White Paper

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Choosing the Best Bit Depth for IQ Captures or Streams

Given unlimited bit depth and sample rate, an IQ capture can perfectly recreate an RF signal from any period in time. In the real world, however, more bit depth and more samples come at a cost of more bits, and these bits can quickly consume gigabytes of storage and tens of gigabits per second of streaming bandwidth. Every capture contains noise. At some point, more bits only serve to better quantify the noise and no longer provide any additional insight into the signal. This paper will attempt to help you understand the mechanism behind this.

Analog Receiver Limitations

A perfect receiver will measure noise proportionally to the bandwidth of the received signal. At microwave and RF frequencies, thermal noise is relatively flat with respect to frequency and can be approximated as -174 dBm/Hz. If 1 Hz is captured, the thermal power is -174 dBm, but if a 1 MHz signal is captured, the power is 1 million times higher, or -114 dBm. How close a receiver is to matching the theoretical noise limit is usually a published figure of merit for the receiver, known as the noise figure. Receivers have another figure of merit, known as the dynamic range. In addition to being limited by noise, receivers are also limited to how much power they can accurately measure. High powers cause analog "compression" where the capture is no longer a good representation of the actual signal. Dynamic range measures the ratio of how strong of a signal can be measured to how weak of a signal can be measured. It is important to understand that this number is dependent upon the analysis bandwidth used. In a spectrum analyzer, a narrow resolution bandwidth (RBW) will generally result in a higher dynamic range than a wide RBW.

Digital Limitations

A digital representation of a capture has analogous limitations. Digital signals are "quantized," meaning the analog signal is rounded to the nearest bit, and this creates a kind of noise called "quantization noise." On the other end, fixed signals are limited in how high they can go before we run out of bits and the signal is "railed" to the maximum integer. In general, it is desirable to choose a digital representation such that the quantization noise is smaller than the analog noise, while at the same time choosing a representation where the analog signal will be compressed before the digital signal will rail to the maximum integer. Once this has been well achieved, it is undesirable to extend too much farther on either the high or low side, as this will only waste bits or storage. Most receivers, including the Field Master Pro™ MS2090A, match the level at which a signal rails digitally to the level at which an analog compression happens, and the user does not need to be involved in choosing this.

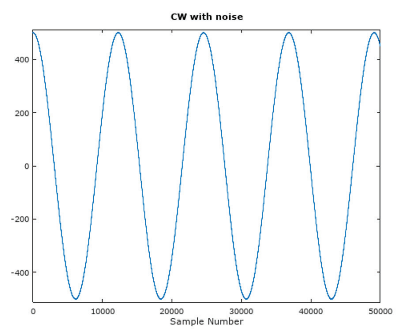
Sample Rate

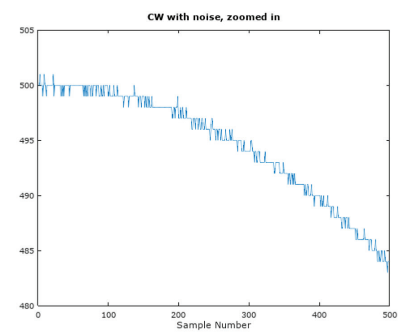
The wider the sample rate the more bandwidth that may be captured. For a "real" signal, the sample rate must be double the bandwidth to satisfy Nyquist's criterion. For IQ captures, we have both an "I" and a "Q" sample at each sample point, so we only need the sample rate to be larger than the analog bandwidth. Filters are not perfect, however, and some bandwidth must be allocated for the transition bands of the filter, resulting in a usable bandwidth that is smaller than the sample rate. Most receivers, including the Field Master Pro MS2090A, publish how much usable bandwidth is available at each sample rate. It is desirable to choose the smallest sample rate that provides the desired usable bandwidth. Larger sample rates waste bits.

Quantization Noise

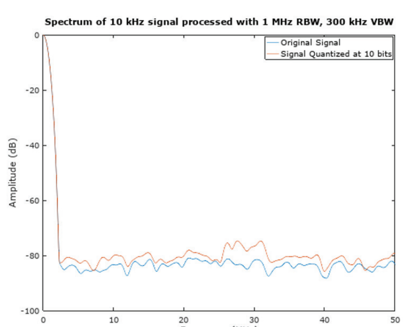
Quantization noise is an interesting topic. As stated previously, it is the error created when an input signal is rounded to the nearest bit. More bits create less noise, with 6.02 dB less quantization noise for each additional bit stored. When the least significant bits are chaotically changing due to thermal noise or due to a wideband signal, quantization noise is "white," or uniformly spread across all frequencies. When quantization noise has this property, it may be treated the same as any other noise source. Reducing the resolution bandwidth during analysis will reduce the quantization noise, and narrowband signals that have a negative signal to noise ratio at wide bandwidths can be easily identified with narrow bandwidths.

The following plots are of simulated signals created and analyzed in Gnu Octave, a free signal processing tool similar to MATLAB. In these plots, a CW signal of amplitude 1000 peak-to-peak is quantized in to 10 bits (so full scale is -512 to +511). A small amount of white noise has been added. The two plots are the same signal with the one on the right zoomed in.



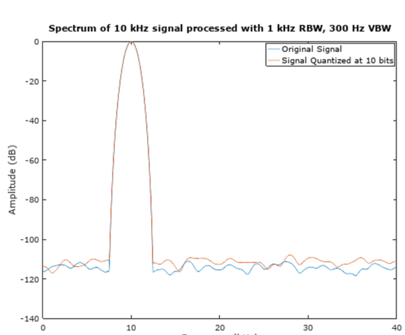


The signal amplitude is 500 and the quantization noise amplitude is 0.5, so the SNR is about 60 dB. However, the quantization noise is spread across a bandwidth equal to the sample rate. If the sample rate is 122.8 MHz, a 1 MHz RBW may be used to achieve 20 dB of "processing gain" and reduce the quantization noise to 80 dB below the signal level.



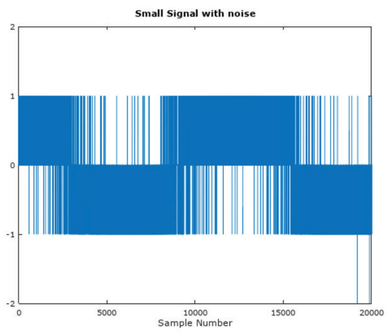
Here, the orange trace is the spectrum of the quantized signal while the blue trace is the spectrum of the original signal with a small amount of white noise.

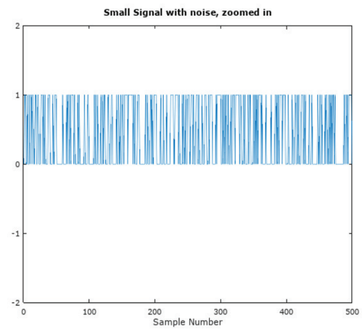
If a much narrower RBW is used on the same data, the quantization noise is pushed much lower to about -110 dB.



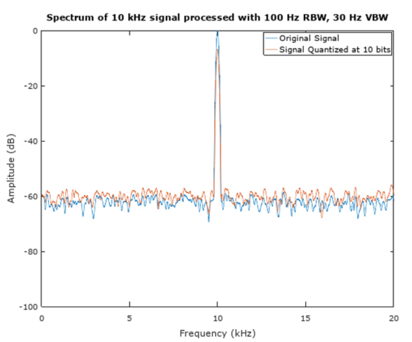
Intriguingly, despite the original quantization to 10 bits, a signal that has a smaller amplitude than 1 bit may still be analyzed.

With the same added white noise, if the amplitude of the sine wave is changed from 500 to 0.4, here's what the first 5000 samples look like.

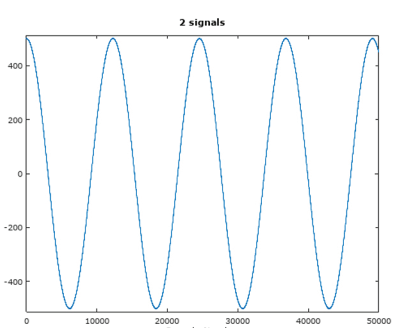


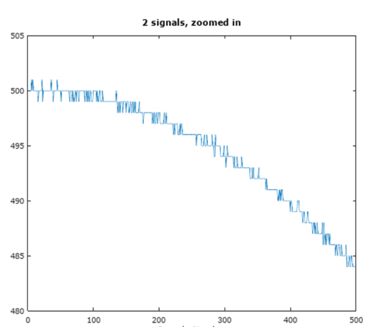


Here's what the spectrum looks like with a 100 Hz RBW, where the 10 kHz sine wave is clearly visible and more than 50 dB stronger than the noise.

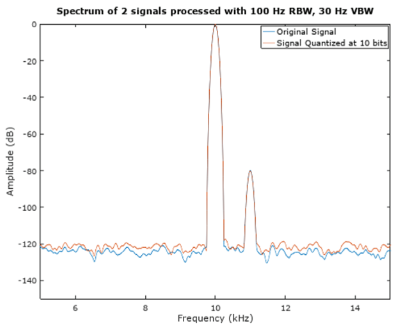


A similar thing may be done with a strong signal near a weak signal. In the following plots, the input is a 10 kHz CW with amplitude 500, and an 11 kHz signal with amplitude 0.05, a tiny fraction of 1 bit. The tiny signal is of course invisible in the raw data.





But it stands out quite clearly when analyzed with a 100 Hz RBW, where the 11 kHz signal is correctly shown 80 dB below the main signal.



This shows that quantization noise often acts the same as white noise – a broadband source of noise. Lowering the RBW during analysis (equivalently using more fast Fourier transform [FFT] points) will lower the amount of quantization noise. There are occasions, however, where quantization noise is not at all "noise-like." If there is very little analog noise in a system and if the signal power is small compared to 1 bit, then it's possible to have a situation where no bits are being toggled and the quantization noise is not noise-like but instead highly correlated to the signal with opposite sign. To avoid this problem in the above plots, a small amount of "analog" white noise was added in each case. This small amount of analog noise randomly flips bits, which converts the quantization noise to white noise instead of allowing it to be correlated to the signal.

Quantization Noise vs. Thermal Noise

When the quantization noise is uncorrelated to the signal (which is a "normal" case), the quantization noise and thermal noise degrade the signal in the same ways and their energy densities simply add. If the quantization noise can be made much smaller than the thermal noise, then the quantization noise becomes irrelevant. It's often a design goal of the digital system to make the quantization noise 10 dB less than the other sources of noise. If the quantization noise is higher, then it will impair the signal. If the quantization noise is lower, then the extra bits are not doing much other than taking up more disk space. This is sometimes impractical and, in fact, it is sometimes difficult to make the quantization noise at all lower than the analog noise. This does not invalidate the measurements, it only means that the system performance is being limited by the digital performance.

The effect of sample rate on quantization noise

The energy in quantization noise is spread across the entire captured spectrum. If the sample rate is doubled, then the quantization noise energy density is halved, as the same amount of energy is spread over double the spectrum. In practice, this means that very high sample rates do not require very high bit depth and more than 16 bits at 100 MSPS is usually unnecessary.

More bits are more efficient than more samples

While a higher sample rate reduces the quantization noise energy density, more bits are usually more efficient at doing this. One additional bit reduces the quantization noise energy density by 6 dB. Doubling the sample rate reduces the quantization noise energy by 3 dB. A 10 bit capture at 200 MSPS, therefore, has the same quantization noise energy density as a 12 bit capture at 25 MSPS.

The system design goal, therefore, involves choosing the minimum sample rate necessary to capture a signal that needs to be analyzed, then choosing a bit depth such that the digital quantization noise is lower than the analog noise.

Reference Level

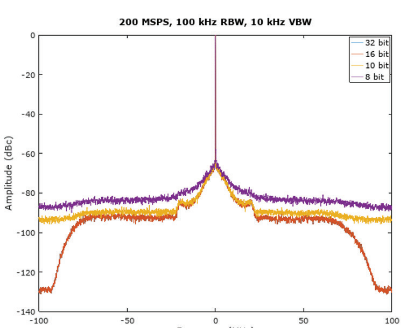
A spectrum analyzer has analog amplifiers and attenuators to optimize the level of the signal. To make the best use of a limited number of bits, it can be useful to fine tune this receiver gain. If the input signal is too high, the signal will overflow the fixed bits. For example, the Field Master Pro MS2090A will report "ADC Overrange" in such a circumstance. If this happens, more attenuation should be used, either by manually adding attenuation, or by increasing the reference level for auto attenuation. If the input signal is low, then the quantization noise is higher compared to the signal.

The reference level on a spectrum analyzer is usually chosen such that a typical signal that displays below the reference level will not overrange the digital section. Broadband signals generally have more energy hitting the receiver's analog-to-digital converter (ADC) than energy inside the instruments RBW filter. To manage this, an instrument does not overrange just slightly above the reference level, but rather many dB above the reference level. If the signal being measured is narrowband, then the most efficient use of bits involves a signal that is input above the reference level. In general, the best choice of bits can be made by reducing attenuation or adding amplification until the instrument reports that it has overranged, and then adding 5 dB attenuation to prevent it from overranging during the capture.

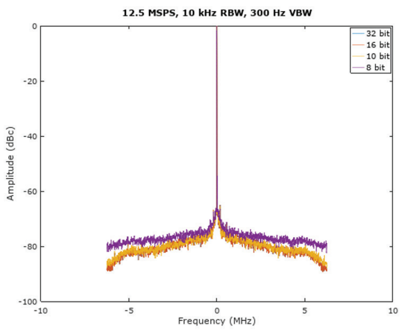
Example Plots

The following plots are of signals captured by the Field Master Pro MS2090A at the specified sample rate and bit depth. A CW signal was used as the input. The input signal was sent above the instrument reference level, but below the level at which the instrument reports "ADC Overrange" to maximize the analysis range. They were then analyzed in Gnu Octave. The RBW and VBW are chosen during the analysis in Octave.

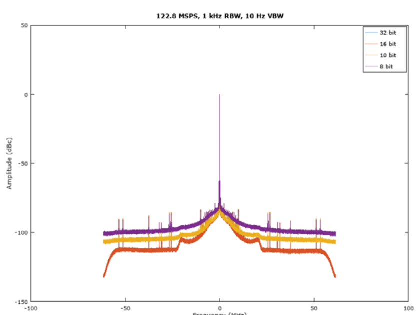
This figure shows how the choice of bit depth changes the noise floor. Near the carrier, 8 bits is sufficient, as the combined phase noise of the signal and receiver exceed the 8 bit quantization noise. By 10 MHz offset from the carrier, the 8 bit quantization noise is clearly higher than the analog noise floor and is degrading the measurement. The 200 MSPS capture uses an analog filter with a 110 MHz wide passband. At 70 MHz offset, the receiver is no longer receiving much analog signal due to the analog filter and the quantization noise of the lower bit depths becomes visible. The lower noise floor near the edges does not matter for actual measurements, as the signal has been filtered out at these frequencies. At this sample rate, 10 bits is usually sufficient for real measurements. 32 bits is clearly overkill as the 16 bit plot perfectly aligns with the 32 bit plot.



Even at 12.5 MSPS, 10 bits does reasonably well, as the phase noise of the source and receiver are still greater than the quantization noise.



It is possible to see more than 100 dB down even with 8 bits. The next plot shows how spurs at 90 dBc are clearly visible even with an 8 bit capture. In this plot, the analysis was done with a 1 kHz RBW when the 8 bit quantization noise was spread across 122.88 MHz. As with other kinds of noise, the dynamic range of a CW signal compared to the noise depends upon the RBW used, with smaller RBWs resulting in larger dynamic ranges.



Field Master Pro MS2090A Considerations

The Field Master Pro MS2090A allows captures of up to 2 GB to be stored. Choosing a lower sample rate or bandwidth will allow a longer time record to be captured. This table shows how many seconds it takes to fill 2 GB.

BIT DEPTH

SAMPLE RATE	32	16	10	8
200	1.34	2.68	4.02	5.36
122.88	2.18	4.36	6.55	8.73
100	2.68	5.36	8.04	10.7
12.5	21	42	64	85
0.045	5965	11930	17895	23860

The Field Master Pro MS2090A can also stream data through a user selected Ethernet/USB3/high-speed data port. This data may be captured to a file and post processed by a PC application for detailed analysis, for example the Bird Spectro-X. The streamed data is sent continuously, but the bandwidth of the channel or receiving device might limit the sample rate or bit depth that may be used without data loss. If the channel or recording device cannot handle the data speed, the stream will have gaps in the stream at random places, making analysis of the data difficult. If the data gaps are not accounted for, the discontinuities at the boundaries of the gaps will artificially spread energy across the spectrum, resulting in undesirable spectrum artifacts. Multiple IQ captures might work better than one very large stream that contains gaps.

This table shows recommended bit depths at various sample rates. Cells labeled as “Too Much” indicate that the extra bits are very unlikely to improve the measurement. Cells labeled as “Too Little” indicate that the quantized bit depth is likely to degrade the measurement, although, as demonstrated above, the measurements may still be quite usable. Cells labeled as “Almost” indicate that the quantization noise is unlikely to significantly impact the measurement, but it might for certain types of signals.

BIT DEPTH

SAMPLE RATE	32	16	10	8
200	Too Much	Too Much	Good	Almost
122.88	Too Much	Good	Good	Too Little
100	Too Much	Good	Good	Too Little
12.5	Too Much	Good	Too Little	Too Little
0.36	Good	Good	Too Little	Too Little
0.045	Good	Almost	Too Little	Too Little

Time Stamps

The Field Master Pro MS2090A has the option to add timestamps into the IQ data. If the feature is turned off, then the samples are unaffected. If the feature is turned on, then one least-significant bit (LSB) of many samples will be overwritten by the timestamp instead of the data. At 32 bits, the LSB is in the noise and is irrelevant. At 16 bits, for most sample rates, the LSB is likely to be in the noise and unimportant. The 10 bit format consists of 3 samples every 32 bits, and the timestamp is embedded in one of the two unused bits, so the 10 bit format is unaffected by the timestamp. If the 8 bit format is used, however, one of every four samples will have one of its bits overwritten by the timestamp. This will result in a noticeable increase in quantization noise.

Summary

This paper explains the relationship between noise, sampling rates, and bit depth in a system designed for IQ capture. With an understanding of these interdependencies, it is possible to optimize the configuration of a receiver, such as the Anritsu Field Master Pro MS2090A, when capturing IQ data to minimize the memory size of the resulting data file. Smaller files are typically easier to analyze in post processing tools making the identification of all signals faster and easier.

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