

The 20-Bit DAC Is the Easiest Part of a 1-ppm-Accurate Precision Voltage Source

By Maurice Egan

Introduction

A common use of high-resolution digital-to-analog converters (DACs) is providing controllable precision voltages. Applications for DACs with resolution up to 20 bits, precision up to 1 ppm, and reasonable speed include gradient coil control in medical MRI systems; precision dc sources in test and measurement; precision set-point and position control in mass spectrometry and gas chromatography; and beamprobing in scientific applications.

Over time, the definition of what constitutes a precision integrated-circuit DAC has changed rapidly as semiconductor processing and on-chip calibration technologies have advanced. Once, high-precision 12-bit DACs were considered to be hard to achieve; in recent years, 16-bit accuracy has become widely available for use in precision medical, instrumentation, and test and measurement applications; and over the horizon, even greater resolutions and accuracies are called for in control and instrumentation systems.

High precision applications for integrated circuits now require 18-bit and 20-bit, 1-ppm-accurate digital-to-analog converters, a performance level previously achieved only with cumbersome, expensive, and slow Kelvin-Varley dividers—the preserve of standards labs and hardly suitable for instrumentation systems in the field. More convenient semiconductor-based, 1-ppm-accurate solutions to such requirements using assemblies of IC DACs have been around for some years; but these complex systems use many devices, require frequent calibrations and great care to achieve accuracy, and are both bulky and costly (see [Appendix](#)). The precision instrumentation market has long needed a simpler, cost-effective DAC that doesn't require calibration or constant monitoring, is easy to use, and offers guaranteed specifications. A natural evolution from 16-bit and 18-bit monolithic converters—such a DAC is now a reality.

The AD5791 1-ppm DAC

Advances in semiconductor processing, DAC architecture design, and fast on-chip calibration techniques make possible highly linear, stable, fast-settling digital-to-analog converters that deliver better than 1-ppm relative accuracy, 0.05-ppm/°C temperature drift, 0.1-ppm p-p noise, better than 1-ppm long-term stability, and 1-MHz throughput. These small, single chip devices have guaranteed specifications, do not require calibration, and are easy to use. A typical functional diagram for the AD5791 and its companion reference- and output buffers is shown in Figure 1.

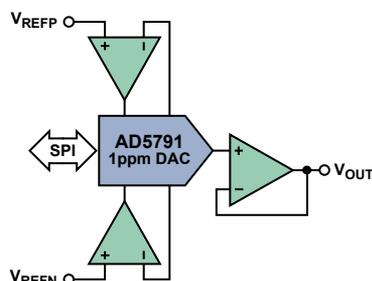


Figure 1. AD5791 typical operating block diagram.

The [AD5791](#) single-chip, 20-bit, voltage-output digital-to-analog converter specifies 1-LSB (*least-significant bit*) *integral nonlinearity* (INL) and *differential nonlinearity* (DNL), making it the world's first monolithic

1-ppm-accurate digital-to-analog converter (1 LSB at 20 bits is one part in 2^{20} = one part in 1,048,576 = 1 ppm). Designed for use in high-precision instrumentation and test and measurement systems, it offers a significant leap in all-around performance compared to other solutions, providing greater levels of accuracy and repeatability in less space and at lower cost, permitting instrumentation applications that previously would not have been economically feasible.

Its design, shown in Figure 2, features precision voltage-mode R-2R architecture, exploits state-of-the-art thin-film resistor-matching techniques, and employs on-chip calibration routines to achieve 1-ppm accuracy levels. Because the device is factory calibrated and, therefore, requires no run-time calibration routines, its latency is no greater than 100 ns, so the AD5791 can be used in waveform-generation applications and fast control loops.

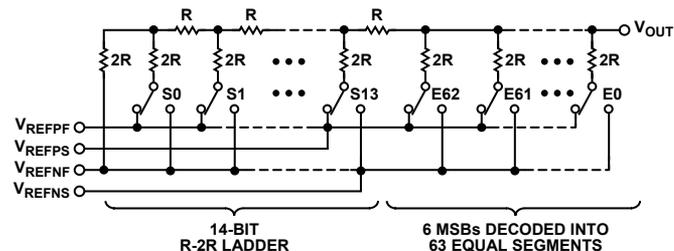


Figure 2. DAC ladder structure.

Besides its impressive linearity, the AD5791 combines $9 \text{ nV}/\sqrt{\text{Hz}}$ noise density, 0.6- μV peak-to-peak noise in the 0.1-Hz to 10-Hz frequency band, 0.05-ppm/°C temperature drift, and better than 0.1-ppm long-term stability over 1000 hours.

A high-voltage device, it operates from dual supplies of up to $\pm 16.5 \text{ V}$. The output voltage span is set by the applied positive and negative reference voltages, V_{REFP} and V_{REFN} , offering a flexible choice of output range.

The precision architecture of the AD5791 requires high-performance external amplifiers to buffer the reference source from the 3.4 k Ω DAC resistance and facilitate force-sensing at the reference input pins to ensure the AD5791's 1-ppm linearity. An output buffer is required for load driving to unburden the 3.4 k Ω output impedance of the AD5791—unless a very high-impedance, low-capacitance load is being driven—or attenuation is tolerable and predictable.

Because the amplifiers are external, they can be selected to optimize for noise, temperature drift, and speed—and the scale factor can be adjusted—depending on the needs of the application. For the reference buffers, the [AD8676](#) dual amplifier is recommended, based on its low noise, low offset error, low offset error drift, and low input bias currents. The input bias current specification of the reference buffers is important, as excessive bias currents will degrade the dc linearity. The degradation of integral nonlinearity, in ppm, as a function of input bias current, is typically:

$$\text{Extra INL Error} = \frac{0.2 \times I_{BIAS}}{(V_{REFP} - V_{REFN})^2}$$

where I_{BIAS} is in nA; V_{REFP} and V_{REFN} are in volts. For example, with a $\pm 10\text{-V}$ reference input span, an input bias current of 100 nA will increase the INL by 0.05 ppm.

The key requirements for an output buffer are similar to those for the reference buffers—except for bias current, which does not affect the AD5791's linearity. Offset voltage and input bias current can affect output offset voltage, though. To maintain dc precision, the [AD8675](#) is recommended as an output buffer. High-throughput applications require a fast output buffer amplifier with higher slew rate.

Table 1 lists the key specifications of a few appropriate precision amplifiers.

The AD5791 offers reduced design time, reduced design risk, reduced cost, reduced board size, increased reliability, and guaranteed specifications.

Figure 3 is a circuit schematic implementing the AD5791 (U1) as a precision digitally controlled 1-ppm voltage source with a ± 10 V range in 20- μ V increments using the AD8676 (U2) as reference buffers and the AD8675 (U3) as the output buffer. The absolute accuracy is determined by the choice of the external 10 V references.

Performance Measures

The important measures of this circuit are integral nonlinearity, differential nonlinearity, and 0.1-Hz to 10-Hz peak-to-peak noise. Figure 4 shows that typical INL is within ± 0.6 LSB.

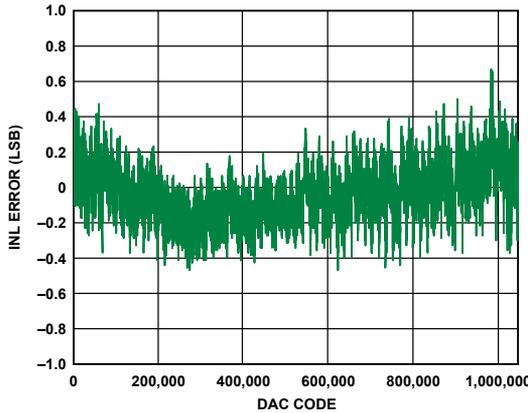


Figure 4. Integral nonlinearity plot.

Figure 5 shows a typical DNL of ± 0.5 LSB; the output is guaranteed monotonic over the entire range of bit transitions.

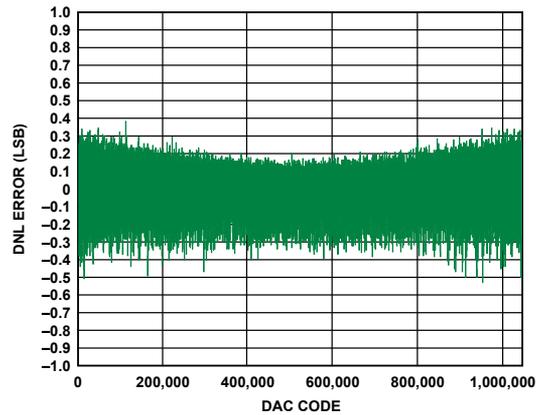


Figure 5. Differential nonlinearity plot.

Peak-to-peak noise in the 0.1-Hz to 10-Hz bandwidth is about 700 nV, as shown in Figure 6.

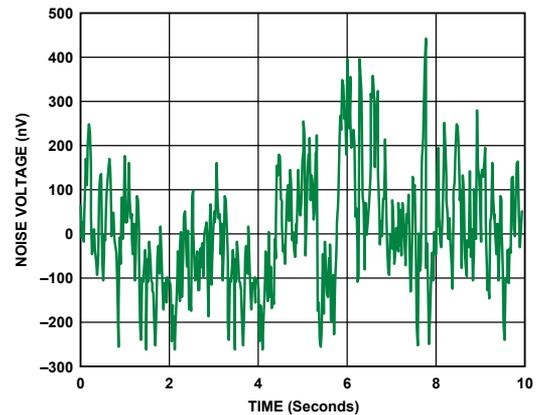


Figure 6. Low-frequency noise.

Table 1. Precision Amplifier Key Specifications

	Noise Spectral Density	1/f p-p Noise (0.1 Hz to 10 Hz)	Offset Voltage Error	Offset Voltage Error Drift	Input Bias Current	Slew Rate
AD8675/AD8676	2.8 nV/ $\sqrt{\text{Hz}}$	0.1 μ V	10 μ V	0.2 μ V/ $^{\circ}$ C	0.5 nA	2.5 V/ μ s
ADA4004-1	1.8 nV/ $\sqrt{\text{Hz}}$	0.1 μ V	40 μ V	0.7 μ V/ $^{\circ}$ C	40 nA	2.7 V/ μ s
ADA4898-1	0.9 nV/ $\sqrt{\text{Hz}}$	0.5 μ V	20 μ V	1 μ V/ $^{\circ}$ C	100 nA	55 V/ μ s

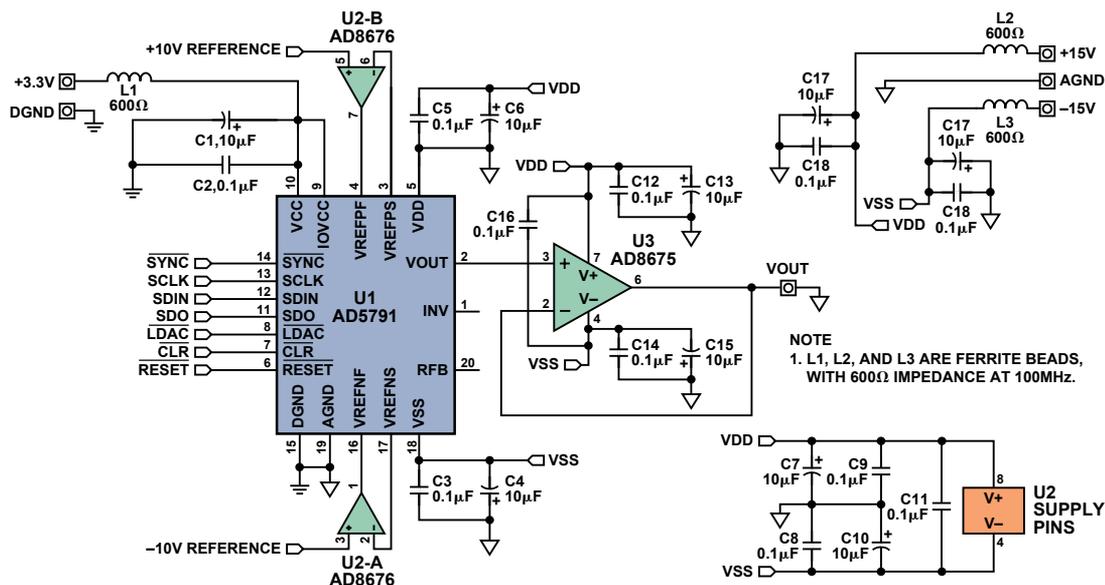


Figure 3. A 1-ppm accurate system using the AD5791 digital-to-analog converter.

The AD5791 Is Only the Beginning:

1-ppm Circuit Complexities

Even though precision sub-1-ppm components such as the AD5791 are available on the market, building a 1-ppm system is not a task that should be taken lightly or rushed into. Error sources that show up at this level of precision must be carefully considered. The major contributors to errors in 1-ppm-accurate circuits are noise, temperature drift, thermoelectric voltages, and physical stress. Precision circuit construction techniques should be followed to minimize the coupling and propagation of these errors throughout the circuit and the introduction of external interference. These considerations will be summarized here briefly. Further information can be found in the [References](#).

Noise

When operating at 1-ppm resolutions and accuracies, it is of utmost importance to keep noise levels to a minimum. The noise spectral density of the AD5791 is $9 \text{ nV}/\sqrt{\text{Hz}}$, mostly from the Johnson noise of the $3.4\text{-k}\Omega$ DAC resistance. All peripheral components should have smaller noise contributions to minimize increases to the system noise level. Resistor values should be less than the DAC resistance to ensure that their Johnson noise contribution will not significantly add to the root-sum-square overall noise level. The AD8676 reference buffers and the AD8675 output buffer have a specified noise density of $2.8 \text{ nV}/\sqrt{\text{Hz}}$, well below the DAC's contribution.

High-frequency noise can be eliminated relatively easily with simple R-C filters, but low-frequency $1/f$ noise in the 0.1-Hz to 10-Hz range cannot be easily filtered without affecting dc accuracy. The most effective method of minimizing $1/f$ noise is to ensure that it is never introduced into the circuit. The AD5791 generates about $0.6 \mu\text{V}$ p-p of noise in the 0.1-Hz to 10-Hz bandwidth, well below the 1-LSB level (1 LSB = $19 \mu\text{V}$ for a $\pm 10\text{-V}$ output span). The target for maximum $1/f$ noise in the entire circuit should be about 0.1 LSB, or $2 \mu\text{V}$; this can be ensured through proper component choice. The amplifiers in the circuit generate $0.1\text{-}\mu\text{V}$ p-p $1/f$ noise; the three amplifiers in the signal chain generate a total of approximately $0.2\text{-}\mu\text{V}$ p-p noise at the circuit output. Add this to the $0.6\text{-}\mu\text{V}$ p-p from the AD5791, and the total expected $1/f$ noise is about $0.8 \mu\text{V}$ p-p, a figure that closely correlates with the measurement displayed in Figure 5. This offers adequate margin for other circuitry that may be added, such as amplifiers, resistors, and a voltage reference.

Besides random noise, it is important to avoid errors caused by radiated, conducted, and induced electrical interference. Such techniques as shielding, guarding, and scrupulous attention to grounding and proper printed-circuit-board wiring techniques are imperative.

Temperature Drift

As with all precision circuits, drift of all components with temperature is a major source of error. The key to minimizing the drift as much as possible is to choose critical components with sub-1-ppm temperature coefficients. The AD5791 exhibits a very low $0.05\text{-ppm}/^\circ\text{C}$ temperature coefficient. The AD8676 reference buffers drift at $0.6 \mu\text{V}/^\circ\text{C}$, introducing an overall $0.03\text{-ppm}/^\circ\text{C}$ gain drift into the circuit; the AD8675 output buffer contributes a further $0.03\text{-ppm}/^\circ\text{C}$ output drift; this all adds up to a figure of $0.11 \text{ ppm}/^\circ\text{C}$. Low drift, thermally matched resistor networks should be used for scaling and gain circuits. Vishay bulk metal-foil voltage-divider resistors, series 300144Z and 300145Z, with a temperature coefficient of resistance tracking to $0.1 \text{ ppm}/^\circ\text{C}$, are recommended.

Thermoelectric Voltages

Thermoelectric voltages are the result of the Seebeck effect: temperature-dependent voltages are generated at dissimilar

metal junctions. Depending on the metallic components of the junction, the generated voltage can be anywhere from $0.2 \mu\text{V}/^\circ\text{C}$ to $1 \text{ mV}/^\circ\text{C}$. The best case, a copper-to-copper junction, will generate less than $0.2 \mu\text{V}/^\circ\text{C}$ of thermoelectric EMF. In the worst case, copper-to-copper-oxide can generate up to $1 \text{ mV}/^\circ\text{C}$ of thermoelectric voltage. This sensitivity to even small temperature fluctuations means that nearby dissipative elements or slow-moving air currents crossing over a printed circuit board (PCB) can create varying temperature gradients, which in turn generate varying thermoelectric voltages that are manifested as a low-frequency drift similar to low-frequency $1/f$ noise. Thermoelectric voltages can be avoided by ensuring that there are no dissimilar junctions in the system and/or eliminating thermal gradients. While it is virtually impossible to eliminate dissimilar metal junctions—many different metals exist in IC packaging, PCB circuits, wiring, and connectors—keeping all connections clean and oxide-free will go a long way to keeping thermoelectric voltages low. Enclosing the circuit to shield circuitry from air currents would be an effective thermoelectric voltage stabilizing method, and it could have the added value of providing electrical shielding. Figure 7 shows the difference in voltage drifts between a circuit that is open to air currents and one that is enclosed.

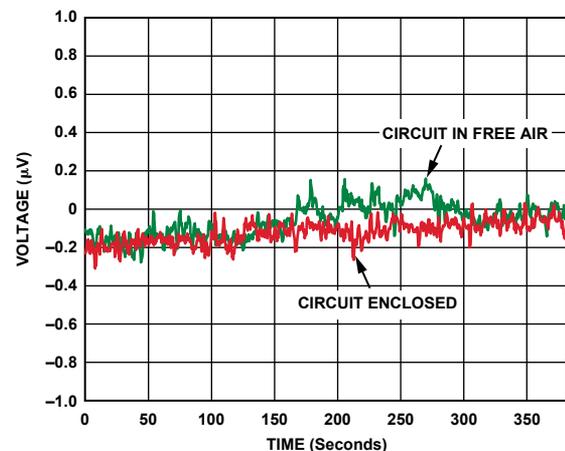


Figure 7. Voltage drift vs. time for open- and enclosed systems.

To cancel out the thermoelectric voltages, compensating junctions could be introduced into the circuit, a task that would involve considerable trial and error and iterative testing to ensure the correct pairing and positions of the inserted junctions. By far the most efficient method is to *reduce* the number of junctions in the circuit by minimizing component count in the signal path and stabilizing the local and ambient temperatures.

Physical Stress

High-precision analog semiconductor devices are sensitive to stress on their package. Stress relief compounds used within the packaging have a settling effect, but they cannot compensate for significant stress due to pressure exerted directly on the package by local sources, such as flexing of the PCB. The larger the printed circuit board, the more stress that a package could potentially suffer, so sensitive circuitry should be placed on as small a board as possible—with connection to the larger system through flexible or nonrigid connectors. If a large board cannot be avoided, stress relief cuts should be made around sensitive components, on two or (preferably) three sides of the component, greatly reducing the stress on the component due to board flexing.

Long-Term Stability

After noise and temperature drift, long-term stability deserves consideration. Precision analog ICs are very stable devices but do undergo long-term age-related changes. Long-term stability for the

AD5791 is typically better than 0.1 ppm/1000 hours at 125°C. The aging is not cumulative but follows a square root rule (if a device ages at 1 ppm/1000 hours, it ages at $\sqrt{2}$ ppm/2000 hours, $\sqrt{3}$ ppm/3000 hours, ...), and the time is typically 10 times longer for each 25°C reduction in temperature; so, at 85°C operation, one can expect aging of 0.1 ppm over a 10,000 hour period, approximately 60 weeks. If this is extrapolated, 0.32 ppm aging can be expected over a 10-year period, so the data sheet dc specifications can be expected to drift by 0.32 ppm over a 10-year period when operating at 85°C.

Circuit Construction and Layout

In a circuit where such a high level of accuracy is important, careful consideration of the power supply and ground return layout helps to ensure the rated performance. Design the PCB such that the analog and digital sections are separated and confined to separate areas of the board. If the DAC is in a system where multiple devices require an analog-to-digital ground connection, establish the connection at one point only. Establish the star-point ground as close as possible to the device. There should be ample power supply bypassing of 10 μ F in parallel with 0.1 μ F on each supply terminal, as close to the package as possible, ideally right up against the device. The 10- μ F capacitors should be of the tantalum bead type. The 0.1- μ F capacitor should have low effective series resistance (ESR) and low effective series inductance (ESL), such as the common multilayer ceramic types—to provide a low-impedance path to ground at high frequencies to handle transient currents due to internal logic switching. A series ferrite bead on each power supply line will further help to block high-frequency noise from getting through to the device.

The power supply traces should be as large as possible to provide low-impedance paths and reduce the effects of glitches on the power-supply line. Shield fast-switching signals, such as clocks, with digital ground to avoid radiating noise to other parts of the board. They should never be run near the reference inputs or under the package. It is essential to minimize noise on the reference inputs because it couples right through to the DAC output. Avoid crossover of digital and analog signals, and run traces on opposite sides of the board at right angles to each other to reduce the effects of feedthrough on the board.

Voltage Reference

Holding the performance of the entire circuit firmly within its grasp is the external voltage reference; its noise and temperature coefficient directly impact the system's absolute accuracy. To capitalize on the challenge posed by the 1-ppm AD5791 digital-to-analog converter, the reference and associated components should have temperature drift and noise specifications comparable to those of the DAC. Although a reference with temperature drift of 0.05 ppm/°C is nothing short of fantasy, 1 ppm/°C and 2 ppm/°C voltage references with 0.1-Hz to 10-Hz noise of less than 1 μ V p-p do exist.

Conclusion

As the accuracy requirements of precision instrumentation—and test and measurement applications—increase, more accurate components are being developed to meet these needs. They have guaranteed precision specifications at the 1-ppm level without further user calibration and are easy to use. However, when designing circuitry for this level of precision, one must bear in mind the many environmental and design-related challenges that exist. Successful precision-circuit performance will come as a result of considering and understanding these challenges and making correct component choices.

References

(Information on all ADI components can be found at www.analog.com.)

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Author

Maurice Egan [maurice.egan@analog.com] is an applications engineer with the Precision Converters Product Technology Group based in Limerick. Maurice joined Analog Devices in 1998 and holds a BEng in electronic engineering from the University of Limerick, Ireland.



Appendix

Figure 8 shows a block diagram of a typical contemporary 1 ppm DAC solution. The core of the circuit consists of two 16-bit digital-to-analog converters—a major DAC and a minor DAC—the outputs of which are scaled and combined to yield an increased resolution. The major DAC output is summed with the attenuated minor DAC output so that the minor DAC fills the resolution gaps between the major DAC's LSB steps.

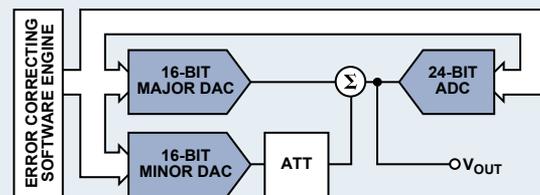


Figure 8.

The combined DAC outputs need to be monotonic, but not extremely linear, because high performance is achieved with constant voltage feedback via a precision analog-to-digital converter, which corrects for the inherent component errors; thus, the circuit accuracy is limited by the ADC rather than the DACs. However, because of the requirement for constant voltage feedback and the inevitable loop delay, the solution is slow, potentially requiring seconds to settle.

Although this circuit can, with significant endeavor, ultimately achieve 1 ppm accuracy, it is complex to design, likely to require multiple design iterations, and requires a software engine and precision ADC to achieve accuracy. To guarantee 1-ppm accuracy the ADC will also require correction—since an ADC with guaranteed 1-ppm linearity is not available. The simple block diagram of Figure 8 illustrates the concept, but the actual circuit in reality is far more complex, with multiple gain, attenuation, and summing stages, involving many components. Also required is significant digital circuitry to facilitate the interface between both DACs and the ADC—not to mention the software required for error correction.