Calibration Technique for SFP10X family of measurement ICs

Application Note
April 2015

Overview of calibration for the SFP10X

Calibration, as applied in the SFP10X, is a method to reduce the gain portion of the measurement errors. For example, when a current is measured, the reported measured value will differ from the actual:

\[ I_{\text{measured}} = I_{\text{actual}} \times (1 + \text{Gain Error}) + \text{Offset Error} \]

The reported measured value has two independent errors: the gain error and the offset error. There are many ways to express the gain error. For example, as shown in the formula above, a small bipolar unitless number that modifies an ideal unity gain for the actual value; often the gain error is expressed as a percentage deviation from unity gain.

Utilizing the built-in functionality in SFP10X measurement IC, it is possible to null-out this gain error.
Sources of Gain Error

**Figure 1:** A typical current measurement system

Significant contributors to the gain error are the current sensor, the amplifier, and the reference for the A/D converter.

In the current-measurement system implemented with the SFP10X, the resistive shunt is connected to the IC that has the amplifier and reference built-in. However, the deviation of the shunt’s resistance from the nominal value typically makes the largest contribution to the gain error.

The calibration functionality in the SFP10X simultaneously corrects gain errors from all sources.

**Utilization of the calibration value in the SFP10X**

The SFP10X simply multiplies the raw measured data (after the offset adjustment) by a correction factor that compensates for all combined gain errors from various sources:

\[
I_{\text{CALIBRATED}} = I_{\text{RAW}} \times \left(2^{16} + \text{SHNT}_{\text{CAL}}\right) / 2^{16}
\]

where \(2^{16} + \text{SHNT}_{\text{CAL}}\) / \(2^{16}\) is the gain correction factor. It is just greater than 1 when the shunt resistance is too small and less than 1 if the shunt resistance is too large. Resolution of the adjustment is about 15 ppm (0.0015 %).
The calibration value is stored in the `SHNT_CAL` register (address 0x41). It is a non-volatile register—it retains the programmed value even in the case of a complete power loss.

Because of the high A/D resolution and the specific method used in the SFP10X (64-bit numerical precision), there are no errors (resolution or rounding-off) after this multiplicative correction. Subsequently, while the `SHNT_CAL` is only a 16-bit signed 2’s complement value, the reported data after adjustment is still 24-bit, with 24 bits of resolution.

**Enabling the automatic application of the calibration value for the SFP10X**

Automatic application of the calibration value should be enabled by clearing the disable bit in the `COMP_CTRL` register (address 0x44). This means writing a value of 0xFE (clearing of the flag `SHNT_CAL_DIS`, the least-significant bit in that register). The default factory value programmed into that location is 0xFF (i.e. do not use the calibration feature).

The `COMP_CTRL` is a non-volatile register, just like the `SHNT_CAL` register.

After the above enabling process, the automatic calibration functionality will be applied after the next reset of the IC. To evoke an IC reset, the power could be cycled, or a reset command can be issued to the SFP10X.

Once the flag `SHNT_CAL_DIS` is cleared, the data available in the `CUR_OUT` register (addresses 0x32, 0x33, and 0x34) is automatically corrected by the calibration value, without any other user intervention. Likewise, all Coulomb count registers will accumulate the charge-proportional value that has been corrected by the calibration adjustment.
Determining the calibration value
The effect of the calibration adjustment should be the equity of the actual and measured values.

If the actual (expected) value of the current and the measured (but yet uncorrected) value of current are both known, the calibration value can be calculated as follows:

$$SHNT_{CAL} = \text{ROUND} \left\{ \frac{\text{Expected\_value}}{\text{Measured\_value}} - 1 \right\} \times 2^{16}$$

where ROUND is an operator that rounds the result of multiplication by $2^{16}$ to the nearest whole number. Therefore, the calculation above produces a signed integer result.

Methods to acquire the data for the determination of the calibration value are described later in this document.

Required hardware set-up for the calibration
Following the common terminology, the system being calibrated and consisting of the shunt connected to the SFP10X will be called DUT (Device Under Test).

There are many possible hardware configurations for effecting the current calibration, however, they all fall into two categories:

1. A constant DC current is supplied to the DUT, and the value of this calibrating current is known. In other words, a current Calibrator is utilized. Real-time data from the DUT are collected and processed (together with the known value of the DC current) for determination of the calibration value.

2. An unknown current from a current source is passed through both the DUT and through a precise current measurement apparatus. Real-time data from both the DUT and from the current measurement apparatus are collected and processed for determination of the calibration value.
Calibration errors

This part of the application note deals with the errors in the calibration (and in the measurements). It provides a very brief and simplified review of the accepted terminology, symbols used for descriptions of various quantities, and approaches to estimating the errors.

All measurements have errors. Since calibration is achieved by measurements that have errors, it will have errors that depend, to some degree, on the errors of the measurements and data collected during the process of calibration.
**Accuracy and Precision**

In common engineering tasks, the terms of accuracy and precision are often used.

Accuracy describes how close a measured value is to the reference or actual value. Precision defines how repeatable and reproducible the measurements are.

NIST and other National Metrology Institutes consider accuracy and precision as descriptive and qualitative concepts only. The proper term for expressing errors quantitatively is uncertainty.

For further information please consult:

1. NIST Technical Note 1297
2. International, National, and Regional “Basic and General Terms in Metrology” (VIM)
3. “Guide to the expression of uncertainty in measurement” (GUM)

**Uncertainty**

The term uncertainty reflects the probabilistic basis of the errors in measurements.

The uncertainty is characterized as Type A and Type B, based on the methods used for their evaluation. The Type A uncertainty is evaluated using statistical methods, and Type B uncertainty is evaluated using methods other than statistical; however statistical methods are still used for combining Type A and Type B uncertainties.

Type A uncertainty is said to be a component of uncertainty arising from random effects (with typically assumed normal / Gaussian probability distribution). Example: A group of individual measurements of the same value. This uncertainty can be reduced by averaging.

Type B uncertainty is said to be a component of uncertainty arising from an unknown systematic effect (with typically assumed rectangular probability distribution). Example: specification of a Digital Volt Meter (DVM) on a 10 V scale, the error is ±0.1 V. Averaging cannot reduce this uncertainty.
**Figure 3:** Illustration for accuracy and precision, and their relation to Type A and Type B uncertainties

**Uncertainty-related symbols**

Symbols used in describing measurement and uncertainty-related quantities are as follows (Note that these quantities are variable rather than constants; thus all symbols are italicized per IEEE and NIST guidelines):

The unknown value we are attempting to measure is called the measurand; symbol \( Y \).

The measurement result is denoted by symbol \( y \).

They are related by the following expression:

\[
y - U \leq Y \leq y + U
\]

also commonly written as \( Y = y \pm U \)

Symbol \( U \) is a quantity called expanded uncertainty. It represents such a value of uncertainty that lets us confidently believe that the above equation is true, meaning the measurand \( Y \) is within the interval \( \{y - U\} \) to \( \{y + U\} \). The degree of confidence is controlled by how expanded uncertainty \( U \) is calculated. The calculation of the expanded uncertainty \( U \) is explained later.
Type A uncertainty \( (u_i) \) is for “random” errors such as white noise, likely with Gaussian probability distribution. These errors can be evaluated by statistical methods.

Type B uncertainty \( (u_j) \) is for “systematic” errors, with presumed uniform or other probability distribution. These errors are evaluated by means other than statistical.

Combined standard uncertainty \( (u_c) \) incorporates both \( u_i \) and \( u_j \). The rules for combining \( u_i \) and \( u_j \) change depending on the type of measurements and metrology standards used. Typically \( u_c = \sqrt{u_i^2 + u_j^2} \), in special cases \( u_c = u_i + u_j \) or some other equation.

When combined standard uncertainty \( (u_c) \) is known (i.e. combined and calculated from both \( u_i \) and \( u_j \)), the expanded uncertainty \( (U) \) can be calculated as follows:

\[
U = k \, u_c
\]

Suggested symbol \( k \) is called coverage factor. It affects the level of confidence that equation \( \{y - U \leq Y \leq y + U\} \) is true.

![Figure 4: The effects of different values for the coverage factor \( k \) on the measurement’s statistics (numerical values adopted from Table B.1 in NIST TN 1297).](image)

In accordance with NIST guidelines, Sendyne typically uses coverage factor \( k = 2 \). When reporting the results of the measurements using uncertainties, it is important to also state the value utilized for coverage factor \( k \).
Offset, gain, and noise errors

Instrument specifications will typically list errors as:

\[ \pm (\text{% of reading} + \text{% of range}) \]

where percent of reading is the gain error and percent of range (i.e. of full scale) is the offset error. Instead of percent, parts per million (ppm) are sometimes used when the percent value has too many zeroes after the decimal point.

Commonly, noise is specified separately, either as a peak-to-peak value within a stated time interval or as an RMS (Root Mean Square) value. Noise leads to Type A uncertainty; multiple measurements could be averaged or filtered to reduce this error.

Example: A DVM with \((\pm 1 \% \text{ of reading} + 0.05 \% \text{ of range})\) specifications for errors on a 10 V scale, and while measuring a voltage near 5 V, will have an error of \(\pm 0.055\) V (0.05 V from gain error, and 0.005 V from offset error). This is Type B uncertainty; multiple measurements cannot reduce this error.

Calculating uncertainty

In order to report a measurement result (and its error), it is sufficient to provide the measurement result \(y\), its expanded uncertainty \(U\), and state the coverage factor \(k\).

Calculating \(y\), \(U\), and \(k\)

Several measurements of the measurand value \(Y\) are made, namely: \(y_1, y_2, y_3, \ldots, y_n\).

1. Calculate an average value from all individual measurements:

\[ y = \frac{(y_1 + y_2 + y_3 + \ldots + y_n)}{n} \quad [n \text{ is the number of measurements}] \]

The value \(y\) is the measurement’s result. It is an estimate for the measurand \(Y\); this estimate has errors.

Quantitative descriptions for the errors in this measurement result are calculated separately for Type A \(u_i\) and Type B \(u_j\) uncertainties, then a combined standard uncertainty is found \(u_c\), and finally the expanded uncertainty \(U\) is determined using the coverage factor \(k\).
2. Calculating uncertainty $u_i$ (Type A):

$$ u_i = \text{SQRT} \left\{ \frac{\left[ (y_1 - y)^2 + (y_2 - y)^2 + (y_3 - y)^2 + \ldots + (y_n - y)^2 \right]}{(n - 1) n} \right\} $$

Terms $(y_i - y)^2$ are the differences (random errors) between each measurement and the average, squared. The sum of the squared differences divided by the number of samples is the averaged squared error, similar to a squared RMS error.

However, for this calculation the sum is not divided by the number of samples, but by the number of samples less one (by the number of degrees of freedom, $n-1$).

The number of samples $n$ further divides the result of the division performed in the previous step. This reflects how much the random noise is reduced when the average of samples is made. It reflects the fact the Gaussian noise is reduced by the square root of the number of samples. Finally, a square root is extracted from the result of the previous calculations; the result is the Type A uncertainty $u_i$.

The Type A uncertainty is closely related to the RMS noise of the measurements, and to the number of individual measurements that are being averaged into the final result.

In practical calculations, and when the number of individual measurements is quite large (hundreds or thousands of points), it may be acceptable to divide the sum-of-squares from the formula above by the $n^2$. In other words, use the actual value of the RMS noise as the basis for finding the uncertainty $u$. The RMS noise value may be conveniently available from the standard processing modules of a data acquisition software.

The error resulting from this simplification is only the error of the estimate of the uncertainty, not of the measured value $y$. As an example, if there are 100 points in the result’s average, the substitution of $n$ for $(n-1)$ will result in less than 1% incorrectness in the estimation of the uncertainties.

On the other hand, one can always “convert” to the proper definition of uncertainty, using the proper degree-of-freedom divider, by simply using a multiplicative adjustment factor \{SQRT $(n / (n-1))$\}, that is a unitless number slightly larger than 1. For example, it is equal to about 1.005037815 when the number of samples $n$ is equal to 100.
For explanation of why the degree-of-freedom divider is appropriate, consider the value of uncertainty when there is only a single measurement. The Type A uncertainty is infinite – because there is nothing to compare the single measurement to. If there are only two measurements, then the uncertainty is equal to one-half of the difference between the two values; in other words, the interval \((y - u_i)\) to \((y + u_i)\) exactly includes the two measurements.

The units of the uncertainty value \(u_i\) are the same as the units of measurement \(y\) itself.

Since Type A uncertainty can be easily reduced by using a larger number of the averaged individual measurements, the \(u_i\) should be reduced to a value that is less, or preferably, much less than the errors due to Type B uncertainties. The number \(n\) has to be large enough to make Type A uncertainties to be almost inconsequential. Therefore, the total error will be determined only by the specifications of the calibrating or measuring instrument.

3. Calculating uncertainty \(u_j\) (Type B):

\[ u_j = \text{error due to ("% of reading" + "% of range")}/\sqrt{3} \]

The values for \(%\text{ of reading}\) and \(%\text{ of range}\) are the specifications for the reference device (during calibration) or the measuring device itself (for simple measurements). They are taken from the published and guaranteed values for the instruments, and further adjusted/corrected for any dependencies due to actual operating temperature or supply voltage variations at the time of the test.

The actual average value is multiplied by the \((\%\text{ of reading})/100\) to get the reading error in the same units as the measured value. Likewise, the Full-scale of the instrument used for the measurement is multiplied by the \((\%\text{ of range})/100\) to get the offset error that is expressed in the correct units. Then, both errors are added together and divided by \(\sqrt{3}\).

The divisor is the reflection of the fact that the specifications are Type B uncertainty and the probability of the actual correct value being within the limits defined by the specifications is assumed to be rectangular (equally likely within the stated limits).

Note that the final calculation of expanded uncertainty \(U\) using coverage factor \(k\) will negate the effect of divisor \(\sqrt{3}\). For example, if \(k = 2\), then \(2/\sqrt{3} = 1.1547\). In this case, the
reported influence of the instrument’s Type B error will actually be a little larger than the specifications.

4. Calculate combined standard uncertainty $u_c$:

$$ u_c = \sqrt{u_i^2 + u_j^2} $$

5. Calculate expanded uncertainty $U$:

$$ U = k \cdot u_c $$

Per NIST guidelines Sendyne uses coverage factor $k = 2$.

6. Final result is $(y \pm U)$, state $k$ (i.e. $k = 2$).

It may be more convenient to report the errors in percentage form; in other words, to report relative expanded uncertainty ($U_r$). In this case, the above result can be reported as

$$ \{y \text{ [units of } y]\pm(100 \times U/ y) \%\} = \{y \text{ [units of } y]\pm(100 \times U_r) \%\} $$

**Example 1: Voltage Calibration**

The SFP101EVB is calibrated on voltage measurement channel with the following set-up:

A DC power supply is connected in parallel to the voltage input of the SFP101EVB and Keithley 2010 low-noise multimeter.

The Keithley is set on 100 V range and is within the 1-year calibration schedule. Its specifications for 1 year on the 100 V scale are: ±35 ppm of reading and ±5 ppm of range.

Input DC test voltage is approximately 25 V.

The errors of the multimeter, expressed in Volts, are:

$$ \text{GAIN ERROR} = 25 \text{ V} \times 35 \text{ ppm} = 0.000875 \text{ V} (875 \mu\text{V}) $$

$$ \text{OFFSET ERROR} = 100 \text{ V} \times 5 \text{ ppm} = 0.000500 \text{ V} (500 \mu\text{V}) $$

Multimeter Type B uncertainty

$$ u_j = (0.000875 \text{ V} + 0.000500 \text{ V}) / \sqrt{3} = 0.00079386 \text{ V} (793.86 \mu\text{V}) $$
After acquiring 1000 measurements, the average value from the multimeter is 25.130954 V.

During the same time, after acquiring 1000 measurements, the average value from the SFP101EVB is 25.136899 V and RMS noise is 0.002483 V.

For SFP101EVB, Type A uncertainty $u_i = \frac{0.002483 \text{ V}}{\sqrt{1000}} = 0.00007852 \text{ V} (78.52 \mu\text{V})$.

The correction for the degrees-of-freedom is neglected, as the correction value of 1.0005 would only change the uncertainty by 0.05 %.

This uncertainty is approximately ten (10) times smaller than the Type B uncertainty of the multimeter. In other words, the noise in measurements will affect the result very slightly, much less than the uncertainties of the multimeter.

The reason that Type A uncertainty for the multimeter is not calculated is that the noise in measurements for the SFP101EVB comes mostly from the noise (and drift) of the voltage source (DC power supply); and to a much lesser degree from its own noise. Both of these are already accounted for. The noise of the Keithley multimeter is orders of magnitude smaller when compared to the noise of the voltage source, so this does not need to be taken into consideration.

The recorded RMS noise of the multimeter for this test was 0.002492 V, a value that is almost the same as the RMS noise of the SFP101EVB. This further demonstrates that the noise mostly comes from the voltage source.

The noise for the multimeter (0.002492 V) is slightly larger than that of the SFP101EVB (0.002483 V). This is due to the fact that SFP101 uses all continuous data, without any interruptions, in order to produce the average value, while the multimeter may have dead-time between individual conversions. The input is not averaged during these dead-time periods. In this particular test, the difference amounts to about +0.4 % for the noise of the multimeter, not a considerable disparity.
The combined standard uncertainty

\[ u_c = \sqrt{u_i^2 + u_j^2} = \sqrt{0.000078522 V^2 + 0.000793862 V^2} = 0.000797734 V \ (797.73 \, \mu V) \]

This number is only slightly greater than the multimeter uncertainty (of 793.86 \, \mu V), due to very small contribution from noise.

Finally, the expanded uncertainty

\[ U = k \cdot u_c = 0.001595468 V \ (\sim 1.6 \, mV), \text{ coverage factor } k = 2. \]

Expressed as the percentage, the expanded uncertainty is

\[ 1.6 \, mV / 25.130954 V = 0.0064 \, \% . \]

Note that the average value reported by the multimeter was used. Almost the same result would be obtained if the reported average value is supplied by the SFP101EVB, as both measurements were adequately close to each other.

The result of the measurement is

\[ 25.130954 V \pm 1.6 \, mV, \ k = 2 \]

or \[ 25.130954 V \pm 0.0064 \, \%, \ k = 2. \]

This provides an indication that the calibration will be performed to about 0.0064 \, \% plus the granularity of the calibration adjustment of 0.0015 \, \% (15 ppm), for a total that is less than 0.01 \, \%.

Using the reported (average) values for the multimeter and the SFP101EVB, the voltage calibration value for the SFP101 can be calculated, as follows:

\[
\text{VOLT\_CAL} = \text{ROUND} \left\{ \left[ \frac{25.130954 V}{25.136899 V} - 1 \right] \times 2^{16} \right\} = -15
\]
The integer value of -15 (0xFFF1) should be written to the voltage calibration register VOLT_CAL (address 0x55).

In order to verify the effect of the calibration, the whole calibration measurement cycle should be repeated. The averaged values obtained from the multimeter and the SFP10XEVB should match to better than 0.01 %, provided that the thermal environment for the verification test is the same as for the calibration.

While this particular calibration provided only a small correction, and the initial error of the voltage channel happened to be small, the calibration adjustment can accommodate deviations as large as ±50 %.

For the prevention of human errors in calculations, it is best to automate both the data collection and calculations of results / calibration values.

**Example 2: Automated Current Calibration as an Algorithm**

This algorithm assumes a hardware configuration that consists of the current source that is able to report its own current, and connected to the shunt that is attached to SFP10X IC (further called DUT). A computer running data acquisition and control software, such as LabVIEW, will accumulate and process data from both current source and DUT.

At the beginning of the procedure, the hardware connections are made, the current source is set to output an appropriate current, and the ambient temperature is recorded, as well as any other pertinent information.

The software should execute the following steps:

1. Automatic application of the calibration value should be disabled in the SFP10X by setting the disable bit in the COMP_CTRL register (address 0x44). This means writing a value of 0xFF (setting of the flag SHNT_CAL_DIS, the least-significant bit in that register). The default factory value programmed into that location is also 0xFF (i.e. do not use the calibration feature), however this should be verified, or simply re-written as specified above.

2. An array of multiple measurement points is recorded from both the current source and the DUT, for a pre-determined number of points (n). To reduce noise, it is preferable that these measurements should be made at a fixed frequency.
When the data collection completes, the hardware can be powered down if desired.

3. An average value is calculated for both the output of the current source and for the DUT, from the data saved by the software. The averaged value for the current source is the “expected” value for the calculation of the calibration value. The averaged value for the DUT is the “measured” value for the calculation of the calibration.

4. The RMS noise value is calculated for both current source and DUT. The noise value of the current source will not be used in calculations, but it has to be checked against the noise of the DUT. The RMS noise of the current source from the reported current values should be smaller than or only slightly larger than the noise of the DUT, by no more than several percent. If the noise of the current source is larger than the noise of the DUT, this would indicate some malfunction—a problem in connecting wires (intermittent contact), or plain unsuitability of the current source for the task.

5. The RMS noise value of the DUT is evaluated for its effect on the calibration. It is desired that the RMS noise divided by the square root of the number of samples (√n) is much smaller than the uncertainty specifications of the current source. It would be advantageous if the ratio is at least 1:10 or more (meaning 1 to over 10). Based on this observation, it may be necessary to repeat the test from step one, utilizing a larger number of points (n). This part does not need to be performed for every test. Preliminary testing may find an appropriate minimum number for the data samples, and the following “production line” calibrations can simply use the predetermined value for n. On the other hand, it is recommended that the third step is always performed, and RMS values are recorded for every calibration, as an indicator of correct functioning of the equipment.

6. Uncertainties are calculated utilizing the published values for the current source instrument (i.e. its Type B uncertainty) and the value of RMS noise over √n for the DUT (i.e. DUT’s Type A uncertainty). Based on the final value of the expanded uncertainty U, it would be possible to determine if this calibration setup is capable of calibrating the DUT to the desired design accuracy. Again, step five does not need to be performed for every calibration. Preliminary testing may
provide the indication for the set-up suitability. Once again, the values produced in step three can be monitored to be below a preset limit, thus assuring that the uncertainty is below a desired value, or the uncertainty increase will be readily detected. Likewise, the specifications for the current source have to be monitored for their compliance (i.e. at the very minimum checking before every calibration that the equipment is still “within calibration interval”; it is also typical that at specific times after their calibration, the guaranteed specs for instruments start to degrade).

7. The calibration value is calculated from “expected” and “measured” values.

8. This value is written to the appropriate register of the SFP10X.

9. Automatic application of the calibration value should be enabled by clearing the disable bit in the COMP_CTRL register (address 0x44). This means writing a value of 0xFE (clearing of the flag SHNT_CAL_DIS, the least-significant bit in that register).

10. If required, the calibration process is repeated in order to check the performance of the DUT with the new calibration value. In this case the Step 1 (disabling of the automatic application of the calibration value) should be skipped; indeed, the verification of the calibration must be executed with automatic application of the calibration value enabled.
## Revisions

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