How to Use the World's Smallest 24-Bit No Latency Delta-Sigma™ ADC to its Fullest Potential

Frequently Asked Questions About Delta-Sigma ADCs and the LTC2400

By Michael K. Mayes

Linear Technology's LTC®2400 is the world's first 24-bit ADC in an SO-8 Package. An innovative new delta-sigma architecture has been developed. The result is a small, highly accurate, simple-to-use delta-sigma ADC. This paper was created to educate users on several topics associated with delta-sigma converters and to dispel confusion associated with this new one-shot, or No Latency ΔΣ™, architecture. The key topics addressed here include speed, noise, PGAs, line frequency, rejection, input current, multiplexing, analog input range and key features differentiating the LTC2400 from other delta-sigma ADCs.

LTC2400 FREQUENTLY ASKED QUESTIONS

I. Questions Dealing with Speed

1. I currently use a competitor's delta sigma running at an output rate of 60Hz; can I run the LTC2400 at 60Hz?

Competition: For a 60Hz notch, most of the competition's output rates are 60Hz. However, 3 out of 4 output data are redundant; therefore these results can be thrown away. This, combined with the overhead of calibration and filter settling (up to an additional 3 conversion cycles), reduces the competitors' effective output rate below that of the LTC2400.

LTC2400: The output rate is defined by the notch frequency (f_0) divided by 8. For example, with a notch frequency of 60Hz, the output rate of the LTC2400 is 7.5Hz. Each data output contains nonredundant data. Additionally, the full scale and offset are calibrated transparently to the user for each conversion cycle. The LTC2400 combines all the data into one highly accurate result with much more rejection than the competition. There is no need for the user to sift through redundant data because the filter settles in a single conversion cycle.

2. I currently use a competitor's part running at a 1kHz data output rate with averaging to achieve low noise. Can the LTC2400 run at 1kHz output rate?

No, but for this application, the LTC2400 running at 7.5Hz output rate offers lower noise performance than the competition's running at 1kHz with averaging. Additionally, the competitors part running at 1kHz does not provide rejection of line frequencies (50Hz/60Hz); the user is required to add an external digital lowpass FIR filter to reject line frequency noise.

Competition: Running at 1kHz output rate, the peak-to-peak resolution degrades to 10 bits–12 bits (from 16 bits–20 bits). Averaging the 1kHz output rate 128 times improves the noise performance 3.5 bits. The final effective resolution is only increased to 13.5 bits to 15.5 bits. Additionally, the competitors' part does not reject 50Hz/60Hz.

LTC2400: Running at a 7.5Hz output rate, the LTC2400's noise performance is $1.5\mu V_{RMS}$ (21.6 bits). Additionally, the LTC2400 rejects line frequency noise (50Hz/60Hz + harmonics) by 120dB, without the need for an external DSP. The LTC2400 offers a highly accurate one-shot result, removing the burden of external averaging or digital filtering.

3. What applications are suitable for the LTC2400?

The LTC2400 is the ideal converter for any application requiring high DC accuracy. These applications include DC voltage/current measurements, gas analysis, weigh scales, temperature measurements (thermocouples, RTDs, thermistors), battery charging/monitoring, portable handheld instrumentation, smart transmitters, DC multiplexed data acquisition and digital panel meters.

4. What applications are not intended for the LTC2400?

Digital audio, seismic and signal acquisition applications.

5. What is the maximum conversion rate I can achieve with the LTC2400?

The maximum conversion rate for this particular part is 15Hz (with 120Hz rejection).

6. What does the FFT of the conversion result look like?

There is no FFT associated with the LTC2400. Each conversion is a single-shot result, statistically independent from previous conversion cycles. It is a true DC accurate converter. The filter response may be determined by sweeping the input frequency and calculating the RMS noise associated with the corresponding output.

II. Questions Dealing with Noise and PGAs

1. Do I need a PGA with the LTC2400 (the competitive parts have built-in PGAs)?

No, a PGA is not required with the LTC2400.

Competition: Competitor's ADCs require complex programming of status registers, flushing of filters between PGA gain changes, and are limited to a reduced input range of 0V to V_{REF} divided by the PGA gain.

LTC2400: The ultralow noise performance of the LTC2400 (0.3ppm RMS) combined with total unadjusted errors less than 10ppm enable direct digitizing of low level signals. The input range is not limited to V_{REF}/PGA gain; the part gives equivalent performance over a much wider input range of (–0.125 • V_{REF}) to (1.125 • V_{REF}).

2. How does the noise performance of the LTC2400 compare to that of other delta-sigma converters?

LTC2400: The LTC2400 is the world's quietest delta-sigma ADC. With an input range of 0V to 5V, the RMS noise is 0.3ppm or 1.5µV_{RMS}. This translates to an effective resolution of 21.6 bits.

Competition: The best competition noise performance is 5.3µV_{RMS} (or 19.8 bits) on a ±2.5V input.

3. How does the LTC2400 noise performance change with input voltage?

Competition: Many low noise delta-sigma converters use second order modulators. This approach results in a phenomenon known as fixed pattern noise. As a result, the RMS noise performance of the device depends on the input voltage. The user sees sparkle codes or large noise spikes in the conversion results. The part behaves worse than the specifications state.

LTC2400: The LTC2400 uses a 3rd-order modulator instead of a 2nd-order modulator. This results in noise performance of 1.5µV_{RMS}, independent of the input voltage.

4. What is the effect on noise if I lower V_{REF}?

The noise in µV_{RMS} is independent of V_{REF}. However, the noise in LSB or ppm of full scale is inversely proportional with the reference. For every halving of V_{REF}, the noise in ppm of full scale doubles.The noise at V_{REF} = 5V is 0.3ppm RMS and at V_{REF} = 2.5V is 0.6ppm RMS.

5. How do I measure a small voltage range (100mV) sitting on top of a large DC offset (several volts)?

Competition: The competition limits the maximum input voltage to V_{REF} divided by the PGA gain. As a result, digitizing microvolts sitting on top of volts is difficult. One method requires high PGA gain and an external analog circuit to level shift the input down to 0V from the large DC offset. A second method requires a PGA gain of 1 at the expense of the large RMS noise and large INL errors.

LTC2400: Simply digitize directly. The noise of the LTC2400 is 1.5µV_{RMS}. Additionally, the total unadjusted error of the LTC2400 is 10ppm (many times better then the competition). This enables very accurate measurements of a microvolt input signals independent of the large DC offset voltage.

III. Questions Dealing with Line-Frequency Rejection

1. What is the rejection with 2% variations in line frequency?

Competition: The competition uses 3rd-order sinc (sinx/x) filters. The rejection at ±2% is 100dB even with a very precise external clock (i.e., very low jitter).

LTC2400: The LTC2400 combines a 4th-order sinc filter with a highly accurate, on-chip, low drift oscillator. The filter rejection is 120dB for 60Hz ±2% without requiring any external frequency-setting components.

2. How accurate a clock do I need to generate for my own notch frequency other than 50Hz or 60Hz?

Competition: Other delta-sigma converters incorporate a 1st- or 3rd-order sinc filter. A 3rd-order sinc filter requires the external clock accuracy within ±1% to reject 120dB and ±2% to reject 100dB.

LTC2400: As a result of the 4th-order sinc filter, an external clock can vary up to ±3% and the filter will still reject 120dB. Variations of 5% will still reject >100dB.

3. What value external clock frequency do I need to apply for an 8Hz rejection?

The relationship between notch frequency (f_0) and the externally applied clock frequency (f_{EXT}) is $f_{EXT} = 2560 \bullet f_0$. Therefore, an 8Hz notch frequency is achieved by applying a 20,480Hz clock at pin f_0.

4. How can I get 120dB rejection for 50Hz and 60Hz simultaneously?

Set the notch frequency to 10Hz (f_{EXT} = 25.600kHz). Since the sinc filter rejects the notch frequency (f_0) and its harmonics, both 50Hz and 60Hz are rejected 120dB.

5. For a 60Hz rejection frequency, what is the rejection at 120Hz?

The rejection at 120Hz is in excess of 120dB. The sinc filter rejects 60Hz (f_0) and all its harmonics up to the internal sampling frequency ($f_S = 256 \bullet f_0$ = 15,360Hz).

6. What are the effects of aliasing?

One of the advantages of delta-sigma converters is the reduction in antialiasing filter complexity. Typically, a simple single-pole filter at the input is sufficient to remove aliasing components at the multiples of the internal sample rate ($f_S = 256 \bullet f_0$ = 15,360Hz). This is a common feature of the LTC2400 and other delta-sigma ADCs.

7. If I externally set the notch frequency to 120Hz, what is the rejection at 60Hz?

Delta-sigma ADCs do not significantly reject frequencies below the first notch frequency.

Competition: The rejection is 11.7dB at 60Hz ($sinc^3$ filter).

LTC2400: The rejection is 15.9dB at 60Hz ($sinc^4$ filter).

8. What is the rejection of a 60Hz signal applied to the power supply pin? The V_{REF} Pin?

Competition: In order for the competition to achieve their noise performance, several supply and ground pins are required. This adds complexity to the user's board in terms of supply/ground routing and bypassing.

LTC2400: The LTC2400 has one ground pin common to the input, reference, supply, and digital I/O reducing layout board area. The single supply and the reference pin reject 60Hz noise better than 120dB.

IV. Questions Dealing with Multiplexing

1. Is it possible to put a multiplexer in front of a delta-sigma ADC?

Competition: Due to the long digital filter settling times associated with these converters, multiplexing is difficult and time consuming.

LTC2400: Simple. Convert, read the result, change the channel, convert, read the result, change the channel,... There is no difference between the LTC2400 and conventional SAR ADCs with respect to multiplexing. The LTC2400 utilizes a single-shot conversion, or No Latency $\Delta\Sigma$, architecture.

2. What is the settling time of the converter?

Competition: Other delta-sigma converters require the internal digital filter to accumulate data for several conversion cycles. This forces the user to discard the first 3 or 4 conversion results after the input is changed or a multiplexer is switched.

LTC2400: The LTC2400 has no filter settling time. There is a one-to-one correspondence between the conversion result and the analog input. As a result the LTC2400 is simple to multiplex.

V. Questions Dealing with Input Signal Range

1. What is the input range of the LTC2400?

Competition: The competition limits the input range from 0V to V_{REF}, for single supply operation. For a 2.5V reference, the input range is 0V to 2.5V.

LTC2400: On a single supply, the LTC2400 can convert input signals 12.5% of V_{REF} below ground up to 12.5% above V_{REF}. With a 2.5V reference, the input range is –300mV to 2.8V. With a 5V reference, the input range is –300mV to 5.3V.

2. How far below ground does the LTC2400 still accurately convert?

Competition: Competitors delta-sigma converters, utilizing a single supply, cannot convert below ground (0V) or require external charge pump circuitry.

LTC2400: The LTC2400 is live at zero. The input can go as low as 300mV below ground (even with a single 5V supply) and 300mV above V_{REF}.

3. In the extended input range, what is the data out format?

Competition: Does not allow the user to drive the inputs above V_{REF} or below GND. They either become unstable or clamp the outputs.

LTC2400: Within the normal input voltage range (V_{IN} = 0V to V_{REF}) the digital output ranges from 00000_H to $FFFFF_H$. If the analog input voltage exceeds V_{REF}, an overrange bit is set and the remaining 24 bits correspond to the measured overvoltage. If the analog input is below ground, a sign bit is set high and the digital output becomes two's compliment indicating the measured voltage below GND.

4. What happens to the digital output code if the extended input range is exceeded?

The digital output remains constant at 12.5% above full scale or below ground. Beyond 300mV above V_{CC} or below ground, the input ESD protection diodes begin to forward bias. In extreme cases where the voltage applied to the LTC2400 can exceed these limits, the input current can be limited with an external resistor up to 10k.

VI. Questions Dealing with Input Impedance.

1. What does the input impedance look like?

Competition: Some competitive parts have very high input impedance, and near zero input current. These parts use an internal buffer to isolate the switched-capacitor modulator from the input. These buffers result in major limitations on input swing (50mV above ground and 1.5V below V_{CC}). Most applications do not use this buffer due to its limited input range and output stage's inability to pull to GND. The resulting input impedance without this buffer is similar to that of the LTC2400.

LTC2400: The input to the LTC2400 is a fixed 10pF capacitor, and a dynamic switched-capacitor load equivalent to 1.66MΩ.

2. What is the effect of the input impedance if I have an external resistance in series with the device?

Competition and LTC2400: An external source resistance increases the RC time constant associated with charging the ADC's internal capacitor. In order to achieve 20 bits of accuracy, the input signal applied to the ADC must settle to 14 time constants within the sampling window.

The LTC2400 has an internal sampling capacitor of 10pF and a parasitic input resistance of 5k. The sampling window is 6.5µs. Therefore, the maximum time constant allowed is 6.5µs/14 = 464ns. The resulting maximum external source resistance is 464ns/10pF – 5k = 41.4k. This is an approximation neglecting the effects of input parasitic capacitance. Practically, source resistors up to 10k can be used.

3. If the external source resistance is nonlinear, what is the effect on the linearity of the ADC?

As long as the input settles to 14 time constants within 6.5µs, the input source resistance nonlinearities have no effect on the ADC linearity.

4. What is the effect of the input impedance if an RC filter is used on the input with an external RC time constant greater than 6.5µs/14 time constants?

This results in a overall system gain error. This error is zero at $V_{IN} = V_{REF}/2$, maximum at $V_{IN} = V_{REF}$. For every 3Ω of input source resistance, this error is 1ppm at $V_{IN} = V_{REF}$ and –1ppm at $V_{IN} = 0V$.

VII. Miscellaneous

1. How does the performance change with supply voltage?

Competition: These delta-sigma converters cannot guarantee performance over the entire 2.7V to 5.5V supply range. They typically specify two separate parts, one guaranteed 2.7V to 3.3V and the other 4.5V to 5.5V.

LTC2400: Its performance characteristics are guaranteed for supply voltages from 2.7V to 5.5V, inclusive.

2. What is the effect on INL if I lower V_{REF}?

The INL performance is improved as V_{REF} is reduced. At V_{REF} = 5V, the INL error is 4ppm (0.0004%). At V_{REF} = 2.5V, the INL is 2ppm (0.0002%).

3. How was Linear Technology able to squeeze the LTC2400 into an SO-8 package when no one else could?

Competition: 24-pin DIPs, 28-lead SO, multiple power supply pins, complex user interfaces and external crystals.

LTC2400: The advantage the LTC2400 has over the competitors is an innovative, simple digital sinc filter architecture. This enables the combination of a small die size with an analog optimized process. The result is a highly accurate, S0-8 package, delta-sigma ADC not requiring an external crystal.

4. What are the resolution, linearity and accuracy of the LTC2400 compared to those of other delta-sigma converters?

Resolution: Resolution is typically defined as the noise performance of the ADC in bits. The resolution in bits is: Resolution = $\text{Log}_{10}(V_{REF}/\text{RMSnoise})/\text{Log}_{10}(2)$. The LTC2400 is 21.6 bits and the competition is all below 20 bits. Some competitors claim more than 20 bits; however, they are using a 2nd-order modulator, so the real noise seen by the user is significantly higher than the specification seen in the data sheet.

Linearity: Linearity is defined as the deviation from a straight line drawn from V_{REF} = 0V to V_{IN} = V_{REF} (ignoring offset and full-scale errors). The LTC2400 has a linearity error of 4ppm (18 bits) compared to 30ppm (15 bits) for the competition. Note: 1ppm = 1part per million = 0.0001%

Accuracy: Accuracy is defined as the offset error + full-scale error + linearity error + noise + drift. The LTC2400 is the world's most accurate No Latency $\Delta\Sigma$ ADC. The offset error is less than 1ppm. The drift of the offset with temperature is less than 0.01ppm/°C. The full-scale error is 4ppm, with a drift of 0.02ppm/°C. The linearity is 4ppm, and the noise is 0.3ppm RMS.

VII. Key Features Differentiating the LTC2400 from the Competition

1. S0-8 Package—The LTC2400 is the smallest 24-bit ADC on the market.
2. Absolute Accuracy—The total unadjusted error (TUE) of the LTC2400 is less than 10ppm over 2.7V to 5.5V supply and –45°C to 85°C operation.
3. On-Chip Oscillator—The LTC2400 does not require external crystals or oscillators.
4. Live at Zero—The LTC2400 continues to resolve signals below ground up to –12.5% of V_{REF}.
5. Overrange—The LTC2400 continues to resolve signals above V_{REF} up to 12.5% of V_{REF}.
6. High Accuracy INL—The integral nonlinearity of the LTC2400 is 4ppm with a 5V reference and 2ppm with a 2.5V reference
7. High Accuracy DNL—The LTC2400 outputs 24 bits with no missing codes (guaranteed monotonic).
8. Low Noise—0.3ppm RMS (1.5µV_{RMS}) noise.
9. Ultralow Offset—The offset of the LTC2400 is within 1ppm.
10. Very Low Offset Drift—The offset of the LTC2400 drifts less than 1ppm over the entire temperature range –45°C to 85°C. This corresponds to 0.01ppm/°C drift. No external calibration is required.
11. Very Low Full-Scale Error—The full-scale error of the LTC2400 is within 4ppm. No external calibration is required.
12. Low Full-Scale Drift—The full scale of the LTC2400 drifts less than 2ppm over the entire temperature range –45°C to 85°C. This corresponds to 0.02ppm/°C drift.
13. No Calibration Required—The LTC2400 performs offset/full-scale calibration transparently to the user. Calibration is interleaved continuously within the conversion cycle.
14. Pin Selectable 50Hz/60Hz Notch Frequency—The LTC2400 internal oscillator can be set to reject 50Hz or 60Hz by simply tying the f_0 pin High (50Hz) or Low (60Hz).
15. Simple to Use—The LTC2400 does not contain the overhead of status registers and configuration registers.
16. Superior Rejection—The LTC2400 contains a 4th-order sinc filter. This allows 120dB rejection of line frequencies ±2%, with an on-chip highly accurate oscillator.
17. Flexible Reference Input—V_{REF} may be equal to V_{CC} or as low as 0.1V.
18. Low Supply Current—The LTC2400 consumes 200µA during conversion and 20µA during autoshutdown.
19. Wide Supply Range—The LTC2400 operates from 2.7V to 5.5V supply range.

Linear Technology Corporation
1630 McCarthy Blvd., Milpitas, CA 95035-7417
(408)432-1900 • FAX: (408) 434-0507 • www.linear-tech.com

an80 LT/TP 0799 4K • PRINTED IN USA

LINEAR TECHNOLOGY