Oscilloscope Vertical Resolution

Discussion document of recent advances in Oscilloscope vertical resolution with the introduction of 12 bit A/D converters, high signal-to-noise ratio amplifiers and low noise system architecture.

Overview

Traditional all analogue oscilloscope architecture has given way to digital oscilloscope architecture for a number of years now. The latest digital oscilloscope developments, high definition technology consists of high sample rate 12-bit ADCs, high signal-to-noise ratio amplifiers and a low-noise system architecture looks set to revolutionize digital oscilloscopes and take their performance to a new level.

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History of the Oscilloscope

The first oscilloscopes started to show up in laboratories in the early 1900s and consisted of vertical voltage scaling with a horizontal timebase but without many of the later refinements. In 1946 oscilloscope technology took a leap forward with the addition of triggering circuitry starting the development of the modern day analogue oscilloscope. Then in the early 1980s the first digital oscilloscopes started to appear, and have become the dominant technology with analogue oscilloscopes now virtually extinct.

Advantages of Digital Oscilloscopes

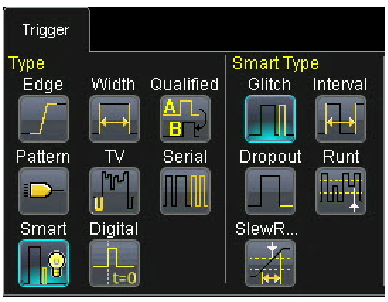
The development of the digital oscilloscope has brought many advantages over the now obsolete analogue oscilloscope technology. Initial advantages of digital oscilloscope technology include

- Real time acquisition
- No fading or blooming of on-screen waveform traces
- Improved horizontal measurement accuracy
- Pre-trigger waveform viewing
- Waveforms can be saved as a data files
- Screen images can be printed or saved as JPG files
- Possability of Remote control

But the ongoing development of the digital oscilloscope since the 1980s has brought a continuous stream of new and more advanced features

- Sophisticated triggering
- Automatic measurements
- Deeper memory
- Higher acquisition bandwidths
- Advanced Math and real time Math on waveforms
- Trigger and decoding of high speed and low speed serial buses
- Pass / fail testing
- Jitter analysis
- Probe de-embedding

Sophisticated Triggering Options In A Modern Digital Oscilloscope



Digital Oscilloscope Horizontal Accuracy

The digital oscilloscope brought a vast improvement in the horizontal axis accuracy, and with it, a dramatic improvement in horizontal based measurement accuracy such as frequency, width, duty cycle, phase, delay, skew, etc, and enabling more sophisticated measurements such as jitter.

The typical analogue oscilloscope would have a horizontal accuracy of +/- 3% (or +/- 5% on magnified waveforms). This was very good performance in the days before the digital oscilloscope revolution. But the digital oscilloscope brought with it horizontal accuracies in the region of +/- 0.01%, a vast improvement of 300 times better than the analogue oscilloscope's 3%, which is reflected in the digital oscilloscope's vastly improved horizontal measurement accuracy. Many modern oscilloscopes now have horizontal accuracies in the region of +/- 0.0005% or better.

Digital Oscilloscope Vertical Accuracy

The first digital oscilloscopes came out with 6 bit A/D converters. This equates to 2^6 = 64 distinct voltage levels. Within a couple of years all digital oscilloscope architecture had moved to 8 bit A/D converters, which yields 256 distinct voltage levels (2^8 = 256). The 8 bit A/D converter has been used in oscilloscopes for the past 30 years with much of the performance improvements coming in higher sampling speed enabling higher speed real time acquisition.

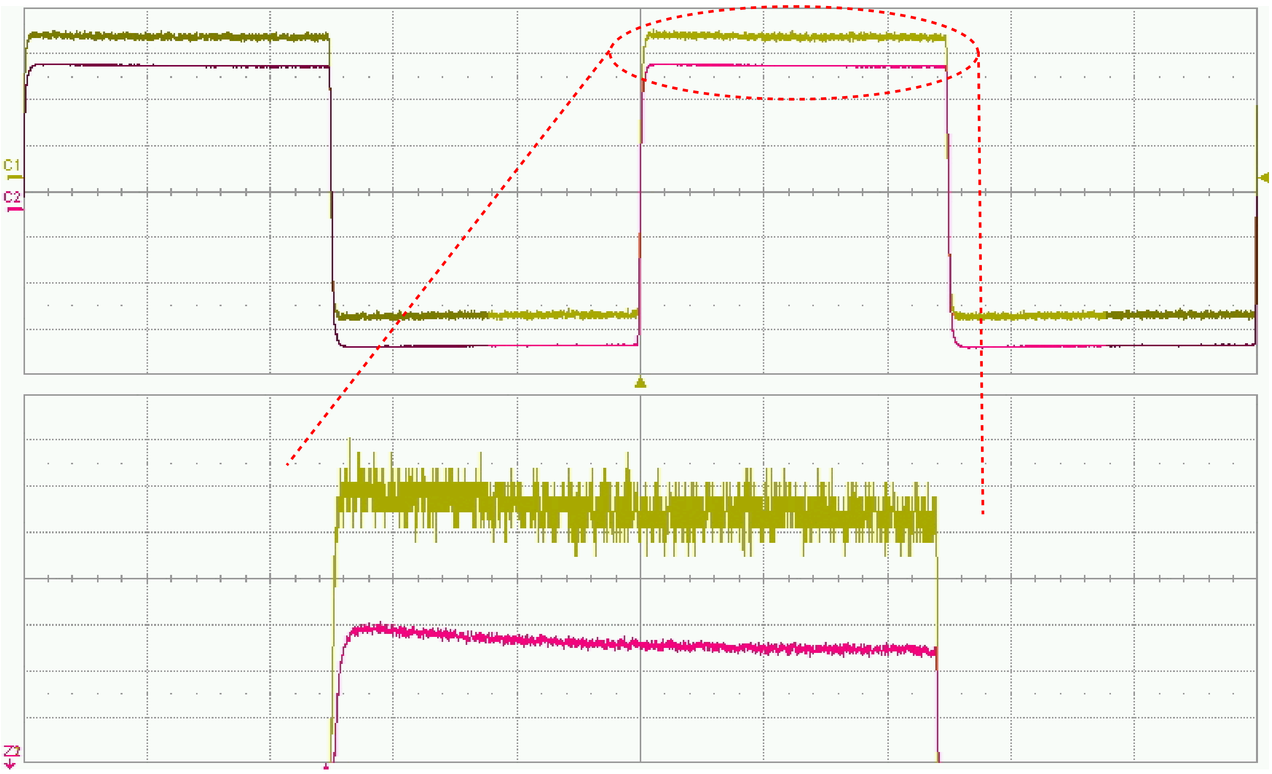
Whilst 8 bit A/D converters produce very good performance for general purpose applications it has always been the case that post acquisition viewing of fine detail has often left something to be desired.

The traditional workarounds to improve vertical resolution have involved either multiple acquisition averaging or a post acquisition enhanced resolution math filter.

Multiple Acquisition Averaging

The multiple acquisition averaging involves acquiring multiple waveform traces and averaging each point over the acquisition with the same point in the previous acquisition. The rational for this is that uncorrelated noise with be averaged out yielding more accurate vertical voltage measurements along with more effective vertical 'bits'.

Example of Averaging A Continuous Square Wave Waveform

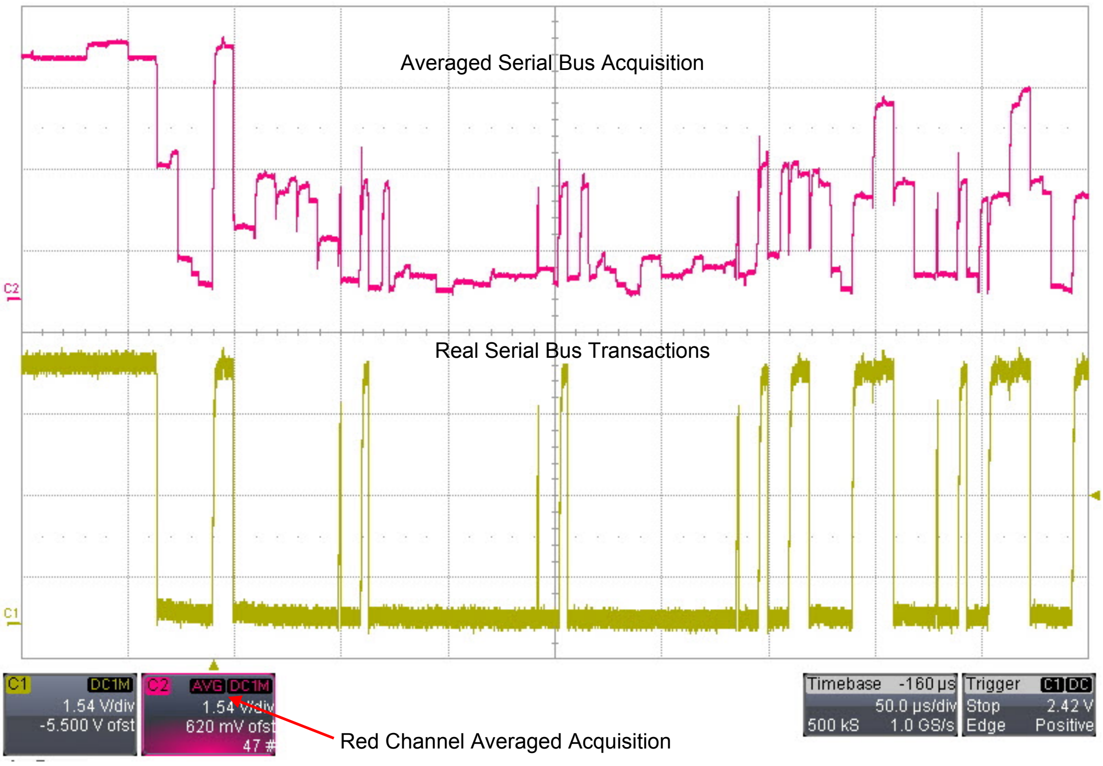


The averaging image on the previous page clearly produced improved results as we can see in the comparison of the single shot yellow trace compared to the 16 times averaged red trace. The lower zoom window shows this improvement.

Unfortunately everything is not always this simple. For example some scopes will not zoom on an averaged trace, so when one tries to zoom the averaged trace the last single acquisition is actually shown.

Another drawback with averaging is that it is not possible to average non-repetitive waveforms, for example circuit startup or shut down waveforms, a PRBS (Pseudo Random Binary Sequence) waveform or even a serial data waveform. Any waveform that is not repetitive in nature simply cannot be averaged without producing a meaningless display.

Example of Averaging A Serial Data Bus



In the diagram above we can clearly see the serial bus data states in the yellow trace, but the 16 times averaged serial data bus in the red trace is meaningless as the averaging has actually removed any useful or meaningful information. Clearly averaging should not be used for serial bus analysis or analysis of any other non-repetitive waveform.

The yellow trace is relatively ‘thick’ due to the noise on the digital serial bus. You can easily see this by comparing the yellow trace above with that on page 2.

Digital Oscilloscope Enhanced Resolution or High Resolution Mode

This mode is a post process math filter which uses adjacent waveform acquisition samples to mathematically produce a waveform display with an enhanced vertical resolution. The advantage of this is that an 8 bit oscilloscope can effectively become an 11 or 12 bit oscilloscope, with all that extra accuracy. 11 bits equaling 2048 and 12 bits equaling 4096 distinct voltage levels, a far cry from the 256 levels of the 8 bit A/D converter.

Unfortunately Enhance Resolution or High Resolution Oscilloscope modes also have a disadvantage, and that is a bandwidth trade-off against the extra vertical resolution.

Even worse the bandwidth trade-off of the Enhanced Resolution or High Resolution mode is not straight forward since it depends on the actual acquired waveform sample rate. This sample rate may depend on other factors such as acquisition memory depth available and the required timebase setting. As the timebase is changed so may the sample rate if there is insufficient memory for the A/D to run at its fastest rate. See example tables below comparing the bandwidth of two oscilloscopes at different maximum sample rates.

Oscilloscope set to 10GS/s Sample Rate	
Additional Bits	- 3dB point
0 (None)	Full Bandwidth
+1 Bit	1.205 GHz
+2 Bits	290 MHz
+3 Bits	80 MHz

Oscilloscope set to 2.5GS/s Sample Rate	
Additional Bits	- 3dB point
0 (None)	Full Bandwidth
+1 Bit	301.2 MHz
+2 Bits	72.5 MHz
+3 Bits	20 MHz

Both above oscilloscopes appear to have ample performance on paper, but when we look at the oscilloscope bandwidth performance with the Enhanced Resolution or High Resolution filter turned on we clearly see the trade off of bandwidth for vertical resolution with the different sample rates available.

4GHz Analogue Bandwidth Oscilloscope with 40GS/s A/D Converter showing -3dB bandwidth frequency point at various Enhanced Resolution / High Resolution Settings at different sample rates.						
	40GS/s - 3dB	20GS/s - 3dB	10GS/s - 3dB	5GS/s - 3dB	2.5GS/s - 3dB	1GS/s - 3dB
+1 Bit	4.82 GHz	2.41 GHz	1.205 GHz	602.5 MHz	301.2 MHz	120.5 MHz
+2 Bits	1.16 GHz	580 MHz	290 MHz	145 MHz	72.5 MHz	29 MHz
+3 Bits	320 MHz	160 MHz	80 MHz	40 MHz	20 MHz	8MHz

This idea has been expanded in the table above to show how the bandwidth is changing depending upon the digitizing rate and number of additional vertical resolution bits.

We also need to keep in mind that the digitizing rate of an oscilloscope will change depending on the available acquisition memory depth and timebase setting. As the timebase is set to a slower value so more memory is required to maintain the high sample rate. There comes a point where no more memory is available, therefore the sample rate is changed automatically by the oscilloscope. This ‘dynamically’ changes the oscilloscope -3dB bandwidth.

Some oscilloscopes will give a read out of the bandwidth when these Enhanced Resolution and High Resolution filters are used, as below, whereas others do not.

Example of different -3dB bandwidth readouts at different oscilloscope Enhanced Resolution / High Resolution settings

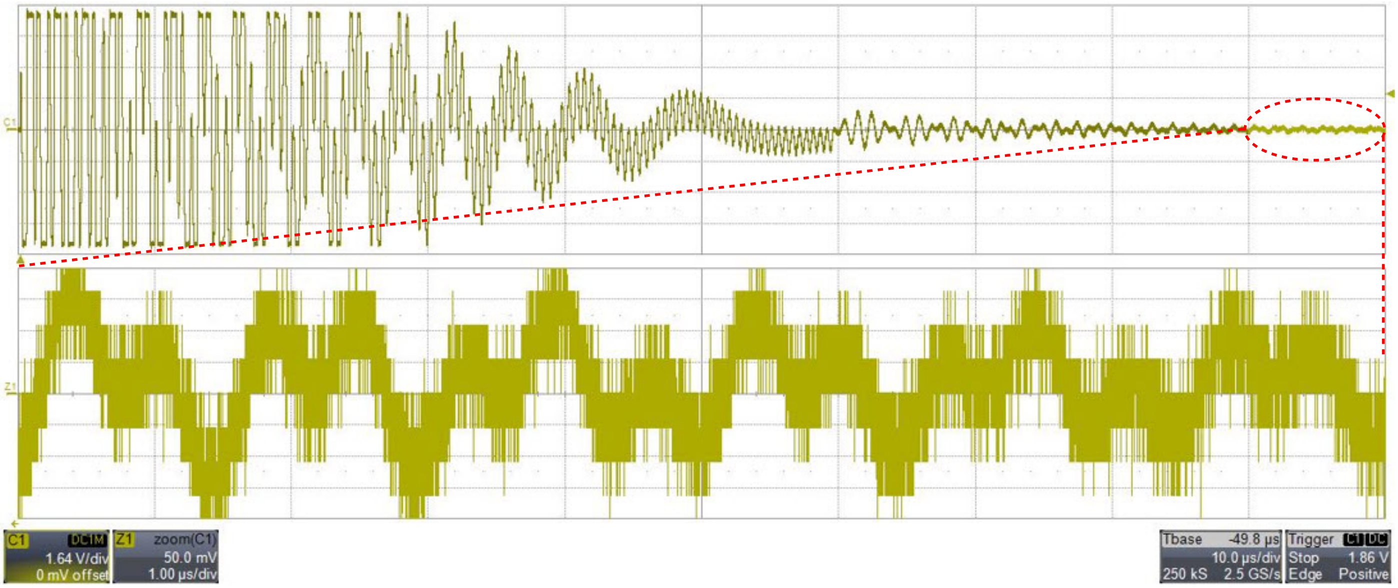
True 12 Bit Oscilloscope Technology

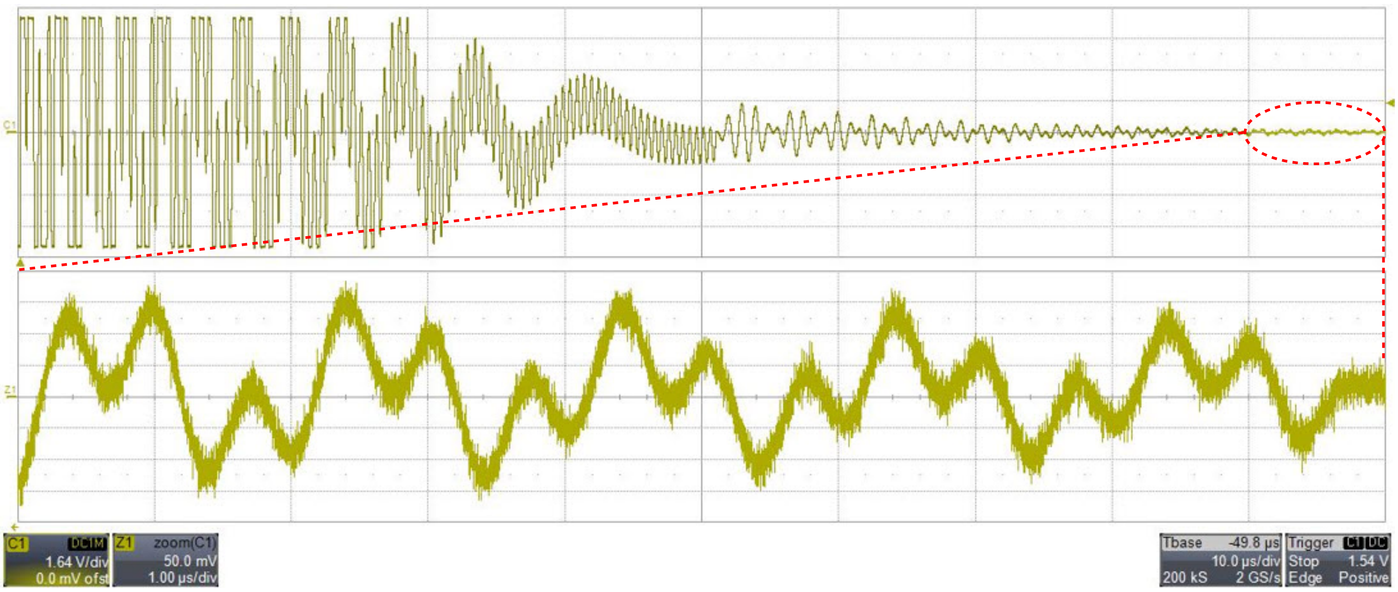
8 Bit oscilloscopes have been with us now for 30 years and have delivered excellent performance over this time, but it is clear from the need for averaging or Enhanced Resolution / High Resolution mode that real higher resolution is required. At present most oscilloscope manufacturers are trying to mathematically turn 256 discrete levels into 4096 discrete levels, this is hard to do and fraught with limitations brought on by different applications as we have seen.

Teledyne LeCroy has a range of true 12 bit oscilloscopes which allow users to make these more detailed measurements without needing to resort to the limitations of averaging and Enhanced Resolution / High Resolution mode.

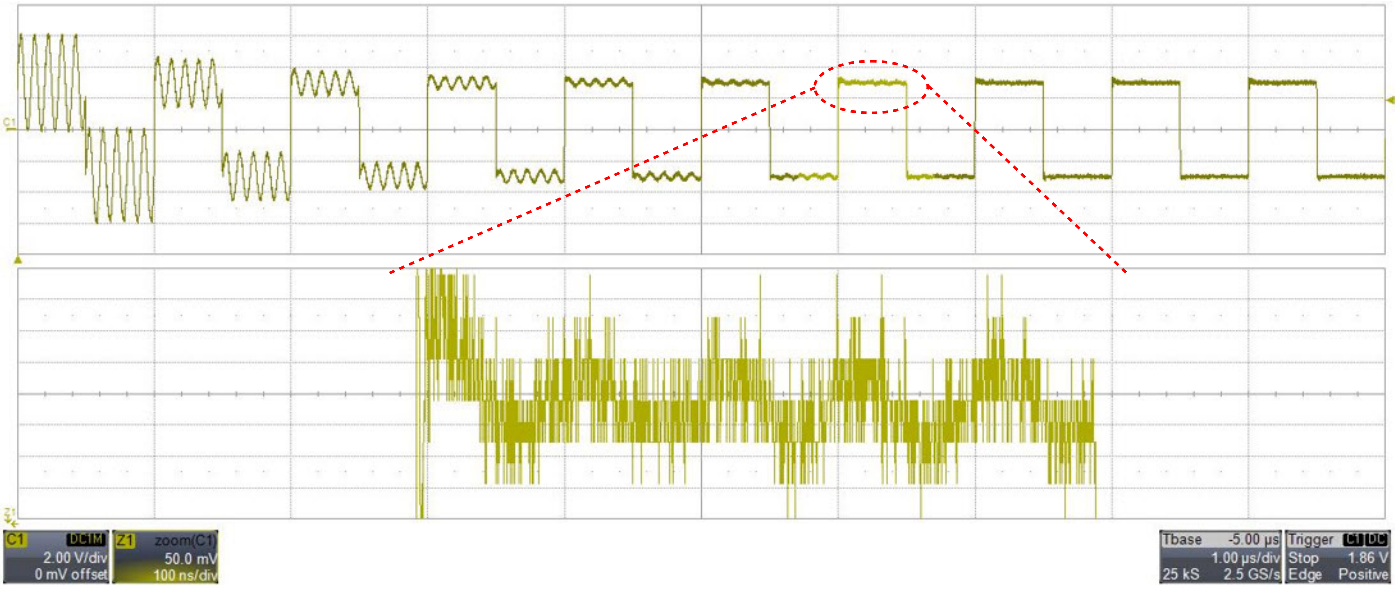
Below we can see the capture of a circuit power off event. The upper acquisition is on an 8 bit oscilloscope whereas the lower acquisition is on a true 12 bit oscilloscope.

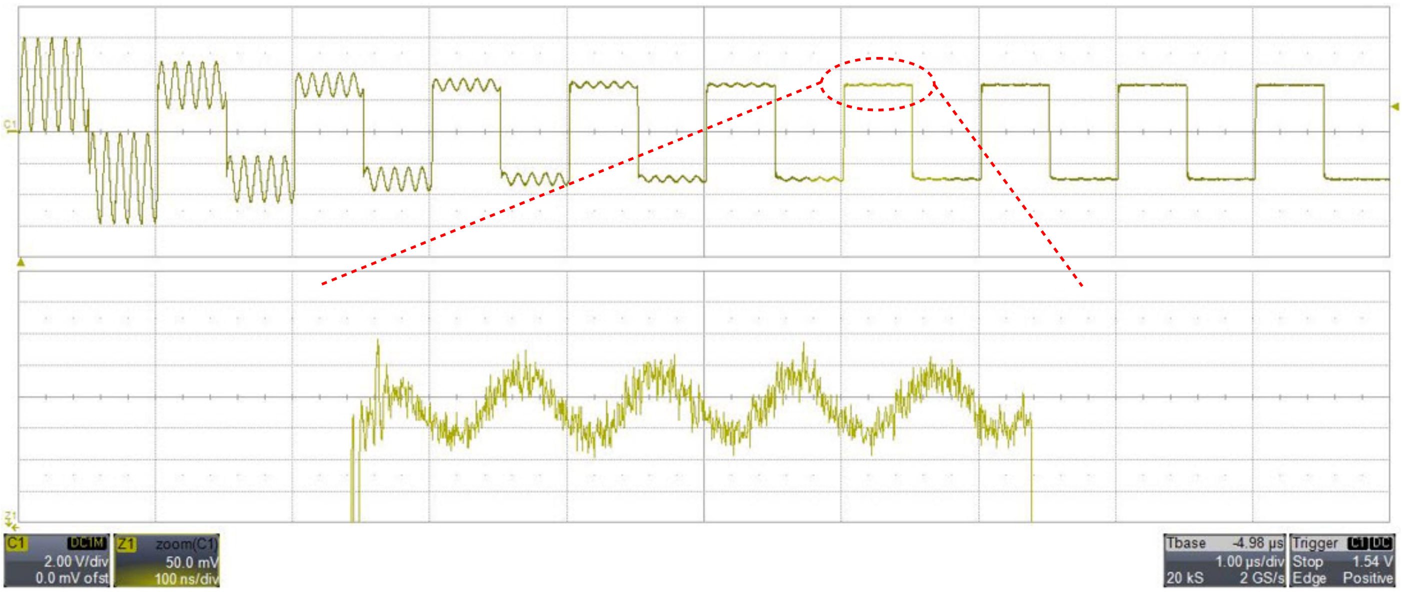
It is clear to see the additional benefit of the 12 bit technology over the 8 bit technology: cleaner, clearer waveforms without the need for averaging or a mathematically extracted High Resolution mode.





Another example below once again shows the benefits of the 12 bit architecture over the 8 bit architecture, where the fine detail at the top of the squarewave is far clearer with the additional resolution that a real 12 bit A/D converter provides.





In conclusion, it is clear to see that the 16 times vertical resolution increase that real 12 bit technology brings over 8 bit technology contributes significantly to the accuracy and clarity of modern day oscilloscope measurements. Many 8 bit oscilloscope manufacturers will recommend using averaging or high resolution modes to achieve the same ends, but this is not the same as we have seen. Besides this, if averaging and high resolution modes can be used to 'clean up' a signal then this option can be used on top of Teledyne LeCroy's 12 bit architecture to push the limit further out to 13, 14 or 15 effective bits.

It is paramount to start with the best acquired waveform possible before measurements or further mathematical manipulation. This is achieved by the 16 times vertical accuracy improvements that 12 bit acquisition technology brings over 8 bit acquisition technology.