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CS328A Performance

SNR, Noise, dynamic range and cross talk

Contents

1 Summary

The CS328A is offered in 10, 12 and 14 bit sampler configurations. This document examines the noise, dynamic range, cross talk, and ground noise performance of a typical off-the-shelf acquisition unit. We check the performance using instantaneous, averaged, and moving averaged acquisition methods.

2 ADC parameters

This section tabulates the parameters of the ADC's used in the Cleverscope Acquisition Unit. All values are typical.

Parameter	LTC2280	LTC2282	LTC2284	unit
Resolution	10	12	14	Bits
Sample Rate	100	100	100	MSPS
INL	±0.1	±0.4	±1.5	Bit
DNL	±0.1	±0.2	±0.6	Bit
SNR (30 MHz)	61.6	70.1	72.3	dB
SFDR (30 MHz)	85	86	86	dB
SINAD (30 MHz)	61.6	70	72.1	dB
IMD (40 +41 MHz)	85	85	85	dB

The analog front end uses the lowest noise and distortion components we could find that meet the price/performance environment we are working in. Our input chain is OPA355 – AD8337 – AD8138 – ADC.

These parts are all high bandwidth, low noise, and low distortion components.

3 Explanation

First, an explanation of some of the terms we use. When discussing signals and noise, it is common to talk about power into a known termination, and the noise figure, based on the impedances of the source and termination. However, we will depart from this, because the output impedance of the driving source is not known, and the input impedance to the scope varies with frequency, and is usually as high as we can make it. Thus it is difficult to measure the power, and derive the noise figure. Instead, we will express all measurements in dBV. Given the appropriate impedance transformations, power can be derived from this.

We will make our measurements over a defined bandwidth of 20 MHz. Given a wideband noise source, the rms voltage in a particular bandwidth is proportional to the square root of the bandwidth ratio. When using an FFT analyser the full band noise is distributed into the number of frequency bins used, according to this ratio. We will use 4096 frequency bins. When viewing frequency spans off less than 20 MHz, without an anti-aliasing filter (the case here) the full 20 MHz band noise is still distributed over the frequency bins used (4096 in our case).

3.1 Signal to Noise Ratio

The signal to noise ratio is the ratio between the integrated noise (we can use the signal information standard deviation value) and the largest signal we can measure in the presence of the integrated noise. As we are using volts, SNR = 20 log($V_{largest}$/V_{noise}). This can also be expressed as Effective Number of Bits (ENOB) as ENOB = (SNR – 1.76)/6.02

3.2 Internal noise

We have three factors limiting the displayed noise floor, which is determined by acquisition unit internal noise:

1. The bandwidth of the frequency bin we look over. A narrower frequency bin will result in a lower noise floor, because the integrated noise voltage is lower over a narrower bandwidth.

2. The resolution of the digitizer. The 'quantization noise' is proportional to the number of bits digitised. A digitizer will yield a quantization error of best case ±½ LSB about the true value. We can resolve 1 part in 1024 for the 10 bits sampler, 1 part in 4096 for the 12 bit sampler, and 1 part in 16384 for the 14 bit sampler. Thus the quantization noise is 12 dB down in voltage going from 10 bits to 12 bits, and 24 dB down from 10 to 14 bits.
3. The electrical noise floor of the acquisition system.

The Cleverscope acquisition unit varies the front end gain and offset to ensure that only the displayed scope graph amplitude window range is presented to the digitizer. In this way we maximize the signal to noise ratio available. For high gain (ie full scale volts are small < 100 mV), the electrical noise floor dominates, and the full dynamic range of the digitizer cannot be used. For lower gain (ie full scale volts are larger, > 1V), the digitizer resolution dominates, and the quantization noise dominates. In both cases, reducing the measurement bandwidth will lower the noise floor. This document finds the crossover point between the electrical and quantization noise floors.

3.3 External noise

External noise, such as noise in the system under test, reception of radio and TV stations, and noise generated by LCD and CRT monitors, and computers, all serve to increase the noise floor, and reduce the dynamic range. Without careful design and shielding of the unit under test, these factors may compromise the maximum available dynamic range.

3.4 Dynamic range

The dynamic range is the difference, in dB, between the noise floor, and the largest narrow band signal that can be measured. Either the electrical noise floor, for high sensitivity settings, or the digitizer resolution, for lower sensitivity settings, will limit it.

3.5 Cross talk

Cross talk is another source of effective noise – the proportion of signal on the other channel leaking into the channel under test. If we are measuring two signals at the same time (as we do for gain/phase plots), the cross talk may wind up being the limiting factor when measuring the dynamic range.

3.6 Ground noise

The acquisition unit is a dynamic system which includes switch mode power supplies, and high speed digital circuits. These generate noise. Great care has been taken to reduce the transmission of this noise to a minimum, but common mode electrical noise output by the acquisition unit can be turned into differential input noise via any series impedances. We measure the ground noise to quantify it.

4 Cleverscope acquisition unit construction

The Cleverscope acquisition unit uses these methods to reduce noise:

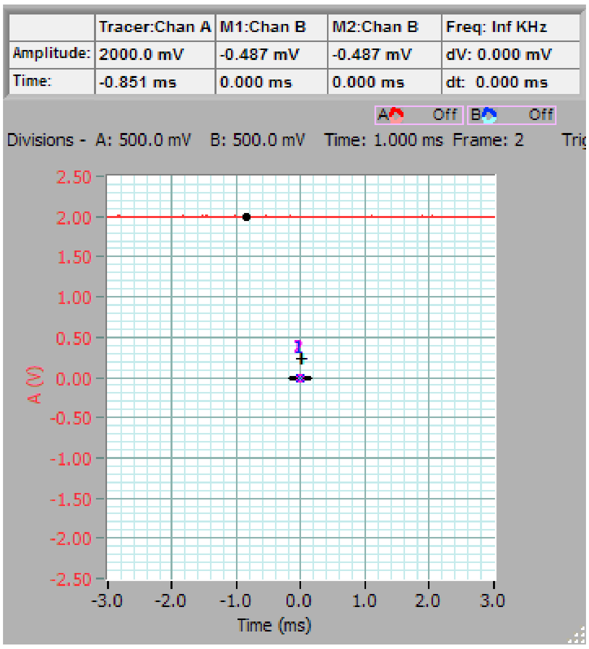
1. The plastic case is internally coated with aluminium, and aluminium sheet is used for the front and rear panels. The panels are held by U-grooves to eliminate E field leakage into or out of the unit. The two mating halves use coated U grooves to minimize leakage. The panels, and aluminium coating are earthed.
2. A six layer printed circuit board is used, with controlled impedance tracks used for most signal lines. Many of the signal lines are differential to reduce the effects of common mode noise.
3. Two distributed ground planes are used – one for the top surface components, and the other for the bottom surface components. These ground planes reduce the amplitude of the E field emanating from the PCB tracks and components.

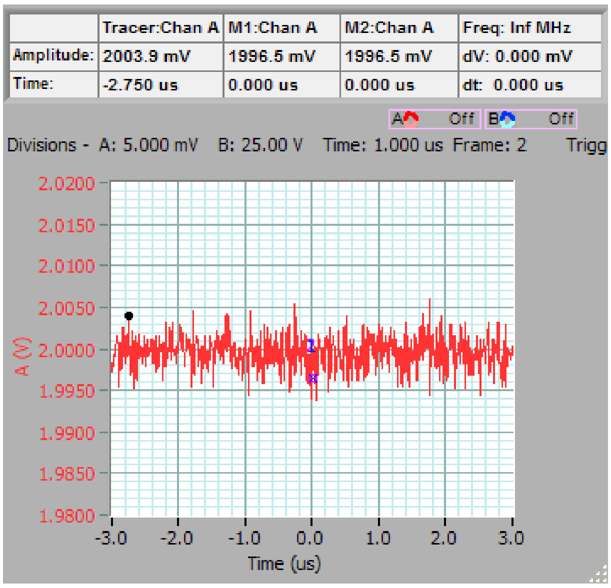
4. A partitioned power plane is used to ensure that recirculating power/ground currents are contained, and to minimize digital to analog ground current coupling.
5. Monolithic multi-layer PI filters are used at the outputs of each switch mode power supply to reduce high frequency switch energy from propagating into the analog front end.
6. Monolithic multi-layer PI filters are used between each digital control line and the analog front end and the control components (ADC's, DAC's and switches) to limit digital switch noise from propagating into the analog front end.
7. Spatial separation is maintained between the analog and digital sections to minimize E-field sharing, with particular emphasis on the power supply runs to stop ground current mixing.
8. A ground pour on the top and bottom layers ensures further reduction of signal coupling between components.
9. A distributed power scheme is used, with very low noise, high PSRR linear regulators used to provide power to individual circuit functions to minimize power supply coupling of unwanted signals, and reduce power supply sourced noise at high frequencies.

5 Signal to Noise

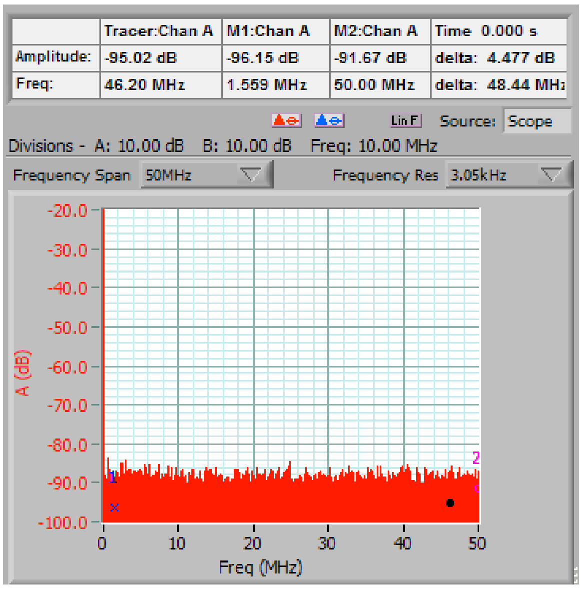
As a first experiment, we measure the Signal to Noise Ratio achievable with the acquisition unit. We use a 14 bit capture, no filters, capturing a 2.0V DC signal, without any filtering. We capture over a period of ±3ms, with a ±2.5V amplitude range. We use DC because it is easy to filter, and gives us the best case SNR.

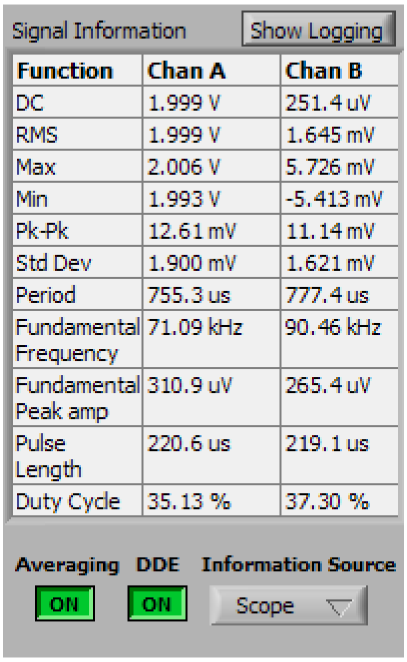
Below you can see the scope graph with 2.0V DC signal, and the tracking graph which is zoomed on the DC signal, in volts and time.





The spectrum graph which shows a flat noise floor at about -85 dBV





Signal Information

Show Logging

Function	Chan A	Chan B
DC	1.999 V	251.4 uV
RMS	1.999 V	1.645 mV
Max	2.006 V	5.726 mV
Min	1.993 V	-5.413 mV
Pk-Pk	12.61 mV	11.14 mV
Std Dev	1.900 mV	1.621 mV
Period	755.3 us	777.4 us
Fundamental Frequency	71.09 kHz	90.46 kHz
Fundamental Peak amp	310.9 uV	265.4 uV
Pulse Length	220.6 us	219.1 us
Duty Cycle	35.13 %	37.30 %

Averaging ON DDE ON Information Source Scope

The signal information shows a standard deviation of 1.9mV. This represents the integrated rms noise level.

The Peak-Peak value represents ±4 standard deviations away from mean, and therefore values that are much less likely to happen.

Throughout this discussion we are working with typical or average values.

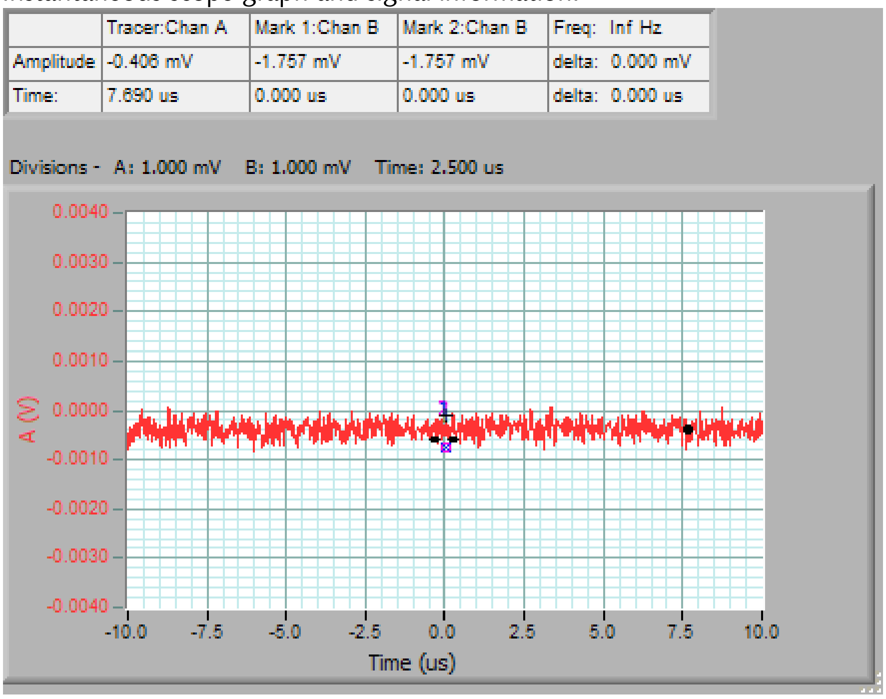
We have a dynamic range of ±2500 mV, with a standard deviation of 1.9mV. This is 1 part in 2630. The SNR = 20 log(2500/1.9) = 68.4 dB. ENOB = (68.4-1.76)/6.02 = 11.1 bits ENOB. This is the basic capability of the scope.

6 Electrical Noise

6.1 Internally sourced noise

These measurements were made with a 14 bit digitizer, a scope graph set to 1mV/div, 8 mV FSD, peak captured, scope graph width of +/-10us, and a spectrum graph with a frequency span of 17 MHz, and 2.44 kHz frequency resolution. The 20 Mhz filter was used. A desktop PC was used , with grounded power supply, and the standard Franmar switchmode power supply. The digitizer was switched between 10,12 and 14 bit resolution to verify quantization noise floor. The inputs were open. This setup minimizes the noise floor.

Instantaneous scope graph and signal information:

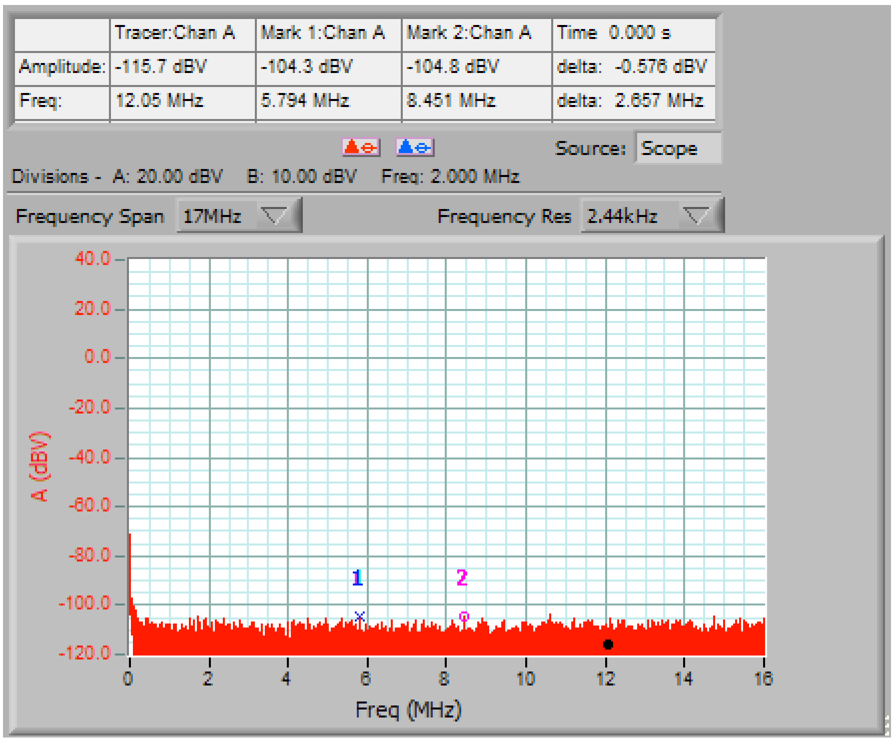


Signal Information — Show Logging

Function	Chan A	Chan B
DC	-379 uV	-1.90 mV
RMS	404 uV	1.90 mV
Max	58.0 uV	-1.48 mV
Min	-841 uV	-2.35 mV
Pk-Pk	899 uV	875 uV
Std Dev	150 uV	152 uV
Period	191 ns	472 ns
Fundamental Frequency	5.68 MHz	11.7 MHz
Fundamental Peak amp	34.4 uV	38.9 uV
Pulse Length	146 ns	410 ns
Duty Cycle	76.3 %	86.8 %

Averaging: OFF — Information Source: Scope

The spectrum graph (instantaneous):



Discussion

Peak-peak noise was 899uV. The standard deviation, a measure we will use from now on (as the spectrum graph shows rms values in a frequency bin) is 150 uV. This noise is present across the filter limited oscilloscope bandwidth (because we used peak captured acquisition, with the 20 Mhz filter on). We can see from the spectrum graph that the noise floor is about –105 dBV. Further to resolve 1 LSB, we want the LSB to be 2x larger than the noise floor. Thus one LSB represents –99 dBV (2x = 6 dB) when noise limited. This is the same as 11.3 uV. Based on this value, the minimum rms signal levels we can measure, and maintain full digitizer resolution for instantaneous measurements are:

10 bit: 11.3 uV x 1024 =~ 12 mV
12 bit: 48 mV
14 bit: 192 mV

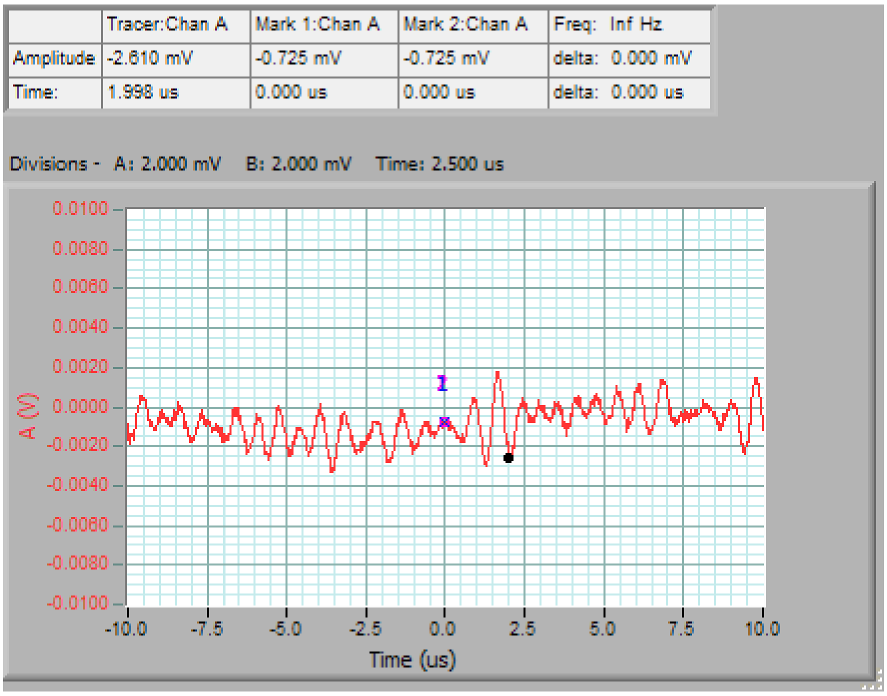
We make a distinction between instantaneous and averaged resolution here. Because noise is random, and a signal is not, we can average to reduce the noise, while maintaining the signal. In this way we can reduce the noise limited minimum rms signal level for which we get full digitizer resolution. We will look at this while measuring a signal. We also assume that the measured signal is not itself polluted by externally sourced noise.

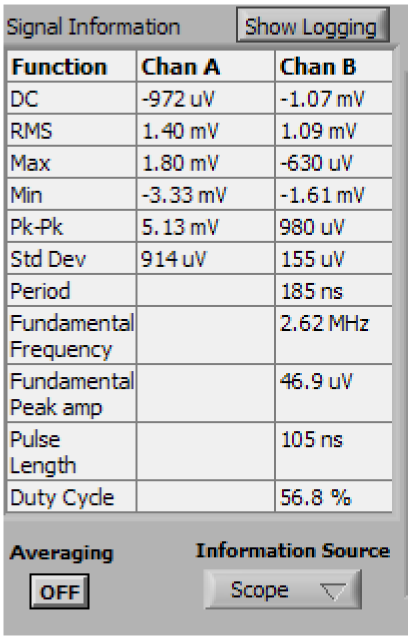
6.2 *Externally sourced noise*

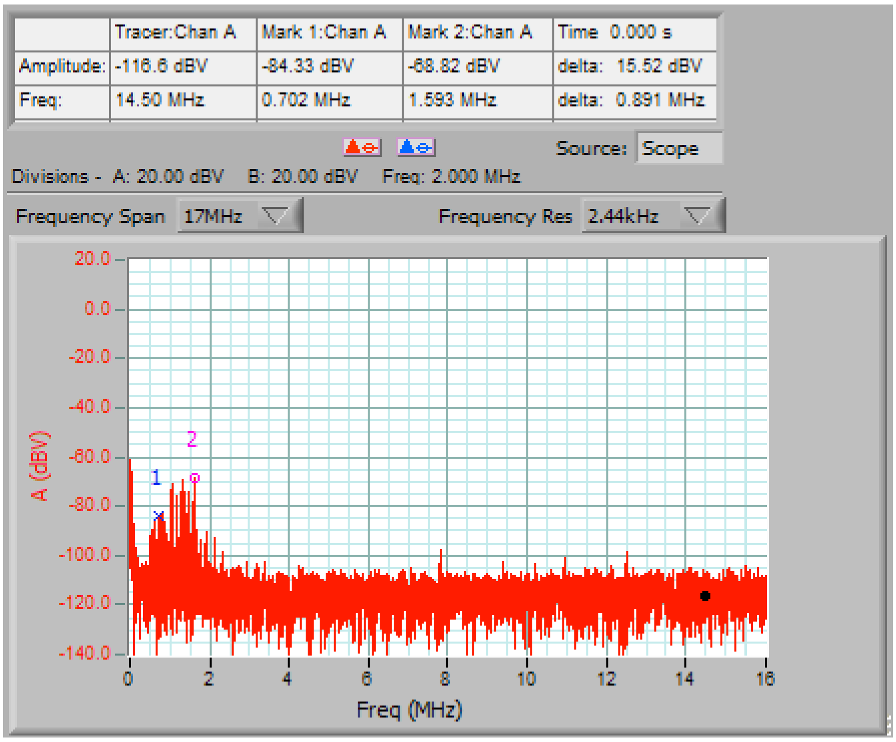
External noise is noise injected into the measuring channel from outside sources. For low level signals, external noise sources are significant and have to be managed.

Most urban settings have significant RF noise emanating from Radio and TV stations, ADSL telephone loops, Wifi networks, PCs and PC peripherals. Though some of the energy transmitted maybe out-of-band, any non-linear element (such as a diode or transistor) in the signal chain can demodulate the RF signal, and present an in-band signal.

As an example a 50mm piece of wire was inserted into the Chan A BNC Cleverscope input. The resulting graphs are:

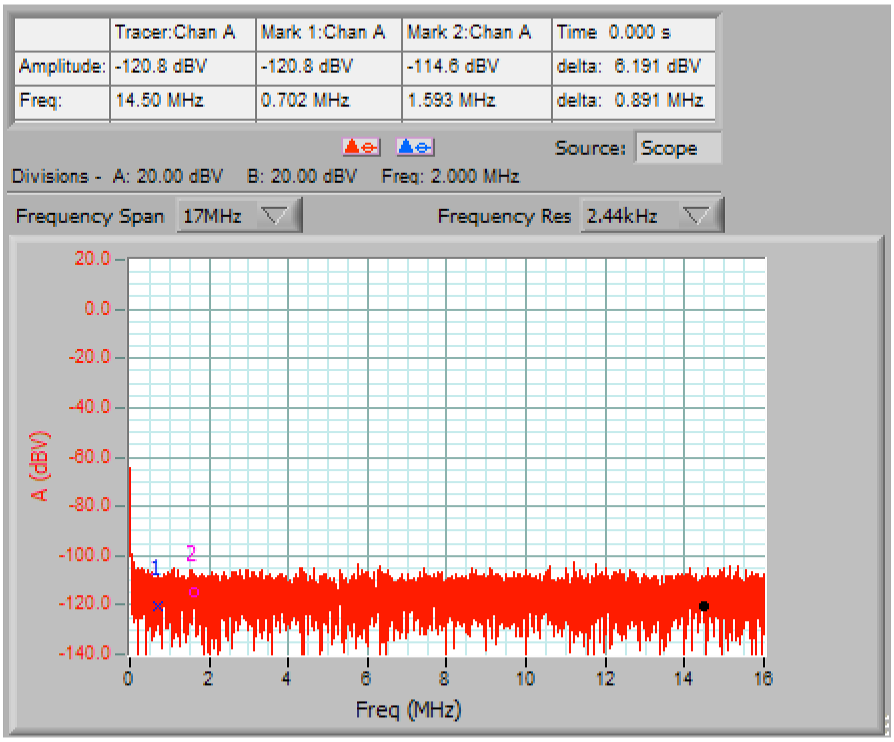






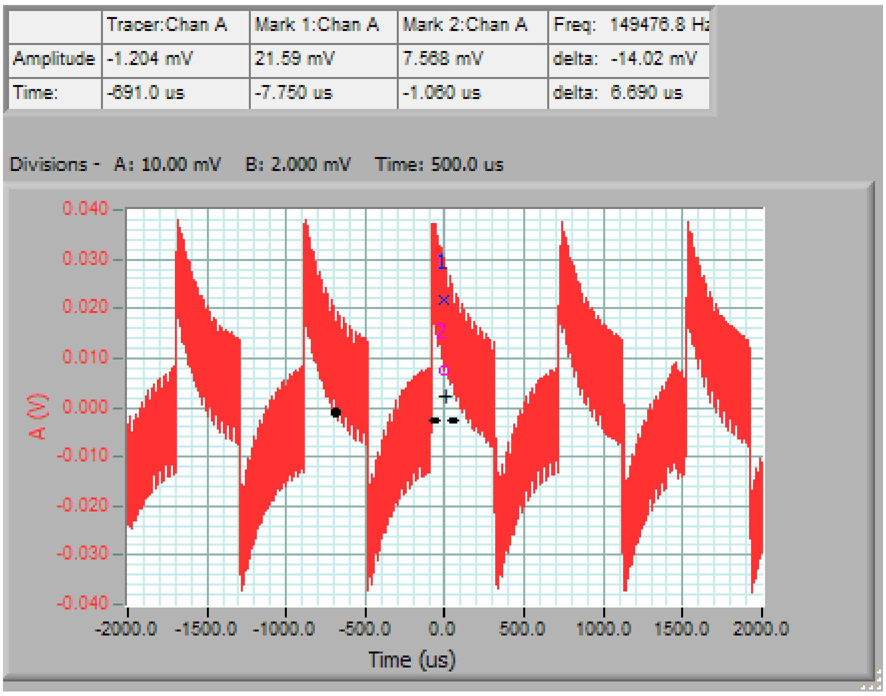
The spectrum graph shows the presence of several local AM radio stations between 702 kHz and 1593 kHz:

The entire Cleverscope acquisition unit was placed in an earthed Faraday cage (a metal box large enough to hold the unit and the antenna, with surrounding airspace space around the acquisition unit to allow internal radiation if it was occurring), and the following spectrum graph resulted:



This shows fairly clearly that the noise is externally sourced. It also tells us that even short stubs of wire or PCB track can act as antennas for signals we did not expect. To maximize dynamic range for low level signals you will need good shielding around all the circuit modules used – particularly when used near PC's and LCD display's.

Here is the field measured 100mm from the LCD screen of a Tektronix TDS210 oscilloscope, with a standard scope probe with grabbing tip fixed, 10:1 switch setting:



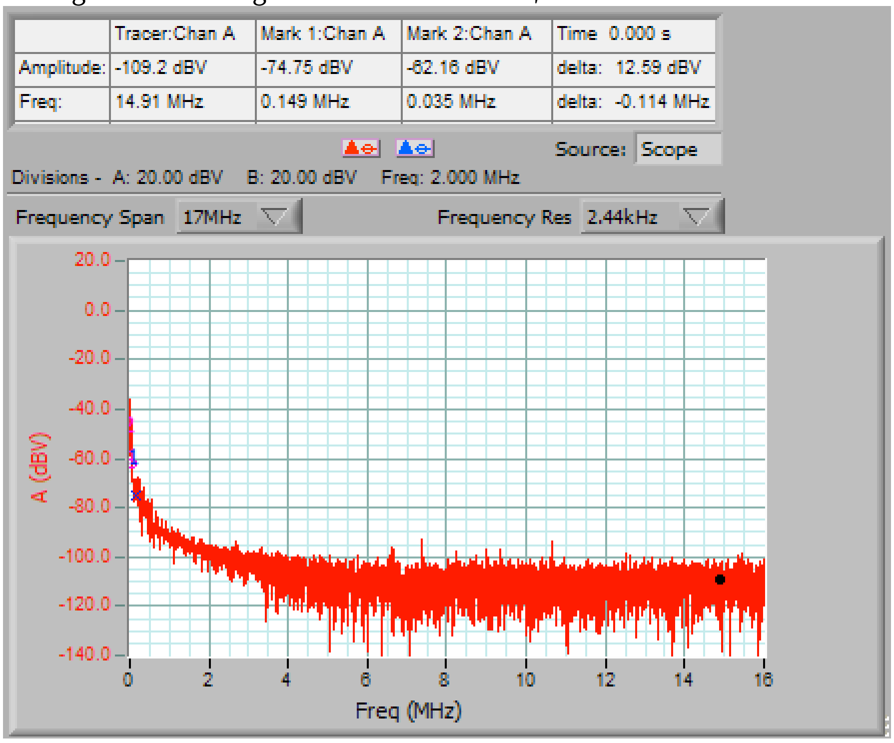
Signal Information Show Logging

Function	Chan A	Chan B
DC	197 uV	-929 uV
RMS	15.3 mV	1.02 mV
Max	38.1 mV	-140 uV
Min	-37.8 mV	-1.64 mV
Pk-Pk	75.9 mV	1.50 mV
Std Dev	15.2 mV	415 uV
Period	799 us	9.46 us
Fundamental Frequency	1.24 kHz	320 kHz
Fundamental Peak amp	16.4 mV	32.9 uV
Pulse Length	417 us	7.32 us
Duty Cycle	52.1 %	77.4 %

Averaging OFF

Information Source Scope

This signal results in significant RF interference, still measurable half a meter from the screen:

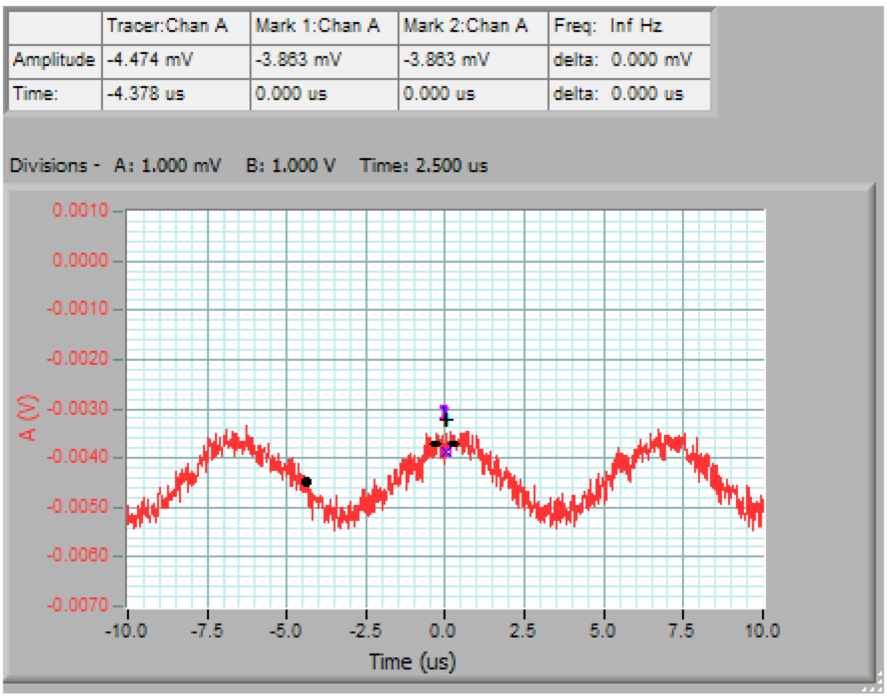


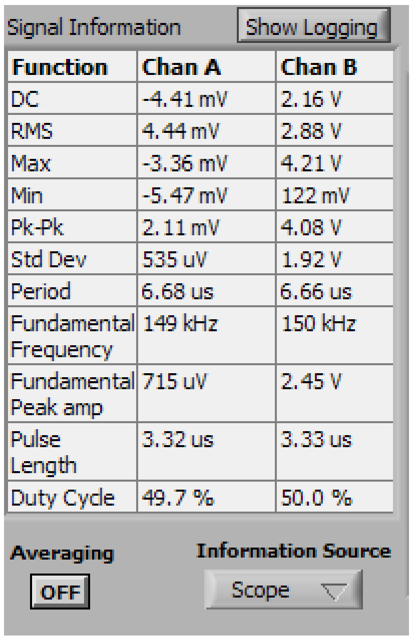
The region 0 – 4Mhz has significantly raised noise floor.

7 Dynamic Range

We use an Agilent 33120A signal generator as the signal source, a 10:1 probe, and 50 ohm terminating resistor acting as an attenuator on the 10:1 probe to measure performance with a 500 uV rms signal. We used a 150 kHz sine wave, because the low pass trigger filter will still work at this frequency, to stabilize the trigger. Later we used the 33120A sync output with a 100:1 probe on the B channel as sync. We used the 100:1 probe to minimize the possible effects of cross talk.

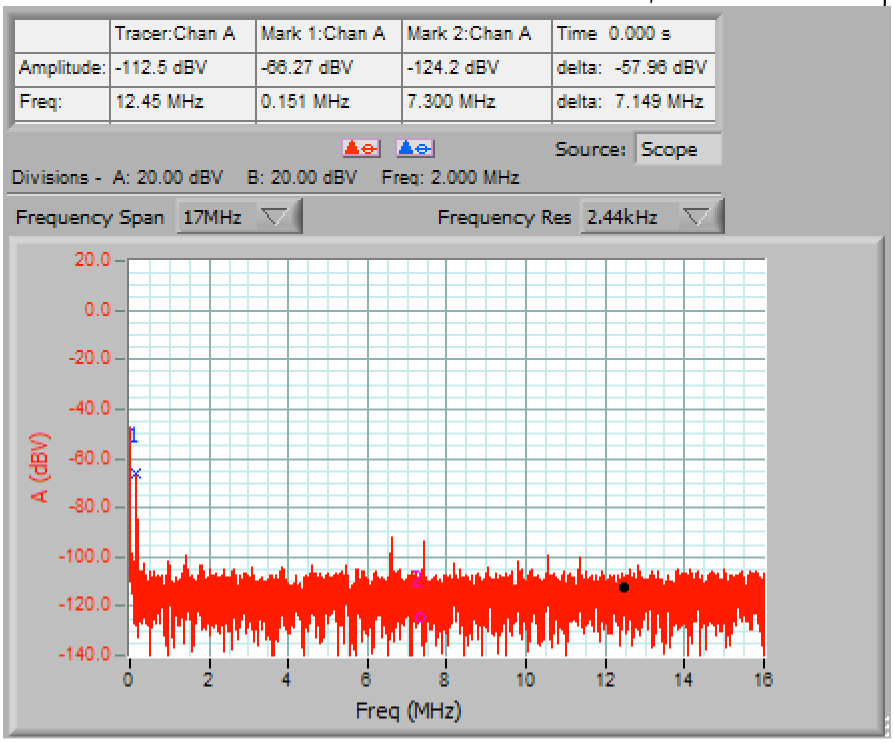
Here is the signal without averaging:





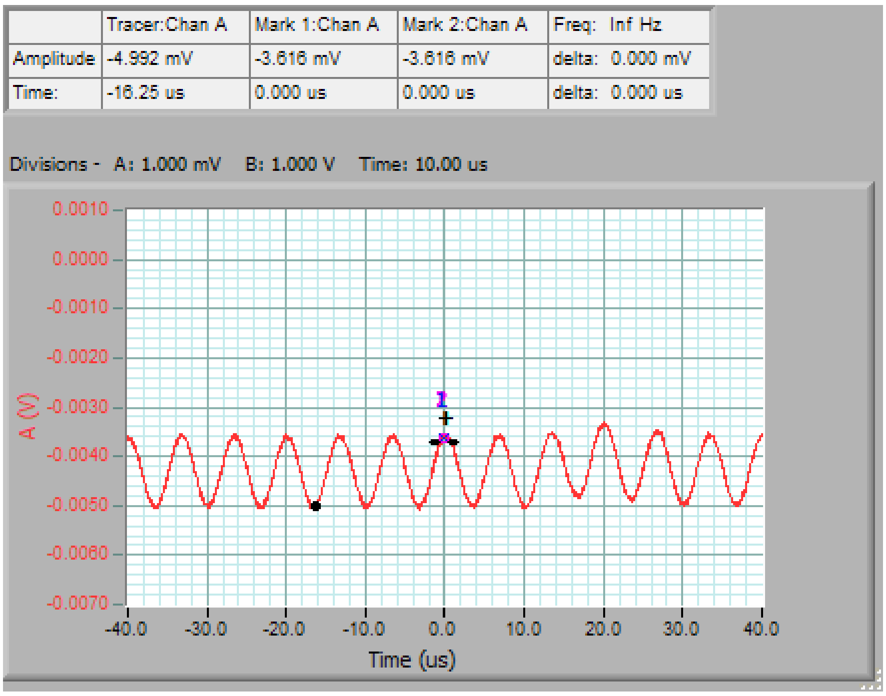
Function	Chan A	Chan B
DC	-4.41 mV	2.16 V
RMS	4.44 mV	2.88 V
Max	-3.36 mV	4.21 V
Min	-5.47 mV	122 mV
Pk-Pk	2.11 mV	4.08 V
Std Dev	535 uV	1.92 V
Period	6.68 us	6.66 us
Fundamental Frequency	149 kHz	150 kHz
Fundamental Peak amp	715 uV	2.45 V
Pulse Length	3.32 us	3.33 us
Duty Cycle	49.7 %	50.0 %

We use the standard deviation to measure the rms value, which is what the spectrum graph displays:



The 150 kHz signal can be seen highlighted by Marker 1. The amplitude is reported as –66.2 dBV, or 490 uV.

Now we use averaging to gain a better estimate of the signal. We average over a few more cycles to gives us our best estimate, and look with the spectrum graph at a narrower region of interest. Note that narrowing the graph does not give better noise floor, because the complete bandwidth noise values alias into the spectrum window used. A filter would have been required (this can be done with the maths) to reduce the actual bandwidth, and therefore the noise floor.



Spectrum Information Show Logging

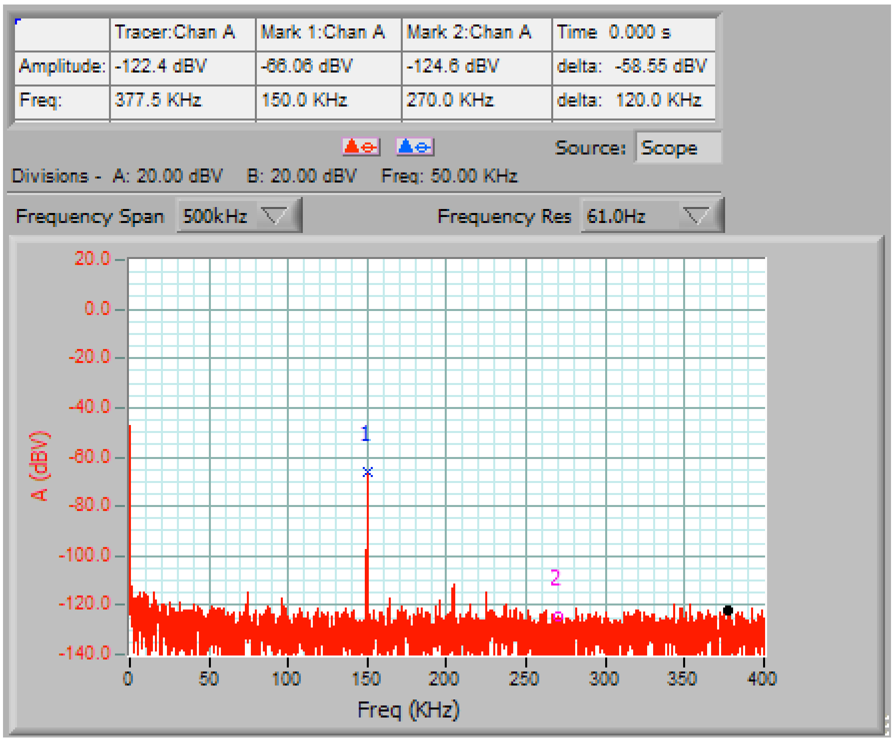
Function	Chan A	Chan B
DC	-4.32 mV	2.16 V
RMS	4.35 mV	2.89 V
Fmax	0.00 Hz	0.00 Hz
Vmax	-47.3 dBV	6.70 dBV
F1	150 kHz	150 kHz
V1	-66.0 dBV	4.77 dBV
F2	300 kHz	300 kHz
V2	-113 dBV	-33.9 dBV
F3	450 kHz	450 kHz
V3	-110 dBV	-4.85 dBV
SINAD	9.95 dB	7.37 dB
THD	-36.2 dB	-8.29 dB
HD2+3	-47.3 dB	-38.6 dB

Averaging OFF

Information Source Spectrum

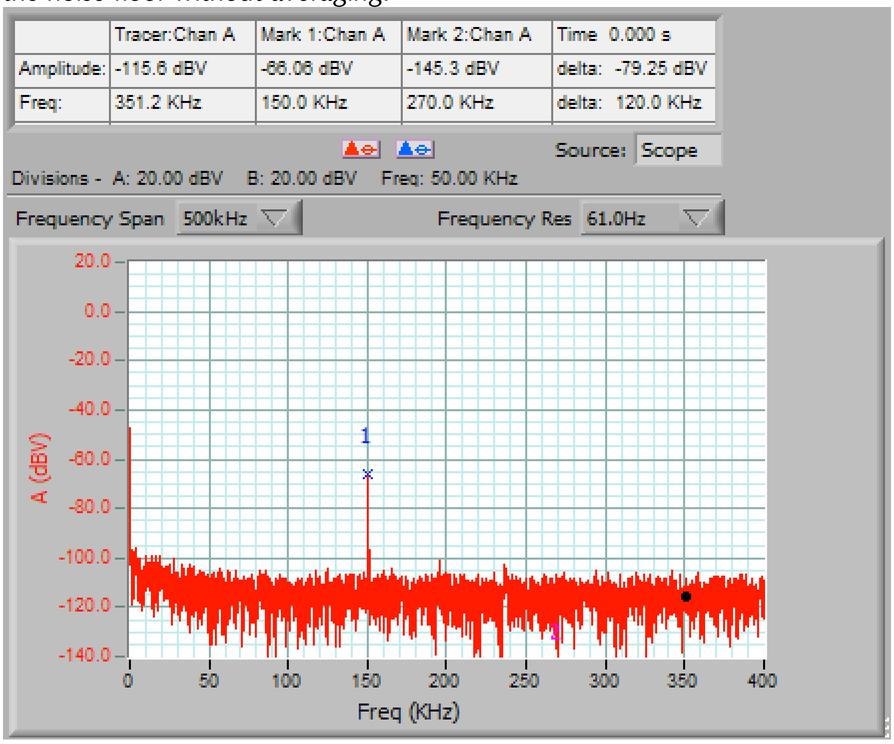
We used 20 averages. The information shows the amplitudes in the frequency domain, by using the spectrum graph as the information source.

Here is the spectrum graph:



The 150 kHz signal amplitude is –66dBV. This is 10 ** (-66/20)= 501 uV.

The important thing to notice is the averaging process (using 20x averages) has lowered the noise floor. Here is the noise floor without averaging:



The noise floor is about 20 dB lower with averaging. Increasing the number of averages can make further gains.

Assuming 10x averages, we can see that the we can easily get a 10 dB improvement in dynamic range (about 3x). Given these values, the averaged noise limited signals levels are:

10 bit: 3 mV
12 bit: 12 mV
14 bit: 50 mV.

We can see that for the 500 uV test signal, we have about 34 dB of headroom in the non-averaged case, meaning we should be able to resolve about 10 uV, and about 44 dB of headroom in the averaged case. We should be able to resolve about 3uV in this case.

7.1 *Proving Dynamic Range*

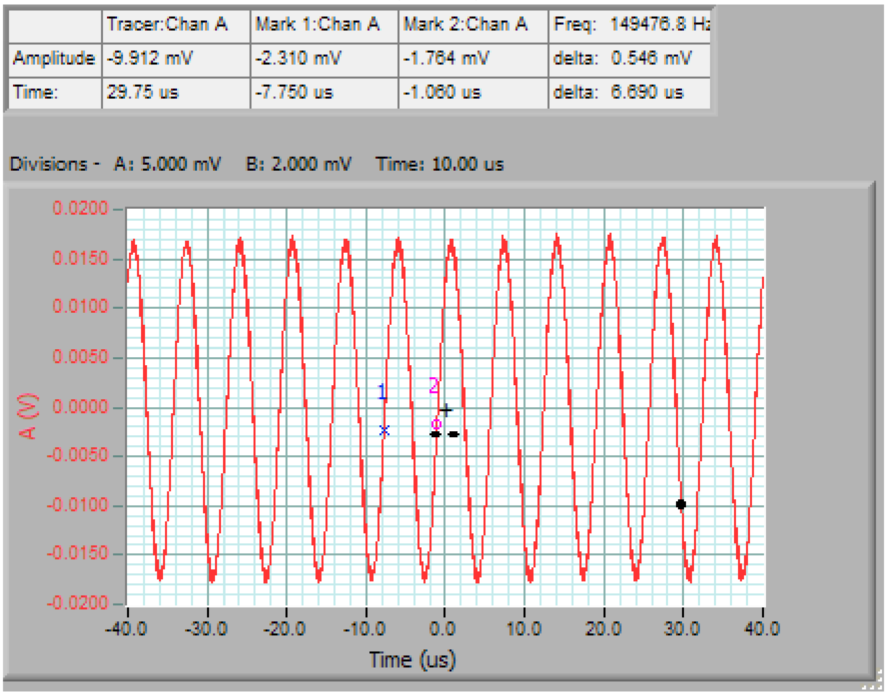
Given the measurements above, we will prove the dynamic range possible, for the averaged and non-averaged cases.

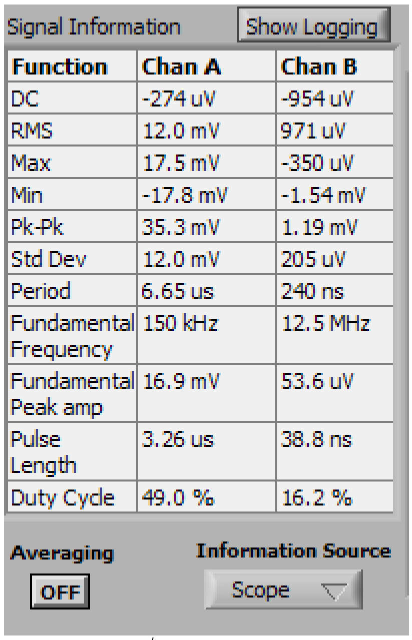
We found that for the non-averaged case, we should be able to measure these noise limited values

- 10 bit: 12 mV
- 12 bit: 48 mV
- 14 bit: 192 mV

7.1.1 10 bit resolution

Here are the results for a 12mV signal digitized with 10 bit resolution:



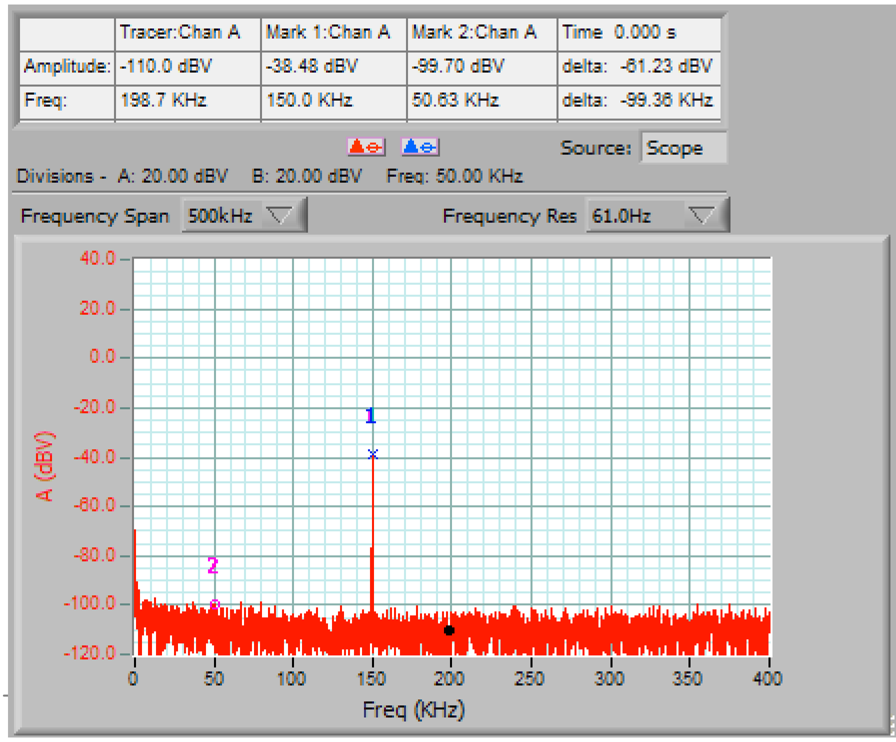


Signal Information — Show Logging

Function	Chan A	Chan B
DC	-274 uV	-954 uV
RMS	12.0 mV	971 uV
Max	17.5 mV	-350 uV
Min	-17.8 mV	-1.54 mV
Pk-Pk	35.3 mV	1.19 mV
Std Dev	12.0 mV	205 uV
Period	6.65 us	240 ns
Fundamental Frequency	150 kHz	12.5 MHz
Fundamental Peak amp	16.9 mV	53.6 uV
Pulse Length	3.26 us	38.8 ns
Duty Cycle	49.0 %	16.2 %

Averaging OFF — Information Source Scope

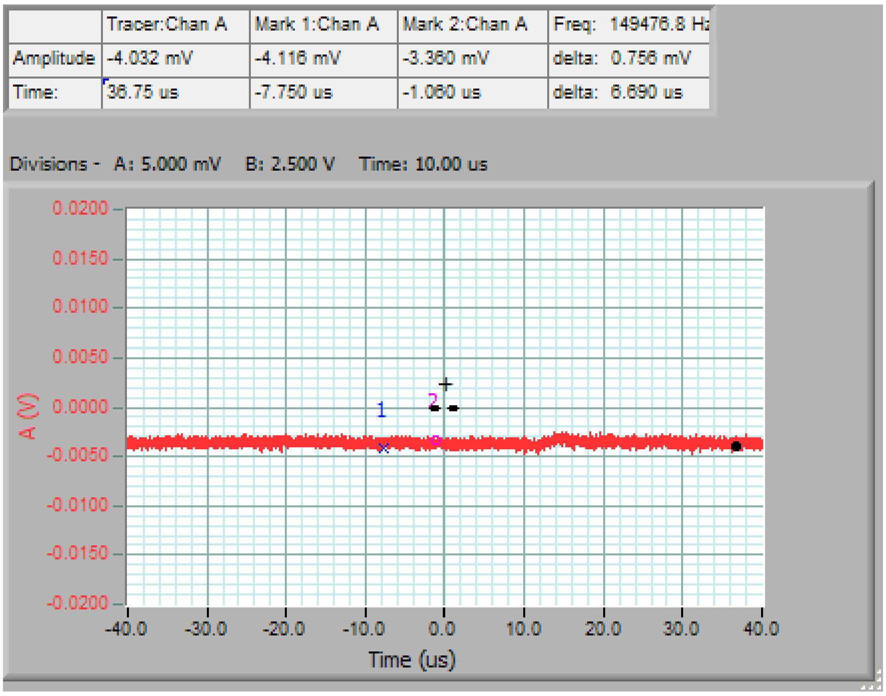
The Std Dev is 12 mV. (Note the Fundamental peak amp is given in peak units, which are √2 times higher than the RMS value). The frequency graph shows:



The amplitude is –38.48 dBV or 11.9 mV.

The noise floor is about –100 dBV or 10 uV. This is a ratio of 1 part in 1190. We have 10 bit resolution.

We used the sig gen sync output for synchronization. Here we introduced a divider to 30 uV. The scope graph is still set for the same axis values as when measuring 12mV:



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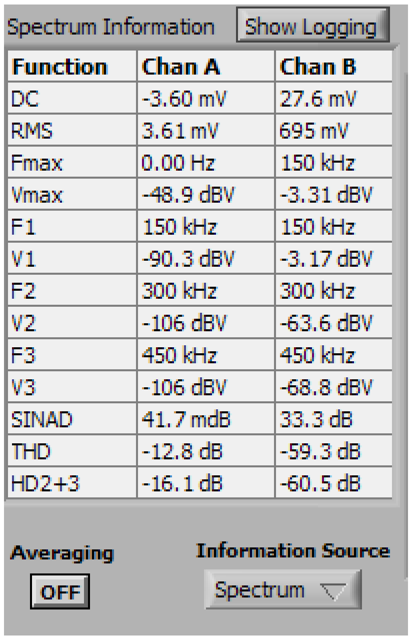
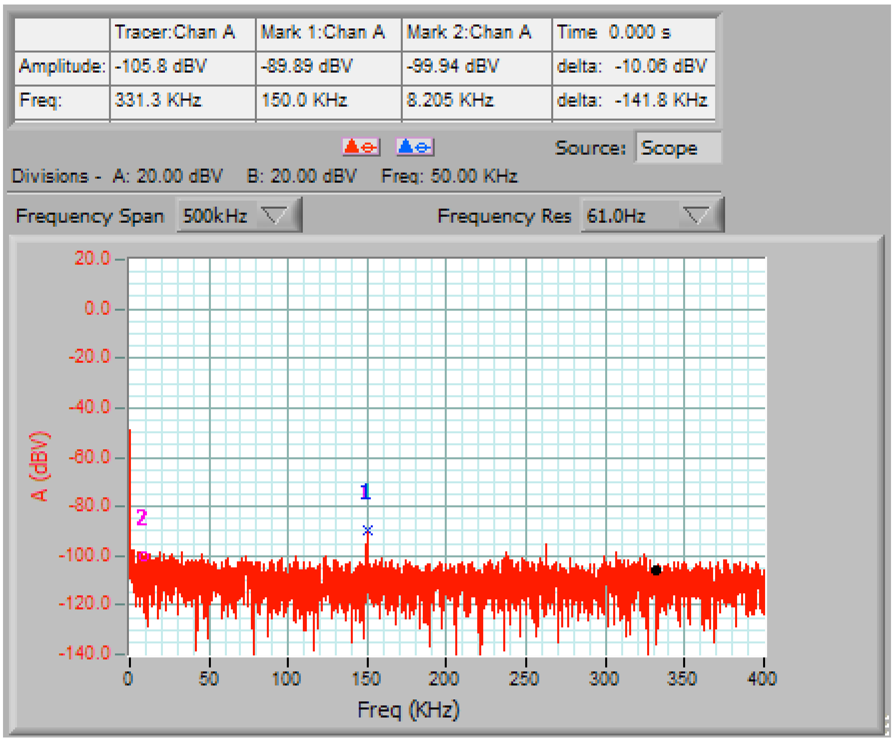
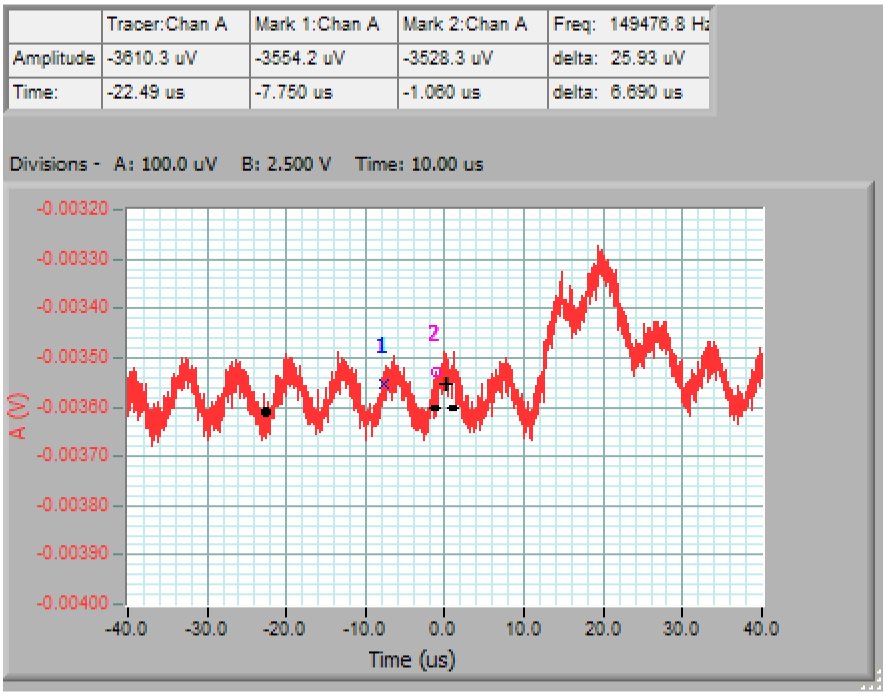


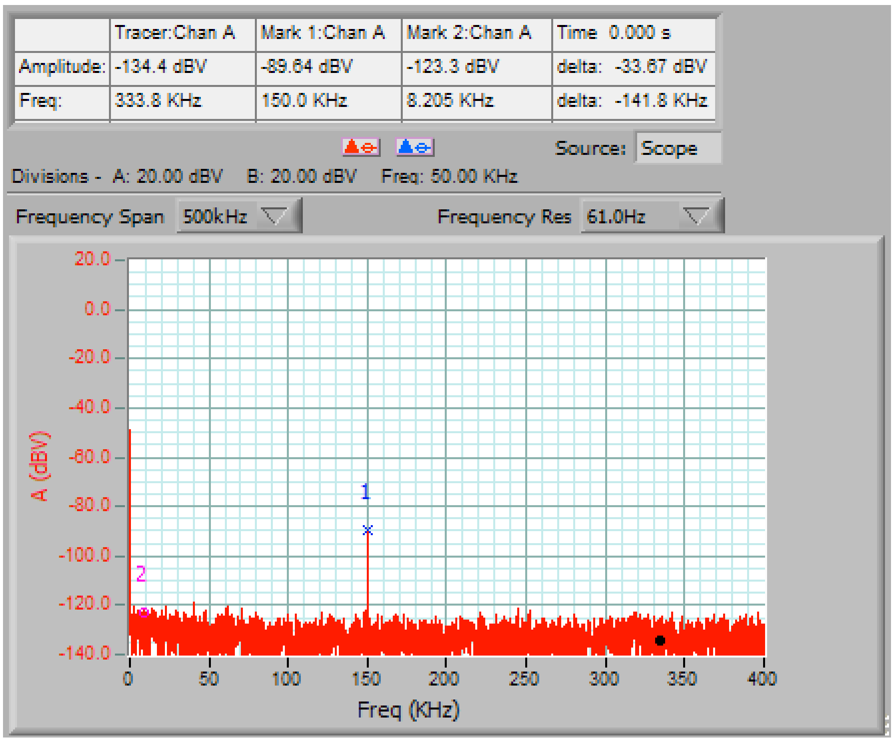


The spectrum graph shows the 150 kHz signal, at –90 dBV. This corresponds to 31.6uV. There is still 10 dB (3x) headroom, meaning we can still resolve 10uV.

Averaging can be used to increase the noise floor, as previously explained.
In the next acquisition, we average 20x. After acquisition, we expanded the amplitude axis (meaning the acquisition unit has been operating the whole time with the same amplitude gain):



The 200 uV jump in level between 10 and 20us is caused by the trigger LED coming on, and injecting charge into the analog front end. We have filtering to try and minimize this effect. This problem has since been resolved.



Spectrum Information | Show Logging

Function	Chan A	Chan B
DC	-3.57 mV	27.5 mV
RMS	3.58 mV	694 mV
Fmax	0.00 Hz	150 kHz
Vmax	-48.9 dBV	-3.21 dBV
F1	150 kHz	150 kHz
V1	-90.6 dBV	-3.18 dBV
F2	300 kHz	300 kHz
V2	-110 dBV	-64.5 dBV
F3	450 kHz	450 kHz
V3	-108 dBV	-68.6 dBV
SINAD	49.6 mdB	33.4 dB
THD	-12.3 dB	-58.3 dB
HD2+3	-19.9 dB	-61.3 dB

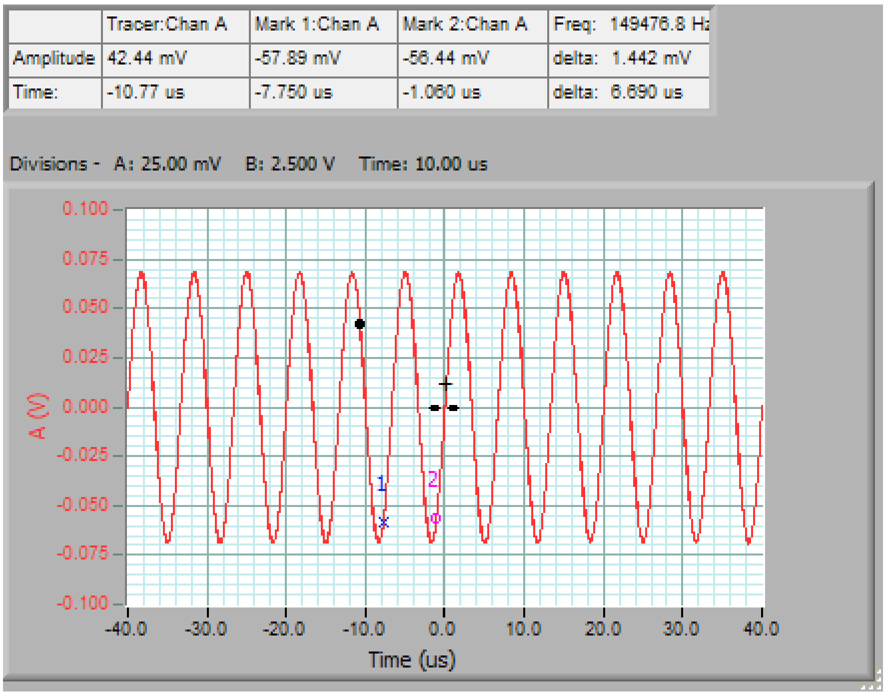
Averaging OFF | Information Source Spectrum

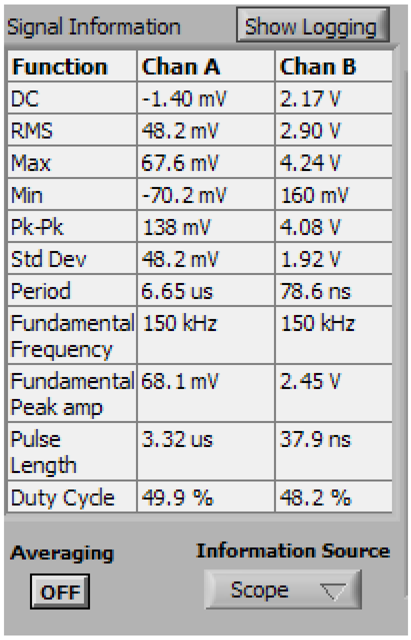
After averaging 20x, we have improved the noise floor to about –120 dB. The dynamic range has increased by about 20 dB (or 10x, about the same as an extra 3 bits of resolution).

7.1.2 12 bit resolution

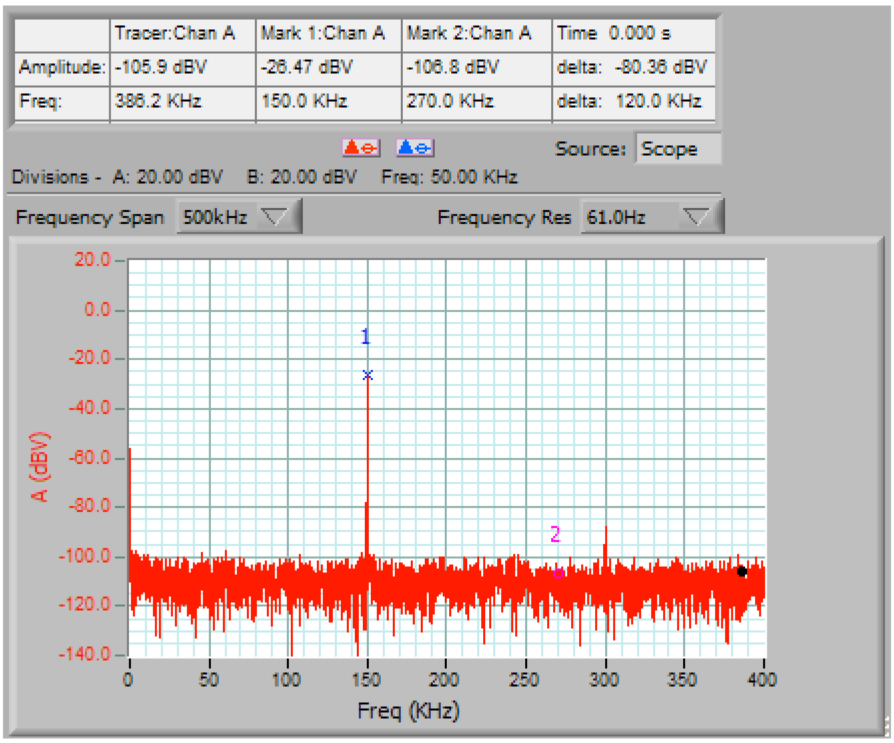
With the resolution set to 12 bit, we repeat the two experiments above, but with a 48 mV signal.

Here is the scope graph:





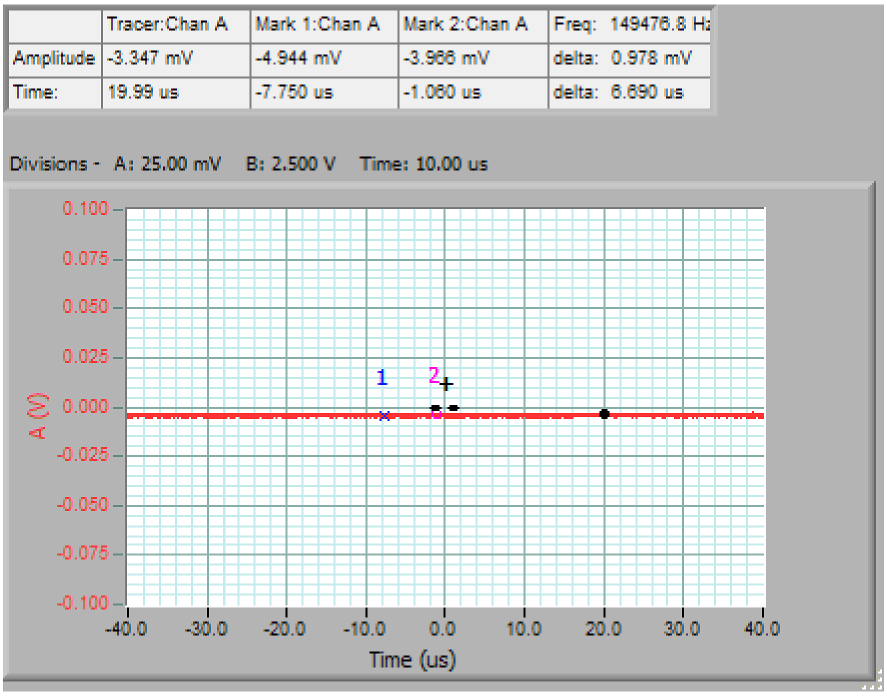
The spectrum graph:

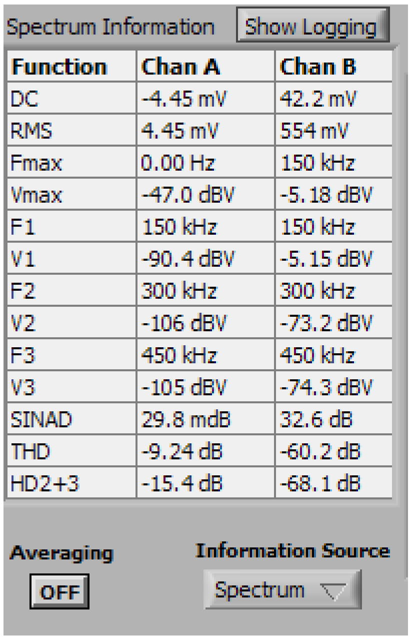


The spectrum graph shows-26.47 dBV (or 47.5 mV). We have about 74 dB headroom (so 5000x). This means we should be able to resolve 12 bits before being affected by noise.

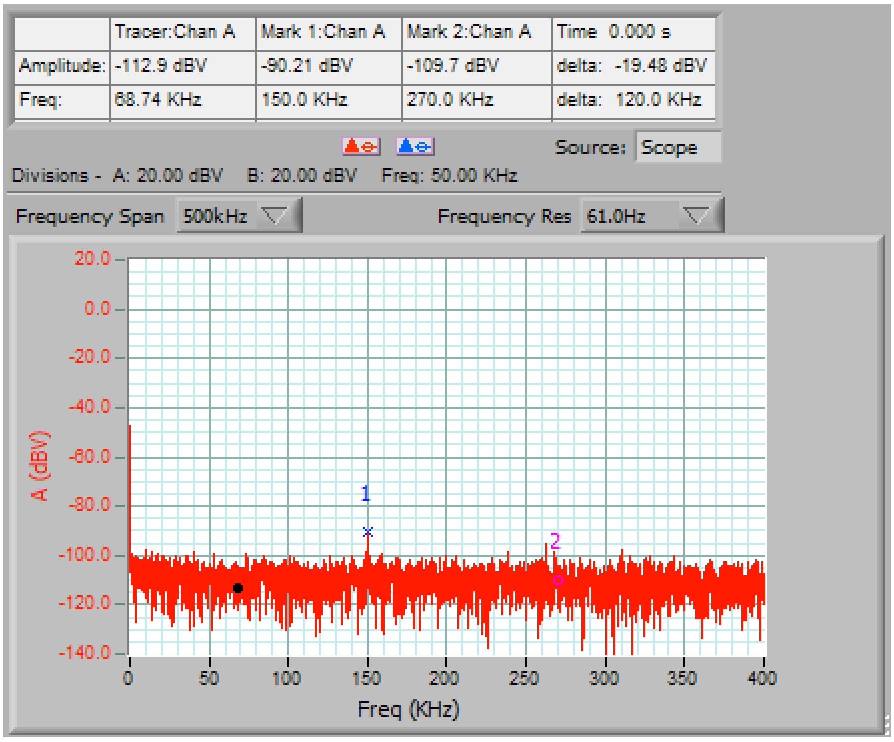
Next we use the same 30uV signal as before.

Here are the time graphs:

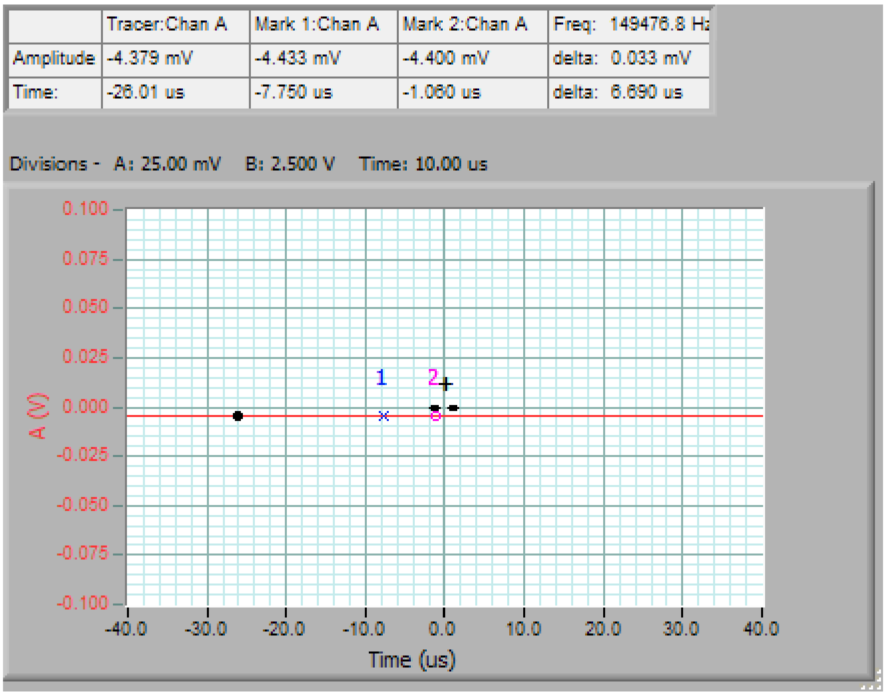




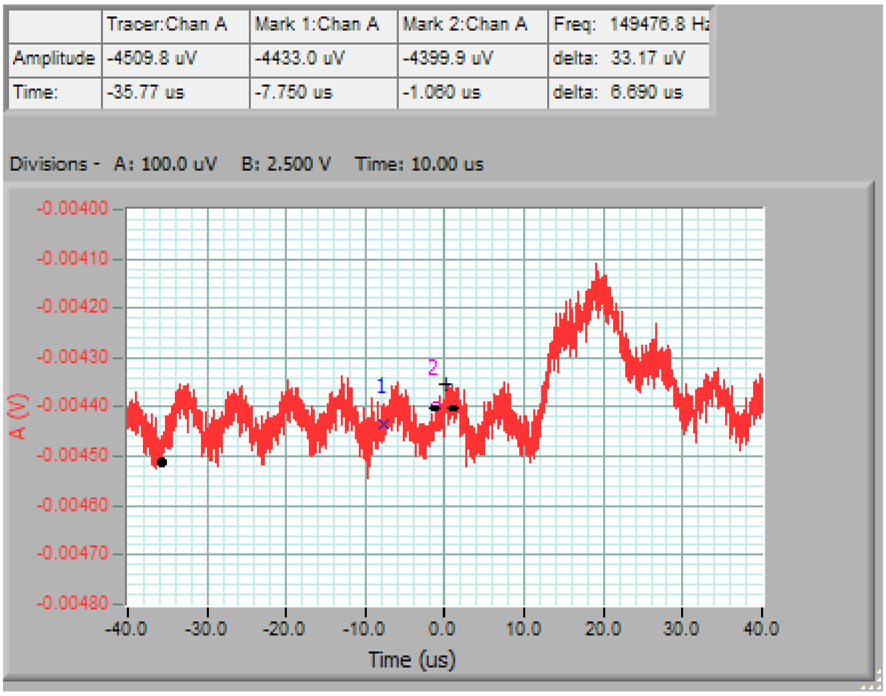
We see the spectrum graph showing –90.2 dBV, or 30.9 uV. We still have 10dB of headroom, and so are able to resolve 10uV. We are achieving 12 bit performance.



Again we repeated the averaging (20x), and obtained the scope graph with the same axis values:

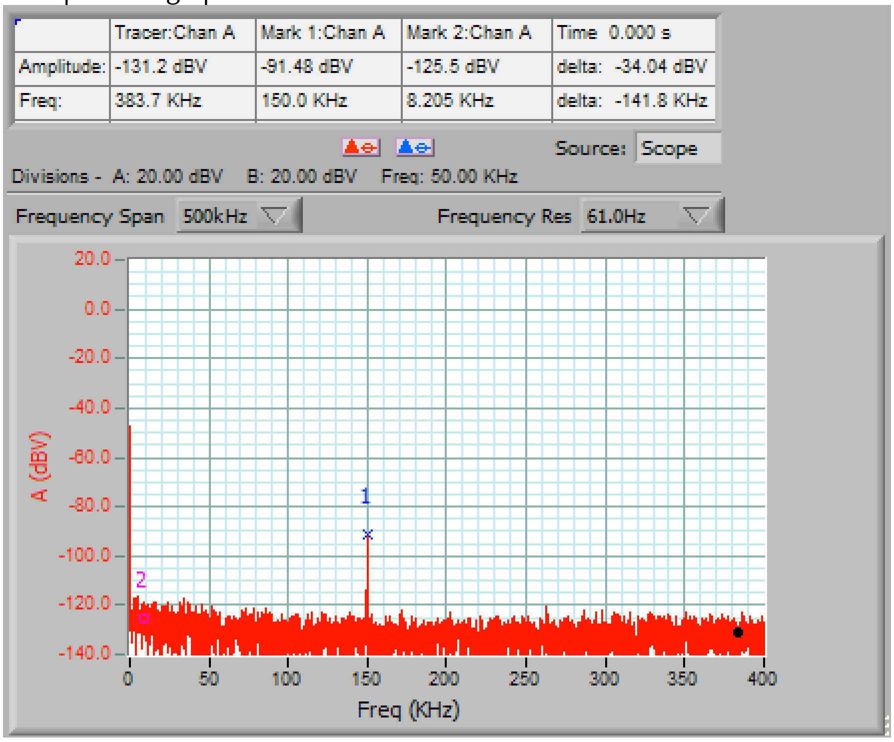


zooming in after the average we see:



so we are maintaining the same 10uV resolution as for the 10 bit setting.

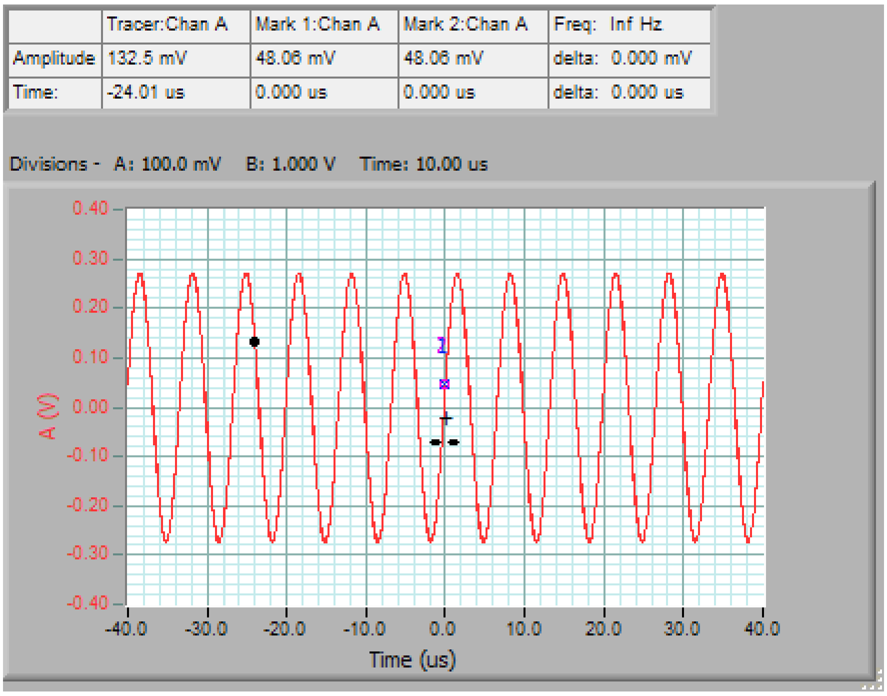
The spectrum graph shows:

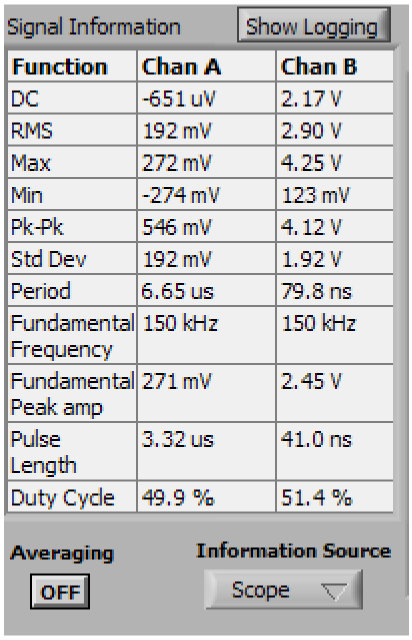


We again reduced the noise floor by about 20 dB by using averaging.

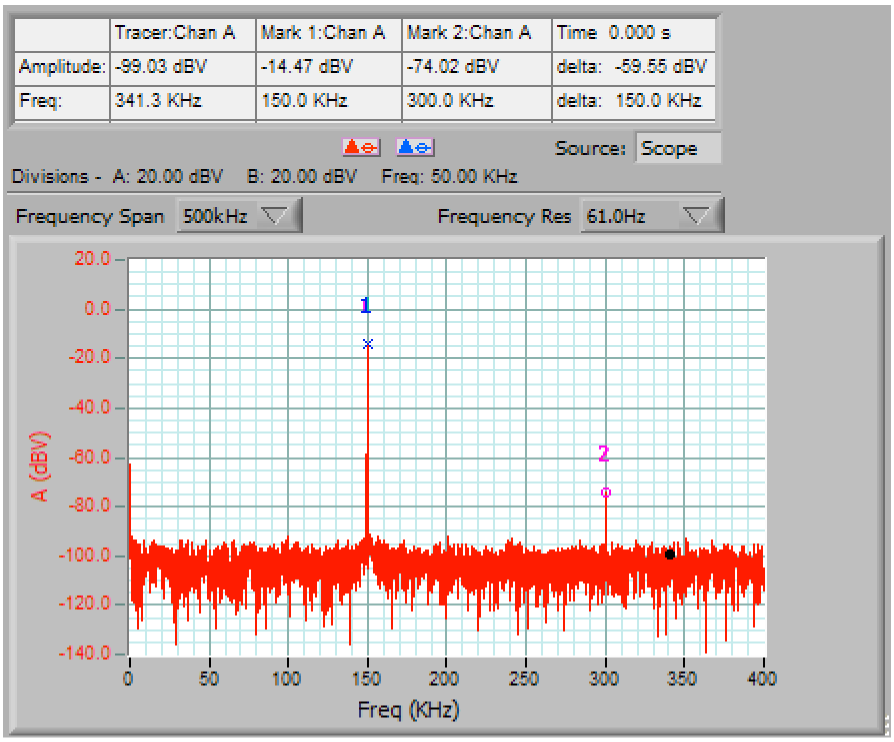
7.1.3 14 bit resolution

We use the same methods to test the 14 bit digitizer. This time we digitize a 192 mV signal. The scope graph response is:





The spectrum graph shows a peak at –14.5 dBV, or 188 mV rms. This is non averaged.



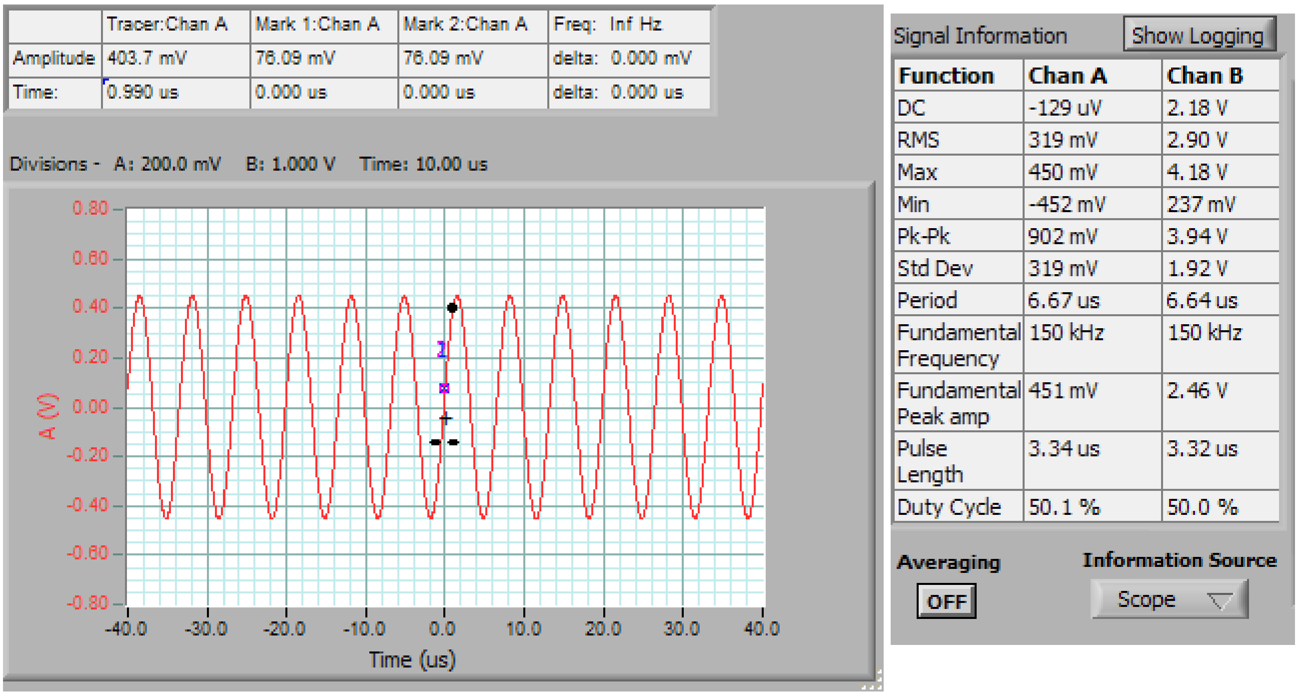
As the gain drops (the FSD has changed from 200mV to 800 mV), the noise floor has increased. This is because at high gains the noise floor is limited by the front end amplifier noise, while at lower gains we see a transition to the intermediate gain chain output noise dominating the noise floor.

In any case the noise floor has risen to about –92 dB. 14 bit accuracy predicts that the minimum signal needs to be 6 + 20 log (16384) = 90 dB above the noise floor. This is clearly not the case. We see that the input signal needs to be at –2 dBV or greater (794 mV rms or greater), for the non averaged case.

Thus to achieve 14 bit accuracy with a low level signal we will need to do some averaging.

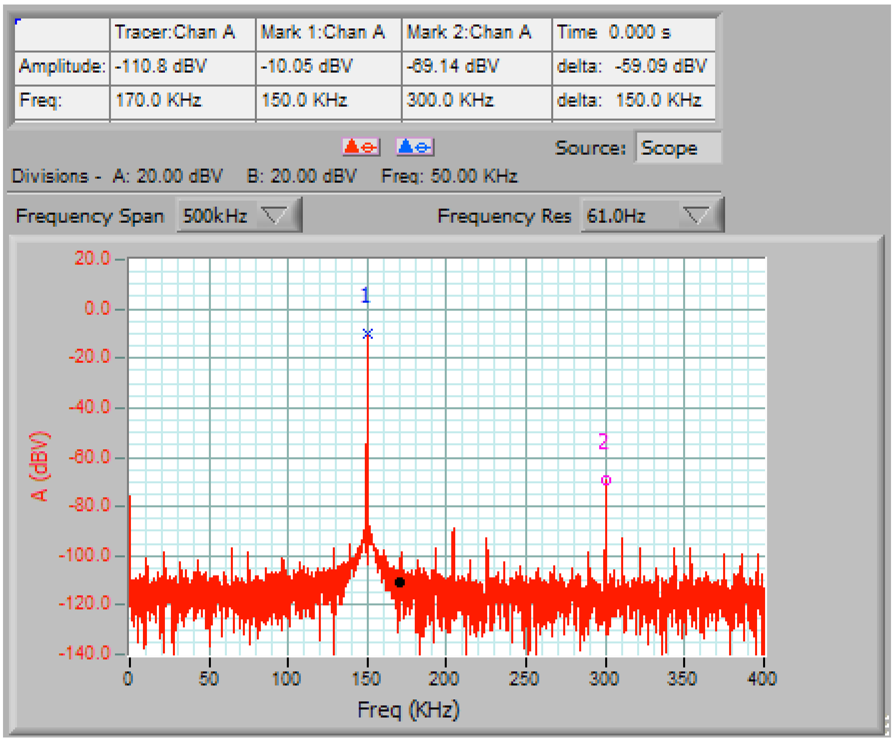
We did the averaging and found that signal generator noise was starting to dominate the noise floor, and we had to increase the signal level to 320 mV rms to achieve the 90 dB difference between signal and noise floor.

Here is the signal:



The amplitude is nearly 320 mV rms.

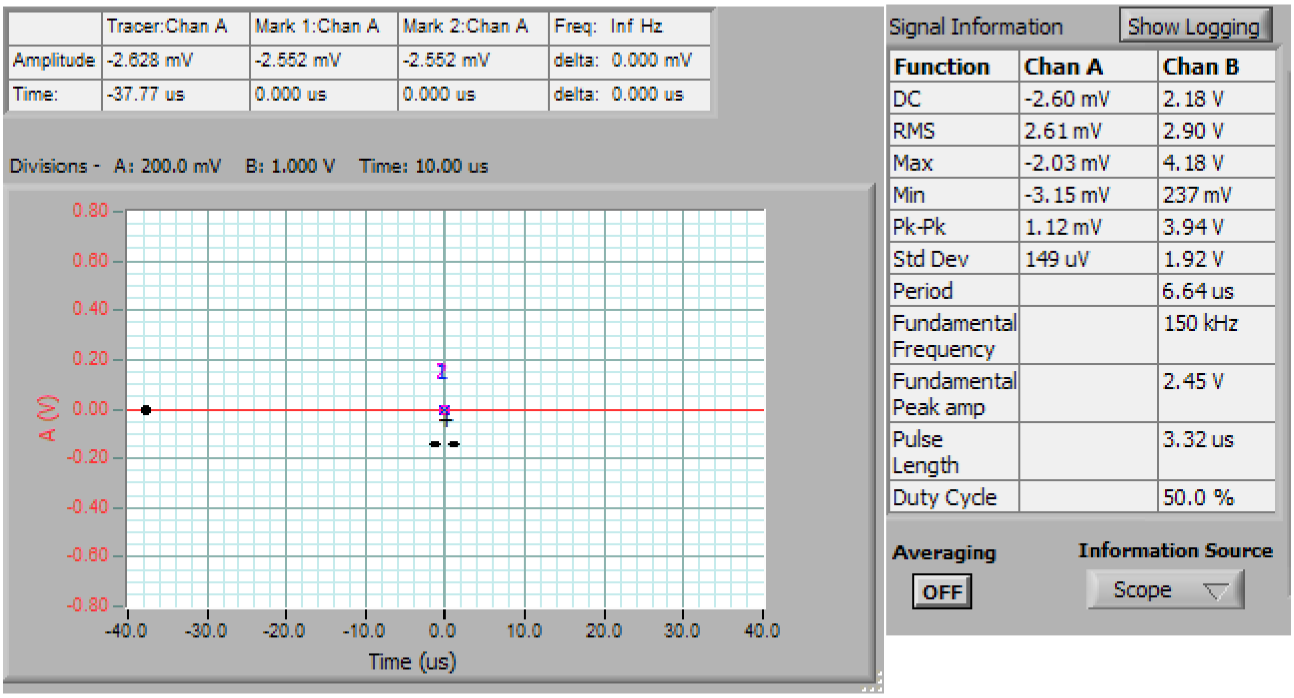
Here is the spectrum graph:



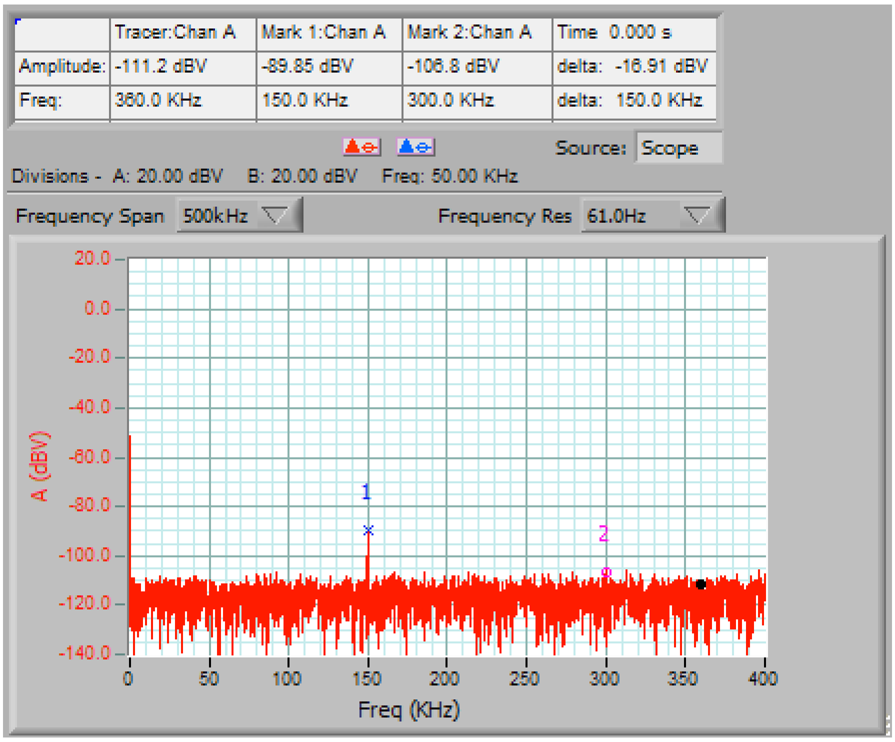
The noise floor is now about –100 dBV, but there are intrusions – caused by the signal generator noise floor. The signal has been averaged 20 times.

Again we used a signal at –90 dBV (30 uV):

Here is the scope graph:



The spectrum graph shows that the increased attenuation needed to achieve the –90 dBV signal, has also dropped the signal generator output noise floor:



We have a noise floor now of about –105 dBV, so a margin of 15 dB on the –90 dBV signal.

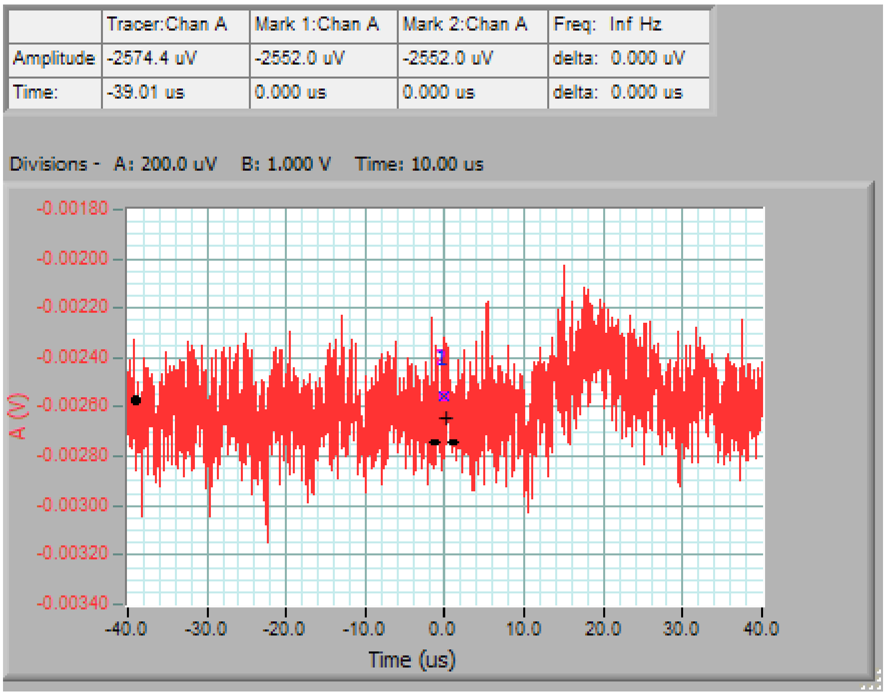
This is sufficient to resolve a signal 5.6x smaller. Thus we could resolve to 30/5.6 = 5.3uV, which is less than the 19.5uV we need to achieve 14 bit resolution (320mV/16384).

Note that if a full scale signal is present, very careful design in the signal source will be needed to achieve a low enough noise floor to get the full 14 bit resolution, even with averaging.

For the HP 33120A sig gen, we can only just achieve the 90 dB dynamic range in the presence of the full scale signal.

Notice that as we attenuated the signal generator output, the noise floor dropped to the Cleverscope native noise floor. We can see with a noise floor (averaged) of –105 dBV, we should be able to achieve 14 bit resolution with a –15 dBV signal (178 mV). Without averaging, this signal needs to be 10dB bigger, or –5dBV (562 mV rms).

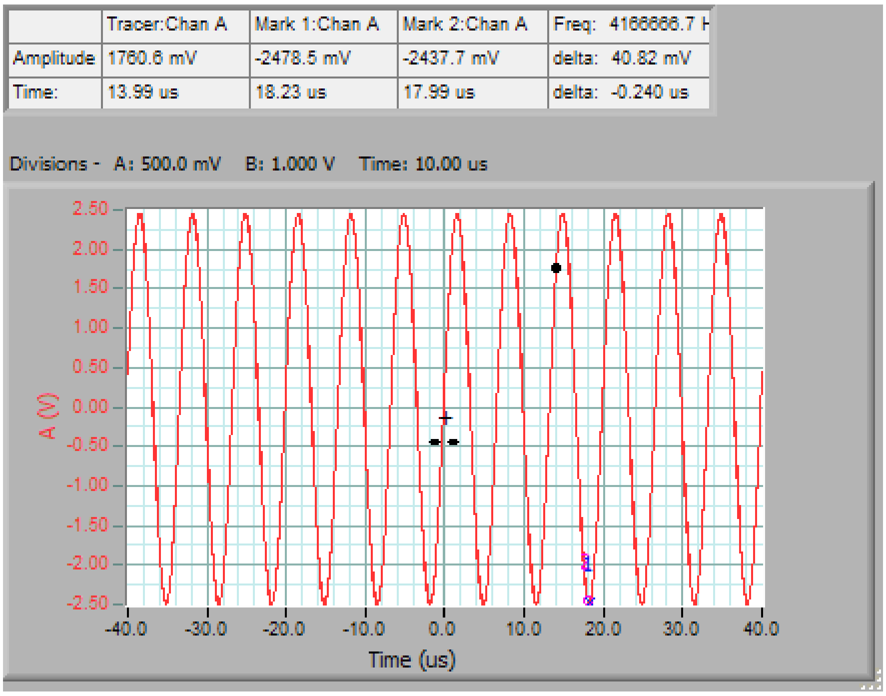
It is interesting to look at the zoomed in version of the scope graph to see the signal we captured with a 1.6V FSD amplitude range:



We can still see the outline of the signal, and the 200uV transient when the triggered LED is turned on. However the noise floor is 15dB worse than the previous graphs, and so the signal is much noisier.

Verifying 14 bit at high amplitude.

We used the lower range full scale signal (the lower range is +/-2.5V) of 1.75V rms or 4.7 dBV. Here is the signal:



Signal Information | Show Logging

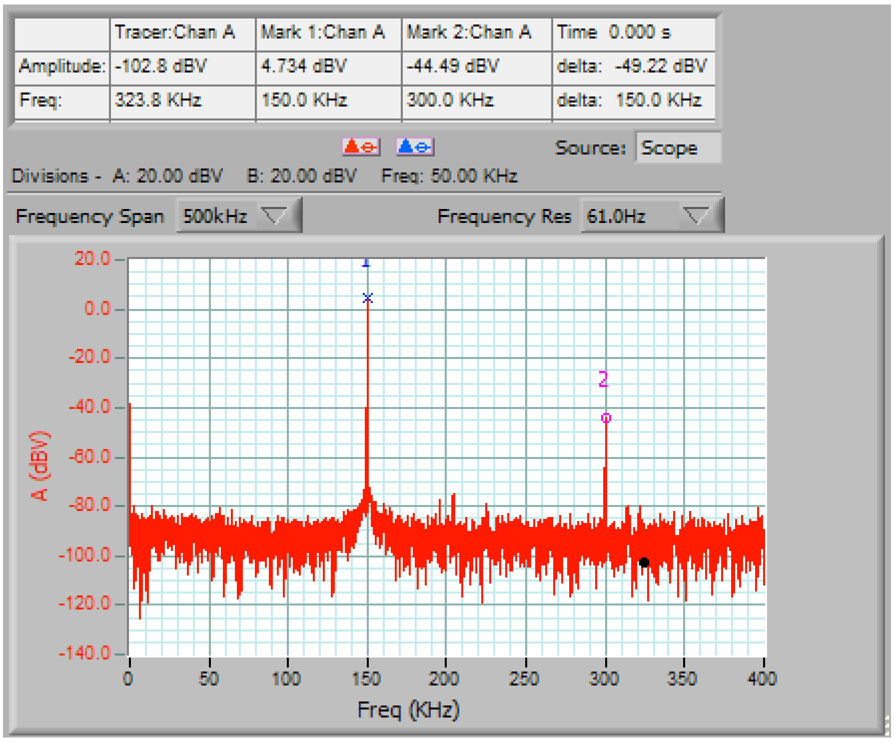
Function	Chan A	Chan B
DC	-11.8 mV	2.18 V
RMS	1.75 V	2.91 V
Max	2.46 V	4.26 V
Min	-2.50 V	160 mV
Pk-Pk	4.96 V	4.10 V
Std Dev	1.75 V	1.93 V
Period	6.65 us	79.7 ns
Fundamental Frequency	150 kHz	150 kHz
Fundamental Peak amp	2.47 V	2.47 V
Pulse Length	3.32 us	39.5 ns
Duty Cycle	49.9 %	49.6 %

Averaging: OFF

Information Source: Scope

The Cleverscope acquisition unit has two hardware ranges - ±2.5V and ±20V. By using a signal of 5V p-p we optimise for the maximum signal that fits into the low range.

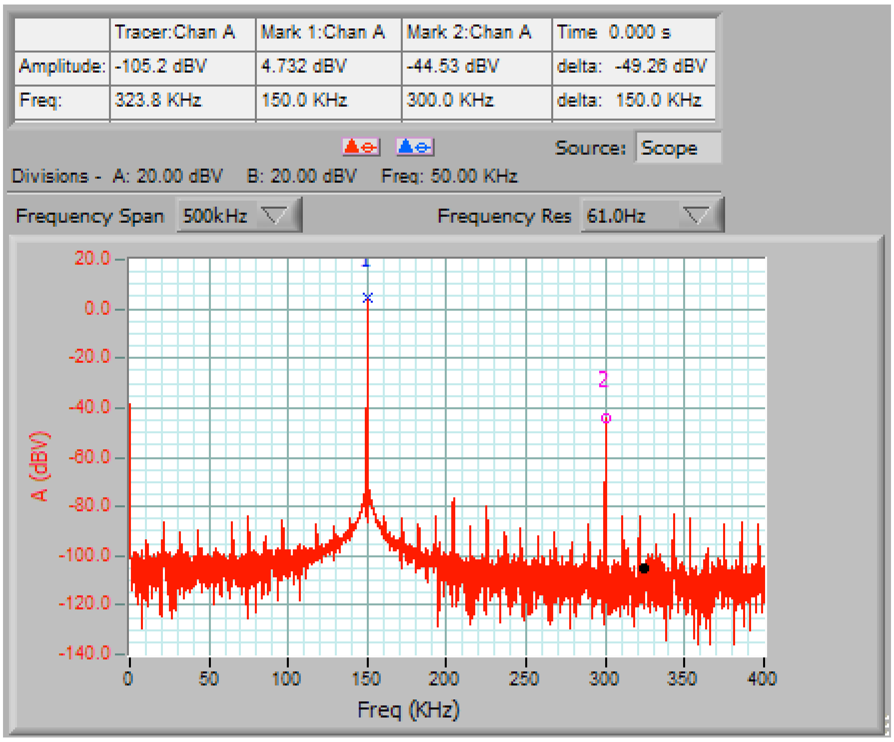
Here is the spectrum response:



As can be seen the signal generator output noise is now dominating. We see a noise floor of about –80 dBV, giving a dynamic range of about 84 dB. This is marginal for 14 bit measurements.

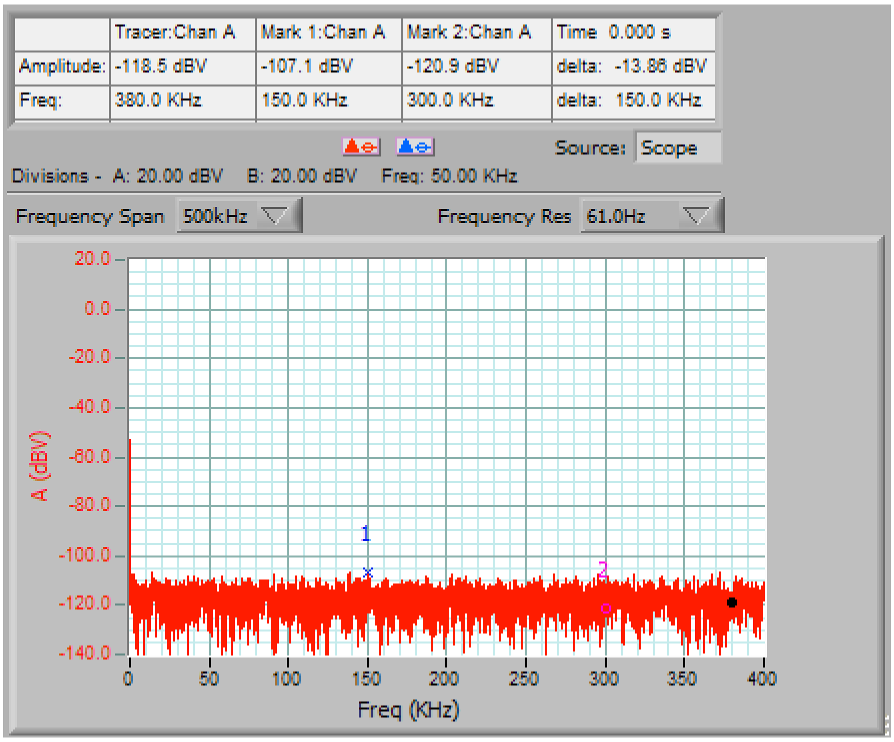
Applying averaging will only reveal the sig gen output noise features, and will not improve the noise floor.

Here is the averaged (20x) response:



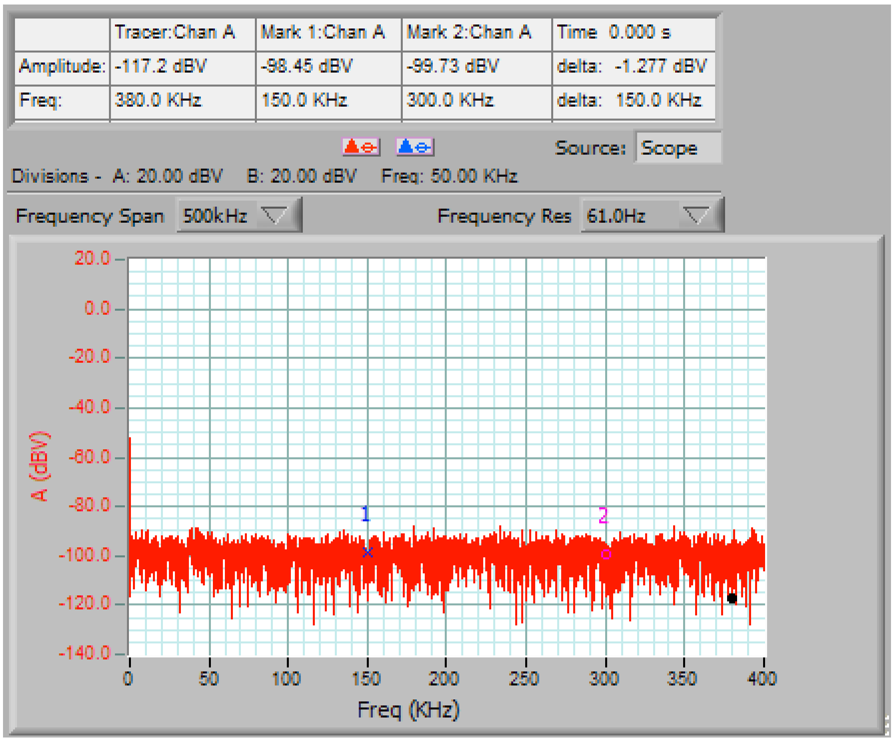
The features seen are probably remnants of the internal signal generator power supply, and digital processing system.

We removed the input signal, while continuing to sync off the channel B sync signal. The result is below:



This is the averaged response with no input signal, with 5V FSD input range, as used to measure the spectra above.

We can see that the acquisition unit's averaged noise floor is below that of the signal generator.



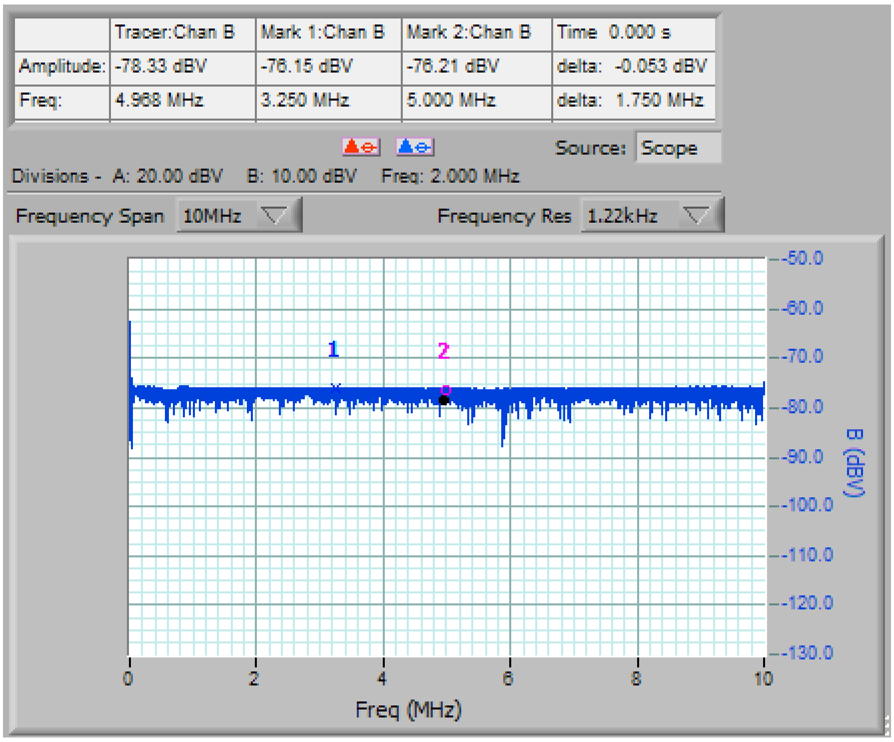
The non averaged response is given below:
We see a noise floor (non averaged) of about –90 dBV. We are able to display signals to +4.7 dBV with the 5V FSD range used, and so our total dynamic range (non-averaged) is 94.7 dBV. This is sufficient to achieve 14 bit dynamic range.

8 Cross Talk

Cross talk is the generation of an attenuated signal of the same frequency in the other channel in response to a signal being injected into the test channel. It happens because there is un-intended coupling between the two channels.

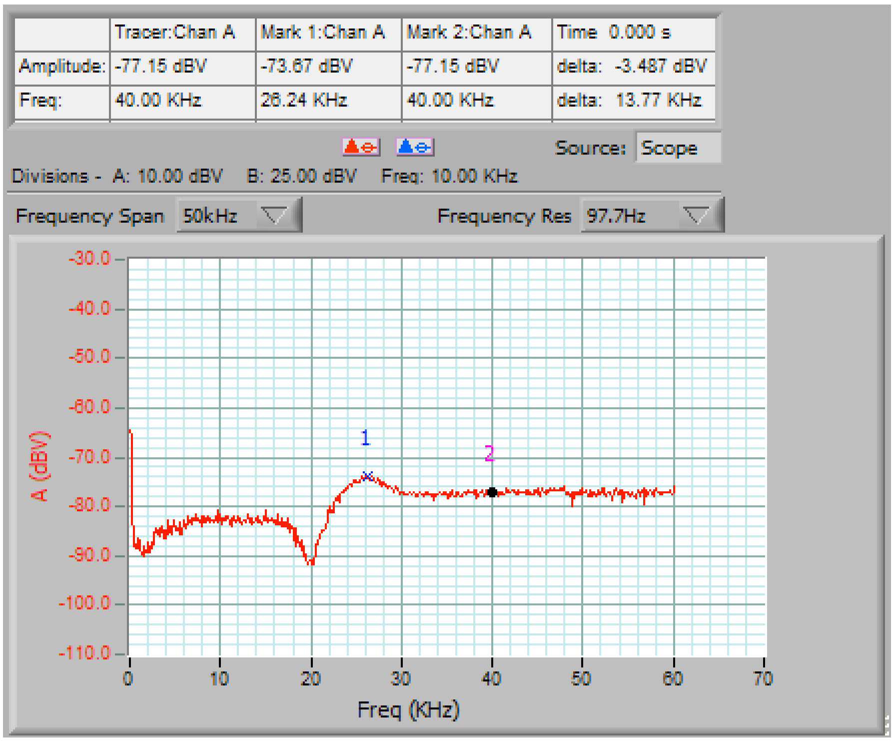
We used peak hold capture to show the maximum cross talk in response to a 0 dBV signal across a 10 MHz bandwidth. The alternate channel is left open.

Here is the Channel B cross talk in response to a swept 0-10MHz signal, at 0dBV (1V rms) into channel A:



We can see that the cross talk is not frequency dependant, and is a fixed –76dB. This is equivalent to 1 part in 6300. Thus we achieve better than 12 bit performance, provided the interferer is of less amplitude than the peak signal expected on the signal of interest.

This level of cross talk will compromise 14 bit performance, and so needs to be taken into account.



The channel A response is very similar.

At lower frequencies the characteristic changes somewhat, with a cross over at 20 kHz. Below 20 kHz, the offset amplifier is providing the low impedance offset source. Above 20 kHz, the offset source is passive, and constant impedance. The offset source necessarily has some coupling from channel to channel (though we naturally attempt to minimize it). Here is the A channel response for a signal of 0 dBV on the B channel, being swept from 1 kHz to 60 kHz.

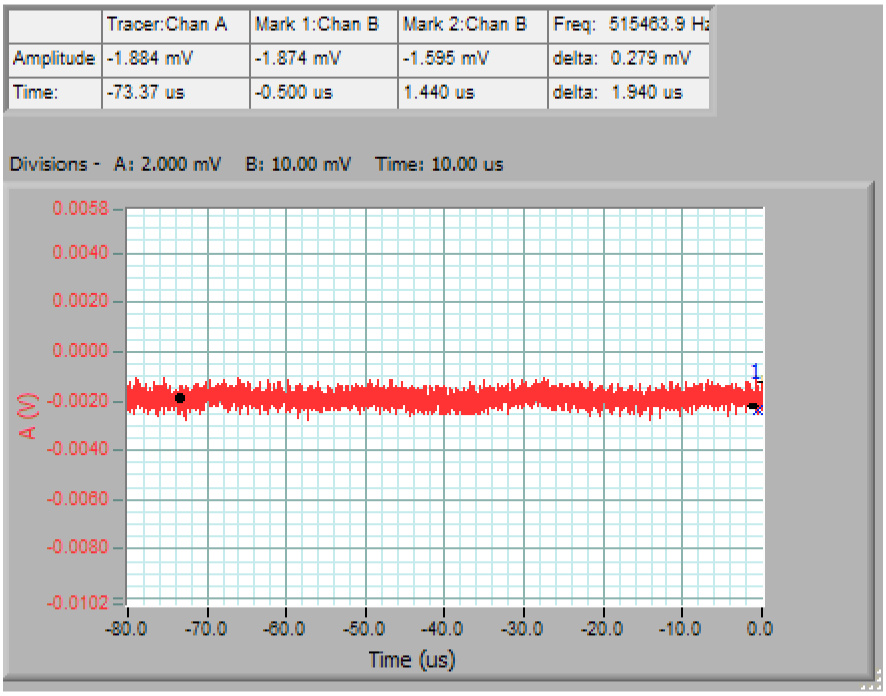
9 Ground Noise

The Cleverscope acquisition system uses a grounded front panel for safety reasons (if a user inadvertently clips the ground clip to a live connection, we want the fuse or RCD to open, saving the user, and the computer connected via the non-isolated USB link).

Where multiple grounds exist, it is possible to get a potential difference between them, and therefore a signal that can be converted from a common mode voltage to a differential mode voltage, and appear as an interfering signal to compromise the noise floor. This signal is not avoidable unless the common ground is stiff, and low impedance.

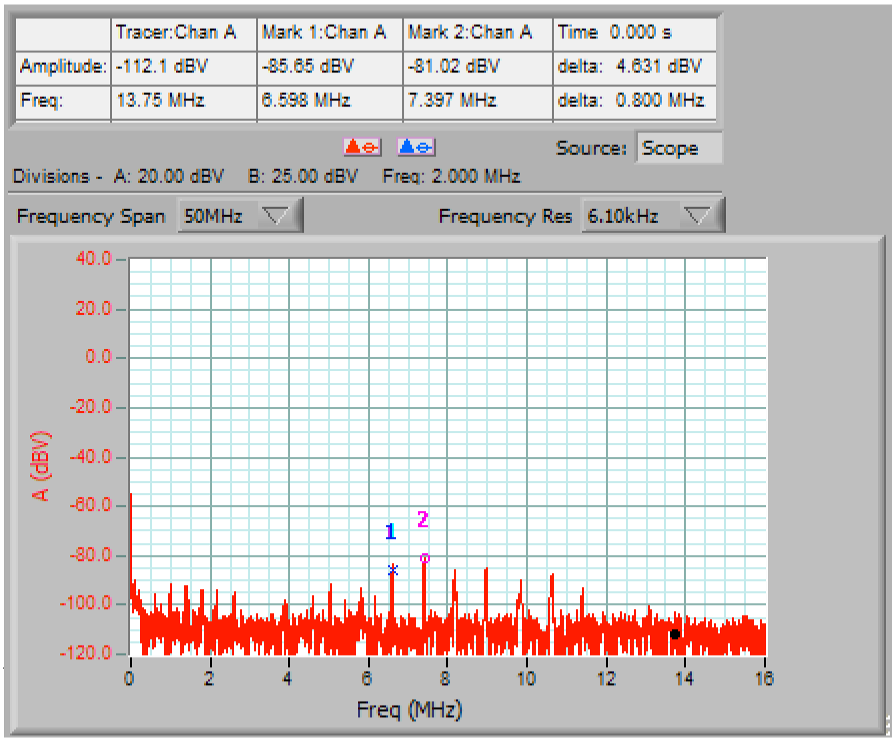
In addition, the acquisition unit, and connected PC, include many active elements such as switch mode power supplies, processors, and clocks. It is possible for these elements to modulate the internal ground current and act as a signal source when connected to other equipment.

A Tektronix TDS2012 was used to measure the ground noise. A coaxial cable was connected from the acquisition unit Channel A to the Tek Ch 1 input. Any ground noise should show up as differential signal visible on the Tek screen.



Using persistence and the voltage markers, the Chan A signal was measured at 1.44 mV p-p. With the Tek input open, the Tek measured 1.36 mV p-p.

At the same time the Cleverscope Chan A value was captured. We see 1.85 mV p-p. The spectrum and signal information are shown below.



Signal Information | Show Logging

Function	Chan A	Chan B
DC	-1.89 mV	-1.99 mV
RMS	1.93 mV	2.03 mV
Max	-956 uV	-851 uV
Min	-2.81 mV	-3.08 mV
Pk-Pk	1.85 mV	2.23 mV
Std Dev	340 uV	432 uV
Period	12.9 us	242 ns
Fundamental Frequency	12.5 MHz	12.5 MHz
Fundamental Peak amp	62.5 uV	78.9 uV
Pulse Length	6.61 us	51.0 ns
Duty Cycle	51.4 %	21.1 %

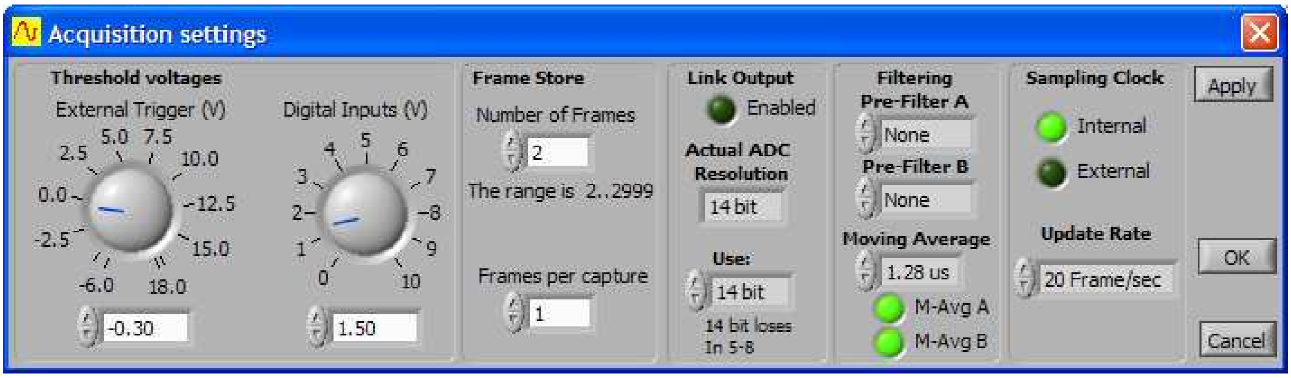
Averaging: OFF

Information Source: Scope

10 Moving Average Resolution Enhancement

The previous discussion has been focused on the raw capability of the Cleverscope Acquisition Unit, with frame to frame averaging used to maintain wide bandwidth while improving signal to noise.

There is another way to improve signal to noise, which is moving average resolution enhancement. The moving average system is turned on using the 'Settings/Acquisition Settings' dialog:



The Moving Average time constant sets the sample time period that is averaged to achieve one output sample. In the example above this is 1.28 us (128 samples at 10ns/sample). The average takes the last 128 samples, averages them, and emits the new value. On the next sample being received, a new average is calculated again, based on the last 128 samples (one of which will be new). We use internal buffers to ensure that the averaged, non-averaged and digital values all remain synchronized.

We use the moving average because it is optimal for reducing random noise, while maintaining the step response. As it is linear phase, it leads to no phase distortion, and therefore edge distortion. The noise reduction achieved is the equal to the square root of the number of samples averages. Thus our 128 sample average (1.28us) yields a voltage noise reduction of a factor of 11.3. This improves SNR by 20 $\log_{10}(11.3)$ = 21 dB. Recall that SNR = 6.02 N + 1.76 dB (in dB). As we are making a relative change here, we have improved ENOB by 21/6.02 = 3.5 bits.

However, while we improve SNR, it comes at the cost of bandwidth. The Moving Average filter acts as a slow roll off low pass filter. The filter -3dB occurs at $1/[2\ T_{\text{moving average}}]$. For a $T_{\text{moving average}}]$ of 1.28us, the -3dB point is at 390 kHz. Because of the shallow filter slope, the signal frequency must be 4 times lower than this not to be affected in amplitude. For the 1.28us case, a signal frequency of 97.5 kHz will have no amplitude reduction. Above this frequency the amplitude will slowly reduce to being -3 dB (0.7071 Va) at 390 kHz. Thus there is a tradeoff between SNR improvement and bandwidth.

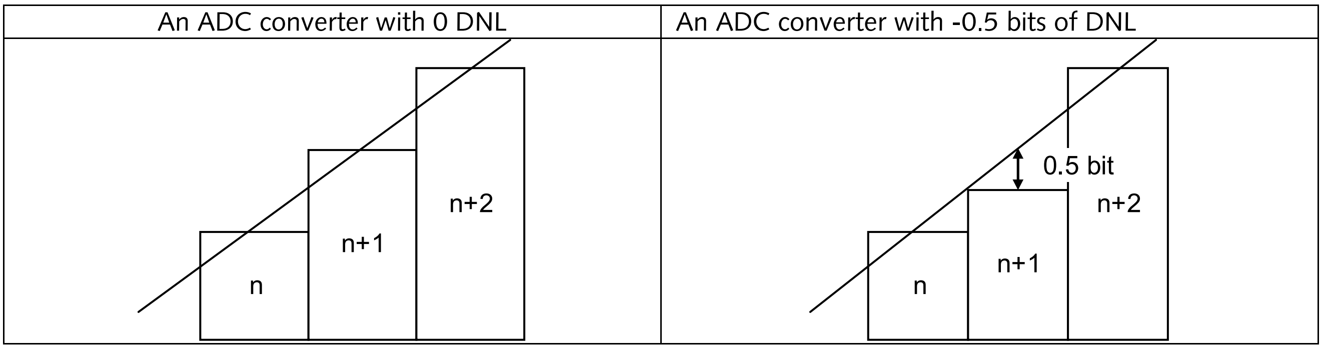
The Moving Average can be conducted over 40, 80, 160, 320, 640 and 1280 ns. The following table shows the improvement in SNR gained, and the resulting -3dB bandwidth:

Average period (ns)	Num Samples	Noise Reduction	dB SNR improvement	ENOB improvement	-3dB bandwidth (MHz)
40	4	2.0	6.0	1.0	12.50
80	8	2.8	9.0	1.5	6.25
160	16	4.0	12.0	2.0	3.13
320	32	5.7	15.1	2.5	1.56
640	64	8.0	18.1	3.0	0.78
1280	128	11.3	21.1	3.5	0.39

It is important to note that this process cannot continue for ever. The Analog to Digital Converter (ADC) includes a key parameter which defines the ultimate linearity achievable – the Differential Non-Linearity (DNL).

This value represents the maximum error between the center point of one digitized voltage level, and the next. Usually this error is represented in terms of bits.

Here is a graphical explanation:



If we carry on increasing the period of the moving average filter, we will eventually expose the inherent non-linearity of the ADC. Carrying on past this point yields no gain, as it is ADC defects we see, and not signal features.

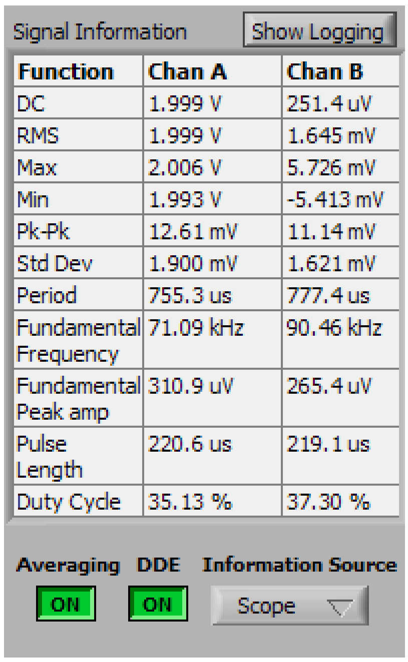
For the Cleverscope CS328A range we use these ADC converters:

Part Number	Bit Resolution	DNL (typ)	Maximum Enob improvement possible	Resulting real Bit Resolution
LTC2280	10	±0.1	3.3	13.3
LTC2282	12	±0.2	2.3	14.3
LTC2284	14	±0.6	0.7	14.7

This means that we can use moving average filtering to improve noise, but we cannot hope for anything better than a real 14.7 bits effective for the LTC2284 based 14 bit cleverscope.

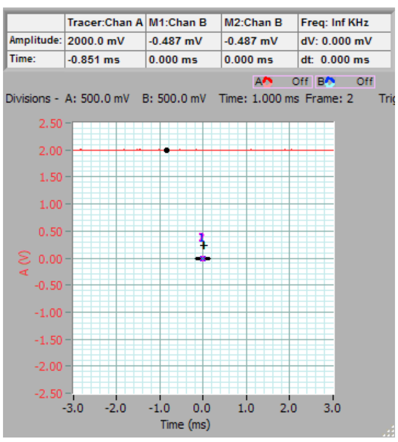
[Some of our competitors seem to have forgotten this fact. The ADC08D500 dual channel 500 MSPS 8 bit sampler used in many competing products offers a typical DNL of ±0.15, allowing 2.7 bits of improvement. Thus the maximum real bit resolution is 10.7 bits after averaging. 12 bits is not achievable].

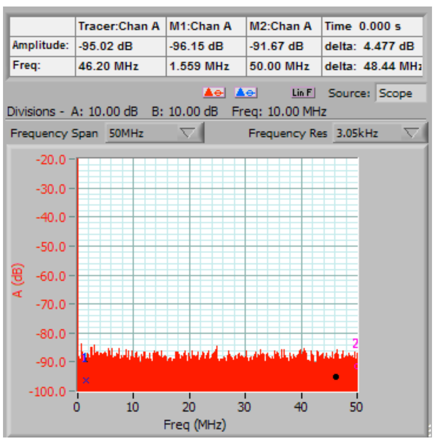
To measure the effectiveness of the moving average filter, we do tests using a DC signal, because we can filter it enough to ensure that noise from the DC signal is not a contributor. In this test we used a standard range of ±2.5V, with sampled capture over a time duration of ±3ms and the signal information display to make measurements.



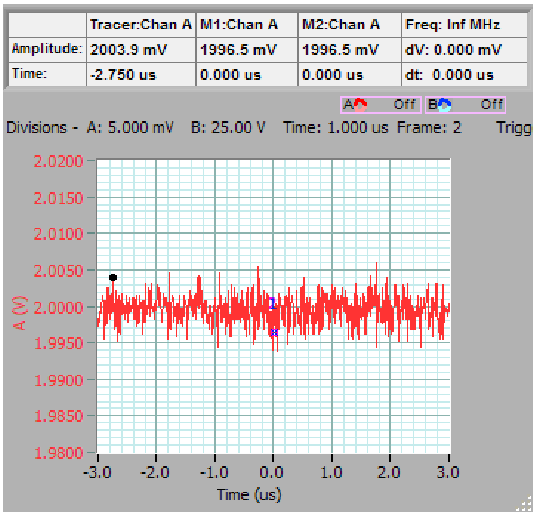
Function	Chan A	Chan B
DC	1.999 V	251.4 uV
RMS	1.999 V	1.645 mV
Max	2.006 V	5.726 mV
Min	1.993 V	-5.413 mV
Pk-Pk	12.61 mV	11.14 mV
Std Dev	1.900 mV	1.621 mV
Period	755.3 us	777.4 us
Fundamental Frequency	71.09 kHz	90.46 kHz
Fundamental Peak amp	310.9 uV	265.4 uV
Pulse Length	220.6 us	219.1 us
Duty Cycle	35.13 %	37.30 %

First off, 14 bit capture, no filters, capturing a 2.0V DC signal, without any processing. We see a standard deviation of 1.9mV, with a noise floor of about -85 dBV. The spectrum is flat noise.





We can use the tracking graph to examine the 2.00V signal in detail:

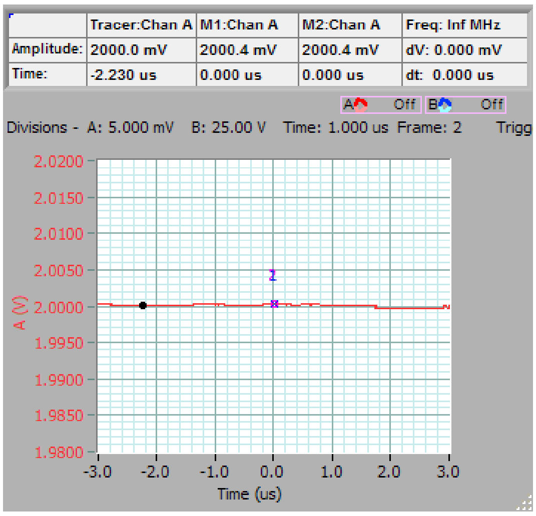


We have a dynamic range of ±2500 mV, with a standard deviation of 1.9mV. This is 1 part in 2630, or a signal to noise ratio of 68.4 dB, equal to (68.4-1.76)/6.02 = 11.1 bits ENOB.

In order to achieve 14 bits ENOB we would need to achieve a signal to noise ratio of:

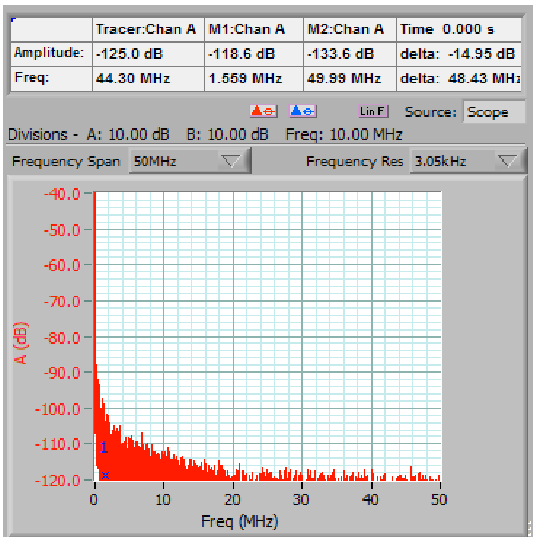
SNR = 6.02N + 1.76 = 86 dB.

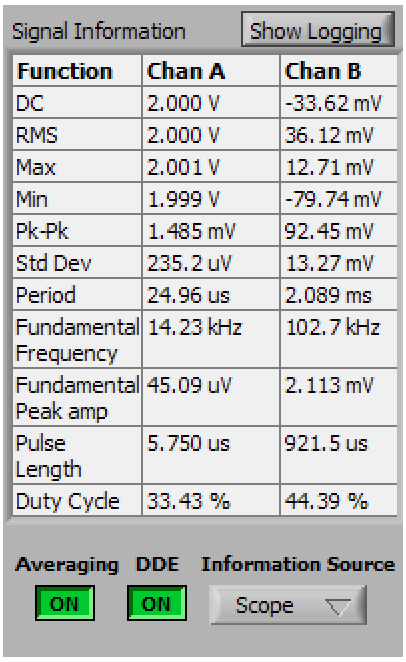
This requires 1 part in 20,000 noise, or a standard deviation of 250uV. We set the moving average time constant until we achieve this, and find it is between 640ns and 1.28 us. We choose 1.28 us.



With a 1.28us moving average the amplitude of the noise in the tracking graph has reduced to the sub mv level.

The Spectrum graph shows the noise floor is now reduced significantly.





Signal Information | Show Logging

Function	Chan A	Chan B
DC	2.000 V	-33.62 mV
RMS	2.000 V	36.12 mV
Max	2.001 V	12.71 mV
Min	1.999 V	-79.74 mV
Pk-Pk	1.485 mV	92.45 mV
Std Dev	235.2 uV	13.27 mV
Period	24.96 us	2.089 ms
Fundamental Frequency	14.23 kHz	102.7 kHz
Fundamental Peak amp	45.09 uV	2.113 mV
Pulse Length	5.750 us	921.5 us
Duty Cycle	33.43 %	44.39 %

Averaging: ON | DDE: ON | Information Source: Scope

The signal information shows an std deviation of 235 uV. This is the same as 1 part in in 21, 276 or an SNR of 86.6 dB or 14.1 effective bits.

The moving average filter allows us to significantly improve the SNR at the expense of bandwidth.

11 Conclusions

11.1 Signal to Noise Ratio

We found that a Cleverscope acquisition unit can achieve an ENOB of 11.1 bits or SNR of 68.4 dB without any processing. By using coherent averaging or a moving average filter, we can improve this to an ENOB of better than 14 bots, or SNR of > 86 dB. We have shown that the ADC DNL is not limiting the ENOB.

11.2 Dynamic Range

We found:

1. The acquisition unit exhibits full dynamic ranges when the input signal is greater than a value which ensures at least one significant bit of signal above the noise floor. We have found that we can achieve:
   a. 10 bit resolution with a minimum input signal of 12 mV rms (non-averaged) or 4 mV rms (averaged).
   b. 12 bit resolution with a minimum input signal of 48 mV rms (non-averaged) or 12 mV rms (averaged).
   c. 14 bit resolution with a minimum input signal of 562 mV rms (non-averaged) or 180 mV rms (averaged).
2. Very careful design will be required in the signal source to keep the output noise floor low enough to achieve 14 bit dynamic range.
3. Very careful attention to eliminating external noise sources such as Radio, TV, PC or electronic equipment needs to be done to maintain the dynamic range, especially for the 14 bit digitizer.
4. The non-averaged noise floor, for amplitude Full Scale Deviations (FSDs) of less than 400 mV is about –95 dBV. Averaging reduces this by 10 - 20dB. As the FSD increases, so does the noise floor. At 5V FSD, the noise floor is about –90 dBV. At below 10mV FSD the 20 MHZ anti-aliasing filter automatically switches in, and the noise floor drops to –105 dBV.

11.3 Cross Talk

We found:

1. The Cross talk between channels over the frequency range 20 kHz to 10 Mhz is uniformally flat, with cross talk on the measured channel being 76 dB down from the signal channel.
2. At frequencies below 20 kHz, the Cross talk improves, to around 90 dB down at 1 kHz.

11.4 Ground Noise

We found:

1. Ground noise when tested with another mainstream oscilloscope was found to be less than 1.44 mV p-p.
2. There are some frequency components at 6.6 and 7.4 Mhz of around –80 dBV. However it is hard to tell if these are internal or external to the Cleverscope.
3. As a side note, we tested the Cleverscope with two signal generators – an Agilent 33120A, and a simple test sig gen – an Exact model 119. With the Agilent we found no additional noise when connected. However with the Exact we found quite significant noise on the high range of 20 mV p-p. Thus there can be quite a variation in signal generator capability.

We find that the Cleverscope can be used to do 10, 12 and 14 bit measurements, provided the limitations in minimum signal level are taken into account. We found cross talk to be sufficiently low to be useful for all 10 and 12 bit applications, while some care may be required in 14 bit applications. We found the ground noise to be low.