22RPT02 *True*8DIGIT

Towards a true 8-digit digitizer

Recent improvements in multi-tone testing of Analogue to Digital Converters

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Contributors to multitone measurement system

JV Norway :

- Zhe Ban (Practical measurements of AD4630 -24 and COPA and provision of test equipment)

INTI Argentina :

- Ricardo Luzzolino (design, and construction of COPA and software driver for AD4630-24)

SC Wales UK

- Allan Belcher (generation and analysis of IMD waveform files and practical advice on making measurements)

Scope of presentation

- Background to the IMD test method
- Use in True 8 digit project
- Recent advances allowing wideband IMD testing of an AD4630-24 using low resolution arbitrary waveform generator
- Application to testing of our COPA amplifier connected to the AD4630-24

Why use multi-tones?

- Amplifiers between the ADC component and the source may limit performance but this may not appear using a standard single tone test signal frequency. For audio systems this is usually 1kHz.
- Theory (and experiments) have shown that, *provided there are enough tones*, the power in the intermodulation energy can be orders of magnitude more than the power in harmonics.
- The power generated also increases with the order of the nonlinearity so is more sensitive to discontinuities such as those present in quantising .
- This can make it a more sensitive test than a harmonic based test.

Why do we use Multitone testing with ADCs?

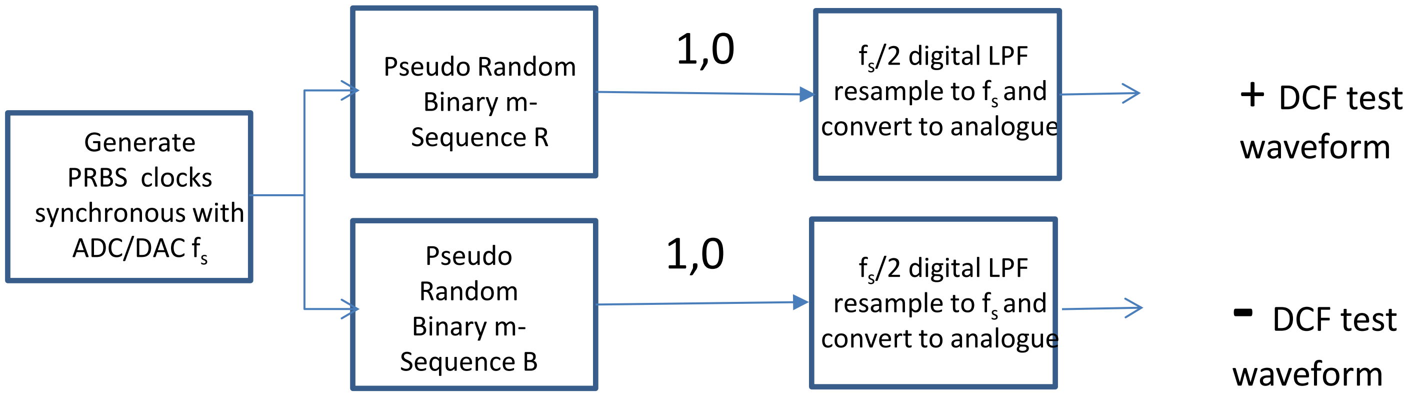
- Can be representative of ‘real world’ waveforms and spectra.
- *Only* if there are so **many** signal frequencies present that it has similar properties such as statistics and power loading.
- The multitone waveform must be periodic and ‘noise-like’ .
- A Pseudo –Random Binary Sequence is a well known solution in testing digital and radio communications systems.
- In our work we are using periodic waveforms that have more than 200 spectral lines (tones) in the waveform: these can fill the complete operating bandwidth.

Frequency domain or time domain measurement of IMD

- FFT is the conventional way. Synchronous test signals or windowing must be used. Sine wave testing of THD using FFT is well known. Standardised Intermodulation measurements use a small number of tones and FFT analysis. The test must move these across the measurement bandwidth, identify and measure individual products. Unfortunately, there is no accepted formulae to estimate the THD from this standard IMD result.
- Multi-tone testing of ADCs, using special periodic multitone signals conforming to IEC 60748-4-3 , requires synchronous digital filters. *It was originated by the BBC ,known as the double comb filter (DCF) method, for testing analogue audio systems using very simple digital processing*
- Simpler and faster than FFTs; power can then be measured in the time domain. THD can be estimated from this IMD (IEEE Alternative ENOB).

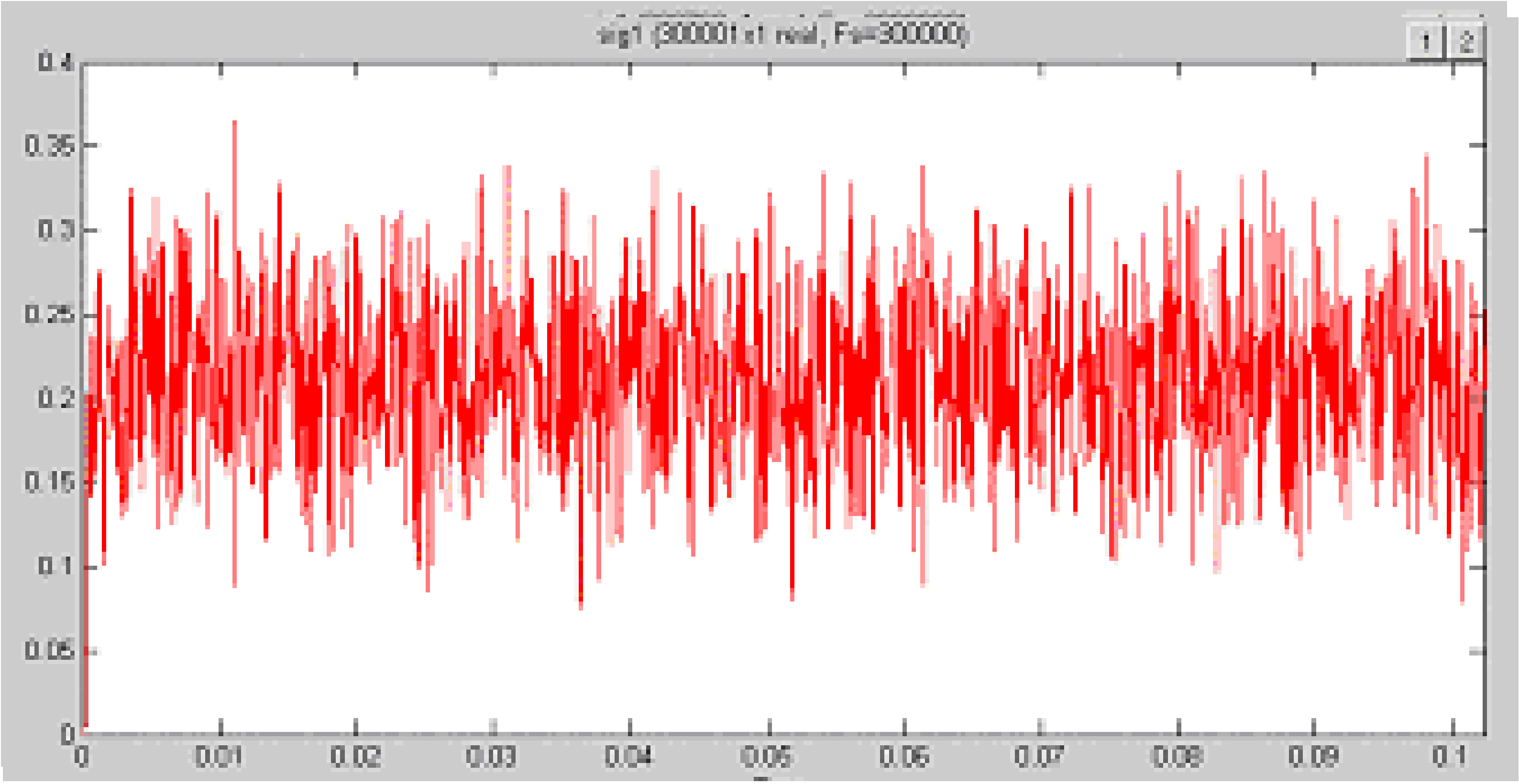
FFT display is useful for routine test

- Modern ADCs are designed with ‘balanced’ (+ and -) circuits on chip. This ensures that non-linearity and signal to noise ratio is maximised.
- A typical application requires an external balanced amplifier to drive the ADC. If only the + or the – input is used it allows an unbalanced or ‘single ended’ signal to be used.
- In our application we apply harmonic spectra signals to + and – inputs. Individually ,harmonic and intermodulation energy in + or - is hidden in the FFT lines . But when they are summed in the ADC, intermodulation energy between the harmonic spectra appears in the FFT gaps so can be measured and clearly *visible* if the FFT display is expanded. Harmonics are hidden on the line spectra, but the energy lost is not significant.



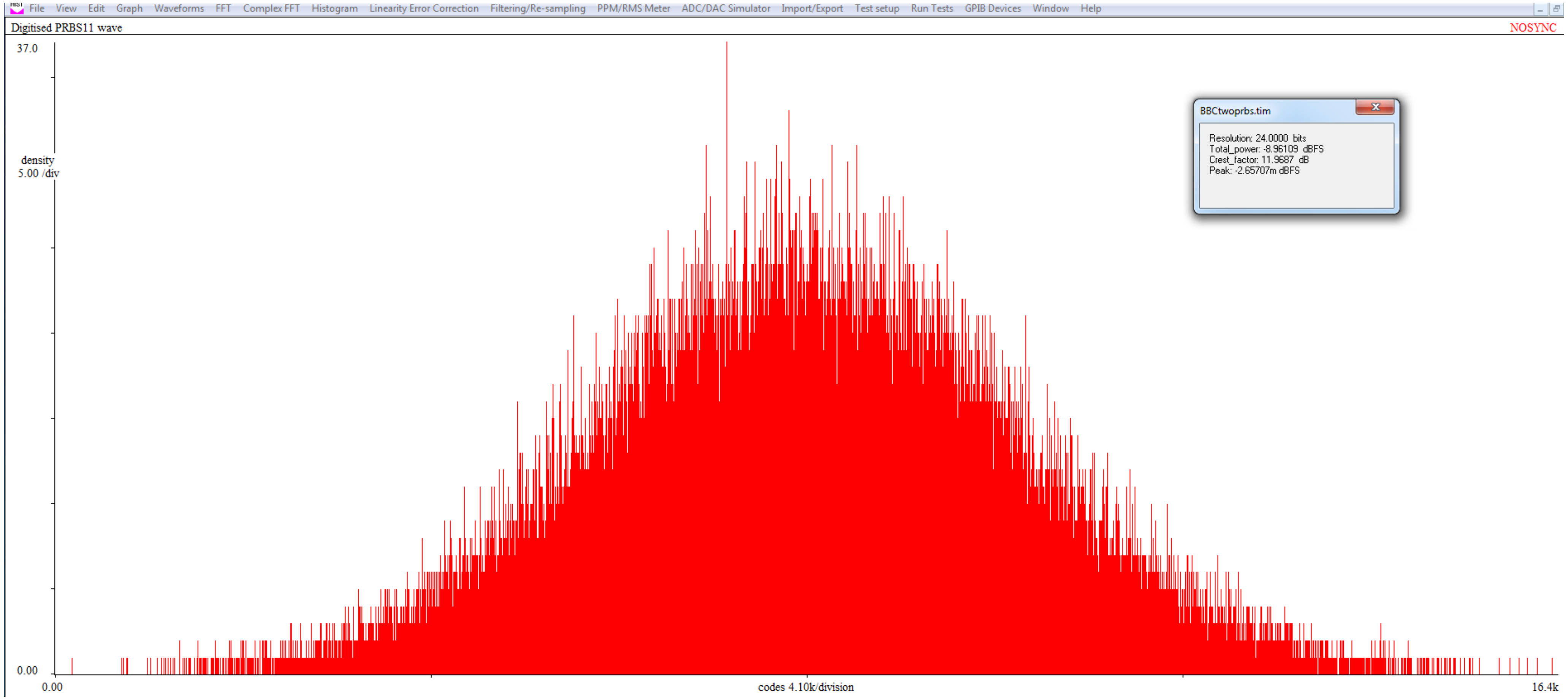
Synchronous DCF two channel (balanced) test signal generator

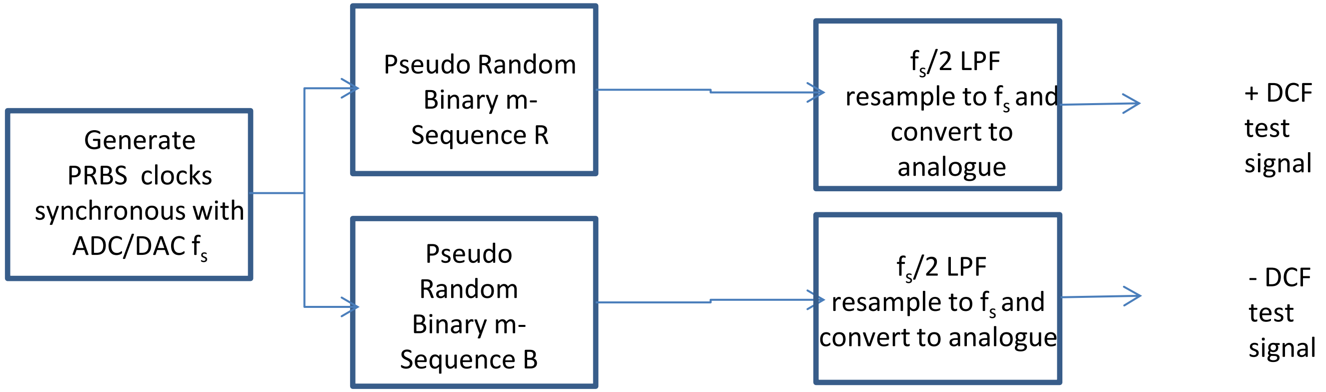
BBC test signal generator Waveforms



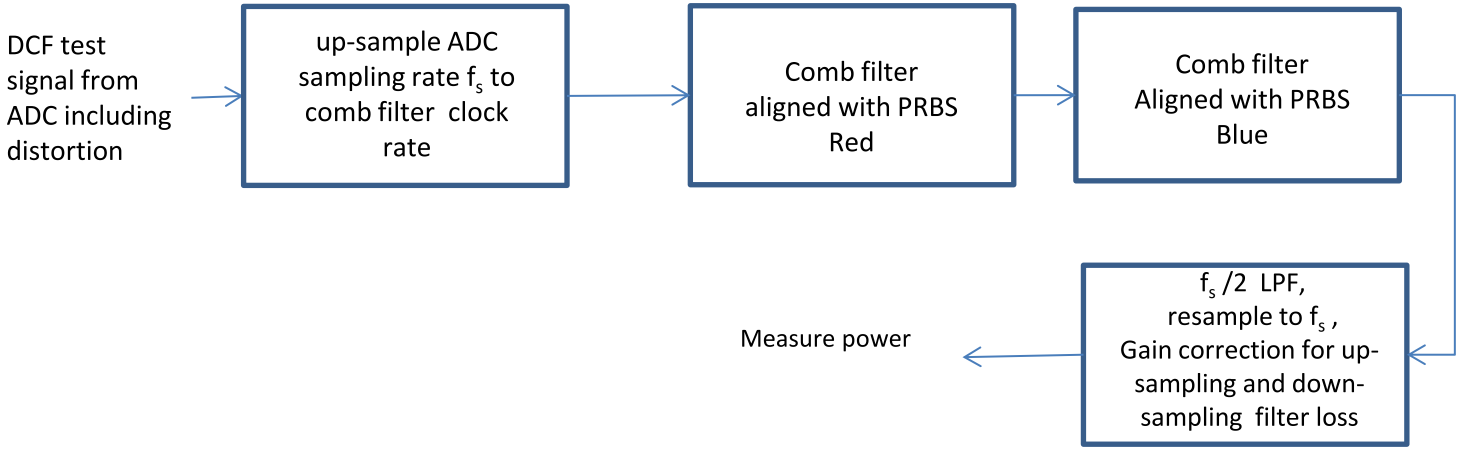
SIGNAL Conversion

Test Signal generation



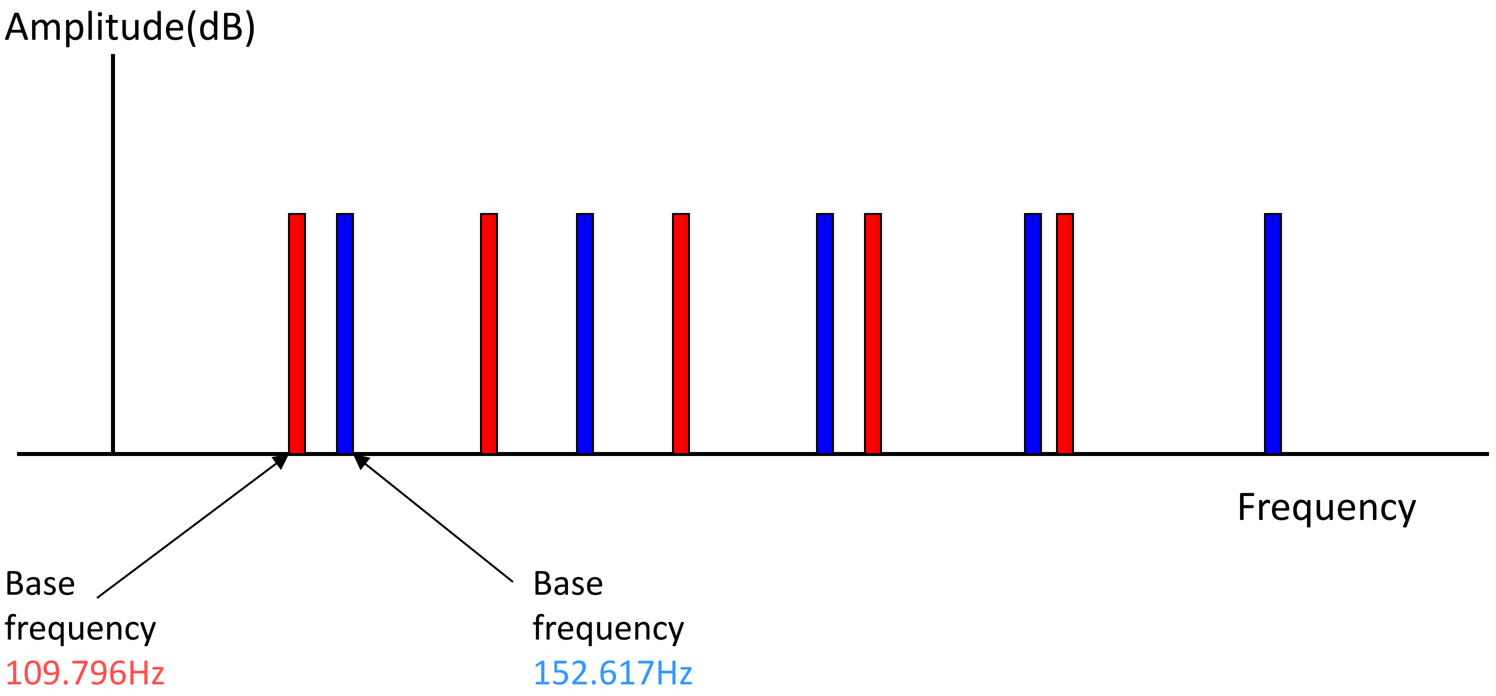


Synchronous DCF test signal generator



Time domain measurement of IMD

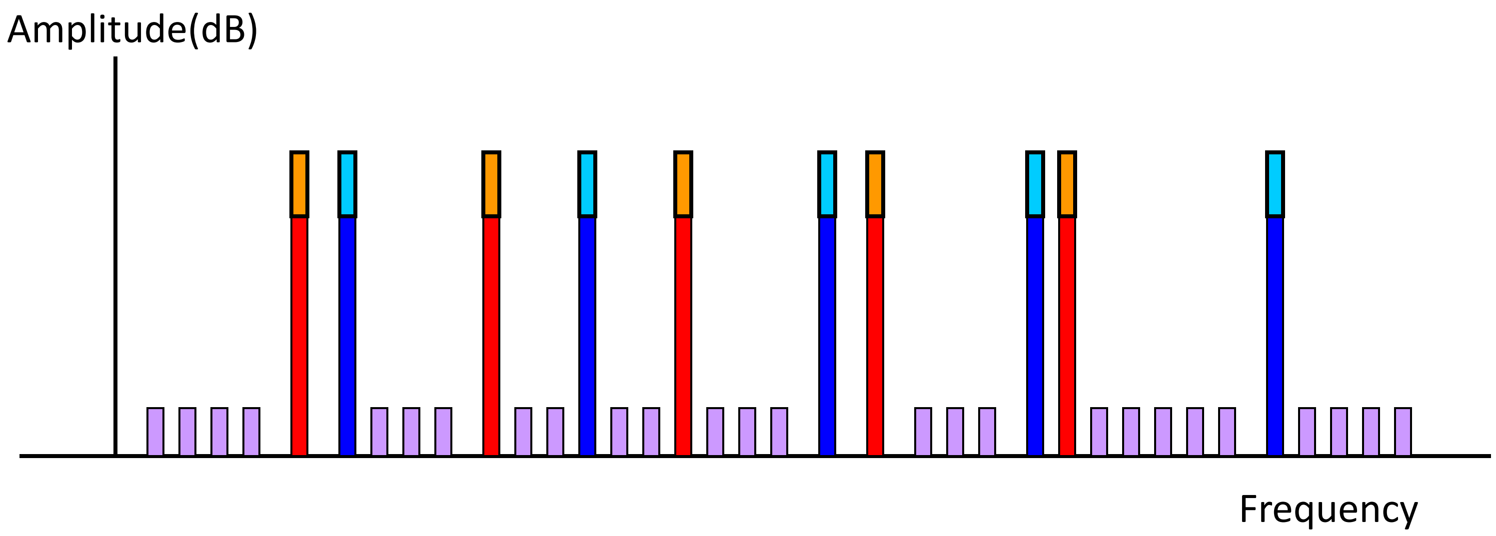
BBC Audio Test Signal Generator



SIGNAL Conversion

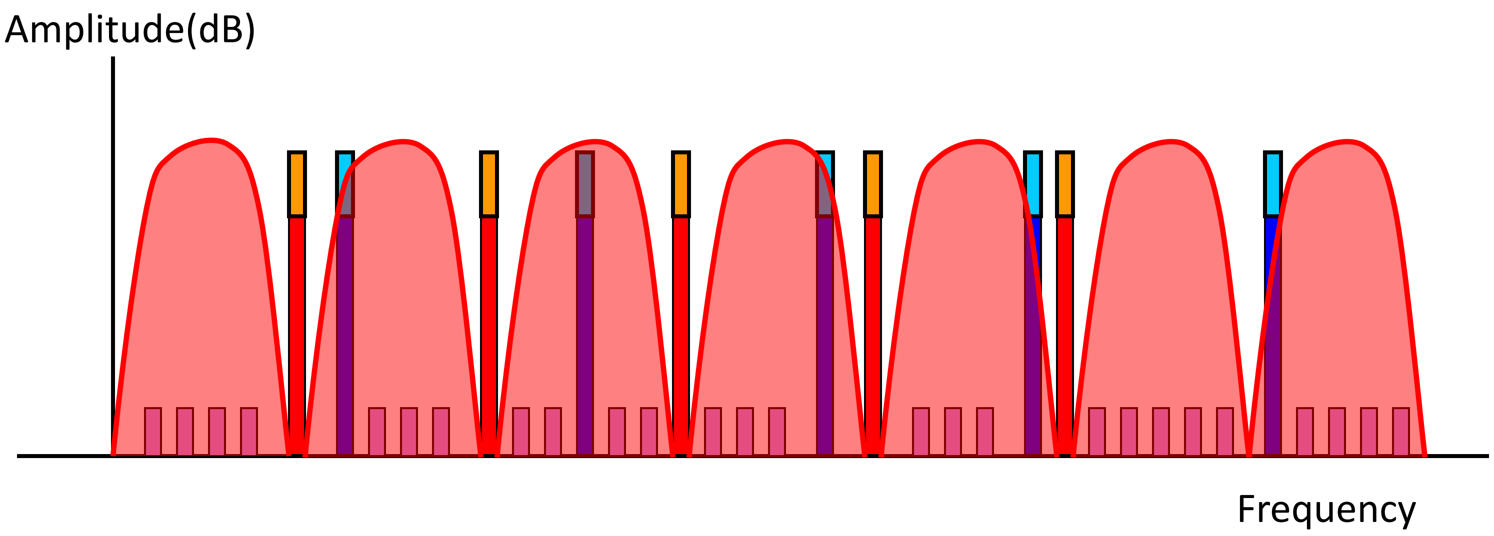
System Under Test

Distortion spectra generated by ADC/DAC under test appears *between* test signal and *on top* of test signal



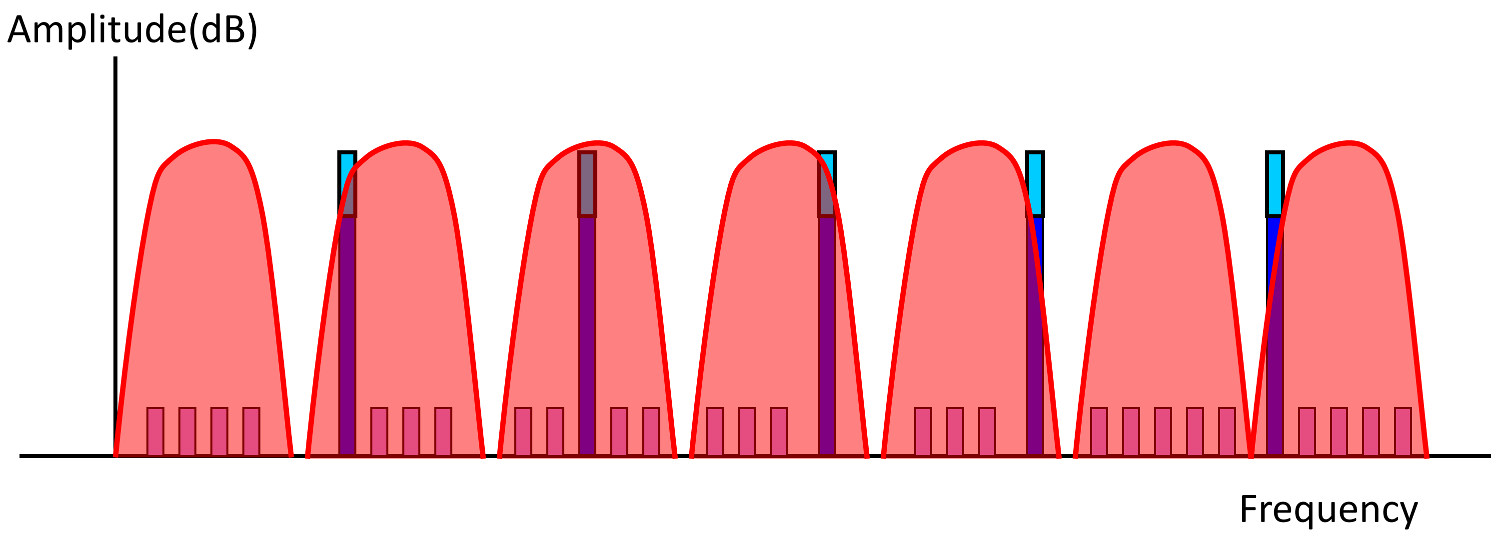
Test Signal Analyser

Red comb filter aligned with Red prbs spectrum



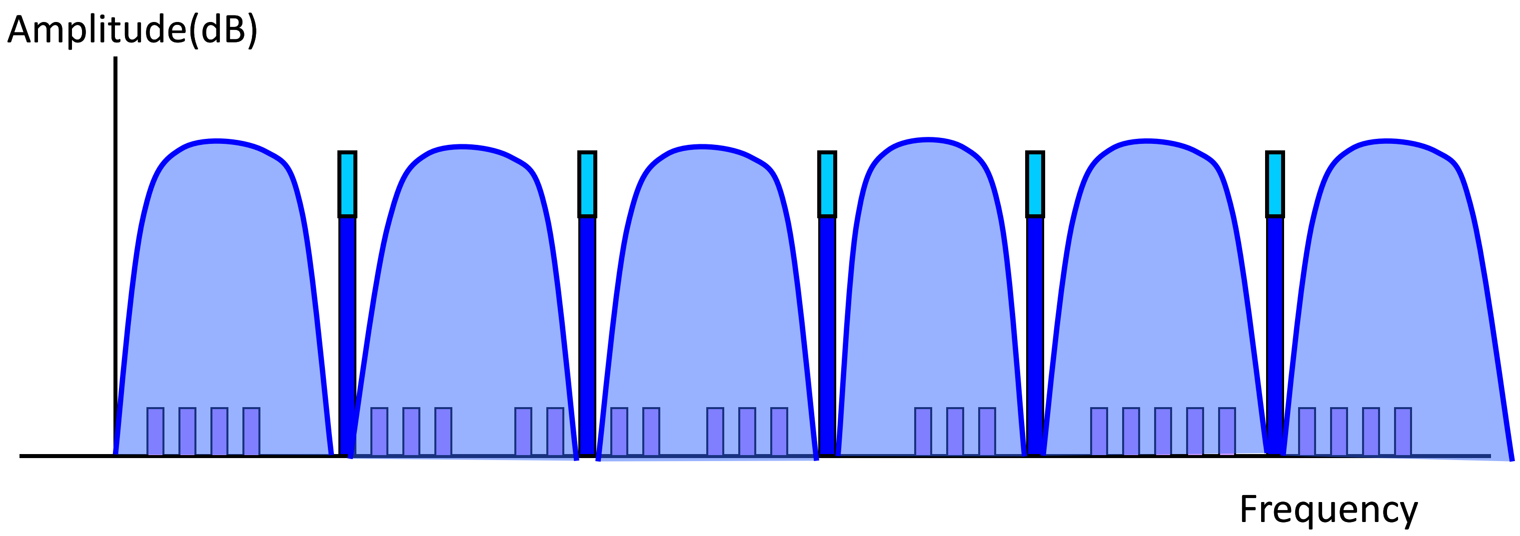
Test Signal Analyser

- Red PRBS spectrum removed



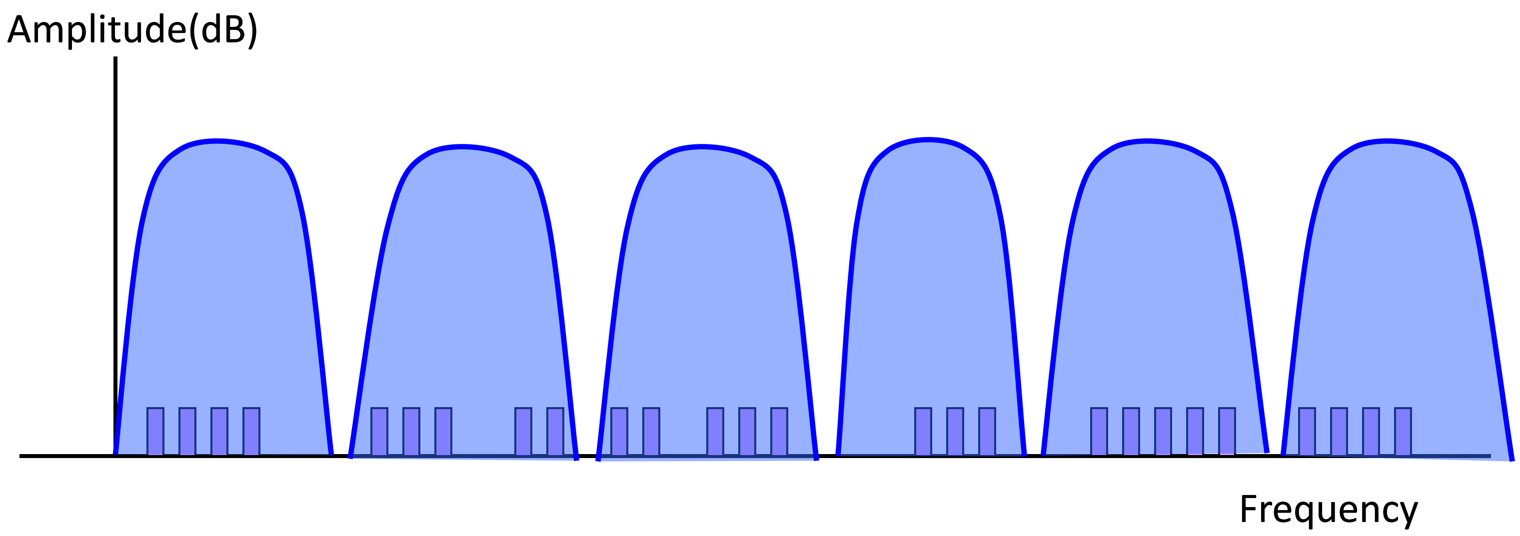
Test Signal Analyser

Blue comb filter aligned with blue PRBS spectrum



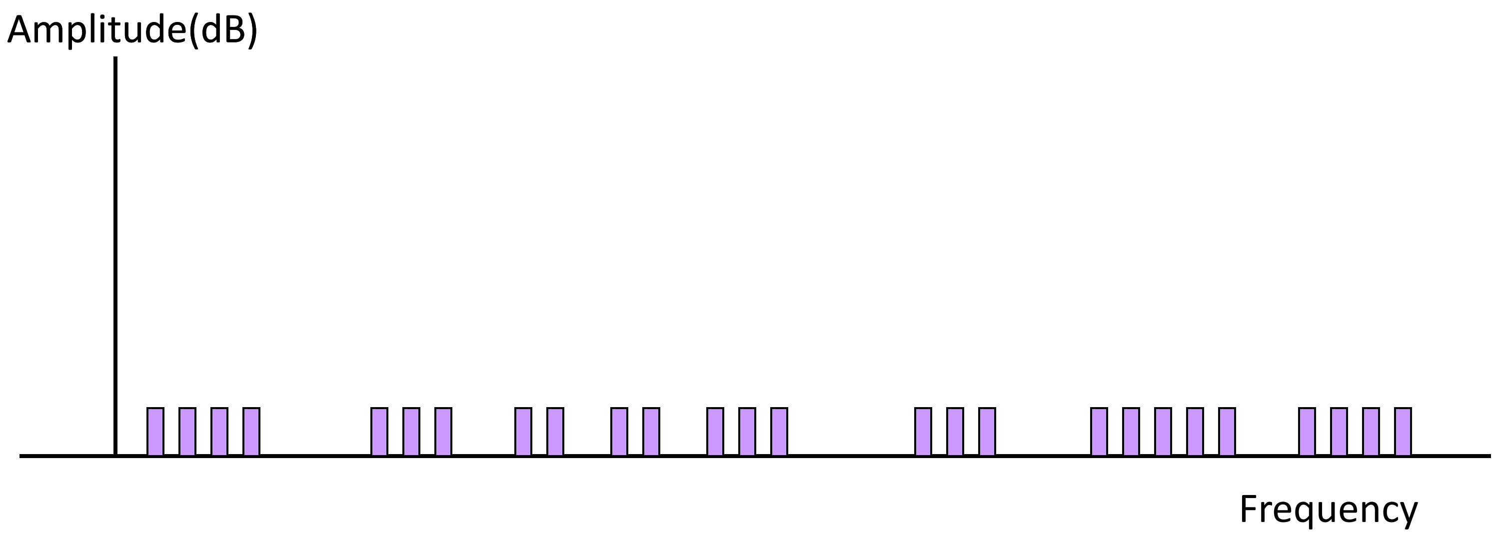
Test Signal Analyser

- Blue PRBS removed



Distortion Analyser

Distortion power measured in time domain;
no windowing, fast as no FFT



BBC double comb filter method measured IMD of an analogue system. It used an oversampled ADC

- In the BBC analogue audio test system, a 1-bit sigma delta oversampling ADC was employed to make the comb filter measurements. The analogue system IMD is already present in the input waveform so digital comb filters are used to remove the test signal, leaving only the IMD waveform.
- Digital comb filters were simple shift registers followed by XOR gates.
- (Adding or subtracting the 1-bit sigma delta patterns needed only an XOR gate.)
- An analogue low pass filter was sufficient to convert the 1-bit filtered output to a waveform.
- *This method may be of interest for built in testing of modern sigma delta ADCs.*

True8digit application of wideband IMD

- Digitisers are used to measure standardised analogue values .
- The precision of analogue values are specified according to the application
- Maximum precision (‘number of decimal digits displayed on an instrument’) in Metrology is primarily for DC and low frequency waveforms. Sine waves are required and THD is the parameter measured.
- If we trade a lower precision for a higher frequency or bandwidth, we can use wideband signals to provide an alternative metric. This is standardised in IEC and also published in IEEE .

Applications covered

- Characterising the internal ADC in an Audio Precision AP5XXX audio analyser.
- ENOB result agreed well with sine wave based ENOB (IEEE publication)
- The audio waveform was applied to an AD4630-24 ADC and the results observed using FFT. The AP5XXX and the ADC were not synchronised and bandwidth was limited to the audio specifications.
- Next steps and recent developments….

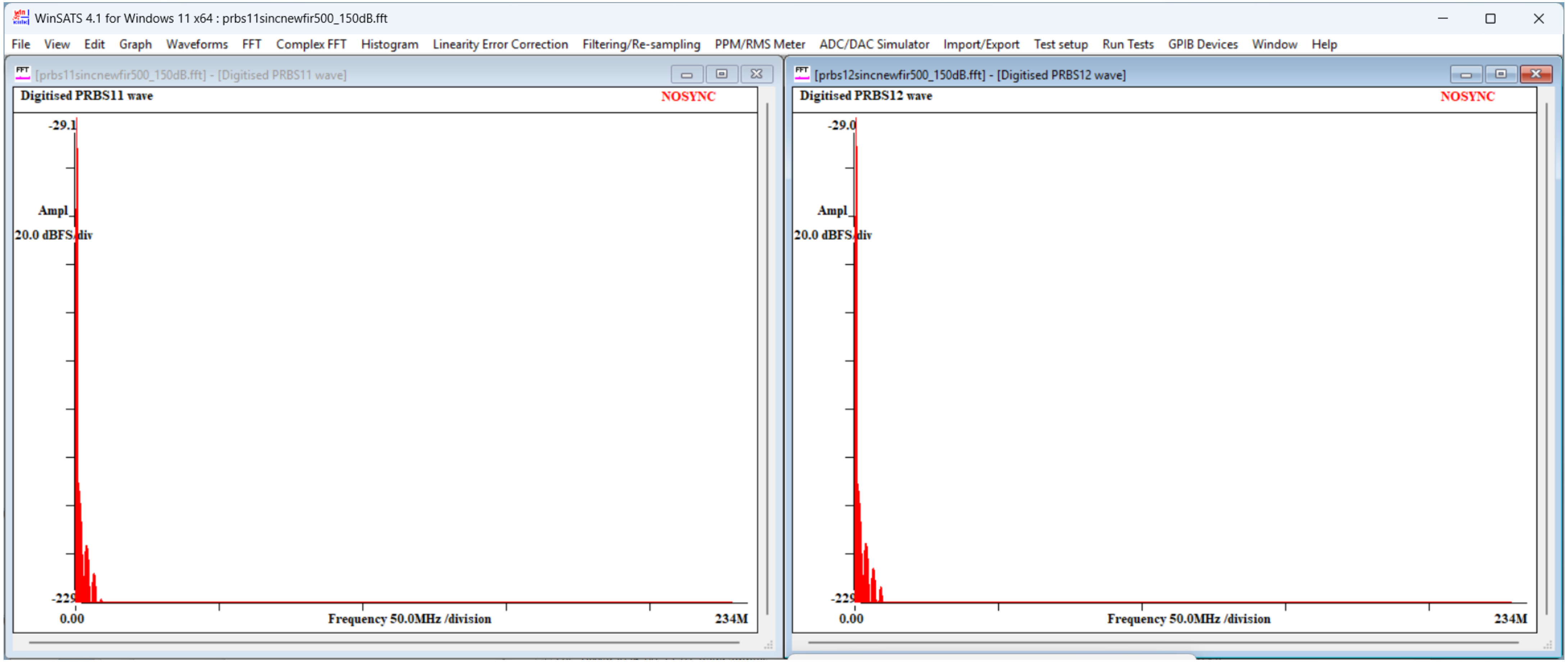
Generating wider bandwidth test signals

- The analogue performance of the TRue8digit COPA amplifier has been measured using sine waves and it is a requirement to also make IMD measurements of this amplifier.
- These measurements require a high performance digitiser with the best available bandwidth, signal to noise ratio and linearity . Our survey identified the AD4630-24 2 MHz 24-bit ADC as a suitable platform.
- We next moved to generating the IMD waveforms with Keysight 1 GHz 14-bit arbitrary waveform generator model 33622A. Unlike the AP5xxx, these are available in several of our partner laboratories.

3366A configuration

- Synchronous testing is required to make the IMD measurements.
- The ratio between ADC sampling frequency and comb spacing has been set to be the same as in the BBC selection. Other possibilities were investigated but the BBC values minimised spectral overlap so are an optimum choice.
- As the ADC sampling rate was 2MHz, the AWG must sample at 936 MHz to provide a 0.7 MHz bandwidth test signal. Sampling the same waveform at 468MHz halves the signal bandwidth. This option is used in the results to be presented.

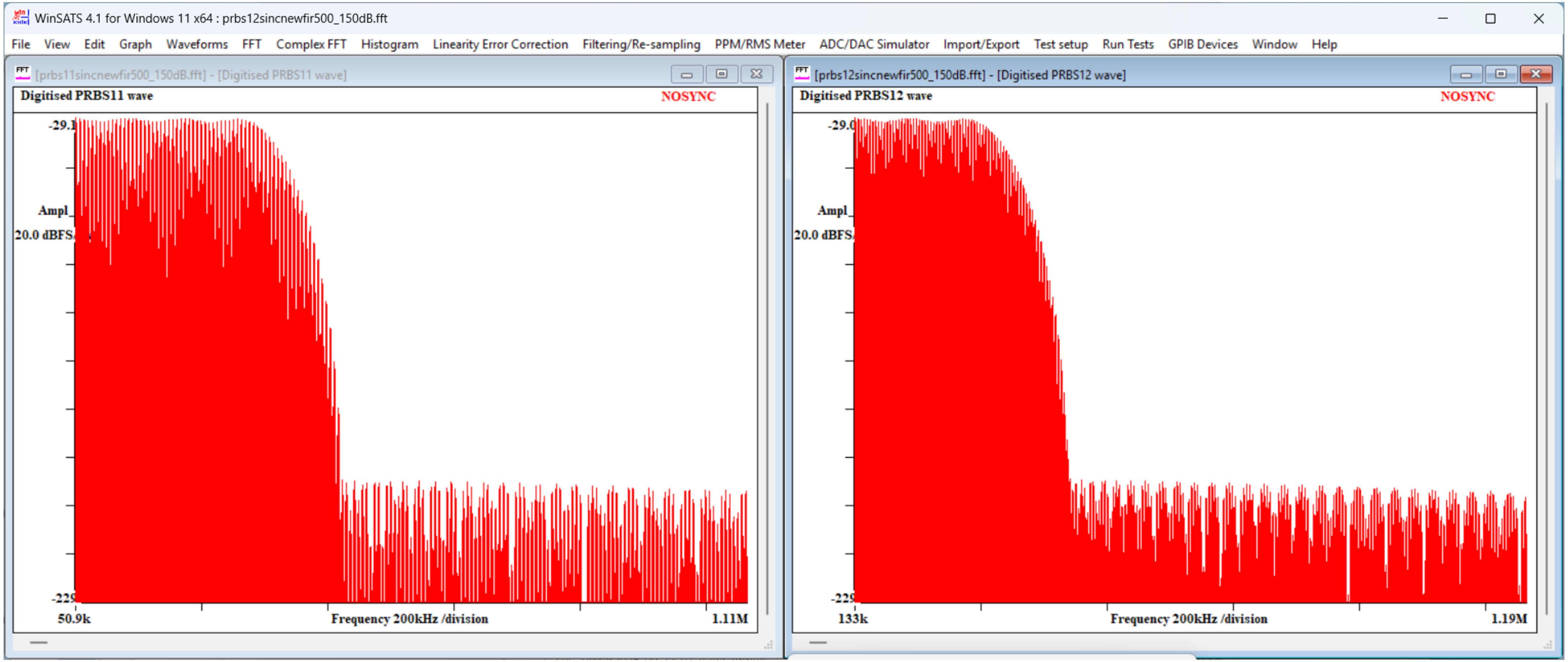
PRBS 234 oversampled ideal two channel DAC full spectrum



Selection of test signal bandwidth

- The digital lowpass filter fixes a 500:1 ratio between PRBS bandwidth and the AWG clock rate.
- With the AWG clock rate at 936MHz, this enables a full bandwidth IMD measurement of the 2Msps ADC.
- We selected an AWG clock rate of 468MHz so that the effect of analogue anti-aliasing filters could be observed in the FFT spectrum between a quarter and half sampling rate.
- This part of the spectrum is removed in the digital measurement filters as only in band IMD is required.

First 1 MHz of Ideal DAC waveform (330kHz bandwidth)



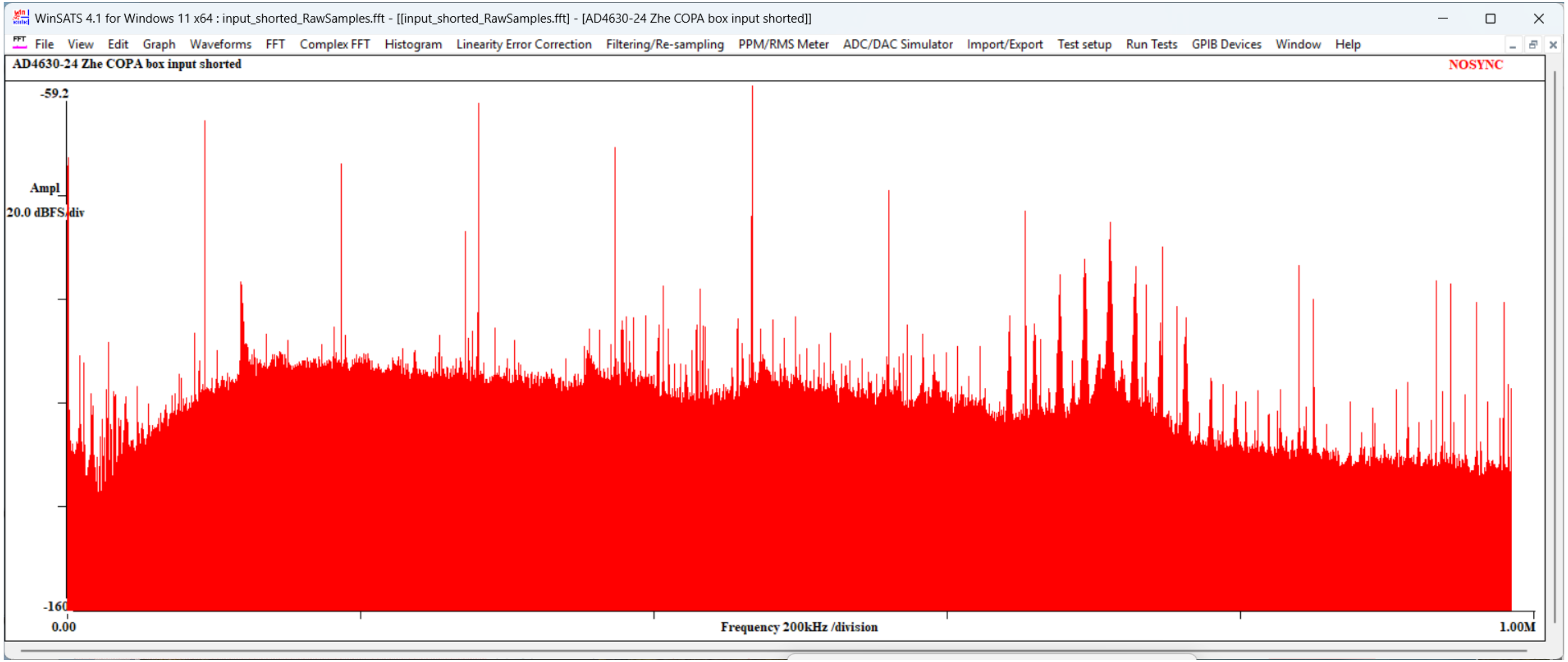
Unwanted aliasing of comb spectrum

- The 3366A produces a wide band signal as its update frequency is set to 468MHz . Each channel has a 14-bit DAC that clocks at this frequency so potentially generates a wide band width spectrum.
- It is important to ensure that any signals above 1MHz are reduced as far as practicable. Otherwise, the ADC will alias these so that become unwanted in band signals that degrade the measurement process
- The digital code that defines the waveform has a -150dB stop band low pass filter so will not in itself produce aliasing.
- The main factor that generates unwanted signals is inherent non-linearity in a 14 bit AWG.
- To address this, we added 50 ohm Mini-Circuits passive lowpass filters to the outputs of the AWG.

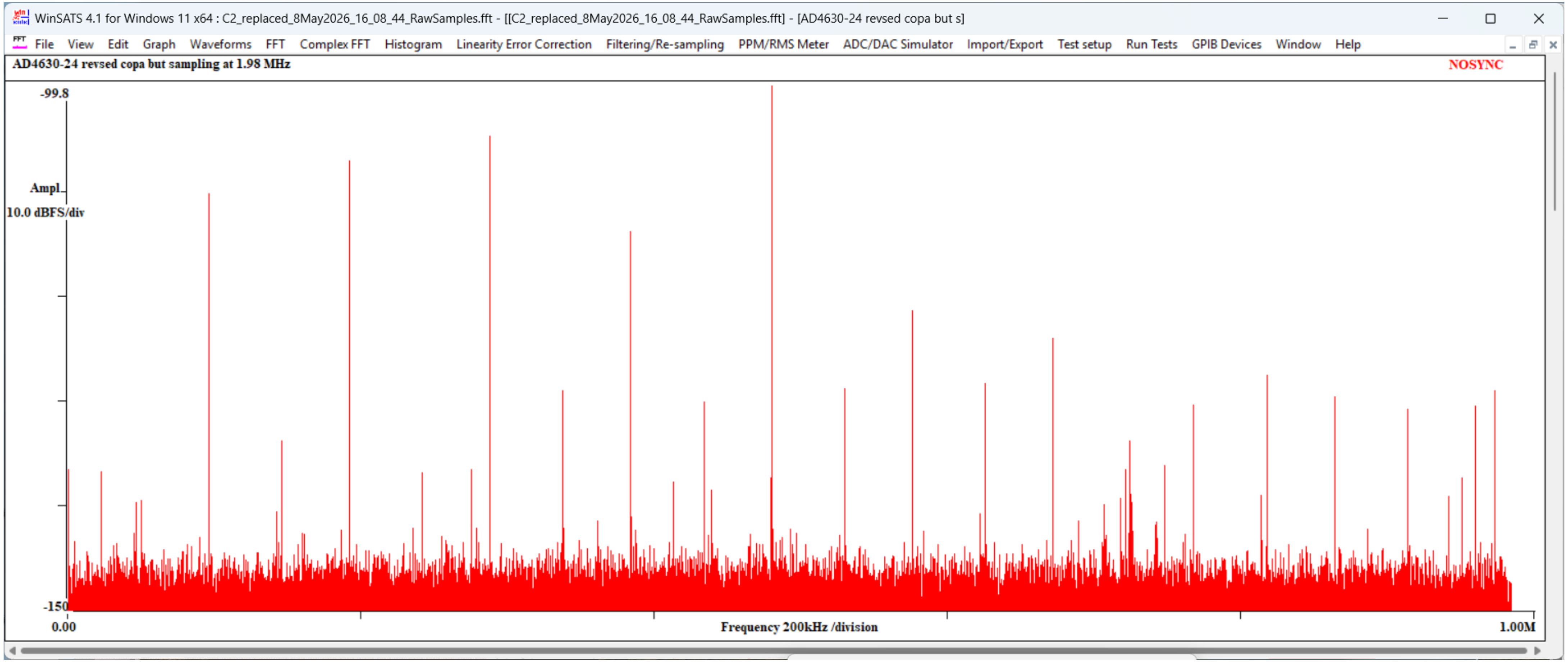
3366A waveform files

- The AWG waveform files are produced by my company's WinSATS software.
- A version of this has been made available free of charge for research use so all partners can continue make improvements.
- The waveforms were initially produced with 14-bit quantising as this appeared to follow Keysight documentation. However, the full amplitude DAC waveform would not produce full amplitude from the AWG.
- Eventually, JV was able to obtain an explanation from Keysight:
- Keysight AWGs assume all integer waveform file data is 16 bits and is rescaled internally to suit each DAC.
- So the 14-bit data gave an output 12dB below the value expected. This problem was resolved just by rescaling the integer values.

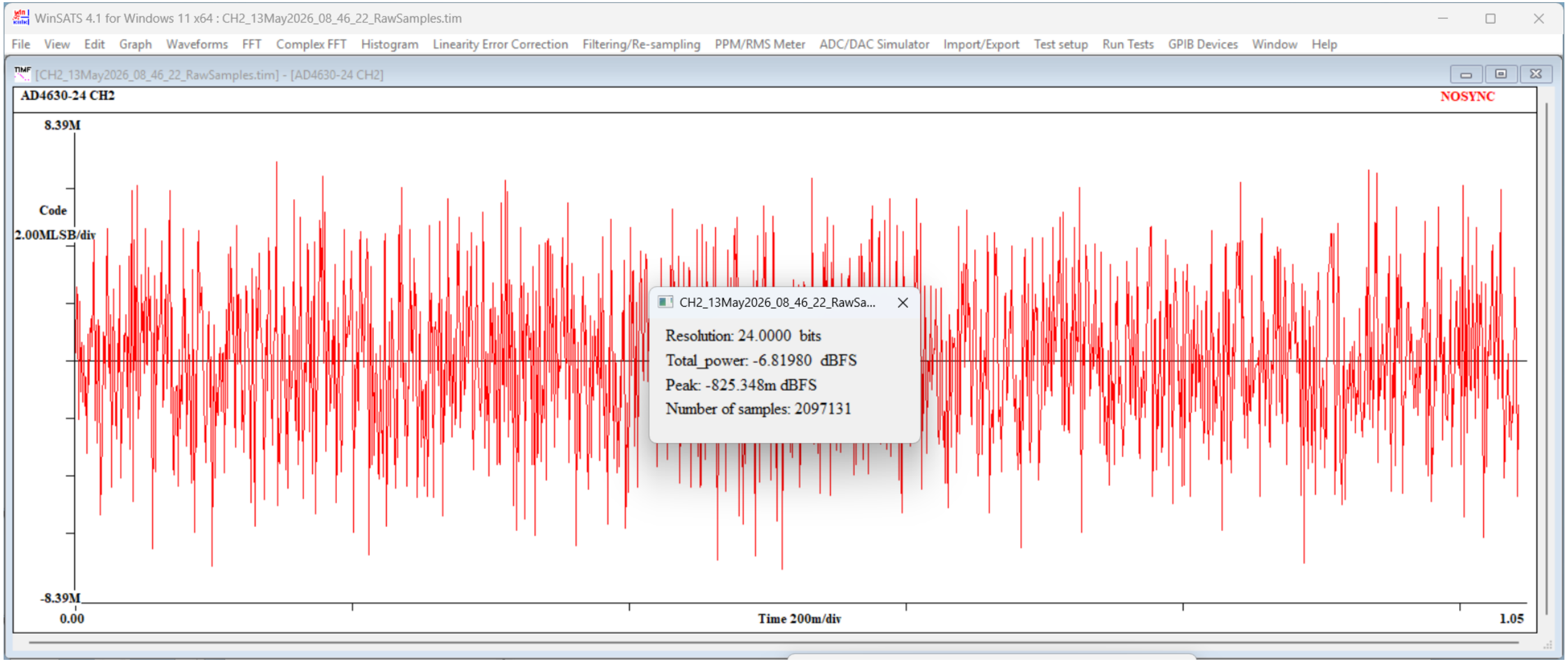
COPA input shorted FFT spectrum of AD4630-24



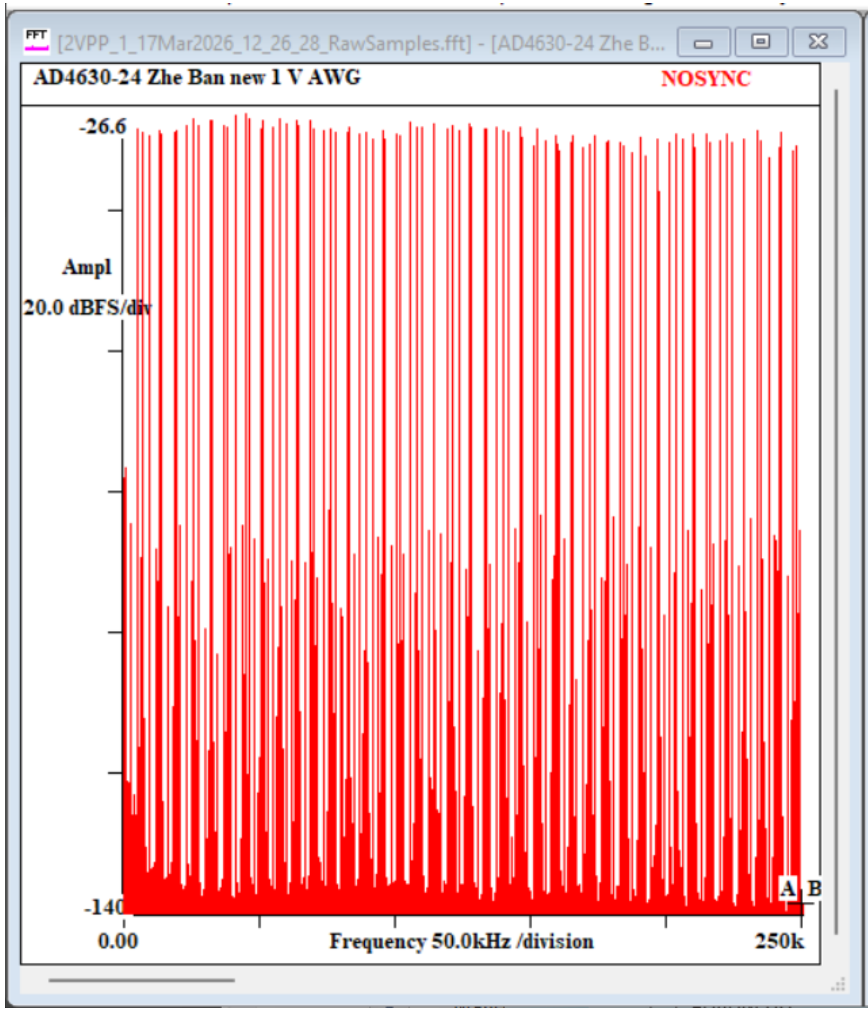
Modified COPA: noise levels normal

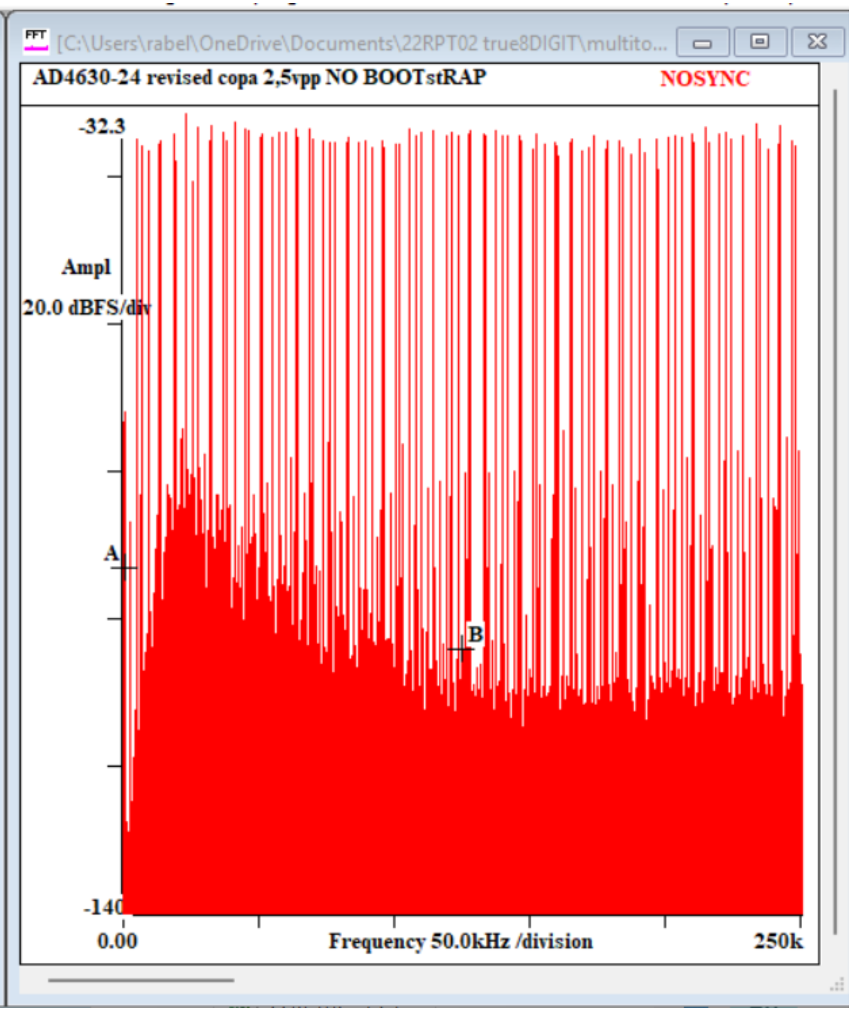


Multitone output from AD4630-24 CH2. Keysight AWG signal produces -1 dBFS

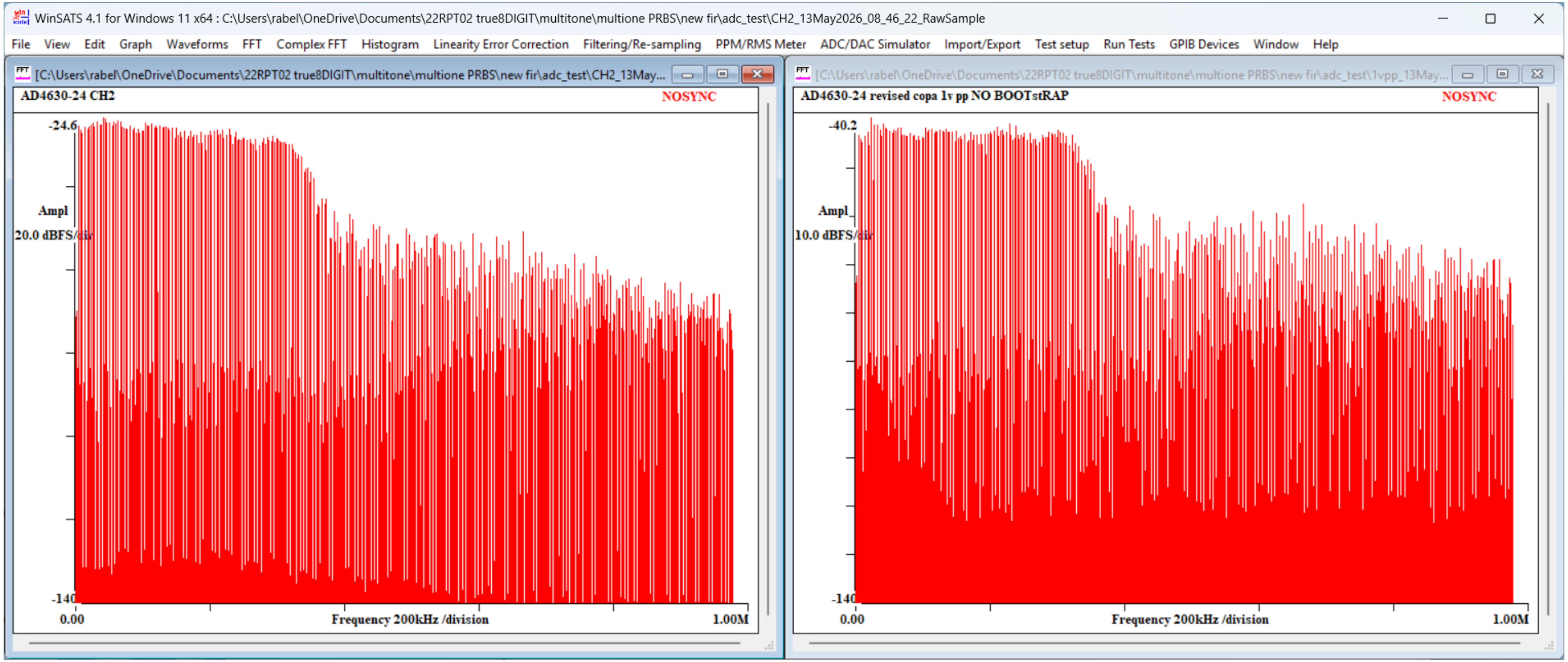


IMD AD4630-24 COPA + AD4630-24

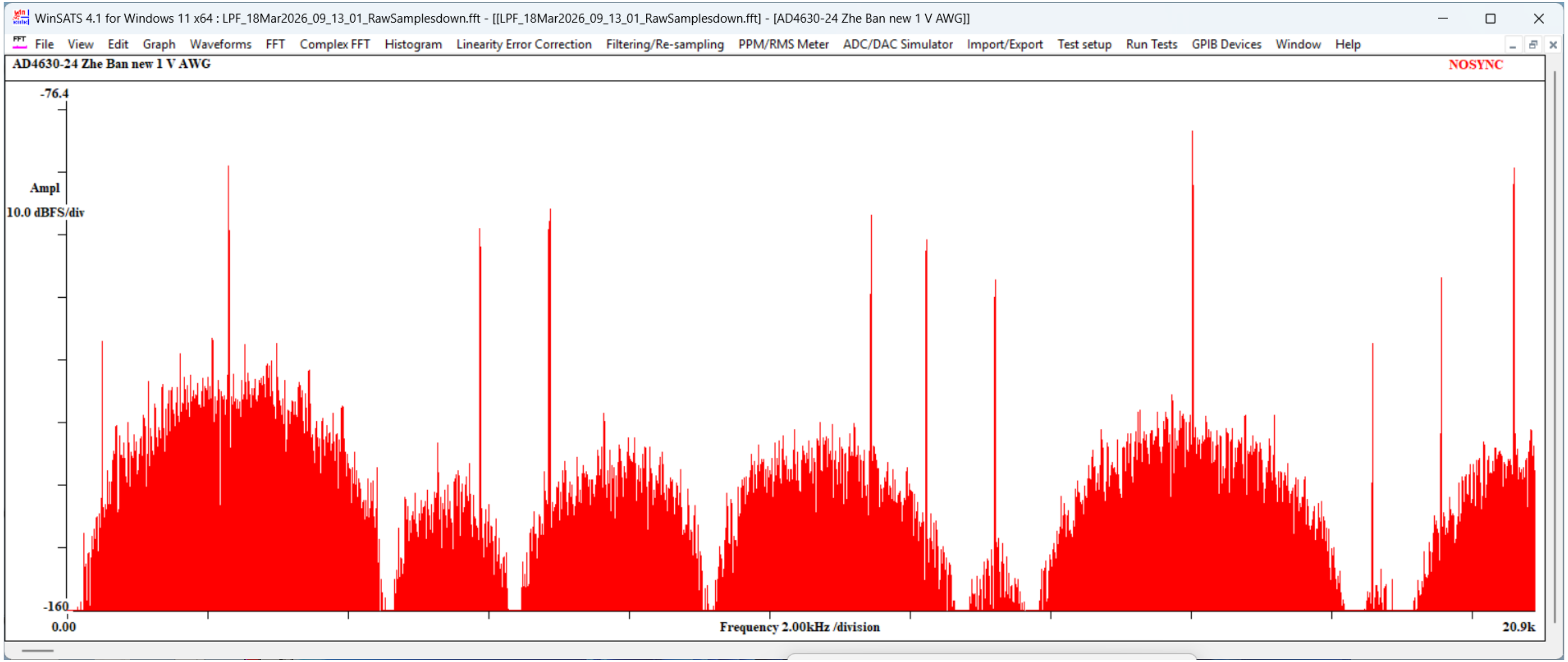




Effect of reducing COPA amplitude to 1V p-p
Left is CH2 with 2.5V p-p and right is CH1 with 1 Vp-p



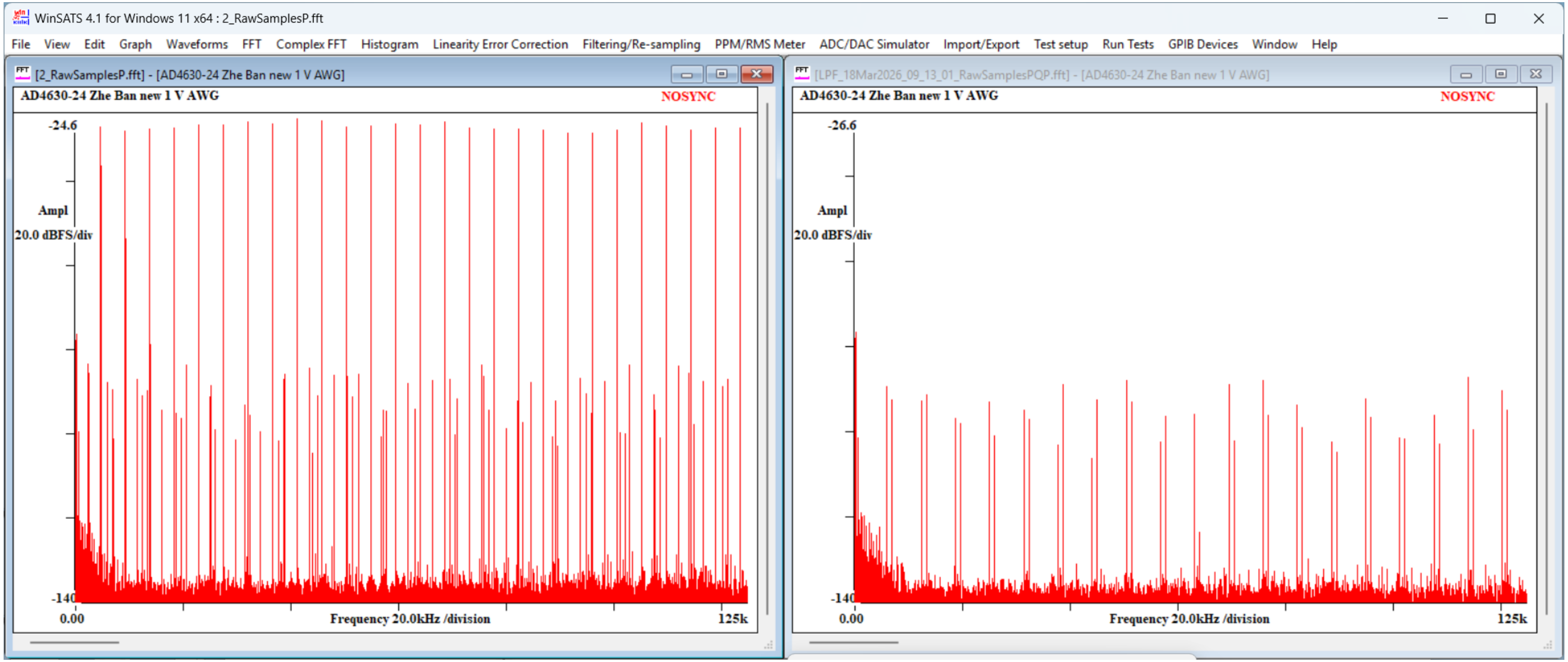
Zoomed to low frequency showing comb filter notches and aliased harmonics of comb spectra



Aliasing of PRBS harmonics

- The aliased harmonics of the PRBS comb spectra do not fall on the same frequencies as the comb spectrum. BUT, they therefore are not removed by the comb filters.
- A recent improvement to the processing has indicated a way to approach this problem. In principle, an FFT filter could be made to remove these aliased test signal harmonics.
- As the comb spectrum frequencies, harmonics and ADC sampling frequency are all known, Calculations show that they still have the same frequency spacing, but are offset by a frequency that can be calculated. They can be removed from the FFT spectrum but will require the use of windows to include the asynchronous tests.
- This approach was begun by simply removing the line spectra of the test signal to show the aliased signals.

PRBS comb spectra removed using FFT filtering left: one removed, right: both removed.



COPA bandwidth considerations for future tests

- The COPA has a design band width of 100 kHz but we applied a 330kHz band width test.
- If it was decided to repeat the test at a lower band width it would simply involve changing the AWG clock rate to , for example, 117 MHz.
- The PRBS bandwidth would then become 82.5kHz.
- Supplying lower frequency analogue anti-aliasing filters may also be needed to avoid exceeding the slew rate limit of the COPA.

Summary of improvements

- Previously, multitone test waveforms were produced in the Audio precision AP555 at PTB. This proved successful in measuring the effective number of bits of its internal 24-bit ADC using its internal DAC. The internal DAC was known to be not sufficiently linear for sine wave tests.
- A 24 bit 2 MHz ADC has been tested in balanced mode using a very wide band two channel 14-bit AWG. This 14-bit AWG is not specified to produce sine waves suitable for testing a 24-bit ADC.
- The AWG Amplitude non-linearity generates harmonics which requires an ant-aliasing filter in each ADC channel.
- Harmonics above the 330kHz digital low pass filter bandwidth are removed.
- Other test signal Harmonics are aliased to predictable frequency positions and are removed by FFT processing.
- Further tests are in progress at JV which will provide ENOB for different bandwidths.

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