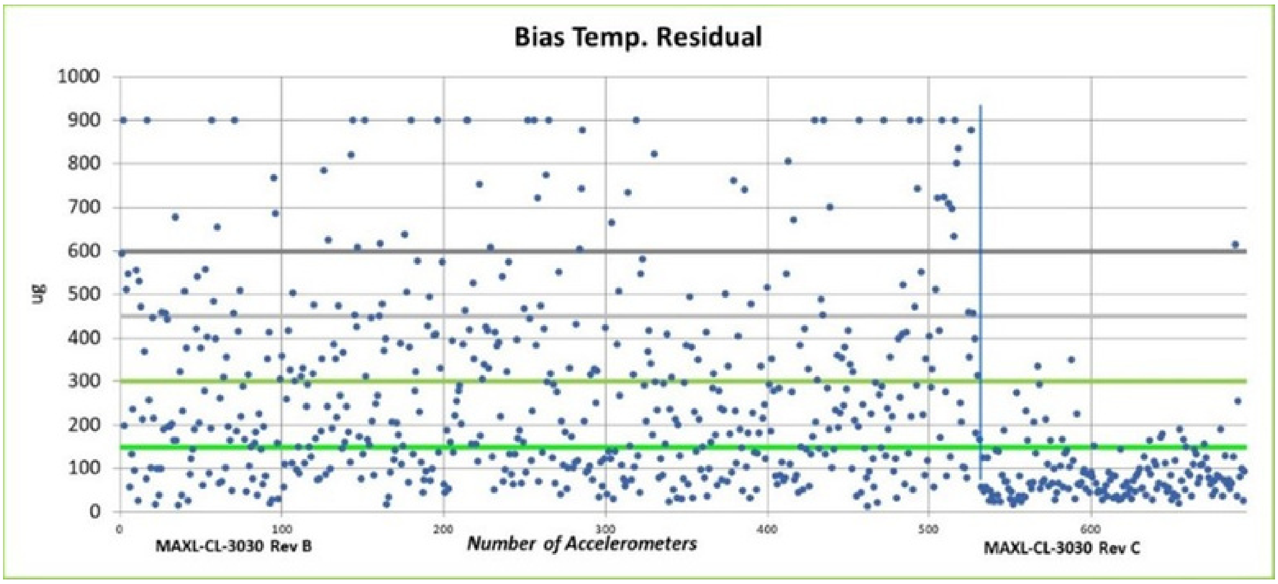


Figure 5a: Residual Bias comparison between previous (Rev B) and 3rd Generation (Rev C) MAXL-CL-3030 Revisions

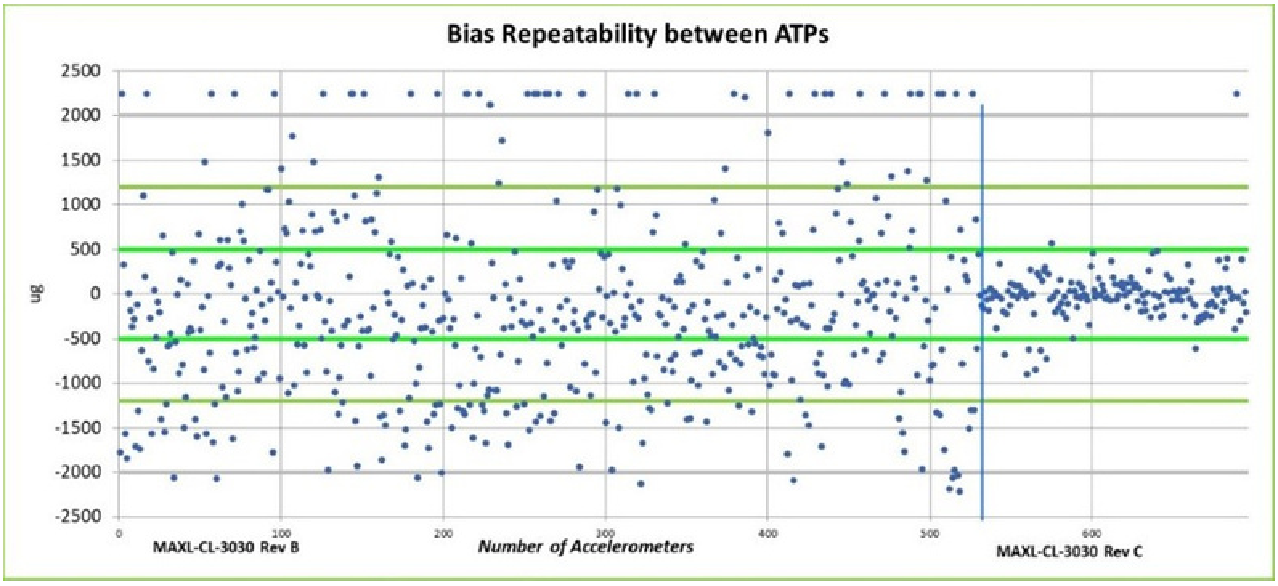


Figure 5b: Bias repeatability comparison between previous (Rev B) and 3rd Generation (Rev C) MAXL-CL-3030 Revisions

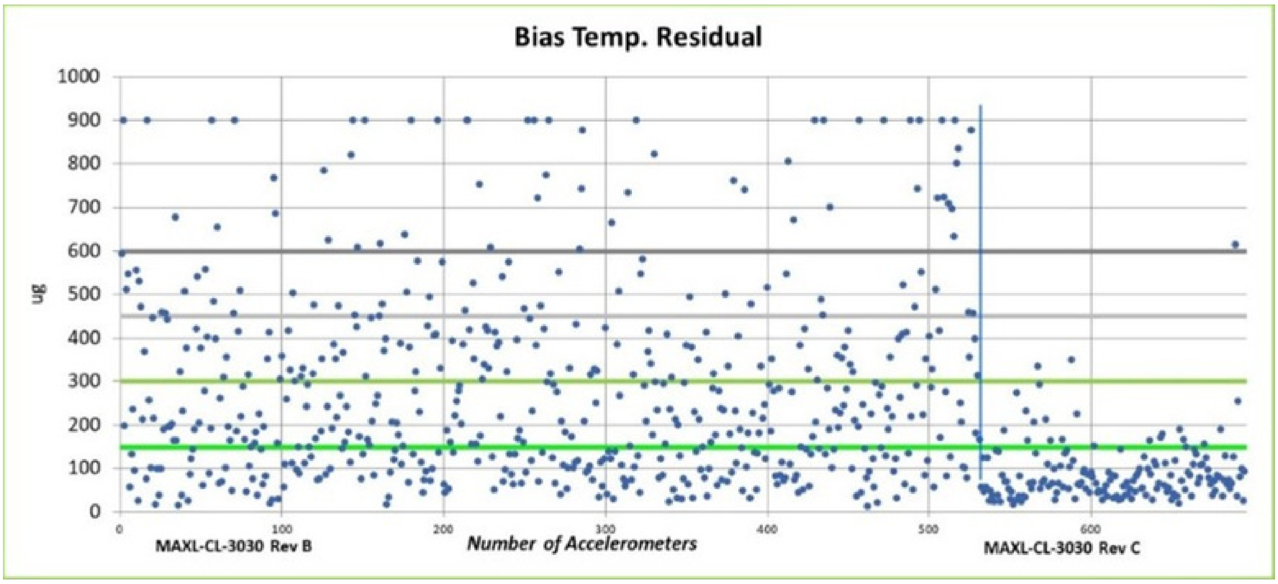
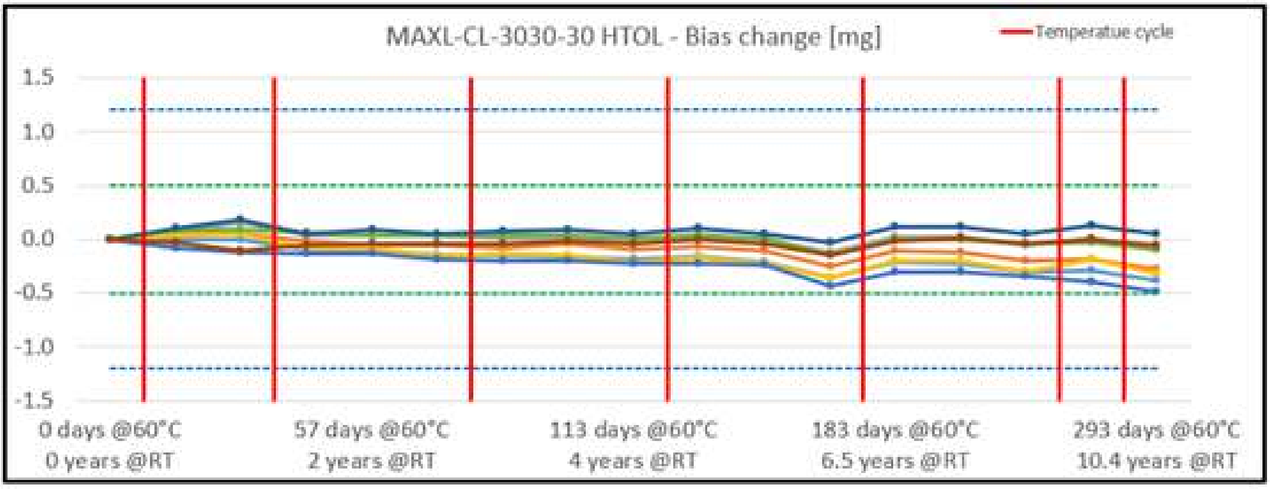


Figure 5c: TOTO comparison between previous (Rev B) and 3rd Generation (Rev C) MAXL-CL-3030 Revisions

Step 4: Accelerated Lifetime Testing

Important parameters that verify inertial grade compliance are the errors which the sensor gains along lifetime. Figure 6 shows bias and scale factor (SF) measurements that were taken on MAXL-CL-3030 accelerometers. After 293 days at 60°C (equivalent to 10.4 years at room temperature) and 7 temperature cycles from -40°C to +85°C. 100% of tested accelerometers have maintained Navigation grade performance with long term bias repeatability <0.5 mg and Scale factor repeatability <400 ppm.



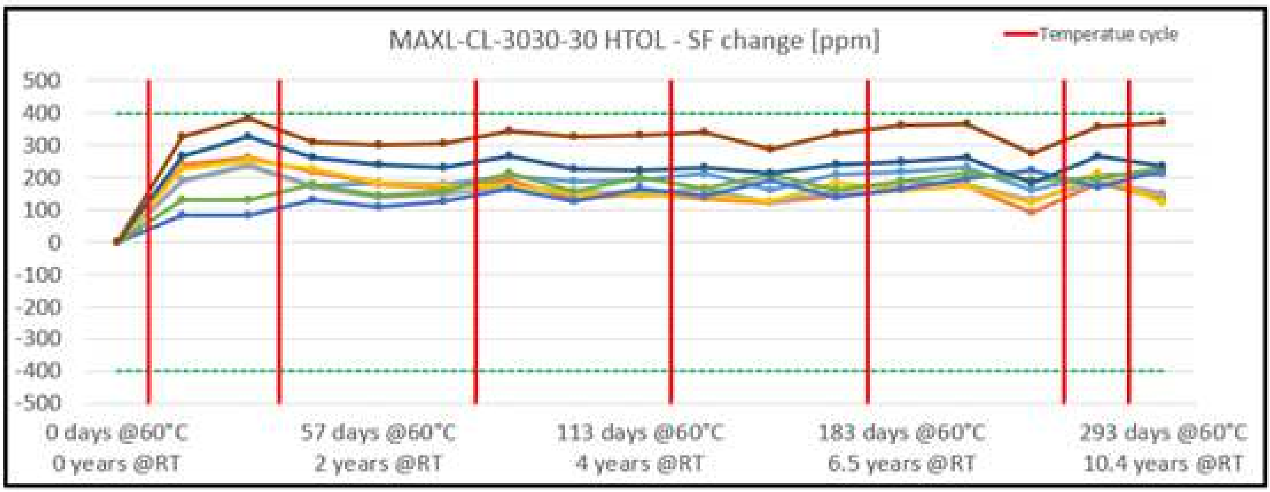


Figure 6: MAXL-CL-3030-30 accelerated lifetime test – Long term bias & SF repeatability

In April 2021, after completion of the tests, we conducted the last temperature cycle, identical to the first cycle performed last year. Standard deviation of the residual errors was calculated as before, while using the model from the first temperature cycle. In addition, Bias and SF temperature mean shifts are calculated, as the mean value between the first temperature cycle the last temperature cycle.

Accelerated lifetime testing was performed on different grades of MAXL-CL-3030. In this paper, as an example, we present the results of the highest grade MAXL-CL-3030-30.

Success Criteria was to verify MAXL-CL-3030-30 specifications with long term bias repeatability error <500μg and SF repeatability error < 400 ppm. Table 1 summarizes bias and scale factor errors of last temperature cycle with comparison to the first cycle indicating excellent temperature model repeatability.

	Bias Residual Error [μg]	Bias Mean Shift [μg]	SF Residual [ppm]	SF Mean Shift [ppm]
Unit 1	45	372	43	150
Unit 2	68	293	51	70
Unit 3	103	112	41	91
Unit 4	105	329	53	63
Unit 5	46	422	31	222
Unit 6	33	107	48	221
Unit 7	96	11	53	133
Unit 8	73	60	36	276
Mean	71	213	45	153
STD	28	158	8	79

Table 1: MAXL-CL-3030-30 Residual and Mean Shift repeatability errors after 293 days storage at 60°C (=10.4 years at room temperature) and 7 operational temperature cycles from -40°C to +85°C

Summary

During NPI steps 1, 2, and 3 of new products MAXL-CL-3050 and MAXL-CL-3070, we have accomplished in recent weeks the last NPI step, number four, of the 3rd generation MAXL-CL-3030.
In this paper, we presented Physical Logic's methodology of the 4 NPI steps which were executed after the successful development of new charge release features for minimizing charging effects on MEMS device surfaces. This development enabled mass production of a highly reliable product qualified using Mil-standard specifications.