

# Accurately measuring ADC driving-circuit settling time

By **Rajiv Mantri**, *Strategic Marketing Engineer* (Email: rajivmantri@ti.com),  
and **Bhaskar Goswami**, *Test Development Engineer* (Email: bhaskar@ti.com)

## Introduction

Many modern data acquisition systems consist of high-speed, high-resolution ADCs.<sup>1</sup> CMOS-switched, capacitor-based ADCs are often chosen for such designs due to their low cost and low power dissipation. These ADCs use an unbuffered front end directly coupled to the sampling network. To effectively minimize noise and signal distortion, it is necessary to drive the ADC with a high-speed, low-noise, low-distortion operational amplifier.<sup>2</sup> To achieve minimal distortion it is important for the op amp output to settle to the desired accuracy within the acquisition time of the ADC. Normally the op amp settling time is either calculated from the frequency response specified in the datasheet or measured by probing the output with an oscilloscope that has a limitation on resolution. Sometimes the difference between the op amp input and output is amplified to achieve better accuracy. These methods are limited by the oscilloscope resolution or circuit parasitic. Moreover, the settling time of the op amp is affected by the parasitic capacitance and inductance introduced by the oscilloscope probe. In another method, the difference between output and input is amplified to increase the resolution of the measurement. None of these methods includes the parasitic capacitance and inductance present in the ADC sampling circuit and package.

## Definition of settling time

*Settling time* is the time elapsed from the application of an ideal instantaneous step input to the time at which the closed-loop amplifier output has entered and remained within a specified symmetrical error band. Settling time includes a very brief propagation delay, plus the time required for the output to slew to the vicinity of the final value, recover from the overload condition associated with slewing, and finally settle to within the specified error. For high-resolution ADCs, the specified error band is usually one fourth of one least significant bit (LSB) of the ADC.

## Basic setup

The ADC used here is the Texas Instruments (TI) ADS8411, which is a 16-bit, 2-MSPS successive approximation register (SAR) ADC. The driver op amp is the TI THS4031. Figure 1 shows the evaluation setup.

The instantaneous step input is generated with an analog multiplexer (MUX) (the TI TS5A3159) by switching its two channels. A dc voltage,  $V$ , is applied to channel 2, and channel 1 is connected to ground; so this setup can produce

a step input rising to  $V$  from 0 or falling to 0 from  $V$ . Alternatively, the step input can be generated from any step generator. The step generator should settle much faster than the op amp settling time.

## Explanation

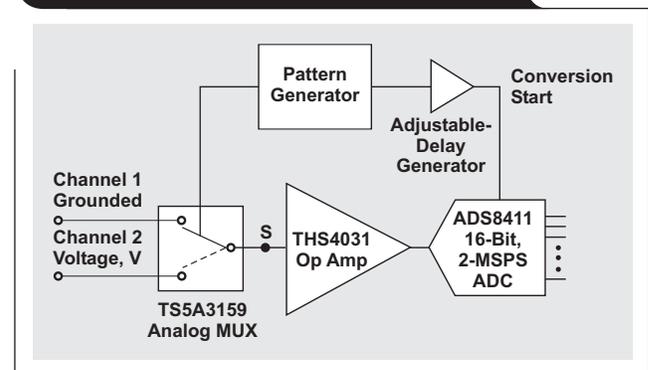
### Step 1

ADC samples channel 1 (connected to ground) first. A long sampling time is provided to make sure that the input capacitor of the ADC is fully discharged.

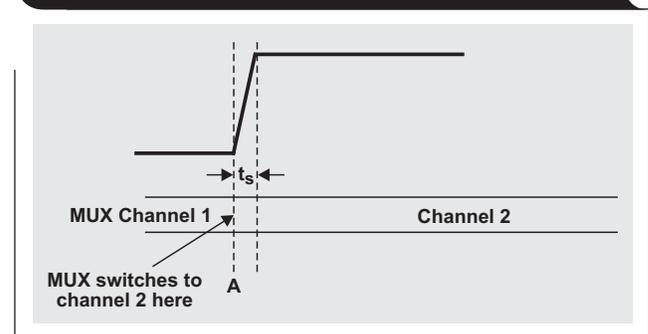
### Step 2

The analog MUX is switched to channel 2 from channel 1 at instant A in Figure 2. This diagram shows the voltage at point S (Figure 1) when the MUX switches over to channel 2 from channel 1. The settling time of the MUX is denoted by  $t_s$ . It is assumed that  $t_s$  is much shorter than the op amp settling time.

**Figure 1. Settling time evaluation setup**



**Figure 2. Settling time for MUX channel change**





**all-electronics.de**  
ENTWICKLUNG. FERTIGUNG. AUTOMATISIERUNG



Entdecken Sie weitere interessante Artikel und News zum Thema auf all-electronics.de!

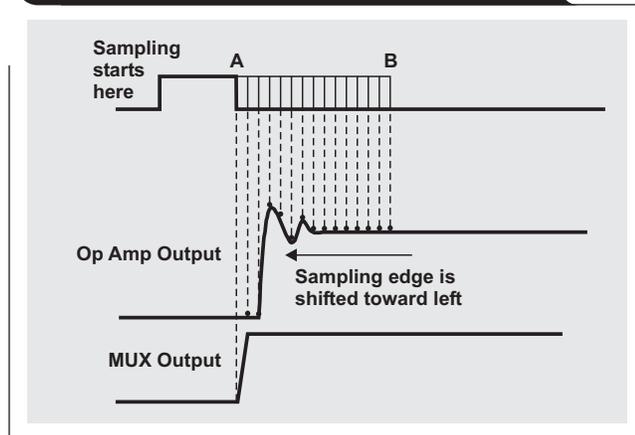
**Hier klicken & informieren!**



### Step 3

Once the analog MUX is switched at instant A, the input of the op amp starts changing. The output of the op amp starts changing after a very brief propagation delay after instant A. The op amp settling time ( $t_{ideal}$ ) is approximately calculated from the slew rate and bandwidth specified in the op amp datasheet. The method proposed here plots the op amp output from instant A to instant B (Figure 3). The time difference between instant B and instant A is  $2t_{ideal}$ .

**Figure 3. Averaging n samples from B to A increases accuracy**



### Step 4

The first ADC sampling edge appears at instant B, and n number of readings (digital outputs from the ADC) are taken. The n number of readings are averaged for better accuracy (discussed later). Next the sampling edge is shifted to the left by 1 ns (Figure 3) with the help of a pattern generator and an adjustable-delay generator (Figure 1), and again n number of readings are taken. This way the sampling edge is shifted toward the left from instant B to instant A in 1-ns steps. At each sampling edge the average is stored in an element of an array. The array is plotted against the time to get the true picture of the op amp output settling (Figure 3).

### Averaging to achieve better resolution

Input of an n-bit ADC should settle to at least n+2 bits, but measured output is an n-bit digital code from the ADC. The resolution can be increased by repeatedly sampling the same input and taking multiple (n) readings from the ADC. Finally an average is taken on the n digital output codes. It can be shown that for each additional bit of resolution, the number of readings should be 4, so w extra bits of resolution require  $4^w$  readings.

For each additional bit, the signal-to-noise ratio (SNR) increases by 6.02 dB. In this case the 16-bit ADC should settle with at least 18-bit accuracy.

$$SNR = 6.02 \times N + 1.76,$$

where N is the ADC resolution. SNR is 110.08 dB for 18-bit accuracy, so an extra bit (w) of resolution required is

$$\frac{110.08 - 86^*}{6.02} = 4.$$

The number of samples (n) needed for each reading is  $4^4 = 256$ .

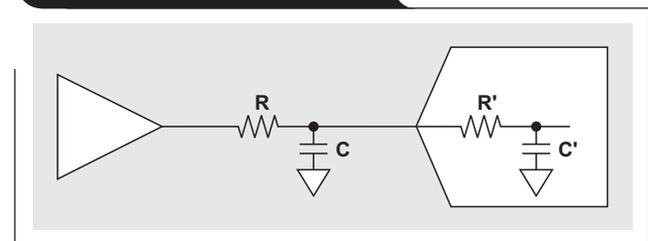
### Results

An RC filter is used at the output of the op amp to filter the external noise. An ADC sampling circuit always consists of another RC ( $R'$ ,  $C'$ ), as shown in Figure 4.

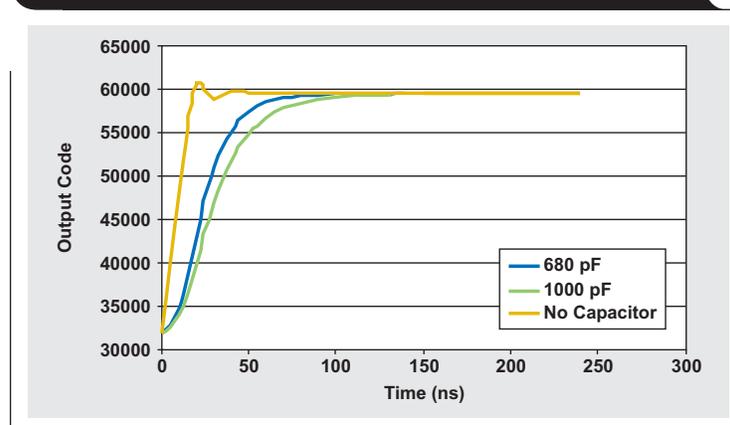
Figure 5 shows the settling behavior when three different values of an external capacitor are used for RC filtering.

\*Typical SNR specification of ADS8411

**Figure 4. Typical noise filter**



**Figure 5. Input settling time with an external capacitor**



**Figure 6. Expanded scale magnifies settling-time behavior shown in Figure 5**

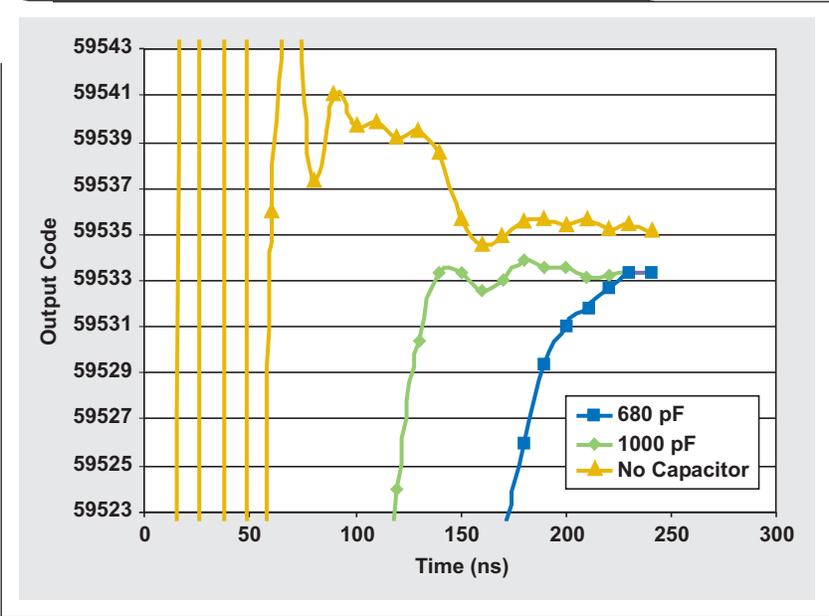


Figure 6 is a zoomed-in version of Figure 5 to show the settling more accurately. While the output code is based on 16-bit sampling, the resolution of the measurement is more than 16-bit because 65536 samples were captured and averaged for each reading. The result shows significant ringing and underdamping of the system when no capacitor was used. Also note that use of a bigger (1000-pF) capacitor significantly increases the settling time.

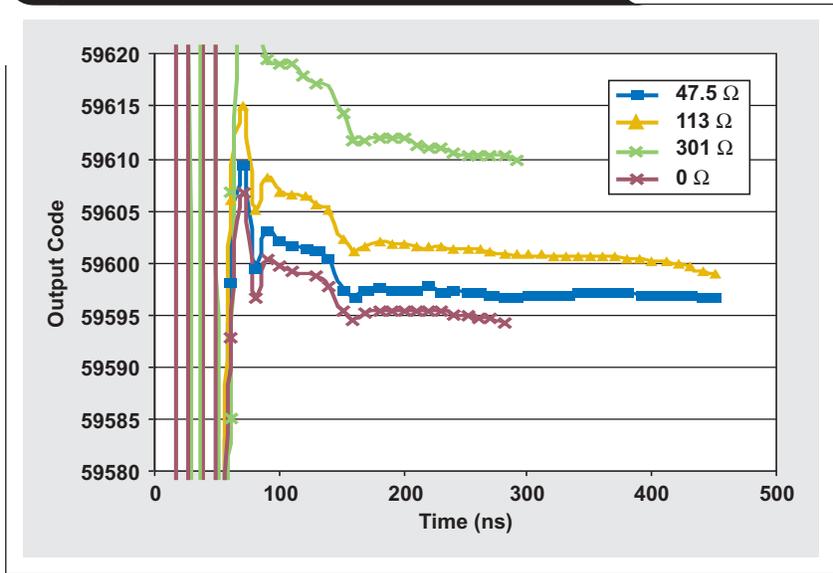
A summary of these results is shown in Table 1. Averaging the output data can improve the resolution of the result beyond 16-bit.

**Table 1. Comparison of edge-shift method versus traditional method**

METHOD		CAPACITOR, C (pF)	ACCURACY* (%)	SETTLING TIME (ns)
Datasheet Specification	10-Bit	No Spec	0.1	45
	13-Bit		0.01	80
Edge-Shift Method (R = 20 Ω)	25	680	0.1	55
			0.01	140
			0.0015	150
	1000	680	0.1	109
			0.01	130
			0.0015	140
	1000	1000	0.1	152
			0.01	195
			0.0015	220

\*16-bit LSB deviation = 0.0015%

**Figure 7. Effects of changing feedback resistors**



**Measurement of bias current**

Figure 7 shows op amp settling behavior with different values of feedback resistors. The difference between the settled voltages indicates the offset voltage shift caused by bias current. From this the bias current can be calculated as 3 μA, which matches the typical specification of the THS4031. This experiment validates the correctness of this setup.

**Bias current calculation**

The settled value with 0 Ω in the feedback is 59595. The settled value with 301 Ω in the feedback is 59610.

Delta (offset voltage) = bias current × resistor  
(used in the feedback).

$$\text{Delta (offset voltage)} = \frac{(59610 - 59595) \times 4.096}{65536} = 938 \mu\text{V}.$$

$$\text{Bias current} = \frac{938}{301} = 3.12 \mu\text{A}$$

(compared to the datasheet typical specification of 3 μA).

**Conclusion**

This is a practical and simple method to accurately measure the settling time of an ADC driving circuit. The settling behavior is unaffected by the measurement, because no

additional component is used for the setup. This method can be implemented as a built-in self-test (BIST) in the future. The averaging of multiple readings improves the accuracy of the result.

**References**

For more information related to this article, you can download an Acrobat Reader file at [www-s.ti.com/sc/techlit/litnumber](http://www-s.ti.com/sc/techlit/litnumber) and replace “litnumber” with the **TI Lit. #** for the materials listed below.

Document Title	TI Lit. #
1. Kevin M. Daugherty, <i>Analog to Digital Conversion: A Practical Approach</i> (McGraw-Hill Companies, 1993).	—
2. Ron Mancini, ed., “Op Amps for Everyone,” Design Reference (Rev B) . . . . .	.slod006

**Related Web sites**

[amplifier.ti.com](http://amplifier.ti.com)  
[www.ti.com/sc/device/partnumber](http://www.ti.com/sc/device/partnumber)  
 Replace *partnumber* with ADS8411, THS4031, or TS5A3159

## 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.

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.

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

### Products

Amplifiers	<a href="http://amplifier.ti.com">amplifier.ti.com</a>
Data Converters	<a href="http://dataconverter.ti.com">dataconverter.ti.com</a>
DSP	<a href="http://dsp.ti.com">dsp.ti.com</a>
Interface	<a href="http://interface.ti.com">interface.ti.com</a>
Logic	<a href="http://logic.ti.com">logic.ti.com</a>
Power Management	<a href="http://power.ti.com">power.ti.com</a>
Microcontrollers	<a href="http://microcontroller.ti.com">microcontroller.ti.com</a>

### Applications

Audio	<a href="http://www.ti.com/audio">www.ti.com/audio</a>
Automotive	<a href="http://www.ti.com/automotive">www.ti.com/automotive</a>
Broadband	<a href="http://www.ti.com/broadband">www.ti.com/broadband</a>
Digital control	<a href="http://www.ti.com/digitalcontrol">www.ti.com/digitalcontrol</a>
Military	<a href="http://www.ti.com/military">www.ti.com/military</a>
Optical Networking	<a href="http://www.ti.com/opticalnetwork">www.ti.com/opticalnetwork</a>
Security	<a href="http://www.ti.com/security">www.ti.com/security</a>
Telephony	<a href="http://www.ti.com/telephony">www.ti.com/telephony</a>
Video & Imaging	<a href="http://www.ti.com/video">www.ti.com/video</a>
Wireless	<a href="http://www.ti.com/wireless">www.ti.com/wireless</a>

## TI Worldwide Technical Support

### Internet

**TI Semiconductor Product Information Center Home Page**  
[support.ti.com](http://support.ti.com)

**TI Semiconductor KnowledgeBase Home Page**  
[support.ti.com/sc/knowledgebase](http://support.ti.com/sc/knowledgebase)

### Product Information Centers

#### Americas

Phone	+1(972) 644-5580	Fax	+1(972) 927-6377
Internet/Email	<a href="http://support.ti.com/sc/pic/americas.htm">support.ti.com/sc/pic/americas.htm</a>		

#### Europe, Middle East, and Africa

Phone			
Belgium (English)	+32 (0) 27 45 54 32	Netherlands (English)	+31 (0) 546 87 95 45
Finland (English)	+358 (0) 9 25173948	Russia	+7 (4) 95 98 10 701
France	+33 (0) 1 30 70 11 64	Spain	+34 902 35 40 28
Germany	+49 (0) 8161 80 33 11	Sweden (English)	+46 (0) 8587 555 22
Israel (English)	180 949 0107	United Kingdom	+44 (0) 1604 66 33 99
Italy	800 79 11 37		
Fax	+(49) (0) 8161 80 2045		
Internet	<a href="http://support.ti.com/sc/pic/euro.htm">support.ti.com/sc/pic/euro.htm</a>		

#### Japan

Fax			
International	+81-3-3344-5317	Domestic	0120-81-0036
Internet/Email			
International	<a href="http://support.ti.com/sc/pic/japan.htm">support.ti.com/sc/pic/japan.htm</a>		
Domestic	<a href="http://www.tij.co.jp/pic">www.tij.co.jp/pic</a>		

#### Asia

Phone			
International	+886-2-23786800		
Domestic	Toll-Free Number		
Australia	1-800-999-084	Malaysia	1-800-80-3973
China	800-820-8682	New Zealand	0800-446-934
Hong Kong	800-96-5941	Philippines	1-800-765-7404
India	+91-80-41381665 (Toll)	Singapore	800-886-1028
Indonesia	001-803-8861-1006	Taiwan	0800-006800
Korea	080-551-2804	Thailand	001-800-886-0010
Fax	+886-2-2378-6808	Email	<a href="mailto:tiasia@ti.com">tiasia@ti.com</a>
Internet	<a href="http://support.ti.com/sc/pic/asia.htm">support.ti.com/sc/pic/asia.htm</a>		
			<a href="mailto:ti-china@ti.com">ti-china@ti.com</a>

### C010307

**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.

**Trademarks:** All trademarks are the property of their respective owners.

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

© 2007 Texas Instruments Incorporated