

## **All-Passive, All-Analog, Electrically-Adjustable Resistor Tempco for Post-Package Temperature-Conditioning**

**New Technology for Analog Designers:** Microbridge Technologies has developed a breakthrough technology for analog designers, *electrical adjustment of a single passive resistor's resistance and TCR to independent values*, allowing unprecedented flexibility for control of temperature-related circuit problems, in an all-passive, all-analog solution, called "eTC" technology<sup>1</sup>, for electrical Temperature Compensation.

**Analog System Designers at the Mercy of Temperature Problems:** Temperature dependencies of components have been the bane of the analog designer for decades. Even with extreme care in using the best analog design practices, the design typically doesn't succeed unless considerable thought is devoted, "early and often", to how the accumulated tolerances, mismatches and variances will be fixed (trimmed) at the end. Resistance trimming (using other approaches such as lasers, fuses, analog potentiometers, etc) allows the engineer to directly<sup>2</sup> trim only room-temperature variances and mismatches in currents and voltages.

**Digital solutions require more engineering, higher on the electronics food chain:** Perhaps because of decades of not having enough direct control over the temperature behavior of their materials, the engineering community has also developed digital techniques to compensate. In cases where these digital techniques are justified and/or available (such as in a high-end sensor system), these techniques essentially reinterpret what emerges from the material properties of the analog devices. An explicit temperature sensor, (and logic, memory, ADC, DAC), adds a conditioning overlay to the signals. This represents moving even higher on the electronics food chain in order to recover from uncertainties in the material properties, consuming power and adding errors (such as quantization effects) that reduce accuracy.

**Change the material properties directly:** Microbridge approaches the problem by heading in an unusual direction – more toward the source of the uncertainties, *allowing direct modification of the material properties of an all-analog, all-passive resistor, called an "eTC-Rejutor"*. Microbridge's innovations use the inherent material-instability of typical resistor materials at very high temperatures (several hundred degrees-C, far out of normal electronics operating ranges), to enable this adjustability. Instability at any temperature is typically seen as a disadvantage, but in this case it is used advantageously to allow high-precision adjustment. By thermally-isolating portions of resistive films typically found in integrated circuits, and by providing a highly localized and electrically-controllable heat source, resistance elements are raised by many hundreds of degrees-C, to temperatures approaching, or even greater than, the film deposition temperatures. Here the material properties such as room-temperature resistivity and TCR can be deliberately manipulated by careful design of the heating and cooling schedule.

**High-temperature materials-instability – not necessarily a bad thing:** While previous researchers have noticed high temperature instability in resistance films, most of the prior art on intentional high-temperature adjustment of resistors has addressed simple integrated resistors which were not sufficiently thermally-isolated to allow enough control over the instability. Microbridge uses microstructures which provide substantial thermal-isolation from the main substrate, to allow very localized heating of the resistance element without affecting the rest of the surrounding chip. With thermal isolation in the range of a few tens of degrees-K per mW dissipated in the microstructure, the thermal mass being heated is small enough that rapid heating and cooling is possible, allowing a software-controlled feedback-based adjustment algorithm. A 1-5-second<sup>3</sup> sequence of electrical heating pulses, governed by Microbridge's proprietary algorithms, is enough to fine-tune the material properties of the patterned resistor film.

<sup>1</sup> "eTC" refers to "electronic temperature-coefficient adjustment", or "electronic temperature-compensation", a technology different from, and more advanced than Microbridge's standard Low-TCR products. eTC is tailored for applications which require explicit temperature-conditioning.

<sup>2</sup> Note that in some analog circuits such as voltage references, room-temperature resistance trimming is used to indirectly adjust temperature behavior.

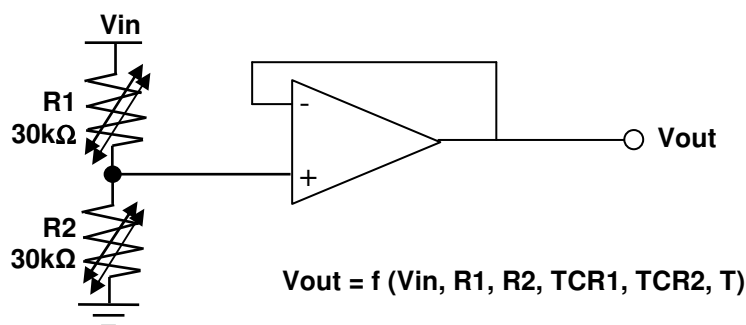
<sup>3</sup> Using Microbridge's scalable production-calibration hardware (based on the NI-DAQ platform from National Instruments) and Rejust-it software, multiple units can be calibrated simultaneously during roughly the same amount of time.

**Predictably change resistance and TCR:** When a resistance element is adjusted in this way, its TCR changes in a specific manner as a function of its change in resistance. For example, the TCR of typical CMOS-gate polysilicon increases by about 20-30ppm/K per percent of resistance adjustment. By itself, this property would not allow independent adjustment of resistance and TCR. However, Microbridge has developed a useful set of high-temperature-adjustable materials with different as-manufactured TCR, as well as different TCR response as resistance is adjusted, which forms a “toolkit” with which to build temperature-conditioning solutions.

**A toolkit for many types of temperature-conditioning applications:** Individual resistance elements may be matched to the needs of a particular application. For example, in the adjustment of TC-sensitivity of a piezoresistive bridge-based sensor, it is advantageous for the resistor to have a large negative TCR, AND have the TCR become more positive as it is trimmed down.

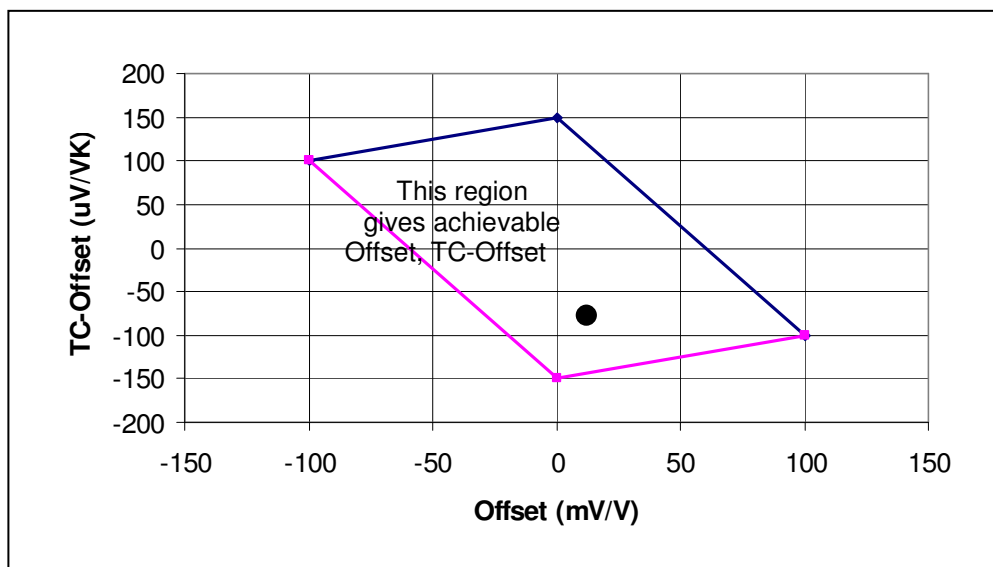
**Adjustment of resistance and TCR to independent targets:** OR, more fundamental for the broader analog field, several elements of the toolkit can be used in combination to allow the adjusting of a resistor’s resistance and TCR to independent targets. The result is a simple two-terminal passive resistor, an “eTC-Rejistor”, with adjustable material properties. No extra temperature sensor is needed -- as a passive TC-controlled component, it *is* its own temperature sensor, as well as being the adjustment device. Amplifier offset and TC-offset can be compensated in the analog domain, right at the source, before it eats into the dynamic range or otherwise skews the performance of the larger circuit. No lookup-table, ADC or DAC needed. There is no wiper resistance. Continuous-valued adjustment means no quantization noise. The adjustment is done electronically after board assembly and thus the design engineer can wait for all other parameter variances to “have their say”, and then simply null out the cumulative effects out during final test.

**“Fix”, or explicitly temperature-condition, a signal or reference:** Typical analog electronic circuits require precise and temperature-stable reference voltages and/or currents, as well as fine-calibrated amplification or attenuation. Consider the simple circuit shown in Fig.1 – a voltage divider powered by a (generic) circuit voltage ( $V_{in}$ , which may be a reference or a signal), setting a (different) buffered drive level. In practice, the input voltage can be non-ideal, and/or can have undesired temperature variations. Or, even if it were ideal, one may explicitly *want* the drive level to have a *specific non-zero temperature coefficient*, because of specific characteristics of the device being driven.



**Fig. 1:** An eTC-Rejistor divider, where each Rejistor’s resistance and TCR can be adjusted to independent targets, with buffered divider output shown for convenience. Note that  $V_{out}$  is a function of both resistance values and both TCR’s.

**A new tool – adjust both offset and TC-offset simultaneously:** If the voltage divider is a voltage divider made with Microbridge eTC-Rejutors, this provides a new tool with which to craft and adjust an application circuit. The TC-Offset vs. Offset characteristics of a specific Microbridge eTC divider are shown in Fig. 2 below. The Offset is the deviation of the divider output voltage  $V_{in} \cdot (R_1 / (R_1 + R_2))$ , measured in mV per volt of divider input voltage  $V_{in}$ , away from  $V_{in} \cdot (R_{10} / (R_{10} + R_{20}))$ , where  $R_{10}$  and  $R_{20}$  are the nominal unadjusted divider resistance values. The TC-Offset is the temperature coefficient of that divider output voltage, measured in  $\mu\text{V}$  per degree-C (K) per volt of divider input voltage. Microbridge's eTC adjustment software allows one to pick target values for Offset and TC-Offset as a point within the roughly-parallelogram-shaped region shown in Fig. 2. For example, if initially the divider input voltage is low by 5% (50mV/V) from its designed value, and, additionally, it has an undesired +75 $\mu\text{V}/\text{VK}$  temperature variation, and if it is desired that the drive level be temperature-stable at the nominal  $V_{in} \cdot (R_{10} / (R_{10} + R_{20}))$ , then one programs the divider to the point (+50mV, -75 $\mu\text{V}/\text{KV}$ ), as shown in the figure.



**Fig. 2:** A typical plot of the achievable sets of values for a real voltage divider made from a specific example of eTC Rejutors. The adjustment allows you to pick a target spot within this roughly parallelogram-shaped region. One specific example point is shown, at Offset = +50mV/V and TC-Offset = -75 $\mu\text{V}/\text{VK}$ , (+50mV/V, -75 $\mu\text{V}/\text{VK}$ ).

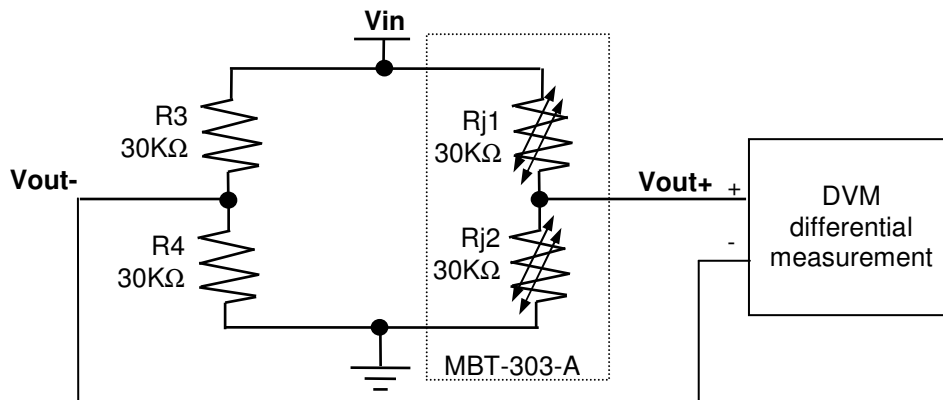
**How do you do this, in practice?** You electrically connect the calibration pins of the two adjustable resistors, and output drive level, to Microbridge's calibration hardware, program your targets in to the software, and press "Calibrate". The software automatically manages the electrical signals, while monitoring the drive output level. Microbridge's specialized and scaleable hardware manages and delivers signals to calibrate multiple devices (8, 16 ... devices) simultaneously in parallel, to independent targets.

**Set a batch TC target ...** : If you know ahead of time the target TC (e.g. because you have characterized enough of your batch to know that they all have temperature non-ideality roughly 75uV/VK), then you don't need to temp-cycle your devices – the software can roughly hit the TC target needing only output voltage feedback, as long as the transfer function between Rejustors and circuit output is well-enough known. The precision of adjustment (for both offset and TC-offset) using this method will depend on how well-known is this transfer function. In the circuit shown in Fig. 1 the output level can be affected by non-idealities in the buffer-amp, but a tolerance of +/-20uV/VK in TC setting, usually better, can be anticipated. The precision of Offset adjustment is also subject to this transfer function, but usually you care more about the overall output than you do about hitting your spot in Fig. 2 – thus effective Offset precision is typically excellent (+/-1mV/V).

**... or set different TC targets for individual devices:** Of course, if you are set up to temperature-cycle and individually characterize each of your assembled/packaged circuits, then further adjustment precision is attainable. In this case, even if you cannot (or don't want to) sort out which of your unruly circuit elements is at fault when the drive signal doesn't behave the way you need it, ... you can still adjust it all out at the end!

**Unprecedented flexibility to null out cumulative temperature-sensitivities:** This new technology gives unprecedented flexibility in designing an analog circuit. In present mainstream analog circuit design, an active trim lets one compensate for the cumulative manufacturing variances in component resistance values. If such an active-trim resistance-adjustment technique lets you get away with buying 20%-toleranced components, you pay a lot less than if you buy 2%- or 5%-toleranced circuit components. Similarly, this TCR adjustment technology allows an analog designer to compensate for or null out the cumulative temperature-sensitivities of (all) other components in the system ... at the same time as compensating for those component-resistance variations!

**A practical example:** Consider a passive bridge circuit as shown in Fig. 3, used in this case to showcase the general capabilities of this new technology. In the ideal, if the bridge resistors are well-matched, (or even if the ratio  $R_{j1}/R_{j2}$  is well-matched to the ratio  $R3/R4$ ), the voltages at the two points,  $V_{out+}$  and  $V_{out-}$  would be exactly equal, and remain exactly equal over the entire industrial or automotive temperature range. However, due to manufacturing variances, there is always some offset and/or TC-offset, usually directly limiting the performance of the device. In this example, the resistors  $R_{j1}$ ,  $R_{j2}$  at the right side of the bridge are an eTC-Rejistor-divider, nominally 30kohms per Rejistor with a 1:1 ratio.

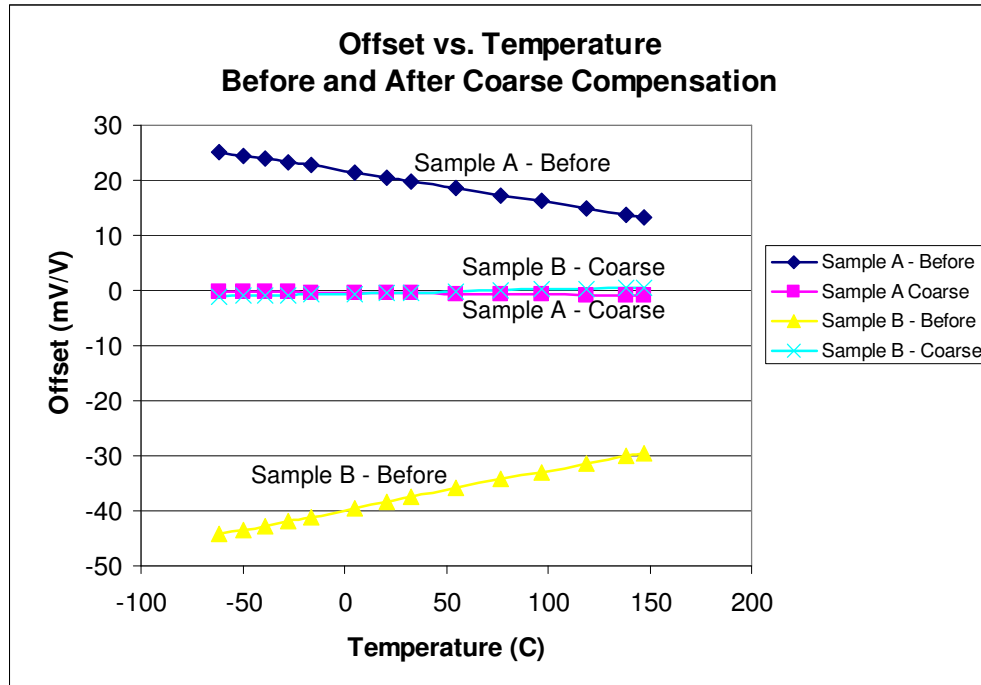


**Fig. 3:** Passive bridge circuit, consisting of Rejistors  $R_{j1}$ ,  $R_{j2}$ , and fixed resistors  $R3$ ,  $R4$ , with digital voltmeter (DVM) connected to measure the differential output signal ( $V_{out+} - V_{out-}$ ).

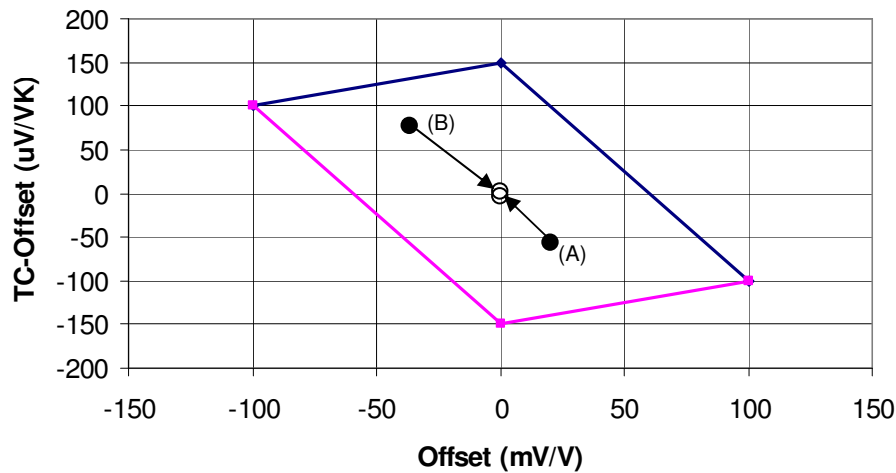
**“Coarse Adjustment”:** Fig. 4a shows two examples of the output voltage of such full-bridges measured vs. temperature, from below  $-55^{\circ}\text{C}$  to above  $+145^{\circ}\text{C}$ , “before compensation” and “compensated”. The Offset and TC-Offset numbers are listed in the Table below. The “compensated” curves in Fig. 4a show the results of adjustment using only single-temperature (e.g. room-temperature) output-voltage ( $V_{out+} - V_{out-}$ ) feedback during adjustment, where the adjustment targets have been calculated based on an initial measurement of Offset and TC-Offset Fig. 4b represents the same two examples on TC-Offset vs. Offset axes, similar to Fig. 2 above.

Temperature: $-61.9$ to $-147.1$ C	TC offset ( $\mu\text{V}/\text{VK}$ )	Offset <sup>4</sup> (mV/V)
Sample (A) before compensation	-56.5	+20.26
Sample (A) compensated	-2.98	-0.50
Sample (B) before compensation	72.3	-38.00
Sample (B) compensated	7.74	-0.44

<sup>4</sup> Offset measured at room temperature

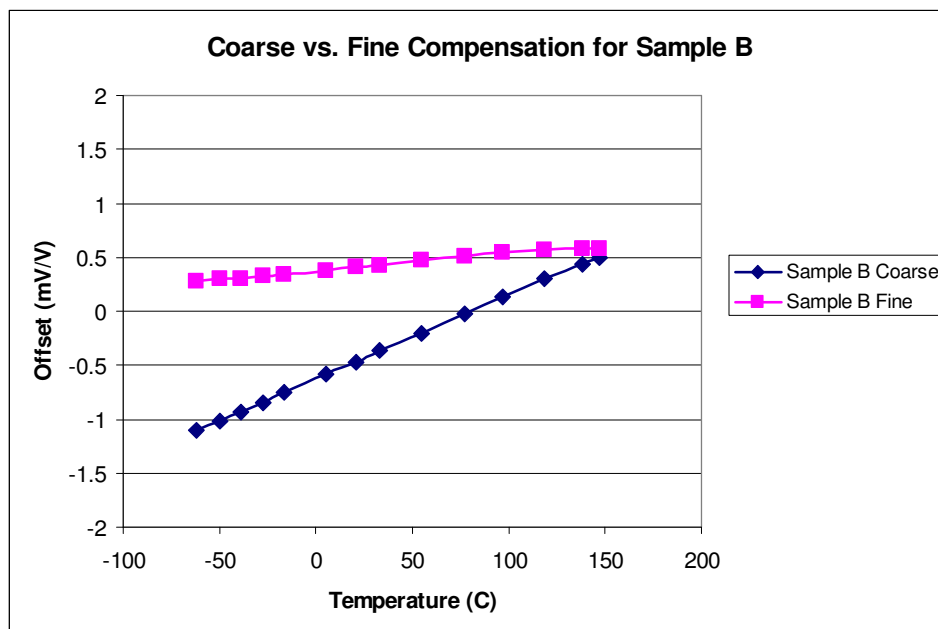


**Fig. 4a:** Measured bridge Offset vs. Temperature for the circuit shown in Fig. 3, two different samples, before and after eTC Rejursor adjustments.



**Fig. 4b:** Plot of Offset and TC-Offset vs. Offset for the two examples shown in Fig. 4a.

**“Fine Adjustment”**: The above can be considered as a single “coarse” adjustment. If better precision is desired, one can perform a second measurement of Offset and TC-Offset to calculate new Offset and TC-Offset targets, and then a second (fine) adjustment, again using only output voltage feedback. Fig. 5 shows results of a coarse adjustment (sample (B)), and subsequent measurement (-0.44mV/V, +7.7uV/VK), and a subsequent fine adjustment of the same sample (B), where the TC-Offset has been significantly improved (+0.42mV/V, +1.7uV/VK). Note that  $V_{out}$  vs.  $T$  has good linearity over the full temperature range from below -55C to above +145C.



**Fig. 5:** Measured bridge Offset vs. Temperature for the circuit shown in Fig. 3, for a given eTC Rejutor divider, first coarse-adjusted, then fine-adjusted.

**Conclusion:** eTC Rejutor technology offers analog designers a solution for all-passive, all-analog, electrically-controlled tempco adjustment, for post-package temperature conditioning. Each resistor’s resistance and TCR can be adjusted to independent targets, allowing unprecedented flexibility for control of temperature-related circuit problems. For example, amplifier offset and TC-offset can be compensated, still in the analog domain, with continuous-valued adjustment. The adjustment is done electronically after board assembly and thus the design engineer can wait for all other parameter variances and temperature-sensitivities to “have their say”, and then simply null out the cumulative effects during final test.