Sharing historical data on tactical-grade MEMS-based IMUs delivered to global customers for almost a decade

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Abstract

Sensonor has since 2009 produced tactical-grade MEMS-based IMUs and gyro-modules. During this time, approximately 20,000 parts, containing 60,000 MEMS gyros, have been shipped. Prior to this, Sensonor has been the supplier of high-reliable MEMS sensors, including gyros, to demanding safety applications in the automotive industry for more than 20 years.

This paper will focus on the MEMS gyros and present data on key-parameters such as Bias, Angular Random Walk, In-Run Bias Stability, Scale-factor, Non-Linearity and Axis-Misalignment. Distributions and trend-plots, based on thousands of tactical-grade gyros, will be presented to provide information on what to expect in terms of variation from a MEMS-based gyro. This data is extracted from Sensonor's vast production database containing data from every IMU and gyro-module manufactured.

Further, data related to long-term drift from e.g. HTOL (High Temperature Operating Life) and data measured on parts over a longer period of time, such as "golden devices" used to verify stability of production test-processes, will be presented.

Finally, some key lessons learned from the long period as a MEMS supplier to the automotive industry will be shared. This includes topics like high-reliability and continuous improvements.

1. Short summary of the history of Sensonor

Sensonor was founded in 1985 as a spin-out company of the Norwegian company AME (Aker Mikro Elektronikk). Its MEMS-technology had been specifically developed with high-reliability in mind, and Sensonor's products were well established within the demanding fields of medical, aerospace and military. During the first two decades, Sensonor had its focus on the automotive segment, delivering more than 35 million accelerometers to airbag applications, more than 250 million pressure sensors and accelerometers to tire-pressure applications and more than 2 million gyros to roll-over applications. Sensonor was certified and in compliance with all relevant and required quality standards and gained through this period solid experience and mind-set of high-volume production of products with safety and high-reliability requirements. From 2009, Sensonor changed its focus to high-precision, tactical-grade 3-axis gyro-modules (STIM202 and STIM210) and IMUs (STIM300), addressing the segment of high-precision gyros typically covered by fiber-optic gyros. The new products were all based on the technology and know-how established during the previous two decades of high-volume production and deliveries to highly demanding applications.

2. Data from production testing

Sensonor manufactures all products in-house, from the processing of MEMS gyro sensor dies through assembly of gyro-modules and IMUs to aging, calibration and test.

During assembly, calibration and test, the 3-axis gyro-modules (STIM202 and STIM210) are each subjected to 22 test-insertions accumulating up to more than 650 tests. For the 9-axis IMU (STIM300) the corresponding numbers are 25 test-insertions and more than 1,450 tests. Yield is continuously monitored for all tests, and trends are monitored for selected key-parameters.

An overview of the number of delivered STIM300 gyro-axes (three in each IMU) in the period 2013-2016 is shown in figure 1:

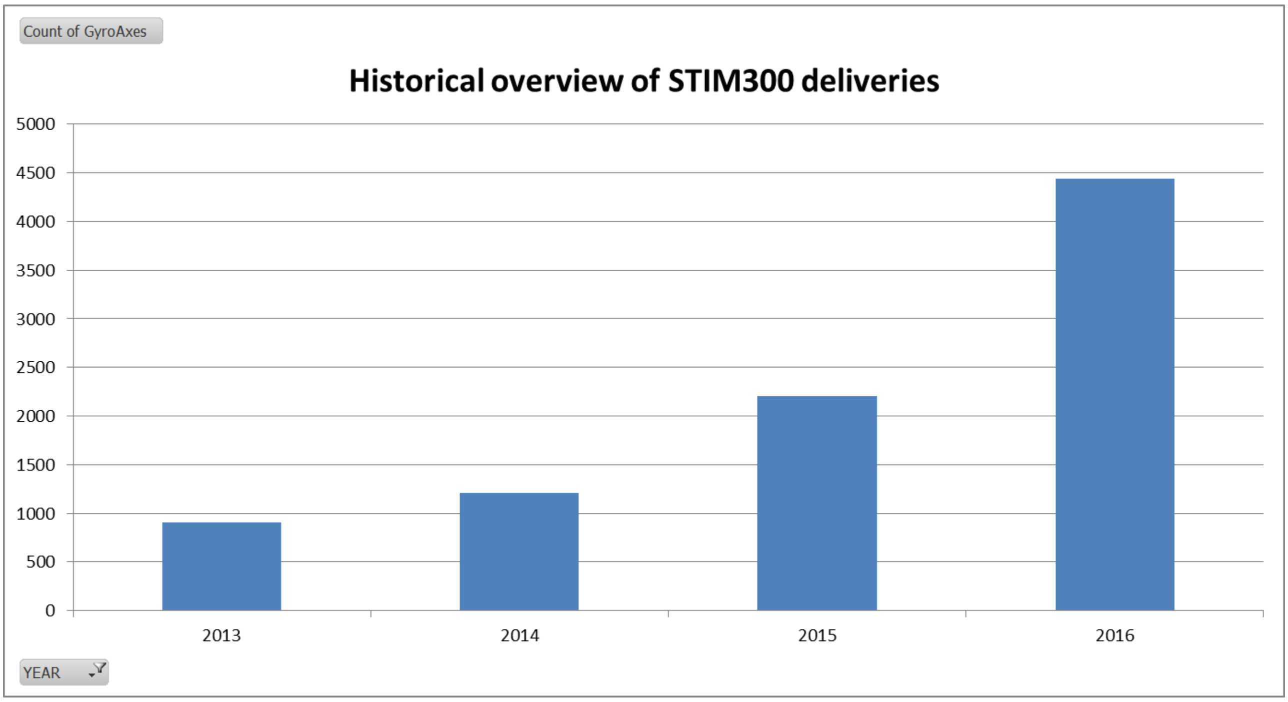

Figure 1. Historical overview of STIM300 deliveries

This section will present the production data on a selected sub-set of relevant parameters for delivered STIM300s representing almost 10,000 gyro-axes. All presented parameters have been measured during the verification phase, i.e. after the parts have completed calibration. The data should give an understanding of the current status and spread of the chosen parameters. Each parameter is presented with a histogram and a trend-plot, with the nominal value from the latest specifications put in as reference. Please note that the number of delivered gyro-axes in 2016-07 (summer vacation) was low, leading to a general high spread in the presented data for this particular month.

2.1 Bias related production data

The selected parameters related to bias are listed in table 1:

Table 1: Overview of the bias related parameters

Figure	**Parameter**	**Description**
Figure 2	Bias_25	Gyro output at 0°/s and steady ambient temperature of +25°C
Figure 3	BiasSTD	The standard deviation of the relative change in gyro output at 0°/s and steady ambient temperatures: +85, +55, -10 and -40°C compared to Bias_25
Figure 4	ARW (noise)	Angular Random Walk of the gyro output at 0°/s and steady ambient temperature of +25°C calculated from the root Allen variance curve at 1 second integration time
Figure 5	IRBS	In-Run Bias Stability is the minimum point of the root Allen variance curve plotted from a 18-hour measurement of the gyro output at 0°/s and steady ambient temperature of +25°C

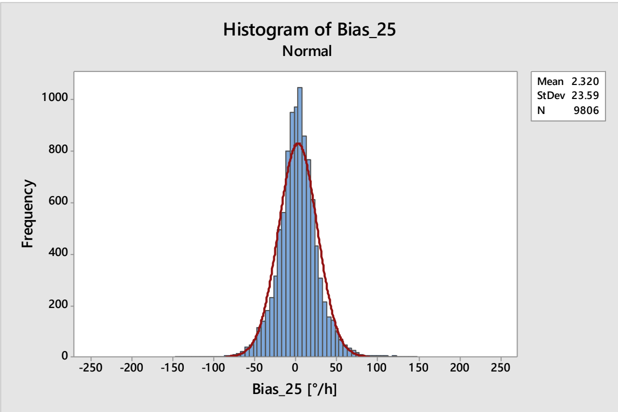

Figure 2a. Histogram of Bias_25

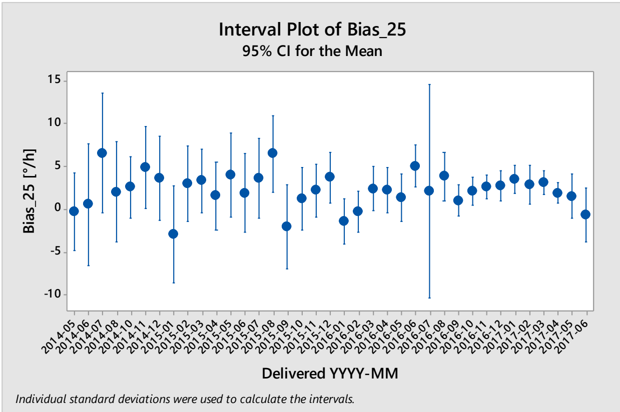

Figure 2b. Trend-plot of Bias_25

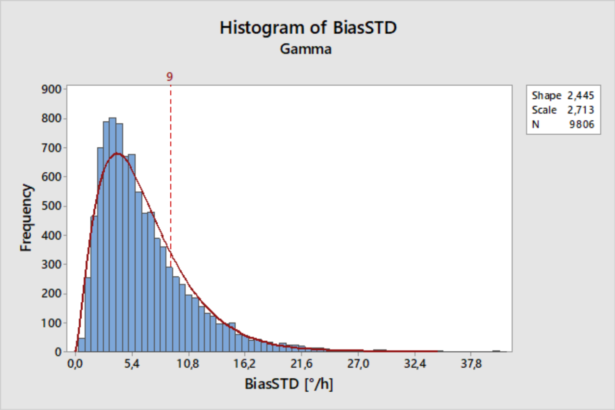

Figure 3a. Histogram of BiasSTD

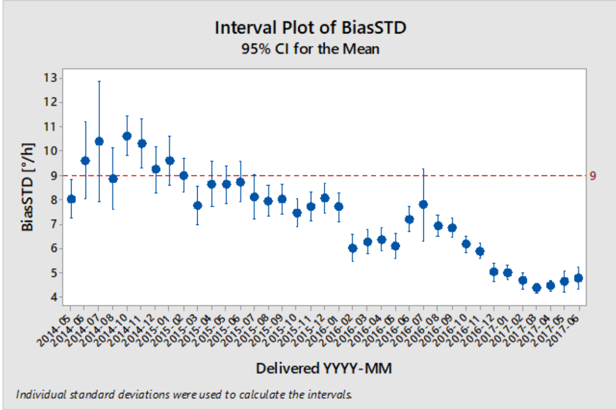

Figure 3b. Trend-plot of BiasSTD

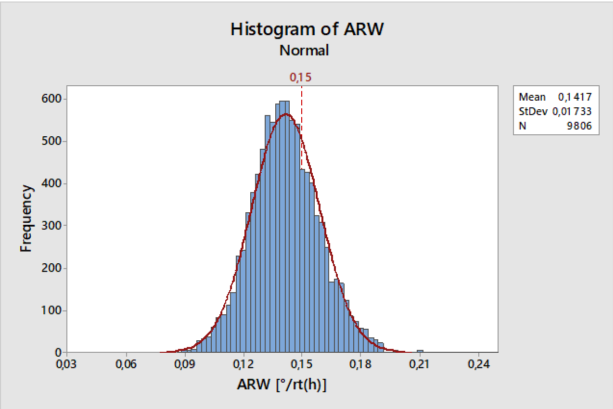

Figure 4a. Histogram of ARW

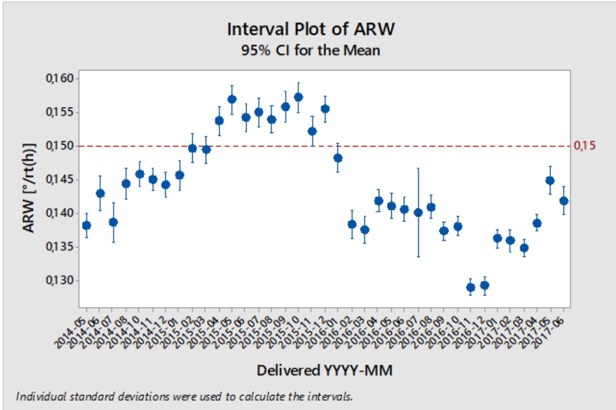

Figure 4b. Trend-plot of ARW

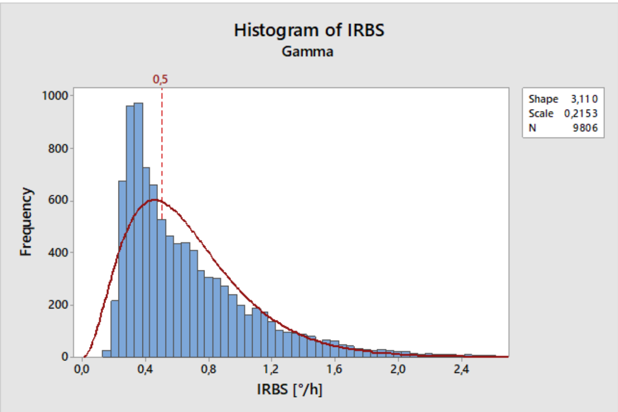

Figure 5a. Histogram of IRBS

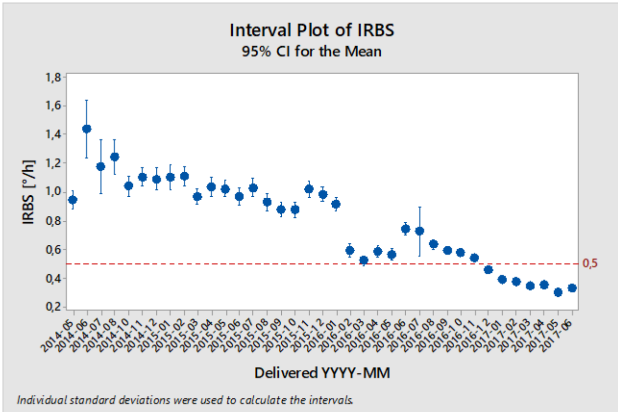

Figure 5b. Trend-plot of IRBS

2.2 Comments to presented bias related production data

There has been a continuous focus on bias and its related parameters from day one. The general trend is that spread and month-to-month variation are reduced over time as a natural consequence of increased maturity of product, parts and processes, ref. all trend-plots.

2.3 Angular rate related production data

The selected parameters related to the measurement of angular rate are listed in table 2:

Table 2: Overview of the angular rate related parameters

Figure	**Parameter**	**Description**
Figure 6	SF_dev_25	The deviation in scale-factor measured at ±200°/s and steady ambient temperature of +25°C
Figure 7	SF_dev_rms	The rms value of the deviation in scale-factor measured at ±200°/s and the steady ambient temperatures: +85, +55, +25, -10 and -40°C
Figure 8	NonLin400_25	The non-linearity is the calculated deviation from the best-straight-line fit from measurements at 0, ±125, ±200, ±250 and ±400°/s and at steady ambient temperature of +25°C
Figure 9	NonLin400_rms	The rms value of the non-linearity measured at steady ambient temperatures of +85, +55, +25, -10 and -40°C

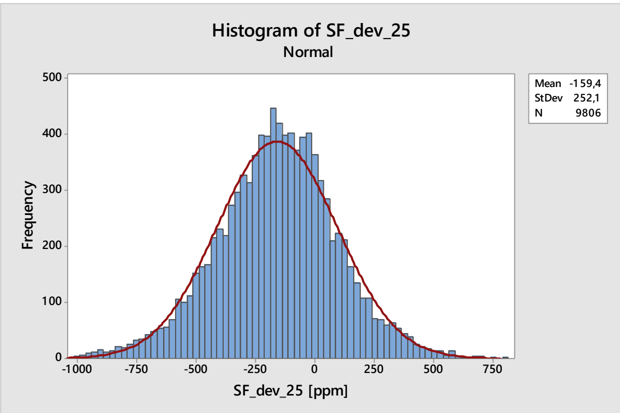

Figure 6a. Histogram of SF_dev_25

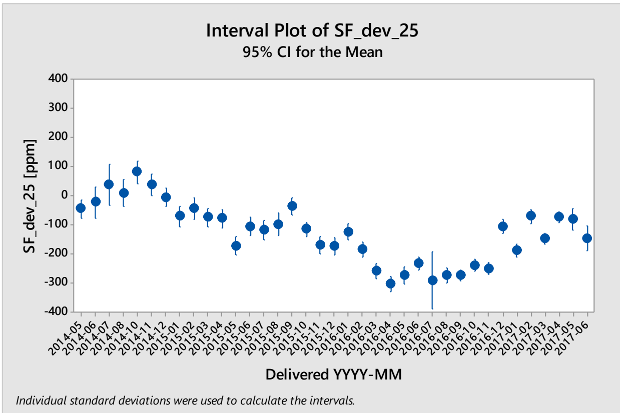

Figure 6b. Trend-plot of SF_dev_25

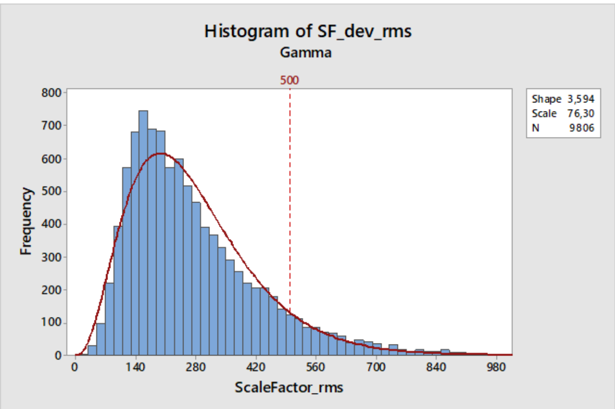

Figure 7a. Histogram of SF_dev_rms

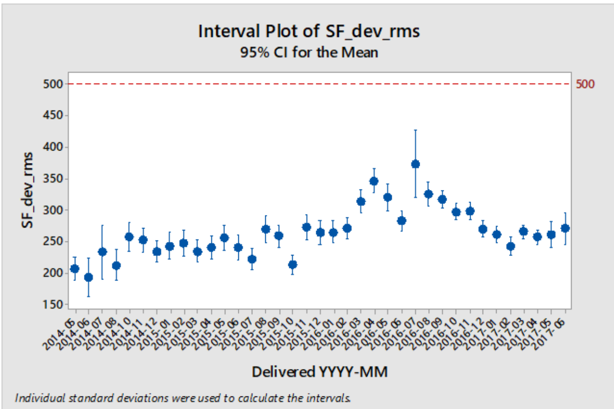

Figure 7b. Trend-plot of SF_dev_rms

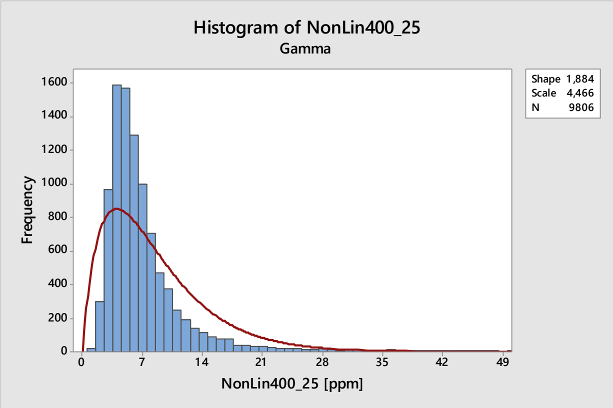

Figure 8a. Histogram of NonLin400_25

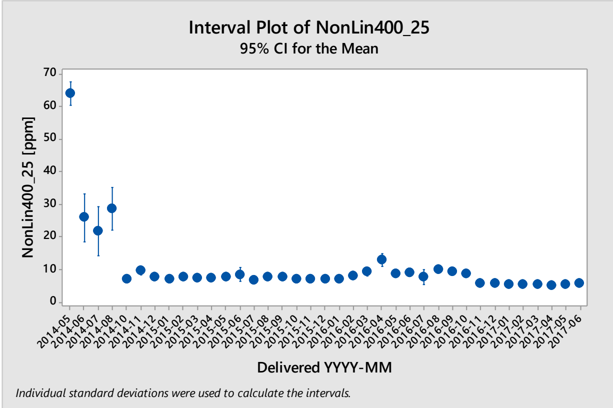

Figure 8b. Trend-plot of NonLin400_25

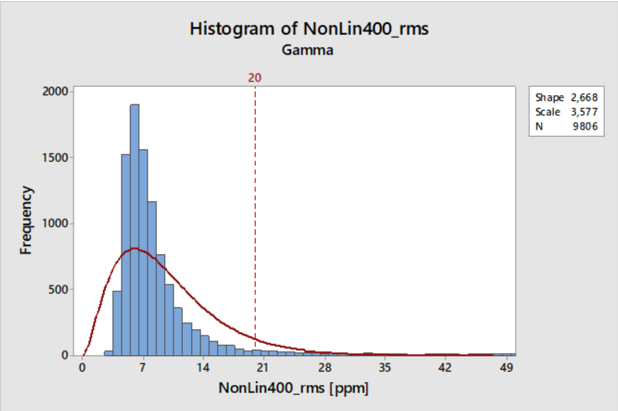

Figure 9a. Histogram of NonLin400_rms

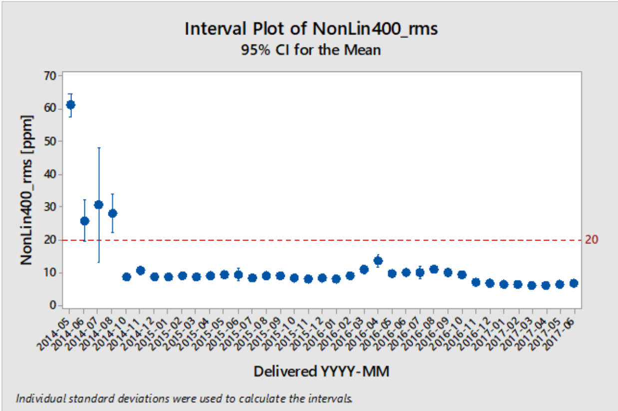

Figure 9b. Trend-plot of NonLin400_rms

2.4 Comments to presented angular rate related production data

During the first years of production, the highest focus was on bias, being a consequence of the applications of the early users of STIM300. This changed in 2016, where the work to understand scale-factor error and drift was intensified. The positive results from this work is evident in the figures above.

2.5 *Axis alignment related production data*

The selected parameters related to axis alignment are listed in table 3:

Table 3: Overview of axis alignment related parameters

Figure	Parameter	Description
Figure 10	Misalign_25	The misalignment of a gyro-axis to the defined reference axes as defined on the outer body of the IMU measured at steady ambient temperature of +25°C
Figure 11	Misalign_rms	The rms value of the misalignment measured at the steady ambient temperatures: +85, +55, +25, -10 and -40°C
Figure 12	Ortho_dev_25	The orthogonality deviation a gyro-axis to the other gyro-axes in the same IMU measured at steady ambient temperature of +25°C
Figure 13	Ortho_dev_rms	The rms value of the orthogonality deviation measured at the steady ambient temperatures: +85, +55, +25, -10 and -40°C

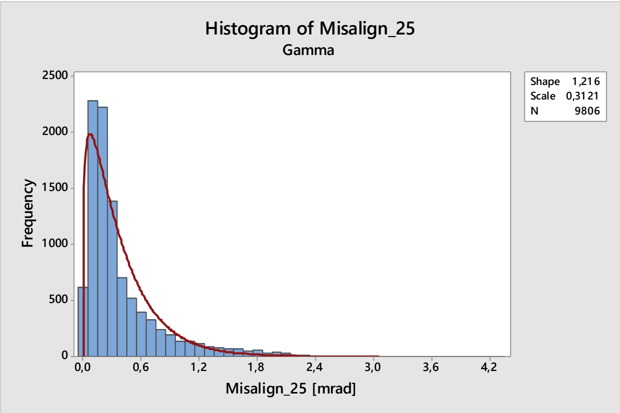

Figure 10a. Histogram of Misalign_25

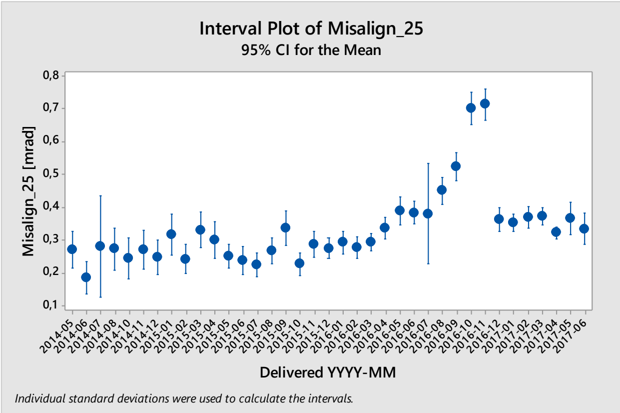

Figure 10b. Trend-plot of Misalign_25

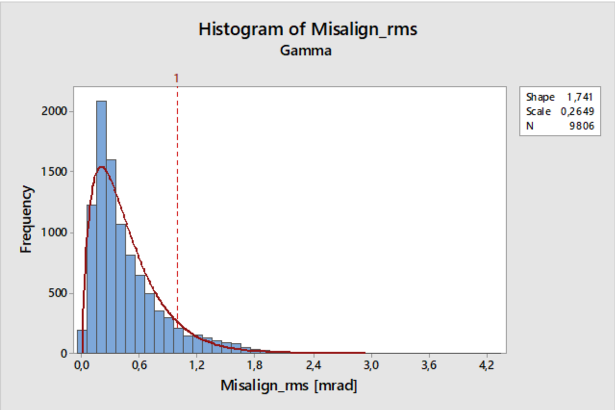

Figure 11a. Histogram of Misalign_rms

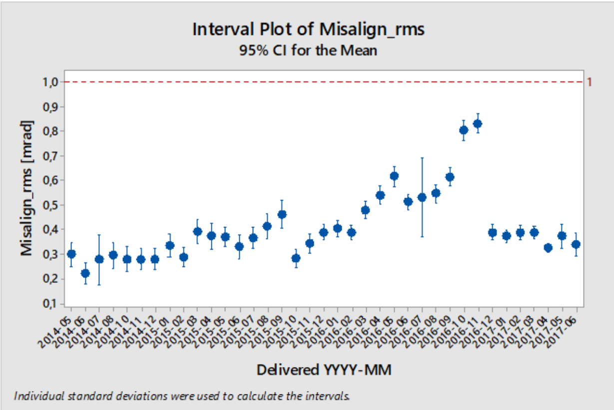

Figure 11b. Trend-plot of Misalign_rms

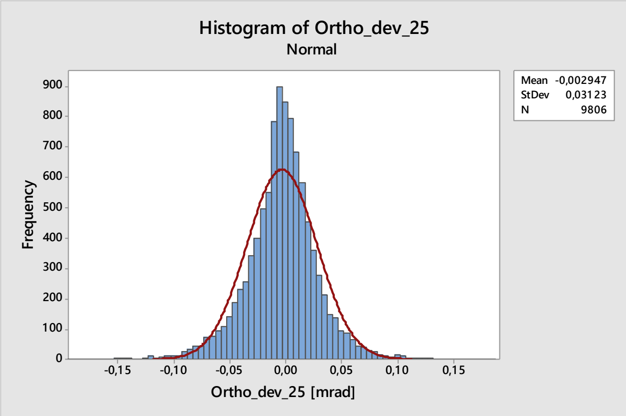

Figure 12a. Histogram of Ortho_dev_25

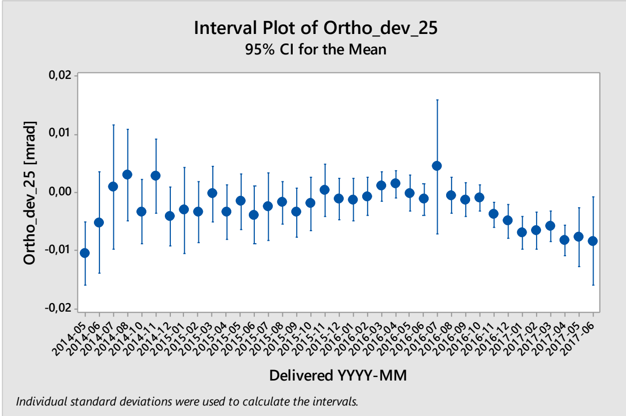

Figure 12b. Trend-plot of Ortho_dev_25

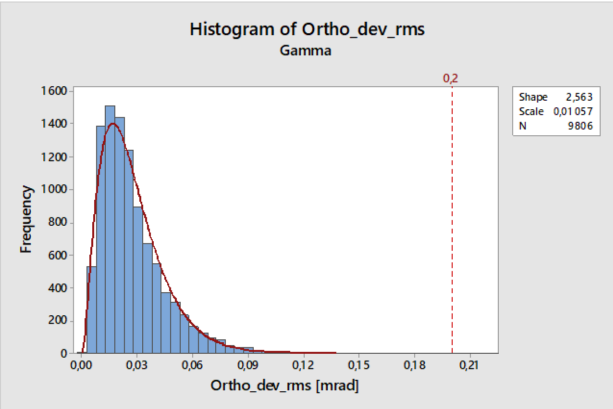

Figure 13a. Histogram of Ortho_dev_rms

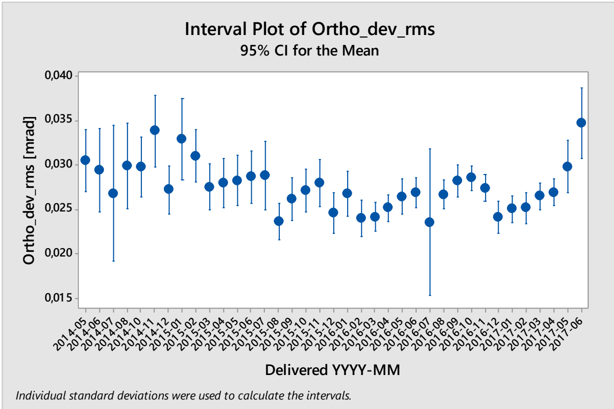

Figure 13b. Trend-plot of Ortho_dev_rms

2.6 Comments to presented bias related production data

The misalignment is dominated by the mounting precision of the gyro-modules and IMUs in the test-fixtures on the rate-table during calibration and verification. This is shown by the significant difference in the data for misalignment and orthogonality. To exemplify the precision needed: the distance between two of the reference points on the gyro-module body is 25mm. An offset of 25µm, equivalent to a piece of hair, would lead to an alignment error of 1mrad.

3 Long-term drift

This section presents some data on long-term drift of bias and scale-factor.

3.1 Long-term drift of bias

A study was performed on STIM210 where twenty-four parts were measured at t_0 and then stored un-powered at room temperature. At storage-times ranging from one week to forty-eight weeks, three parts (nine gyro-axes) where taken out and measured once. The initial bias at t_0 and then the change in bias for the three parts measured at the different storage-times are plotted in figure 14.

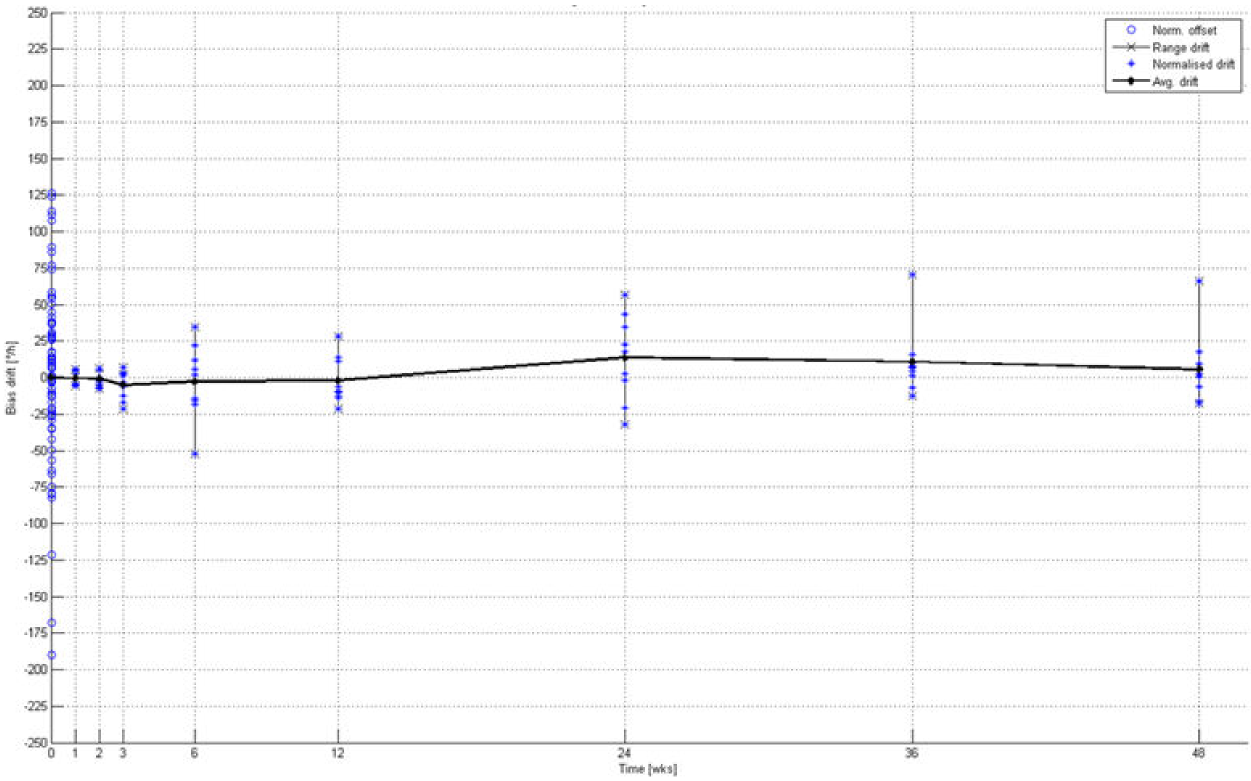

Figure 14. STIM210 Long-term bias stability

3.2 Long-term drift of scale-factor

"Golden samples" are used as part of the process control to ensure that the test-fixture for axis-alignment calibration is correctly aligned with respect to the axes of the rate-table. Scale-factor is also being measured as part of this process set-up verification, hence data on long-term drift can be plotted and investigated. The relative change in scale-factor over just less than one year, measured on four STIM202s used for this purpose, is plotted in figure 15.

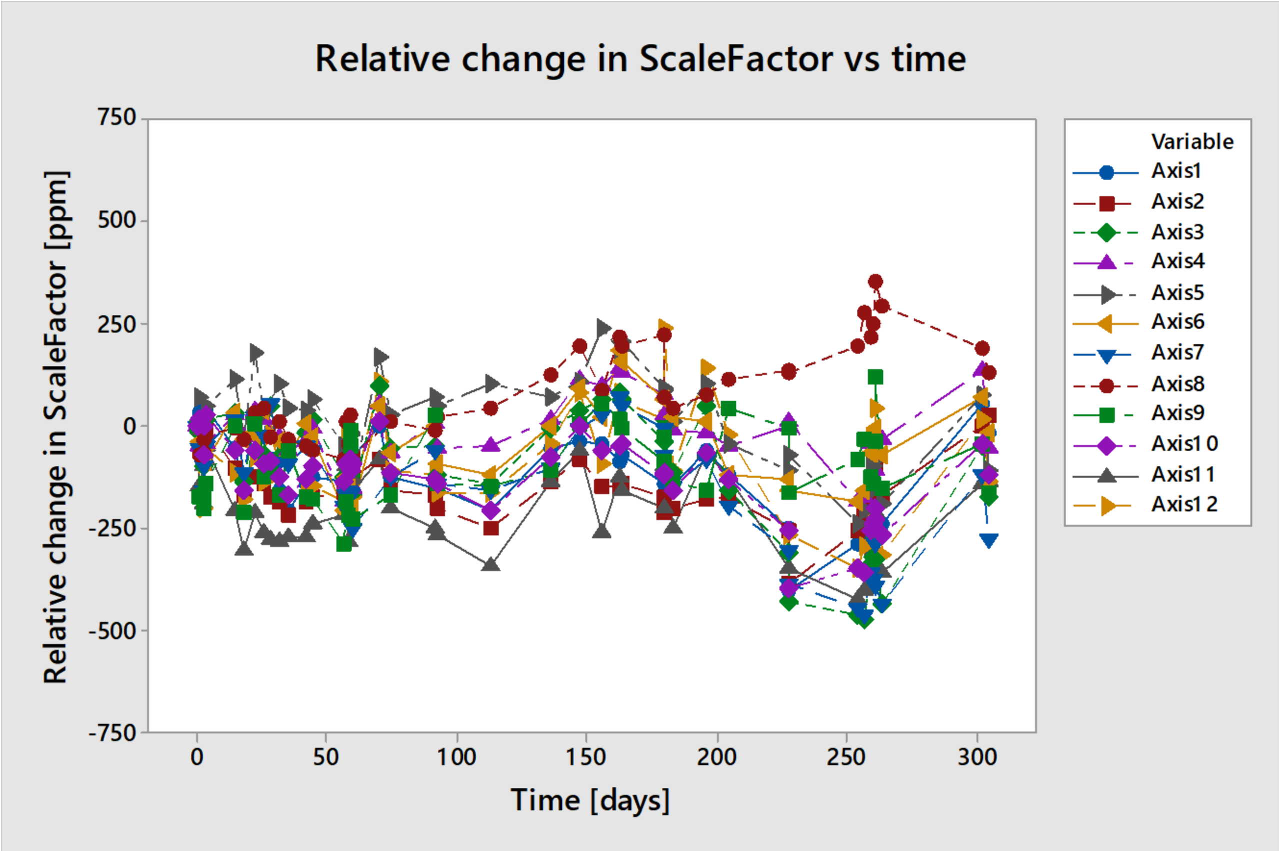

Figure 15. Relative change in abs(scale-factor) over time

3.3 Drift in bias and scale-factor after application of environmental stress tests

All Sensonor's gyro-modules and IMUs undergo product qualifications where the parts are subjected to a number of environmental stresses meant to represent and simulate what a product would see through its typical lifetime. With Sensonor's products being standard-components, and thereby serving a variety of applications, the qualification program is a result of typical demands from main applications and experience from the past.

The change in bias (rms shift) after having been exposed to different environmental stimuli is shown in figure 16:

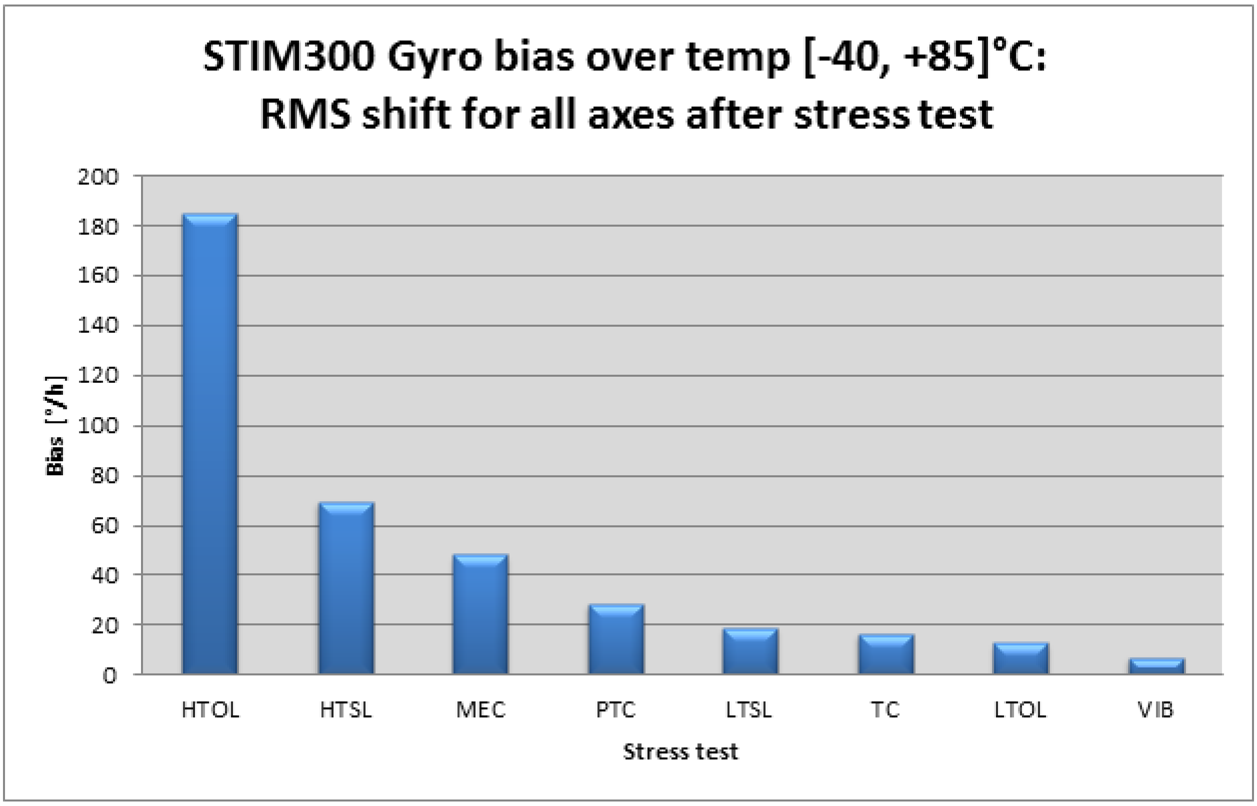

Figure 16: RMS shift of gyro bias after stress tests

A short description of the mentioned stress tests in figures 16 and 17 is given in table 4:

Table 4: Short description of stress tests

Stress test	**Description**
HTOL	High Temperature Operating Life: 1000 hours @+85°C, 5V power
LTOL	Low Temperature Operating Life: 1000 hours @-40°C, 5V power
HTSL	High Temperature Storage Life: 1000 hours @+90°C, unpowered
LTSL	Low Temperature Storage Life: 1000 hours @-55°C, unpowered
PTC	Powered Temperature Cycling: -40/+85°C, 250 cycles, 5V power
TC	Temperature Cycling: -40/+85°C, 250 cycles, unpowered
MEC	Mechanical Shock: 1500g, 0.5ms half-sine, 5 shocks in each direction, 5V power
VIB	Random Vibration: : MIL-STD-810E 514.4-8 "High Performance Aircraft“, 14.83g rms, 5V power

Similarly, the change in scale-factor (rms shift) can be found in figure 17:

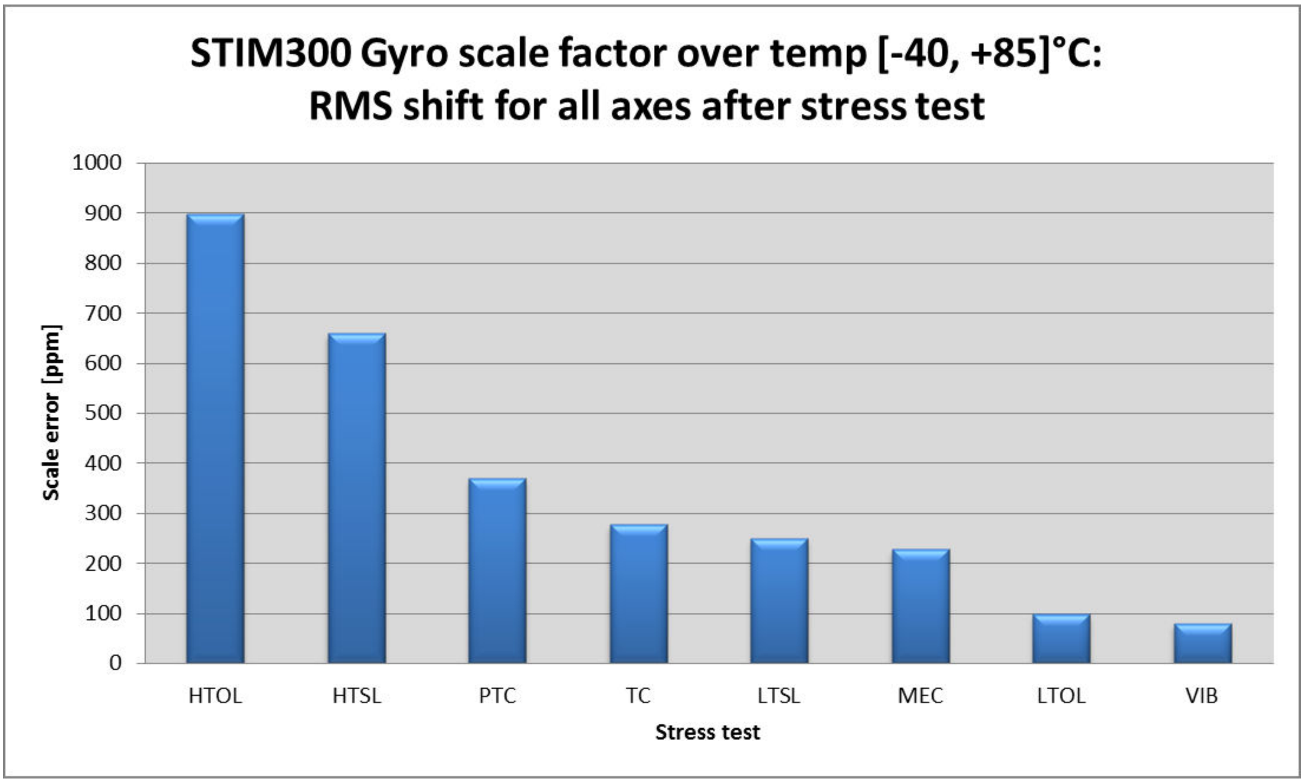

Figure 17: RMS shift of scale-factor after stress tests

4 Lessons learned from automotive industry

With experience from decades in the automotive industry, Sensonor continues its focus on high-reliability design and manufacturing of today's gyros and IMUs. The following sub-sections touch base on some lessons learned related to methodologies, design-philosophies and strategies with focus on high reliability and robustness.

4.1 Play it safe

The gyro sensor die used in Sensonor's MEMS gyro-modules and IMU is the same as was used during the production and delivery of more than 2 million roll-over sensors. By remaining at the same operating conditions (essentially keeping the same low excitation amplitude), this ensures a continuum of the proven in-field high reliability.

Increasing the excitation amplitude would directly increase scale-factor and reduce noise. Sensonor has avoided this temptation as it could compromise on reliability and proven experience from field. Instead, noise has been improved by redesign of the electronics, bringing the noise down to a competitive level. There is a potential to bring the noise down even further by redesign of the electronics, keeping the excitation amplitude at an unchanged level.

4.2 Control of critical parameters through automated assembly processes

Delivering millions of sensors annually to the automotive industry could not have been done without fully automated assembly processes. In addition to provide high volumes, automated assembly machines also provide accuracy and repeatability. Mechanical stress from the assembly of the gyro sensor die is a dominating and limiting factor with respect to long-term effects. Through the automotive era, Sensonor gained specialized competence in the art of die assembly, and has applied this to establish a well-controlled and repetitive assembly process.

4.3 Self-test and signal integrity

Having successfully supplied products to safety-critical applications like airbags, this has made a big impact in the design-philosophy at Sensonor. Topics like self-test during operation and signal integrity are a natural part of the development process.

The gyro sensor dies are driven at their respective resonances. By continuously monitoring parameters like resonance-frequency and -amplitude, the result is a continuous self-test covering the seismic mass, its free movement and the integrity of drive- and detection-electrodes. Hence the need for a triggered self-test, which will disrupt the signal output for some period of time, is thereby avoided.

Through risk-mitigation processes like design-FMEAs (Failure Mode and Effect Analyses), critical system parameters have been identified, including reference voltages, system oscillator, temperatures and integrity of flash-content both for software and calibration coefficients. A separate diagnosis function has been implemented to provide a built-in self-test, continuously checking the internal integrity. The built-in self-test in STIM210 is currently running 69 different tests. For STIM300 the corresponding number is 109. There is even a check to verify that the built-in self-test itself is running. The result of these tests is reported in a status-byte accompanying each transmitted package of measurements ("datagrams").

However, Sensonor's focus on signal integrity does not stop here. By adding a signal to better synchronize to the transmitted datagrams and features like a datagram-counter + CRC (Cyclic Redundancy Check) in the datagrams, the user now have good tools available to verify that all transmitted data have been received and assess the integrity of the data transmission itself.

4.4 Test-strategies

The number of tests performed on each part may seem overwhelming. There are several test-strategies in play. One test-strategy is to always start off with a high number of tests, and then reduce tests when sufficient knowledge and confidence have been established. This is a natural consequence of the increased maturity or TRL (Technology Readiness Level) over time and volumes.

Another test-strategy is to move problems or yield-issues towards their source. Yield is tracked on every tested parameter and pareto-analyses guide the yield-teams to the current major yield-detractors. Based on the root-cause findings from the yield-teams, new tests may be established to identify the problem at an early stage or preferably at the point of origin. This could be back to an earlier step in production or back to a supplier. Having the complete production-line in-house, including the wafer fab of the gyro sensor dies, Sensonor has full control over the manufacturing processes and short feedback-loops for corrective measures and adjustments.

4.5 Continuous improvement

Continuous improvements essentially mean a never-ending strive towards perfection. This is evident in the production data, e.g. IRBS (ref. figure 5), displaying a reduction both in spread and average value over time. However improvements are a result of changes, and changes are associated with risks. Sensonor has a good and well-proven flow for handling changes, always involving a change-FMEA to assess risks and possible side-effects of implementing changes. By keeping the changes small and always carefully considering whether a change would affect "form, fit or function", the products are improved with no compromise to quality, functionality or impact on existing customer applications.

5 Conclusions

Sensonor has since 2009 gained a solid position as supplier of tactical-grade gyros.

The increase in volume over time illustrates the conservatism in the field of tactical-grade gyros, with typically 3 years or more from shipment of first evaluation parts to production deliveries.

Sensonor has the know-how to produce in volumes, based on deliveries in the millions during two decades to the automotive industry. The presented production data shows sound distributions, suggesting good control of key parameters. This is a prime condition to be able to continuously deliver parts with predictable performance.

The gyro sensor die has been more or less unchanged for the past 20 years, representing a safe and reliable foundation for Sensonor's gyro-modules and IMU now and in the years to come.

Sensonor has a mind-set for high-reliability and quality. This permeates the whole company, e.g. during the design-processes with focus on self-test and signal integrity, in up-front risk-mitigation when changes for improvement are being proposed and in all aspects of the production.