

## Dealing with noise on ZoomingADC

### 1. Introduction

With its three amplification stages, the ZoomingADC is able to amplify the input signal up to 1000 times. What are the benefits of this big amplification? How can I improve the linearity?

This Technical Note discusses the Programmable Gain Amplifier (PGA) of the ZoomingADC. It gives some advice to best use it.

### 2. Input circuit

The ZoomingADC is used in many Semtech sensing products from the simple SX8725 to the more complex XE8000. It always integrates a multiplexer and a PGA before the Sigma-Delta modulator.

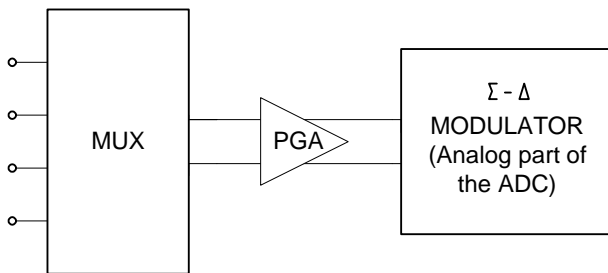


Figure 1. The PGA before the ADC

The Zooming ADC has an architecture composed of 3 amplifiers with 2 offset cancellation stages.

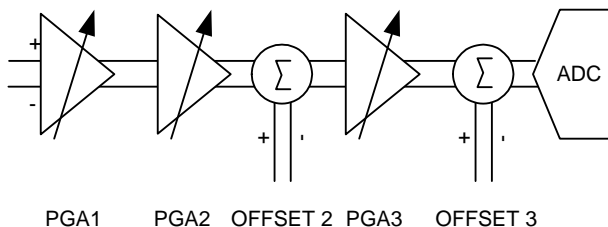


Figure 2. ZoomingADC architecture

The offset cancellation permits to recenter the signal and not saturate the amplifier. By this way a high gain setting is possible even if the signal has a DC component.

### 3. Linearity

The total gain is calculated by multiplying the gain of the 3 stages. If a PGA is not used it should be disabled: the current consumption is decreased and no noise is added to the signal.

The gain depends on the full scale input voltage. It is recommended to take margin for temperature drift then the maximal gain should be around:

$$gain = \frac{FullScaleInputVoltage}{VBATT} \times 0.8$$

The first PGA is designed for millivolts full scale signal. If the total gain is less than 100, it should not be enabled. Its transfer function is very linear while its output is in the range  $\pm VBATT/5$ .

PGA2 has an offset cancelling block to recenter the signal around 0. It is possible to add or subtract an offset up to  $VBATT$ . The output should not be more than  $\pm VBATT/2$  after offset cancellation to preserve the good INL of the circuit.

PGA3 is directly connected to the ADC. It is linear on all the range. PGA3 output range should match  $\pm Vref/2$  which is the ADC input range.

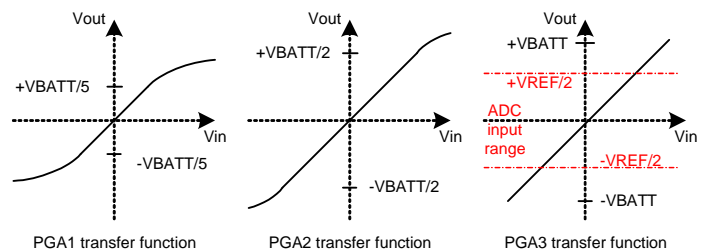


Figure 3. PGA transfer functions

Linearity is an important characteristic when sensor are used because a good linearity gives a good accuracy on the measurement.

To make the amplification optimized in linearity, output of the first stages (PGA1, PGA2) should be as little as possible and less than  $\pm VBATT/5$  and  $\pm VBATT/2$  respectively. That is the case when the strongest gain is set on the stage closest of the ADC. The gain is set first on PGA3 then PGA2 and at last on PGA1 if needed.

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For example, a total gain of 50 is set with PGA3=10, PGA2=5 and PGA1 disabled.

For more explanation on the way to set the gain, see the application note AN8725: Understanding pressure measuring with SX8725.

### 4. Noise

The quantization noise of the ADC is different than the PGA thermal noise. The quantization noise comes from the rounding error between the analog input voltage to the ADC and the output digitized value. This noise is signal-dependent and varies with the ADC resolution.

The quantization noise of an ADC with a full scale input signal is  $n_q = \frac{q}{\sqrt{12}}$  where q is the LSB size in volt.

Thermal noise comes from the thermal agitation of electrons. It varies with temperature. The thermal noise of a resistor R at temperature T measured on the bandwidth B is given by the following equation:

$$V_n = \sqrt{4kTRB} \text{ (k is the Boltzmann's constant)}$$

We can predict that a cold circuit with narrow band signal will produce less noise than a circuit in a hot environment with large band signal.

The noise in the ZoomingADC is random and follow a Gaussian distribution. Consequently, the probability that an output code is in a certain range is computable. The standard deviation of the data set is the RMS noise level.

$$\sigma = RMSnoise$$

A little bit more than 68% of the output code value are located around  $\pm\sigma$  of the data set mean as shown in figure 4.

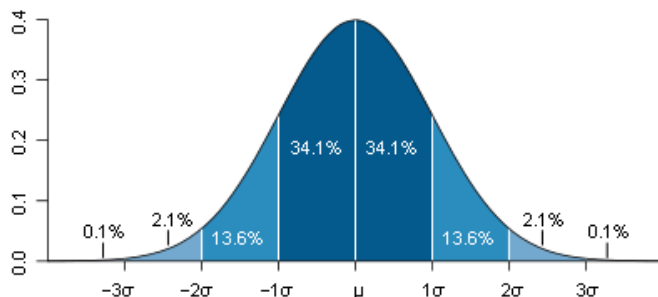


Figure 4. Gaussian curve

We could think that a noise voltage superior to  $4\sigma$  couldn't occur. In fact, it can occur but because the probability is very low the observation time to see this evenement is high.

Therefore, a noise requirement should give a noise threshold to not be exceed with a probability.

For a given percentage of good reading, the standard deviation has to be multiplied by a number given in table 1.

The multiplication factor of 6.6 is often use to compute a peak-peak noise from a rms value. It is a conservative value which implies that 99.9% of the reading are in the noise specification.

Probability that a reading is in the specification(%)	Width of the interval
68.2	2
80	2.56
90	3.28
95	3.92
98	4.66
99	5.16
99.9	6.58

Table 1. Confidence intervals

### 5. Noise on ZoomingADC

In the ZoomingADC, enabling a PGA add a certain amount of noise to the input signal.

The noise measured at the output of PGA3 is the sum of the noise made by PGA1, PGA2 and PGA3. But noise signals are random and uncorrelated. The equivalent RMS is the square root of the sum of the squares.

When PGA1 is turned on, the noise generated at the output of PGA1 is amplified by PGA2 and PGA3. As it can be the dominant noise source, it has been designed carefully to minimise the noise.

The noise measured at the output is often given in volt rms. Mathematically, it is the root of the mean squared voltage. The output noise can be brought back at the input by being dividing by the gain. It is then called input referred noise. The input referred noise formula of the ZoomingADC is given below:

$$InputNoise = \sqrt{\left(\frac{Vn3}{G3 \cdot G2 \cdot G1}\right)^2 + \left(\frac{Vn2}{G2 \cdot G1}\right)^2 + \left(\frac{Vn1}{G1}\right)^2}$$

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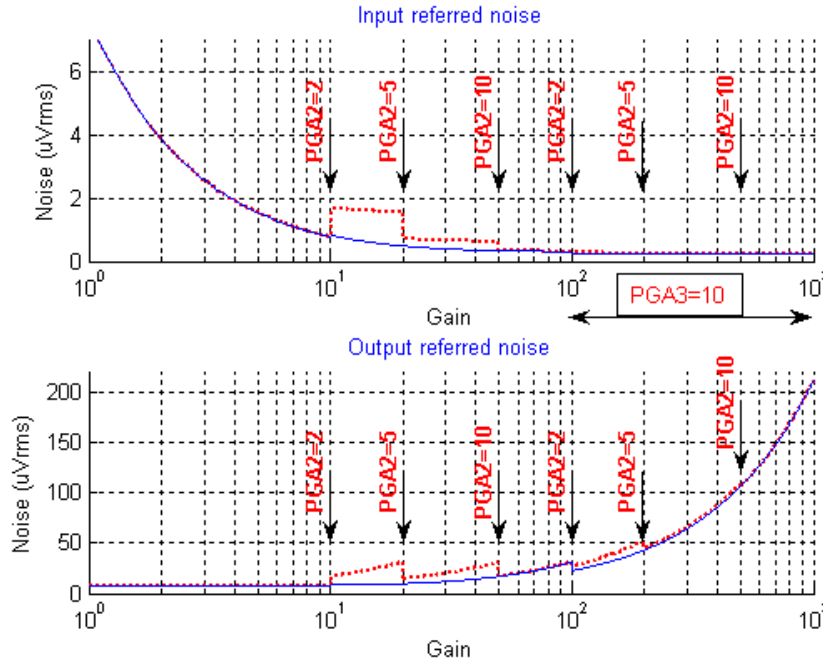


Figure 5. SX8724 Input and output noise  
 fs=500 kHz, OSR=1024, NELCONV=8, Update Rate = 60.97 Hz

OSR and NELCONV are two parameters of the Zooming ADC which set the resolution.

Vn3, Vn2 and Vn1 are respectively the equivalent noise voltage source created by PGA3, PGA2 and PGA1. Vn3=696uV, Vn2=271uV and Vn1=189uV on the SX8724.

The variable Over Sampling Ratio (OSR) and Number of Elementary Conversion (NELCONV) allows noise reduction by averaging.

It is easy to show that for a given gain, the noise could be reduced if the bigger gain is set on the first stages. For example a gain of 500 could be set with PGA1=10, PGA2=10 and PGA3=5 to minimize the noise but be cautious that the output voltage of each amplifier is on the correct linear range.

It is in contradiction with the previous section on linearity which states the biggest gain on the last stage. depending on the application, a trade-off has to be done between noise and linearity.

The curve on figure 5 shows the output and input noise when the SX8724 is set with the maximum of resolution (OSR=1024, NELCONV=8). The red dotted line curve ( shows the noise when the application is optimized in linearity. It presents unsteadiness corresponding to the gain

setting change. The various setting are indicated with arrows.

The blue solid line curve shows the noise for an application optimized in noise. Actually, the noise is lower especially when the gain is around 10 and 100 but the linearity can be degraded.

On the graph of figure 6, from the point OSR=1024, NELCONV=8 to the point OSR=64, NELCONV=1, each successive point is reached by decreasing OSR or NELCONV by a factor of 2.

One can conclude that multiplying OSR or NELCONV by 2 decreases the noise and the data rate by a factor of  $\sqrt{2}$ .

The effective bandwidth is also decreased by  $\sqrt{2}$ .

As a resistor, decreasing the bandwidth lowers the noise.

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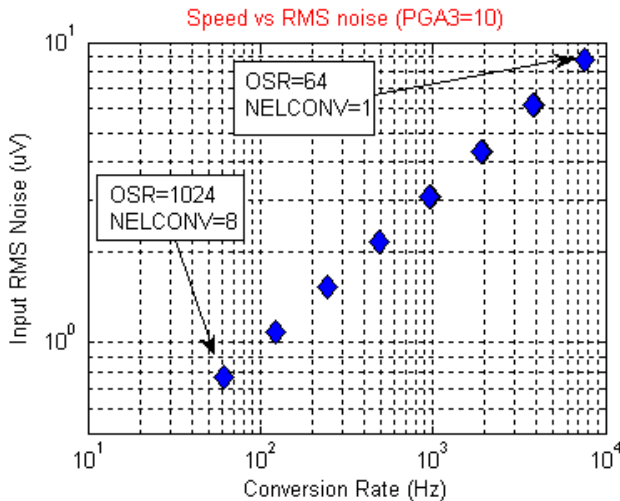


Figure 6. Speed vs. PGA RMS noise for  $f_s=500\text{kHz}$

## 6. ADC resolution

The ADC resolution is also set by setting OSR and NELCONV. The resolution can be set from 6 to 16 bits. The update rate varies with the resolution.

Because of the noise shaping features of the Sigma Delta ADC quantization noise is 2 times better filtered when OSR is doubled than when NELCONV is doubled. That is why the ADC theoretical resolution  $n$  up to 16 bits is given by the following equation:

$$n = 2 \times \log_2(OSR) + \log_2(NELCONV)$$

Even though the resolution is truncated to 16 bit by the output register size, it may make sense to set OSR and NELCONV to higher values in order to lower the bandwidth thus to reduce the influence of the thermal noise in the PGA.

## 7. Input resolution

The primary benefits of having a PGA is that the equivalent input noise decreases when the gain is increased. In other terms, the Signal to Noise Ratio (SNR) increase. In the ideal case, with a gain of 2, the input resolution is doubled. With a gain of 1000, the input resolution is divided by 1000 then it's like the ADC has increased its resolution by almost 10 bits. That is why amplifying a small signal is necessary to gain in resolution.

The input referred resolution is given by the following equation:

$$InputResolution = \frac{LSB}{gain}$$

One could say: the maximum gain you set, the better input resolution you get.

But in fact, it's not as simple because as seen previously the amplifier adds noise to the signal. Enabling PGA3 for example add  $5.9 \mu\text{V}_{\text{rms}}$  of noise which is  $36 \mu\text{V}_{\text{pp}}$  at the output of the amplifier. The LSB size (when gain=1) of a 16 bit ADC with a 3.3V supply is  $50 \mu\text{V}$ . It is bigger than PGA3 noise. Therefore enabling PGA3 to match the amplifier's output range to the input range of the ADC is always efficient.

The typical output and input noise of a SX8724 set up with NELCONV=8, OSR=1024 and various gain is shown on table 2.

Gain	Amplifier output RMS Noise ( $\mu\text{V}$ )	Input referred RMS noise ( $\mu\text{V}$ )
10	5.91	0.591
20	32.3	1.615
50	33.1	0.662
100	33.9	0.339
200	53.7	0.2685
500	111	0.222
1000	208	0.208

Table 2 SX8724 in 16bits mode ( $V_{\text{BATT}}=3.3\text{V}$ )  
Update Rate = 60.97 Hz

The noise free code resolution of an ADC is the number of bits of resolution beyond which it is impossible to distinctly resolve individual codes. When the gain increase, the noise free counts decrease because of the noise effect. This can be seen on table 3.

Gain	Output noise (LSB)	Noise free counts	Noise free code resolution
10	>1	65536	16
20	4.2	15604	13.9
50	4.3	15241	13.9
100	4.4	14895	13.9
200	7	9362	13.2
500	14.5	4520	12.1
1000	27.3	2401	11.2

Table 3 Noise free counts and code resolution

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However the input referred resolution does improve with gain. For example, a 20 mV full-scale input signal can be converted with 50uVpp noise resolution which corresponds to the quantization noise when the ADC is supplied in 3.3V and the gain is set to 1. If the same signal is converted with a gain of 100, the noise resolution is  $(4.4 \times 50 / 100) = 2.2 \mu\text{Vpp}$ .

Resolution	Pressure resolution (Pa)	Average size	Right shift	Maximum bandwidth (Hz)
16 bit	1	1		500
17 bit	0.5	4	>>1	125
18 bit	0.25	16	>>2	31.25
19 bit	0.125	64	>>3	7.8
20 bit	0.0625	256	>>4	1.95

Table 4 Average to increase resolution

### 8. Increasing the resolution

Digital filtering permits to increase the resolution to the detriment of the data rate.

Dividing the data rate by 2 decreases the noise voltage level by  $\sqrt{2}$  and increase the resolution of the measurement by 0.5 bit.

In a more general way, for each additional bit of resolution  $n$  added, the signal must be oversampled four times. This technique uses the theory of oversampling and decimation. It assumes that:

- ◆ The signal-component of interest should not vary significantly during a conversion
- ◆ The amplitude of the noise should be at least 1 LSB.

To show the efficiency of the method, we can take an example. The measurement of a hyperbaric chamber must be done with a great resolution. The range of the pressure is 0-65535 Pa. The pressure is stable for several hours but has to be measured accurately.

A resolution of 0.1 Pa must be resolved for this application. Therefore an ADC with a noise free count of at least 650k samples is required which means a 20 bit ADC is needed.

The ZoomingADC is used for its ability to interface easily a pressure sensor. It is set to 16 bit with an update rate of 1000 samples per second. One set of 256 samples are taken.

The pressure input range is the exact resolution of the 16 bit ADC, therefore the resolution is 1 Pa. To achieve 20 bit of resolution, 256 samples must be averaged. The trade-off is the output rate (or the bandwidth) has been divided by 256 and the CPU usage has increased.

### 9. Measuring noise

The SX8724 evaluation kit (ref. XE8000EV121) can be used to measure the noise on the ZoomingADC.

The input should be grounded or connected to a DC source. The software permits to set the various parameter of the ADC (Gain, Sample rate) and collect a data set. The standard deviation gives the RMS noise level of the circuit and the histogram permit to check that the noise is Gaussian. If the noise is not Gaussian, it could indicate either a bad PC board layout, poor grounding techniques or improper power supply decoupling.

The following figure show a measure of the noise taken with 10000 output codes on a SX8724 set with a gain of 500.

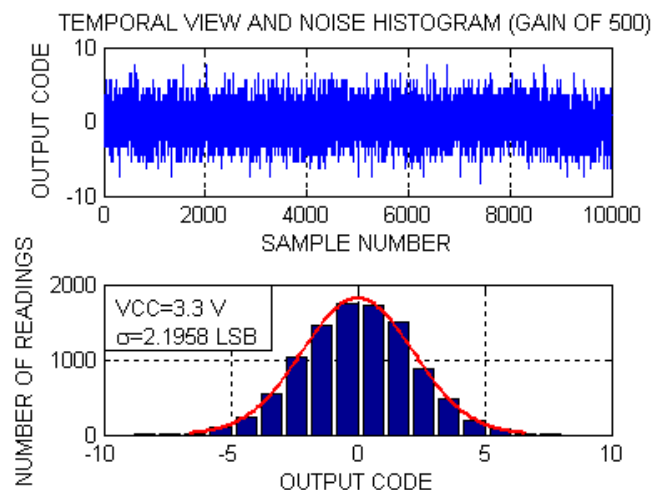
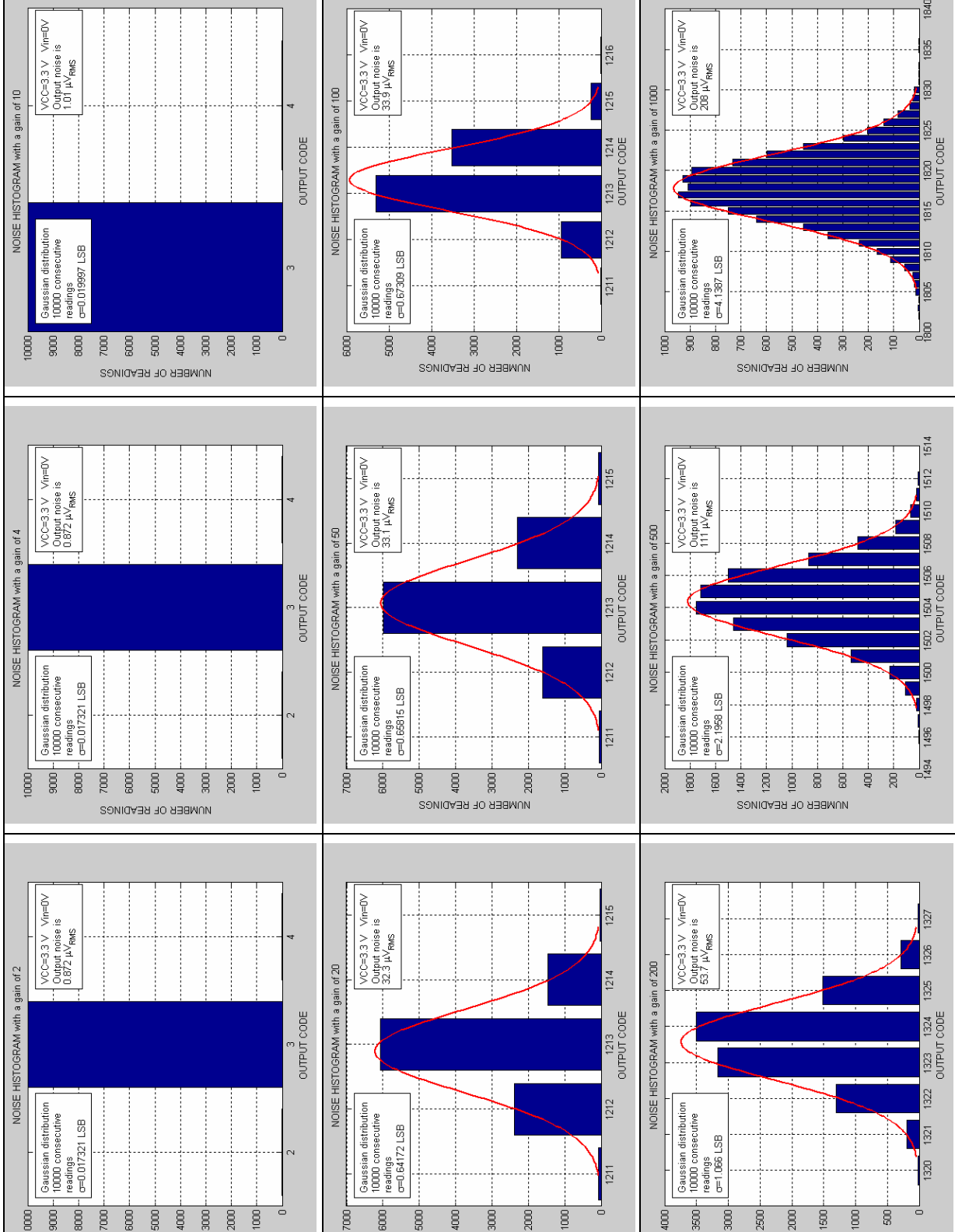


Figure 7. SX8724 noise with OSR=1024, NELCONV=8

In concordance with table 2, you can find in appendix the noise histogram for various gain settings for the SX8724.

### Appendix: Noise histogram

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