VXI Analog System Calibration

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1 Introduction

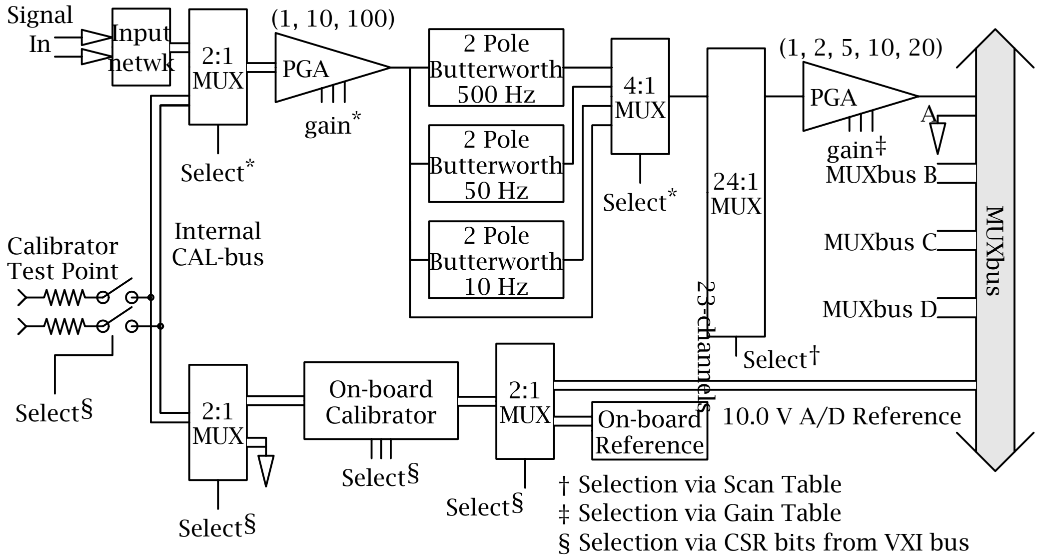
The KineticSystems *Silver Bullet* family of modules are designed for high performance, high accuracy applications. This family share a number of common *family* design philosophies including calibration.

In the design of analog hardware, two design approaches are possible. One is to select precision analog components and trim such parameters as gain and offset to acceptable tolerances during manufacture. This technique results in a module that requires considerable effort to calibrate and necessitates component tradeoffs between precision and long term stability.

The alternative approach, which is used in the KSC Silver Bullet line, is to choose components based foremost on stability and performance and to achieve precision by performing a calibration prior to data acquisition. Some of the advantages of this approach include better price/performance due to the need for fewer precision components and the end-to-end checkout of analog and digital paths prior to collecting data.

2 Calibration Technique

A standard calibration philosophy is used across the KSC VXI-family of analog input modules. Each signal conditioning module is capable of switching the front-end analog circuitry between the input signal that is to be measured, ground and the output of a hybrid calibrator. The reference for the hybrid calibrator can be either an on-board reference or a reference voltage provided by the V207 or V208 ADC. This approach provides an end-to-end calibration of the analog sections and at the same



† Selection via Scan Table
‡ Selection via Gain Table
§ Selection via CSR bits from VXI bus
* Selection from VXI bus in groups of 8-ch.

Figure 1: Typical analog front-end illustrating calibration paths

time provides verification that the entire data acquisition system is functional. Refer to Figure 1.

2.1 Precision Reference and NIST Traceability

The precision reference for the signal conditioning modules and ADCs is adjusted at the factory to +10.0 Volts using an NIST traceable Digital Voltmeter (DVM). The precision reference is a Burr-Brown REF102CM with a temperature coefficient of 2.5ppm/°C, and 5ppm/1000hr drift.

For applications where accuracy and NIST traceability are important KineticSystems recommends that a *periodic system calibration* be performed at approximately 6 month intervals using a NIST traceable DVM to calibrate the precision reference. In general users should choose a periodic calibration interval that is appropriate for their situation. Test points are provided on the front panel of modules which contain precision references. The user can adjust the precision reference output to 10.0 Volts using a recessed screwdriver adjustment and the NIST traceable DVM.

2.2 On-board Calibrator

A custom active hybrid calibrator is used at each signal conditioning module to provide a precision programmable voltage divider for the reference voltage. The output of the calibrator is capable of generating output voltages from ±2mV to ±10V in a 1, 2, 5, 10 progression. The calibrator divides the voltage in two steps: a *decade divider* with ranges of 1, 0.1, 0.01, and 0.001; and a *vernier divider* of 1.0, 0.5, and 0.2. Output accuracy is summarized for each stage in Table 1.

Table 1: Hybrid calibrator maximum error and temperature stability table.

Stage	Gain	Max Error (%)	Max ppm/°C
Polarity	±1.0	±0.01%	±6 ppm/°C Max
Decade	1.0	0%	0
	0.1	±0.007%	0
	0.01	±0.03%	±10 ppm/°C Max
	0.001	±0.1%	±50 ppm/°C Max
Vernier	1.0	±0%	0 ppm/°C Max
	0.5	±0.005%	±2 ppm/°C Max
	0.2	±0.007%	±2 ppm/°C Max

For example the **maximum** error for a 5mV calibration output from a 10.0 volt reference is the sum of the polarity, decade and vernier errors

$$0.01 + 0.1 + 0.005 = 0.115\%$$

or $\pm 5.75\mu$Volts.

Temperature stability of the hybrid calibrator is also given in Table 1. For example the worst case temperature stability of the hybrid calibrator on the 5mV scale is

$$6 + 2 + 50 = \pm 57 \mathrm{ppm}/^{\circ}\mathrm{C}\ \mathrm{Max}$$

Long term drift of the hybrid calibrator is ±50 ppm/1000 hours.

3 Standard Calibration Procedure

For optimum accuracy it is recommended that the user perform a calibration of the channels to be used prior to acquiring data. The calibration procedure should be performed following a minimum equipment warm-up of approximately 1/2 hour. Each channel or group of channels which share common active input circuitry should be calibrated following warm-up and prior to acquiring data.

It is recommended that the following calibration procedure be followed. The calibration should be performed with no more than 8 independent channels per hybrid calibrator to minimize loading of the calibrator and that no more than 8 hybrid calibrators be switched to a single reference source at one time (a consideration when the ADC reference source is used). The calibration measurement should be made with the calibrator range (k) set per note 3 below for each channel (j).

1. Acquire N-samples with grounded inputs selected $\ldots X_i^j(0)_{i=1,N}$.
2. Acquire N-samples with +CAL inputs selected $\ldots X_i^{jk}(\text{+CAL})_{i=1,N}$.
3. Acquire N-samples with -CAL inputs selected $\ldots X_i^{jk}(\text{-CAL})_{i=1,N}$.

Notes:

1. Be sure to allow adequate settling time between switching input levels *especially if lowpass filters are present* in the analog path. The time for a simple RC filter to settle to one lsb of a 16-bit ADC is 10.38 time constants or $1.66/f_c$ where f_c is the filter cutoff frequency. Filters with sharper roll-off typically require proportionally longer settling times.
2. It is recommended that at least N=20 samples be acquired for each input level.
3. The calibrator voltage should be set to give an output voltage that is near full scale on the ADC. For example with a gain of 100 the input range of the ADC is ±102.4mV so the calibrator should be set to the ±100mV range.

From this calibration data a slope (m_j) and an offset (b_j) are computed for each channel (j). These quantities are then used to convert the measured ADC counts for channel j to volts.

3.1 Determining the offset b_j and slope m_j

The offset b_j for channel j is computed from the N *calibration* measurements $X_i^j(0)$ with the input switched to ground as follows:

$$b_j = \frac{1}{N}\sum_{i=1}^{N} X_i^j(0)$$

The slope m_j^k for channel j is computed from the N measurements X_i^{jk}(+CAL) with calibrator range k (+CAL) selected and the N measurements X_i^{jk}(-CAL) with calibrator range k (-CAL) selected as follows:

$$m_j^k = \frac{\frac{1}{N}[\sum_{i=1}^{N} X_i^{jk}(\text{+CAL}) - \sum_{i=1}^{N} X_i^{jk}(\text{-CAL})]}{E_0^k(\text{+CAL}) - E_0^k(\text{-CAL})}$$

Where:

X_i^{jk}	is the ith measured ADC counts for channel j using calibrator range k.
E_0^k	is the published calibrator voltage value for range k.

3.2 Applying the calibration to data

The input voltage to be measured V_j is computed from the acquired ADC count X_j by the following relation:

$$\boxed{V_j = \frac{(X_j - b_j)}{m_j^k}.}$$

Where:

V_j	is the *derived* analog input voltage for channel j in Volts.
X_j	is the *measured* analog input for channel j in ADC counts
b_j	is the offset for channel j as determined from the calibration run prior to taking data as outlined in Section 3.1.
m_j^k	is the gain for channel j as determined from the calibration run prior to taking data as outlined in Section 3.1.

3.3 Periodic System Calibration

As discussed earlier KineticSystems recommends that the precision reference source used during pre-acquisition calibration be calibrated at approximately 6 month intervals or an interval that is appropriate to the users situation. The calibration is accomplished by attaching a NIST traceable DVM on the test points provided on the module front panel and adjusting the output of the precision reference to 10.0 Volts.

4 High Precision Calibration Procedure

For some low-level applications, for example thermocouples, accurate voltage measurements at millivolt signal levels may be required. Some Silver Bullet signal conditioning modules such as the V243 implement a further level of calibration to achieve accuracies of a few microvolts. These accuracies are achieved by calibrating the internal calibrator and channel-to-channel thermal EMF differences between the actual signal input connector and the common switched ground used for calibration. These second-order correction factors are stored in EEPROM for **each** module when the module is calibrated at the factory. These correction factors can be read by the application software and applied at the time the data is read.

Two second-order corrections are involved in the precision calibration:

1. A gain correction term ϵ_k that represents a second-order correction to the gain based on the hybrid calibrator range k. Note that the gain correction is most significant at high gains since the hybrid calibrator accuracy is most accurate at calibration levels of 100mV and above when compared to 16-bit ADC measurement accuracy of 0.003% . Refer to Table 1.

2. An offset correction δ_j that represents a second-order correction to the offset for channel j which represents slight thermal EMF differences due to different signal paths from the front connector to the input amplifier and the common switched input ground used in during calibration to determine channel offsets. Note that the offset correction is only important at high gains when measuring

low-level signals where μVolt offset differences can be resolved by the ADC.

When using the second-order correction terms, the measured input voltage is given by the expression:

$$\boxed{V_j = \frac{(X_j - b'_j)}{m_j^k}.}$$

Where:

V_j	is the *derived* analog input voltage for channel j in Volts.
X_j	is the *measured* analog input for channel j in ADC counts
b'_j	is the offset for channel j as determined from the calibration run prior to taking data as outlined in Section 4.2 that includes a second order offset correction term.
m_j^k	is the gain for channel j using calibrator range k as determined from the calibration run prior to taking data as outlined in Section 4.2.

4.1 Pre-acquisition Calibration

As noted earlier the equipment should be turned on and temperatures allowed to stabilize for a minimum of 1/2 hour prior to performing the calibration and data collection. It is also recommended that temperature fluctuations be held to a minimum during the warmup, calibration and data acquisition.

The second order calibration is based on gain correction terms which not only correct for the precision of the hybrid calibrator, but also corrects for any deviation of the precision reference from 10.0 Volts. For these reasons the following considerations apply:

- Only the internal precision reference source in the module should be used with this calibration technique (not the common ADC reference source).
- The periodic calibration procedure no longer *requires* calibrating the precision reference source since the second order correction terms correct for any long term drift.
- A switched set of test points for measuring the calibrator output permit a common NIST traceable DVM to be used for a completely automatic periodic calibration.

4.2 Determining the offset b_j and slope m_j^k

Prior to taking data a calibration run should be performed to determine the offset b'_j and gain m_j^k for each data channel. These quantities are derived as follows:

$$b'_j = \frac{1}{N}\sum_{i=1}^{N} X_i^j(0) + m_j^k \cdot \delta_j \cdot 10^{-9}$$

> Note: Since the offset correction δ_j is small the published gain can be used in place of m_j^k in the above expression for the offset b'_j with out loss of accuracy.

$$m_j^k = \frac{\frac{1}{N}[\sum_{i=1}^{N} X_i^{jk}(\text{+CAL}) - \sum_{i=1}^{N} X_i^{jk}(\text{-CAL})]}{(E_0^k(\text{+CAL}) - E_0^k(\text{-CAL}))(1 + \epsilon_k \times 10^{-6})}$$

where:

$X_i^j(0)$	is the ith measured ADC counts for channel j with inputs switched to internal ground.
$X_i^{jk}(\pm\text{CAL})$	is the ith measured ADC counts for channel j using calibrator range k.
E_0^k	is the published calibrator voltage value for range k.
ϵ_k	is the 16-bit signed 2s complement integer "calibrator correction factor" stored in EEPROM for CAL range k scaled by 10^6 (e.g. ±2mV, ±5mV, ±10mV, ...) ranges.
δ_j	is the 16-bit signed 2s complement integer "offset correction factor" stored in EEPROM for channel j scaled by 10^9.

4.3 Periodic Calibration Procedure

The periodic high precision calibration differs from the general periodic calibration. It is no longer necessary to adjust the precision reference source voltage as any drift in the precision reference is reflected in the second-order gain corrections that are derived and stored in EEPROM during the periodic calibration.

It is recommended that the periodic *gain calibration* be performed at approximately 6 month intervals. It is expected that the *offset periodic calibration* need only be performed once over the life of the module. This calibration is performed at the factory during final testing.

When the system is configured with a common bused cable between the calibrator test points and a NIST traceable DVM which is computer controlled, the periodic gain calibration can be performed automatically without operator intervention.

4.3.1 Second-order Periodic Gain Calibration

The calibrator or gain correction terms ϵ_k for the high precision calibration procedure are computed and stored in EEPROM based on factory measurements using a NIST traceable DVM. The recommended interval for this calibration is approximately 6 month intervals for applications requiring a high level of precision. The user should determine the calibration interval based on the individual situation.

The calibration procedure is to connect a NIST traceable DVM of suitable accuracy to the calibrator output which is available on the front panel of the module. The module is then set up through software to select the desired calibrator output range k and +CAL output using the precision reference source internal to the module being calibrated and selecting the calibrator output to the front panel test points. The DVM reading D^k(+CAL) is recorded. A similar measurement D^k(-CAL) is made. The value of ϵ_k is then computed for each calibrator range k and stored as a signed 16-bit integer in EEPROM as follows:

$$\epsilon_k = \frac{[D^k(\text{+CAL}) - E_0^k(\text{+CAL})] - [D^k(\text{-CAL}) - E_0^k(\text{-CAL})]}{[E_0^k(\text{+CAL}) - E_0^k(\text{-CAL})]} \times 10^6$$

Where:

D^k is the calibrator output voltage measured with an NIST traceable DVM for calibrator range k.

E_0^k is the published calibrator voltage value for range k (e.g. 5mV, 10mV, 20mV, ...).

Note:

> The value of ϵ_k before scaling is a small number ($\ll$1). For the *ideal* calibrator $\epsilon_k = 0$. To store the value of ϵ_k in a computer architecture independent representation we have chosen to store it as a scaled 16-bit 2s complement binary integer which has a range of ±32767. This gives the correction multiplier $(1+\epsilon_k)$ a range from 0.967233 to 1.032767 to an accuracy of $1:10^6$ (0.0001%).

4.3.2 Offset Correction

The offset calibration is expected to be considerably less sensitive to long term drift and is expected to be stable over the life of the module. This calibration is performed at the factory and the results stored in EEPROM. The calibration can also be performed in the field. For this calibration the input wiring *must* be disconnected and a special shorting connector installed in its place.

The offset correction terms δ_j are computed and stored in EEPROM based on measurements of the differences in offsets for each channel between the offset measured with the inputs shorted using a special connector and when the common internal ground is selected that is used during a pre-acquisition calibration (refer to Figure 1). These differences are scaled to nanovolts and stored as 2s complement binary integers in EEPROM.

$$\delta_j = \left(\sum_{i=1}^{N} X_i^j(\text{Input-gnd}) - \sum_{i=1}^{N} X_i^j(\text{Internal-gnd})\right)\frac{1}{Nm_j} \times 10^9$$

where:

X_i^j(Input-gnd)	is the ith measured ADC counts for channel j with the inputs grounded.
X_i^j(Internal-gnd)	is the ith measured ADC counts for channel j with inputs switched to internal ground.
m_j	is the channel gain. This can be the gain determined from a simple calibration or just the published channel gain since the error introduced by the latter is minimal.

5 Error Budget Analysis V243/V208

The following is an error budget analysis of various error sources for the V243/V208 on the 5 millivolt scale (gain=2000) and a temperature range of $\pm 4^\circ C$. It is assumed in this analysis that the high precision calibration method is used. In all cases *typical* (1σ) error estimates are used in this analysis. Note that these may differ from the respective data sheets where *worst case* errors are given.

The following error budget analysis is provided as a
preliminary engineering estimate.

5.1 Systematic Errors

	Typical (1σ) Error	Accuracy $\pm 4^\circ C$
Precision Reference:		
Temperature Stability	±2.5ppm/°C	±0.05μV
Long Term Drift	±5ppm/°C	±0.025μV
Calibration Accuracy	±5μV on 10V scale	±0.025μV
Calibrator:		
Polarity	±2.4ppm/°C	±0.048μV
Decade (0.001)	±20ppm/°C	±0.40μV
Vernier (0.5)	±0.8ppm/°C	±0.016μV
Instrumentation Front-end:		
Offset	±0.1 + 0.5/Gain (μV/°C)	±0.42μV
Gain Stability	±10ppm/°C	±0.2μV
Total Systematic Error(see note):		±0.619μV

Note: The total systematic error is determined by adding the square root of the sum of the squares of the individual errors.

5.2 Measurement Errors

	Typical (1σ) Error	Accuracy $\pm 4^\circ C$
ADC:		
Diff Non-linearity	0.001%	±0.05μV
Integral non-linearity	0.0015%	±0.075μV
Crosstalk	-90dB	±0.16μV
V243 Front-end:		
Integral non-linearity	0.001%	±0.05μV
Noise RTI	±0.3μV RMS	±0.3μV
Cross Talk	-90dB	±0.16μV
Gain Accuracy after cal		±1.0μV
V243 Total Measurement Error (see note)		±1.037μV

Note: The total measurement error is determined by adding the square root of the sum of the squares of the individual errors.