

# Using fully differential op amps as attenuators, Part 1: Differential bipolar input signals

By Jim Karki

Member, Technical Staff, High-Performance Analog

## Introduction

Conditioning high-voltage input signals to drive ADCs from high-voltage sources can be challenging. How can a higher-voltage signal like  $\pm 10$  V be attenuated and level-shifted to match the significantly lower differential and common-mode-voltage input required by the ADC? In this article, Part 1 of a three-part series, we consider a balanced, differential bipolar input signal and propose an architecture utilizing a fully differential operational amplifier (FDA) to accomplish the task.

We consider this type of circuit first because it most clearly shows how to approach the design, keep a balanced circuit, and not introduce unwanted offsets. Parts 2 and 3 will appear in future issues of the *Analog Applications Journal*. Part 2 will show how to adapt the circuit to a single-ended bipolar input. Part 3 will show the more generic case of a single-ended unipolar input with arbitrary common-mode voltage. The level of complexity will increase with each step, but ordering the presentation in this manner should help the reader better understand why values are chosen for the final circuit the way they are.

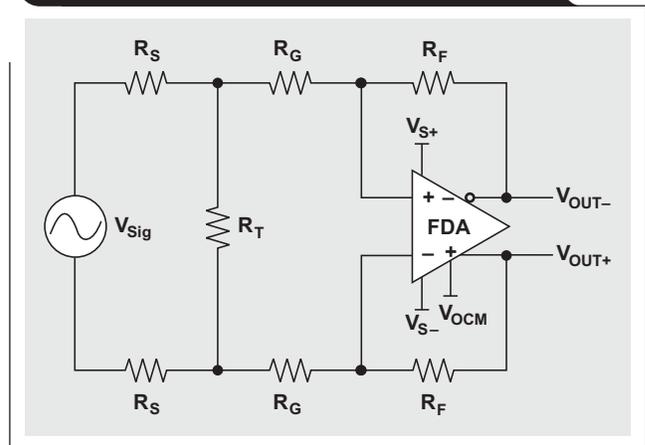
## Differential bipolar input

The fundamentals of FDA operation are presented in Reference 1. Since the principles and terminology presented there will be used throughout this article, please see Reference 1 for definitions and derivations.

FDA's can easily be used to attenuate large signals, convert single-ended signals to differential signals, and level-shift voltages to match the input requirements of lower-voltage ADCs. The trick is to implement them in a way that will perform these tasks while keeping the amplifier stable.

FDA's have been compared to two standard, inverting, single-ended output op amps configured in a differential architecture. While this has some validity, one important difference is that a unity-gain, stable op amp is compensated for a noise gain\* of 1, while a unity-gain, stable FDA is typically compensated for a noise gain of 2. The implication of this in the context of implementing an attenuator

**Figure 1. Attenuator circuit for differential bipolar input**



circuit is that the gain resistors can no longer be chosen simply to provide the attenuation. Two approaches are identified in this article; one implements an input attenuator with resistor values chosen to provide a noise gain of 2, and the other implements the attenuator using the gain-setting resistors with added components to get a noise gain of 2.

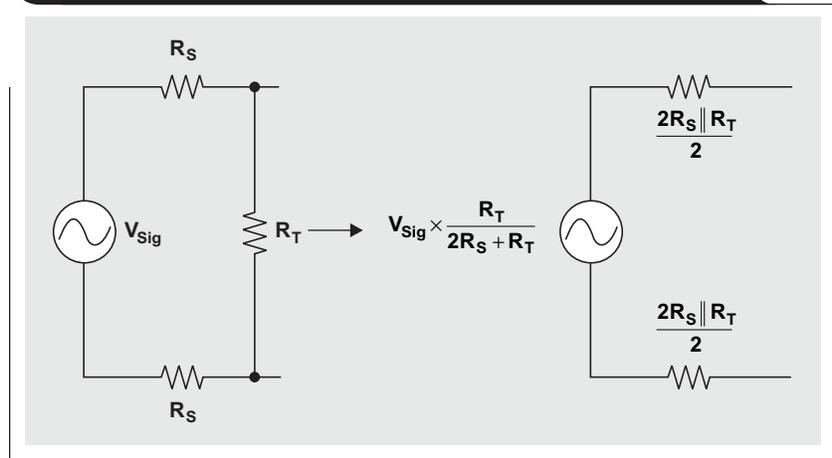
### Using an input attenuator

The proposed input-attenuator circuit for a balanced, differential bipolar input signal is shown in Figure 1, whose parameters are defined as follows:

- $V_{S+}$  and  $V_{S-}$  are the power supplies to the amplifier.
- $V_{Sig}$  is the input-signal source.
- $R_S$  and  $R_T$  are the resistors that provide attenuation of the signal from the source. Their parallel combination also affects the noise gain of the amplifier.
- $R_G$  and  $R_F$  are the main gain-setting resistors for the amplifier.

\*Noise gain is used to define the stability criteria of an op amp and is calculated as the gain from the input terminal of the op amp to the output. Generally, one speaks of op amp stability in terms of the minimum noise gain required, where larger values are fine, but lower values may lead to instability or oscillation.

Figure 2. Thevenin-equivalent input source and attenuator



For analysis, it is convenient to assume that the FDA is an ideal amplifier with no offset and has infinite gain. The first step in analyzing the circuit in Figure 1 is to simplify it by using only its attenuator portion and the Thevenin equivalent of the input source. This is shown in Figure 2. With the circuit in this form, it is easier to see that its overall gain can be calculated by the formula

$$\frac{V_{OUT\pm}}{V_{Sig}} = \frac{R_T}{2R_S + R_T} \times \frac{R_F}{R_G + \frac{2R_S \parallel R_T}{2}} \quad (1)$$

The noise gain of the FDA can be set to 2 by making the second half of Equation 1 equal to 1:

$$R_G + \frac{2R_S \parallel R_T}{2} = R_F \quad (2)$$

With this constraint, the overall gain equation reduces to

$$\frac{V_{OUT\pm}}{V_{Sig}} = \frac{R_T}{2R_S + R_T} \quad (3)$$

There are two degrees of freedom for choosing components in the gain equation—an infinite number of combinations of  $R_S$  and  $R_T$  that will give the desired input attenuation, and an infinite number of  $R_F$  and  $R_G$  values to set the gain.

The differential input impedance of this amplifier circuit is given by  $Z_{IN} = 2R_S + R_T \parallel 2R_G$ . Depending on the attenuation needed, the input impedance is approximately  $2R_S$ .

It is recommended that  $R_F$  be kept to a range of values for the best performance. Too large a resistance will add excessive noise and will possibly interact with parasitic board capacitance to reduce the bandwidth of the amplifier; and too low a resistance will load the output, causing increased distortion. Design is best accomplished by first choosing  $R_S$  close to the desired input impedance, then choosing  $R_F$  within the recommended range for the device. For example, the THS4521 performs best with  $R_F$  at about 1 k $\Omega$ . Next, the value of  $R_T$  required to give the desired attenuation is calculated. Then  $R_G$  is calculated for the

desired gain. These equations are easily solved when set up in a spreadsheet. To see an example Excel® worksheet, click on the Attachments tab or icon on the left side of the Acrobat® Reader® window. Open the file FDA\_Attenuator\_Examples\_Diff\_Bipolar\_Input.xls, then select the Diff Bipolar FDA Input Atten worksheet tab.

#### Design Example 1

As a design example, let's say we have a 20- $V_{PP}$  differential bipolar ( $\pm 10$ -V) signal, and we need a 2-k $\Omega$  differential input impedance. We want to use the ADS8321 SAR ADC with a 5- $V_{PP}$  differential input and a 2.5-V common-mode voltage. We choose  $R_S = 1$  k $\Omega$  and  $R_F = 1$  k $\Omega$ . Rearranging Equation 3 and using substitution, we can calculate

$$R_T = \frac{2R_S}{\frac{V_{Sig}}{V_{OUT\pm}} - 1} = \frac{2 \text{ k}\Omega}{4 - 1} = 666.7 \Omega.$$

The nearest standard 1% value, 665  $\Omega$ , should be used. Then, rearranging Equation 2 and using substitution, we can calculate

$$R_G = R_F - \frac{2R_S \parallel R_T}{2} = 1 \text{ k}\Omega - \frac{2 \text{ k}\Omega \parallel 665 \Omega}{2} = 750 \Omega,$$

which is a standard 1% value. These values will provide the needed attenuation function and will keep the FDA stable. The  $V_{OCM}$  input on the FDA is then used to set the output common-mode voltage to 2.5 V.

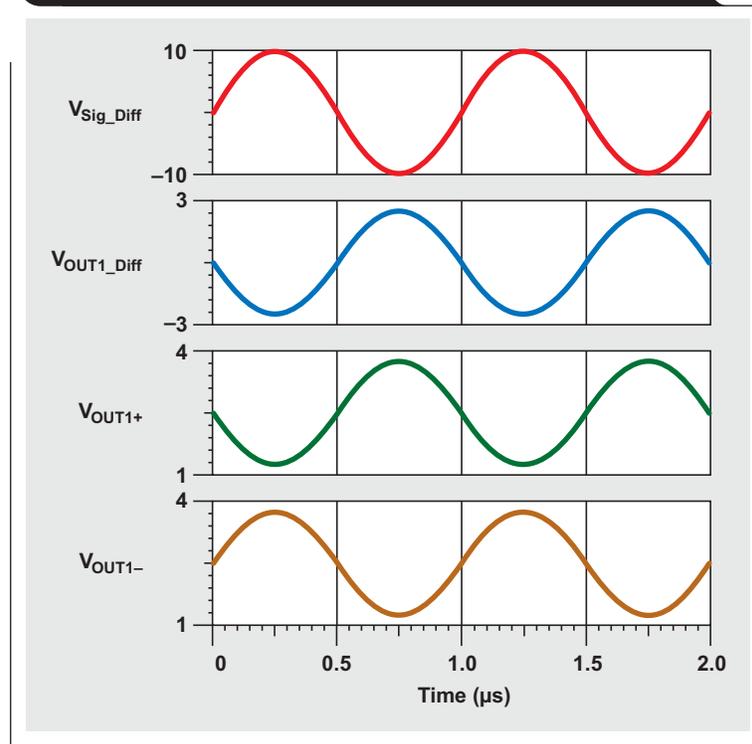
The input impedance is

$$Z_{IN} = 2R_S + R_T \parallel 2R_G = 2 \text{ k}\Omega + 665 \Omega \parallel 1.5 \text{ k}\Omega = 2461 \Omega,$$

which is higher than desired. If the input impedance really needs to be closer to 2 k $\Omega$ , we can iterate with a lower value. In this case, using  $R_S = 806 \Omega$  and  $R_F = 1$  k $\Omega$  will yield  $Z_{IN} = 2014 \Omega$ , which comes as close as is possible when standard 1% values are used.

SPICE simulation is a great way to validate the design. To see a TINA-TI™ simulation of the circuit in Example 1,

**Figure 3. TINA-TI simulation waveforms of differential bipolar input in Example 1**



click on the Attachments tab or icon on the left side of the Acrobat Reader window. If you have the TINA-TI software installed, you can open the file FDA\_Attenuator\_Examples\_Diff\_Bipolar\_Input.TSC to view the example (the top circuit labeled “Example 1”). To download and install the free TINA-TI software, visit [www.ti.com/tina-ti](http://www.ti.com/tina-ti) and click the Download button.

The simulation waveforms in Figure 3 show that the circuit simulates as expected.  $V_{Sig1\_Diff}$  is the 20-V<sub>PP</sub> input;  $V_{OUT1\_Diff}$  is the differential output of the amplifier circuit; and  $V_{OUT1+}$  and  $V_{OUT1-}$  are the individual outputs of the amplifier.

#### Using an FDA's $R_F$ and $R_G$ as an attenuator

The proposed circuit using gain-setting resistors to obtain a balanced, differential bipolar input signal is shown in Figure 4. In this circuit, the FDA is used as an attenuator in a manner similar to using an inverting op amp. The gain (or attenuation) is set by  $R_F$  and  $R_G$ :

$$\frac{V_{OUT\pm}}{V_{Sig}} = \frac{R_F}{R_G}$$

$R_T$  is used to set the noise gain to 2 for stability:

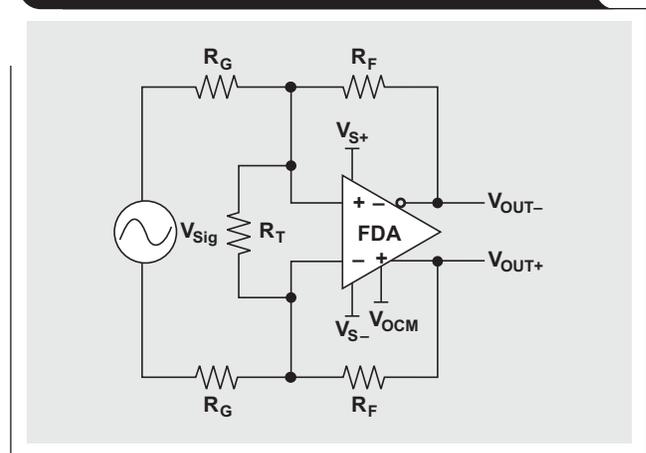
$$R_F = R_G \parallel \frac{R_T}{2}$$

The equation for input impedance is  $Z_{IN} = 2R_G$ .

#### Design Example 2

Using the same approach as for Example 1, with  $R_F = 1 \text{ k}\Omega$ , we calculate  $R_G = 4 \text{ k}\Omega$  (the nearest standard 1% value is 4.02 k $\Omega$ ) and  $R_T = 2.67 \text{ k}\Omega$  (a standard 1% value). This makes  $Z_{IN} = 8.04 \text{ k}\Omega$ . The simulation results are the same as before, but with this approach the only freedom of choice given the design requirements is the value of  $R_F$ .

**Figure 4. Using FDA's  $R_F$  and  $R_G$  as attenuator for differential bipolar input**



To see an example Excel worksheet, click on the Attachments tab or icon on the left side of the Acrobat Reader window. Open the file `FDA_Attenuator_Examples_Diff_Bipolar_Input.xls`, then select the Diff Bipolar FDA Rf\_Rg Atten worksheet tab. To see a TINA-TI simulation of the circuit in Example 2, click on the Attachments tab or icon on the left side of the Acrobat Reader window. If you have the TINA-TI software installed, you can open the file `FDA_Attenuator_Examples_Diff_Bipolar_Input.TSC` to view the example (the bottom circuit labeled “Example 2”). Note that this circuit provides the same results as for the circuit in Example 1. To download and install the free TINA-TI software, visit [www.ti.com/tina-ti](http://www.ti.com/tina-ti) and click the Download button.

## Conclusion

We have analyzed two approaches to using an FDA to attenuate and level-shift high-amplitude, differential bipolar signals to the input range of lower-voltage input ADCs. The first approach uses an input attenuator with values chosen to provide the required attenuation and to keep the noise gain of the FDA equal to 2 for stability. The second approach uses the gain-setting resistors of the FDA in much the same way as using an inverting op amp, then a resistor is bootstrapped across the inputs to provide a noise gain of 2. The two approaches yield the same voltage translation that is needed to accomplish the interface task. Other performance metrics were not analyzed here, but the two approaches have substantially the same noise, bandwidth, and other AC and DC performance characteristics as long as the value of  $R_F$  is the same.

The input-attenuator approach shown in Example 1 is more complex but allows the input impedance to be adjusted independently of the gain-setting resistors used around the FDA. At least to a certain degree, lower values can easily be achieved if desired, but there is a maximum

allowable  $R_S$  where larger values require the  $R_G$  resistor to be a negative value. For example, setting  $R_S = 4 \text{ k}\Omega$  results in  $R_G = 0 \Omega$ . The spreadsheet tool provided will generate “#NUM!” errors for this input as it tries to calculate the nearest standard value, which then replicates throughout the rest of the cells that require a value for  $R_G$ ; but this value will work.

It should be noted that a circuit similar to the one in Example 1, with a maximum  $R_S$  value and  $R_G = 0 \Omega$ , results in the same circuit as the one in Example 2 that uses the gain-setting resistors as the attenuator. It should also be noted that the source impedance will affect the input gain or attenuation of either circuit and should be included in the value of  $R_S$ , especially if it is significant.

The approach in Example 2 is easier, but the input impedance is set as a multiplication of the feedback resistor and attenuation:  $Z_{IN} = 2 \times R_F \times \text{Attenuation}$ . This does allow some design flexibility by varying the value of  $R_F$ , but the impact on noise, bandwidth, distortion, and other performance characteristics should be considered.

## Reference

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. Jim Karki, “Fully-Differential Amplifiers,” Application Report. . . . .	sloa054

## Related Web sites

[amplifier.ti.com](http://amplifier.ti.com)  
[www.ti.com/sc/device/ADS8321](http://www.ti.com/sc/device/ADS8321)  
[www.ti.com/sc/device/THS4521](http://www.ti.com/sc/device/THS4521)  
[www.ti.com/tina-ti](http://www.ti.com/tina-ti)

## 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/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:

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

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](http://support.ti.com)

### TI Semiconductor KnowledgeBase Home Page

[support.ti.com/sc/knowledgebase](http://support.ti.com/sc/knowledgebase)

## Product Information Centers

<b>Americas</b>	Phone	+1(972) 644-5580
<b>Brazil</b>	Phone	0800-891-2616
<b>Mexico</b>	Phone	0800-670-7544
	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	
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	<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	+91-80-41381665
Domestic	<u>Toll-Free Number</u>
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	<a href="mailto:tiasia@ti.com">tiasia@ti.com</a> or <a href="mailto:ti-china@ti.com">ti-china@ti.com</a>
Internet	<a href="http://support.ti.com/sc/pic/asia.htm">support.ti.com/sc/pic/asia.htm</a>

**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**

TINA-TI is a trademark of Texas Instruments. Acrobat and Reader are registered trademarks of Adobe Systems Incorporated. Excel is a registered trademark of Microsoft Corporation. All other trademarks are the property of their respective owners.