

Digital Gain Control With Analog VCAs

Abstract

In many cases, a fully analog signal path provides the least compromise to sonic integrity, and ultimately delivers the best sounding audio products at the lowest cost. What is often needed, however, are methods for varying the gain and other parameters of the analog circuitry, under digital control.

While several methods are available to the designer, the best combination of sound quality, control range, and control resolution can be obtained from two easily-combined building blocks—a high-performance, exponential-control, Voltage Controlled Amplifier (VCA), and a low-cost Digital-to-Analog Converter (DAC).

The advantages to this approach are multi-fold. The analog signal path provides the highest possible dynamic range, reduces or avoids alto-

gether such common digital artifacts as zipper noise, spectral spreading, digital feedthrough, and idle tones, and eliminates the need for a high-resolution Analog-to-Digital Converter (ADC).

The exponential gain control of the VCA means that the equal step sizes of an ordinary DAC will translate to gain increments which are of uniform size in decibels. As a result, an inexpensive DAC of relatively low precision (e.g. 8 bits) will provide all the gain range and resolution required for almost any application.

This paper explains how to build gain-control blocks using DACs and VCAs, a solution which provides both the convenience and reprogrammability of digital control, and the highest quality audio that comes from the use of an analog signal path.

Digital Gain Control With Analog VCAs

While digital signals and digital signal processing have grown in popularity in recent years, there are significant advantages to the use of an all-analog signal in professional audio equipment. These include:

- No digital artifacts such as digital feedthrough and idle tones;
- No need for an expensive, high-resolution Analog-to-Digital Converter (ADC)

At the same time, designers want to take advantage of the convenience and reprogrammability afforded by modern micro-controllers. As we will see, the use of a DAC to manipulate the gain of an exponentially-controlled Voltage Controlled Amplifiers (such as the THAT 2180 and THAT 2181 families of integrated circuit VCAs) is a near-perfect solution to the problem of digital gain control of analog signals, and provides the following additional advantages over other approaches:

Wide gain range, with equal dB gain steps

An ordinary linearly-controlled gain element will provide gains that increase in equal, but linear, increments. The result is a gain range that is

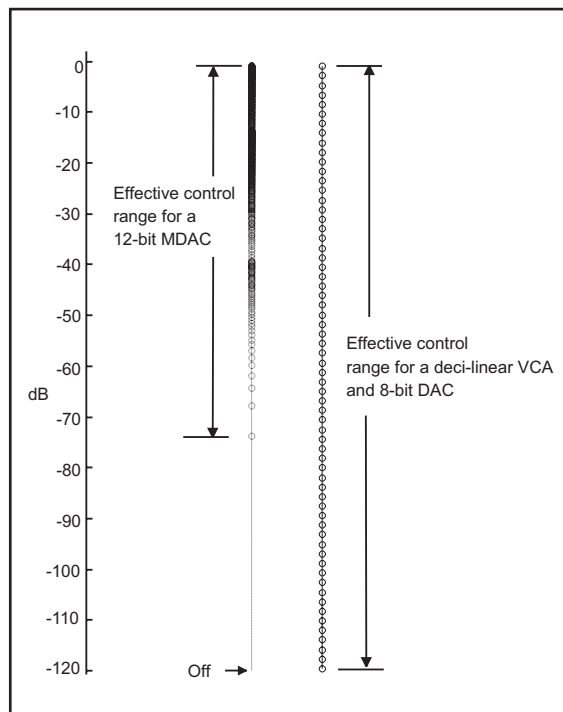


Figure 1. Comparison of control resolution and range for an exponential-control VCA/8-bit DAC, and a 12-bit MDAC

both severely restricted and whose gain steps, when viewed on a decibel scale, vary widely and inefficiently from one end of its gain range to the other.

An exponentially-controlled VCA's linear-in-decibels control port characteristic, on the other hand, results in much more efficient use of a DAC's dynamic range. For example, the graph of Figure 1 contrasts a 12-bit MDAC used as a gain control device, with a THAT 2180 or THAT 2181 VCA whose gain is controlled by an 8-bit DAC. At the lowest non-zero setting the attenuation of the 12-bit MDAC is -72dB and its step size is 6 dB, while at the upper end of the adjustment range the step size is 2 mdB (0.002 dB). Compare this to the THAT VCA whose gain is adjusted from an inexpensive 8-bit DAC: the step size is 0.5 dB throughout its entire adjustment range, and that range extends to nearly 128 dB (beyond the range of the graph in Figure 1).

In fact, it would take a 20-bit MDAC to achieve 120 dB of control range, and this device, like all linear-control gain elements, would still have a step size of 6 dB at its lowest setting.

Light sensitive resistors are another example of an analog gain control element, but they are typically limited to about 60dB of attenuation, and

tend to exhibit wide variations in their control characteristics.

Continuous (rather than discrete) transitions between gain steps

The analog VCA is, by nature, a continuous device. By providing some amount of filtering at the VCA's control port, the gain will pass from one gain setting to the next smoothly and in a continuous fashion. As a result, there is no need for the zero-crossing detection required by MDACs and other digital control devices in order to control waveform discontinuities. It should be pointed out that, even with zero-crossing detection, the MDAC will cause an abrupt change in the derivative of the analog signal when the gain is changed in the presence of a signal. A DAC-controlled VCA, on the other hand, while still imposing a derivative change in the waveform, will do so smoothly, without an abrupt transition, resulting in a smoother sound during the gain change.

Use of the full dynamic range afforded by the analog power supply

An analog signal path with VCA gain control eliminates the need to "squeeze" the audio through the limits of a digital device's supply rails. As a re-

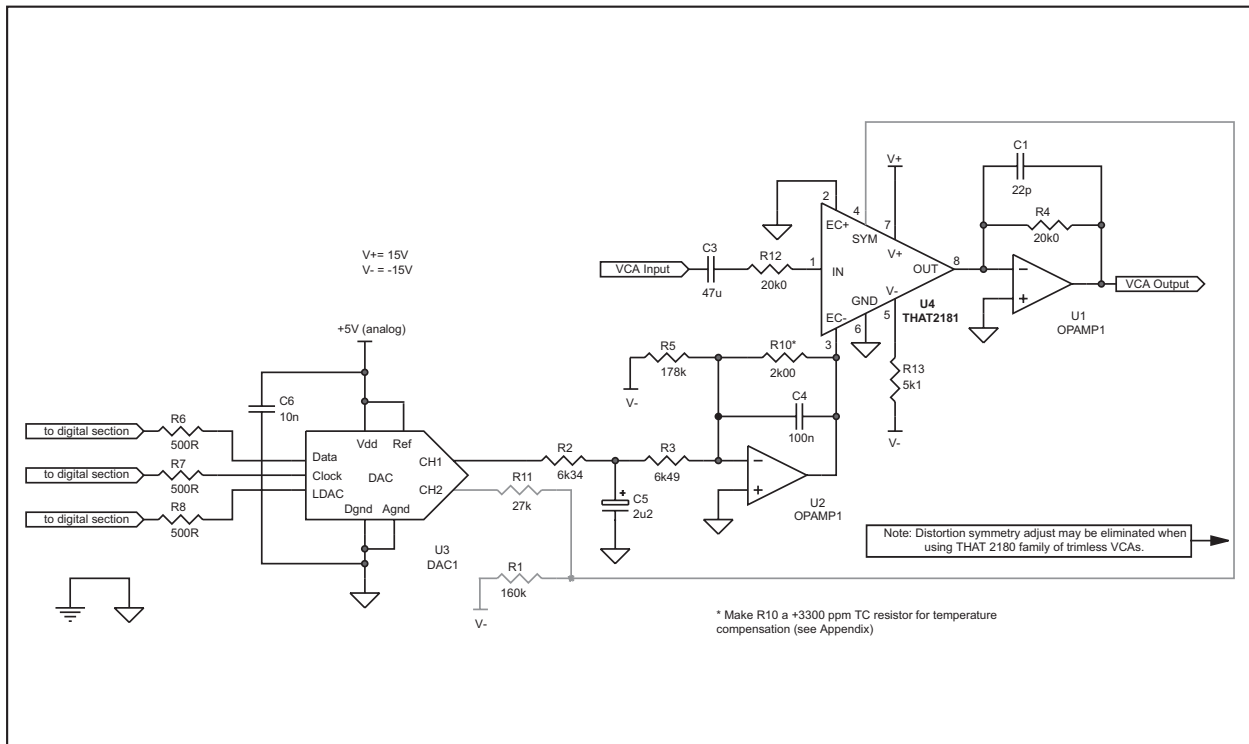


Figure 2. Basic DAC-controlled VCA

sult, the full dynamic range of the analog supplies is available to the designer.

Flexibility

Unlike an MDAC, a VCA configured as a gain control element can, with a minimum of additional circuitry, serve *simultaneously* as a compressor, gate, or other type of dynamics processor. This flexibility can be the source of significant cost savings, particularly in recording consoles and other components with large numbers of audio channels.

Typical Application Circuit

Digital gain control with no artifacts can be implemented with as little as a VCA, an 8-bit DAC and a smoothing filter, as shown in Figure 2. THAT Corporation's VCAs are 2-quadrant multipliers with a linear signal input and an exponential gain-control input. With the use of a dual DAC, one channel will generate the VCA's control signal, while the other channel can be used to generate the symmetry correction voltage for lowest VCA distortion. An alternative to the use of a DAC symmetry trim is the traditional trimpot. Note that the symmetry adjustment may be omitted altogether if using any of the trimless THAT 2180 series ICS.

Op amp U2 acts as a control voltage buffer, and sets the control voltage offset. Since this circuit drives the control port through E_c ,

$$Gain_{dB} = \frac{-E_c}{k_c}$$

where E_c is the voltage at the control port, and k_c (the control voltage constant) is approximately equal to 6.1 mV/dB. R10, it should be noted, is to compensate the VCA's gain against variations in temperature. For more discussion on temperature compensation, see the Appendix at the end of this paper.

The DAC in Figure 2 is a generic, multiple, serial 8-bit DAC which can typically be purchased for a few tens of cents per DAC. Unlike the case where analog audio is passing directly through the DAC, the output of this DAC can, and should, be filtered to create continuous transitions between gain settings at the VCA's control port. The parallel combination R2 and R3 in conjunction with C5 results in $\tau \approx 7mS$. This combination has proven to provide good audible results in fader-type applications, though the designer should feel free to experiment and find the filter characteristic that suits the project's needs.

The DAC output varies from 0 to 4.98 volts, which is scaled by the control voltage buffer to be

$$4.98 V \times \frac{20k}{6.34k + 6.49k} = 0.776 V.$$

When this voltage is divided by the VCA's control voltage constant, the resulting gain control range is

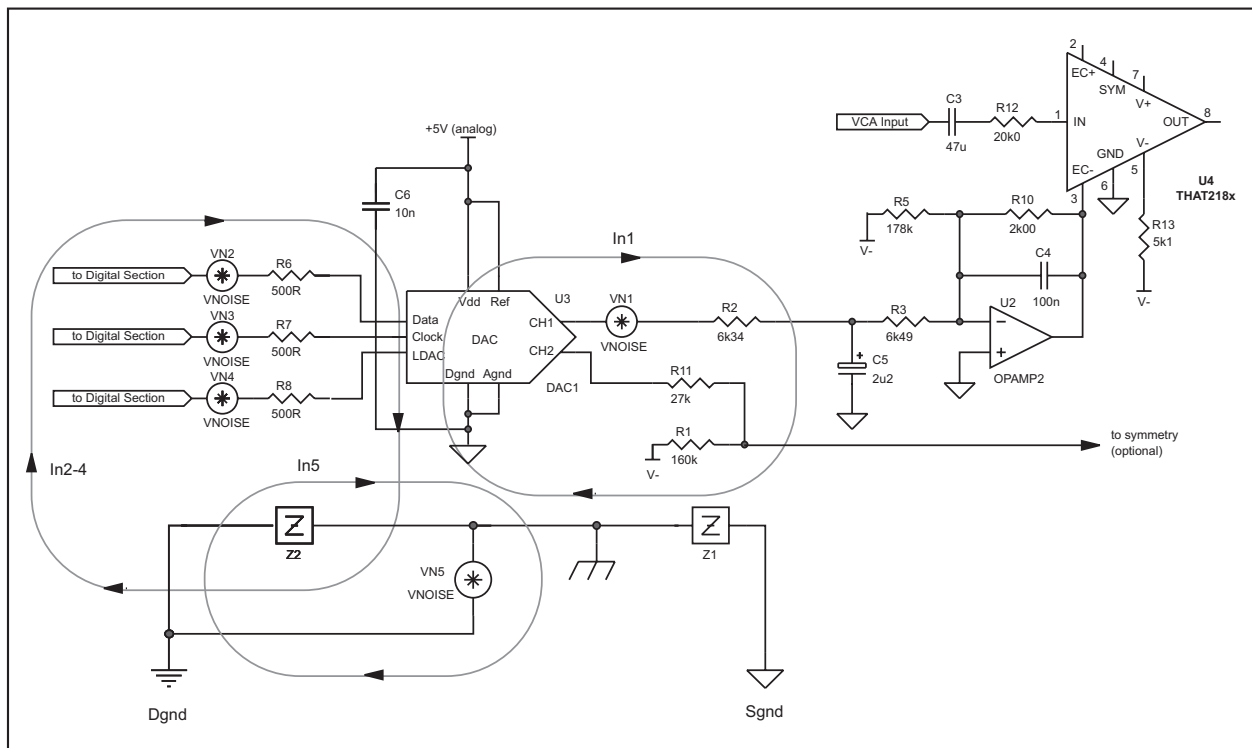


Figure 3. Diagram showing noise sources and parasitic impedances

$$\frac{0.776 \text{ V}}{6.1 \text{ mV/dB}} = 127.3 \text{ dB.}$$

R5 is used to offset the gain control signal by +27.5 dB to allow the VCA's gain to be varied from -100 dB to +27.5 dB in steps of 0.5 dB.

Grounding

Grounding of THAT Corporation's VCAs presents no special difficulties, as long as the local ground is low impedance and noise free. THAT VCAs are current-in, current-out devices, with input current flowing into a virtual ground, and the output current converted into a voltage with a trans-impedance amplifier (e.g. an op amp). As such, no dynamic current flows into the local ground. The internal current mirrors that bias the IC are referenced to ground, and the mirror bias current, drawn through the ground pin, is a few hundred microamps of DC current.

The most difficult grounding issues are a) managing the transient current coming from the digital section, and b) keeping the local (signal) ground quiet. Figure 3 is a grounding diagram showing noise sources and parasitic impedances, as well as

several differentiated grounds. The boxes labeled Z1 and Z2 are the impedance, usually a few tens or hundreds of nano-henries, between signal (Sgnd) and digital (Dgnd) ground. Vn1 is the digital noise source inside the DAC due to internal coupling. Vn2-4 represent noise coupled from the digital section via the DAC's control lines. Vn5 is the lumped representation of the noise between digital Dgnd and Sgnd.

The DAC should run off a supply that is derived from the analog supply, (labeled "+5V (analog)"), and which should be bypassed to Sgnd near the DAC with a high quality ceramic capacitor. In addition, the DAC's reference can be connected directly to this same supply. R2 and C5, the filter capacitor, should be physically near to the DAC, and the grounded leg of C5 should return to the Dgnd and Agnd pins of the DAC prior to connecting to the remainder of Sgnd, as should the DAC's decoupling capacitor. This will keep the transient currents resulting from Vn1 in a small loop local to the DAC.

Unlike Vn1, Vn2-4 are referenced to Dgnd, and therefore the resulting currents must return to

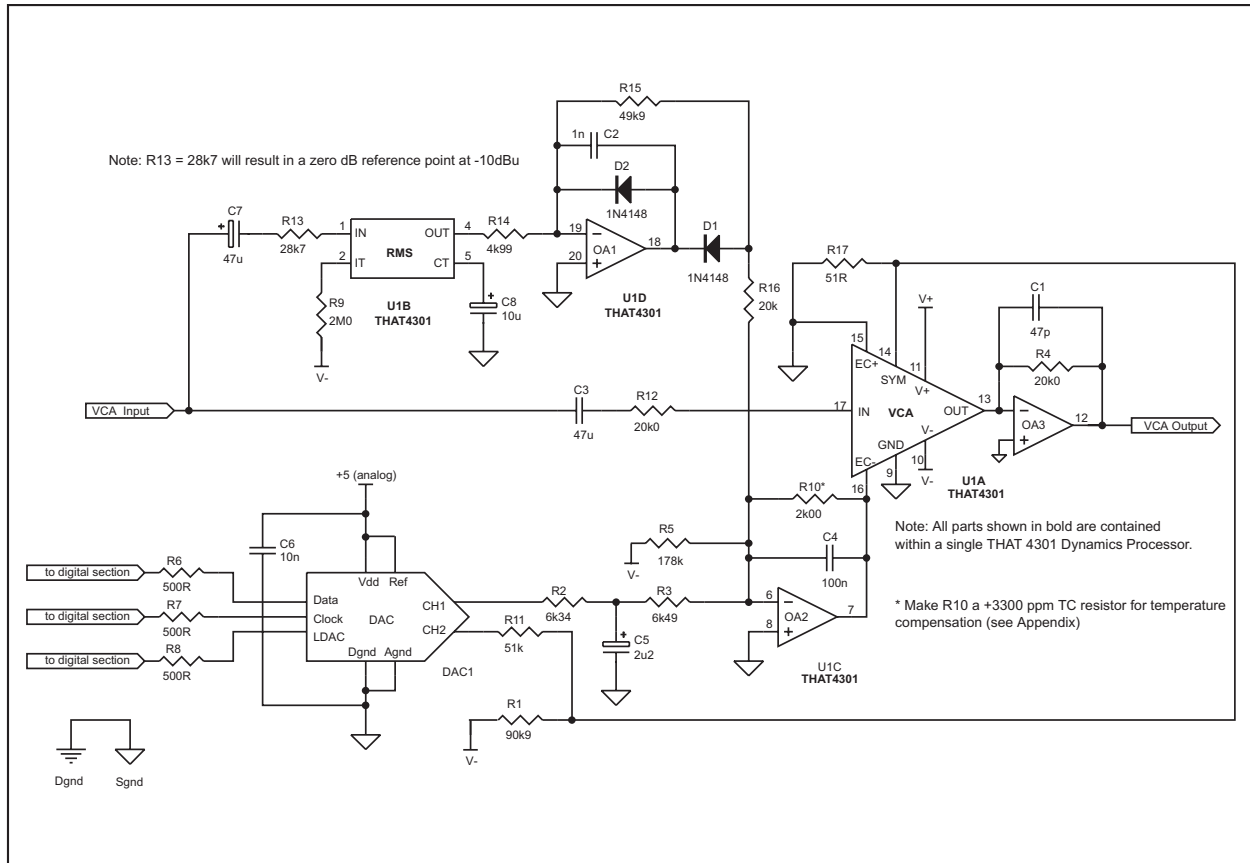


Figure 4. Digital gain control with feed-forward limiting function (using THAT4301 Analog Engine™)

Dgnd. The return current will produce a voltage across Z2 which only affects the noise margins of the digital devices, provided that these currents are kept from flowing through impedances between other analog components. R6-8 are intended to minimize this current, but the designer may need to add ferrite beads to further limit high frequency current.

Vn5 represents the switching noise that results from other components of the digital circuitry, such as the micro-processor. The resulting noise current follows a path through Z2, and does not couple into the signal as long as there is only one connection between Dgnd and Sgnd.

Simple design extensions

The use of THAT Corporation's VCAs in a design provides an opportunity to include simultaneous dynamic audio processing (compressors, limiters, gates, and the like) with minimal additional circuitry. The circuit of Figure 4 is a simple limiter that can be added to the gain control circuit discussed previously. This circuit is designed around a THAT 4301 "Analog Engine™", a versatile building block integrating a high-performance VCA and RMS-detector combination, along with three general purpose op amps.

The 4301's RMS detector monitors the VCA's input, and generates a signal that is proportional to the input signal's level in decibels. In this design, the RMS detector's 0 dB reference level is set to -10 dBu by making R13 equal to 28.7 kΩ. Internal op amp OA1 is a threshold detector set for zero volts. When the signal level exceeds -10 dBu, the output of the RMS detector exceeds the threshold and the circuit begins to reduce the VCA's gain. This action implements an above threshold AGC or limiter, and only

simple modifications to this basic circuit will result in a wide variety of dynamics processors.

Some closing thoughts

When designing digitally-controlled analog circuits, exponentially-controlled VCAs provide a simple, cost-effective means to realize a wide variety of dynamic elements. Isolation of the digital and analog signals is easily maintained since the analog signal never has to traverse circuitry referenced to digital ground. The ability to add a smoothing filter to the controlling DAC's output enables artifact-free gain control, while "zipper noise" and "spectral splatter" are all but eliminated due to the resultant continuous nature of the gain changes.

THAT VCAs provide additional versatility and cost-savings opportunities as a result of their ability to do double-duty, with a single component acting as both gain control and effects processor. "Grouping" is simplified since exponentially-controlled VCAs at different gain levels can have their gain incremented as a group in like dB steps (as a result of the VCA's linear-in-dB control port characteristic) by simply adding the same integer to each VCA's DAC. The overall simplicity and sensibility of VCAs make them the designers choice where digital control of analog signal is desired.

Suggested reading

- Digital Control of Analog Level, Carl Malone, *AES 13th International Conference*
- Digitally-Controllable Audio Filters and Equalizers, Gary K. Hebert and Fred Floru, *AES 13th International Conference*

APPENDIX: PTAT REFERENCE

While temperature compensation of VCAs is often unnecessary, the most accurate systems use temperature compensated control voltages. This appendix demonstrates two simple methods of implementing a PTAT (proportional to absolute temperature) voltage reference, either of which can be used in conjunction with a DAC to generate a properly compensated control signal for VCAs. A master reference such as this can be useful when multiple VCAs are to be controlled.

Each method generates a V_{ref+} and a V_{ref-} . Referring to Figures 2 and 4, V_{ref-} replace the V_{-} connections to R1 and R5, while V_{ref+} will connect to the DAC's reference input. Resistors R1, R5, and R11 will need to be scaled by the ratio of V_{ref} to V_{-} . Note that when either Method A or Method B are employed, R10 should NOT be a TC type resistor.

Method A, shown in the upper half of Figure 5, uses $+3300\text{ppm}/^{\circ}\text{C}$ resistors to generate the PTAT voltage. Either one or two TC resistors may be

used, depending on the degree of compensation desired. When a single TC resistor is used, a $+3300\text{ppm}/^{\circ}\text{C}$ resistor is used at the location shown for R7. R19 programs a fixed reference current which develops across R7, the TC resistor. The reference voltage changes at $+3300\text{ppm}/^{\circ}\text{C}$ due to the positive temperature coefficient of R7. This PTAT reference voltage is trimmed via the DAC and R17. Where temperature compensation is necessary, this technique provides a large measure of correction at low cost.

Even so, there is slight interaction between the level trim adjustment and the temperature compensation when using only one TC resistor. One may also use a $+3300\text{ppm}/^{\circ}\text{C}$ resistor in the trim leg of the circuit (R17) as well as for the feedback resistor. Figure 6 shows the effect of various levels of reference compensation over a 30°C range (54°F) for a VCA at $+20\text{dB}$ gain. The line labeled "Uncompensated" shows a gain variation of $\sim 2\text{dB}$ over this temperature range for a VCA with an uncompensated reference.

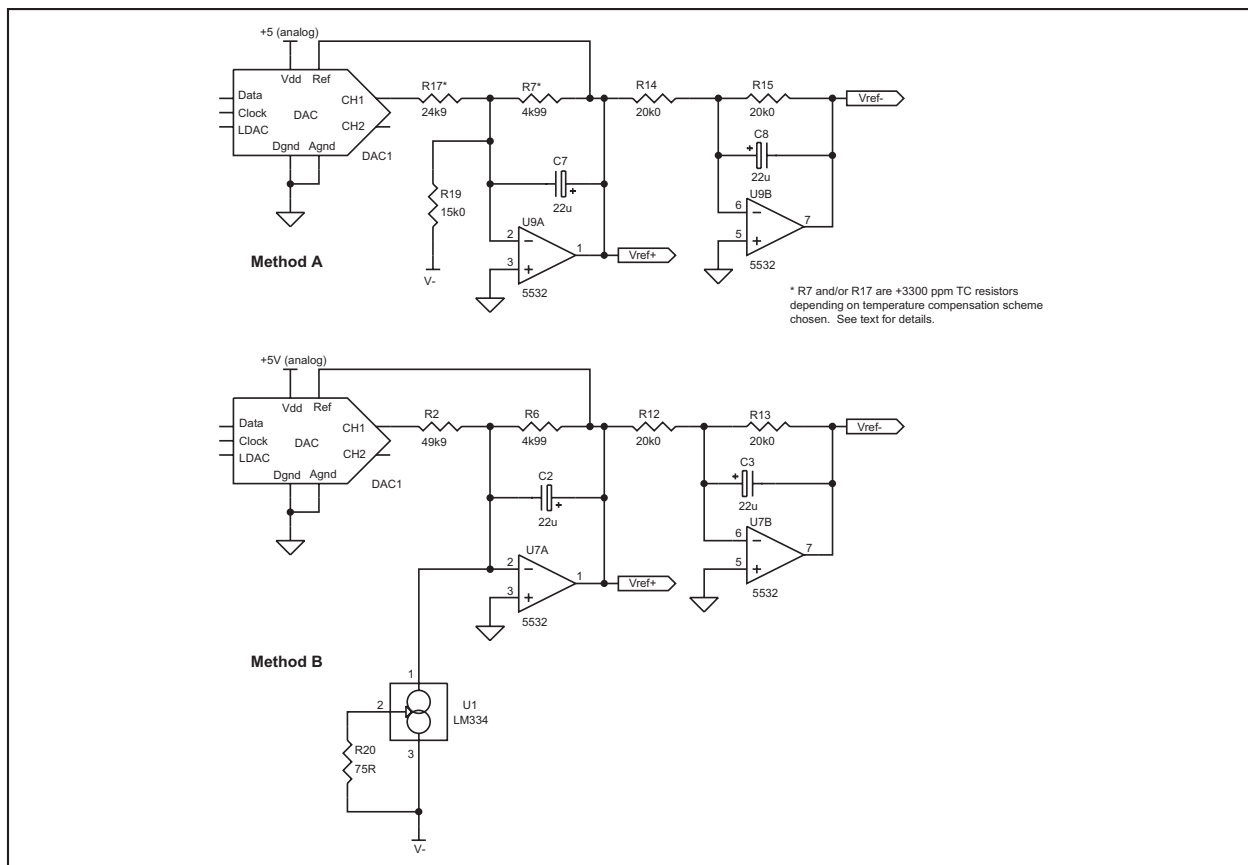


Figure 5. Methods for generating a PTAT voltage reference

The line labeled "Single +3300ppm resistor" shows the improvement when temperature compensating with a single TC resistor is used. If +3300ppm/°C resistors are used in both legs of the circuit outlined in Method A, or if Method B (described in the next paragraph) is used, the residual errors are negligible. Note these results are dependent on the temperature sensing element correctly reflecting the temperature of the VCA.

Method B for generating a PTAT voltage reference is shown in the lower half Figure 5. In this technique, an LM334 is configured in the simplest manner possible, making a current source that is directly proportional to absolute temperature. This PTAT current develops across R6 to generate the PTAT volt-

age reference. Trimming is through R2, the same as before, but since the trim doesn't appear in parallel with the TC element, there is no interaction between the trim and the temperature coefficient. The design equations for using a single LM334 are, assuming the desired $V_{ref} = 4.5 \text{ V}$, and with $V_r = 64 \text{ mV at } 25^\circ\text{C}$ (from the LM334 data sheet),

$$I_{set} = \frac{V_{ref}}{R_6} = \frac{4.5\text{V}}{4.99\text{k}\Omega} = 901 \mu\text{A}$$

$$R_3 = R_{set} = \frac{V_r}{I_{set}} \times (1.059) = \frac{0.064}{900 \mu\text{A}} \times (1.059) = 75 \Omega$$

Note: $V_{ref} = 4.5 \text{ volts at } 25^\circ\text{C}$ is chosen to allow the reference to change with temperature without exceeding the +5V analog supply of the MDAC.

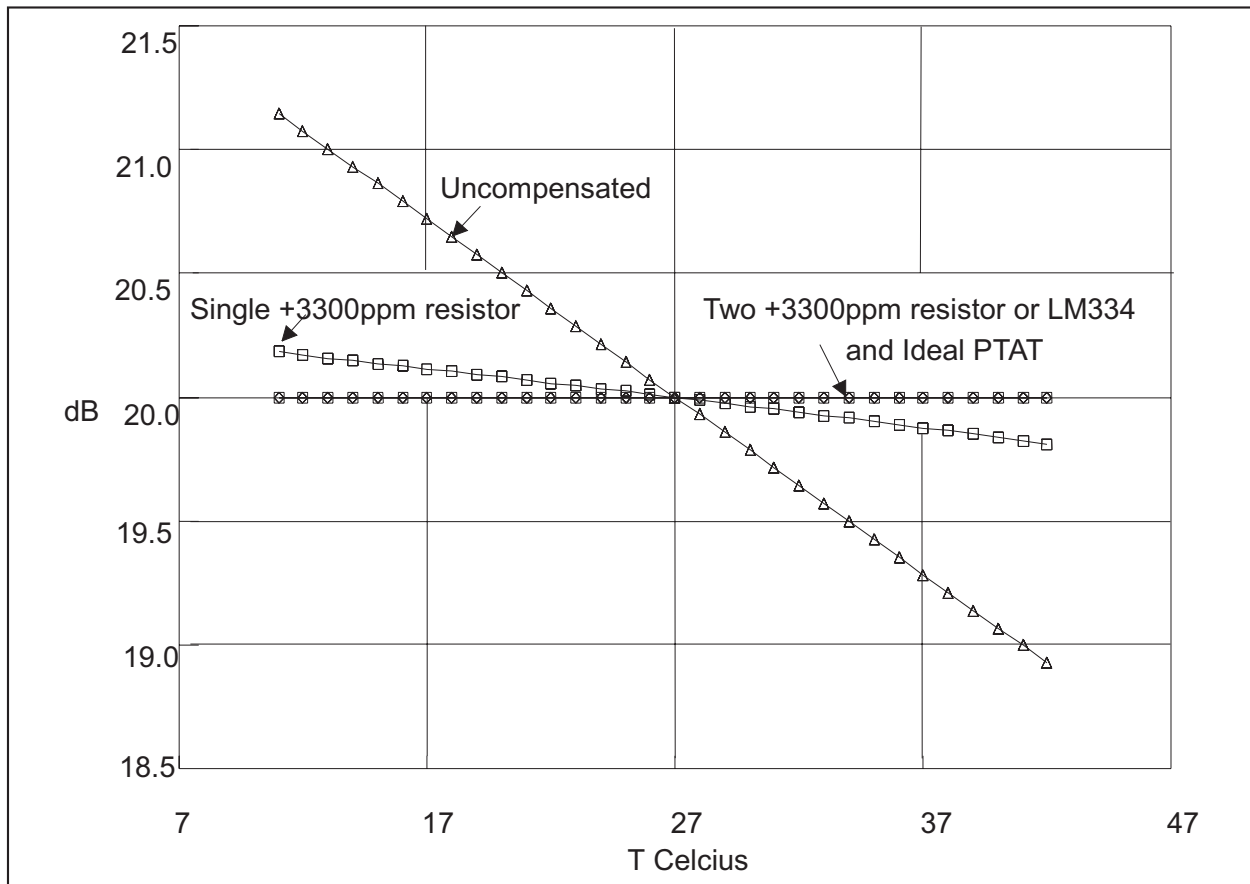


Figure 6. Gain change vs. Temperature for an uncompensated reference, a partially-compensated reference, and a fully-compensated reference, all at +20 dB gain

Notes