Measuring Nonlinearities of MCA527

24.9.2018
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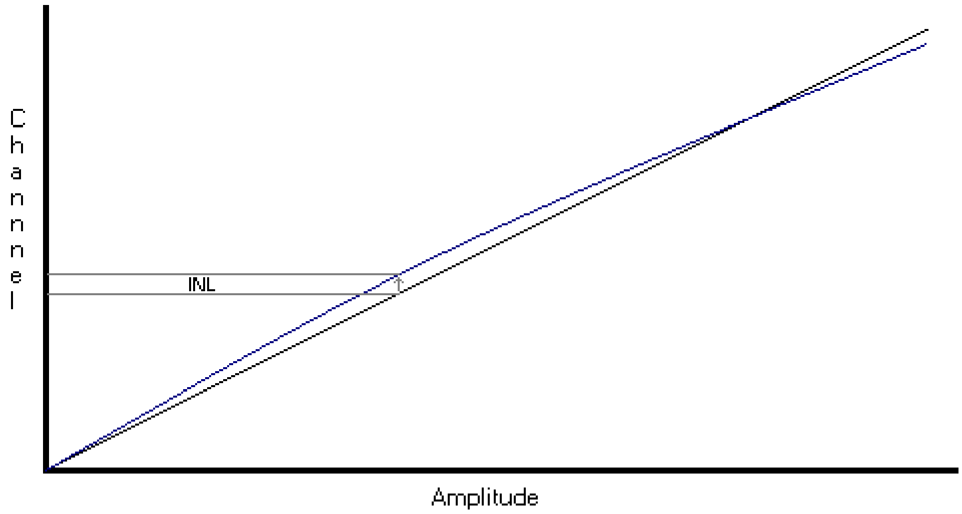
Abstract
Some of the basic quality parameters of a digitizing system, as an analog-digital converter (ADC) or a multichannel analyzer (MCA) are integral and differential nonlinearity. While good values for the linearities do not at all guarantee a good performing MCA or gamma spectroscopy system, bad values will limit inherently limit the precision of the measurements the MCA is used for.
Measuring the linearities is quite challenging, as the components for an MCA as amplifiers or ADCs are typically from the high end and the effects to measure are very small. This paper describes how the nonlinearities of the MCA527 are measured and what pitfalls to avoid.

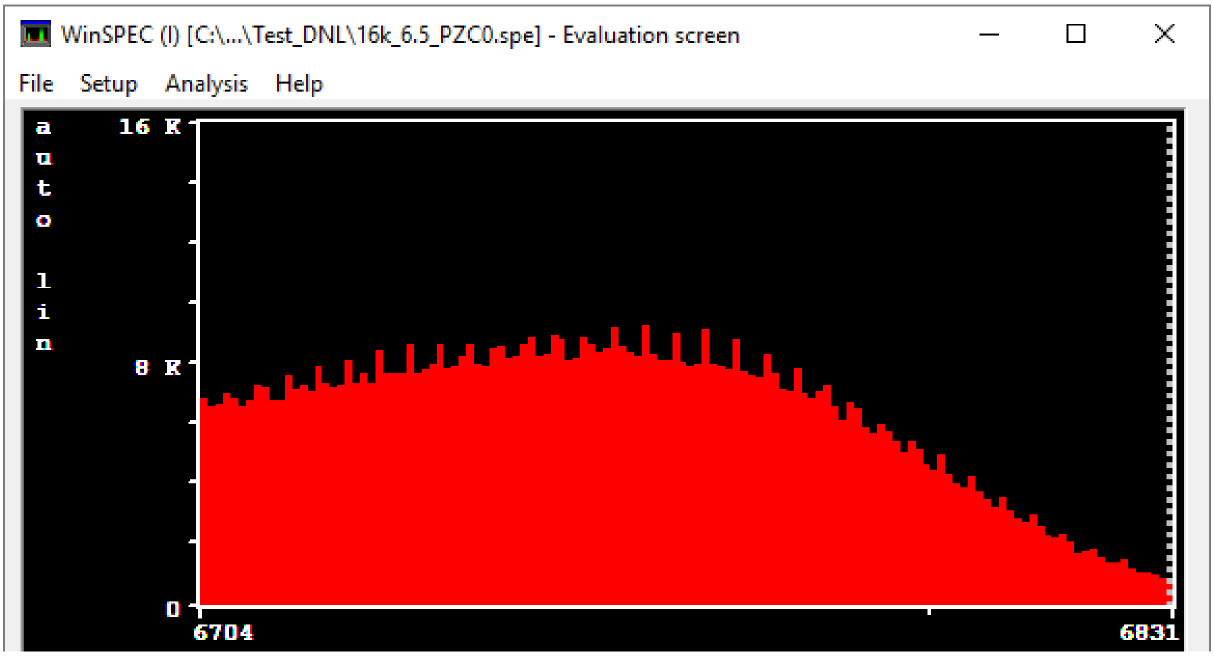
Integral nonlinearity
Integral nonlinearity (INL) describes the deviation of the channel to amplitude ratio from a straight line. This is mostly important when doing precise energy measurements with a high purity germanium detector (HPGe). With lower resolution detectors, this is normally not such interesting, as the nonlinearities of the detector will dominate the behavior of the system.



INL describes the maximum deviation from a straight line in the channel to amplitude ratio.

The integral nonlinearity of the 14-bit ADC used in the MCA527 is according to data sheet max. 4 LSB, which is 0.024% of full scale.
Typical INL stated for an MCA are <0.1%. The INL of an MCA may be dominated by the INL of the used ADC, but also nonlinear elements in the signal path, as filters, amplifiers or overvoltage protection elements may contribute to this.
For the measurement of the INL it is mostly important to have a signal source which is very precise and linear, at least with an INL <0.01%. Standard arbitrary signal generators hardly fulfill this.

Differential nonlinearity
Differential nonlinearity (DNL) describes the deviation of the width of an individual channel from the average channel width. A small differential nonlinearity is important when measuring spectra with very good statistics, something like a large number of counts within a channel. A bad differential nonlinearity may show structures in a spectrum where there is nothing, and this may be irritating for peak search algorithms and other evaluation.



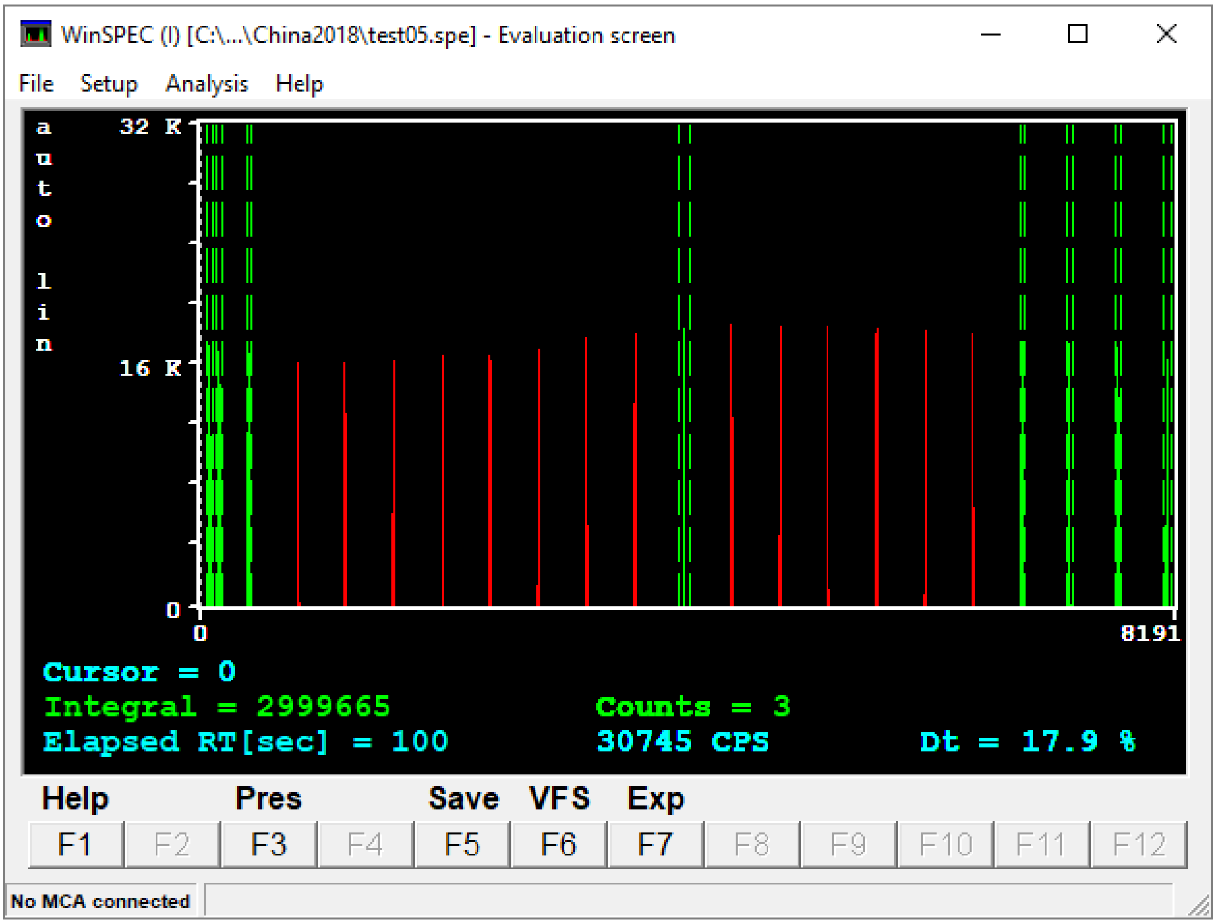
Example for a spectrum measured with bad differential nonlinearity, up to 15% here. Typical are comb like structures in the spectrum which do not fit at all to the detector resolution. With the MCA527, such behavior can only be provoked with very extreme settings (shaping time 0.1s, fine gain 6.5, 16k resolution, PZC=0) which normally don't make any sense at all.

DNL is a property of the ADC used. Wilkinson ADCs, where the time to charge a capacitor is measured, offer a quite nice DNL. However, they are slow and dead time depends on amplitude. Somehow more popular are SAR (successive approximation) ADCs, which are much faster and better to get. But they are at best offered with DNL <50%, or "No missing codes" or at least "monotonic". Typical are periodic structures in the bin width. Without additional measures they cannot be used for spectroscopy. A typical measure for analog filter MCAs with a single conversion is "sliding scale linearization". There, a defined but slowly changing offset is added to the signal and digitally subtracted after conversion.
For a digital filter MCA as the MCA527, the final channel value is calculated from many ADC values (MCA527 default settings: 52) which are all weighed differently, and so the original large DNL is averaged out. With very short and trivial filters and amplifying the result to the most extend, DNL effects still can be seen, but typical such settings have no real value.

Measuring Integral nonlinearity with MCA527
For the measurement of the linearity a CAEN digital detector emulator, model DT5800D, is used. This special signal generator allows to simulate detector signals with high precision. The output of this is realized as 16-bit DAC, and its integral nonlinearity is specified as <+/-2.5 LSB, which is 0.004% and should be good enough for this test.
For the INL measurement, the generator is set to deliver a spectrum with 22 discrete energies, relative to full scale at 1%, 2%, 5%, 10%, 15%, 20%, 25%, …, 95%, 100%. The values 1% and 2% are to check if there are any special effects at the very lower end of the energy scale.

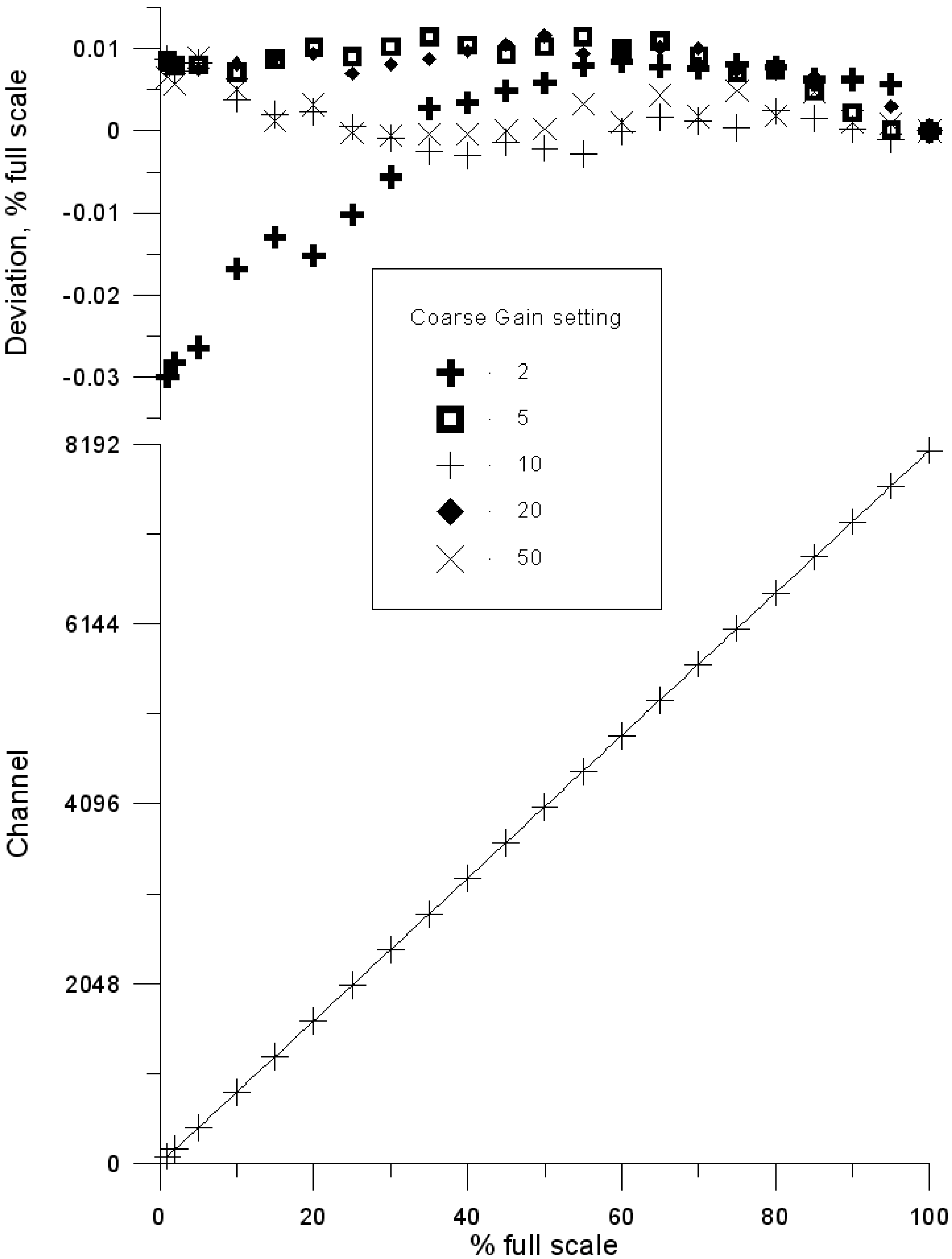
As the input stage amplifier may also contribute to nonlinearity, the measurement is done with all coarse gain settings from 2 to 50. The default filter/amplifier settings are used: shaping time 1µs, flattop 1.2µs, fine gain 1.0000, Pole zero 1600, trigger filter 10-201. The MCA is set to 8192 channels.

The amplitude of the generator is set such that the highest peak is close to the upper end, about channel 8120. Count rate of the generator is set to 30 kcps.
For the coarse gain setting of 2 there is one exception: As the maximum amplitude for the generator is 4 V, count rate there is set to 5 kcps in order not to drive the generator output to saturation, and fine gain is set to 1.333 instead of 1.



Spectrum with 22 different energies.

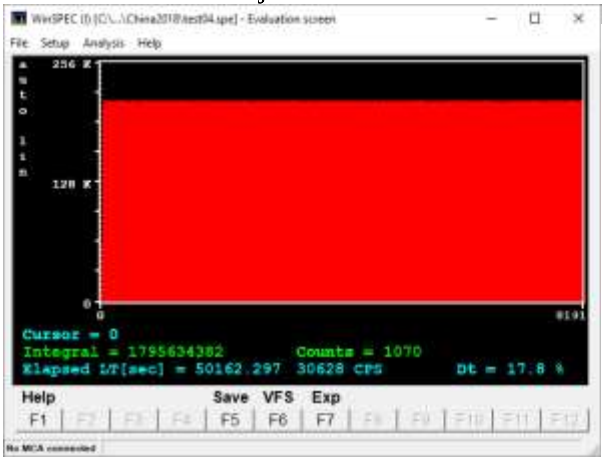
Plotting channel vs. amplitude shows no visible deviation from a straight line through origin. In order to see something, its necessary to plot the deviation from the straight line vs. amplitude.
The strongest deviation can be seen at gain 2 where the signals with the highest amplitudes are used, but with 0.03% max. its still below the 0.05% stated in the data sheet. With the other gain settings, deviation is always below 0.015%, and there seems not to be any significant offset.

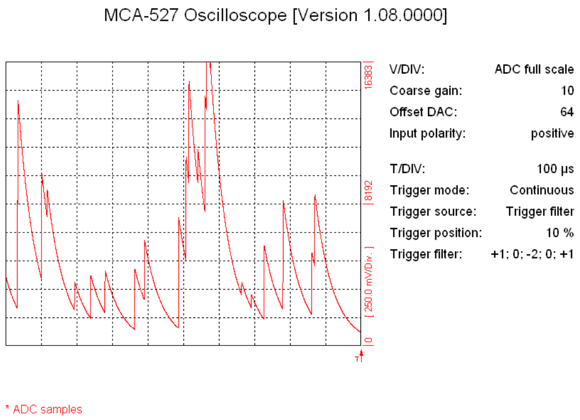


*Lower diagram: Measuring channel vs. amplitude, gain 10*1. No visible deviation from a straight line through origin can be seen. Upper diagram: Relative error vs. amplitude with different coarse gain settings. The deviation is at worst 0.03% of full scale (gain 2). However, there the test generator is working at its amplitude limits. With the other gain settings, the nonlinearity error is always <0.015%.*

Measuring Differential nonlinearity with MCA527

For this, also the CAEN digital detector emulator DT5800D is used. Here it was set to generate a spectrum with equally distributed amplitudes. As good statistics are required for this, the count rate was set to 30 kcps and the total measurement time was 17h. The MCA was set to 8192 channels, for the rest just the default settings were used, coarse gain 10, fine gain 1, shaping time 1µs, flattop 1.2 µs, PZC 1600, Trigger filter +10-20+1, BLR1/16, PUR on, Jitter corr and LF reject off.





Measured Spectrum for DNL evaluation. Right: the signal used.

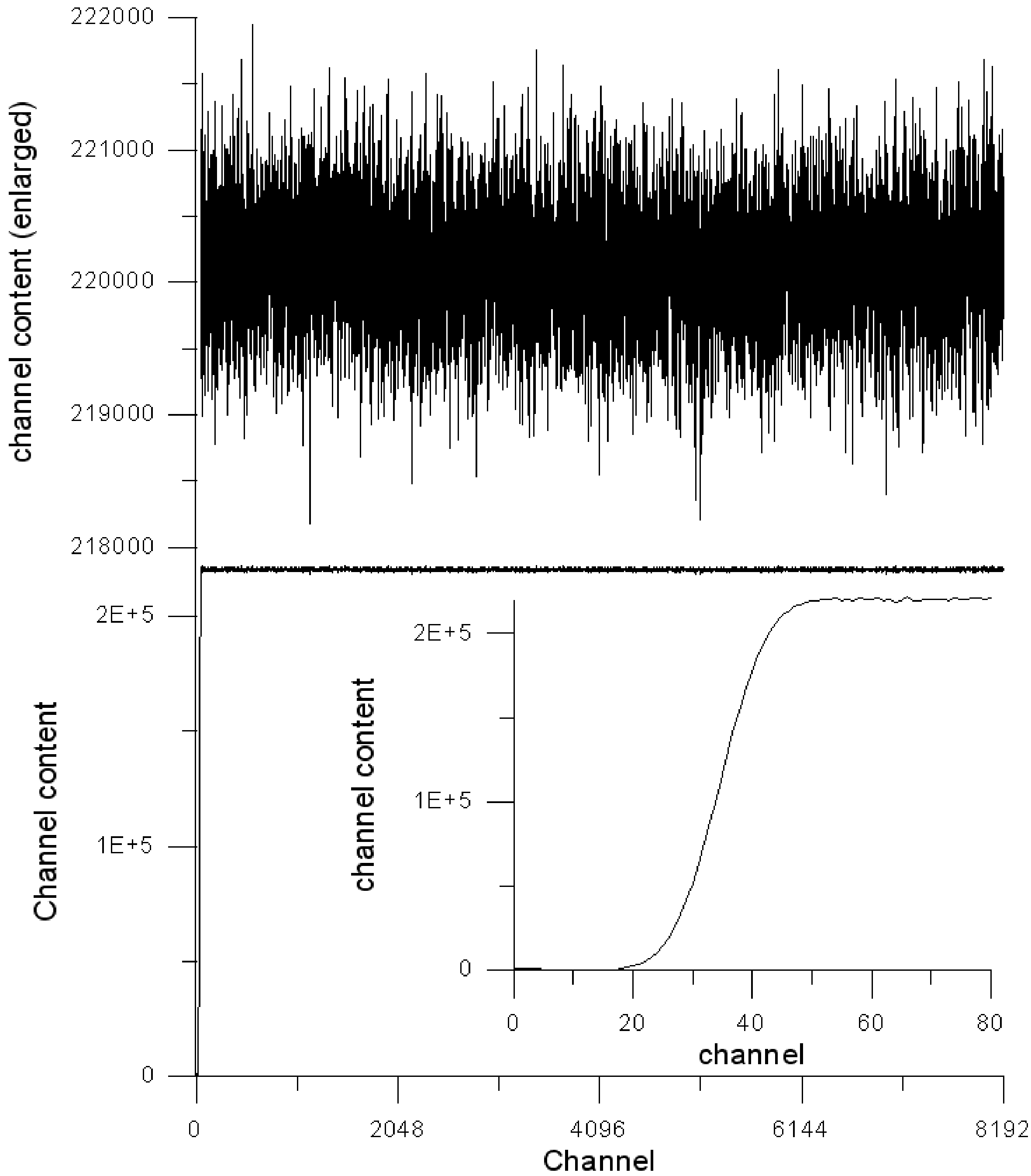
The measurement time was long enough so there were about 220k counts in each channel resulting in an expected accuracy of 0.2%. A statistical evaluation of the spectrum in 4 regions is made:

Channel range	Average channel content	std. deviation expected	Standard deviation	min/max
200-2000	220168.5	469.2	468.65 / 0.21%	218178/221950 (-0.9%/+0.81%)
2000-4000	220129.1	469.2	465.3 / 0.21%	218483 / 221756 (-0.75%/+0.74%)
4000-6000	220084.8	469.1	470.5 / 0.21%	218207/221609 (-0.86%/+0.69%)
6000-7800	220136	469.2	459.9 / 0.21%	218393/221535 (-0.8%/+0.64%)

The average channel content is within 0.04% in all 4 regions the same, which is also a hint for good integral nonlinearity. The standard deviation from the average for the single channels is very close to what is expected from the statistics, any systematic error would have led to an increased standard deviation. Also, the most extreme deviations from the average (-0.9%) still may be explained by statistics; with 8000 samples, outliers of around 4 standard deviations are still expected.

So, this measurement may only give an upper limit for the differential nonlinearity (0.9%). As all results can be explained by statistics, the real differential nonlinearity may be much lower. However, this would require much longer measurement times and may be only of academic interest.

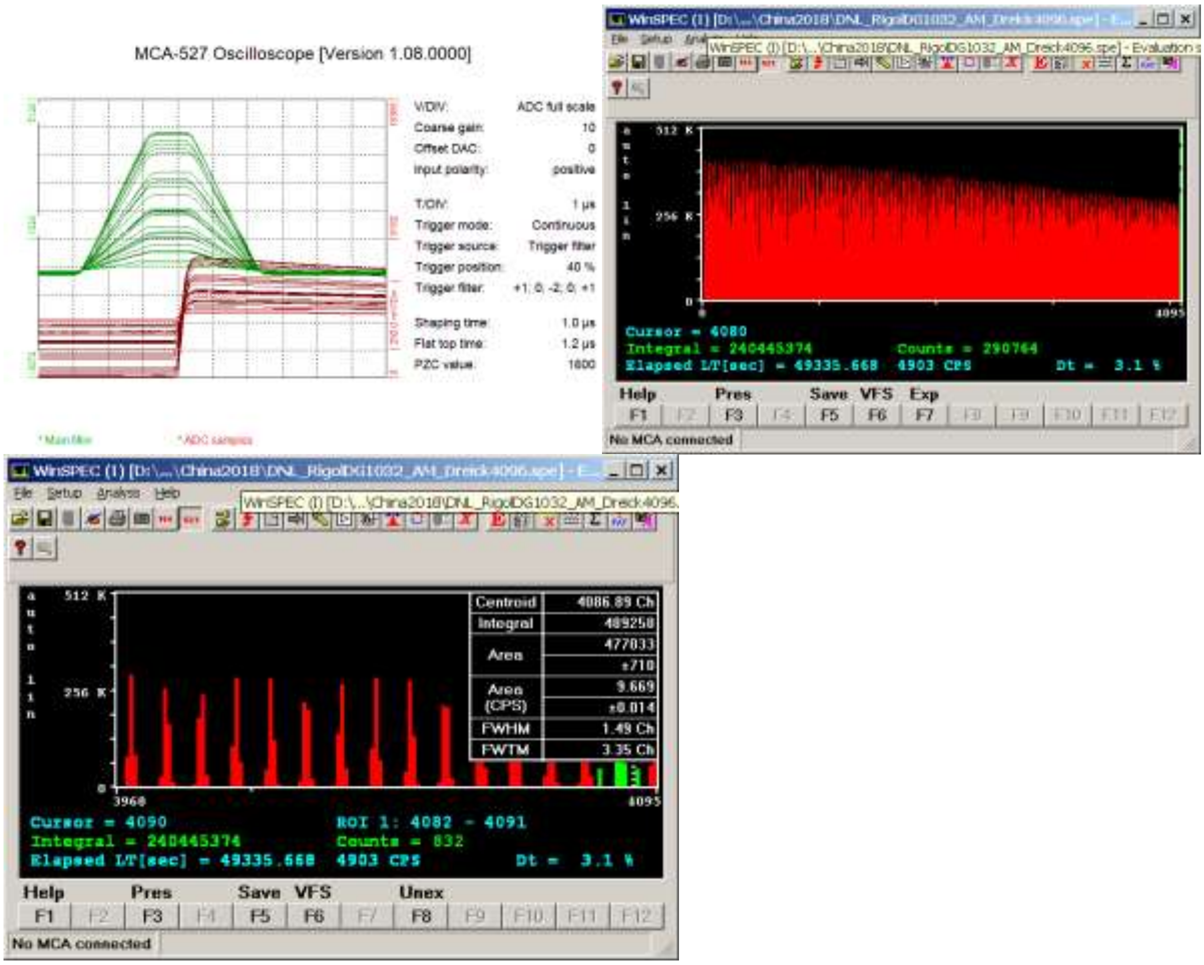
The range where DNL can be measured with this method is from around 0.7% to 100% of spectrum range. Below 0.7% of full range, events are no more reliable triggered and sensitivity diminishes fast, so this part of the spectrum may be cut off.



Details of the spectrum for DNL evaluation. In the lower part the full spectrum, with an insert from the lowest 1% where the spectrum is limited by the trigger threshold. In the upper part, the interesting part about +/-0.9% around the average is magnified.

Pitfalls when measuring DNL using a standard arbitrary signal generator

A first idea to measure DNL was to use a cheap but still very nice arbitrary signal generator, here the Rigol DG1032, set it to exponential decay waveform, which comes much close to a preamplifier signal, and choose slow AM modulation 100%.



Left: Signal (periodical) fed to the MCA, right achieved spectrum. Below: Magnified upper part of the spectrum.

The result was somehow unexpected, as the spectrum showed a comb like structure with 100% differential nonlinearity, which would be total unacceptable for spectroscopy. Repeating the measurement with various settings left in the end the conclusion that the signal generator was perfect in terms of signal stability and quality (better 0.04%) but its AM modulation had only 9 bit, therefore generating a spectrum with 512 peaks which could be perfectly seen. So, it’s always very important to question the measurement system.

Conclusions

The integral nonlinearity error of the MCA527 with the most used coarse gain settings from 5 to 50 is below 0.015%, so much less than stated in the data sheet.
The differential nonlinearity with standard settings is well below 1%, conformal with the data sheet. More precise measurements would require much more measurement time.