 By Jim Williams, Linear Technology Corp

UNDESIRABLE AND UNINTENDED THERMOCOUPLES ARE THE PRIMARY SOURCES OF ERROR IN LOW-DRIFT CIRCUITS. ATTENTION TO LAYOUT AND OTHER CONSTRUCTION DETAILS IS THE ONLY WAY TO TACKLE THE PROBLEM.

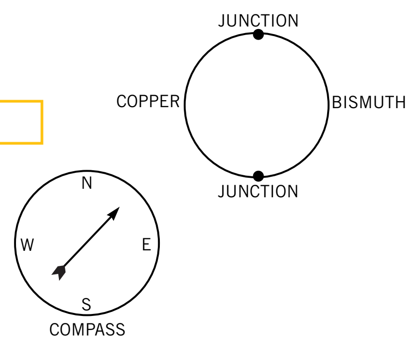
Minimizing thermocouples maintains 20-bit DAC precision

Subtle parasitics can have pronounced and seemingly inexplicable effects on the performance of low-level circuits, and a 1-ppm DAC is certainly in this category. Part 1 of this three-part series discussed the circuit design of a 20-bit DAC with 0.1 ppm/°C of drift, and part 2 discussed the measurement techniques (**references 1** and **2**). This third and final part discusses how you deal with cables, connections, solder, component choice, terror, and circuit arcana.

Perhaps the most prevalent detractors to microvolt-level circuitry are unintended thermocouples. (**Reference 2** also includes considerable discussion on dealing with thermocouples.) In 1822, Thomas Seebeck, an Estonian physician, accidentally joined semicircular pieces of bismuth and copper while studying thermal effects on galvanic arrangements (**Figure 1**). A nearby compass indicated a magnetic disturbance. Seebeck experimented repeatedly with different metal combinations at various temperatures, noting relative magnetic-field strengths. Curiously, he did not believe that electric current was flowing and preferred to describe the effect as "thermomagnetism." He published his results in a paper (**Reference 1**). Subsequent investigation showed the "Seebeck effect" to be fundamentally electrical in nature, repeatable, and quite useful. Thermocouples, by far the most common transducers, are Seebeck's descendants. Unfortunately, unintended and unwanted thermocouples are also Seebeck's progeny.

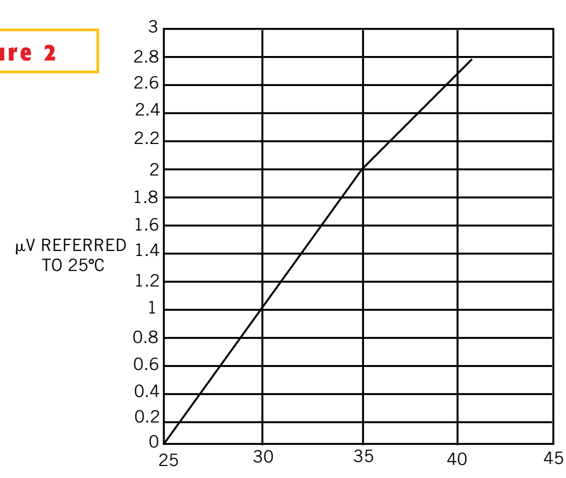
In low-drift circuits, unwanted thermocouples are probably the primary source of error. Connectors, switches, relay contacts, sockets, wire, and even solder are all candidates for thermal-EMF (electromagnetic-field) generation. It is relatively clear that connectors and sockets can form thermal junctions. However, it is not at all obvious that junctions of copper wire from different manufacturers can easily gen-

Figure 1



Joining pieces of bismuth and copper led Thomas Seebeck to his accidental discovery of what he called "thermomagnetism" and what we now call the Seebeck effect.

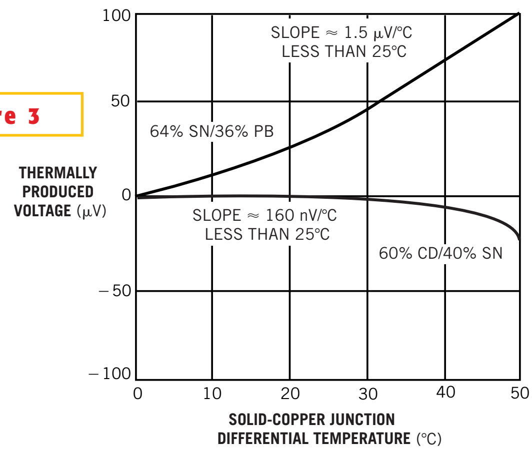
Figure 2



Two supposedly identical copper wires generate thermal EMFs due to oxidation and impurities.

erate drifts of 200 nV/°C, which is four times a precision amplifier's drift specification (**Figure 2**). Even solder can become an error term at low levels, creating a junction with copper, Kovar wires, or pc-board traces (**Figure 3**).

Figure 3



NOTE: SOURCE IS NEW ELECTRONICS 2/6/77.

Solder-copper junctions can create thermal EMFs. Cadmium/tin has notably lower activity but is toxic, unavailable, and not recommended.

Table 1 lists thermocouple potentials for some common materials in electronic assemblies. The information indicates the inadvisability of mixing materials in the signal path. The table also dramatically points out that you must keep copper/copper (top table entry) connections clean or a degradation of 5000-to-1 occurs as they oxidize (bottom table entry). The unusually energetic response of the copper/-copper-oxide combination necessitates cleaning digital voltmeter and Kelvin-Varley divider connections with a copper deoxidant (Caig Labs, "Deoxit" D100L).

If you find the information in **Table 1** to be seemingly academic, the implications in **Figure 4** should wake you up. This **figure** lists thermoelectric potentials for commonly employed laboratory connectors. Thermocouple activity of some connectors is more than 20 times greater than other types, so be careful when using them.

LAYOUT CAN REDUCE THERMAL ERRORS

Minimizing thermal-EMF-induced errors is possible if you pay judicious attention to pc-board layout. In general, it is good practice to limit the number of junctions in the signal path. Avoid as much as possible using connectors, sockets, switches, and other potential error sources. When avoiding the use of these error sources is impossible, attempt to balance the number and type of junctions in the signal path so that differential cancellation occurs. Ensuring this cancellation may involve deliberately creating and introducing junctions to offset unavoidable junctions, which can be a tricky procedure. Repeated and deliberate temperature excursions may be necessary to determine the optimal number and placement of added junctions. Experimentation, tempered by a healthy reserve of patience and abundance of time, is necessary. This practice, which is a common standards-laboratory procedure, can be effective in reducing drifts that originate from thermal EMFs. A simple example uses a nominally unnecessary resistor to promote such thermal balancing (**Figure 5**).

For remote signal sources, connectors may be unavoidable. In these cases, choose a connector specified for relatively low thermal-EMF activity and ensure a similarly balanced approach in routing signals through the connector along the pc board and to circuitry. If some imbalance is unavoidable, deliberately introduce an intentional counterbalancing junction. In all cases, maintain the differencing junctions in proximity, which will keep them at the same temperature. Avoid drafts and temperature gradients, which can introduce thermal imbalances and cause problems. **Figure 6** shows the LTC1150 amplifier in a test circuit to measure its temperature stability. The lead lengths of the resistors connected to the amplifier's inputs are identical. The thermal capacity each input sees is also balanced because of the

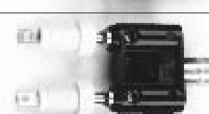
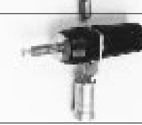
CONNECTION TYPE	DESCRIPTION	THERMOELECTRIC POTENTIAL (µV/°C)
BNC-BNC MATE		0.4
BNC-BANANA ADAPTER		0.35
BNC-BNC "BARREL" ADAPTER		0.4
MALE/FEMALE BANANA MATE SAMPLE #1		0.35
MALE/FEMALE BANANA MATE SAMPLE #2		1.1
MALE/FEMALE BANANA MATE SAMPLE #3 (TYPE SPECIFIED FOR LOW THERMAL ACTIVITY)		0.07
COPPER LUG-COPPER BANANA BINDING POST		0.08
COPPER LUG-STANDARD BANANA BINDING POST		0.5
PLATED LUG-COPPER BANANA BINDING POST		1.7

Figure 4

Measured thermoelectric potentials of some common laboratory connectors can vary widely. The pronounced difference between samples of banana connectors is due to manufacturers' materials choice; the copper-lug/copper-banana post has 20 times lower activity than the plated-lug/copper-banana post.

TABLE 1—THERMOELECTRIC POTENTIALS FOR VARIOUS MATERIALS

Materials	Potential (µV/°C)
Copper/copper	Less than 0.2
Copper/silver	0.3
Copper/gold	0.3
Copper-cadmium/tin	0.3
Copper-lead/tin	1 to 3
Copper/kovar	40
Copper/silicon	400
Copper/copper-oxide	1000

Note: This information comes from Keithley Instruments, "Low level measurements," 1984.

symmetrical connection of the resistors and their identical size. Thus, thermal-EMF-induced shifts are equal in phase and amplitude, and cancellation occurs. Slight air currents can still affect this arrangement. **Figure 7** shows a strip chart of output noise with a small styrofoam cup covering the circuit and with no cover in "still" air. This data illustrates why it is often prudent to enclose low-level circuitry inside some form of thermal baffle.

Thermal EMFs are the most likely, but not the only, potential low-level error source. Electrostatic and electromagnetic shielding may also be necessary. Power-supply-transformer fields are notorious sources of errors that are often mistakenly attributed to an amplifier's dc drift and noise. A transformer's magnetic field impinging on a pc trace can easily generate microvolts across that conductor in accordance with well-known magnetic theory. The circuit cannot distinguish between this spurious signal and the desired input. Attempts to eliminate the problem by rolling off the circuit's response may work, but the filtered version of the undesired pickup often masquerades as an unstable dc term. The most direct approach is to use shielded transformers, but careful layout may be equally effective and less costly.

The transformer's magnetic field may disturb a circuit that requires the transformer to be close by to achieve a good grounding scheme. An RF choke connected across a scope probe can determine the presence and relative intensity of transformer fields, aiding layout experimentation.

Another source of parasitic error is stray leakage current. You must prevent such leakage currents from influencing circuit operation. The simplest way is to connect leakage-sensitive points via Teflon standoffs. Then, stray leakage currents do not affect sensitive points because they never contact the pc board. Although this approach is effective, its implementation may not be acceptable in production.

Guarding is another technique for minimizing board-leakage effects. The guard is a pc trace that completely encircles the leakage-sensitive points. You drive this trace at a potential equal to that of the point, preventing leakage to the "guarded" point. On pc boards, the guard should enclose the node or nodes you want to protect. This guarding technique eliminates the effects of capacitor surface leakage in **Figure 3** of part 2.□

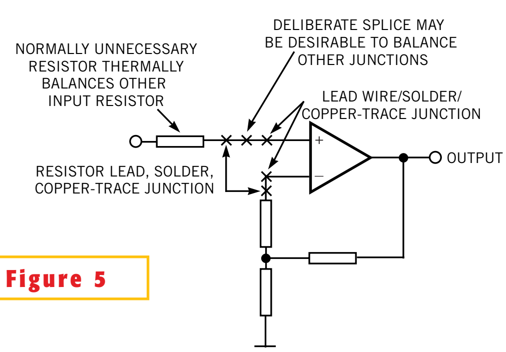


Figure 5

Typical thermal-layout considerations emphasize minimizing and compensating for parasitic thermocouples. The thermal mass at the amplifier inputs should be equal to allow parasitic-thermocouple outputs to arrive matched in phase and amplitude.

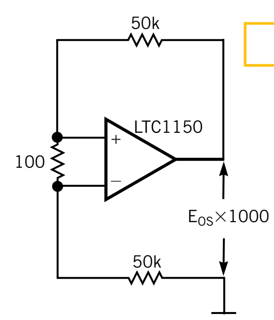


Figure 6

In an amplifier-drift test circuit, thermal EMFs and the thermal capacity at each input must be similar for cancellation to occur.

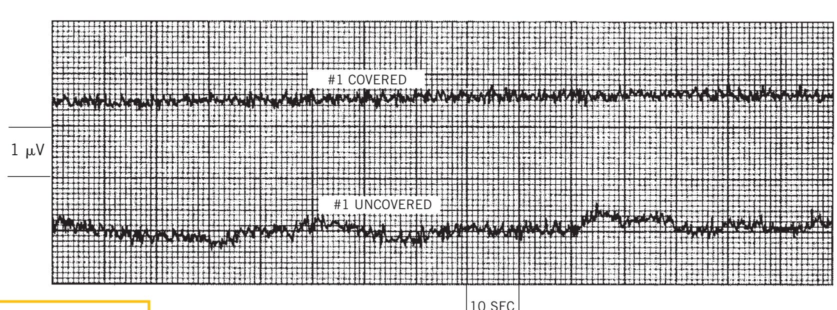


Figure 7

Slight air movement can affect the performance of a thermal baffle for a low-frequency amplifier. In the top trace, a small cup covers the amplifier, and the amplifier in the bottom trace is uncovered. The instability worsens if air movement increases.

References

1. Williams, Jim, "20-bit DAC demonstrates the art of digitizing 1 ppm, Part 1: exploring design options," *EDN*, April 12, 2001, pg 95.

2. Williams, Jim, "Measurement techniques help hit the 1-ppm mark," *EDN*, April 26, 2001, pg 117.

3. Seebeck, Thomas, "Magnetische Polarisation der Metalle und Erze durch Temperatur-Differenz," *Abhaandlungen der Preussischen Akademic der Wissenschaften*, 1822 to 1823, pg 265.

Author's biography

Jim Williams is a staff scientist at Linear Technology Corp (Milpitas, CA, www.linear-tech.com), where he specializes in analog-circuit and instrumentation design. He has served in similar capacities at National Semiconductor, Arthur D Little, and the Instrumentation Laboratory at the Massachusetts Institute of Technology (Cambridge, MA), where he first encountered serious 1-ppm measurement using the Kelvin-Varley divider. A former student at Wayne State University (Detroit), Williams enjoys art, collecting antique scientific instruments, and restoring old Tektronix oscilloscopes.