AN12760

Temperature compensation of accelerometer sensors measurement

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Document information

Information	Content
Keywords	Accelerometer, Compensation, Temperature, Coefficient, Offset, Sensitivity, MEMs, Sensor
Abstract	This application note shows how to derive the temperature coefficients of accelerometer sensor measurement and use them to improve sensor accuracy over temperature.

Rev	Date	Description
1	20220127	Initial release

1 Introduction

AN12760 contains various parameter definitions used in accelerometer sensor data sheets. It explains how to characterize them while proposing formulae to compute them.

Section 2 describes key parameters that define the accuracy of the sensor measurement and its behavior versus temperature. Those parameters are usually referred to as Offset, Sensitivity, Temperature Coefficient of the Offset (TCO), and Temperature Coefficient of Sensitivity (TCS). A few lines from the FXLS8964 data sheet sensitivity specification table are also included for illustration purposes.

Section 3 provides simulated plots to better quantify and visualize how the raw sensor accelerometer data are impacted by Offset and Sensitivity errors, as well as their temperature drift coefficients.

Equation 8 in Section 2.3 is an important and useful outcome of this application note. This final formula removes offset and scaling errors and their temperature drift from the raw sensor data. The correction of these sensor errors and their dependence versus temperature greatly improve accelerometer accuracy over the temperature range.

2 Accelerometer parameters definition and formulae

2.1 Sensor Raw data

For a given axis, the sensor data reading provides a digital number $Raw\ Acc_{count}$, whose unit is LSB or count.

To translate the raw digital data into a raw acceleration value, use the theoretical sensitivity, SEN_{theo}, according to Equation 1:

$$\boldsymbol{RawAcc = RawAcc_{count} \times SEN_{theo}} \tag{1}$$

The theoretical or nominal sensitivity is found in the sensor data sheet (in the typical column) and depends on the selected full scale range. As an example, FXLS8964 sensitivity in ±2 *g* range is:

Table 1. FXLS8964 sensitivity specification

Symbol	Parameter	Conditions	Min	Typ	Max	Unit
SEN	Nominal sensitivity	±2 *g* mode	0.87	0.98	1.12	mg/LSB

$$SEN_{theo} = \frac{1000}{1024} \approx 0.98\ \ (in\ mg/LSB)$$

Note: *The mg/LSB unit used for the theoretical sensitivity is not mandatory. For example, it could be expressed in g/LSB, m/s²/LSB.*

At that stage, a theoretical sensitivity is used as the actual or true sensitivity is not determined. Ultimately and if available, the real (i.e. calibrated) sensitivity can be used to scale the raw data.

$SENS_{theo}$ simply realizes the conversion of the raw digital data into a meaningful accelerometer measurement expressed with a physical unit (for example, m*g*, *g*, m/s²).

This document uses the m*g* unit for sensor raw acceleration data. As an example, for a +1 *g* or –1 *g* orientation, expect the following theoretical value:

$$\boldsymbol{RawAcc_{theo}}(+1\ \boldsymbol{g}) = 1000\ \boldsymbol{mg}$$

$$\boldsymbol{RawAcc_{theo}}(-1\ \boldsymbol{g}) = -1000\ \boldsymbol{mg}$$

Obviously, actual data may deviate from perfect results due to various sensor errors.

This theoretical acceleration can also be expressed in count, which corresponds to the raw data directly read from the sensor:

$$RawAcc_{theo}(+1\ g) = 1024\ LSB$$

2.2 Offset and Temperature Coefficient of the Offset (TCO)

When the axis of interest is orthogonal to the earth gravity, the axis lays in the horizontal plane, the sensor measurement data is expected to be 0 for this axis.

For a given temperature, the offset is simply the actual measurement data:

$$Offset(Temp)(0\ g) = RawAcc(Temp)(0\ g) \tag{2}$$

An example from the FXLS8964 data sheet:

Table 2. Post-board mount offset

Symbol	Parameter	Conditions	Min	Typ	Max	Unit
OFF_{PBM}	Zero-*g* offset, post-board mount [1]	—	–550	±250	550	m*g*

[1] Determined with post board mount data using a standard lead-free reflow profile and NXP recommended landing pattern on a 4-layer FR4 PCB with 1.6 mm (62.5 mil) overall thickness.

Assuming linear law for the offset vs temperature, the TCO is derived from the 2 extreme temperature measurements:

$$\boldsymbol{TCO} = \frac{\boldsymbol{RawAcc}(\boldsymbol{Thigh})(0\ \boldsymbol{g}) - \boldsymbol{RawAcc}(\boldsymbol{Tlow})(0\ \boldsymbol{g})}{\boldsymbol{Thigh} - \boldsymbol{Tlow}} \tag{3}$$

Again, using the example of FXLS8964, TCO has the same unit as raw acceleration data divided by °C, for example, m*g*/°C:

Table 3. Zero-*g* offset temperature coefficient, post-board mount from the mechanical characteristics table of the FXLS8964AF data sheet

Symbol	Parameter	Conditions	Min	Typ	Max	Unit
TCO_{PBM}	Zero-*g* offset temperature coefficient, post-board mount[1]	–40 °C to +105 °C	—	±1	—	mg/°C

[1] Determined with post board mount data using a standard lead-free reflow profile and NXP recommended landing pattern on a 4-layer FR4 PCB with 1.6 mm (62.5 mil) overall thickness.

Still assuming a linear law of the acceleration offset versus temperature, TCO can be represented as:

$$TCO = \frac{RawAcc(Thigh)(0\ g) - RawAcc(Troom)\ (0\ g)}{Thigh - Troom}$$

$$TCO = \frac{RawAcc(Troom)\ (0\ g) - RawAcc(Tlow)\ (0\ g)}{Troom - Tlow}$$

If the law is not linear, approximate the value by a second or eventually third order polynomial, fitted with additional temperature data points.

When needed, the room/ambient temperature measurement can be used as a third data point to fit a second order equation.

TCO is used to compute the offset at any temperature. Equation 4 describes a simple linear law.

$$Offset(Temp)\ (0\ g) = RawAcc(Temp)\ (0\ g) = RawAcc(Troom)\ (0\ g) + TCO \times (Temp - Troom) \tag{4}$$

When Offset drift vs Temperature is not linear, a 3rd order polynomial can be used, as already mentioned.

$$Offset(Temp)(0\ g) = RawAcc(Troom)(0\ g) + TCO_1 \times (Temp\text{-}Troom) + TCO_2 \times (Temp - Troom)^2 + TCO_3 \times (Temp - Troom)^3$$

In such a case, sensor TCO varies vs temperature and follows the derivative of this polynomial. It actually represents the “local slope” of the sensor offset variation vs temperature.

$$TCO(Temp) = \frac{\partial\ Offset(Temp)\ (0\ g)}{\partial\ Temp} = \frac{\partial\ RawAcc(Temp)\ (0\ g)}{\partial\ Temp}$$

$$TCO(Temp) = TCO_1 + 2 \times TCO_2 \times (Temp - Troom) + 3 \times TCO_3 \times (Temp - Troom)^2$$

Name ***AccTCO(Temp)***, the acceleration measurement, at temperature Temp and for any orientation of the sensor, with 0 *g* offset and TCO compensation applied, for example:

$$AccTCO(Temp) = RawAcc(Temp) - RawAcc(Temp)(0\ g)$$

When injecting Equation 4 into the definition of AccTCO(Temp), it translates into:

$$\boldsymbol{AccTCO(Temp) = RawAcc(Temp) - [RawAcc(Troom)(0\ g) + TCO \times (Temp - Troom)]} \quad (5)$$

$$AccTCO(Temp) = RawAcc(Temp) - RawAcc(Troom)(0\ g) - TCO \times (Temp - Troom) \quad (5)$$

By definition, *AccTCO(Temp)(0 g)* is the offset and TCO compensated raw acceleration data, therefore when axis of interest is exposed to 0 *g* (orthogonal to gravity), it should always be:

$$AccTCO(Temp)(0\ g) = 0$$

2.3 Sensitivity and Temperature Coefficient of Sensitivity (TCS)

Aligning the axis of interest in the vertical direction with gravity, is a simple way to derive sensor sensitivity, and TCS.

In order to compute actual sensitivity at a given temperature, perform 2 measurements, one at +1 *g* orientation and another at –1 *g* orientation:

$$\boldsymbol{Sensitivity(Temp) = \frac{RawAcc(Temp)(+1\ g) - RawAcc(Temp)(-1\ g)}{RawAcc_{theo}(+1\ g) - RawAcc_{theo}(-1\ g)} \times SEN_{theo}} \quad (6)$$

Here, the computed *Sensitivity* is simply a ratio of similar quantities multiplied by SEN_{theo}. It has the same unit as SEN_{theo}.

An interesting associated parameter is the normalized sensitivity:

$$SEN_{norm}(Temp) = \frac{Sensitivity(Temp)}{SEN_{theo}}$$

As a ratio of quantities with same unit, compute SEN_{norm} directly from the raw digital data $Raw\ Acc_{count}$, regardless of the chosen unit for SEN_{theo}.

$$SEN_{norm}(Temp) = \frac{RawAcc(Temp)(+1\ g) - RawAcc(Temp)(-1\ g)}{RawAcc_{theo}(+1\ g) - RawAcc_{theo}(-1\ g)}$$

Keeping the initial choice of m*g* for *Raw Acc*, the formulae to compute sensitivity is:

$$Sensitivity(Temp) = \frac{RawAcc(Temp)(+1\ g) - RawAcc(Temp)(-1\ g)}{2000} \times SEN_{theo}$$

This formula produces the sensor actual absolute sensitivity. The accuracy error can be derived which is reflected by the parameter SEN_{TOL} (for example, 2.5 % typical in FXLS8964 data sheet).

Table 4. Sensitivity tolerance

Symbol	Parameter	Conditions	Min	Typ	Max	Unit
SEN_{TOL}	Sensitivity tolerance[1]	—	—	±2.5	—	%SEN

[1] Determined with post board mount data using a standard lead-free reflow profile and NXP recommended landing pattern on a 4-layer FR4 PCB with 1.6 mm (62.5 mil) overall thickness.

$SEN_{TOL}(Temp)$ is the deviation of actual sensitivity vs. theoretical one, at a given temperature:

$$\boldsymbol{SEN_{TOL}(Temp) = \frac{Sensitivity(Temp) - SEN_{theo}}{SEN_{theo}}} \quad (7)$$

It is a ratio of similar quantities, therefore it is unit-less, and expressed in %.

Actual sensitivity vs SEN_{TOL} and theoretical sensitivity can easily be derived:

$$Sensitivity(Temp) = SEN_{theo} \times [1 + SEN_{TOL}(Temp)]$$

Involving $SEN_{norm}(Temp)$, this formula simplifies further into:

$$\frac{Sensitivity(Temp)}{SEN_{theo}} = 1 + SEN_{TOL}(Temp)$$

$$SEN_{norm}(Temp) = 1 + SEN_{TOL}(Temp)$$

When SEN_{TOL} = 0, naturally SEN_{norm} = 1 as expected.

In order to remove offset and TCO impact on the measurement, *AccTCO* is used to compute sensitivity at a given temperature:

$$Sensitivity(Temp) = \frac{AccTCO(Temp)(+1\ g) - AccTCO(Temp)(-1\ g)}{RawAcc_{theo}(+1\ g) - RawAcc_{theo}(-1\ g)} \times SEN_{theo}$$

Replacing *AccTCO* by its formula:

$$Sensitivity(Temp) = \frac{\left\{\begin{matrix}[RawAcc(Temp)(+1\ g) - RawAcc(Troom)(0\ g) - TCO \times (Temp - Troom)] - \\ [RawAcc(Temp)(-1\ g) - RawAcc(Troom)(0\ g) - TCO \times (Temp - Troom)]\end{matrix}\right\}}{RawAcc_{theo}(+1\ g) - RawAcc_{theo}(-1\ g)} \times SEN_{theo}$$

Which simplifies into:

$$\boldsymbol{Sensitivity(Temp) = \frac{[RawAcc(Temp)(+1\ g) - RawAcc(Temp)(-1\ g)]}{RawAcc_{theo}(+1\ g) - RawAcc_{theo}(-1\ g)} \times SEN_{theo}} \quad (8)$$

This formula is the exact same formula as Equation 6. It means that TCS can be derived directly from +1 *g* and –1 *g* raw data measurements without bothering offset or its temperature dependency. Since the offset and temperature dependency are the same for both +1 *g* and –1 *g* orientations, they subtract out (for a given temperature), as shown in the above computation.

Still assuming a linear law for TCS, compute the *Sensitivity(Temp)* directly with *AccTCO*, from a single data point, for example:

$$Sensitivity\ (Temp) = \frac{AccTCO(Temp)(+1\ g)}{RawAcc_{theo}(+1\ g)} \times SEN_{theo}$$

$$Sensitivity\ (Temp) = \frac{AccTCO(Temp)(-1\ g)}{RawAcc_{theo}(-1\ g)} \times SEN_{theo}$$

Note: *The single data point formula implies that the offset and its temperature drift are compensated.*

The TCS parameter is the Temperature Coefficient of Sensitivity, or in other words, the rate of change of sensitivity vs temperature. Assuming a linear law, TCS can be computed as follows:

$$\boldsymbol{TCS = \frac{Sensitivity(Thigh) - Sensitivity(Tlow)}{(Thigh - Tlow) \times Sensitivity(Troom)}} \quad (9)$$

Again, when assuming a linear law for sensitivity vs temperature, these formulas apply:

$$TCS = \frac{Sensitivity(Thigh) - Sensitivity(Troom)}{(Thigh - Troom) \times Sensitivity(Troom)}$$

$$TCS = \frac{Sensitivity(Troom) - Sensitivity(Tlow)}{(Troom - Tlow) \times Sensitivity(Troom)}$$

TCS is a ratio of sensitivity divided by °C and is usually expressed in %/°C as shown in the FXLS8964 data sheet:

Table 5. TCS

Symbol	Parameter	Conditions	Min	Typ	Max	Unit
TCS	Temperature coefficient of sensitivity[1]	–40 °C to +105 °C	—	±0.01	—	%/°C

[1] Determined with post board mount data using a standard lead-free reflow profile and NXP recommended landing pattern on a 4-layer FR4 PCB with 1.6 mm (62.5 mil) overall thickness.

The same comment regarding TCO applies for TCS, a polynomial fit can be used but this necessitates more temperature measurement data points and is usually not necessary.

Again assuming a linear law, TCS allows users to derive actual sensitivity vs temperature:

$$Sensitivity(Temp) = Sensitivity(Troom) \times [1 + TCS \times (Temp - Troom)]$$

$$\boldsymbol{Sensitivity(Temp) = SEN_{theo} \times [1 + SEN_{TOL}(Troom)] \times [1 + TCS \times (Temp - Troom)]} \quad (10)$$

2.4 Sensor raw data correction with TCO and TCS

The complete formula of the computed acceleration compensated for offset, TCO, sensitivity, and TCS is:

$$AccTCOTCS(Temp) = \frac{AccTCO(Temp)}{Sensitivity(Temp)} \times SEN_{theo} = \frac{AccTCO(Temp)}{SEN_{norm}(Temp)}$$

$$AccTCOTCS(Temp) = \frac{AccTCO(Temp)}{Sensitivity(Troom) \times [1 + TCS \times (Temp - Troom)]} \times SEN_{theo}$$

$$AccTCOTCS(Temp) = \frac{AccTCO(Temp)}{SEN_{theo} \times (1 + SEN_{TOL}(Troom)) \times [1 + TCS \times (Temp - Troom)]} \times SEN_{theo}$$

$$AccTCOTCS(Temp) = \frac{AccTCO(Temp)}{[1 + SEN_{TOL}(Troom)] \times [1 + TCS \times (Temp - Troom)]}$$

$$\boldsymbol{AccTCOTCS(Temp) = \frac{RawAcc(Temp) - [RawAcc(Troom)(0\,g) + TCO \times (Temp - Troom)]}{[1 + SEN_{TOL}(Troom)] \times [1 + TCS \times (Temp - Troom)]}} \quad (11)$$

Offset and TCO are additive errors, therefore they are subtracted from the raw data, whereas sensitivity, and TCS errors are multiplicative, consequently they are divided.

The complete correction formula in case TCO and TCS are 3rd order polynomials is:

$$AccTCOTCS(Temp) = \frac{RawAcc(Temp) - [RawAcc(Troom)(0\,g) + TCO_1 (Temp - Troom) + TCO_2 (Temp - Troom)^2 + TCO_3 (Temp - Troom)^3]}{(1 + SEN_{TOL})[1 + TCS_1 (Temp - Troom) + TCS_2 (Temp - Troom)^2 + TCS_3 (Temp - Troom)^3]}$$

3 Parameters and Temperature drift illustration

3.1 General description

In order to better comprehend the impact of error parameters onto the sensor measurement data, practical examples are provided, showing raw data vs temperature or tilt angle.

The illustrations are generated by a spreadsheet and use a few parameters from FXLS8964 data sheet, as previously mentioned. They are based on the following conditions:

Table 6. Temperature range

Parameter	Value
Troom	25 °C
Thigh	105 °C
Tlow	–40 °C

Nominal (or theoretical) sensitivity:

$$SEN_{theo} = \frac{1000}{1024} \approx 0.98 \ \left(in \ mg \middle/ LSB\right)$$

As sensitivity is expressed in m*g*/LSB unit, the “scaled sensor raw data” (referred to as ***RawAcc*** in Equation 1) use the m*g* unit.

First only offset and TCO are considered, followed by sensitivity, and TCS, and finally the 4 parameters altogether.

The effectiveness of the Equation 11 correction formula is also detailed.

3.2 Offset and TCO

Injected Offset and TCO errors:

Table 7. Injected Offset and TCO errors

Parameter	Value
Offset	-20 m*g*
TCO	1 mg/°C
SENtol	0.00 %
TCS	0.000 %/°C
Troom	25 °C

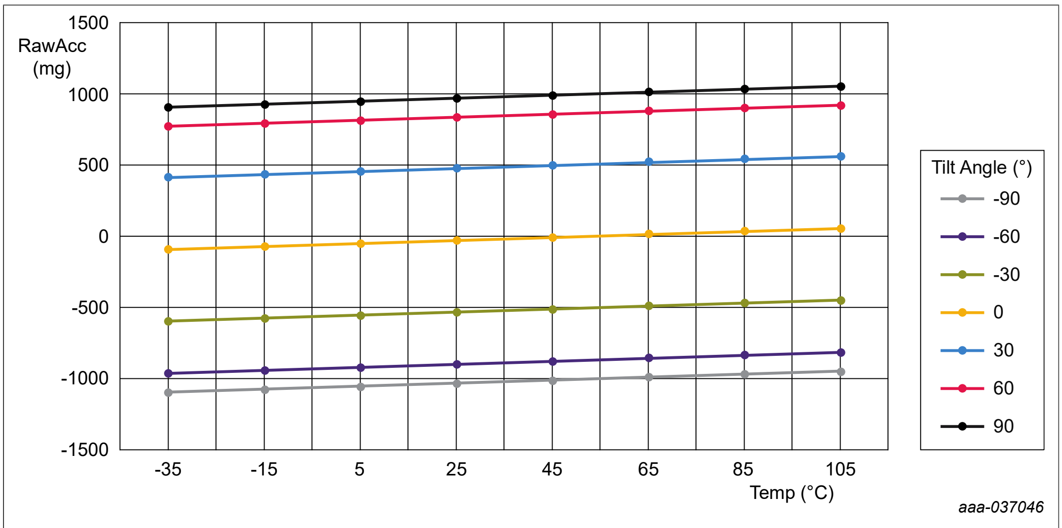


Figure 1. RawAcc vs temp for various tilt angles

For Tilt = 0° the axis is horizontal and should measure 0 *g*.

For Tilt = +90° or –90°, the axis is vertical and should measure +1 *g* and –1 *g* respectively.

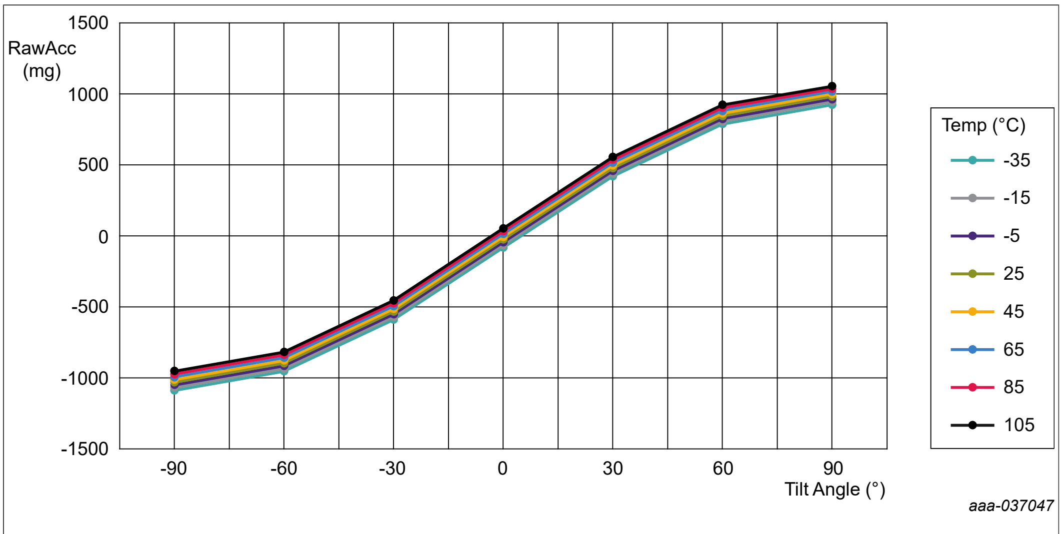


Figure 2. RawAcc vs tilt for various temperatures

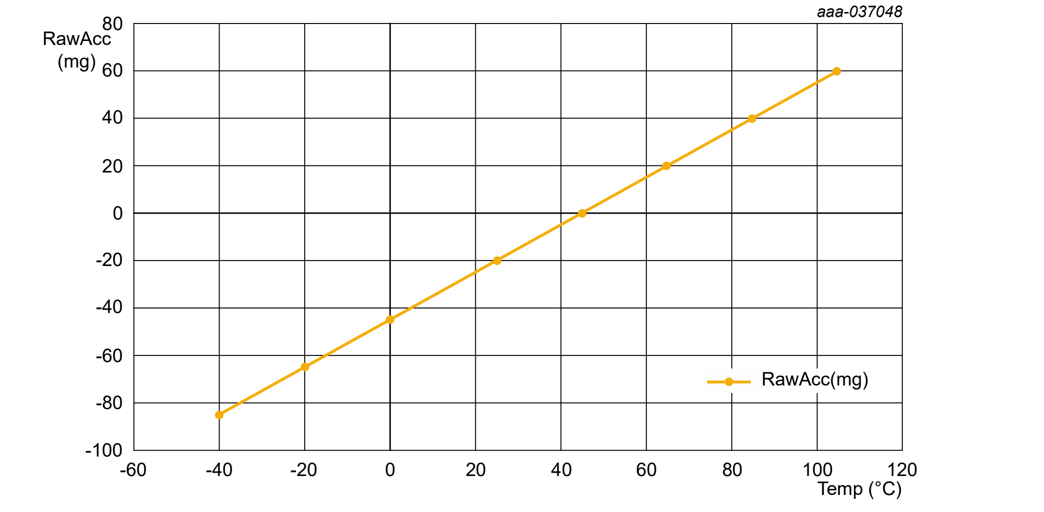


Figure 3. Offset vs temperature = RawAcc(Temp)(0 *g*)

3.3 Sensitivity and TCS

Injected sensitivity, and TCS errors:

Table 8. Injected Sensitivity and TCS errors

Parameter	Value
Offset	0 m*g*
TCO	0 mg/°C
SENtol	2.64 %
TCS	–0.100 %/°C
Troom	25 °C

Note: *The TCS parameter is increased significantly from usual value to better notice the temperature effect.*

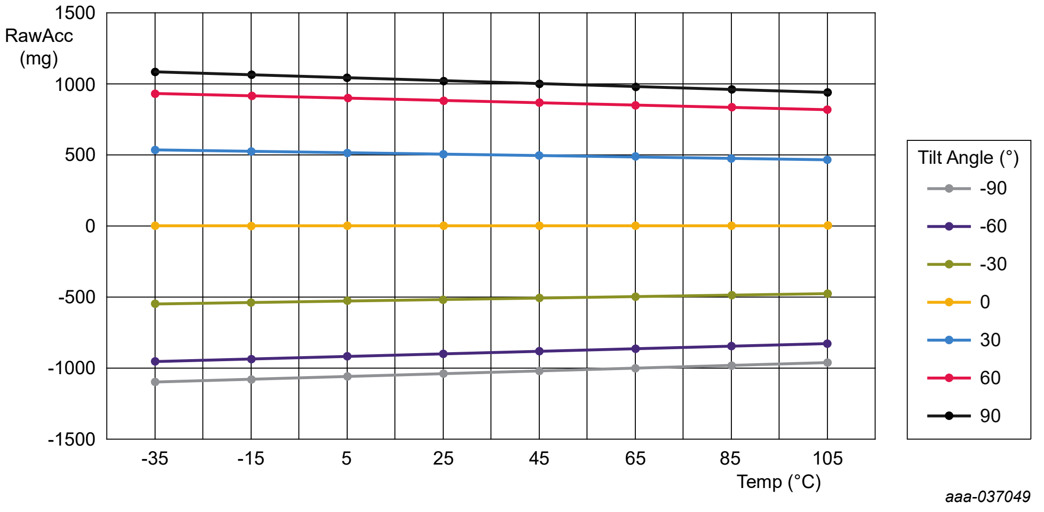


Figure 4. RawAcc vs temp for various tilt angles

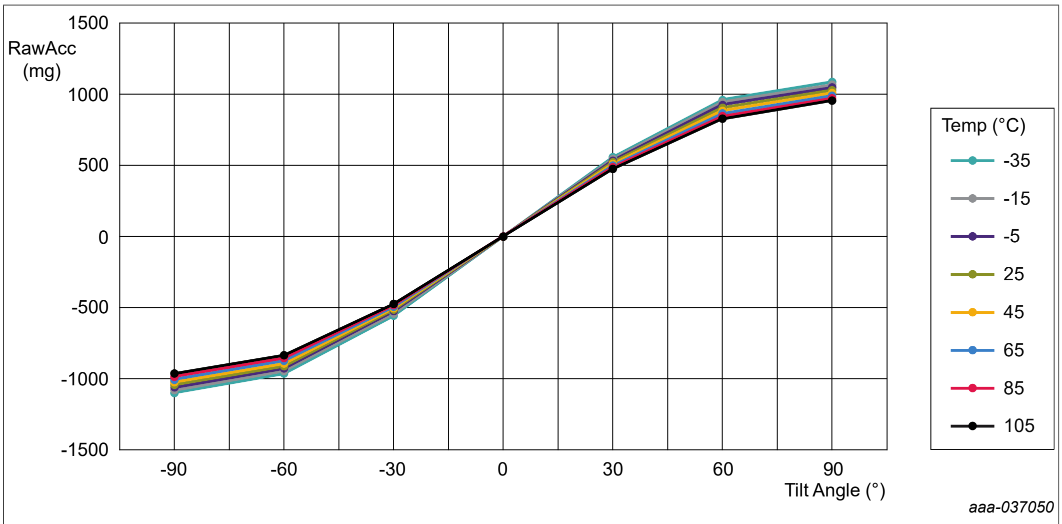


Figure 5. RawAcc vs tilt for various temperatures

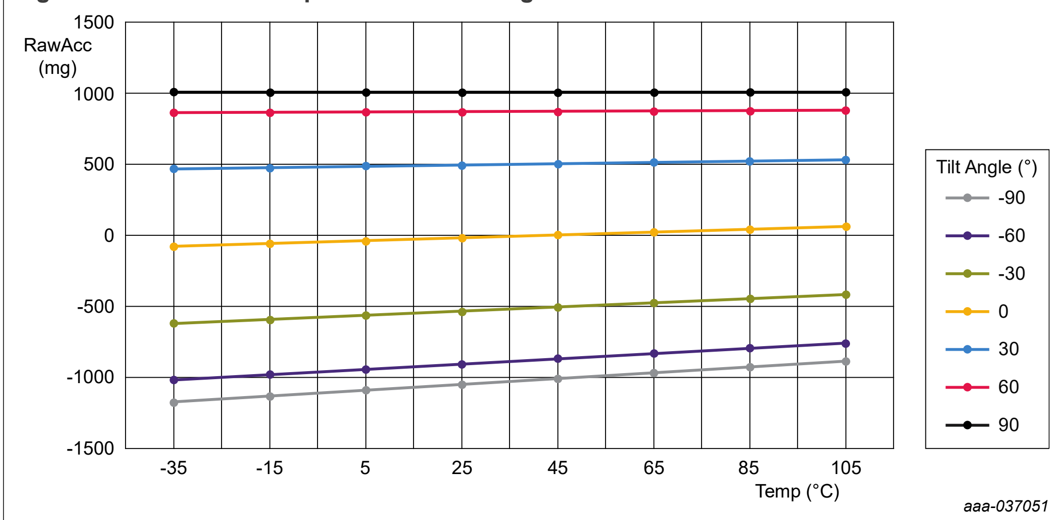
3.4 All error sources combined

Injected offset, TCO, sensitivity, and TCS errors:

Table 9. Injected Offset, TCO, Sensitivity, and TCS errors

Parameter	Value
Offset	–20 mg
TCO	1 mg/°C
SENtol	2.64 %
TCS	–0.100 %/°C
Troom	25 °C

Figure 6. RawAcc vs temp for various tilt angles



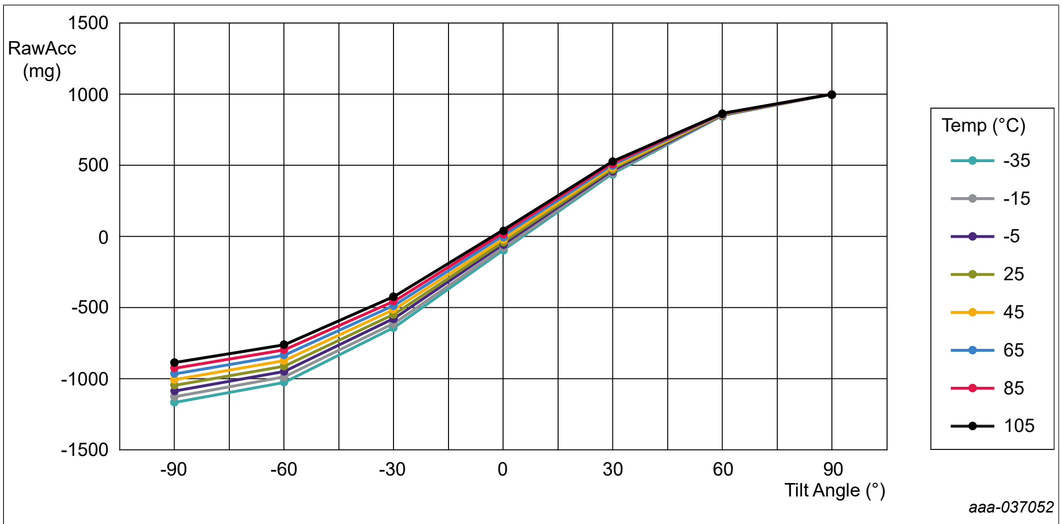


Figure 7. RawAcc vs tilt for various temperatures

3.5 Raw Acceleration corrected data

Now the Equation 3 (AccTCO formula) and Equation 8 (AccTCOTCS formula) are used to compute the Offset/TCO compensated data and the Offset/TCO+Sensitivity/TCS compensated data.

The raw data are affected by the same 4 errors as in Table 4, and are provided in Table 5 (cf RawAcc(m*g*) column), as well as the corrected values, AccTCO and AccTCOTCS.

Table 10. Corrected raw acceleration data

Temp(°C)	Tilt Angle(°)	RawAcc(m*g*)	AccTCO(m*g*)	AccTCOTCS(m*g*)
-40	**-90**	-1178.1	-1093.1	-1000.0
-40	**0**	-85.0	0.0	0.0
-40	**90**	1008.1	1093.1	1000.0
25	**-90**	-1046.4	-1026.4	-1000.0
25	**0**	-20.0	0.0	0.0
25	**90**	1006.4	1026.4	1000.0
105	**-90**	-884.3	-944.3	-1000.0
105	**0**	60.0	0.0	0.0
105	**90**	1004.3	944.3	1000.0

4 Offset and TCO measurement examples

This section is based on actual measurement and provides examples of Offset drift versus Temperature and associated TCO estimate.

Figure 8 corresponds to the typical and friendly case where offset drift is linear vs Temperature. This means that TCO is very constant over the full Temperature range and corresponds to the slope of the curve.

A linear fit yields gives: TCO = 0.64 m*g*/°C

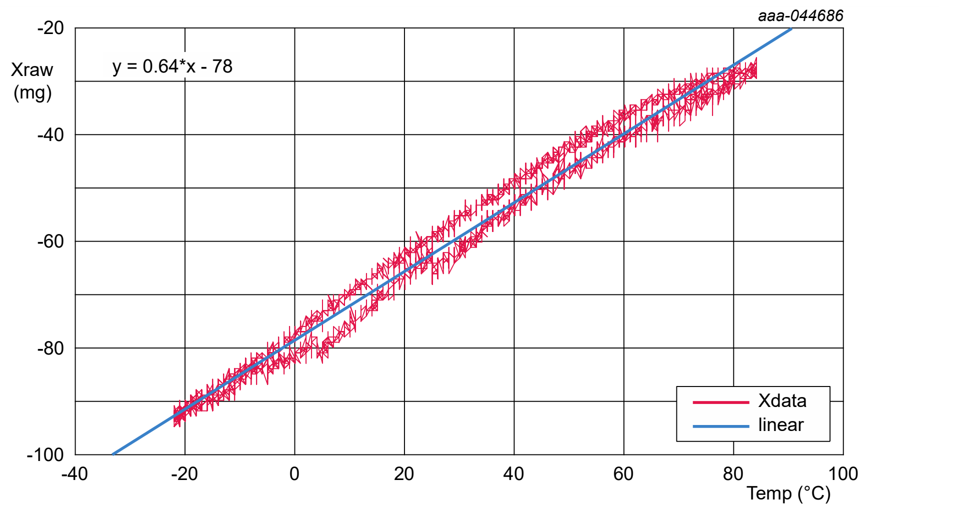


Figure 8. X data vs. Temp

Figure 9 corresponds to a quadratic law between offset drift and temperature.

In that case, the linear fit is obviously not a good choice. At least 3 measurement data points must be considered to better estimate the TCO variation. Those are usually Offset measurement at Cold, Room and Hot Temperature.

As a side note, the 3 data points are often used to compute 2 slopes, with following equations:

$$TCO_{hot} = \frac{RawAcc(T_{hot})(0g) - RawAcc(T_{room})(0g)}{T_{hot} - T_{room}}$$

$$TCO_{cold} = \frac{RawAcc(T_{room})(0g) - RawAcc(T_{cold})(0g)}{T_{room} - T_{cold}}$$

The TCO hot and TCO cold give a good indication on the offset drift linearity. For example, if they are similar, the law should be linear. For this quadratic behavior example, they are almost opposite to each other.

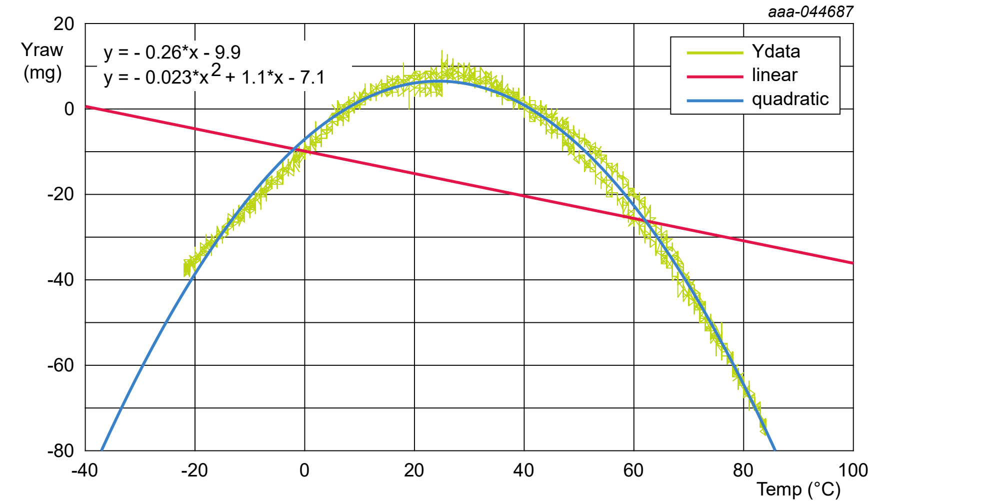


Figure 9. Y data vs. Temp

Figure 10 shows a slightly cubic law.

In this case, the cubic fit is obviously the most accurate but requires at least 4 data points. A simple linear fit can be a reasonable choice to approximate the TCO and provides already decent compensation of the offset drift vs temperature.

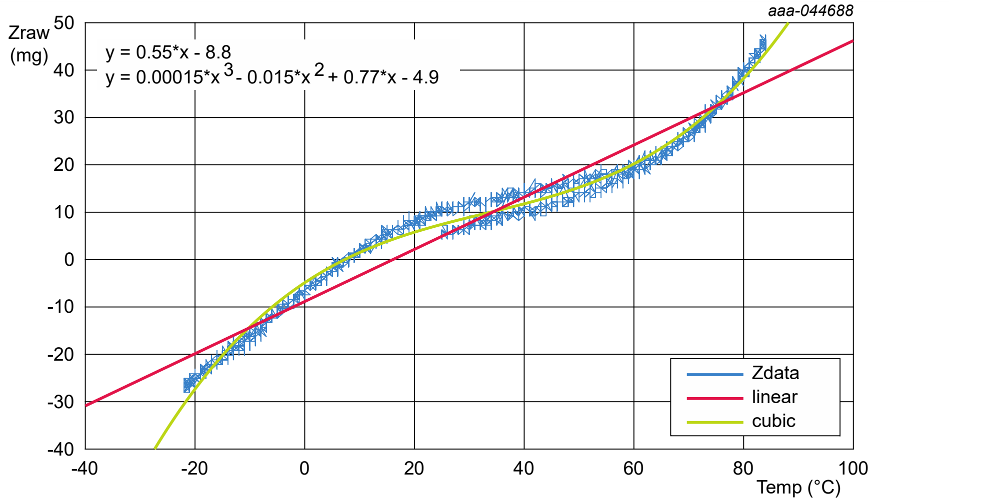


Figure 10. Z data vs. Temp

5 Conclusion

With all the information and formulae that have been provided, one should be able to:

- Better understand the accelerometer parameters.
- Translate the sensor digital data into a physical acceleration value.
- Characterize the behavior of the sensor over temperature.
- Compute the key parameters that represent measurement imperfection and drift.
- Compensate the sensor measurement errors and their temperature drift in order to improve the overall accuracy of the sensor.

In order to optimize sensor accuracy over temperature range, the compensation parameters should be individually measured and computed for each sensor. As this necessitates at least 3 temperature tests (Troom, T_{high}, T_{low}), with 3 different orientations (0 *g*, +1 *g*, –1 *g*) for all 3 axis (XYZ), it obviously represents a significant characterization effort with appropriate equipment.

Sensor cross-axis sensitivity (CAS) is also a potential source of error but is not included in the correction model.

Table 11. Cross-axis sensitivity from the mechanical characteristics table of the FXLS8964AF data sheet

Symbol	Parameter	Conditions	Min	Typ	Max	Unit
CAS	Cross-axis sensitivity	±2/4 *g* mode	—	±0.5	—	%

As an example, the 0.5 % typ, reported in FXLS8964 data sheet, can lead to an offset error of:

$$\Delta Offset(mg) = 1000 \times CAS = 5\ mg$$

The non-linearity (deviation from straight line) of the sensor measurement vs applied acceleration, and the possible temperature hysteresis are not included in the correction model either.

Ultimately, performing an ellipsoid/sphere fitting with a higher number of sensor orientations (9 to 12), and at 3 or more temperature points is an effective and accurate way to calibrate most of the sensor errors (offset, sensitivity, cross-axis) mentioned.

6 Glossary

Table 12.

$RawAcc_{count}$	Sensor measurement digital data
SEN_{theo}	Sensor theoretical sensitivity
RawAcc	Sensor measurement physical data (for example, m*g*)
Offset(Temp)	Sensor offset at temperature Temp
TCO	Temperature Coefficient of the Offset
Sensitivity(Temp)	Sensor actual sensitivity at temperature Temp
SEN_{TOL}	Sensitivity accuracy error vs theoretical sensitivity
AccTCO(Temp)	Sensor data with offset removed
TCS	Temperature Coefficient of the Sensitivity
AccTCO(Temp)	Sensor data with offset and sensitivity error removed
CAS	Cross Axis Sensitivity

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