How the voltage reference affects ADC performance, Part 3

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

This article is Part 3 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). Part 1 (see Reference 1) examined the ADC characteristics and specifications, with a particular interest in the gain error and signal-to-noise ratio, while assessing how the voltage reference impacts the ADC transfer function and DC accuracy. Part 2 (see Reference 2) examined the voltage-reference characteristics, focusing on how the voltage-reference noise produces the most error at the converter’s full-scale range. Part 2 concluded by presenting a design for a voltage-reference circuit that is appropriate for 8- to 14-bit converters. This article, Part 3, tackles the challenge of designing a voltage-reference circuit that is appropriate for converters with 16+ bits. Part 3 examines methods of improving noise filtering and of compensating for losses caused by the improved filters.

Basics of reducing voltage-reference noise

As discussed in Part 2, the two sources of noise in the reference voltage are the internal output amplifier and the bandgap. The voltage-reference circuit from Part 2 that was configured with an 8- to 14-bit ADC can be used as a starting point to continue the discussion. The size of the least significant bit (LSB) of any converter in a 5-V system is equal to 5 V/2^N, where N is the number of converter bits. The 8-bit LSB size in this environment is 19.5 mV, and the 14-bit LSB size is 305 µV. The target value for voltage-reference noise should be less than these LSB values. The bandgap noise of the circuit from Part 2 was reduced by adding an external capacitor to the output to create a low-pass filter. This circuit’s output noise can be further reduced by adding another capacitor as a passive low-pass filter. Figure 1 shows an example of such a design, which uses a voltage reference from the Texas Instruments (TI) REF50xx family. In this design, the 1-µF capacitor (C_1) provides a minimal 21-dB noise reduction at the internal bandgap reference. C_2, in combination with the open-loop output resistance (R_0) of the voltage reference’s internal amplifier (see Reference 4), further reduces the output noise of the reference at the V_{REF_OUT} pin. In this case, the equivalent series resistance (ESR) of the 10-µF ceramic capacitor (C_2) is equal to 200 mΩ.

---

Figure 1. Voltage-reference design appropriate for 8- to 14-bit converter

- Vin
- Voltage Reference REF50xx
- Op Amp
- 10 kΩ
- 1 kΩ
- TRIM
- C_1 1 µF (Ceramic)
- VREF_OUT
- Bandgap Reference
- AIN
- ADC
- VREF_IN
- 10 µF
- D_OUT
Figure 2 shows a fast-Fourier-transform (FFT) plot of the output signal of the circuit in Figure 1. Note that the output-noise level peaks at around 9 kHz because of the response of the circuit’s internal amplifier to the capacitive load ($C_2$). This peaking is the main contributor to the overall measured noise. This output noise, measured with an analog meter over a frequency range of up to 80 kHz, is approximately 16.5 µV$_{\text{RMS}}$. If the voltage-reference circuit was connected to the input of an ADC, the measured noise across a 65-kHz frequency range would be 138 µV$_{\text{PP}}$. This noise level makes the solution in Figure 1 adequate for 8- to 14-bit converters.

**Reducing voltage-reference noise for an ADC with 16+ bits**

Since the voltage-reference circuit in Figure 1 would introduce too much noise into a converter with 16+ bits, another low-pass filter can be added to further reduce the reference’s output noise. This filter consists of a 10-kΩ resistor ($R_1$) and an additional capacitor ($C_3$) as shown in Figure 3. The corner frequency of this added RC filter, 1.59 Hz, will reduce broadband noise as well as noise at extremely low frequencies.
Figure 4 shows that the addition of $R_1$ and $C_3$ has a significant effect on the output noise for this system. The 9-kHz noise peak is gone. With this signal response, the output noise of the reference circuit in Figure 3 becomes $2.2 \mu V_{\text{RMS}}$ or $15 \mu V_{\text{PP}}$, a reduction of nearly 90%. This improvement brings the noise level so well under control that the voltage-reference circuit is now appropriate for ADC resolutions of up to 20 bits.

This is encouraging; however, pulling current through $R_1$ from the ADC reference pin will corrupt the conversion by introducing a voltage drop equivalent to the average charge level from the reference pin of the ADC. Consequently, the output of this new circuit will not be able to adequately drive the ADC’s voltage-reference input. To accomplish this, a buffer will need to be added to the low-pass filters.

**Adding a buffer to the voltage-reference circuit**

Figure 5 shows an example of the fluctuations in ADC reference drive current that can occur during a conversion. The signal was captured with a low-capacitance probe to show the voltage drop across the 10-kΩ resistor ($R_1$) between the input of the ADC voltage-reference pin and $V_{\text{REF.OUT}}$. The top trace in Figure 5 shows the trigger signal that the converter receives to initiate a new conversion. The ADC’s voltage-reference circuit demands different amounts of current (bottom trace) for the initiation of the conversion and for each code decision. Therefore, the voltage-reference analog circuitry connected to the ADC must be able to accommodate these high-frequency fluctuations efficiently while maintaining a strong voltage reference for the converter.
Figure 6 shows a voltage-reference circuit that will adequately drive a high-resolution ADC. In this circuit, the TI OPA350 is placed as a buffer after the low-pass filter that was constructed with $R_1$ and $C_3$ for the circuit in Figure 3. The OPA350 drives a 10-µF filter capacitor ($C_4$) and the voltage-reference input pin of the ADC. The noise measured at the output of the OPA350 in Figure 6 is 4.5 µV\(_{\text{RMS}}\) or 42 µV\(_{\text{p-p}}\). The input bias current of the OPA350 is 10 pA at 25°C. This current, in combination with the current through $R_1$, generates a 100-nV, constant-DC drop. Note that this voltage drop does not change with the ADC’s bit decisions. It is true that the input bias current of the OPA350 changes over temperature, but a maximum current that is no more than 10 nA at 125°C can be expected. This value generates a change of 100 µV over a temperature range of 100°C.

It is useful to put the voltage drop across $R_1$ into perspective. This voltage drop is added to the errors contributed by the REF50xx and the OPA350. The initial error of the REF50xx output is ±0.05%, with an error over temperature of 3 ppm/°C. With a 4.096-V reference (REF5040), the initial reference error is equal to 2.05 mV at room temperature and an additional 1.23 mV at 125°C. Therefore, the reference output error is significantly larger than the errors produced by $R_1$ and variations in the OPA350’s offset and input bias current.

**Amplifier stability**

There is a final word of caution about the circuit in Figure 6. The stability of the OPA350 can be compromised if $C_4$ and the OPA350’s open-loop output resistance ($R_{O_{\text{OPA350}}}$) modify the open-loop voltage-gain ($A_{OL}$) curve to create a marginally stable state. To illustrate this phenomenon, Figure 7 shows how the output capacitor ($C_4$), with a 0.2-Ω ESR and the OPA350’s open-loop output resistance (43 Ω), modifies the OPA350’s $A_{OL}$ curve. These curves can be used to quickly determine the stability of the circuit. A circuit with good stability would basically be one where the rate of closure of the operational amplifier’s modified $A_{OL}$ curve and closed-loop voltage-gain ($A_{CL}$) curve is

---

**Figure 6. Voltage-reference circuit with added buffer and output filter**

- Voltage Reference
  - Bandgap Reference
  - Op Amp
    - $R_0 = 10 \, \Omega$
    - $C_1 = 1 \, \mu F$
  - TRIM
  - $V_{REF\text{OUT}}$

- OPA350
  - $R_1 = 10 \, k\Omega$
  - $C_2 = 10 \, \mu F$
  - $C_3 = 10 \, \mu F$
  - $C_4 = 10 \, \mu F$

- AIN
  - $V_{\text{REF\text{IN}}}$

- ADC
  - $D_{\text{OUT}}$

**Figure 7. Frequency response of buffer with an RC load**

- Open-Loop Gain ($A_{OL}$)
  - Modified $A_{OL}$
  - Closed-Loop Gain ($A_{CL}$)

---
20 dB/decade. This rule of thumb is presented in Reference 4. The open-loop output resistance of the OPA350 is $43 \Omega$, and the ESR of $C_4$ ($R_{ESR_{C4}}$) is $200 \text{ m}\Omega$. The frequency locations of the pole and zero that are created by these values are

$$f_{\text{pole}} = \frac{1}{2\pi \times (R_{O_{-\text{OPA350}}} + R_{\text{ESR_{C4}}} \times C_4)} = 368 \text{ Hz}$$

$$f_{\text{zero}} = \frac{1}{2\pi \times R_{\text{ESR_{C4}}} \times C_4} = 79.6 \text{ kHz}.$$  

Per Figure 7, the circuit in Figure 6 is stable.

**Thinking ahead**

Unfortunately, the voltage-reference designs in this article can degrade ADC performance by adding unwanted temperature drift and initial gain error. Higher-performance systems with 21+ bits may require a voltage-reference design that addresses these issues. Future articles will explore a new approach with auto-zero amplifiers that will compensate for these errors.

**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**  


**Document Title**  


**Related Web sites**

dataconverter.ti.com

www.ti.com/sc/device/OPA350

www.ti.com/sc/device/REF5040
IMPORTANT NOTICE

Texas Instruments Incorporated and its subsidiaries (TI) reserve the right to make corrections, modifications, enhancements, improvements, and other changes to its products and services at any time and to discontinue any product or service without notice. Customers should obtain the latest relevant information before placing orders and should verify that such information is current and complete. All products are sold subject to TI’s terms and conditions of sale supplied at the time of order acknowledgment.

TI warrants performance of its hardware products to the specifications applicable at the time of sale in accordance with TI’s standard warranty. Testing and other quality control techniques are used to the extent TI deems necessary to support this warranty. Except where mandated by government requirements, testing of all parameters of each product is not necessarily performed.

TI assumes no liability for applications assistance or customer product design. Customers are responsible for their products and applications using TI components. To minimize the risks associated with customer products and applications, customers should provide adequate design and operating safeguards.

TI does not warrant or represent that any license, either express or implied, is granted under any TI patent right, copyright, mask work right, or other TI intellectual property right relating to any combination, machine, or process in which TI products or services are used. Information published by TI regarding third-party products or services does not constitute a license from TI to use such products or services or a warranty or endorsement thereof. Use of such information may require a license from a third party under the patents or other intellectual property of the third party, or a license from TI under the patents or other intellectual property of TI.

Reproduction of information in TI data books or data sheets is permissible only if reproduction is without alteration and is accompanied by all associated warranties, conditions, limitations, and notices. Reproduction of this information with alteration is an unfair and deceptive business practice. TI is not responsible or liable for such altered documentation. Information of third parties may be subject to additional restrictions.

Resale of TI products or services with statements different from or beyond the parameters stated by TI for that product or service voids all express and any implied warranties for the associated TI product or service and is an unfair and deceptive business practice. TI is not responsible or liable for any such statements.

TI products are not authorized for use in safety-critical applications (such as life support) where a failure of the TI product would reasonably be expected to cause severe personal injury or death, unless officers of the parties have executed an agreement specifically governing such use. Buyers represent that they have all necessary expertise in the safety and regulatory ramifications of their applications, and acknowledge and agree that they are solely responsible for all legal, regulatory and safety-related requirements concerning their products and any use of TI products in such safety-critical applications, notwithstanding any applications-related information or support that may be provided by TI. Further, Buyers must fully indemnify TI and its representatives against any damages arising out of the use of TI products in such safety-critical applications.

TI products are neither designed nor intended for use in military/aerospace applications or environments unless the TI products are specifically designated by TI as military-grade or “enhanced plastic.” Only products designated by TI as military-grade meet military specifications. Buyers acknowledge and agree that any such use of TI products which TI has not designated as military-grade is solely at the Buyer’s risk, and that they are solely responsible for compliance with all legal and regulatory requirements in connection with such use.

TI products are neither designed nor intended for use in automotive applications or environments unless the specific TI products are designated by TI as compliant with ISO/TSG 16949 requirements. Buyers acknowledge and agree that, if they use any non-designated products in automotive applications, TI will not be responsible for any failure to meet such requirements.

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

Products

| Amplifiers | www.amplifier.ti.com |
| Data Converters | www.dataconverter.ti.com |
| DLP® Products | www.dlp.com |
| DSP | www.dsp.ti.com |
| Clocks and Timers | www.ti.com/clock |
| Interface | www.interface.ti.com |
| Logic | www.logic.ti.com |
| Power Mgmt | www.power.ti.com |
| Microcontrollers | www.microcontroller.ti.com |
| RFID | www.ti-rfid.com |
| RF/IF and ZigBee® Solutions | www.ti.com/rf |

Applications

| Audio | www.ti.com/audio |
| Automotive | www.ti.com/automotive |
| Broadband | www.ti.com/broadband |
| Digital Control | www.ti.com/digitalcontrol |
| Medical | www.ti.com/medical |
| Military | www.ti.com/military |
| Optical Networking | www.ti.com/opticalnetwork |
| Security | www.ti.com/security |
| Telephony | www.ti.com/telephony |
| Video & Imaging | www.ti.com/video |
| 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**

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  001-803-8681-1006

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

---

**Safe Harbor Statement:** This publication may contain forward-looking statements that involve a number of risks and uncertainties. These “forward-looking statements” are intended to qualify for the safe harbor from liability established by the Private Securities Litigation Reform Act of 1995. These forward-looking statements generally can be identified by phrases such as TI or its management “believes,” “expects,” “anticipates,” “foresees,” “forecasts,” “estimates” or other words or phrases of similar import. Similarly, such statements herein that describe the company’s products, business strategy, outlook, objectives, plans, intentions or goals also are forward-looking statements. All such forward-looking statements are subject to certain risks and uncertainties that could cause actual results to differ materially from those in forward-looking statements. Please refer to TI’s most recent Form 10-K for more information on the risks and uncertainties that could materially affect future results of operations. We disclaim any intention or obligation to update any forward-looking statements as a result of developments occurring after the date of this publication.

E093008

Analog eLab is a trademark of Texas Instruments. Acrobat and Reader are registered trademarks of Adobe Systems Incorporated. All other trademarks are the property of their respective owners.
IMPORTANT NOTICE

Texas Instruments Incorporated and its subsidiaries (TI) reserve the right to make corrections, modifications, enhancements, improvements, and other changes to its products and services at any time and to discontinue any product or service without notice. Customers should obtain the latest relevant information before placing orders and should verify that such information is current and complete. All products are sold subject to TI’s terms and conditions of sale supplied at the time of order acknowledgment.

TI warrants performance of its hardware products to the specifications applicable at the time of sale in accordance with TI's standard warranty. Testing and other quality control techniques are used to test the extent TI deems necessary to support this warranty. Except where mandated by government requirements, testing of all parameters of each product is not necessarily performed.

TI assumes no liability for applications assistance or customer product design. Customers are responsible for their products and applications using TI components. To minimize the risks associated with customer products and applications, customers should provide adequate design and operating safeguards.

TI does not warrant or represent that any license, either express or implied, is granted under any TI patent right, copyright, mask work right, or other TI intellectual property right relating to any combination, machine, or process in which TI products or services are used. Information published by TI regarding third-party products or services does not constitute a license from TI to use such products or services or a warranty or endorsement thereof. Use of such information may require a license from a third party under the patents or other intellectual property of the third party, or a license from TI under the patents or other intellectual property of TI.

Reproduction of TI information in TI data books or data sheets is permissible only if reproduction is without alteration and is accompanied by all associated warranties, conditions, limitations, and notices. Reproduction of this information with alteration is an unfair and deceptive business practice. TI is not responsible or liable for such altered documentation. Information of third parties may be subject to additional restrictions.

Resale of TI products or services with statements different from or beyond the parameters stated by TI for that product or service voids all express and any implied warranties for the associated TI product or service and is an unfair and deceptive business practice. TI is not responsible or liable for any such statements.

TI products are not authorized for use in safety-critical applications (such as life support) where a failure of the TI product would reasonably be expected to cause severe personal injury or death, unless officers of the parties have executed an agreement specifically governing such use. Buyers represent that they have all necessary expertise in the safety and regulatory ramifications of their applications, and acknowledge and agree that they are solely responsible for all legal, regulatory and safety-related requirements concerning their products and any use of TI products in such safety-critical applications.

TI products are neither designed nor intended for use in military/aerospace applications or environments unless the TI products are specifically designated by TI as military-grade or "enhanced plastic." Only products designated by TI as military-grade meet military specifications. Buyers acknowledge and agree that any such use of TI products which TI has not designated as military-grade is solely at the Buyer's risk, and that they are solely responsible for compliance with all legal and regulatory requirements in connection with such use.

TI products are neither designed nor intended for use in automotive applications or environments unless the specific TI products are designated by TI as compliant with ISO/TS 16949 requirements. Buyers acknowledge and agree that, if they use any non-designated products in automotive applications, TI will not be responsible for any failure to meet such requirements.

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

<table>
<thead>
<tr>
<th>Products</th>
<th>Applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Amplifiers</td>
<td>Audio</td>
</tr>
<tr>
<td>Data Converters</td>
<td>Automotive</td>
</tr>
<tr>
<td>DLP® Products</td>
<td>Broadband</td>
</tr>
<tr>
<td>DSP</td>
<td>Digital Control</td>
</tr>
<tr>
<td>Clocks and Timers</td>
<td>Medical</td>
</tr>
<tr>
<td>Interface</td>
<td>Military</td>
</tr>
<tr>
<td>Logic</td>
<td>Optical Networking</td>
</tr>
<tr>
<td>Power Mgmt</td>
<td>Security</td>
</tr>
<tr>
<td>Microcontrollers</td>
<td>Telephony</td>
</tr>
<tr>
<td>RFID</td>
<td>Video &amp; Imaging</td>
</tr>
<tr>
<td>RF/IF and ZigBee® Solutions</td>
<td>Wireless</td>
</tr>
</tbody>
</table>

Mailing Address: Texas Instruments, Post Office Box 655303, Dallas, Texas 75265
Copyright © 2009, Texas Instruments Incorporated