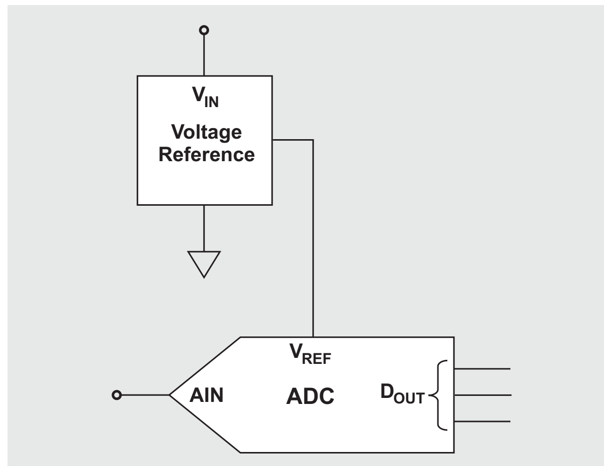
How the voltage reference affects ADC performance, Part 2

By Miro Oljaca, *Senior Applications Engineer,*
and Bonnie Baker, *Senior Applications Engineer*

Introduction

This article is Part 2 of a three-part series that investigates the design and performance of a voltage-reference system for a successive-approximation register (SAR) analog-to-digital converter (ADC). A simplified version of this system is shown in Figure 1. When a design uses an ADC in this system, it is critical to understand the voltage-reference path to the converter. Part 1 (see Reference 1) examined the fundamental operation of an ADC independent of the voltage reference, and then analyzed the performance characteristics that have an impact on the accuracy and repeatability of the system. Part 2 looks at the key characteristics of the voltage-reference block in Figure 1 and the reference's possible impact on the ADC's performance. Part 2 also shows how to design an appropriate external reference for 8- to 14-bit ADCs. Part 3, which will appear in a future issue of the *Analog Applications Journal*, will investigate the impact of the voltage-reference buffer and the capacitors that follow it, discuss how to ensure that the amplifier is stable, and provide a reference design that is appropriate for ADCs with 16+ bits.

Figure 1. Voltage-reference system for SAR ADC

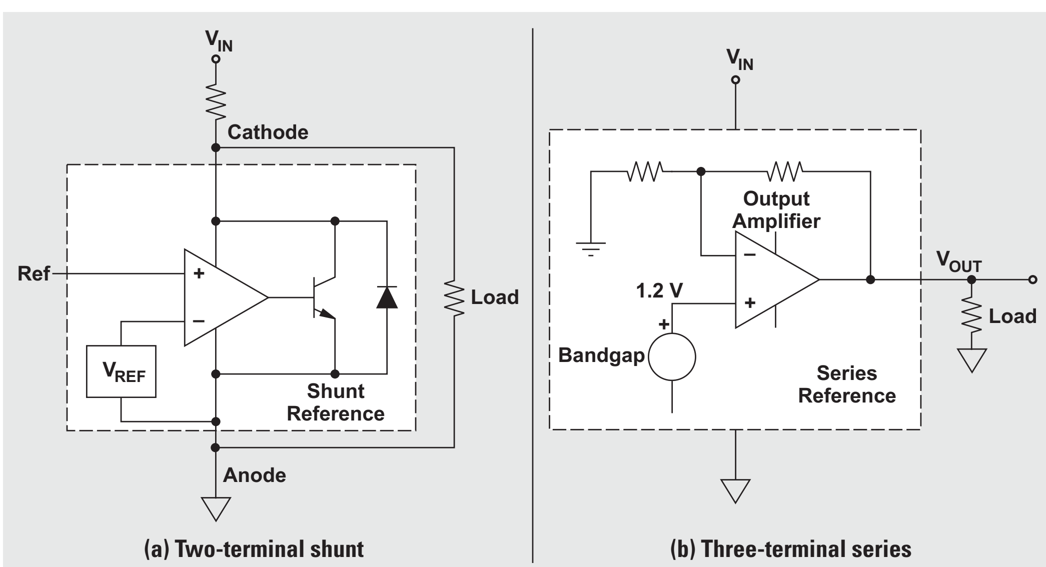


Choosing the correct V_{REF} topology

Voltage references are available in two-terminal shunt or three-terminal series configurations (see Figure 2). Figure 2a shows a two-terminal shunt voltage reference, in which the entire IC chip of the shunt reference operates in parallel to its load. With a shunt voltage reference, an input voltage is applied to the resistor that is connected to the cathode. The typical initial voltage accuracy of this device can be as low as 0.5% or range up to 5%, with a temperature coefficient of approximately 50 to 100 µV/°C. The shunt voltage reference can be used to create positive, negative, or floating reference voltages.

The three-terminal series voltage reference (Figure 2b) operates in series with its load. An internal bandgap voltage, in combination with an internal amplifier, creates the output voltage of this reference. The series voltage reference produces an output voltage between the output and ground while providing the appropriate output current to

Figure 2. Voltage-reference configurations



the external load. As the load current increases or decreases, the series reference maintains the voltage at V_{OUT}.

The typical initial voltage accuracy of a series-reference device can be as low as 0.05% or range up to 0.5%, with temperature coefficients as low as 2.5 ppm/°C. Because of the series reference's superior initial output voltage and overtemperature performance, this type of device would be used to drive the reference pins of precision ADCs. Beyond 8 or 14 resolution bits, where the size of the least significant bit (LSB) is respectively 0.4% and 0.006%, an external series voltage reference ensures that the intended precision of the converter can be achieved.

Another common application for series voltage references is sensor conditioning. In particular, a series voltage reference is useful in bridge-sensor applications as well as applications that have thermocouples, thermopiles, and pH sensors.

The initial accuracy of the series voltage reference in an ADC application (as in Figure 1) provides the general reference for the conversion process. Any initial inaccuracy of the output voltage can be calibrated in hardware or software. Additionally, changes in the accuracy of the voltage-reference output can be a consequence of the temperature coefficient, the line regulation, the load regulation, or long-term drift. The series voltage reference provides better performance in all of these categories.

Figure 3. An ideal, 3-bit ADC transfer function

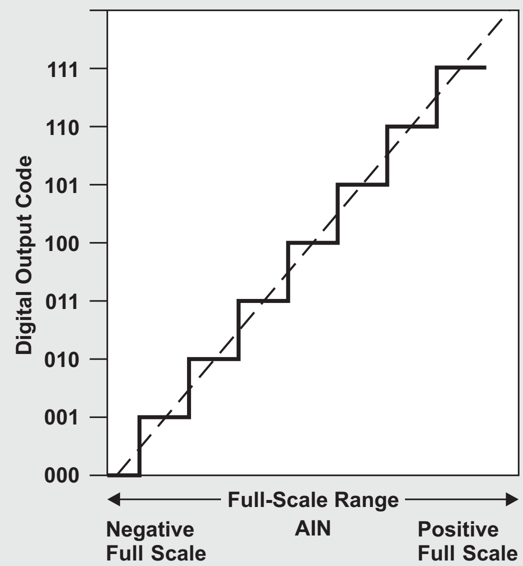
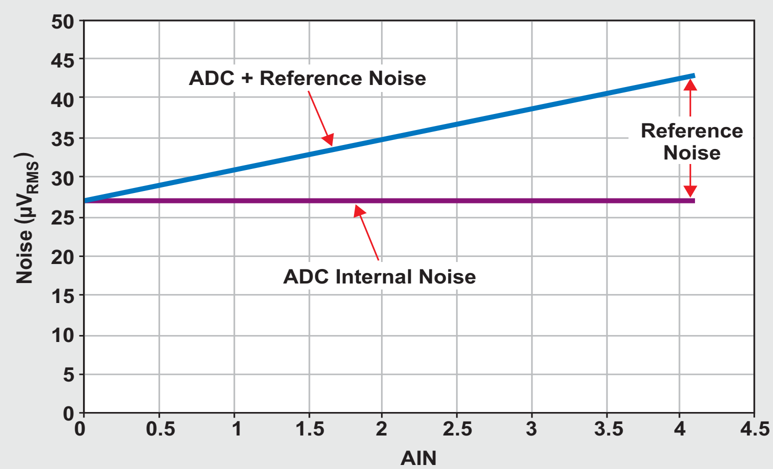


Figure 4. Total noise at ADC output as a function of ADC input voltage



Understanding reference-voltage noise

From Part 1 of this series it can be concluded that the ADC has only one function. That function is to compare an input voltage to a reference voltage, or to create an output code based on an input signal and reference voltage. Part 1 presented diagrams and formulas that describe the basic transfer function of the ADC along with the device's noise characteristics. The typical transfer function of an ideal ADC, shown here in Figure 3, was described as

$$\text{Code} = V_{IN} \times \frac{2^n}{V_{REF}}, \qquad \textbf{(1)}$$

where "Code" is the ADC output code in decimal form, V_{IN} is the analog input voltage to the ADC, n is the number of ADC output bits, and V_{REF} is the analog value of the reference voltage to the ADC. This formula shows that any initial error or noise in the reference voltage translates to a gain error in the code output of the ADC.

If several points from the ADC's negative full-scale input to its positive full-scale input are measured, it becomes clear that the contribution of the reference noise is a function of the ADC input voltage. To evaluate the voltage-reference noise as well as the overall noise, it is necessary to measure the noise close to both the negative full scale and the positive full scale. Figure 4 shows the results of measuring the reference noise and the ADC noise in a system. These results show that the overall noise is not constant but linearly dependent on the ADC's analog input voltage. When this type of system is designed, it is important to keep the reference noise lower than the ADC's internal noise.

Both reference topologies in Figure 2 generate comparable noise over frequency. The voltage noise in series voltage references comes mainly from the bandgap and the output amplifier. Both of these elements generate noise in the 1/f region and the broadband region (see Figure 5).

Noise in the voltage reference's 1/f region

In the data sheets of most series-reference devices, the specification for output-voltage noise is over the frequency range of 0.1 to 10 Hz, which encompasses the 1/f region in Figure 5. Noise in the 1/f region, often called "pink noise," is replaced in the higher frequency domain by the broadband noise.

Noise in the voltage reference's broadband region

Some manufacturers include specifications for the voltage reference's output noise density. This type of specification is usually for noise in the broadband region, such as the noise density at 10 kHz. Broadband noise, which is present over the higher wide-band frequencies, is also known as "white noise" or "thermal noise."

An added low-pass filter with an extremely low corner frequency will reduce the broadband noise at the output of the reference. This filter is designed with a capacitor, the equivalent series resistance (ESR) of the capacitor, and the open-loop output impedance of the reference output amplifier (see Figure 6).

Table 1 shows the noise measured from the Texas Instruments REF5040 for different frequency bandwidths as well as for different external-capacitor values and types. These measurements demonstrate that ceramic capacitors with a low ESR of about 0.1 Ω have a tendency to increase noise compared to tantalum capacitors with a standard ESR of about 1.5 Ω. This tendency is the result of stability problems and the gain peaking of the reference's output amplifier.

As mentioned earlier, the two sources of noise in the reference voltage are the internal output amplifier and the bandgap. The internal schematic of the REF5040 in Figure 7 shows that the TRIM pin provides direct access to the bandgap. An external capacitor can be added to the TRIM pin to create a low-pass filter. This filter provides a

Figure 5. Example voltage-noise regions in the frequency domain

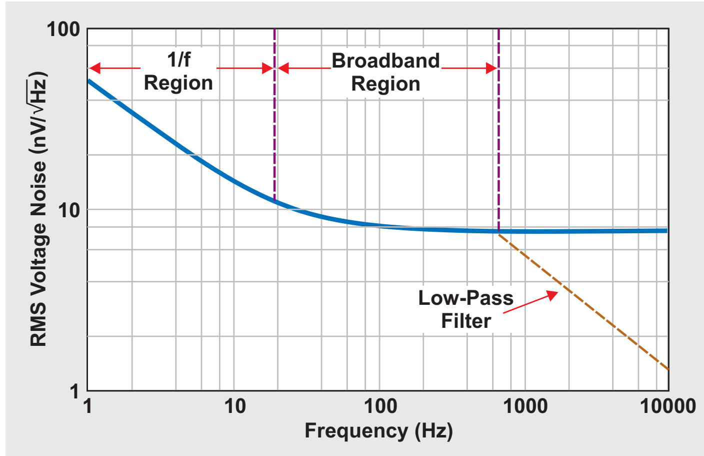


Figure 6. Low-pass filter between series voltage reference and ADC

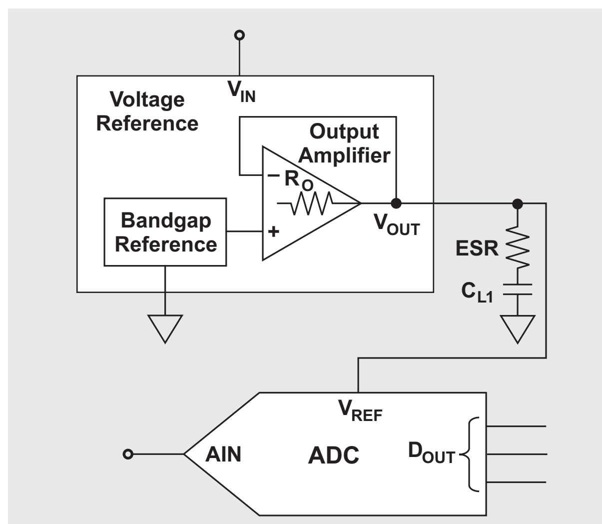


Figure 7. Using TRIM pin to filter REF5040 bandgap noise

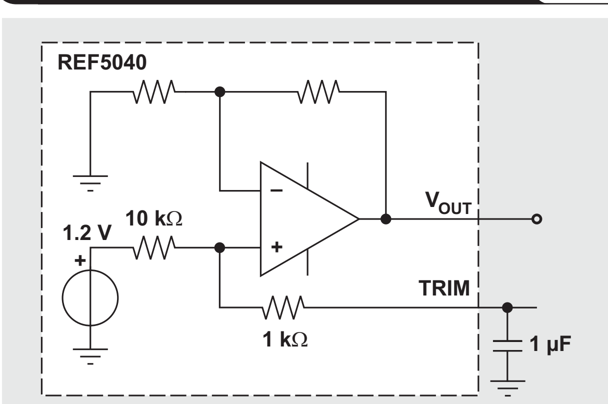


Table 1. Noise measured from REF5040 for different bandwidths and capacitor values and types

CAPACITOR	MEASURED NOISE (μV_{RMS}) FOR FOUR BANDWIDTHS			
	22 kHz (Low-Pass 5-Pole)	30 kHz (Low-Pass 3-Pole)	80 kHz (Low-Pass 3-Pole)	>500 kHz
GND	0.8	1	1.8	4.9
1 µF (tantalum)	37.8	41.7	53.7	9017
2.2 µF (ceramic)	41.7	46.2	55.1	60.8
10 µF (tantalum)	33.4	33.4	35.2	38.5
10 µF (ceramic)	37.1	37.2	37.8	39.1
20 µF (ceramic)	33.1	33.1	33.2	34.5
47 µF (tantalum)	23.2	23.8	24.1	26.5

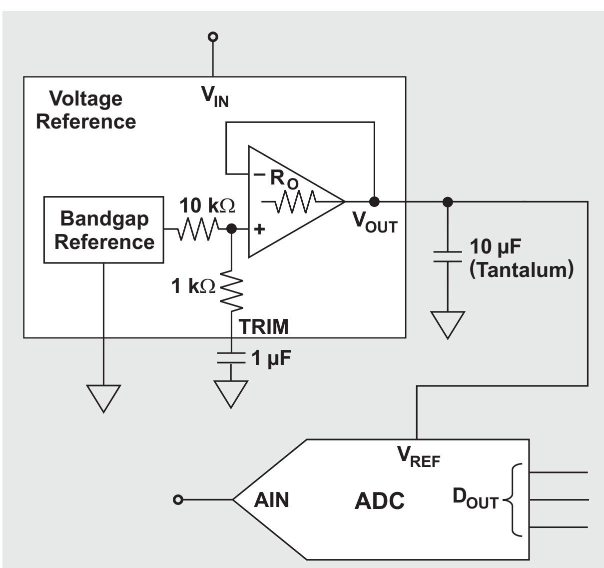
bandgap broadband attenuation of approximately –21 dB. For example, a small 1-µF capacitor adds a pole at 14.5 Hz and a zero at 160 Hz. If more filtering is needed, a larger-value capacitor can be used in place of the 1-µF capacitor. For instance, a 10-µF capacitor will generate a 3-dB corner frequency of 1.45 Hz. This low-pass filter will lower the bandgap noise. Attaching a 1-µF capacitor to the TRIM pin of the REF5040 will lower the total output RMS noise by a factor of 2.5.

Conclusion

Figure 8 shows a complete circuit diagram for a reference system configured with an 8- to 14-bit converter. The accuracy of the voltage reference in this system is important; however, any initial inaccuracy can be calibrated with hardware or software. On the other hand, eliminating or reducing reference noise will require a degree of characterization and hardware-filtering techniques. Part 3 of this article series will explore the proper filtering for the broadband region.

Part 3 will also investigate and explain how to design a reference circuit that is appropriate for converters with 16+ bits. The impact of the voltage-reference buffer and its following amplifier/resistor/capacitor network will be analyzed. With the measurements that follow the final system tuning, the assumptions and conclusions of this article series will be compared to the real world.

Figure 8. Voltage-reference circuit for 8- to 14-bit converters



References

For more information related to this article, you can download an Acrobat® Reader® file at www-s.ti.com/sc/techlit/*litnumber* and replace "*litnumber*" with the **TI Lit. #** for the materials listed below.

Document Title	TI Lit. #
1. Bonnie Baker and Miro Oljaca, "How the Voltage Reference Affects ADC Performance, Part 1," *Analog Applications Journal* (2Q 2009)	slyt331
2. Bonnie Baker, "A Glossary of Analog-to-Digital Specifications and Performance Characteristics," Application Report	sbaa147
3. Tim Green. Operational amplifier stability, Parts 3, 6, and 7. *EN-Genius Network: analogZONE: acquisitionZONE* [Online]. Available: http://www.analogzone.com/acqt*0000*.pdf (Replace "*0000*" with "0307" for Part 3, "0704" for Part 6, or "0529" for Part 7.)	—
4. Bonnie C. Baker and Miro Oljaca. (2007, June 7). External components improve SAR-ADC accuracy. *EDN* [Online]. Available: http://www.edn.com/contents/images/6447231.pdf	—
5. Wm. P. (Bill) Klein, Miro Oljaca, and Pete Goad. (2007). Improved voltage reference circuits maximize converter performance. Analog eLab™ Webinar [Online]. Available: http://dataconverter.ti.com (Scroll down to "Videos" under "Analog eLab™ Design Support" and select webinar title.)	—
6. Art Kay. Analysis and measurement of intrinsic noise in op amp circuits, Part I. *EN-Genius Network: analogZONE: audiovideoZONE* [Online]. Available: http://www.en-genius.net/includes/files/avt_090406.pdf	—

Related Web sites

dataconverter.ti.com
www.ti.com/sc/device/REF5040

Following are URLs where you can obtain information on other Texas Instruments products and application solutions:

Products		**Applications**	
Amplifiers	amplifier.ti.com	Audio	www.ti.com/audio
Data Converters	dataconverter.ti.com	Automotive	www.ti.com/automotive
DLP® Products	www.dlp.com	Broadband	www.ti.com/broadband
DSP	dsp.ti.com	Digital Control	www.ti.com/digitalcontrol
Clocks and Timers	www.ti.com/clocks	Medical	www.ti.com/medical
Interface	interface.ti.com	Military	www.ti.com/military
Logic	logic.ti.com	Optical Networking	www.ti.com/opticalnetwork
Power Mgmt	power.ti.com	Security	www.ti.com/security
Microcontrollers	microcontroller.ti.com	Telephony	www.ti.com/telephony
RFID	www.ti-rfid.com	Video & Imaging	www.ti.com/video
RF/IF and ZigBee® Solutions	www.ti.com/lprf	Wireless	www.ti.com/wireless

Mailing Address: Texas Instruments
Post Office Box 655303
Dallas, Texas 75265

TI Worldwide Technical Support

Internet

TI Semiconductor Product Information Center Home Page
support.ti.com

TI Semiconductor KnowledgeBase Home Page
support.ti.com/sc/knowledgebase

Product Information Centers

Americas	Phone	+1(972) 644-5580
Brazil	Phone	0800-891-2616
Mexico	Phone	0800-670-7544
	Fax	+1(972) 927-6377
	Internet/Email	support.ti.com/sc/pic/americas.htm

Europe, Middle East, and Africa

Phone

European Free Call	00800-ASK-TEXAS (00800 275 83927)
International	+49 (0) 8161 80 2121
Russian Support	+7 (4) 95 98 10 701

Note: The European Free Call (Toll Free) number is not active in all countries. If you have technical difficulty calling the free call number, please use the international number above.

Fax	+(49) (0) 8161 80 2045
Internet	support.ti.com/sc/pic/euro.htm

Japan

Fax	International	+81-3-3344-5317
	Domestic	0120-81-0036
Internet/Email	International	support.ti.com/sc/pic/japan.htm
	Domestic	www.tij.co.jp/pic

Asia

Phone

International	+91-80-41381665
Domestic	Toll-Free Number
Australia	1-800-999-084
China	800-820-8682
Hong Kong	800-96-5941
India	1-800-425-7888
Indonesia	001-803-8861-1006
Korea	080-551-2804
Malaysia	1-800-80-3973
New Zealand	0800-446-934
Philippines	1-800-765-7404
Singapore	800-886-1028
Taiwan	0800-006800
Thailand	001-800-886-0010

Fax	+886-2-2378-6808
Email	tiasia@ti.com or ti-china@ti.com
Internet	support.ti.com/sc/pic/asia.htm