

Introduction to High Performance Digitizer Theory

Application Note



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1 Definitions & Abbreviations

Table 1 lists the definitions and abbreviations used in this document and provides an explanation for each entry.

Table 1: Definitions and abbreviations used in this document.

Term	Explanation
ADC	Analog-to-digital converter
ADQ14	TSPD's 14-bit, 2 GSPS digitizer platform, 2 or 4 channels
ADQ7	TSPD's 14-bit, 10 GSPS digitizer platform, 1-2 channels
AFE	Analog front-end
API	Application programming interface
DC offset	Analog DC level which is added to the input signal inside the digitizer to move it vertically
ENOB	Effective number of bits
FIR	Finite impulse response
fs	Femto (10^{-15}) seconds
FW	Firmware (digitizer feature set)
GSPS	Giga (10^9) samples per second
LNA	Low noise amplifier
NF	Noise figure
NPSD	Noise power spectral density
RL	Return loss
RMS	Root mean square
SDK	Software development kit
SNR	Signal-to-noise ratio
SQNR	Signal-to-quantization-noise ratio
Trigger	A real-time event starting the acquisition of a record
VFS	Voltage Full Scale
Vpp	Voltage peak-to-peak
Waveform	Analog signal with a distribution in time, digitized into a record

2 Introduction



Teledyne SP Devices' ADQ series of digitizers are market leading in the 14-bit high speed segment. Such high performance digitizer opens for new measurements that was not previously possible. This application note gives an introduction to high performance digitizer theory including the critical parameters

- signal power
- noise level
- reflections (impedance mismatch)

An outline on how to connect the input signal to the digitizer to best utilize the advantage of the signal quality due to the high vertical resolution is given. The line of thoughts for an optimized solution is proposed.

3 Benefits of a High Vertical Resolution

Traditional GPS digitizers operate with 8 bits vertical resolution. A vertical resolution of 8 bits means that the digital representation consist of $2^8 = 256$ different amplitude levels. The noise level in such digitizers is typically on a 7 bits level which leaves a dynamic range related to the value $2^7 = 128$, see first row in Table 2.

A 14-bit digitizer operate with 14 bits digital representation, leading to $2^{14} = 16\,384$ different amplitude levels. The noise level is typically on the 10-bit level, implying a dynamic range related to $2^{10} = 1024$. The dynamic range is thus eight times larger than for the 8-bit digitizer. See Table 2 for a collocation of the numbers. The effect is that *8 times weaker* signal can be detected with the 14-bit digitizer. More about definitions of signals and noise in Section 4.

Table 2: Comparison between 8 and 14 bits vertical resolution and how the number of bits affect the dynamic range.

Vertical resolution	Amplitude levels	Typical noise level	Dynamic range
8	256	7	128
14	16 384	10	1024

Note

An eight times weaker signal can be detected with a 14-bit digitizer, compared to an 8-bit one.

3.1 Systems Revelation with Lowered Noise Floor

Compared to an 8-bit resolution, digitizers with 14 bits vertical resolution takes the performance to a new level. Not only eight times weaker signals are revealed but also system artifacts as illustrated in Fig. 1. These tones and peaks were always there, but they where hidden by the noise. One example of previously hidden tones is reflections, which will be covered in Section 6. Another is harmonic distortion.

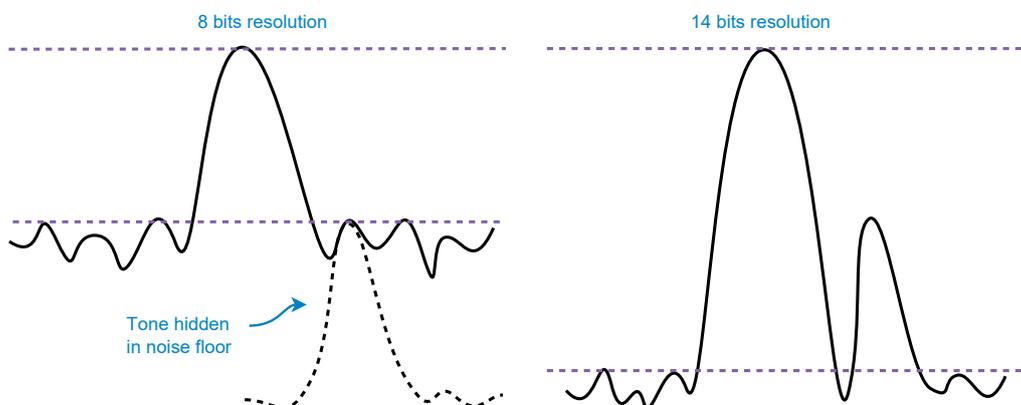


Figure 1: With increased resolution, from 8 bits (left) to 14 bits (right), tones that were hidden in the noise is now seen clearly.

4 Tutorial on Analog Signals Theory

A tutorial introduction to signal and noise definitions is given here, for background reading. The description is simplified to illustrate the methods and thoughts and all numbers are examples.

4.1 Signal Level

An analog signal can be seen as wanted signal information plus a random signal called noise. The strongest analog signal that is allowed into the digitizer is limited by a clipping function¹. Above that level, the signal is saturated. The maximum allowed level is called Full Scale (VFS) and is measured in the unit Voltage peak-to-peak (Vpp). The input signal is single-ended and symmetric around 0 V. Fig. 2 illustrates the full scale sine wave with amplitude VFS/2 [V].

For a pure sine waves, the relationship between amplitude (peak-to-peak) and Root Mean Square (RMS) is fixed and known, as it is for any continuous periodic wave. For a zero-mean sine wave, RMS and peak-to-peak amplitude are related as:

$$RMS = \frac{\text{peak-to-peak}}{2\sqrt{2}} = \frac{VFS}{2\sqrt{2}} = \frac{\text{Amplitude}}{\sqrt{2}} \quad (1)$$

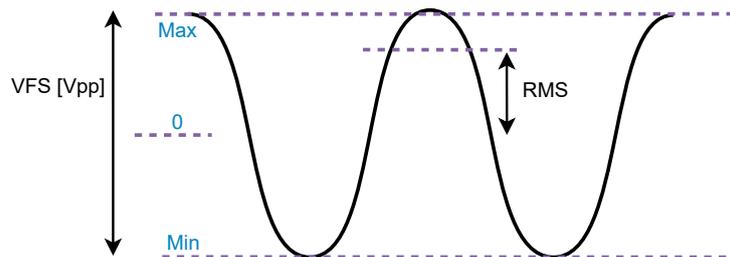


Figure 2: For a zero-mean sine wave, the RMS values is fixed and proportional to the amplitude.

The lowest signal level is limited by noise. Noise is a weak unwanted signal which consist of thermal random noise and electrical disturbances with a random appearance, Section 4.2. The lowest signal level then has to be strong enough to be separated from the noise. Actual required ratio between noise and signal is determined by the system parameters. The ratio between the strongest and the weakest signal is called *dynamic range* and is measured in [dB], which is a logarithmic *relative* power measurement.

4.2 Noise Level

A system has several noise sources that contribute to the noise level. The fundamental noise limit is given by the *thermal noise* as

$$v_n = \sqrt{4k_B TRdf} \quad (2)$$

where k_B is Boltzmann's constant in joules per kelvin [J/K], T is the resistor's absolute temperature in kelvins [K], R is the resistor value in ohms [Ω], and df is the bandwidth.

¹Amplifiers on the other hand, has compression at over-range.

Example

Example 1: A device with analog bandwidth of 1 GHz and 50 Ω system impedance at room temperature introduces a thermal noise of

$$v_n = \sqrt{4 * 1.38 * 10^{-23} * 298 * 50 * 10^9} = 29 \mu V.$$

The ratio between the signal and the noise [in e.g. a digitizer] is called signal-to-noise ratio (SNR). The SNR is given in [dB] and found in the datasheet. The most common reference signal for SNR calculation is a full scale sine wave as in Fig. 2. The noise level of the digitizer is calculated from SNR as

$$V_{RMS} = \frac{VFS}{2\sqrt{2}} \cdot 2^{-(SNR-1.76)/6.02} \quad (3)$$

Example

Example 2: A digitizer with full scale level = 1 Vpp and SNR = 60 dB gives according to (3) a noise level of $V_{RMS} = 433 \mu V$.

A common representation of noise is in the unit [dBm], that is power relative to 1 mW. The calculation is done as (50 Ω system):

$$noise\ level = 10 \log_{10}\left(\frac{noise\ power}{1\ mW}\right) = 10 \log_{10}\left(\frac{v_n^2/50}{10^{-3}}\right) \quad [dBm] \quad (4)$$

Example

Example 3: A detector can be seen as a 50 Ω resistor with 1 GHz bandwidth (Example 1). It has a noise level according to (4) of

$$10 \log_{10}((29 \times 10^{-6})^2/50/10^{-3}) = -78\ dBm.$$

The digitizer in Example 2 has a noise level of

$$10 \log_{10}((433 \times 10^{-6})^2/50/10^{-3}) = -54\ dBm.$$

Thus, the noise from the detector is 24 dB lower than the noise in the digitizer.

In Example 3, the noise from the detector is much lower than the noise level of the digitizer. There is therefore room for amplifying the signal, which is one of the topics of this application note (Section 5.1).

4.3 Effective Number of Bits (ENOB)

The effective number of bits (ENOB) tells what the resolution of the digitizer would be if the only source of error power was the quantization in the ADCs (5). The ENOB is measured with a single full scale sine wave. The first observation is that the ENOB heavily suffers from conversion errors related to the specific type of signal. Often this view is too limited. Example 4 illustrates a situation where the ENOB is not

representative.

$$SQNR = 6.02 * ENOB + 1.76 \text{ dB} \quad (5)$$

4.4 Jitter Contribution

The jitter is sampling time uncertainty translated into amplitude noise, as illustrated in Fig. 3.

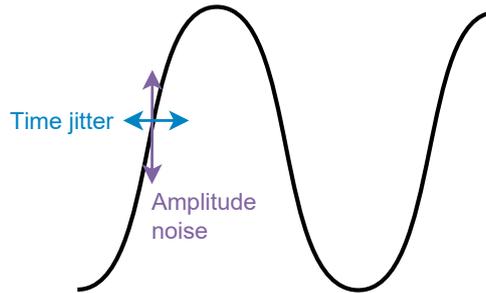


Figure 3: Jitter is sample time uncertainty translated into amplitude noise.

Note that the jitter is independent of the sampling frequency. The jitter induced noise is a part of the noise in the digital signal. It has a flat frequency response and can be reduced by digital filtering. Jitter is not the same thing as phase noise. Jitter causes (in the frequency domain) a *flat* noise floor whereas phase noise causes a skirt around the carrier. See Fig. 4.

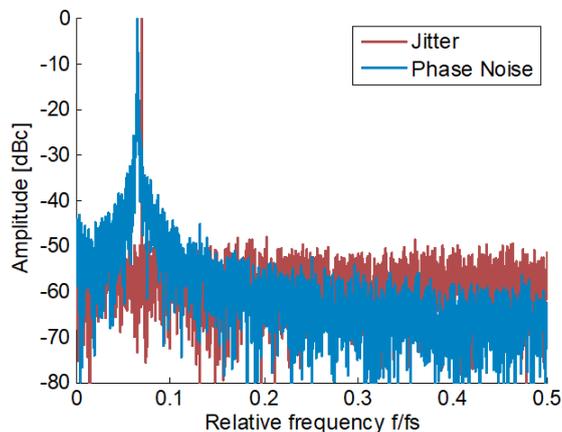


Figure 4: Jitter noise should not be mixed up with phase noise. It causes a flat noise floor in the frequency domain, whereas phase noise causes a skirt around the carrier.

The jitter increase the noise power at high frequencies. That is, the noise from jitter is always flat in the frequency domain, but at a different levels. The level increases with input frequency. For a certain input frequency f_{in} , the sampling jitter will limit the maximum achievable SNR according to (6). A typical

ENOB plot therefore shows a decreasing value at increased frequency, see Fig. 5. The sampling jitter is although only one of several sources affecting ENOB at higher frequencies.

$$SNR_{max} = 20 \log_{10} \frac{1}{2\pi f_{in} \cdot jitter} \tag{6}$$

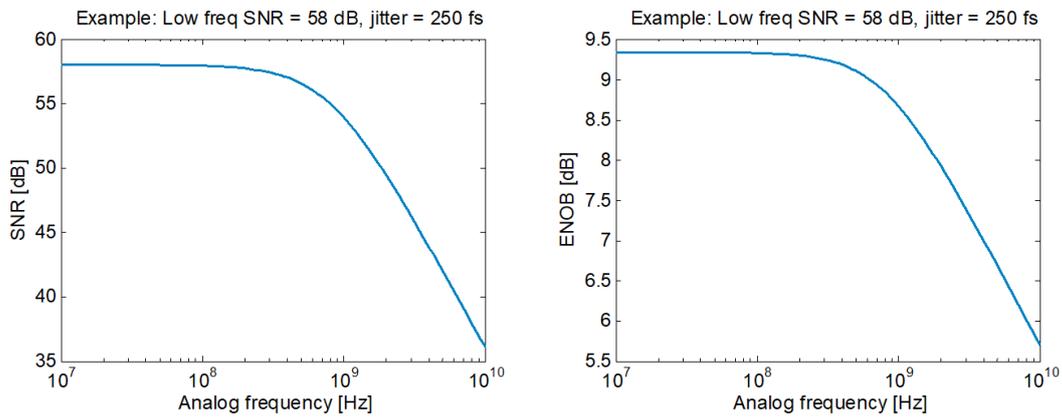


Figure 5: Jitter effect on SNR and ENOB for a varying full scale sine wave frequency.

Example

Example 4: A 2 GHz signal exposed to 250 fs sampling jitter is limited to (6) 50 dB SNR. This is limiting ENOB to (5) 8.0 bits. (Other factors may also contribute to the ENOB. The jitter alone put a cap on 8.0 bits.)

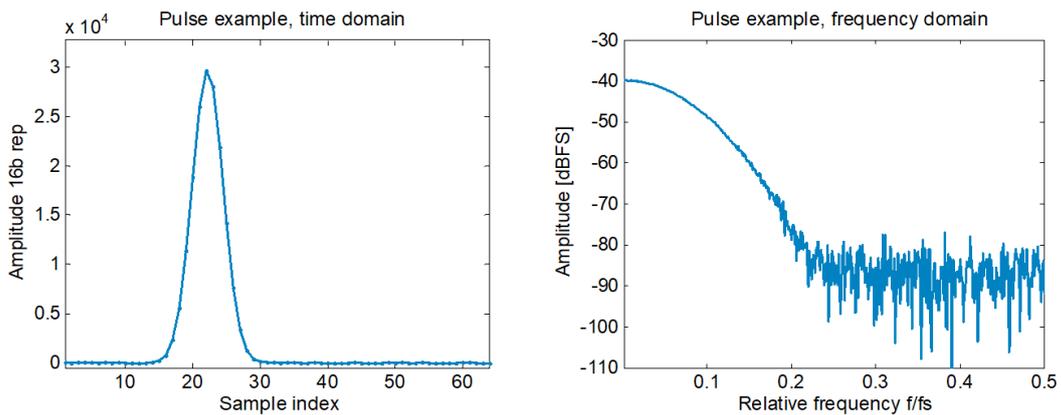


Figure 6: Typical pulse and corresponding spectrum. The pulse power is low frequency.

Pulse data energy is at low frequency, see Fig. 6, which is an advantage in the jitter aspect. The jitter contribution will be limited and the effect on ENOB from jitter is thus not so strong.

5 Connecting a Detector to the Digitizer

5.1 Cascaded Circuits - Detector - Amplifier - Digitizer

The input sensitivity, VFS, of a digitizer is often in the order of 1 Vpp. Many detectors however produce a signal with much lower power. To fully take advantage of the digitizer's dynamic range, the signal level has to be adapted with an amplifier. Parameters to consider when selecting amplifier are:

- Detector signal range compared to the full scale range of the digitizer, that is gain (G), Section 5.3
- Low enough NF², Section 5.3
- Headroom at overshoot, that is, what should happen for signals which are stronger than specified³.

Fig. 7 illustrates the different levels in the signal chain. The detector / sensor / antenna has a certain max signal level and a noise level (purple). The amplifier increase the signal level from the detector, but also the noise level (green). Only considering gain would keep the SNR constant but the amplifier also adds noise. This is indicated by the NF parameter. The SNR is thus reduced after the amplifier by the NF value. The signal out from the amplifier need a system specific margin to the maximum input level of the ADQ digitizer (blue).

The noise level is a tricky systems design parameter; should the detector and amplifier noise dominate or should the ADQ digitizer noise dominate? In the illustration in Fig. 7, the amplifier noise level is allowed to dominate. There are a few rules of thumbs:

- If the detector generate a weak signal with a high noise content, it is recommended to let this noise dominate. This means that the ADQ digitizer does not contribute significantly to the system noise.
- If the detector has a strong signal and high SNR, the digitizer can be allowed to dominate⁴.

5.2 Noise Level of Cascaded Amplifier and Digitizer

There are standard methods to calculate noise in cascaded electrical circuits based on the noise figure, NF⁵. These might be difficult to apply on a design with a digitizer since the nature of components and style of data sheet differ. There is a simple approximation that can be used for calculating the resulting noise level when an amplifier is connected to a digitizer:

$$\text{Resulting noise level} = 10 \log_{10}(10^{(x/10)} + 10^{(y/10)}) \quad (7)$$

where x and y are the noise level (in [dBFS] or [dBm]) from the cascaded electrical circuits, see Fig. 8.

²Noise figure (NF) is a common parameter in RF systems. Literature about RF is recommended for further reading.

³An amplifier compresses the signal when it gets too strong. This is a slow degradation of the linearity. The digitizer on the other hand is a sharp limiter (clipping).

⁴In general, it is expected that the detector and the first amplifier (LNA) is the main contributor to the noise level. However, in wide band systems, the available high bandwidth digitizer may in fact limit performance. The Teledyne SP Devices' digitizers are optimized for this situation when combining high bandwidth and high dynamic range.

⁵See literature on RF systems.

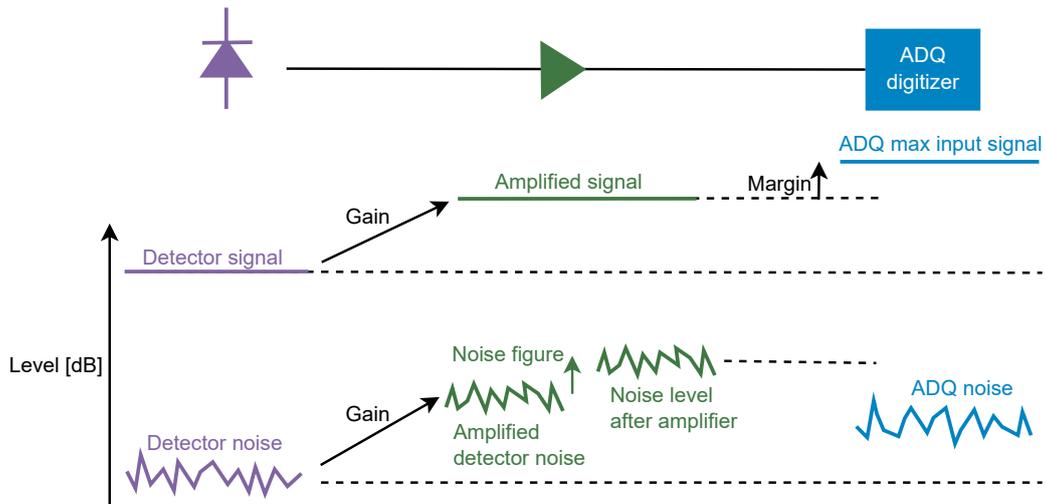


Figure 7: Gain setting.

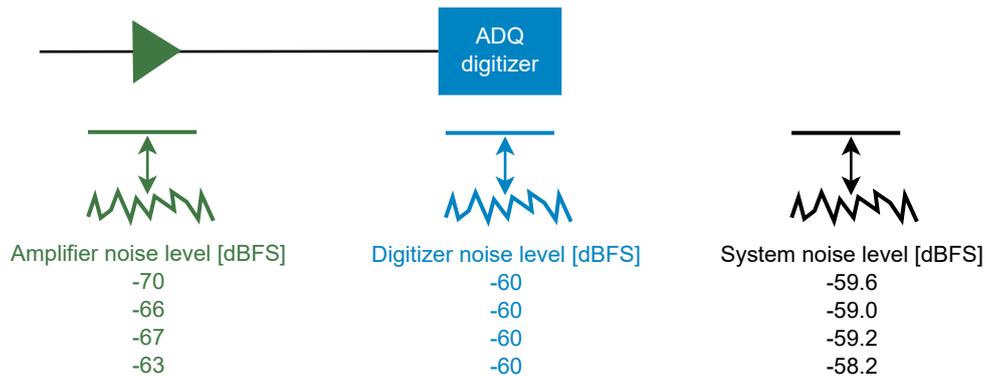


Figure 8: Cascading of two noise sources.

Example

A difference in noise power of 10 dB between amplifier and digitizer (first row of figures in Fig. 8) results in a 0.4 dB loss in SNR when cascading them.

5.3 Amplifier Example

The following setup is given.

- A digitizer with $VFS = 1$ Vpp and $SNR = 60$ dB is given.
- A detector as the one in Example 3 is given, with $VFS = 0.1$ Vpp.

To take advantage of the full dynamic range of the digitizer, the output from the detector needs to be amplified. The amplifier is specified in Gain, G , which is a design parameter for selecting amplifier. With the selection follows the NF parameter. An amplifier with the wanted G and good (low) enough NF has to be found, see Fig. 9.

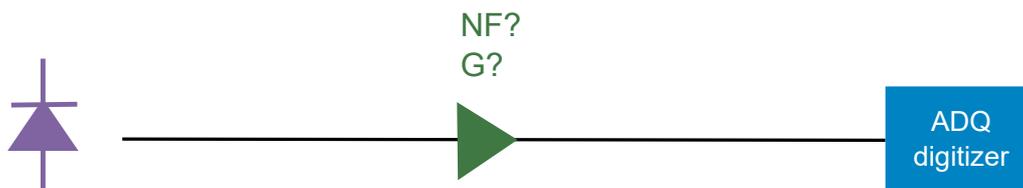


Figure 9: The example in Section 5.3 studies the impact of amplifier parameters G and NF on a given system.

Firstly, G should be calculated. The input signal ranges, V_{FS} , to the detector and the digitizer are 0.1 Vpp and 1 Vpp, respectively. This gives

$$G_{max} = 20 \log_{10}(1/0.1) = 20 \text{ dB.}$$

To avoid overshoot, G is set to 18 dB.

Secondly, the impact of the parameter NF on the system noise is studied. The signal and noise levels in Fig. 7 are therefore calculated.

- Detector signal level (4):

$$10 \log_{10}((0.1)^2/8/50/10^{-3}) \text{ dBm} = -16 \text{ dBm.} \quad (8)$$

- Detector noise level (Section 4.2, Example 3): -78 dBm.
- Amplifier noise level: Assuming that the noise figure is $NF = 4$ dB, which is a good amplifier, the output noise after the amplifier can be calculated as

$$noise_{out} = noise_{in} + G + NF = -78 + 18 + 4 = -56 \text{ dBm} \quad (9)$$

- Digitizer signal level (4):

$$10 \log_{10}(1^2/8/50/10^{-3}) \text{ dBm} = 4 \text{ dBm.} \quad (10)$$

- Digitizer noise level:

$$\text{Digitizer signal level} - SNR = 4 - 60 = -56 \text{ dBm.} \quad (11)$$

- System noise level: The noise (9) adds to the digitizer noise (11) at the same level and the total cascaded system noise is then according to (7) approximately -53 dBm.

The SNR through the system can also be studied:

- Detector: $-16 - (-78) = 62$ dB
- Amplifier: $SNR_{in} - NF = 62 - 4 = 58$ dB
- Digitizer (given): 60 dB
- System SNR (with 2 dB margin⁶): $4 - 2 - (-53) = 55$ dB

We now have all the needed figures to decided if the proposed amplifier with $G = 18$ dB and $NF = 4$ dB is good enough for the application at hand.

- If -53 dBm is an acceptable system noise level and system SNR of 55 dB is OK, we are finished.
- If a better system noise level or SNR is needed, one of two things can be done.
 - Find an amplifier with a better NF.
 - Find a digitizer with lower noise level.

The example is collocated in Table 3.

Table 3: Parameter summary of amplifier example.

Parameter	Detector	Amplifier	ADQ	System
VFS [Vpp]	0.1	-	1	-
signal level [dBm]	-16	2	4	2
noise level [dBm]	-78	-56	-56	-53
SNR [dB]	62	58	60	55

⁶18 dB gain instead of G_{max} (20 dB)

5.4 Cascaded Circuits - Detector - Attenuator - Digitizer

If the input signal is stronger than the full range of the digitizer, a wide band attenuator is used to match the digitizer's input range. See Fig. 10. In this situation the SNR into the digitizer is preserved. The attenuator does not add noise as the amplifier does. The ADQ series of digitizers has a highly sensitive input (this means that the maximum signal level is low) in order to avoid a lot of amplification. The difference between Fig. 7 and Fig. 10 illustrates the advantage of a sensitive input.

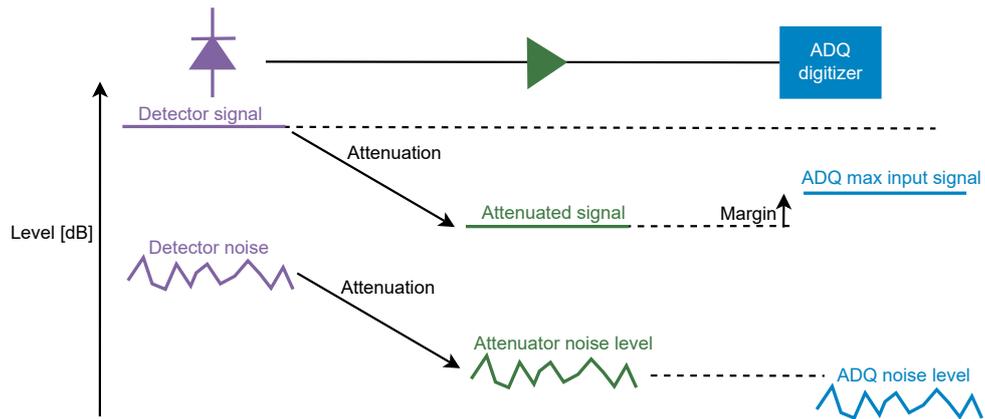


Figure 10: Attenuator setting.

6 Reflections

In a system with short pulses, reflections are inevitable and it is impossible to get rid of them entirely. Why they appear and how large they are expected to be is treated in Sections 6.1 and 6.2. Section 6.3 suggests how to optimize for reflection reduction.

6.1 Size of the Reflection - Return Loss

A 14-bit digitizer typically has 60 dB dynamic range (simplified). A wide band high quality input impedance matching (Return loss, S11)⁷ is in the order of 25 dB. This means that a full scale pulse to the digitizer will be reflected in the cable and travel back to the amplifier. In the amplifier, it gets attenuated 25 dB again and reflected and travel back to the digitizer. A 50 dB attenuated copy of the pulse will appear. Note! this can clearly be seen in a 14-bit system, but was hidden in noise in an 8-bit system. It does not mean that the reflections do not exist in the 8-bit system; they are just hidden by quantization noise. Reflection and return loss is illustrated in Fig. 6.1.

The return loss (i.e. the size of the reflection) is set by the impedance matching between the source output, the cable, and the digitizer input. Even though it is frequency dependent, the input impedance accuracy is given at DC in most data sheets.

$$RL = -20 \log_{10} |\Gamma| = -20 \log_{10} \left| \frac{Z_L - Z_S}{Z_L + Z_S} \right| \quad (12)$$

where Γ is the reflection coefficient, Z_L the load impedance, and Z_S the source impedance (toward the source).

Example

A digitizer specification of input impedance is $50 \Omega \pm 2\%$, which is a good number. This translates in to a return loss according to (12) of $RL = 20 \log_{10} |50 * 0.02 / (50 * 2.02)| = 40$ dB. But nota bene, this is at DC. At higher frequencies, the matching is significantly poorer. A basic component as an attenuator can have 32 dB return loss at 1 MHz but only 22 dB at 2 GHz.

Typically in RF design, a return loss of 25 dB is considered good. Useful literature on this topic is RF amplifier data sheets.

6.2 Timing of the Reflection - Cable Length

The cable between the amplifier and the digitizer is a wave guide where the pulses travel with approximately $0.67 * \text{speed of light}$ ⁸. If a cable of 1 m is used, the reflected signal will travel 2 meters back and forth, which takes about 10 ns, Fig. 12.

6.3 Optimizing for Reflections Reduction

Over a wide band, the best component for reflection reduction is an attenuator, Fig. 13. If it is possible to have extra power in the system, an attenuator may be placed between the amplifier and the digitizer.

⁷Scattering parameters or S-parameters (the elements of a scattering matrix or S-matrix) describe the electrical behavior of linear electrical networks when undergoing various steady state stimuli by electrical signals.

⁸Differs between cables.

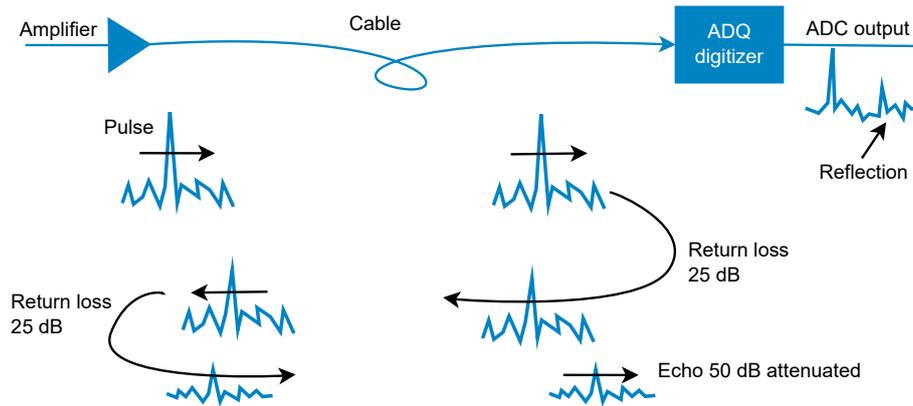


Figure 11: The pulse to the digitizer will be reflected and travel back and forth in the cable. Each reflection is attenuated about 25 dB.

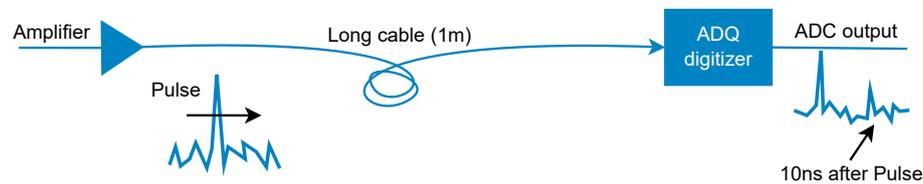


Figure 12: Cable length example. If the cable is 1 m, the reflection of the pulse will appear approximately 10 ns after its original.

The signal will pass the attenuator one time. The reflection will pass through it two times, which means that the ratio is improved.

A high sensitivity input allows for attenuation and thus improved matching. The ADQ14 digitizer has a built-in attenuation of 4.4 dB to improve the matching.

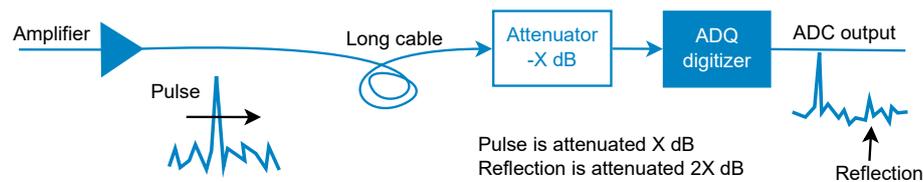


Figure 13: An attenuator can be used to reduce reflections.

The other way of handling the reflection is to let the reflection fall within the pulse. This is done by placing the digitizer close to the source and use a short cable, as illustrated in Fig. 14. If, for example, the pulse is 2 ns wide and the reflection appears 1 ns later it will to a large extent disappear. Note that 1 ns is a 20 cm travel distance and thus a 10 cm cable.

Placing the digitizer close to the source require a compact solution on the analog side. It is not sure that the PC can fit close to the detector. (This may also not be a good solution from a disturbance perspective.) To allow for a separation of the PC and the digitizers, the ADQ14 and ADQ7 come with an USB3.0 and 10Gb Ethernet option. The digitizer is then placed in a small box which allows for free location of the device. The 10Gb Ethernet form factor also allows for optical transmission and thus

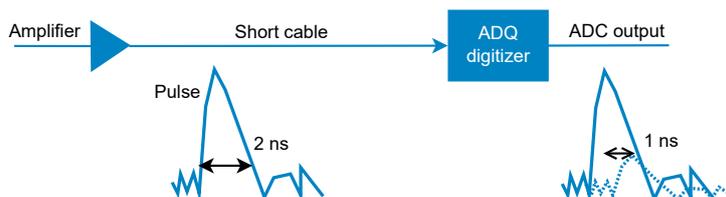


Figure 14: Reflections falls within the pulse if the cable is short enough. The dotted line illustrates the reflection that mostly falls within the pulse.

galvanic isolation between the experiment and the PC. This is an advantage for reducing electrical noise as ground currents.

6.4 Summary

The ADQ digitizers has a highly accurate input stage. Nevertheless, the high accuracy of the 14 bits digitizer will reveal reflections in the system, due to impedance mismatch. To overcome the reflections, the digitizers are offered in cabled solutions; USB3.0 and 10GbE. Then they can be placed close to the detector and the problem with reflections is minimized with short cables.

If the system allows for an attenuator this will also improve the reflection reduction, since the reflection will be attenuated twice and the wanted signal only once.

7 Bandwidth and Noise

7.1 General Representation

The bandwidth of the systems has to be treated carefully since the system mix analog time-continuous representation with digital time-discrete representation. The analog time-continuous representation has infinite representation of unique frequencies. This means that noise from different frequencies can always be separated. The digital time-discrete representation is limited by the Nyquist theorem so that noise is aliased to the Nyquist band. Aliasing is illustrated in Fig. 15.

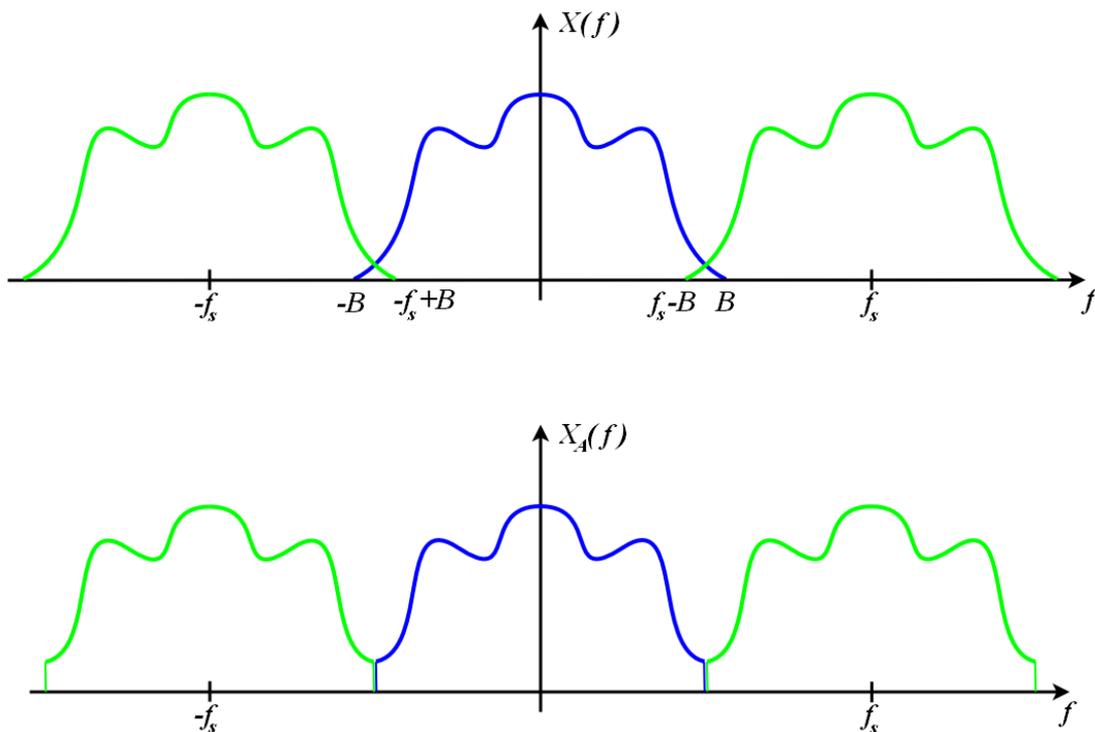


Figure 15: Aliased spectrum. Source: <https://en.wikipedia.org/wiki>.

7.2 Idle Channel Noise

The idle channel noise is the noise level from a digitizer channel when there is no signal present. That noise level determines the weakest signal that can be detected. Idle channel noise is specially important in pulse applications where a key parameter is the ratio between a large pulse (full scale) and a weak pulse. If the large pulse and the weak pulse do not overlap in time, it is only the idle channel noise that determines the minimum detectable pulse. Idle channel noise is measured as noise power spectral density (NPD, NSD, NPSD, PSD, etc) and is given in dBm per Hz (dBm/Hz). To get the total noise power, the NPSD is integrated over the bandwidth. For a digitizer, which is time-discrete, the integration region is from zero up to the Nyquist frequency (half the sample rate, f_s).

7.3 ENOB and Idle Channel Noise

The ENOB is limited by many types of imperfections in the digitizer which vary from situation to situation. One of them is jitter that was treated in Section 4.4. However, an upper limit on the ENOB is always set by the NPSD.

$$ENOB_{limit} = \frac{\text{full scale signal}}{\text{integrated NPSD}} \quad (13)$$

If the NPSD is the same for two different digitizers; ADQ14 sampling at 2 GSPS and ADQ7 sampling at 5 GSPS, the ADQ7 will show a worse ENOB because of the higher bandwidth. However if we compare the digitizers at a similar bandwidth, the ENOB are the same. This view is important when looking at bandwidth limited systems as a radio channel. The bandwidth of one radio channel is the same regardless of the sample rate. This assumes that digital filtering limits the noise in the ADQ outside the radio channel. Then the ENOB equivalent from (13) is the same for both ADQ14 and ADQ7. See illustration in Fig. 16.

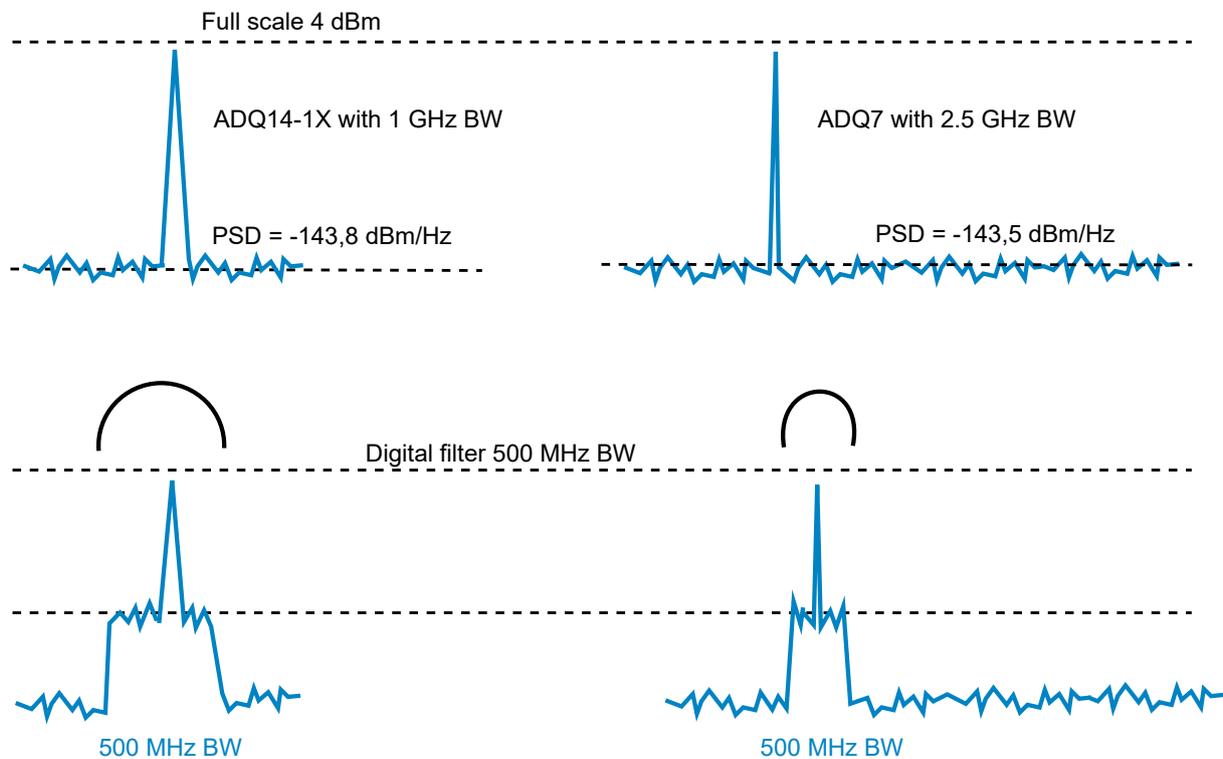


Figure 16: Since PSD is power per unit of bandwidth (dBm/Hz), a wideband device will affect ENOB more than a narrowband device with the same PSD. A channel filter can compensate for this and restore ENOB.

7.4 Reduce Noise by Limiting the Bandwidth

There are two positions to attenuate the noise in the digitizer by filtering:

Analog front-end filter The analog front-end filter reduce the noise into the ADC. This is useful primarily if the amplification is large.

Digital filter For moderate amplification, noise from the AFE is not dominating. The noise in the ADC component itself is dominating the noise. This noise is flat over frequency. A digital band-limiting filter will then reduce the noise proportional to the filter passband width (BW) as:

$$10 \log_{10}(BW/(f_s/2)),$$

where f_s is the sampling frequency. If, for example, the bandwidth is set to half the Nyquist frequency, there is a ≈ 3 dB⁹ improvement in SNR. This is valid for a low pass function as well as band pass and high pass filters. In a pulse data system a low pass filter is used.

Example

Example: An ADQ7 10 GSPS is compared with an ADQ14-2X.

- $SNR_{ADQ14DC-2X} = 58$ dB (1 GHz band)
- $SNR_{ADQ7DC} = 56$ dB (2.5 GHz band)

At first sight, ADQ14 seems to have better SNR, but by filtering the band of ADQ7DC to 1 GHz, the roles may be reversed. An ideal digital filter would increase SNR of ADQ7 with

$$-10 \log_{10}(1/2.5) \approx 4 \text{ dB.}$$

With a finite filter order, this value is lowered a bit and would give about the same SNR as the ADQ14 but more information about the pulse (2.5 times higher time resolution).

Note

The bandwidth reduction is best done in the digital domain in the FPGA except in one situation; where there is so much amplification that the input noise dominates.

⁹Using an ideal lowpass filter width bandwidth $BW = f_s/4$.

8 DC or AC coupling

The AFE of ADQ digitizers' AFE are either DC-coupled or AC-coupled. This section discusses the difference between the two and gives recommendation on when they should be used.

8.1 DC-coupling

DC-coupling means that the DC level of the analog signal is directly translated to the corresponding digital code. In most systems, the DC-level carry no direct information, but it simplifies the analysis to have the DC-level present. From a digitizer perspective, a DC-coupling complicates the high bandwidth analog front-end circuits significantly. This is why the upper bandwidth is often lower on a DC-coupled front-end. The observant reader notices that this is not the case on ADQ7, where the DC AFE has high bandwidth than the AC AFE. Here the real difference is in the distortion at high frequency where the AC AFE is much better.

8.2 AC-coupling

AC-coupling means that there is a lower cut-off frequency where the signal is blocked from the ADC. An AC-coupled front-end can be made passive and will then not contribute with noise to the system. It is easier to achieve high ENOB with a passive front-end. The drawback of a passive front-end is that the sensitivity is worse. An ADQ14AC has an input range of 1.9 Vpp but an ADQ14DC has an input range of 0.5 Vpp. A passive front-end requires more gain (active components) outside the digitizer. An AC-coupled passive front-end moves the gain from the digitizer to an external component. In a general wideband situation this is seldom an improvement. But in many special situations this can be used. For example:

- The source has a very strong signal so attenuation is used.
- The source has a narrow frequency band so that a specific narrowband amplifier can be used with small noise contribution.

! Important

The ADQ7AC has a lower cut-off at 100-300 MHz. This is a difference to all other AC-coupled digitizers from Teledyne SP Devices which has a lower cut-off below 100 Hz. The ADC7AC is designed for RF-applications only. The other AC-coupled front-ends can be used in both RF and pulse data applications.

9 Concluding systems design rules

Finally, some concluding rules of thumb are given.

1. If the signal from the detector is weak compared to the noise, let the noise from the detector dominate the system.
2. If the signal from the detector is strong compared to the noise, let the noise in the digitizer dominate the system.
3. If the reflections are critical (disturbing), make sure to use as short cables as possible.
4. If the reflections are critical (disturbing), add passive attenuator at the digitizer input if possible (if signal power is enough).
5. Form factors USB3.0 and 10GbE in combination with application specific firmware enable placing the digitizer for optimal analog performance. The specific firmware allows for intelligent real-time data processing and data reduction.
6. 10Gb Ethernet interface allows also for galvanic isolation which reduces ground currents and thus electrical noise.
7. To reduce noise, limit the system bandwidth to match the wanted signal bandwidth with digital filtering.

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