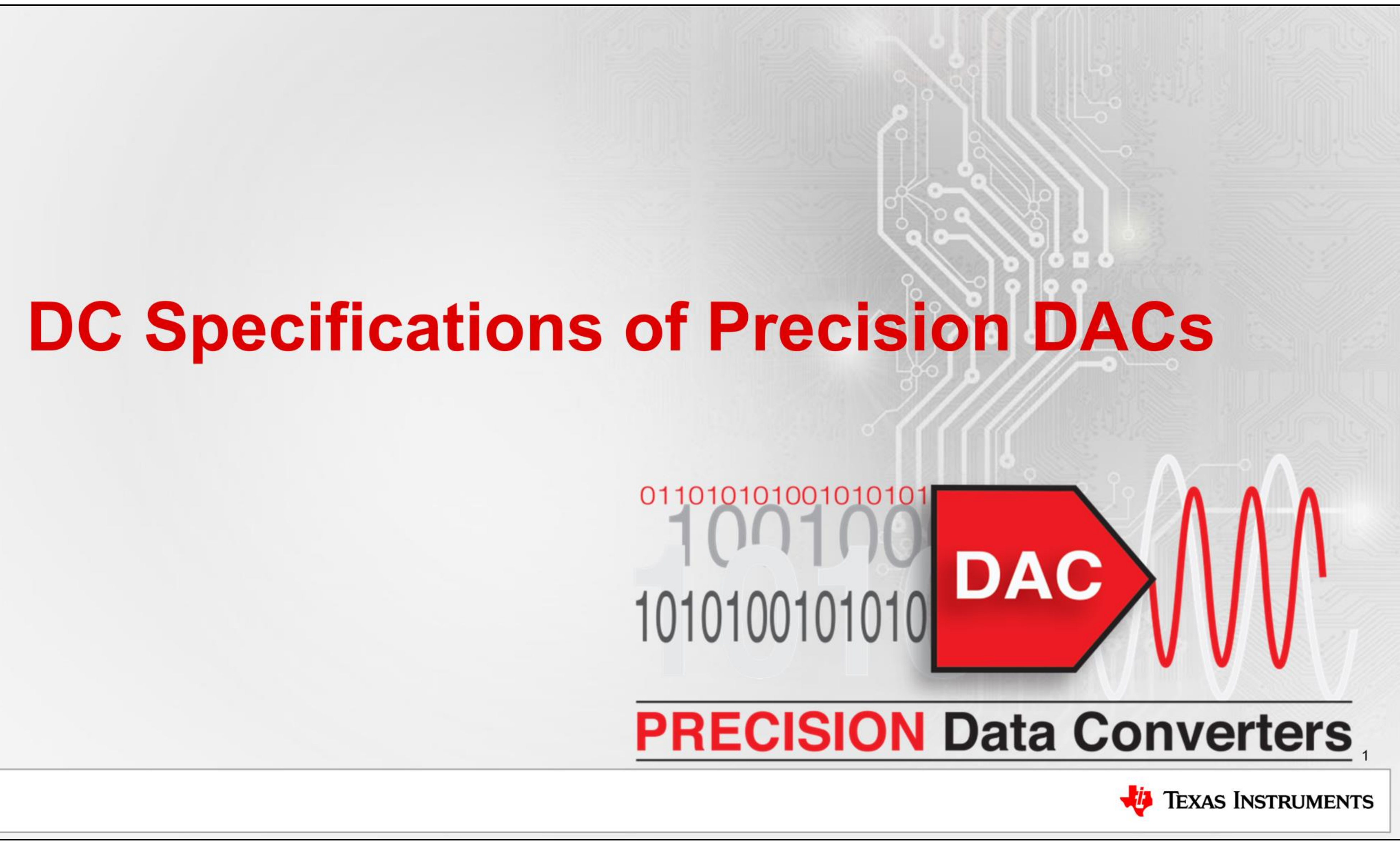
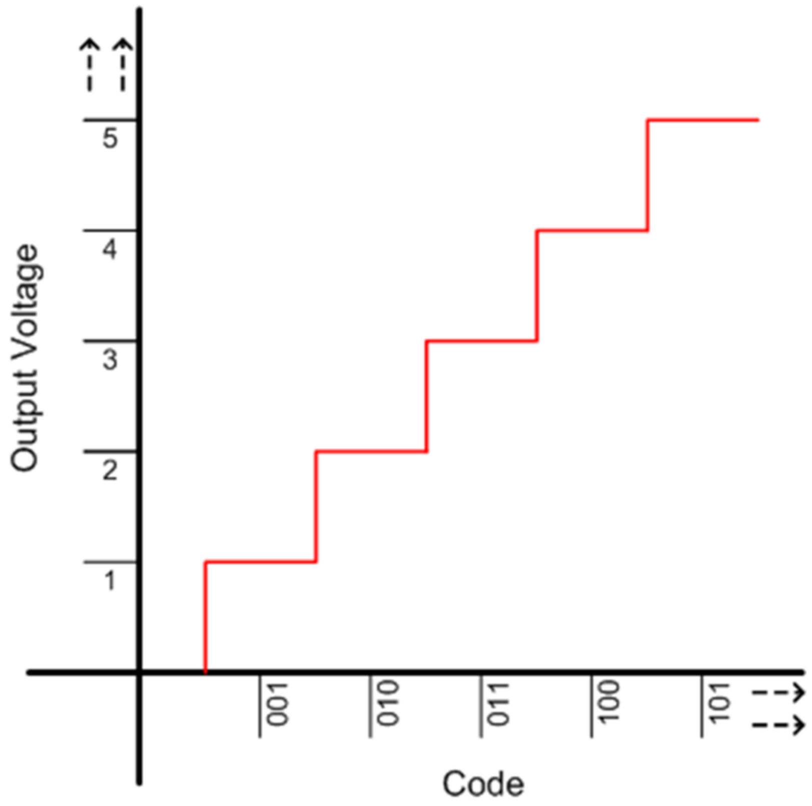


DC Specifications of Precision DACs

Hello, and welcome to the Texas Instruments Precision DAC overview of DC specifications of DACs. In this presentation we will briefly cover the properties of the ideal DAC and several other important DC specifications.

Ideal transfer function



Resolution = ***n*** – The number of bits used to quantify the output

Codes = **2^n** – The number of input code combinations

Full Scale code = **2^n-1** – The largest code that can be written

Reference Voltage = **Vref** – Sets the LSB voltage or current size and converter range

LSB = **Vref / 2^n** – The output voltage or current step size of each code

Full Scale Voltage = **Vref – 1LSB** – Full scale output voltage of the DAC

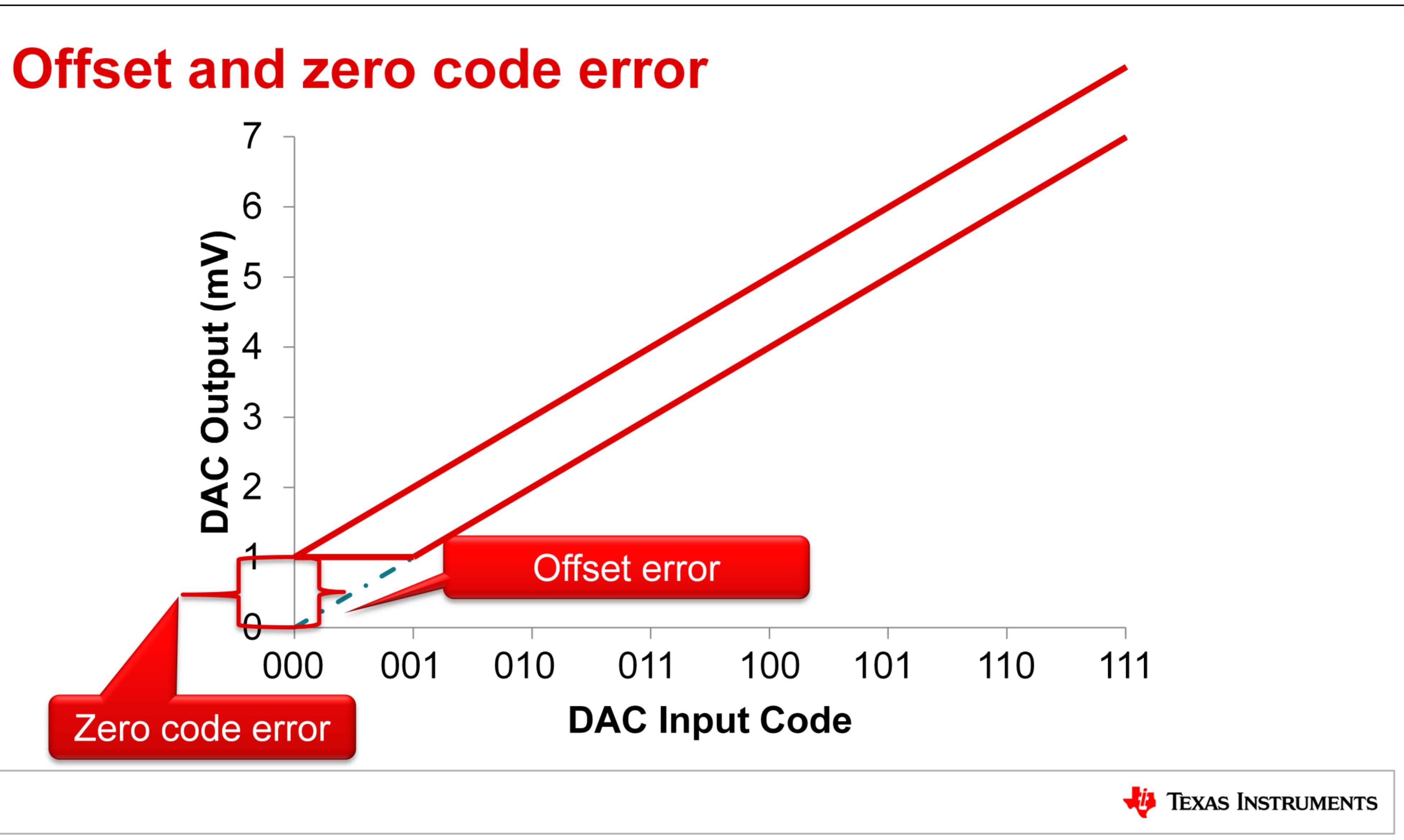
Transfer Function = **Vref x (code/ 2^n)** – Relationship between input data word and output voltage or current

When beginning a study of electronics one of the first things any engineer is exposed to is the ideal op amp. Understanding the properties of the ideal operational amplifier helps simplify circuit analysis but also gives great insight into what causes error in practical op amps. Similarly, we should establish a model for the ideal DAC before exploring where errors are introduced in practical DACs.

The first and most basic parameter for any data converter is its resolution. Resolution simply describes the number of digital bits available to quantify the input or output signal. For this explanation we'll define n as the number of bits. The number of bits or resolution is directly used in calculating the number of input codes. The number of codes is the number of possible combinations of 1s and 0s across all of the converter's bits which is easily defined as 2^n. One of the tricky things about a data converter is understanding that while there are a total of 2^n possible codes that can be written to a DAC, the maximum code is not 2^n. A simple example of this is considering a 2 bit converter, there are a total of 4 possible codes: 0, 1, 2, and 3. The full-scale code is then defined as 2^n – 1.

The reference voltage is arguably the most important piece of any data converter system, any noise on the reference will translate to noise on the DAC output. Additionally the reference voltage defines the output range of a DAC and is used in determining the LSB weight, one of the most important items to understand about a data converter. LSB weight is quantified in volts (or amperes for current output DACs), and is defined as the output step size between sequential codes. Ideally this LSB size can be calculated as Vref/2^n and is consistent across all sequential codes. Note that this is different from calculating data converter LSB weight which is defined as Vref/(2^n - 1). Inherent in all Precision DAC architectures is an inability to actually reach the reference voltage at the output, even assuming perfect resistor values. The full-scale output for a DAC is defined as Vref-1LSB. As the resolution of the DAC increases this error becomes less and less noticeable.

Finally, we can define the ideal transfer function of a DAC as Vref x (CODE/2^n)



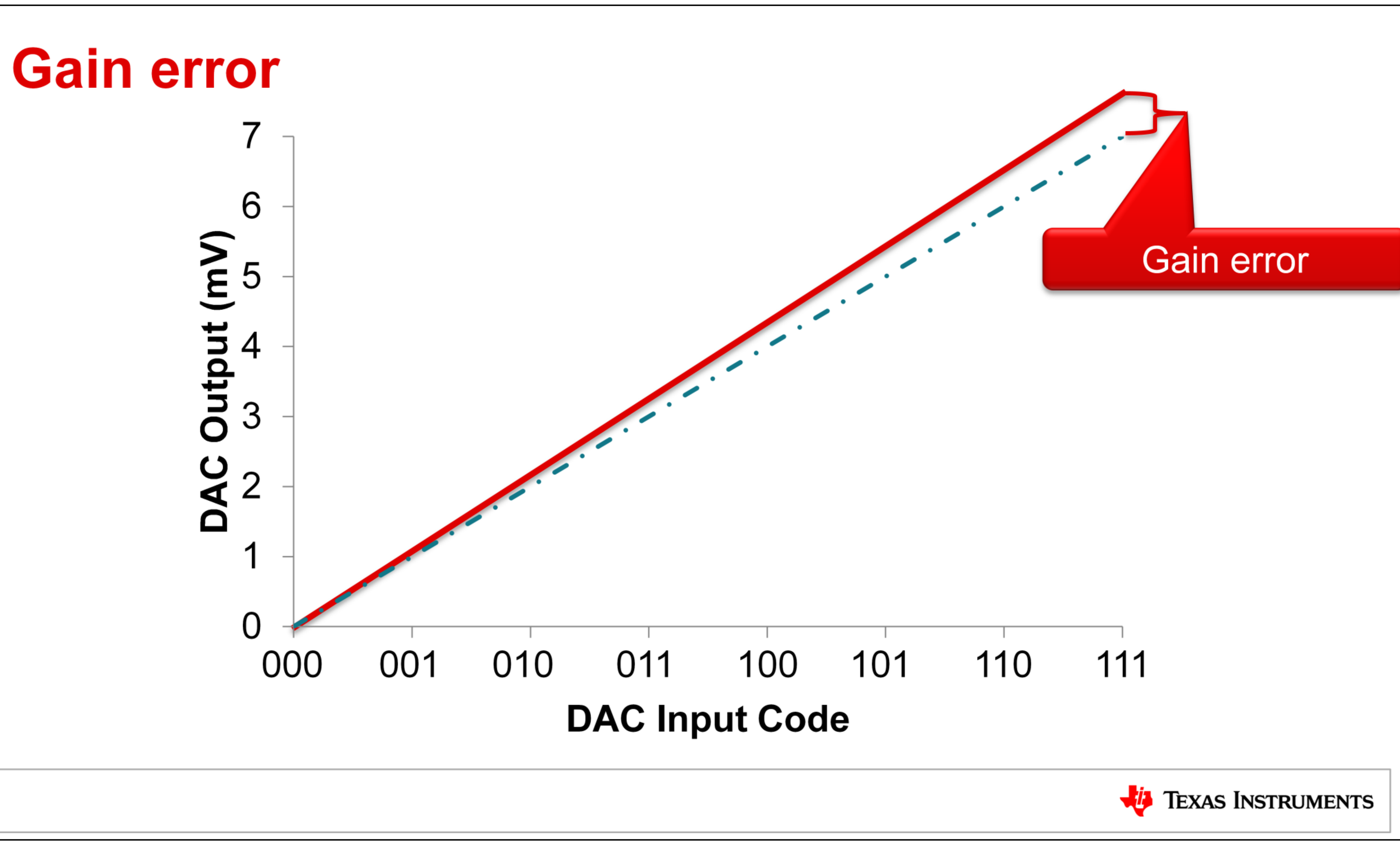
Offset and zero code error

Offset error

Zero code error

TEXAS INSTRUMENTS

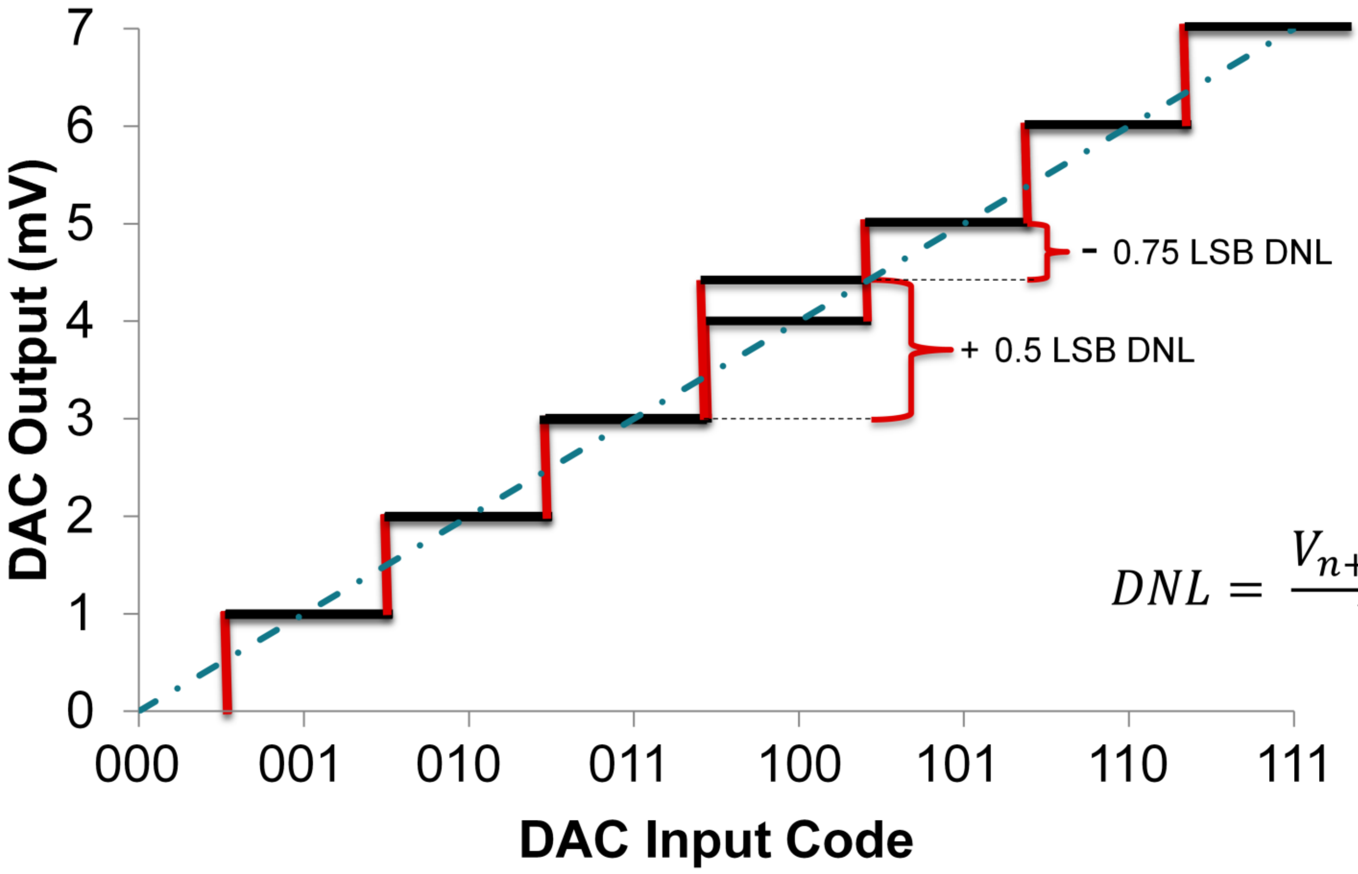
Offset error and zero code error are two very similar specifications for DACs that are often confused. Offset error describes an offset or shift in the entire transfer function across the linear region of operation. Think of it as the b term in y = mx + b. Offset error is calculated based on a line of best fit from a two-point measurement taken across the linear region of operation, typically somewhere between 10% and 90% full-scale range. It may seem clear that if the transfer function is offset that a 0 code will not produce exactly 0V at the DAC output, you might guess that instead it will simply produce the offset term at the output and you would be almost completely correct for bipolar DACs. For a unipolar output DAC, however, operation near the negative rail is non-linear and we will see an additional offset from the expected linear transfer function value. Both unipolar and bipolar DACs will express an offset error & zero-code error term.



Gain error

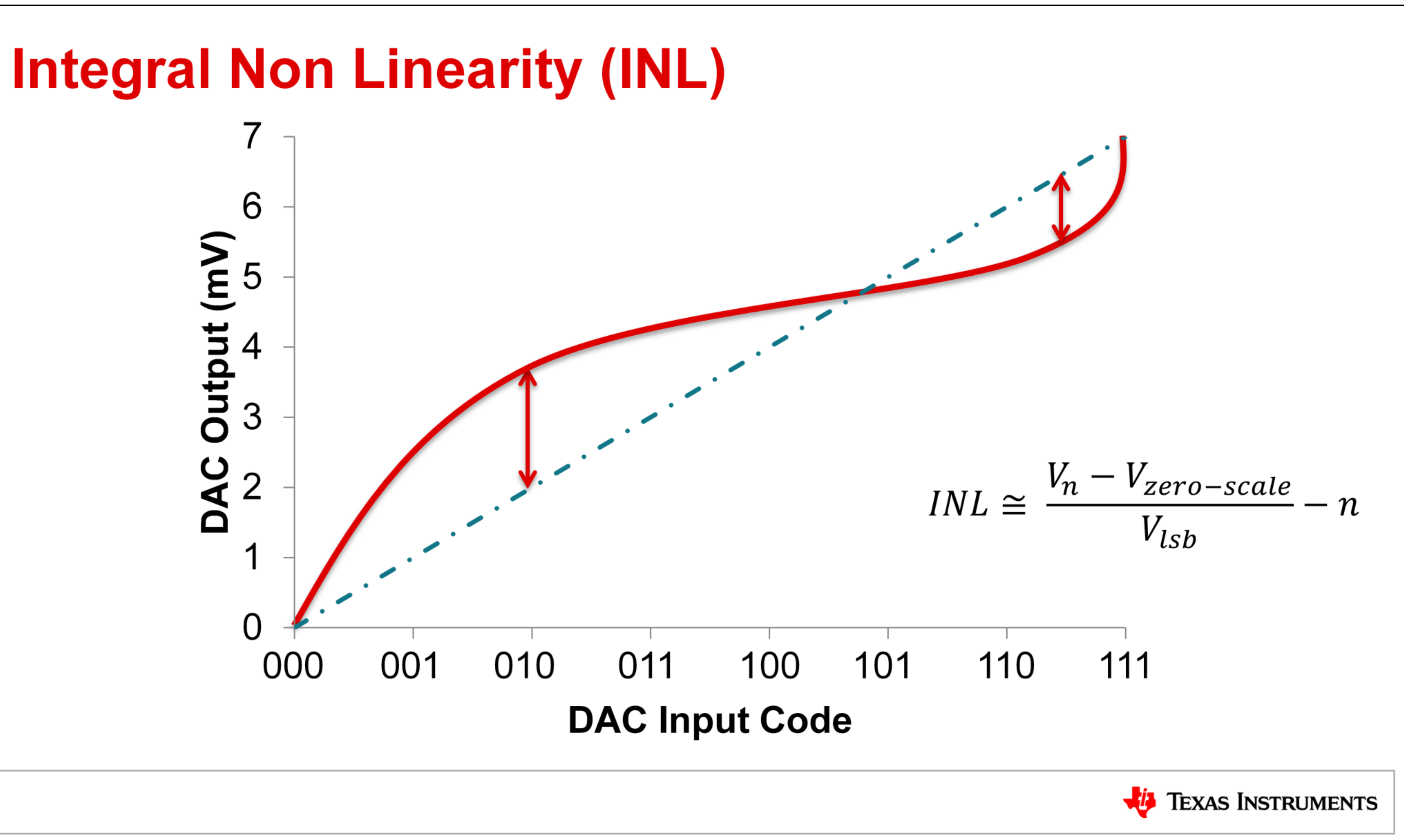
The next specification to consider is **gain error**. If offset error is the b term in y = mx + b then gain error can be considered the m term. Gain error describes the deviation from the ideal slope of the transfer function defined as 1 LSB. Similar to offset error, this is based on a line of best fit taken from a two-point measurement of the DAC output.

Differential Non Linearity (DNL)



$$DNL = \frac{V_{n+1} - V_n}{V_{lsb}} - 1$$

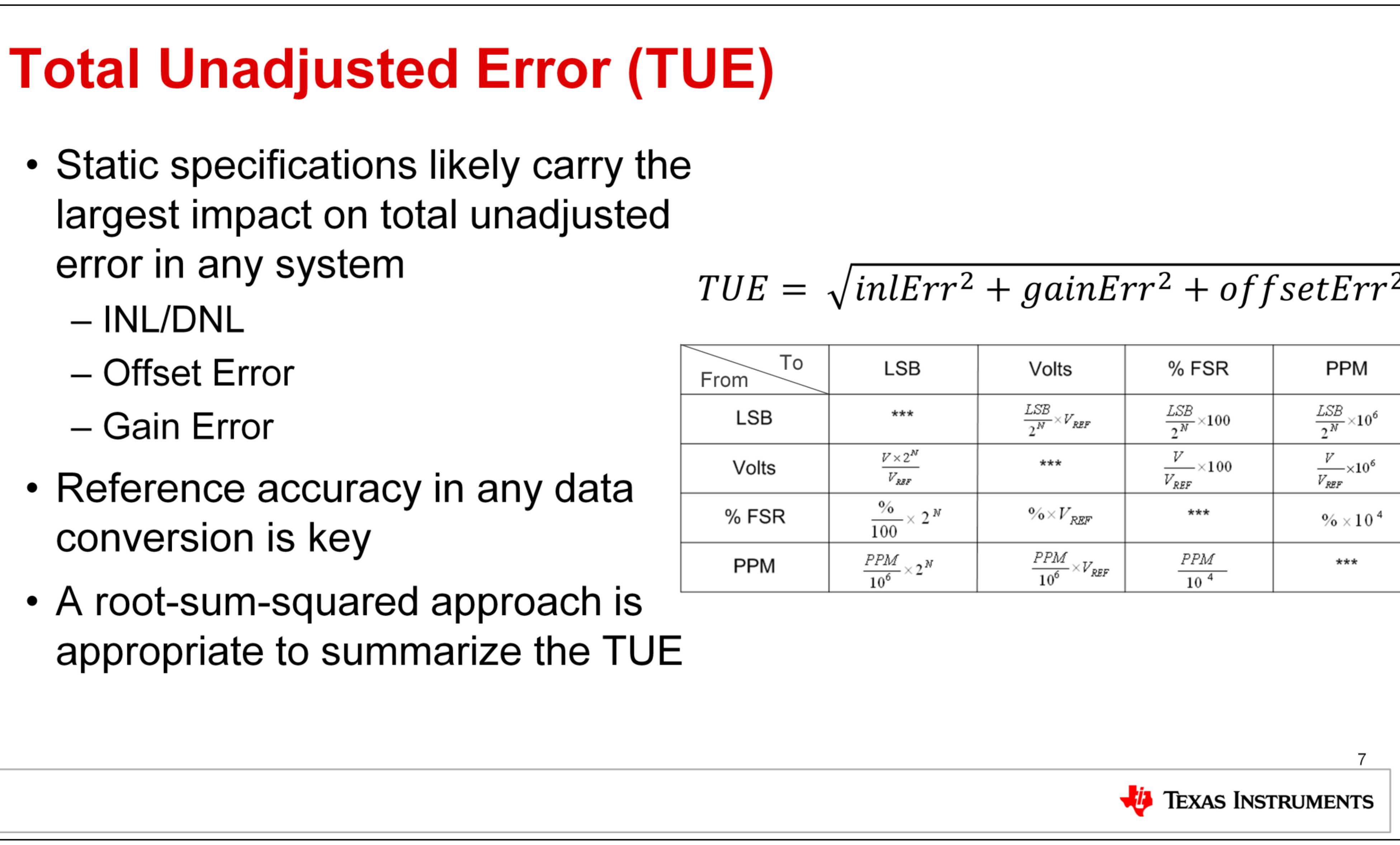
As discussed in the ideal DAC, any two sequential DAC codes should be exactly 1 LSB apart. **Differential non-linearity** measures the worst case deviation any two sequential codes may exhibit across the DAC transfer function. DNL could be specified across each and every DAC code, but in the electrical characteristics table we simply show the worst case expected as a typical value and maximum value. Intuitive methods of understanding and applying DNL are considering monotonicity and a DAC with no missing codes. If DNL at any given transition is less than or equal to -1 the DAC is referred to as non-monotonic. If DNL at any transition were >=1 it may mean that the DAC has missing codes. Generally speaking all of our DACs are monotonic and have no missing codes.



Integral Non Linearity (INL)

$$INL \cong \frac{V_n - V_{zero-scale}}{V_{lsb}} - n$$

Integral non-linearity is very similar to differential non-linearity except rather than a measurement from code-to-code, integral non-linearity is a specification of how the linearity of the measured transfer function differs with respect to the ideal transfer function. As such, integral non-linearity is sometimes referred to as relative accuracy. It should be noted that the INL specification is measured with offset & gain error nullified, i.e. the two point best fit line INL is measured against takes into account offset and gain error or the measured transfer function is calibrated to compensate for offset and gain error. INL purely defines the device linearity and is typically used more frequently than the DNL specification.



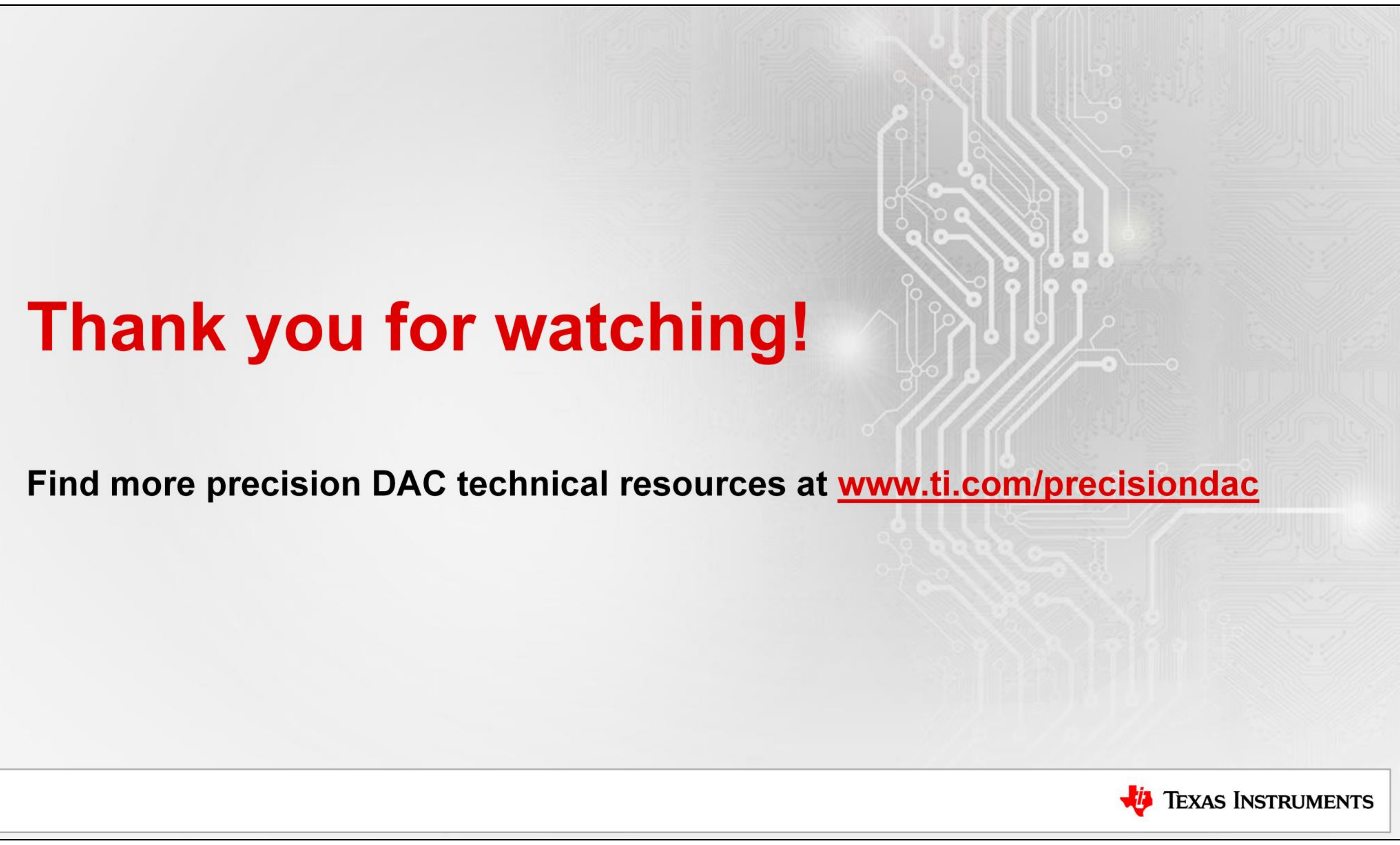
Total Unadjusted Error (TUE)

- Static specifications likely carry the largest impact on total unadjusted error in any system
  - – INL/DNL
  - – Offset Error
  - – Gain Error
- Reference accuracy in any data conversion is key
- A root-sum-squared approach is appropriate to summarize the TUE

$$TUE = \sqrt{inlErr^2 + gainErr^2 + offsetErr^2}$$

To / From	LSB	Volts	% FSR	PPM
LSB	***	$\frac{LSB}{2^N} \times V_{REF}$	$\frac{LSB}{2^N} \times 100$	$\frac{LSB}{2^N} \times 10^6$
Volts	$\frac{V \times 2^N}{V_{REF}}$	***	$\frac{V}{V_{REF}} \times 100$	$\frac{V}{V_{REF}} \times 10^6$
% FSR	$\frac{\%}{100} \times 2^N$	$\% \times V_{REF}$	***	$\% \times 10^4$
PPM	$\frac{PPM}{10^6} \times 2^N$	$\frac{PPM}{10^6} \times V_{REF}$	$\frac{PPM}{10^4}$	***

Having looked at all of these errors, it is useful to have an equation that summarizes all of the DAC errors. Total unadjusted error, or **TUE**, is a calculation that is derived from the basic DC errors using a Root Sum Square approach. It is a probabilistic approximation of the error expected in a system. This is because it is highly unlikely that one system will experience an outlying offset error, and an outlying gain error at the same time. This equation requires two things to be applicable: that all of the errors being added are uncorrelated, and that they all use the same units. Any common unit will work but offset error is usually defined in Volts, Gain error in %FSR and INL in LSBs. A **table** showing the conversion between common units is shown here. Zero and Full-scale errors are not included because they are only end-point errors. TUE only applies within the linear region of the DAC transfer function. DNL is also not included in the TUE equation because the INL spec already accounts for it.



Thank you for watching!

Find more precision DAC technical resources at www.ti.com/precisiondac

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In summary, we learned first about the properties of an ideal DAC. Then we looked at specifications that show where a DAC deviates from being ideal: offset and zero code error, gain error, differential non-linearity, and integral non-linearity. Finally, we finished with total unadjusted error, a way to summarize all of the DC errors in a DAC.

Thank you for watching this video on DC specifications for precision DACs. Please watch our other videos on precision DACs to learn more.