Precision Technology Learning Module
FAQ: Voltage Reference – Basic

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Introduction

The "real" world is analog; we are surrounded by signals that continuously varies with time. For electronics devices to interact with the "real" world, they must be able to map real world measurements (such as speed, pressure, temperature) to a measurable quantity in the electronics world (such as Voltage); to do that, a standard must be set for these data to be measured against, and this standard is provided by the Voltage Reference.

Simply put, a Voltage Reference is a precision circuit element that provides a known, constant potential, even as internal or external parameters change, providing this known potential for as long as the circuit needs it, which could be for hours, days, or years. By comparing analog signals to a known value, any signal can be accurately quantified.

Voltage References are among ADI's wide-arrayed portfolio of products, playing an important role in the data acquisition signal chain. To best explain how they are used, configured, or designed, we shall be using some of these products as reference.

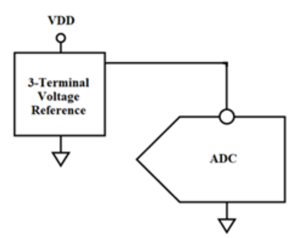
This module, known as the Voltage Reference Easy Module, is the first out of a series of three, focusing on introducing the voltage reference, giving an overview of its functions, configurations, and some of its specifications. For a more in-depth focus on the intricacies of the Voltage Reference, refer to the Moderate or Difficult module.

Application

The basic signal chain for data acquisition in Figure 2 shows the Voltage Reference's function in the basic signal chain for data acquisition, typically playing the vital support role of providing a certain and unchanging value for precision devices such as, but not limited to, ADCs, DACs, and Amplifiers. You will find voltage references in a variety of real-world precision measurement and control systems such as Data acquisition systems (Digital Multimeters), Power Supplies, Digital Medical Devices, Industrial Instrumentations, and Automotive Battery Monitoring.

Analog-to-Digital Converters (ADC)

Voltage references plays an important role in ADC such that it provides the analog value that would be the basis of the ADC's conversion process. The Voltage Reference dictates the ADC's least significant bit (LSB), which is the rightmost bit of a digital code, holding a corresponding analog value that represents a single step. Its typical connection to ADC is seen on Figure 1.



$$V_{Step} = LSB = \frac{V_{Ref}}{2^n}$$

Figure 1. Voltage Reference for ADC

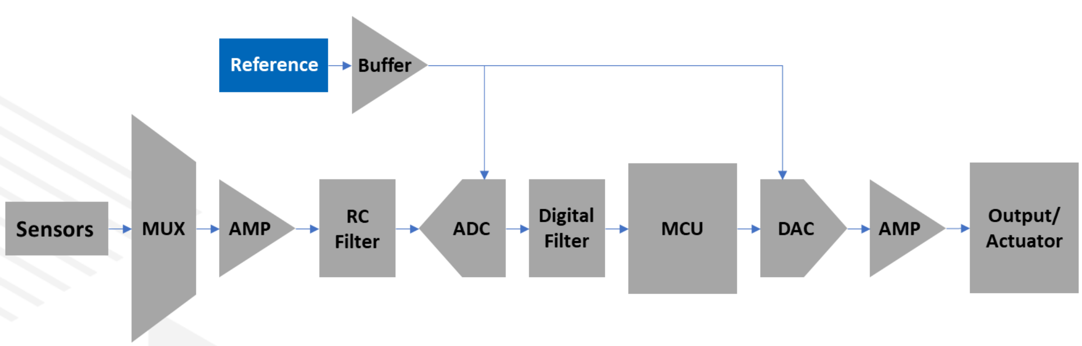


Figure 2. Basic Signal Chain for a DAQ

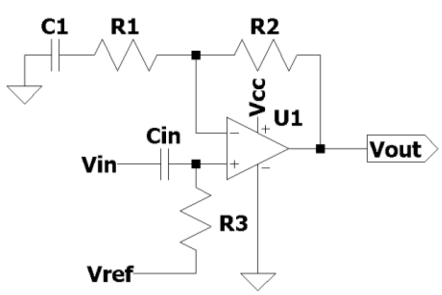
Digital-to-Analog Converters (DAC)

Similar with its role in ADCs, voltage references provide the basis for the DAC's conversion process. The DAC sets its full-scale code value equal to the reference, and by approximation, computes for the equivalent analog value of its output.

$$V_{out} = Code_{10} \times \frac{V_{ref}}{2^n}$$

Amplifiers

One of the Voltage Reference's amplifier applications is to set the middle voltage where the input signal could "swing from" or "ride onto". In Figure 3, the reference voltage used as a bias voltage in the non-inverting input of the AC-coupled Amplifier is the expected output when there is no input signal in Vin. This configuration can be used as signal conditioning circuitry to amplify an AC signal even if the amplifier is operated in single supply.



$$V_{out} = \left(1 + \frac{R_2}{R_1}\right) V_{in} + V_{ref}$$

Figure 3. Voltage Reference as Bias in Amplifiers

Types of Voltage References

There are two types of Voltage References: Series and Shunt. The difference between the two are their number of terminals and their typical applications.

Series

A series reference has three (or more) terminals, operating akin to a low dropout (LDO) regulator, thus sharing many of its advantages, such as consuming a relatively consistent supply current given a range of supply voltages and would only consume current as required by the load.

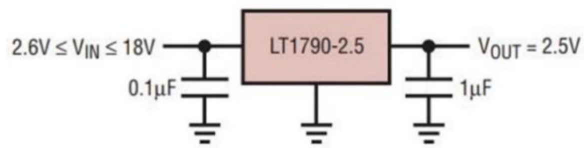


Figure 4. Series Voltage Reference

Ideally, series reference is best used on circuits where large changes on supply voltage and load current occur. Having no series resistor between the reference and supply, they are very useful in circuits requiring large load current. Series references are typically more accurate and less noisy than Shunt, however, the supply voltage is limited to the device's absolute maximum rating.

Shunt

A Shunt Reference is a two-terminal device that operates like a Zener diode, where voltage drop becomes consistent upon reaching the minimum operating current. Shunt references regulate the load by providing a constant voltage drop then shunting excess current to ground.

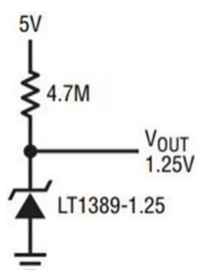


Figure 5. Shunt Voltage Reference

Shunt references are best used when a stable load current is required by the circuit. They are also great for creating single input, multiple stepped reference voltage, and can easily be designed as negative voltage references. Typically, Shunt references are less accurate than series references; It, however, requires a much lower operating current than the other.

Key Specifications

Voltage References are designed in many forms, offering varied features depending on their purpose. In any application, one feature is more preferred than another, but constant above all is the importance of Accuracy and Stability, as the main purpose of a Voltage Reference is to provide a known output voltage.

To determine the key specifications, we'll examine the datasheet of ADR4520, an ultra-low noise, high accuracy voltage reference product by Analog Devices. Voltage references gives a lot of features and specifications to consider based on how it will be used, but the following are the ones to be more concerned of when checking for accuracy and stability.

Initial Accuracy

This is the variance of the output voltage based on its measurement at nominal temperature (typically measured at 25°C). In the datasheet, it is also referred to as the "Initial Voltage Output Error", as seen on Figure 6.

Figure 6 states that the maximum output voltage error is 0.02% or 410uV for B grade and 0.04% or 820uV for A grade. The minute percent error on the output shows that the voltage reference is stable and highly accurate.

Temperature Coefficient

This evaluates the voltage reference's output voltage performance against the changing ambient temperature of the device. The resulting change in output voltage is often influenced by imperfections and nonlinearities in the circuit elements.

Figure 7 shows the temperature coefficient in the datasheet, specified in ppm/°C. This value is based on the device's output voltage at nominal temperature. ADR4520 had been fully tested over three temperature ranges using two different methods: (1) Box Method, and (2) Bowtie Method

Box Method

Box method, the most common method, accounts for temperature coefficient over the full temperature range. It is represented by the following equation:

$$TCV_{out} = \left| \frac{max\{V_{out}(T_1, T_2, T_3)\} - min\{V_{out}(T_1, T_2, T_3)\}}{V_{out}(T_2) \times (T_3 - T_1)} \right| \times 10^6$$

Where:

TCV_{out} is the Temperature Coefficient, expressed in ppm/°C
$V_{out}(T_x)$ is the output voltage at Temperature T_x.
T_1 = -40°C
T_2 = +25°C
T_3 = +125°C

Bowtie Method

Bowtie method calculates the worst-case slope from 25°C, and is thus more useful to devices calibrated at 25°C. It is represented by the following equation:

$$TCV_{out} = \left| max\{TCV_{out\_1}, TCV_{out\_2}\} \right|$$

Where:

$$TCV_{out\_1} = \left| \frac{max\{V_{out}(T_1,T_2)\} - min\{V_{out}(T_1,T_2)\}}{V_{out}(T_2) \times (T_2 - T_1)} \right| \times 10^6$$

$$TCV_{out\_2} = \left| \frac{max\{V_{out}(T_2,T_3)\} - min\{V_{out}(T_2,T_3)\}}{V_{out}(T_2) \times (T_3 - T_2)} \right| \times 10^6$$

TCV_{out} is expressed in ppm/°C
$V_{out}(T_x)$ is the output voltage at Temperature T_x.
T_1 = 0°C
T_2 = +25°C
T_3 = +70°C

Parameter	Symbol	Test Conditions/Comments	Min	Typ	Max	Unit
INITIAL OUTPUT VOLTAGE ERROR	V_{OUT_ERR}					
B Grade					±0.02	%
					410	µV
A Grade					±0.04	%
					820	µV

Figure 6. Initial Output Voltage Error of ADR4520

Parameter	Symbol	Test Conditions/Comments	Min	Typ	Max	Unit
TEMPERATURE COEFFICIENT	TCV_{OUT}	See Terminology section				
B Grade		$-40°C \leq T_A \leq +125°C$ (box method)			2	ppm/°C
		$-40°C \leq T_A \leq +125°C$ (bowtie method)			4	ppm/°C
A Grade		$-40°C \leq T_A \leq +125°C$ (box method)			4	ppm/°C
		$-40°C \leq T_A \leq +125°C$ (bowtie method)			8	ppm/°C

Figure 7. Temperature Coefficient of ADR4520

Parameter	Symbol	Test Conditions/Comments	Min	Typ	Max	Unit
SOLDER HEAT RESISTANCE SHIFT				±0.02		%

Figure 8. Solder Heat Resistance Shift of ADR4520

Parameter	Symbol	Test Conditions/Comments	Min	Typ	Max	Unit
LONG-TERM DRIFT	ΔV_{OUT_LTD}	$T_A = 25°C$				
		250 hours (early life drift)		19		ppm
		1000 hours		25		ppm
		4500 hours		51		ppm

Figure 9. Long Term Drift of ADR4520

Solder Heat Resistance (SHR) Shift

It is the measure of change in the output voltage caused by exposure to reflow soldering. This shift can be attributed to the package materials and the changes that occur on them when subjected to high temperatures. SHR is measured after three reflow cycles. Figure 8 shows this parameter.

Long Term Drift (LTD)

This is defined as the measure of a reference voltage's shift over a long period of time, focused on measuring how much the part's performance drifts from time zero after soldering. This drift comes from the part's recovery to physical stress and thermal stress caused by being subjected to high heat during soldering.

LTD is represented in ppm difference against the nominal output, and can be determined through the following equation:

$$\Delta V_{OUT\_LTD} = \left| \frac{V_{OUT}(t_1) - V_{OUT}(t_0)}{V_{OUT}(t_0)} \right| \times 10^6 \quad [ppm]$$

Where:
$V_{OUT}(t_0)$ is the V_{OUT} at the starting time of measurement.
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Figure 9 shows the long-term drift at nominal temperature over the span of 250, 1000, and 4500 hours respectively, with right after soldering. These rates of shift can be better observed in Figure 10. In the first 250 hours, also known as the early life, the rate of shift is much higher. This is because most of the part's recovery happens during its early life.

After this initial shift, it can be noticed that there is little change in the V_{out} in the next 750 hours. The rate further decreases over the next thousands of hours, with the only significant source of degradation being the electrical changes in the circuit. At this stage, long term drift is often referred to as "aging".

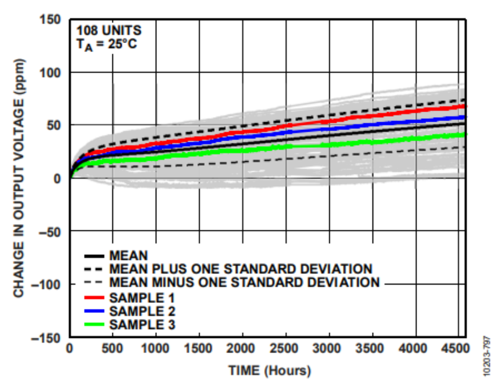

Figure 10. Long Term Drift of ADR4520 over 4500 hours

Parameter	Symbol	Test Conditions/Comments	Min	Typ	Max	Unit
OUTPUT VOLTAGE HYSTERESIS	ΔV_{OUT_HYS}	T_A = temperature cycled from				
		+25°C to +125°C to−40°C to +25°C (full cycle)		−13		ppm
		25°C to 125°C to 25°C (half cycle)		−97		ppm
		25°C to 70°C to 0°C to 25°C (full cycle)		−8		ppm
		25°C to 70°C to 25°C (half cycle)		−17		ppm

Figure 11. Output Voltage Hysteresis of [ADR4520]

Parameter	Symbol	Test Conditions/Comments	Min	Typ	Max	Unit
OUTPUT VOLTAGE NOISE	$e_{Np\text{-}p}$	0.1 Hz to 10.0 Hz		1.0		µV p-p
OUTPUT VOLTAGE NOISE DENSITY	e_N	1 kHz		35.8		nV/√Hz

Figure 12. Voltage Noise of [ADR4520]

Thermally Induced Output Voltage Hysteresis

Although often overlooked, this specification, also known as “Thermal Hysteresis”, is also a dominant source of error. This is measured as the change in output voltage after the part had been exposed to a large temperature cycle and is expressed as a ppm difference from the measured output at nominal temperature.

$$\Delta V_{OUT\_HYS} = \frac{V_{OUT1\_25℃} - V_{OUT2\_25℃}}{V_{OUT\_25℃}} \times 10^6 \quad [ppm]$$

Where:
$V_{OUT1\_25℃}$ is the output voltage at 25°C.
$V_{OUT2\_25℃}$ is the output voltage at after temperature cycling.

The test conditions tab in Figure 11 shows how the temperature is cycled to capture a measurement. It is important to consider this parameter, as it is independent of temperature coefficient and long-term drift; this may also reduce the effectiveness of initial voltage calibration.

Voltage Noise

Voltage noise are random voltage fluctuations that can be measured both in the output of the device; these are produced by active and passive components inside an IC.

Figure 12 shows the voltage noise parameters. It is typical for a reference datasheet to show noise in two frequency bands: (1) the low-frequency noise, expressed in µV p-p, ranging from frequencies 0.1Hz to 10Hz, and (2) wideband noise, expressed in nV/ √Hz, ranging from 10Hz to 1kHz.

For the wideband frequency, the noise is white, such that there is no variation in spectral density even when the frequency changes. For low frequency band, however, the noise density decreases, by 3 dB per octave, as frequency rises. Figure 13 shows this.

In ADC applications, there is an increasing need for ultrahigh precision measurements; as such, it is important to consider minimizing the noise. To calculate for the allowable noise that the system can tolerate, the following formula is employed:

$$e_N \leq \frac{1}{12} \times \frac{LSB}{\sqrt{BW}}$$

Where:
e_N is the noise density.
LSB is the least significant bit.
BW is the bandwidth of the system.

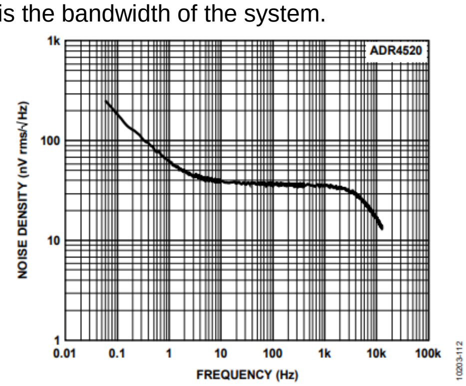

Figure 13. Output Noise Spectral Density of [ADR4520]

Parameter	Symbol	Test Conditions/Comments	Min	Typ	Max	Unit
LINE REGULATION	$\Delta V_{OUT}/\Delta V_{IN}$	$-40°C \le T_A \le +125°C$		1	10	ppm/V
LOAD REGULATION	$\Delta V_{OUT}/\Delta I_L$	$I_L = 0$ mA to +10 mA source, $-40°C \le T_A \le +125°C$		30	80	ppm/mA
		$I_L = 0$ mA to −10 mA sink, $-40°C \le T_A \le +125°C$		100	120	ppm/mA

Figure 14. Line Regulation and Load Regulation of [ADR4520]

Parameter	Symbol	Test Conditions/Comments	Min	Typ	Max	Unit
DROPOUT VOLTAGE	V_{DO}	$-40°C \le T_A \le +125°C$, no load			1	V
		$-40°C \le T_A \le +125°C$, $I_L = 2$ mA			1	V

Figure 15. Dropout Voltage of [ADR4520]

Parameter	Symbol	Test Conditions/Comments	Min	Typ	Max	Unit
MINIMUM OPERATING CURRENT	I_{IN}	$T_A = 25°C$			50	µA
		$-40°C < T_A < +125°C$			60	µA

Figure 16. Minimum Operating Current of ADR5040

Line Regulation

Line Regulation is the measure of change in the output in response to a "per volt" change in the input. It is expressed in different units such as percent per volt, ppm per volt, or µV per volt. This parameter is shown in Figure 14.

Load Regulation

It is the measure of change in output voltage in response to change in output current. It is expressed in different units such as µV per mA, ppm per mA, or ohms of DC output resistance. This parameter is shown in Figure 14.

Dropout Voltage

Dropout voltage is the minimum allowable voltage difference between input and output so that an output voltage accuracy is maintained within 0.1%. This parameter is oftentimes referred to as supply voltage headroom and is expressed with the following equation:

$$V_{DO} = (V_{IN} - V_{OUT})_{min} | I_L = constant$$

Since the dropout voltage is dependent on the current passing through the device, the parameter is specified with a given load rating, as seen on Figure 15.

Note: This parameter is only significant for series references.

Minimum Operating Current

This specifies the minimum current the reference has to draw in order to operate. This minimum current must be drawn at full-load condition. Figure 16 shows the minimum operating current of a shunt reference, the ADR5040.

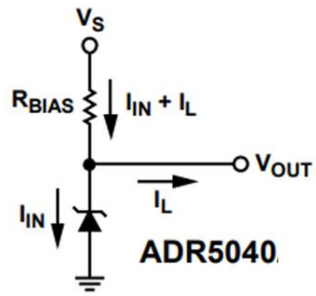

Figure 17. ADR5040 Shunt Reference

Figure 17 shows ADR5040 externally biased by a resistor. Given this setup, it is important to make sure that the resistor used will be able to accommodate both the minimum operating current required by the part and the maximum current drawn of the load.

Note: This parameter is only significant for shunt references.

Voltage Reference vs. Voltage Regulator

The voltage reference and voltage regulator are two sides of the same coin. At face value, they have the same function of providing a stable voltage given a more arbitrary input voltage. How they are used, however, is where they draw a line of differentiation.

Voltage references provides voltage that serves as standard for systems and circuits, thus it is imperative that they are both accurate and stable. Its primary purpose is to constantly maintain this said value for the other circuits to base on, and thus, the current it provides is relatively small.

Meanwhile, the voltage regulator is mostly used to supply a steady voltage and current as demanded by a load. Essentially, it is put in place to control an incoming input voltage and prevent its instability and arbitrariness from damaging the system, much like a consistent power supply. As such, they are designed to be capable of providing higher load currents.

Given the said applications, Voltage Reference tend to be stricter in its output and tolerance as it is mostly used for precision devices. Voltage regulators still need to be stable, but they're less stringent with their tolerances, and more focused on driving the circuit.

Table 1 shows the comparison of a voltage reference and a voltage regulator in terms of the parameters such as output voltage, output current, output noise, line regulation, and load regulation.

Table 1. Specification Comparison of a Reference and a Regulator

	Reference (ADR4550)	**Regulator (ADP7156)**
Output Voltage	5V (Fixed)	2.3 to 5.5V (Varied)
Output Current (Maximum)	10mA	1.2A
Output Noise	2.8uV p-p (0.1 to 10Hz)	1.6 uV rms (10Hz to 100Hz)
Line Regulation	0.0001 to 0.001%/V	-0.1 to 0.1 %/V
Load Regulation	0.0025 to 0.008%/V	0.3%/V

Self-Check:

1. Is ADR4520 a series or shunt reference? What are the significant qualities that identify this product as such?

2. What is the typical Dropout voltage of an ADR3420 if you have a constant current of 2mA running through the load?

3. What is the temperature coefficient of ADR3433 and which method is used to determine this value?

4. What is the minimum operating current of ADR1581?

5. From the equation of noise density, derive the formula for peak-to-peak noise ($e_{Np\text{-}p}$). Hint:
   *Peak-to-peak noise = 6 * RMS_noise*
   *RMS noise = Noise density * √Bandwidth*

6. Assume a 16-bit ADC system with a full-scale value of 10V and the bandwidth of 1000 kHz. Assuming there's no DC inaccuracy, what is the noise density that the system can tolerate?

7. A DC motor has the following specifications:
   - Voltage: 5V
   - Operating voltage: 1.5 to 9.0V
   - No-load current: 0.026A
   - Current at max efficiency: 0.12A
   - Power at max efficiency: 0.33W

   To operate the motor, which device should be used, a reference or a regulator?

Reference:

"How to Choose a Voltage Reference", Analog Devices, March 2009

"ADR4520 - Ultralow Noise, High Accuracy Voltage References", Analog Devices, April 2012

"MT-047 – Op Amp Noise", Analog Devices, October 2008

"Understanding Voltage-Reference Topologies and Specifications", Maxim Integrated (now part of Analog Devices), 2013