SUPPORT NOTE

SN-115

Self Calibration
Accuracy Assurance

Introduction

Instrument calibration is a process of adjusting and/or verifying that it is operating within specified limits of accuracy. This is accomplished by formal comparison or adjustment to a reference standard whose limits of accuracy can be traced to the National Institute of Standards and Technology.

In production, "set and forget" adjustments of potentiometers, variable inductors, and variable capacitors are made to bring a module within published specifications. Afterwards, automatic calibration software is used to compensate for offset and scale factor errors. Manual calibration is not needed unless a precision component (op amp, A/D or D/A converter, reference amplifier, wire-wound resistor, etc.) is replaced.

In conjunction with the Reedholm system DMM, a SelfCal Module (SCM) provides accuracy traceable to NIST for all DC signals and measurements. Capacitance accuracy with the Reedholm 100kHz CMM is assured through use of external two-terminal transfer standards plus internal standards whose uncertainties are linked to external standards.

Why Accuracy Changes

Instrument measurement uncertainty is typically a function of AC line voltage, temperature, humidity, and time. However, not all of them need to be considered for Reedholm instrument modules.

Insignificant AC Line Voltage Effects

AC line voltage changes up to ±10% cannot affect accuracy because instrument power is delivered by a set of dc supplies that have excellent rejection of AC line variations.

Broad Range of Temperatures Tolerated

Reedholm system operation is warranted from 18 to 28°C, a much wider span than experienced in modern semiconductor fabs and labs. Accuracy specifications apply within 24 hours of manual or SelfCal calibration as long as temperature is controlled within ±1C°.

If temperature cannot be controlled that tightly, SelfCal can be run more often so that product measurements are made within a ±1C° window.

Humidity Effects

Reedholm modules have guarding against the effects of surface leakage, and assemblies intended for use at very low currents have bulk guarding as well because it takes very little water vapor to dramatically affect dielectric absorption. As long as relative humidity is kept <50%RH up to 28°C, accuracy is not affected, and accuracy is not warranted above 50%RH.

Drift with Time

All components change with time, and to the best of Reedholm information, the precision components that determine accuracy are assumed to cause a Gaussian distributed uncertainty whose distribution increases with the square root of time. Thus, a specification that is ±0.03% for 24 hours could be predicted to increase by $30^{1/2}$ or to ±0.16% in 30 days. Of course, the drift is not nearly that large because not all of the ±0.03% span is due to 24-hour time drift. In fact, typical drift over one month is less than the ±0.03% specification.

Since Reedholm does not warrant the time drift component of the accuracy specification, customers that do not use SelfCal need to monitor actual accuracy shifts over time to determine a suitable manual calibration period.

Problem with Manual Calibration

Manual calibration requires access to core instrument test and adjustment points. That is easy at Reedholm because modules are adjusted at a workstation with access to the entire board.

On the other hand, manual adjustments in the field requires powering down the system, opening the enclosure or cabinet door, removing the module, installing the extender, plugging the module in, and powering up. That only takes a few minutes, and manual calibration only takes a few minutes more. However, the problem is not the few minutes that power is removed; it is the temperature change at which calibration is performed.

Convection cooling significantly changes temperatures of precision components, so the change in thermal environment means calibration is being done at a temperature far outside the ±1C° specification window.

Once manual calibration is completed, and the system is restored to normal operating status, the module will drift from the calibrated settings as normal operation temperature is restored. Because instrument components have very low dependence of temperature, drift is not great, but is usually enough to push accuracy uncertainty beyond the published specifications.

Calibrating the SelfCal Module

The Self Calibration Module (SCM) and the newer SCM-BP have a precision voltage divider, a reference amplifier, an instrumentation grade power op amp, and a pair of precision resistors that makes it possible to base accuracy of the dc modules on external transfer standard DMM. More information about the SCM and SCM-BP is in the data sheets at:

http://www.reedholm.com/products/pdf/DS11038.pdf

http://www.reedholm.com/products/pdf/DS11106.pdf

SCal Calibration Software

Calibration of the SCM does not require any adjustments. Instead, the SCal program is run. It prompts the person performing calibration to enter measurements from a transfer standard DMM as the SCM is stepped through voltages corresponding to dc module range points from –100V to +100V. In addition, the values of 10kΩ and 10MΩ precision resistors are measured for use in current calibration.

Measurements are made on four test points on the end of the SCM using a shielded, Teflon insulated cable supplied by Reedholm. If a different cable is used, it must have insulation resistance $>10^{11}\Omega$ so that is does not reduce the 10M value by >100ppm. Also, the test clips need to have thermal emf <25µV so that 250mV measurements are not affected by >100ppm. More information on the SelfCal lead set is at:

http://www.reedholm.com/support/suppnotes/sn-116.pdf

Temperature Effects

As with manual calibration, the enclosure cover or cabinet door has to be opened for access to the SCM, but power does not have to be turned off.

However, SCal must be started promptly after gaining access to minimize thermal changes. If SCal cannot be started immediately, the system needs to be buttoned up while the problem is addressed.

The five minutes that it takes to run SCal results in a temperature rise <±5C° for the precision power op amp. Since other precision components do not generate heat, they change <±1C°.

Based on purchasing specifications, the precision components have the following uncertainties relative to operation with covers installed and doors closed. These temperature-induced shifts are factored into the table in the SCM data sheet.

- Offset voltage of the op amp: <±125µV.
- Divider voltages: <±5ppm.
- 10kΩ current calibration resistor: <±5ppm.
- 10MΩ current calibration resistor: <±20ppm.

Drift With Time

Maximum drifts for the precision components in one month, with temperature kept at ±1C°, is:

- Offset voltage of the op amp: <±64µV, but this term is eliminated because SCal uses both polarities for gain calculation.
- Divider voltages: <±20ppm/year or 6ppm/mo.
- 10kΩ current calibration resistor: <±6ppm.
- 10MΩ current calibration resistor: <±15ppm.

Running Self Calibration (SelfCal)

Self-calibration software determines gain and offset errors relative to the SCal data file, SelfCal.dat. During operation, SelfCal forces the SCM and the DMM being calibrated to voltages and currents ~1% below full-Scale range points. Afterwards, DMM#1 is used to calibrate VF and VFIF modules Finally, correction factors are generated for those optional instruments capable of dc calibration (HISMU, HVSMU, PAM, PPG-4, etc.) The 2kV module automatic calibration uses modules calibrated with SelfCal. Thus, accuracy of all dc modules is relative to accuracy of the transfer DMM.

SelfCal Corrections

SelfCal stores offset and scaling correction factors in SelfCal.ini. Except for the DMM, values in the file are used to correct offset and scaling errors. For the DMM, only Scaling errors are needed because DMM offsets are continuously measured and subtracted. More information on offset corrections is at:

http://www.reedholm.com/support/suppnotes/sn-111.pdf

System vs. Transfer DMM Accuracy

The SCM data sheet shows transfer uncertainties for a 24-hour, ±2C° span. Those uncertainties are combined with other sources of uncertainties, plus that of the transfer DMM, in the root-mean-square method.

Term	Definition
Uinit	SCM uncertainty right after SCal
Umonth	Uncertainty increase after one month
Udmm	Uncertainty of transfer DMM
Uvalue	System measurement uncertainty

Measurement Uncertainty at 1V

From the SCM data sheet, Uinit = 0.02% at 1V, or 200ppm. Factoring in the temperature shift and time drift calculated above, after one month the SCM might be different than the transfer DMM by:

$$\mathbf{(Uinit^2 + Umonth^2)^{1/2} =}$$
$$\mathbf{(200^2 + 6^2)^{1/2} = 200.09ppm}$$

If a transfer DMM with ±0.01% uncertainty at 1V were used for SCM calibration, the uncertainty within the system for one month after SCal would be

$$\mathbf{Uvalue = (Uinit^2 + Umonth^2 + Udmm^2)^{1/2}}$$
$$\mathbf{= (200.09^2 + 100^2)^{1/2}}$$
$$\mathbf{= 224ppm}$$

Running SCal more often, or less often, does not have much effect on system accuracy assurance.

- If SCal were run every day, there would be no time drift factor, but the uncertainty would decrease by only <0.1ppm.
- If run every 90 days, Uvalue would be 200.3ppm because time drift would be 10.4ppm, but that contributes <1ppm.
- Running once per year would double time drift, but that would raise Uvalue to only 224.5ppm.

Thus, an 0.01% transfer DMM would assure uncertainty <225ppm at 1V for one year. A 0.001% transfer DMM would assure <201ppm. A 10% reduction would not justify a more accurate DMM.

Measurement Uncertainty at 10V

At 10V, using a more accurate transfer DMM does result in lower measurement uncertainty. For one year, a 0.001% DMM would assure

$$\mathbf{Uvalue = (Uinit^2 + Umonth^2 + Udmm^2)^{1/2}}$$
$$\mathbf{= (100^2 + 17^2 + 10^2)^{1/2}}$$
$$\mathbf{= 102ppm}$$

While a 0.01% transfer DMM would result in higher uncertainty at 142ppm, that is still much better than justified for process control quality assurance.

100nA Measurement Uncertainty

On the SCM data sheet, the highest uncertainty immediately after SCal is on the 100nA range. The 10MΩ resistor is used on that range through the 10µA range. After one year, the SCM might be different than the transfer DMM by:

$$\mathbf{(Uinit^2 + Umonth^2)^{1/2} =}$$
$$\mathbf{(400^2 + 52^2)^{1/2} = 403.4ppm}$$

Uncertainty of 100µA to 10mA Ranges

On the 100µA and higher ranges, the 10kΩ resistor is used, so the time drift factor is smaller. After one year, the SCM might be different by:

$$\mathbf{(200^2 + 17^2)^{1/2} = 200.7ppm}$$

Uncertainty on 100mA and 1A Ranges

SelfCal measures offset and performs offset corrections for all current ranges. Because there are no SCM resistors for converting voltages to currents greater than 10mA, scale factor correction is determined at 10% of scale for the 100mA range. Then the DMM is used to measure PS#1 output at ±95mA using 100mA range correction factors. By forcing the same currents with the DMM on the 1A range, gain factors at ~10% of scale are found.

Because the DMM is at 10% of scale for the 100mA and 1A ranges, the digitization uncertainty of a least significant bit is ten times larger in its effect, or 312.5ppm. At 100mA after one year, SelfCal based measurements might be different by:

$$\mathbf{(200.7^2 + 312.5^2)^{1/2} = 371.4ppm}$$

The 1A range has one more DMM measurement with limited resolution, so its uncertainly is higher at:

$$\mathbf{(371.4^2 + 312.5^2)^{1/2} = 485.4ppm}$$

VFIF and HISMU Scale factors are then adjusted by SelfCal to match DMM#1. Two VFIF's are placed in parallel to assure accuracy of the HISMU.

PAM Measurement (100pA through 100nA)

High values resistors (1GΩ) on the loop back card are measured during SelfCal with the DMM on the 100nA range and a compensated 85V bias. Thus, considerable noise current can be accommodated without overloading the DMM. Then PS#1 provides compensated bias voltage for each PAM measurement.

While the PAM-12 and PAM-16 have different values of feedback resistors, the same relationships pertain. For the lowest ranges, a high value feedback (1GΩ for PAM-12 and 10GΩ for the PAM-16) converts current to voltage, and a lower value resistor (10MΩ and 100MΩ respectively) is used for the higher ranges. For each value of resistor, a 10:1 feedback divider provides a boost for the lower current. Thus, three measurement suffice for gain factors measurements: 85nA, 8.5nA, and 850pA. There is no need to make measurements on the 100pA range.

Dielectric absorption effects are eliminated by waiting >10 seconds for the test current to stabilize. Thus, resistance is known within the uncertainty of the DMM on the 100nA range combined with the DMM voltage measurement uncertainty on the on the 100V range.

For all PAM gain factors after one year, SelfCal based measurements might be different by:

$$\mathbf{(403.4^2 + 142^2)^{1/2} = 427.7ppm}$$

1 Year DC Measurement Uncertainties

The previous examples showed how to calculate system measurement uncertainties as a function of time and transfer DMM accuracy. With yearly calibration, a reasonably priced transfer DMM can provide:

- Voltages, ±0.25V to ±100V: <0.01% inclusive of offset, so 0.005% of value + 0.00125% of range on 1V range is needed for 0.01% at 0.25V.
- 10kΩ resistance: <0.011%.
- 10MΩ resistance: <0.041%.

Running SCal yearly with such a meter results in the maximum transfer errors shown below. Offsets are continuously subtracted, so have no effect.

Range (V)	Error (ppm)
0.25	510
0.50	317
1.00	225
2.50	142
5.00	
10.0	
25.0	
50.0	
100	

Range (A)	Error (ppm)
100p	592 (PAM)
1n	
10n	
100n	
100n	575
1µ	
10µ	
100µ	229
1m	
10m	
100m	387
1	498

100kHz CMM Uncertainties

Calibration of the 100kHz CMM is done by measuring response on each range and each excitation level to a pair of external reference capacitors, nominally 100pF and 1nF. Customers are provided with a set of those external reference capacitors that are measured and maintained under Reedholm manufacturing methods. Scale or gain factors are stored in the CMMstd.ini file also used for Boonton based CMM calibration. Offsets are not stored because they are a function of factors that do not affect scale factors but that can change with time and temperature.

Measurement Uncertainty

The final calibration step measures three very stable mica or NPO ceramic capacitors (100pF, 1nF, and 10nF) using scale factors based on 100pF and 1nF reference capacitors. Those scale factors are used for CMM self-calibration performed at least every 15 minutes. As a result, a calibration done after system warm-up has drift characteristics of the internal calibration capacitors, not the collection of components that affect gain. A root-mean-square error calculation following calibration with external capacitors is <±164ppm based on shifts of:

- ±120ppm for temperature over a ±2C° span,
- ±100ppm for time of one year, and
- ±50ppm for voltage change between 15mV and 100mVrms.

Translation to 10nF Range

Since measurement of the 1nF external reference capacitor is done at 1/10th scale on the 10nF range, digital resolution of 350fF amounts to 0.035% or 350ppm. Assuming there is 0.5lsb, or ±175ppm, random uncertainty in digitizing during calibration, the 10nF range uncertainty is 240ppm.

Extension to Use of External Reference

Reedholm assures accuracy of two terminal capacitors standards by bootstrapping from a pair of three terminal standards with BNC connections. Assuming that the transfer standards are known within ±200ppm, these uncertainties could be held for one year.

Range	Error (ppm)
100pF	259
1nF	
10nF	312