6 September 2024
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Summer Student Project Report
Performance of High Resolution GS/s Oscilloscopes used for RF Measurements

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Keywords: Oscilloscope, Effective number of Bits, Transfer function, Power calibration

Contents

1 Introduction

Oscilloscopes are commonly used devices for fast measurements of the longitudinal beam profile of the accelerators at CERN. Data sheets from manufacturers list key performance figures, however information on how exactly the analog and digital signal treatment is designed inside the device is generally not available. Therefore, the aim of this project is to better understand the oscilloscope using acquired data in a test setup under well defined conditions. This uncovers some of the internal processing and limitations that impact performance and gives guidance to which settings are best used for a particular application. Relevant parameters to study the performance of an oscilloscope are the *Transfer Function* and the *Effective Number of Bits*. The frequency dependent transfer function of an oscilloscope describes how the measured amplitude depends on the frequency of the input signal. The number of bits of an analog-to-digital converter (ADC) is a commonly used measure for its resolution, but noise and distortions of the signal reduce this number. This leads to an *Effective Number of Bits* (ENOB) of the oscilloscope that is lower than the ideal number of bits of its ADC. The ENOB are subject to an IEEE Standard [1] and the approach used in this project to measure them is from a technical note by Rhode & Schwarz [2].

2 Test Setup

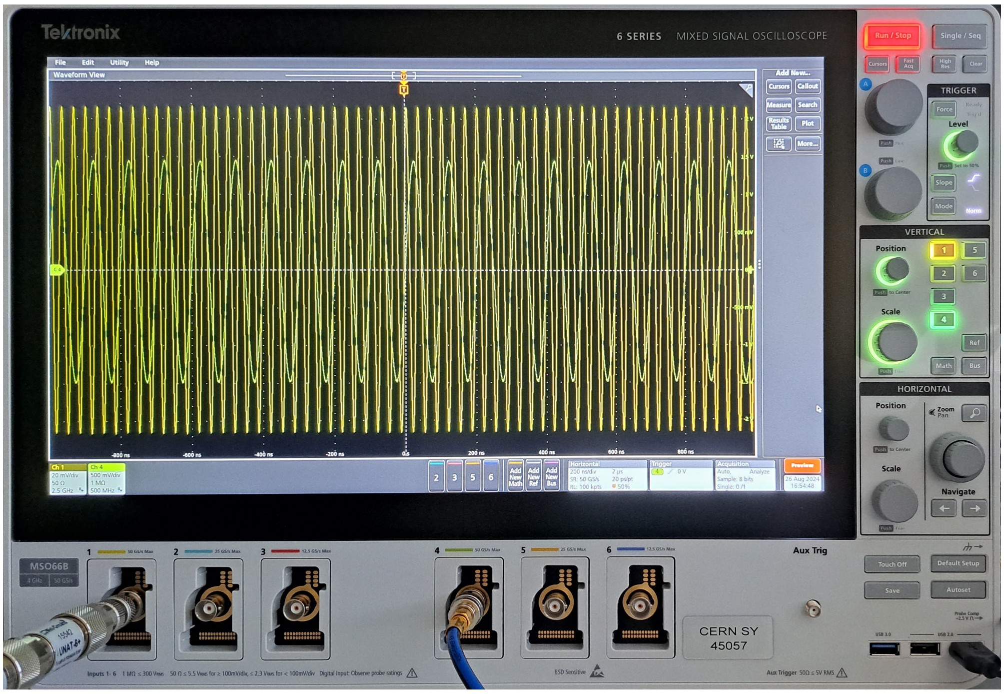


Figure 1: Oscilloscope MSO66B from Tektronix[3]

The focus of this project is on the MSO66B oscilloscope (4 GHz bandwidth version, fig. 1) from Tektronix [4]. It will replace the previous generation oscilloscope (Tektronix DPO 7254C [5]) that is currently used for RF measurements. The specifications of the oscilloscope that are important for the following measurements can be found in table 1. Even though the maximum bandwidth is 4 GHz most of the measurements in this report are done at 2.5 GHz bandwidth because this is the maximum bandwidth of the previous oscilloscopes and thus, measurements are comparable.

Max. bandwidth (BW)	4 GHz
Max. sampling rate (SR)	50 GS/s
Internal filters	two options for flatness or optimized step response
Acqusition modes	high resolution (12 bits), sample (8 bits)

Table 1: Key specifcations of the MSO66B Oscilloscope 4 GHz version under study[3]

For the high resolution mode it must be kept in mind that the maximum bandwidth gets reduced about a factor 1/2 and only the flatness filter is available.
To measure ENOB and transfer function of the oscilloscope of interest a sine wave signal is needed. For this an SMB 100A signal generator from Rhode & Schwarz is used. The RF output of the generator is connected to the oscilloscope using a cable and two attenuators (2 dB and 6 dB leading to a total attenuation of 8 dB), one on each side of the cable to cope for the imperfect 50 Ω-termination of the oscilloscope and generator (see schematic of test setup in fig. 2). For the measurements of the ENOB it is important to have very clear signals which means the harmonics from the generator must be highly suppressed. To achieve this a set of ten filters (see fig. 3) is used. Their characteristics can be found in table 2. The S-parameters S11 and S21 of the attenuators and filters were measured with a network analyser to check that they work as expected in the relevant frequency range up to 4 GHz.
To measure the transfer function of the oscilloscope it is important to know the exact frequency

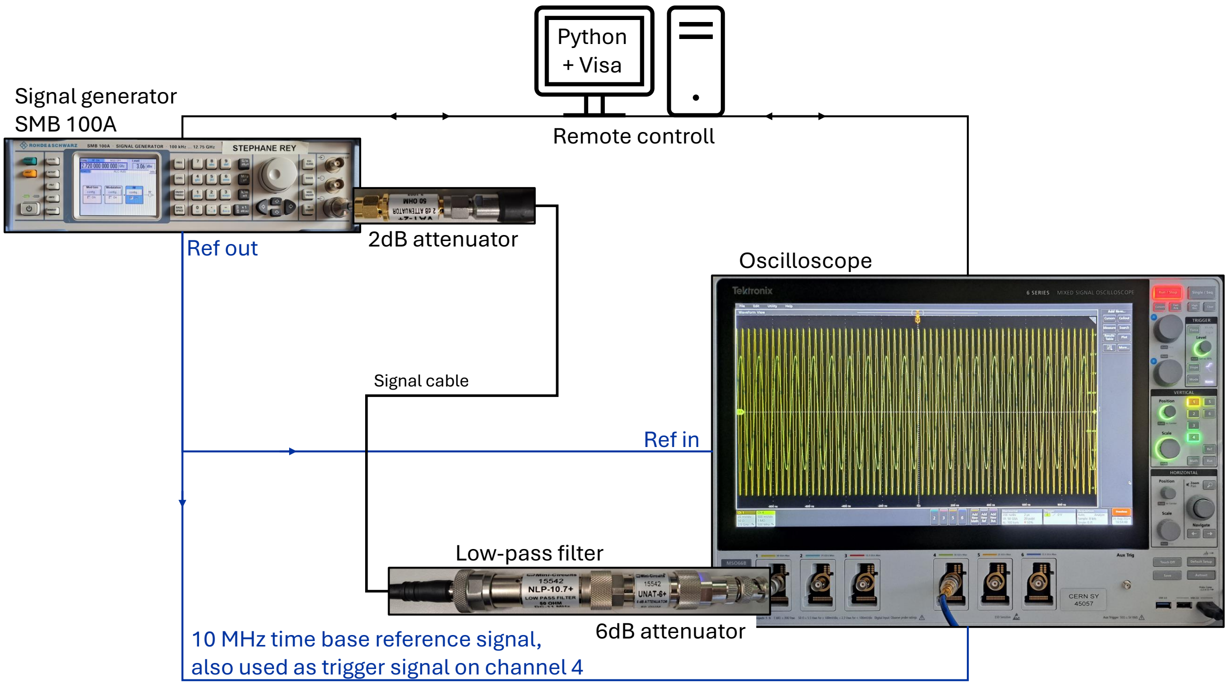


Figure 2: Test setup to measure ENOB and transfer function consisting of a signal generator connected to the oscilloscope with a signal cable (Huber+Suhner, Sucotest 18 SMA/Nm/48) and two attenuators (8 dB in total), the low-pass filter is only used for the ENOB measurements. The 10 MHz reference signal of the generator is used to lock the oscilloscope clock and also as a trigger on channel 4 of the oscilloscope. Everything is remotely controlled using Python and Visa.

dependence of the signal generator's output level and the used cables otherwise the oscilloscope's frequency dependence cannot be differentiated from those other contributions. Therefore a calibration of the power is performed with a power meter.

Range label	Range in measurement
DC - 11 MHz	10-11 MHz
DC - 32 MHz	20-32 MHz
DC - 98 MHz	65-98 MHz
DC - 190 MHz	125-190 MHz
DC - 225 MHz	140-225 MHz
DC - 400 MHz	240-400 MHz
DC - 780 MHz	470-780 MHz
DC - 1000 MHz	600-1000 MHz
DC - 2200 MHz	1310-2200 MHz
DC - 2700 MHz	1500-2700 MHz

Table 2: Ranges of the low-pass filters according to their lables and the measurement range they were used to suppress harmonics of the generator at the input of the oscilloscope. Measurement steps were 5 MHz for the ranges up to 125 - 190 MHz and 10 MHz for all higher ranges. The passband attenuation of these filters is very low (see sec. A.1) and therefore they are only used in the ENOB measurement while the power measurements of the generator and the transfer function measurements of the oscilloscope where done in a single frequency scan over the full range without these filters.

Figure 3: The ten low-pass filters that are used for ENOB measurements. They are from the NLP series from Mini Circuits.

2.1 Power Measurement of the Signal Generator

To measure the frequency dependence effects of the oscilloscope it is crucial to know the frequency dependence of the signal generator. For this purpose measurements of the signal generator output with the power meter are made. The test setup for this is shown in fig. 4. Because the passband attenuation of the external low-pass filters used for the ENOB measurements is very low, the measurement and calibration of power was done in a single scan of the full range without these filters. The power level of the signal generator is calculated such that the peak voltage of the output signal will have a value of 90% full scale of the oscilloscope for the different voltage scales that will

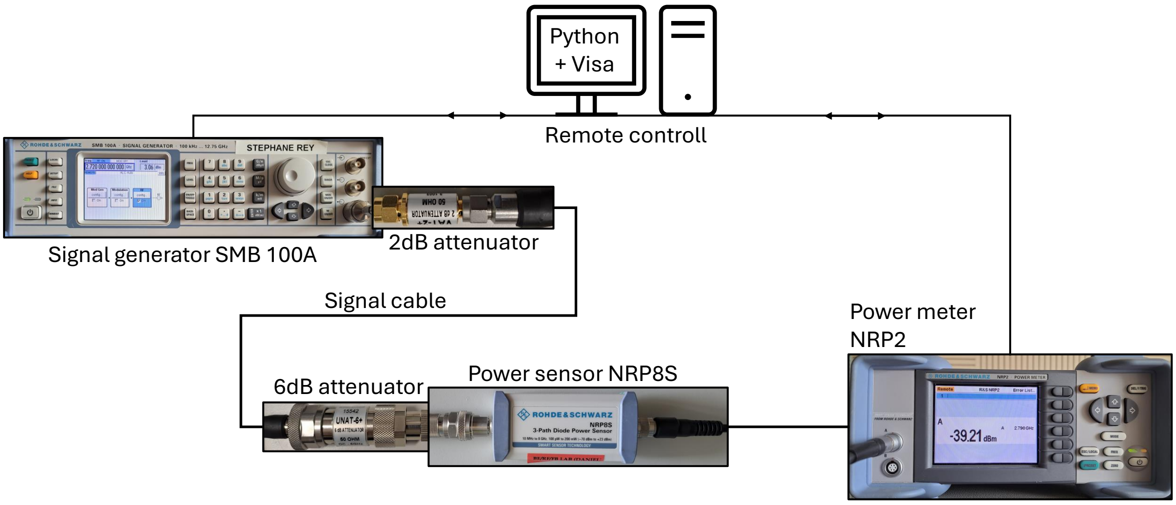
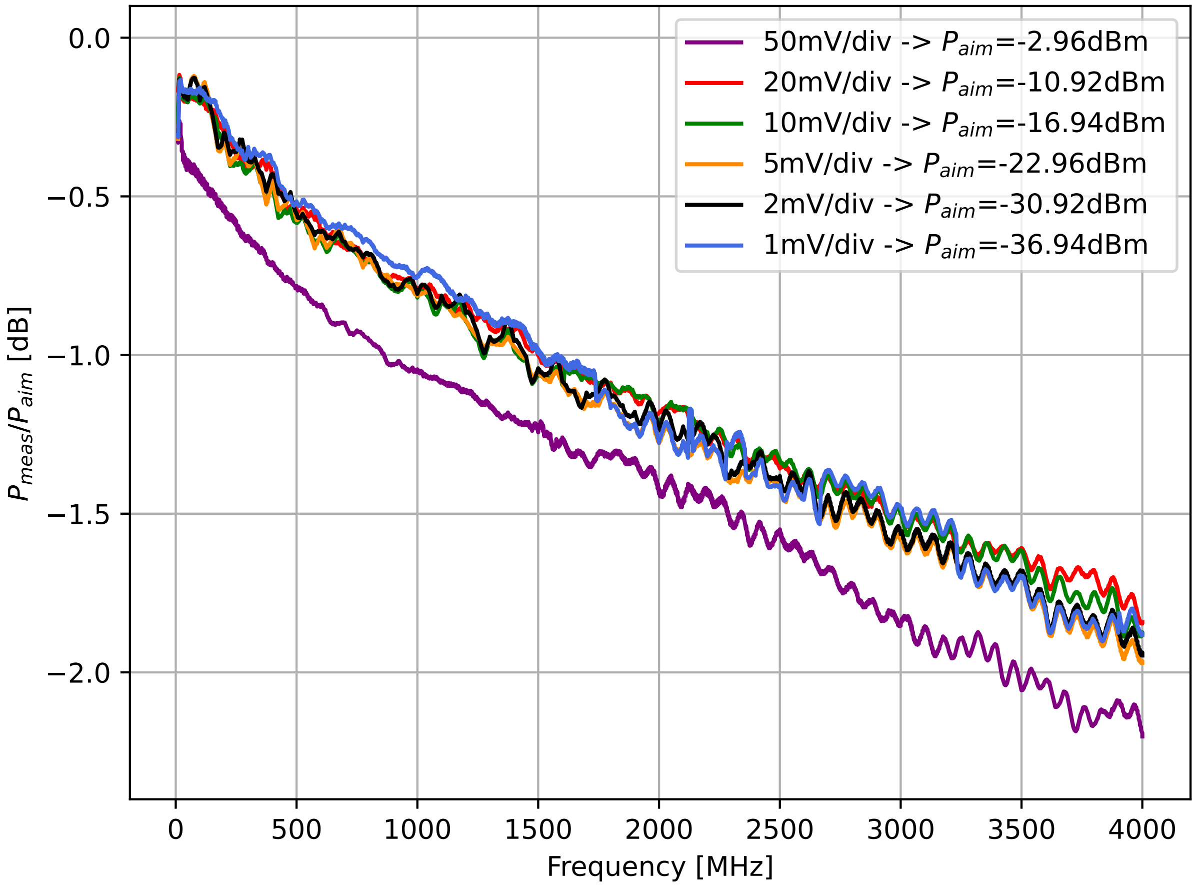
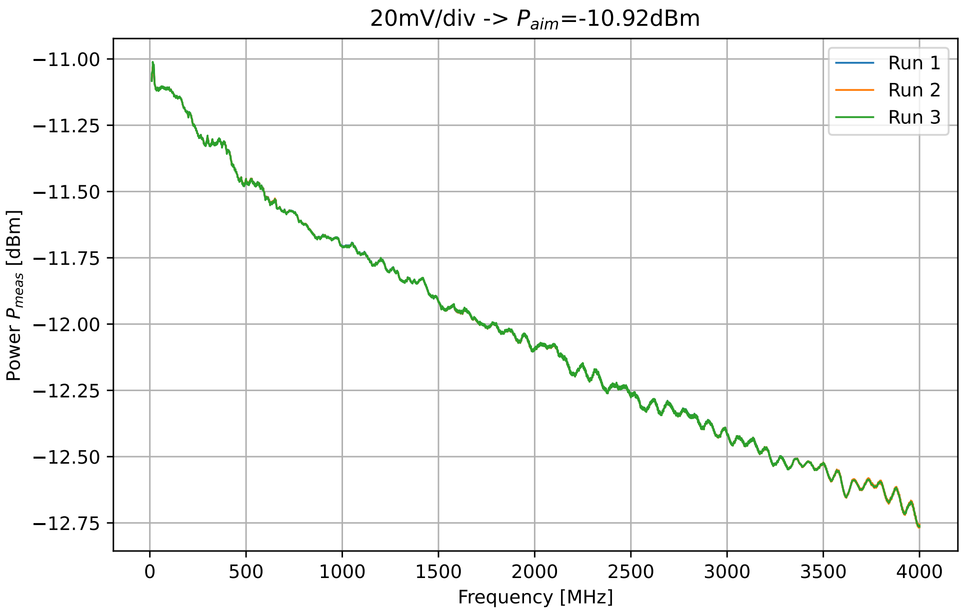


Figure 4: Test setup to measure the power delivered from the signal generator with a power meter. The generator is connected to a power sensor that is well matched to 50 Ω with a signal cable and two attenuators (8 dB in total), such that the signal is measured which is used as input for the oscilloscope. The power meter applies correction factors for the frequency of the signal and therefore, the set frequency on the signal generator is always set in the power meter. Everything is remotely controlled using Python and Visa.

be tested, taking into account the two attenuators with a total attenuation of 8 dB. The full scale of the oscilloscope is 10 times the set voltage scale (in mV/div).
The result of the measurement is shown in fig. 5. In fig. 5(a) the ratio of measured power to the power that was aimed for, meaning the set power minus 8 dB attenuation, is plotted against the frequency of the signal. Because the y-scale is in dB this ratio should be 0 dB but it is lower. Also a decrease over frequencies is visible, which is dominated by the losses in the cable. Between the setting for voltage scale 50 mV/div and the other scales a jump in the power occures. It is probably due to a step attenuator in the signal generator that switches at a power between those settings and is a little bit off. Especially at high frequencies above 1.5 GHz oscillations over frequencies can be seen. Those are dependent on the cable length and thus caused by reflections of the signal in the cable. Luckily all these deviations are very much reproducible, as can be seen in fig. 5(b) where an example for the measured power at one power setting is shown. The data of three measurements is plotted on top of each other and they overlapp very well. This means that the power setting of the signal generator can be adjusted according to this deviations.
The power is adjusted in two steps: the measurements of the power with a fixed power setting are used to calculate the deviation between measured power and calculated input power for the oscilloscope and this is averaged over three measurements. The deviation is used as a correction factor for the power settings of the next three measurements. Again the deviations are calculated, averaged and used as the second correction factor. After the two stages of correction the measured

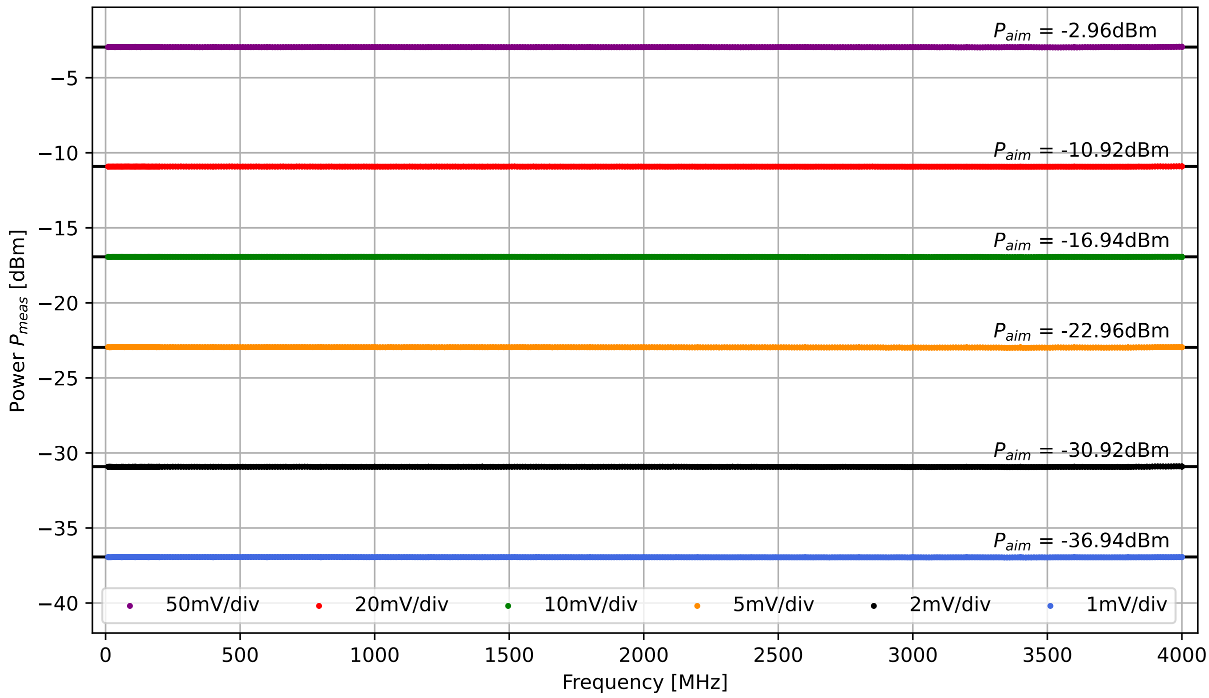


(a) Ratio of measured power to power that is set minus 8 dB attenuation

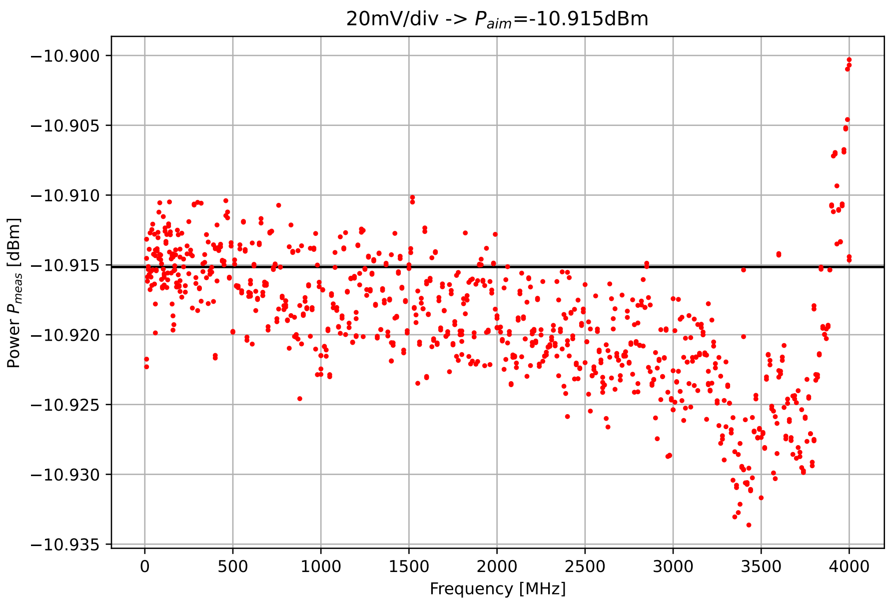


(b) Measured power in three measurements of the power setting for a voltage scale of 20 mV/div

Figure 5: Power measurements before correction



(a) Measured power after correction for the different voltage scales plotted together with the calculated power P_{aim} for the specific voltage scale setting.



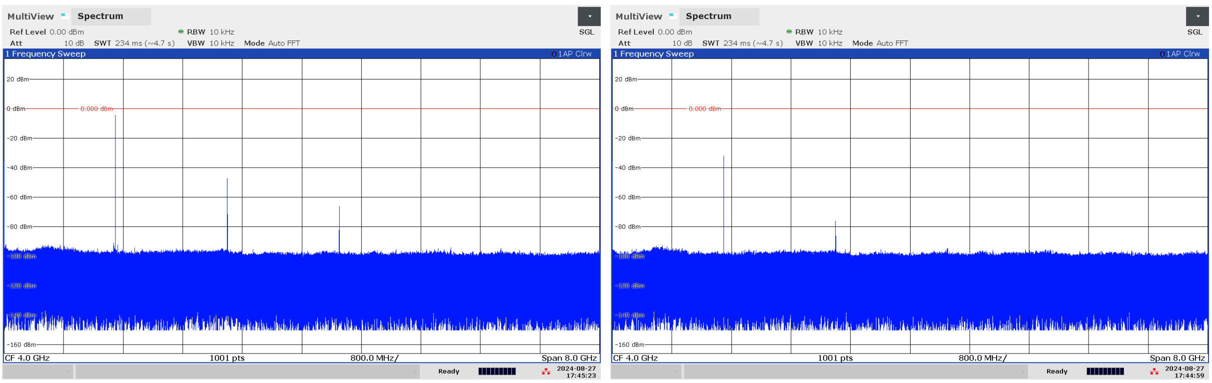
(b) Measured power for the 20 mV/div voltage setting as an example to see the systematic deviations from P_{aim}

Figure 6: Power measurements after correction

power level is much closer at the calculated power. This is shown in fig. 6(a), where the measured powers for the different voltage scales is plotted against the frequencies. Here the measurements align well with the calculated powers marked in the plot with horizontal lines as P_{aim}. Fig. 6(b) shows in one example that the measured power still has some systematic deviations towards higher frequencies, but these deviations are small. With the power setting corrected like this the transfer function of the oscilloscope can be measured.

2.2 Spectrum Measurement of the Signal Generator

Additionally to the measurement of the generator power also the spectrum is measured with a spectrum analyzer (R&S FSW). This result is shown in fig. 7 for two exemplary power settings. For the higher power setting (fig. 7(a)) additionally to the signal frequency of 1.5 GHz two harmonics are visible of which the first one is approximatly 40 dB lower than the signal. The measurement with the lower power setting shows only one significant harmonic beside the signal at 1.5 GHz. This means that measurements with lower power will be less affected by the harmonics from the signal generator. Nevertheless, low-pass filters are needed for the measurement of the ENOB to suppress the harmonics.



(a) High power level: 5.05 dBm (- 8 dB external attenuation), two harmonics visible

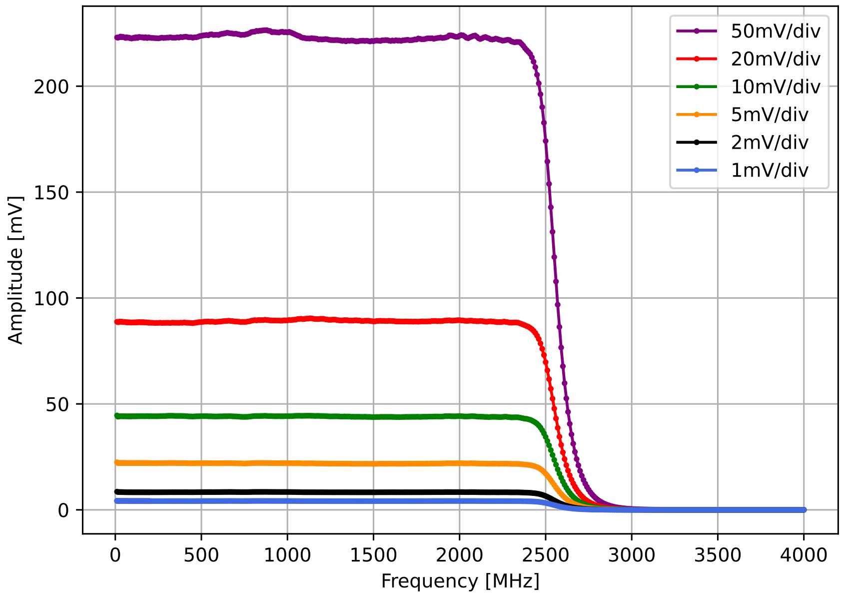
(b) Low power level: -22.92 dBm (- 8 dB external attenuation), only one harmonic with very low power

Figure 7: Spectrum measurements with R&S FSW spectrum analyzer show the signal and harmonics in the frequeny spectrum of the signal generator. The set frequency is 1.5 GHz and two different power levels are measured

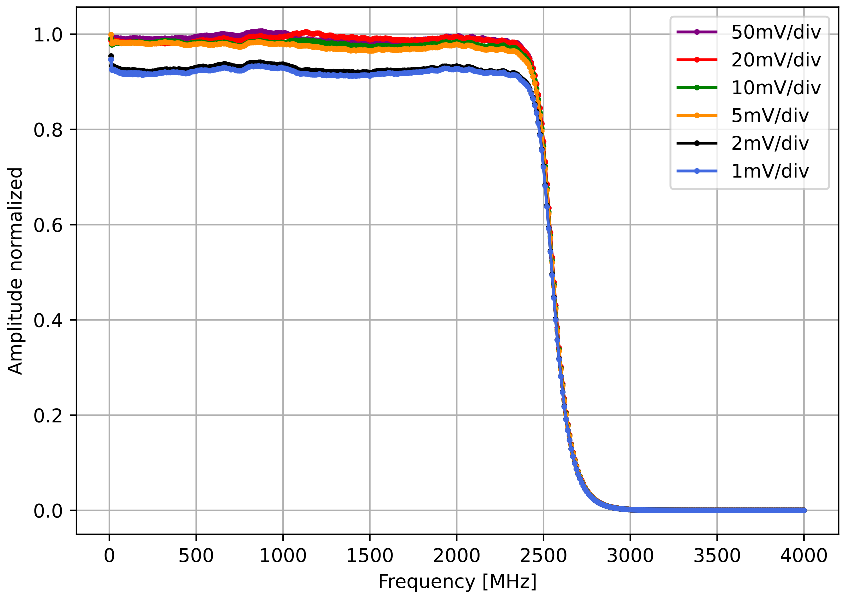
The fact that the power of the first harmonic is 40 dB lower than the signal power justifies also that the power measurements are done without a filter. The error the 40 dB lower harmonic causes in the total power is 0.01% or 1% error in the amplitude which is not enough to be seen in the measurement of the transfer function as shown later.

3 Transfer Function

The transfer function is measured in sample mode with 50 GS/s and for the two different settings of the internal filter that are called *flatness* (a Brick-wall filter with sharp cut-off) and *step response* (Bessel-Thomson filter with gradual roll-off). The results are shown in fig. 8 and 9. As expected the bandwidth at 2.5 GHz is clearly visible as the point where the amplitude drops, while it stays roughly constant for lower frequencies. In the plots of the normalized amplitudes (fig. 8(b) and

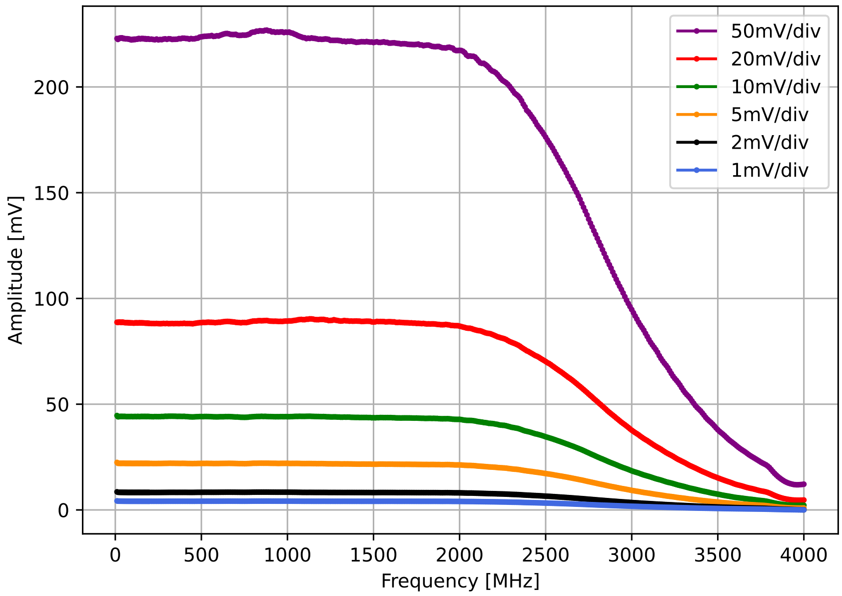


(a) Measured amplitude plotted against the frequency of the input signal for the different voltage scales

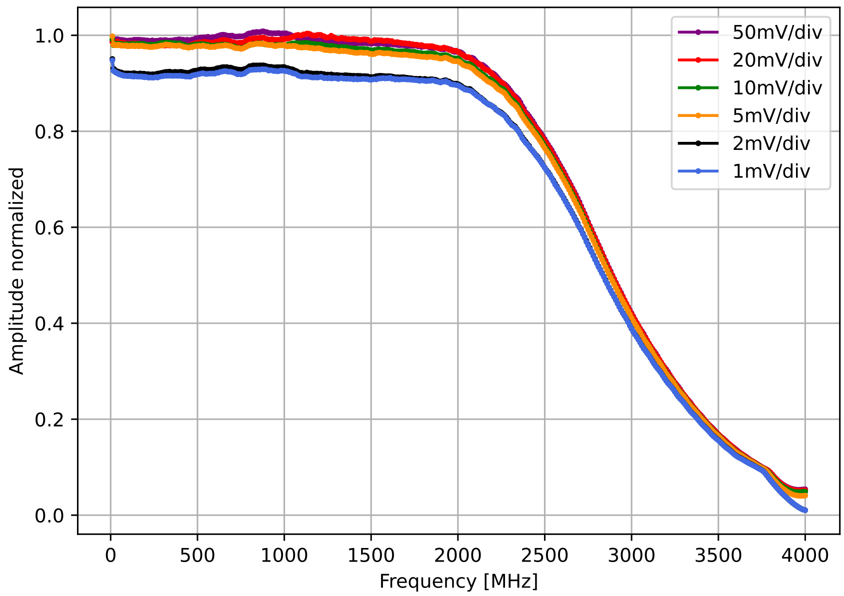


(b) Amplitude normalized to 90% full scale to get a better comparison between the voltage scales

Figure 8: Transfer function measured with internal filter option *flatness*



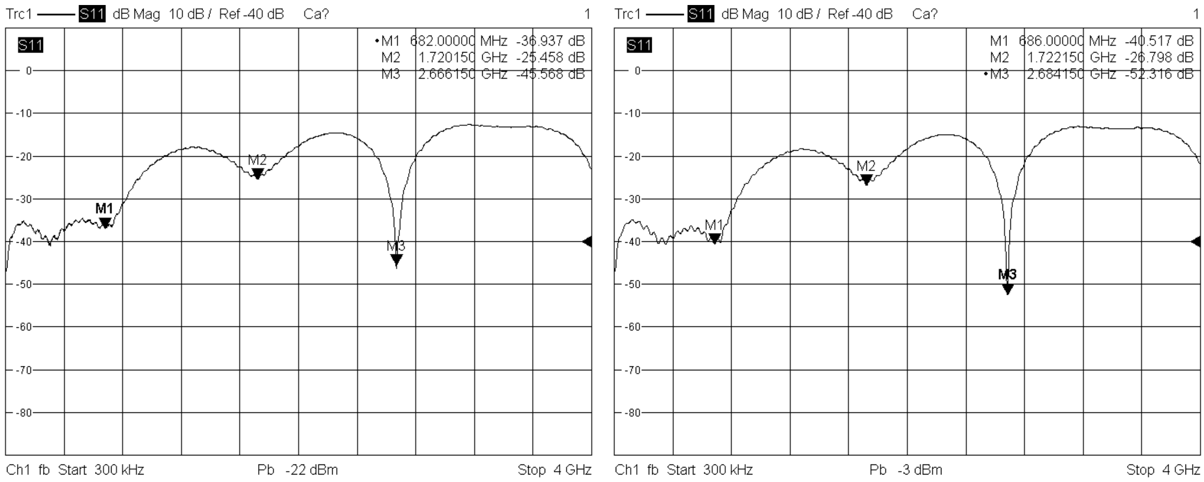
(a) Measured amplitude plotted against the frequency of the input signal for the different voltage scales



(b) Amplitude normalized to 90% full scale to get a better comparison between the voltage scales

Figure 9: Transfer function measured with internal filter option *step response*

9(b)) it can be seen that the deviations of a constant value before the bandwidth limit are different between the different voltage scales while they are similar between the two filter settings. Also they do not align with the structure in the S11-parameter measurements of the oscilloscope input, which is also very similar over the whole range of voltage scales measured (fig. 10). Only for higher voltage scales something switches in the interanl hardware and a change is visible between the 50 mV/div and 100 mV/div settings, but this is not relevant to the measurements done here. The S11-parameter is a measure of the quality of the 50 Ω-termination of the oscilloscope. All together it is probable that the deviations are within the error of the power calibration, but this assumption needs further invesigation. Anyways the deviations are higher than the 1% error coming from the fact that the measurements for the power calibrations were done without a filter.



(a) Measurement at vertical scale 5 mV/div (b) Measurement at vertical scale 50 mV/div

Figure 10: Measurement of the S11-parameter (S11) of the input channel of the oscilloscope using a N-to-BNC connector

In the plot of the normalized ampitude measured with the *step response* filter there is a bend visible at approximatly 3.8 GHz. This bend can be explained by the systematic deviations that are visible in the measurement of the corrected power (see fig. 6(b)) for high frequencies. The effect is not visible in the measurements with the *flatness* filter option because the signal is already highly suppressed by the bandwidth limit at this high frequencies.
The comparison between the measurements with the two filter options shows that the filters work as expected. For the filter *flatness* a sharp cut-off at the bandwidth limit is visible (see fig. 8) while the *step response* filter leads to a more gradual decrease of the amplitude (see fig. 9). For measurements of the longitudinal bunch profiles the latter setting is to be preferred because the actual shape that contains also frequencies over the bandwidth limit is displayed better than when higher frequencies are cut-off directly at the bandwidth limit.

4 Effective Number of Bits (ENOB)

The ENOB depends on the signal that is measured, the noise and distortion and on the explicit settings of the oscilloscope. It can be calculated with the following equation

$$\mathrm{ENOB} = 0.5 \cdot log_2(\mathrm{SINAD}) - 0.5 \cdot log_2(1.5) - log_2\left(\frac{A}{U}\right), \tag{1}$$

where SINAD is the signal to noise and distortion ratio. The last term is an amplitude correction with the peak-to-peak amplitude A of the sine wave that is measured and the full scale range U of the oscilloscope. The SINAD can be calculated according to

$$\mathrm{SINAD} = \frac{P_S}{P_{\mathrm{NAD}}}, \tag{2}$$

where P_S is the signal power and P_{NAD} is the noise and distortion power. They can be found evaluating the FFT of the measured wave form. P_S is the power of the FFT bin at the input frequency, P_{NAD} is the sum of all other bins up to and including the Nyquist frequency bin but excluding the DC bin. This includes bins with spurious signals. For this to work it is important that the input frequency is set such that it falls exactly into one frequency bin of the FFT which means that the measured wave form should contain only full periods of the signal. To achieve this the following formula is used to calculate suitable frequencies:

$$f = f_{SR} \cdot \frac{J}{M}. \tag{3}$$

There f_{SR} is the sampling rate of the oscilloscope, M is the number of data points and J is the number of full periods in the measured data set. To get a higher precision of the measurement of the wave form and sample the wave form at a different set of phases, M and J should have no common factors. Otherwise every measured point is always exactly at the same position within a period. [2][6]

To have enough points for an acurate FFT here $M = 1000000$ is used and the values for J are chosen such that frequencies in the range 10 MHz to 4 GHz are the result. The amplitude of the signal is set to 90% full scale of the oscilloscope, but because of the correction term in eq. 1 the calculated value of the ENOB should not be sensitive to the exact amplitude.

If not statet otherwise the measurements of the ENOB are performed in high resolution mode with a max. sampling rate of 25 GS/s, a bandwidth of 2.5 GHz and the filter setting *flatness*.

4.1 Measurement without a Filter

To show the effect of the harmonics of the generator on the ENOB a first measurement of the ENOB without a filter is made. The result is shown in fig. 11. For the higher voltage scales a sudden increase is visible at half of the maximum bandwidth. This is exactly the point from where on harmonics of the signal are suppressed by the bandwidth limitation. It shows that the measurement is heavily affected by the harmonics from the signal generator and low-pass filters are definitly needed. The reason why the increase at half of the bandwidth limit is not clearly visible for the lower scales is that the power is low enough that the harmonics of the signal are very low and therefore do not spoil the measurement as much as for higher power settings (see also section 2.2).

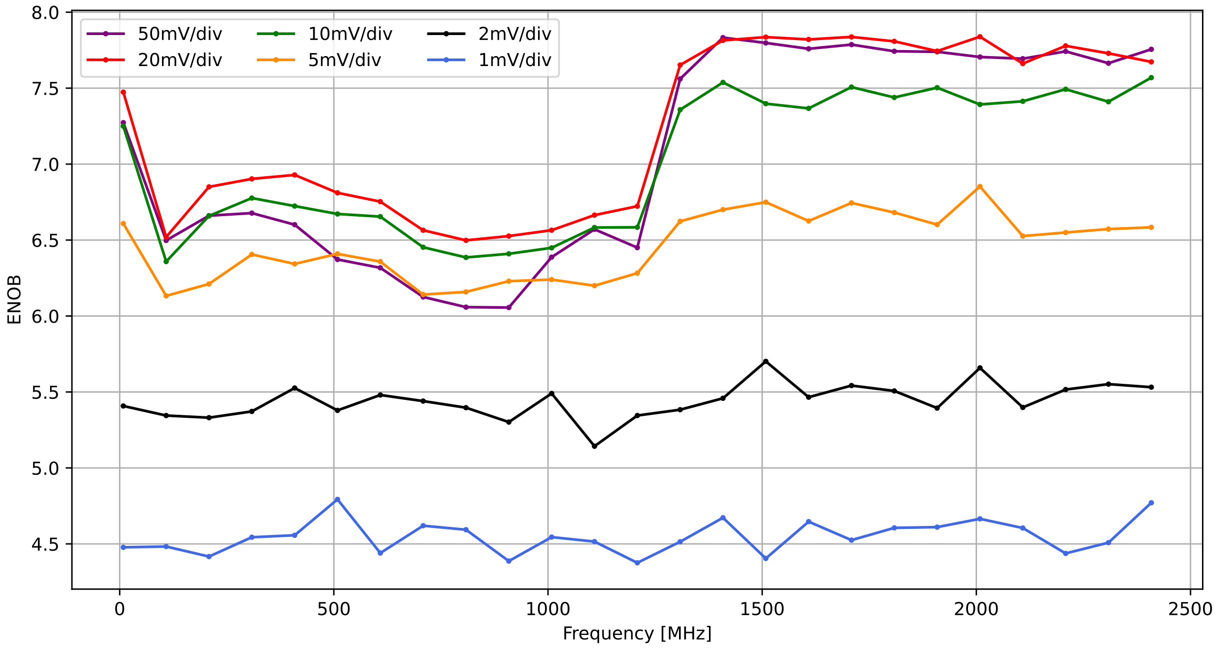


Figure 11: ENOB measurement without a filter

4.2 Measurements with Filters

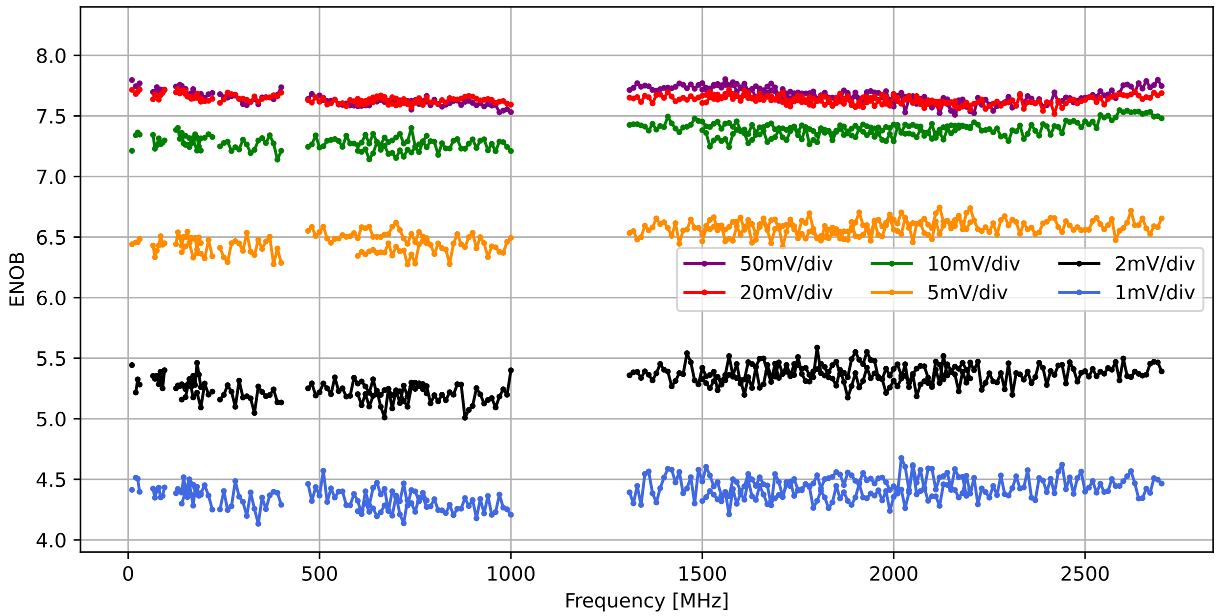


Figure 12: ENOB measurement using different low-pass filters

The measurement of the ENOB is repeated using the set of low-pass filters for the different frequency ranges as stated in table 2. The results are shown in fig. 12. As expected the jump at half of the bandwidth disappeared, but two things stand out. The data fluctuates a lot, this is especially visible at the parts where the frequency ranges of two filters overlap. Furthermore, the difference between the ENOB of the 1 mV/div and 2 mV/div scale setting is approximatly 1 bit. Why this is interesting can be understood with a quick calculation:
Going from 1 mV/div to 2 mV/div the amplitude is doubled, which means a factor 4 in powers $P_S \rightarrow 4 \cdot P_S$. Assuming that the noise and distortion stays constant $P_{\text{NAD}} = constant$ leads to $\text{ENOB} \rightarrow \text{ENOB} + 0.5 \cdot log_2(4) = \text{ENOB} + 1$. This is exactly the 1 bit difference that occures in the data.
For 1 mV/div to 5 mV/div the same calculation leads to a value of 2.32 difference between the scales which is close to the observed value of a little more than 2 bits. This means that from the perspective of ENOB there is no gain in using the very small scales because going from 2 mV/div to 1mV/div the noise does not decrease, only the amplitude. To verify the assumption of constant noise a measurement of the noise floor is made in the following section.

4.3 Noise Floor Measurements

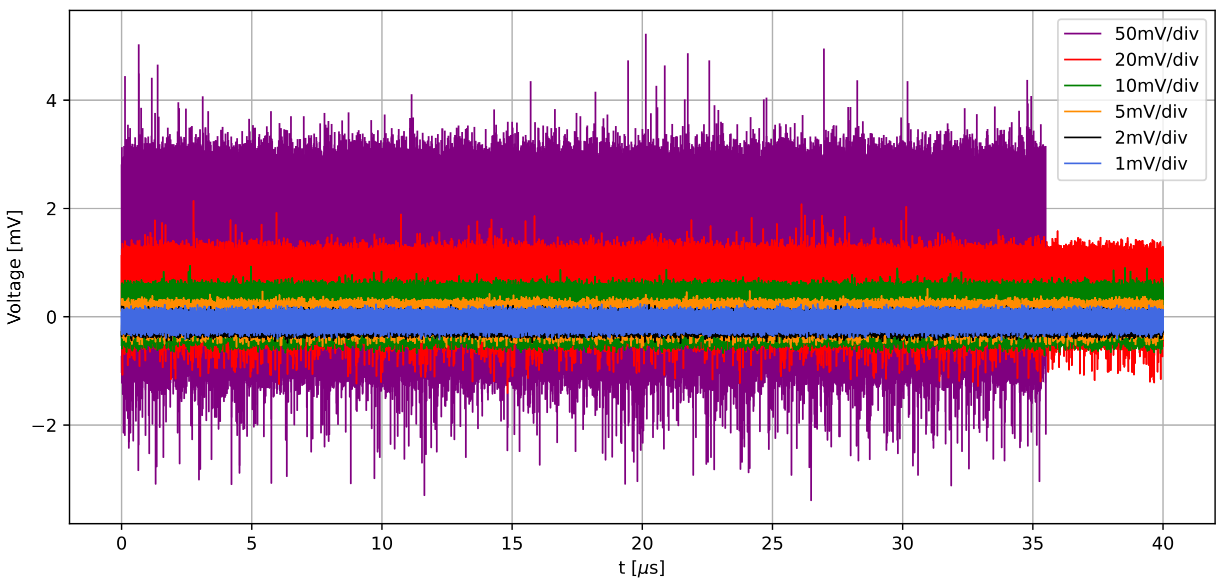
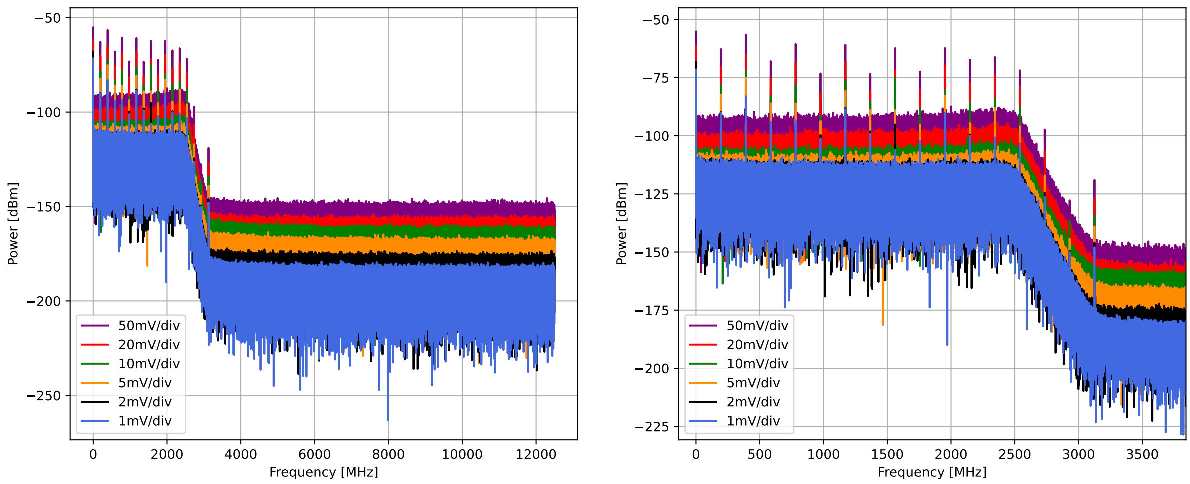


Figure 13: Noise measurement (amplitude measured over time) for the different voltage scales

To measure the noise floor of the oscilloscope instead of a signal a 50 Ω-termination is connected to the measurement channel. The measurement is done with the same settings as the ENOB measurements before (high resolution mode, 25 GS/s, *flatness*). In fig. 13 the result is shown. As expected from the short calculation before, the noise does not increase between 1 mV/div and 2 mV/div and only very little to 5 mV/div, while it increases a lot between the higher scales. The small vertical scales are dominated by a constant baseline noise in contrast to the high scales where a scale depended noise leads to an increase of the noise with the scale setting.
A FFT of the noise measurement leads to the plots in fig. 14. At multiples of approximatly 195 MHz spurious signals occure up to over 3 GHz for all vertical scales tested. Where those come



(a) Full range of FFT spectrum from DC to Nyquist frequency

(b) Spectrum zoomed in to the spurious signals

Figure 14: FFT spectrum of the measurement of the noise floor for different vertical scales

from is not clear but it is worth trying what are the resulting ENOB if those signals are taken out of the calculation.

4.4 ENOB without Spuries Signals

The ENOB are measured again, this time taking the spurious signals out of the calculation. The result for the six different scales as before is shown in fig. 15. In this data the high fluctuations are gone and the ENOB are in general higher. Fig. 16 shows a comparison for two voltage scales of the data with and without spurs. Additionally the reference values from Tektronix [3] are plotted. Those fit for 2 mV/div much better with the data without spurs, while for the high scale (50 mV/div) the data points with spurs fit better.

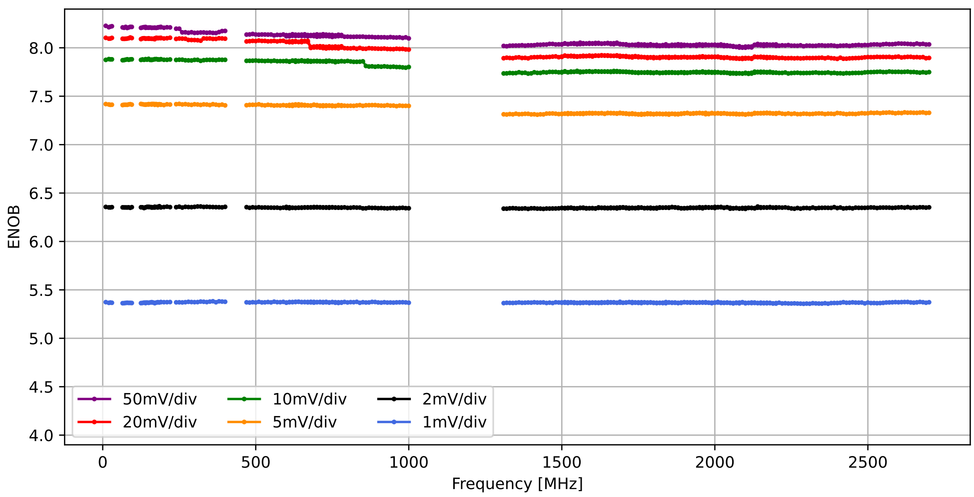


Figure 15: ENOB measurement without the spurious signals

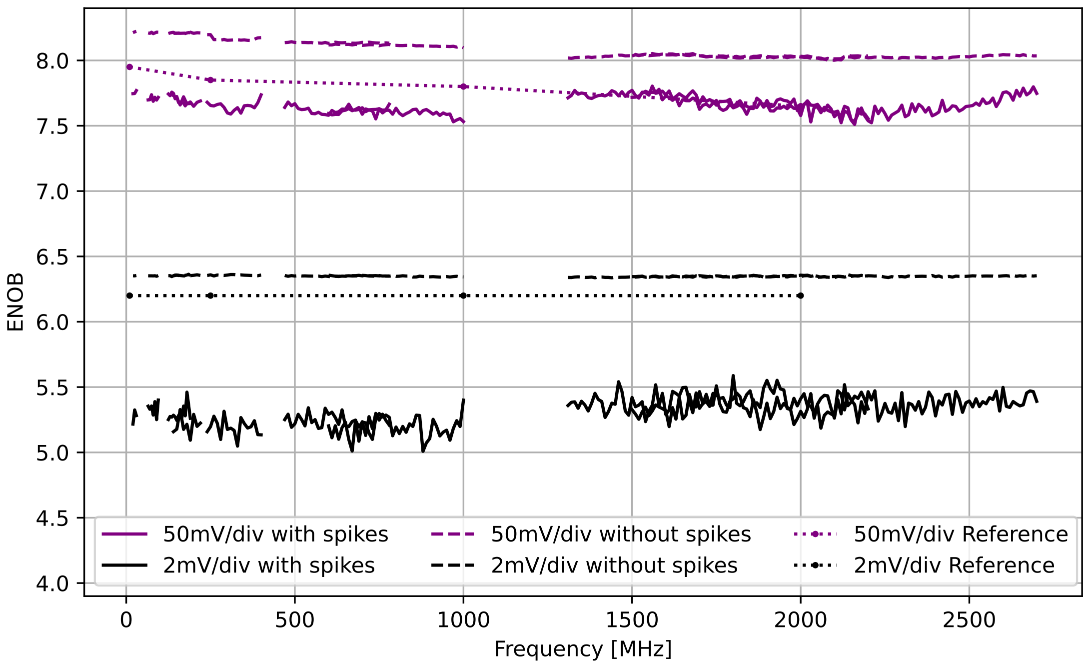
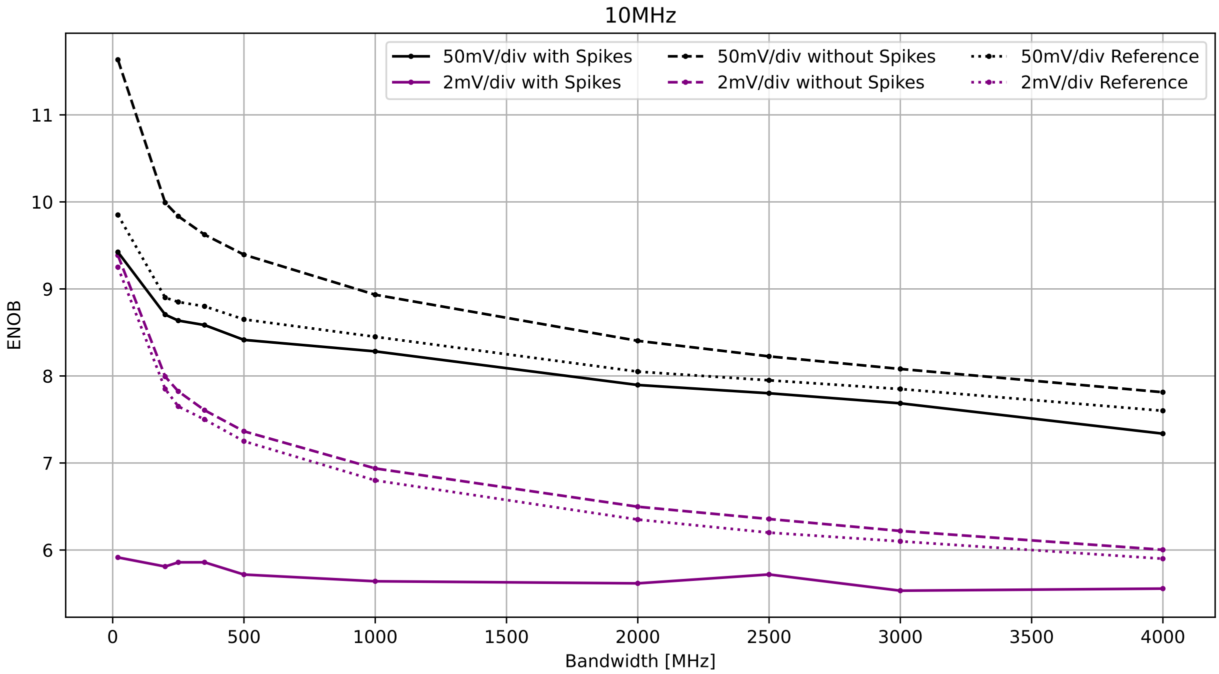
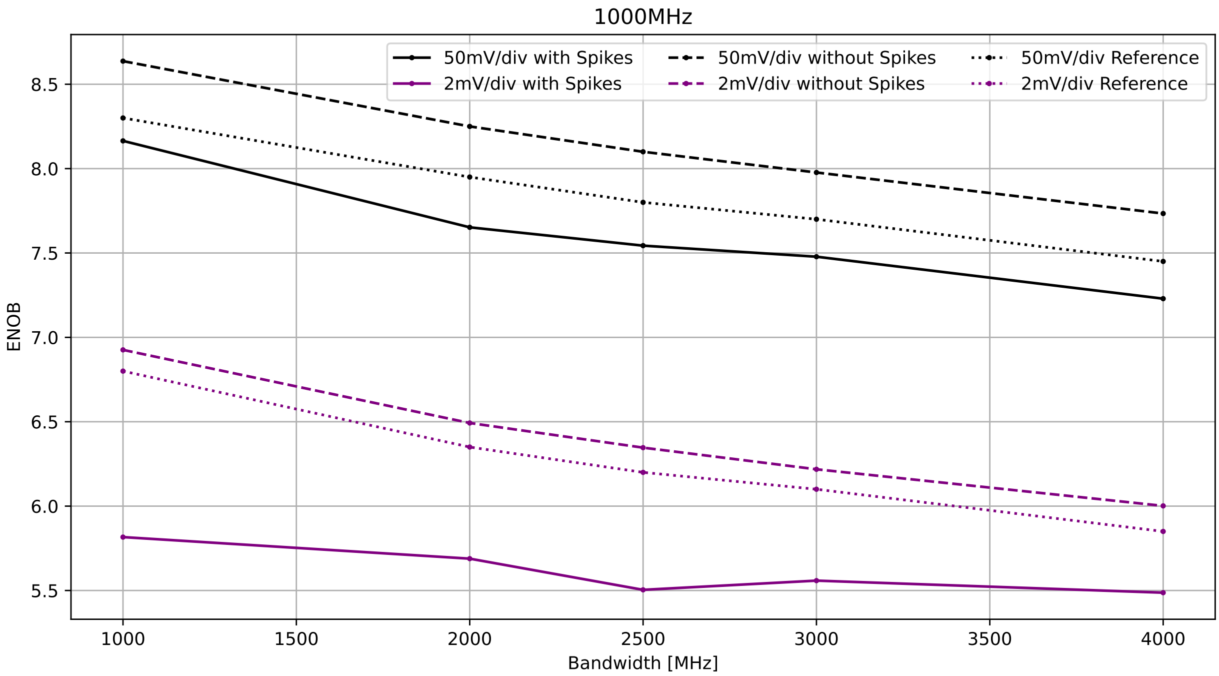


Figure 16: Comparison between ENOB with and without spurious signals (spikes) and the reference values from Tektronix [3]

Another measurement is done where instead of sweeping over input signal frequencies the bandwidth of the oscilloscope is changed and the input signal stays the same. This is measured for two frequency settings (10 MHz and 1 GHz) and the result is shown together with the reference values in fig. 17. As before, for the higher scales the signal without spurs is comparable with the reference value while the data for 2 mV/div is a lot lower than the reference value if the spurs are kept in the calculation and does not even follow the same slope.



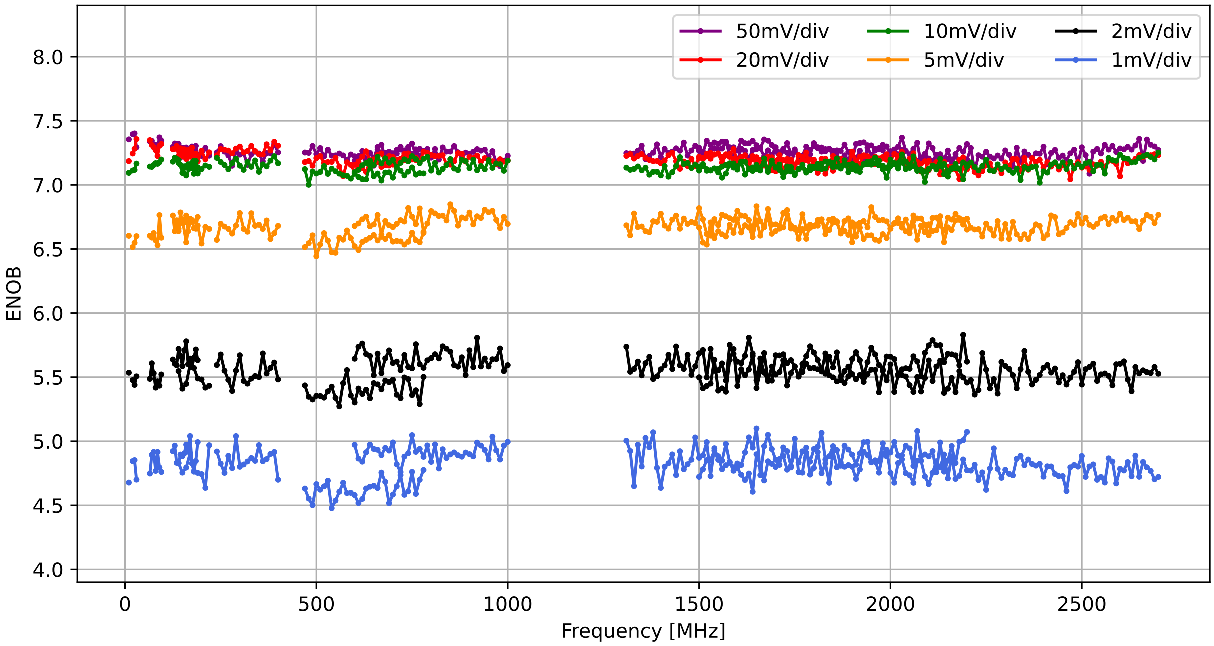
(a) Measurement for 10 MHz input frequency



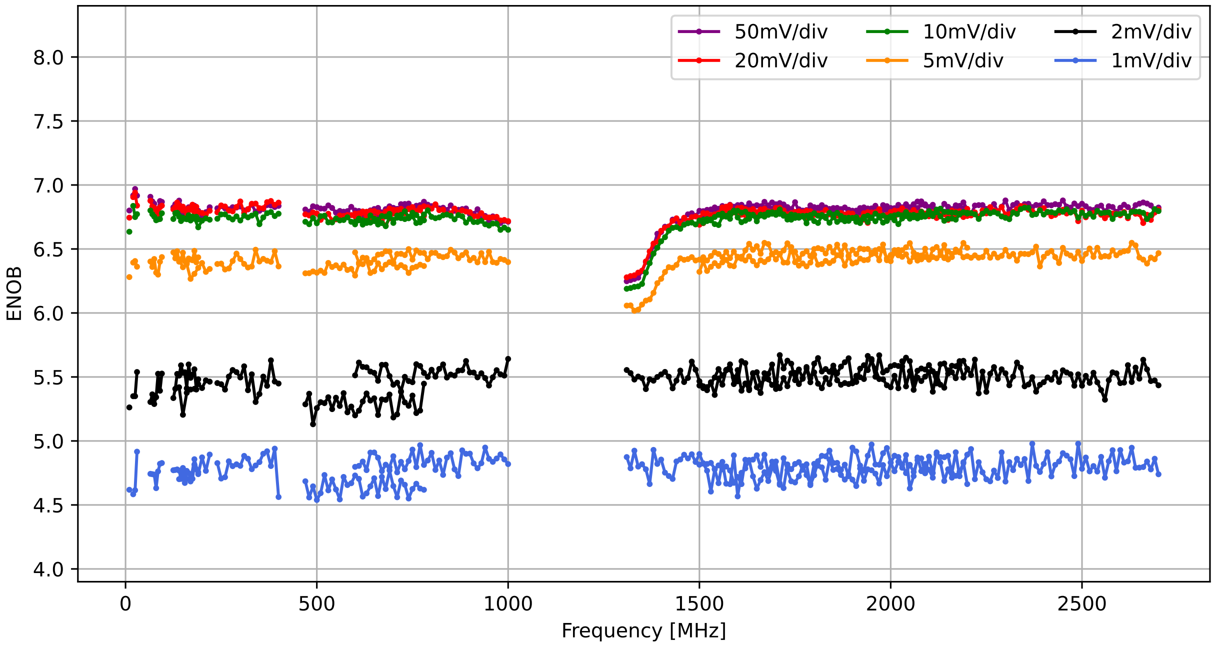
(b) Measurement for 1 GHz input frequency

Figure 17: ENOB measured for the different bandwidth limits of the oscilloscope, data with and without spurious signals (spikes) is compared with the reference values from Tektronix [3]

4.5 Comparison Sample Mode vs High Resolution Mode



(a) Internal filter *flatness*



(b) Internal filter *step response*

Figure 18: Measurement of the ENOB in sample mode, results with spurious signals

The sample mode of the oscilloscope has 8 bit instead of 12 bit, which means a lower ENOB is expected than in the high resolution mode. This is visible for the high voltage scales in the comparison between the measurement in sample mode in fig. 18(a) and in high resolution mode in fig. 12 for the same filter setting. But for the lower voltage scales the ENOB of the sample mode are even higher than in the high resolution mode. Also in sample mode it is possible to use the internal filter setting *step response*. The result of this is shown in fig. 18(b). Compared to the *flatness* filter setting the ENOB of the higher voltage scales are even lower and a jump to lower values followed by an increase is visible between the ranges of the filters for up to 1 GHz and from 1.3 GHz. This means that for the range of the increase, not the low-pass filter filtered out the harmonics in the measurements but the bandwidth limit. For the *step response* setting where the bandwidth limit is not a sharp cut-off (see sec. 3) this filtering is not as efficient. So to measure the ENOB in the range of the increase correctly a different external low-pass filter would be needed to suppress the harmonics in this range.

5 Results of the second Oscilloscope

The second oscilloscope is of the exact same type with the same specifications. The only difference is that the oscilloscope used so far got a firmware update (to version 2.8.1.1496) at the start of this work, while the one with that the following measurements were made did not get this update (still version 2.6.38.1348).

5.1 Noise Floor

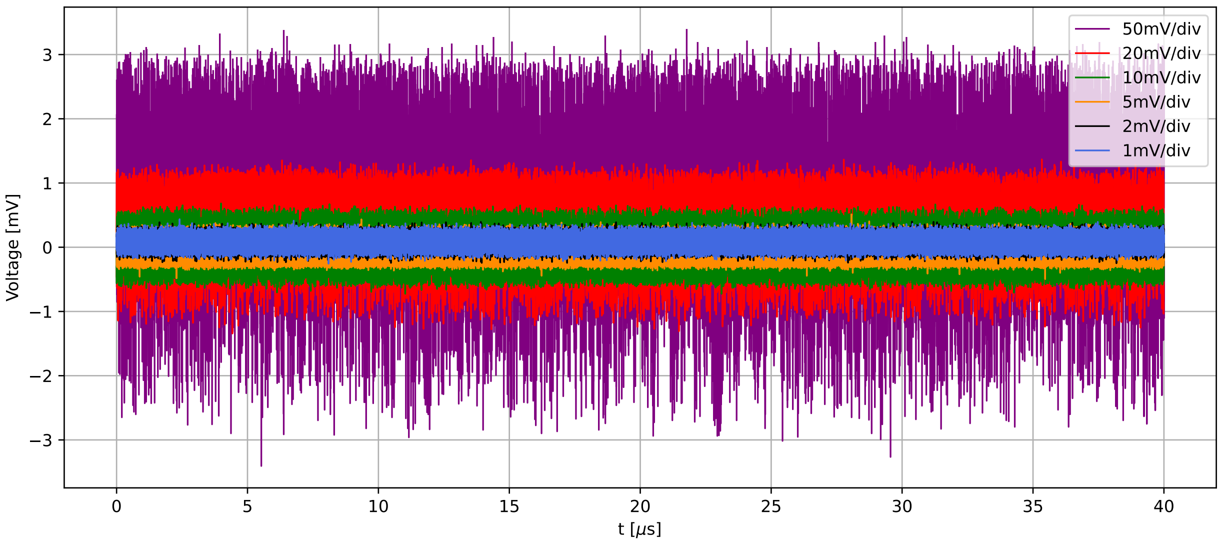


Figure 19: Noise measurement (amplitude measured over time) for the different voltage scales of the second oscilloscope

The noise measurement of the second oscilloscope (fig. 19) shows a similar result than the measurements before: constant baseline noise dominates at low voltage scales, for higher scales the noise scaling with the voltage range dominates. Also spurious signals occure in the FFT (fig. 20) at the same values, but with a bit lower amplitude and less regular height. A quick check with the

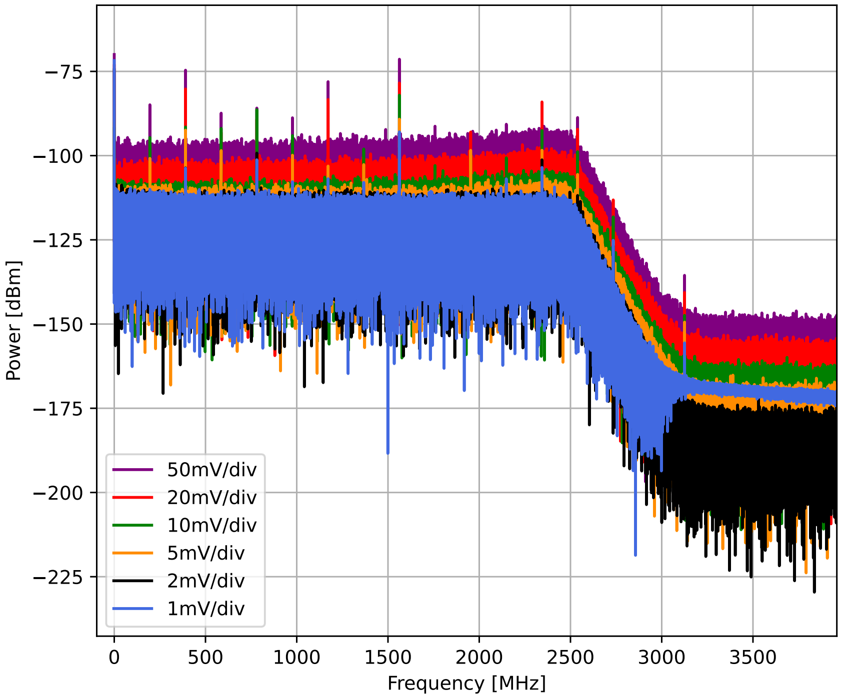


Figure 20: FFT spectrum of the measurement of the noise floor for different vertical scales of the second oscilloscope

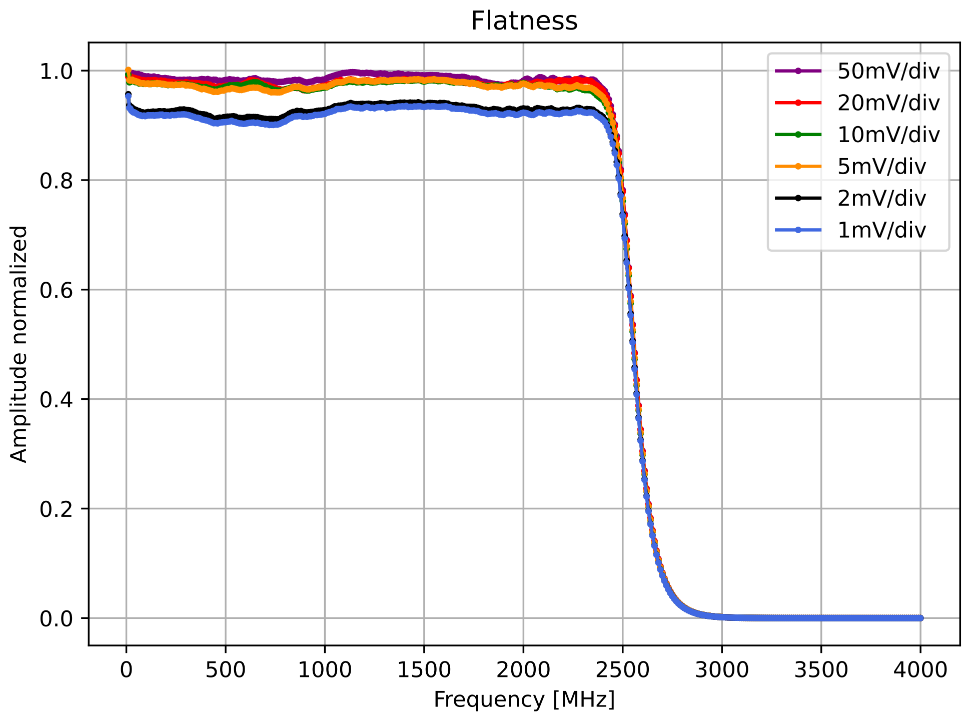
previous generation oscilloscope that does not show the spurs verifies that those are not coming from an external source.
Due to the similar noise behaviour the expectation for the ENOB is that those are also very similar between the two oscilloscopes, but possibly a bit higher for the second oscilloscope because of the lower spurs.

5.2 Transfer Function

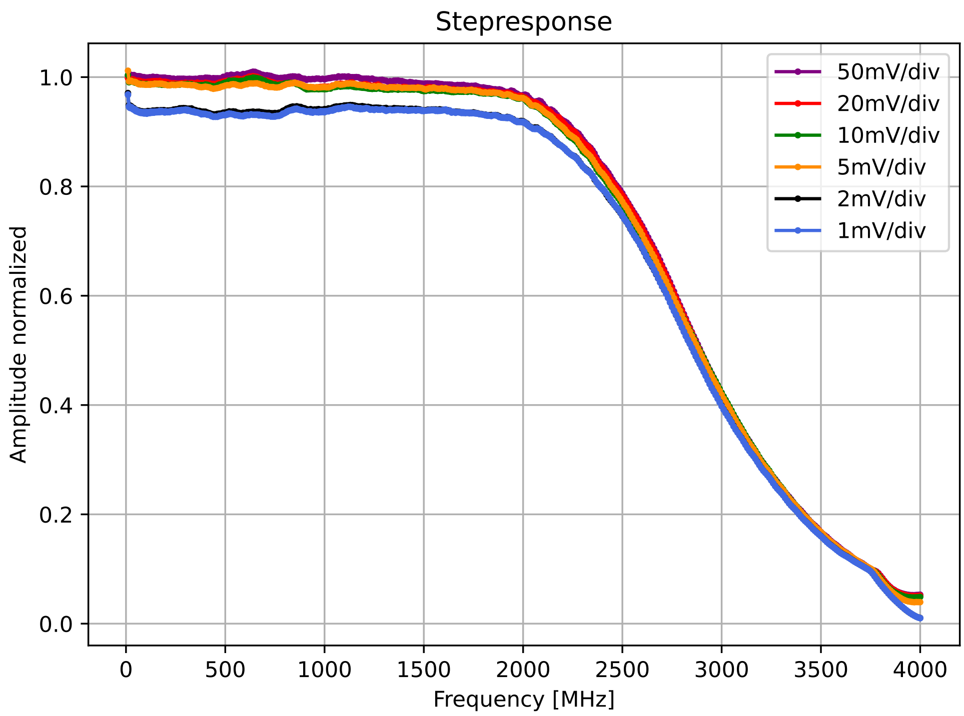
The transfer function of the second oscilloscope is measured under the same conditions as for the first oscilloscope (sample mode, 50 GS/s, 2.5 GHz bandwidth) and shows the same effects as seen before (fig. 21 compared with sec. 3). The drop at the bandwidth limit of 2.5 GHz is visible according to the different filer settings and also the slight deviations from the constant value at frequencies lower than the bandwidth limit. The bend at high frequencies in the measurement with the *step response* setting is at the same postion, which again is a hint to it results from the error of the generator power calibration. The same is the case for the fact that the voltage for 1 mV/div and 2 mV/div does not reach the 90% full scale value.

5.3 ENOB

The ENOB measurement (fig. 22) with the spurs shows the same fluctuations as the measurement with the first scope, but a little higher values in total. This can be explained by the smaller spurs, which also fits together with the fact that the results without the spurious signals are pretty much the same between the two oscilloscopes.

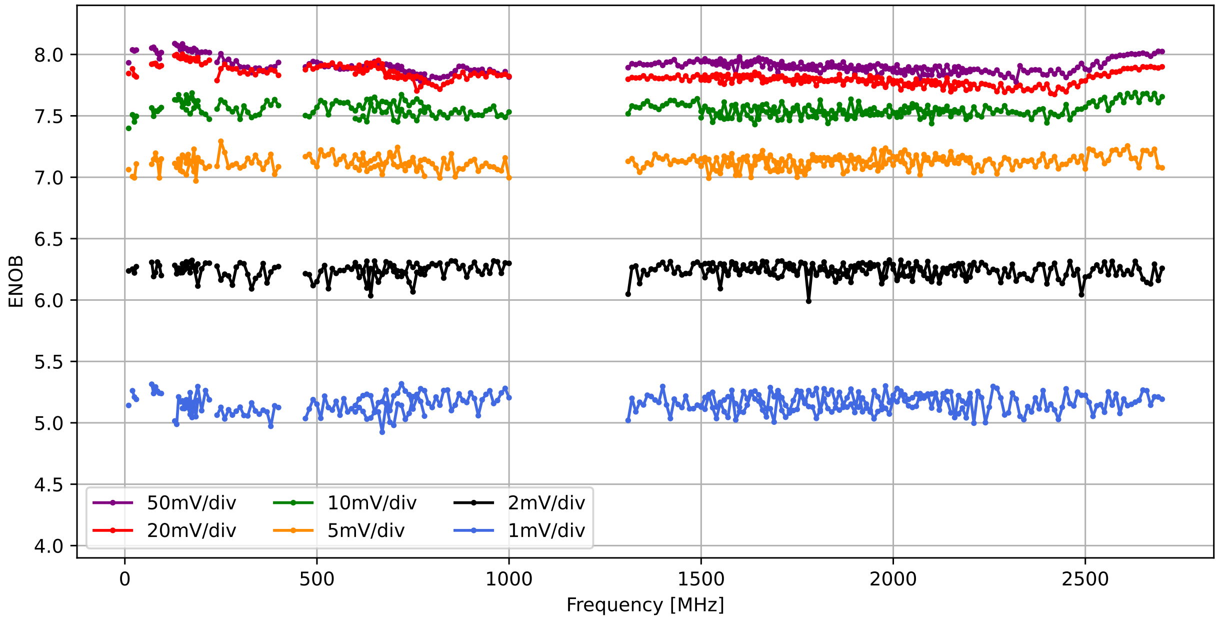


(a) Internal filter setting *flatness*

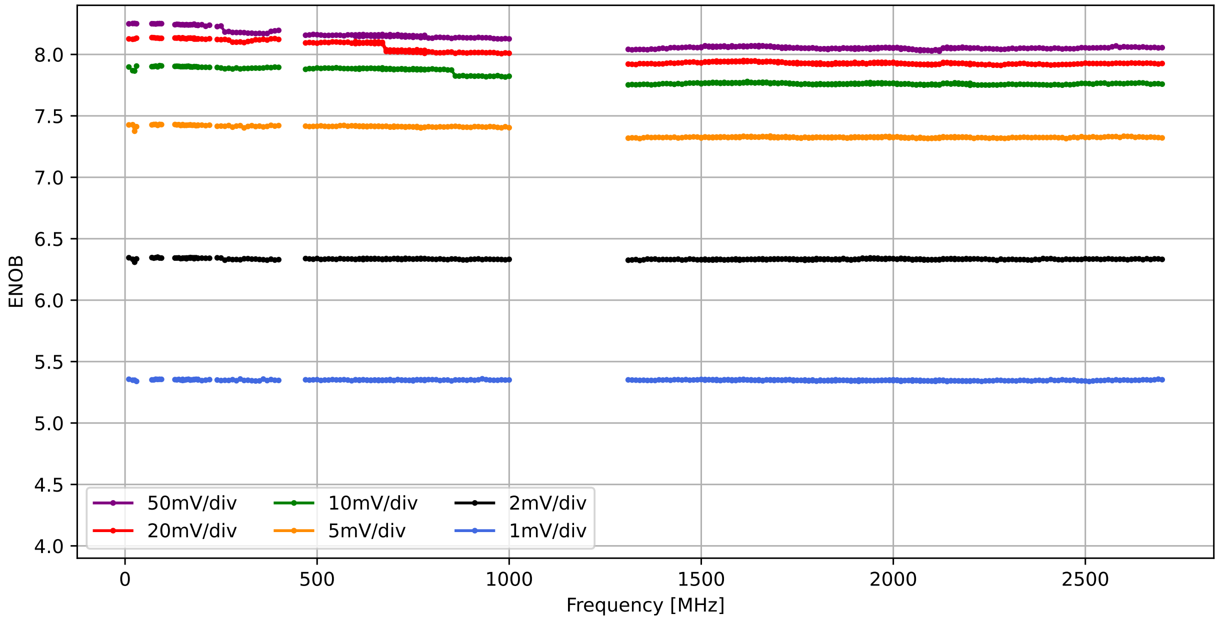


(b) Internal filter setting *step response*

Figure 21: Transfer functions of the second oscilloscope, normalized to 90% full scale values, for the different voltage scale and internal filter settings



(a) ENOB with spurious signals



(b) ENOB without spurious signals

Figure 22: ENOB measurements with the second oscilloscope show a similar result as the first oscilloscope before

6 Conclusion

The measurements of the transfer function showed the expected results. But on the other hand the ENOB of the low voltage scales do not fit the reference values given from Tektronix because the noise is high and the spurious signals appear that are not fully understood. This leads to the conclusion that using the smallest voltage scales does not bring an advantage. Also for beam measurements the *step response* setting of the internal filter is favourable because like this higher frequency parts of the signal are not as much suppressed as with the *flatness* setting. But using the *step response* option requires also the use of the sample mode instead of the high resolution mode.

As expected the second oscilloscope used for testing shows a very similar behaviour to the initial one, the biggest difference is that the spurious signals are a bit lower and therefore, the ENOB are a bit higher. In comparison with the previous generation oscilloscopes that are used so far the ENOB increased, the specification given for those is 5.6 bits at 50 mV/div voltage scaling and 2.5 GHz bandwidth limit [5].

Nevertheless, a lot of other interesting measurements could be done. First of all a measurement of the frequency dependent phase shift would be usefull, which turned out to be a very difficult task. One approach could be to use a limiter and look at the phase between the signal peaks in the FFT. Also a more detailed error analysis, especially of the power calibration, is needed to better understand the measurements that were done. Additionally it would be good to measure even higher voltage scales to see if the ENOB stay approximatly constant after a certain scale. The reason this has not been measured yet is the power limit of the generator which in combination with the attenuators that are needed for input matching does not allow higher powers that would be needed to reach 90% full scale for higher scales.

Acknowledgements

First of all, I would like to thank my supervisors Wolfgang Höfle and Heiko Damerau that I got the great opportunity to work with them at CERN. Also Daniel Sittard, Stephane Rey and Thomas Bohl were a great help to me. All the time everybody took to explain things was very valuable for my work. Thanks to the whole SY-RF-BR section for the great time I had with you, I really appreciated everything that I learned from you and enjoyed also the social activities.

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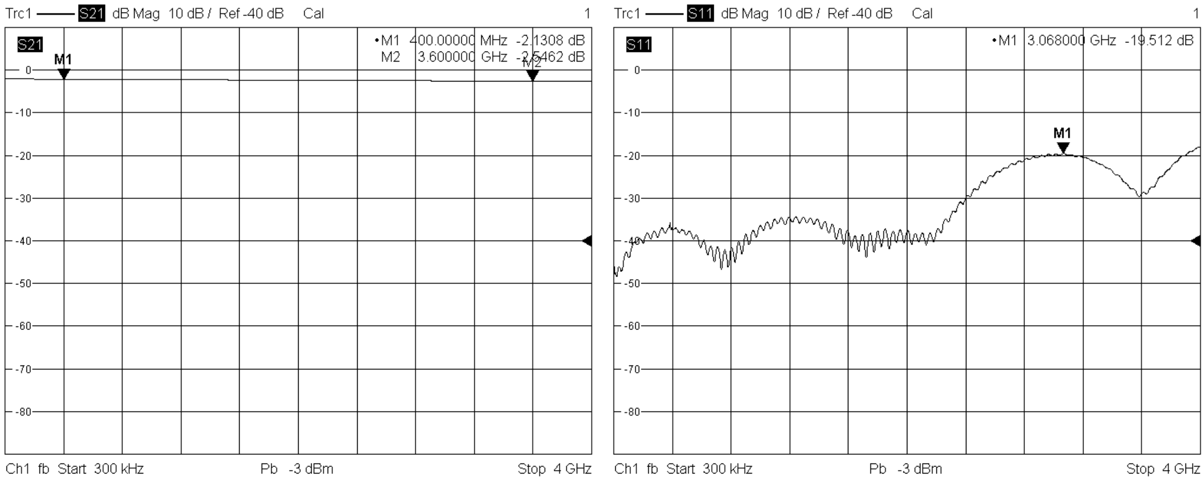
A Appendix

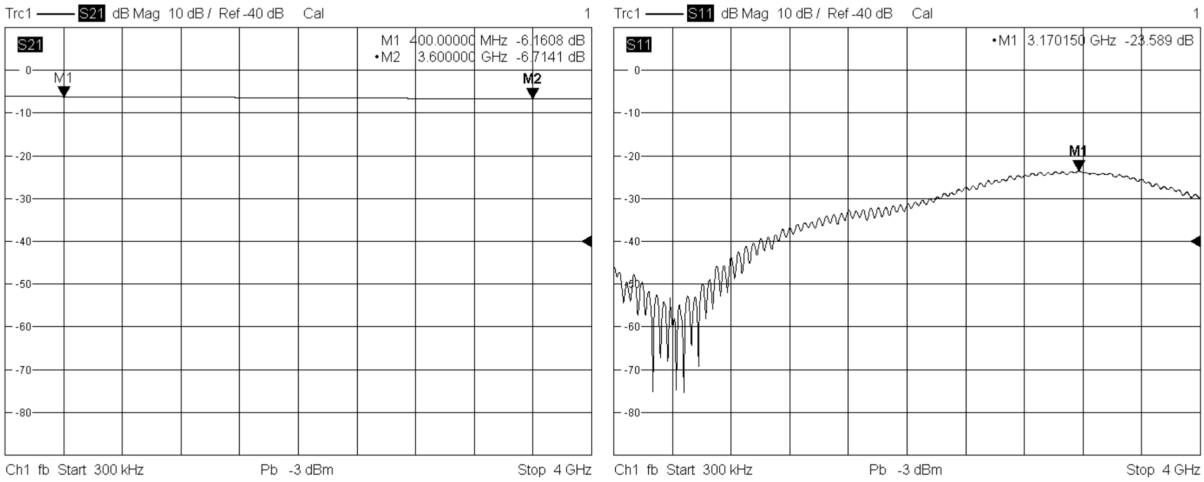
A.1 Measurement of S-Parameters with Network Analyzer

To ensure that the filters and attenuators work as expected a measurement of the S-parameters S11 (reflection) and S21 (transmission) is performed with a Network Analyzer ZVB4 from Rhode & Schwarz. Fig. 23 till 34 show screenshots of the results.



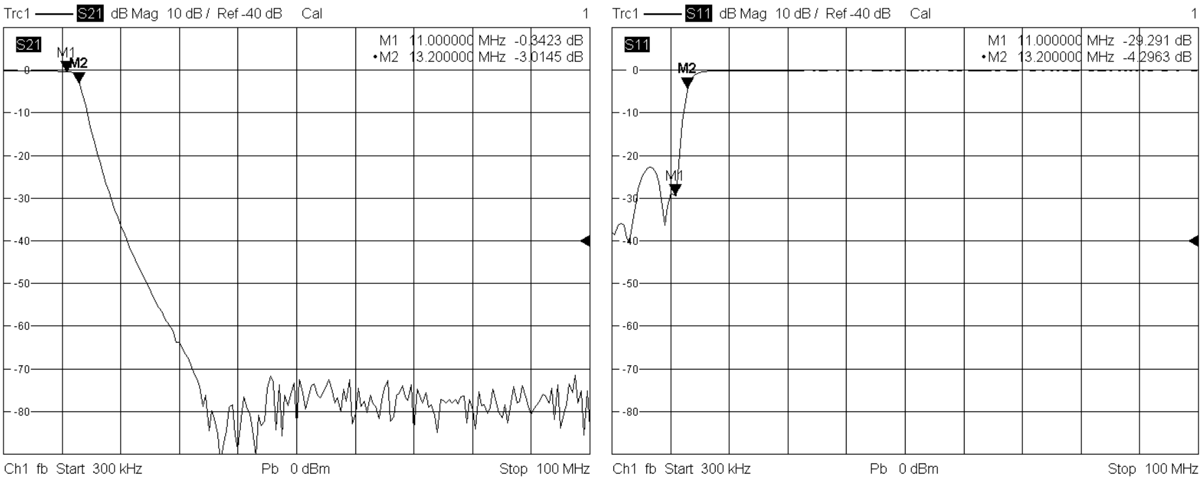
(a) S21 (b) S11

Figure 23: 2 dB attenuator (SMA connections)



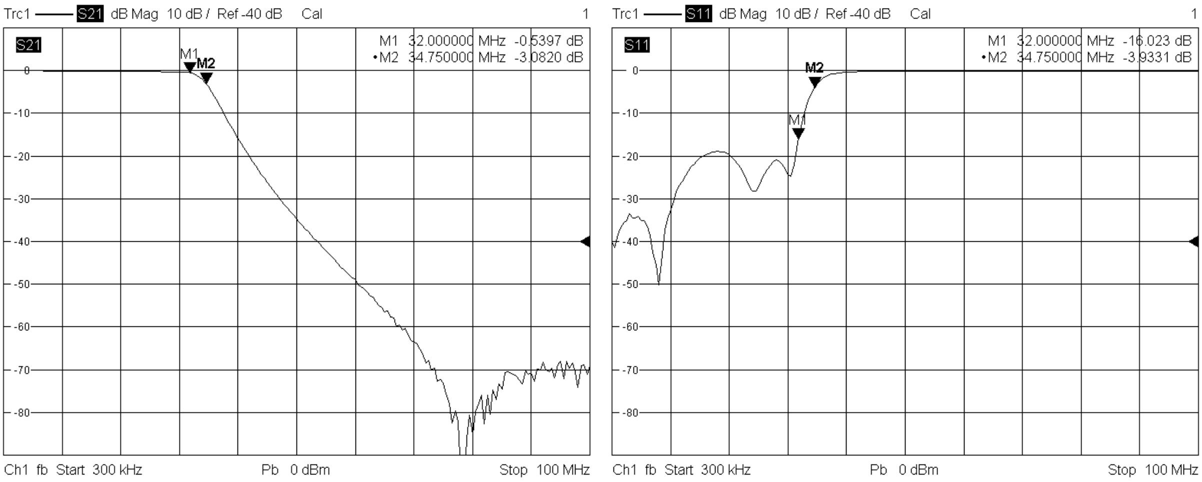
(a) S21 (b) S11

Figure 24: 6 dB attenuator (N connections)



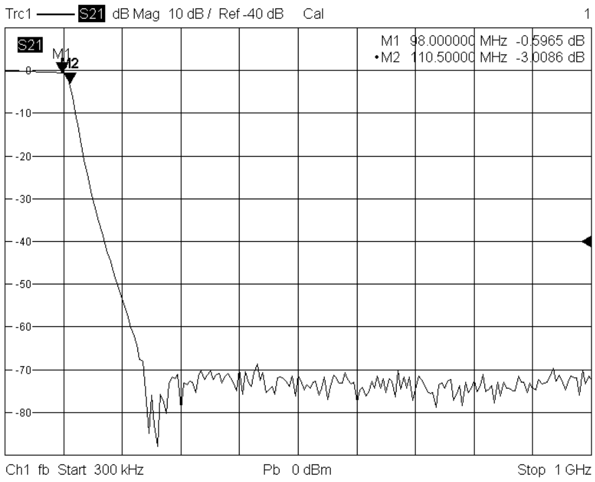
(a) S21 (b) S11

Figure 25: 11 MHz filter

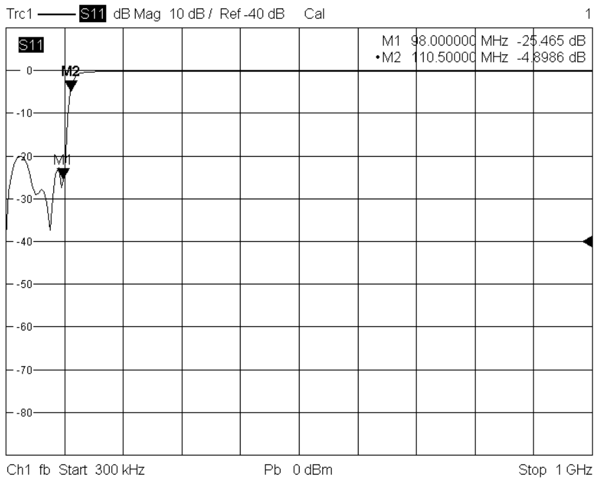


(a) S21 (b) S11

Figure 26: 32 MHz filter

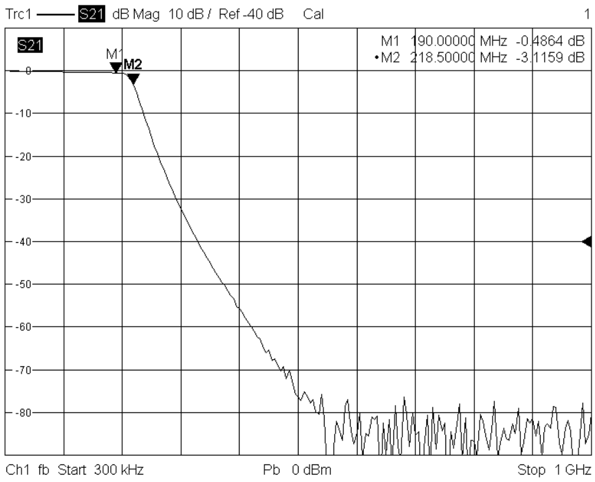


(a) S21

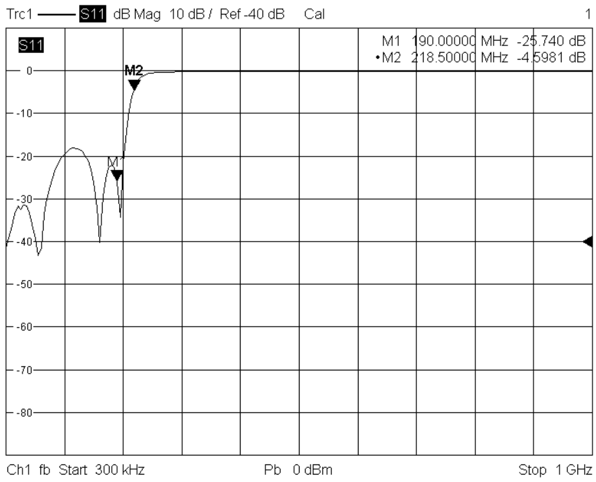


(b) S11

Figure 27: 98 MHz filter

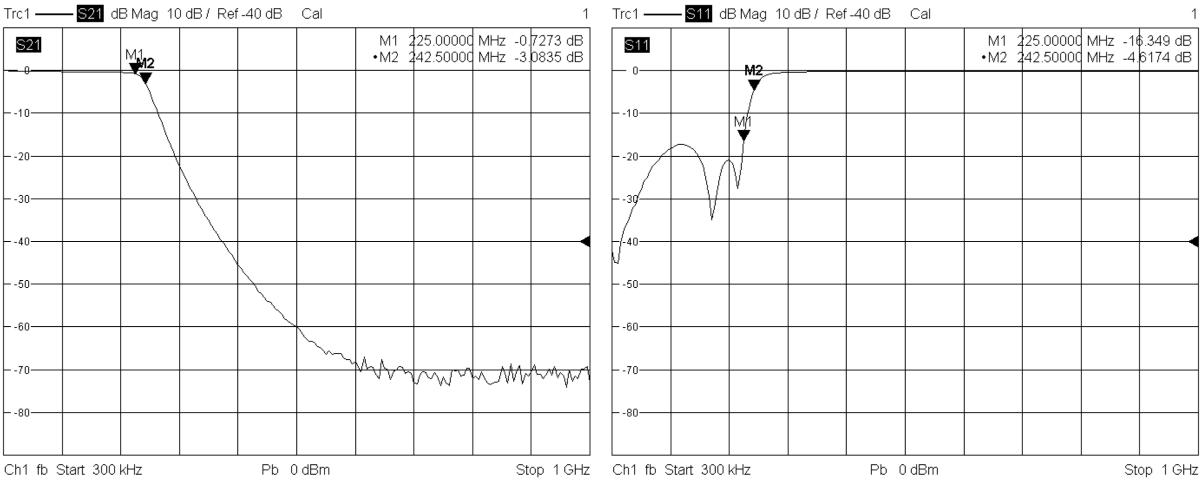


(a) S21



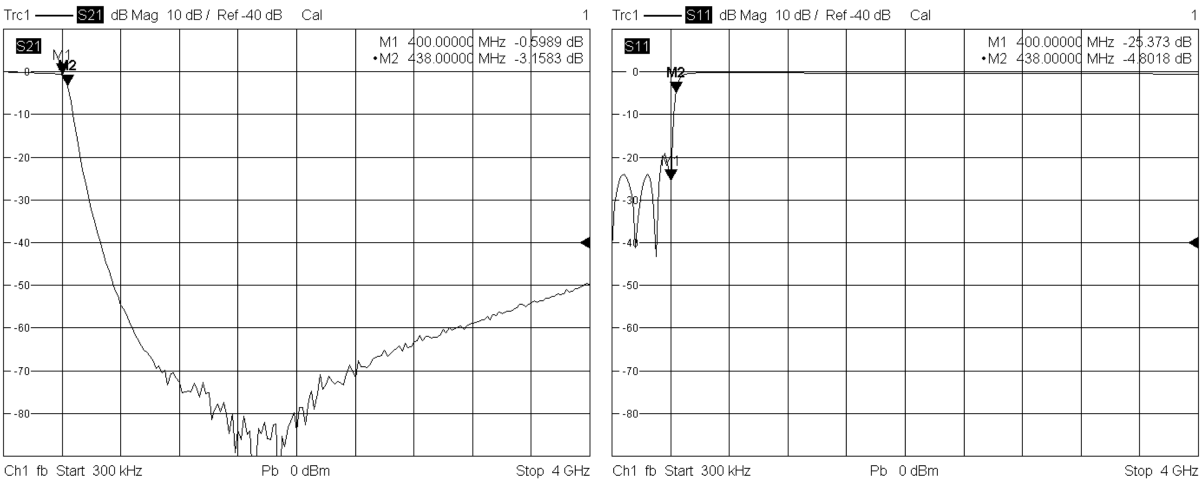
(b) S11

Figure 28: 190 MHz filter



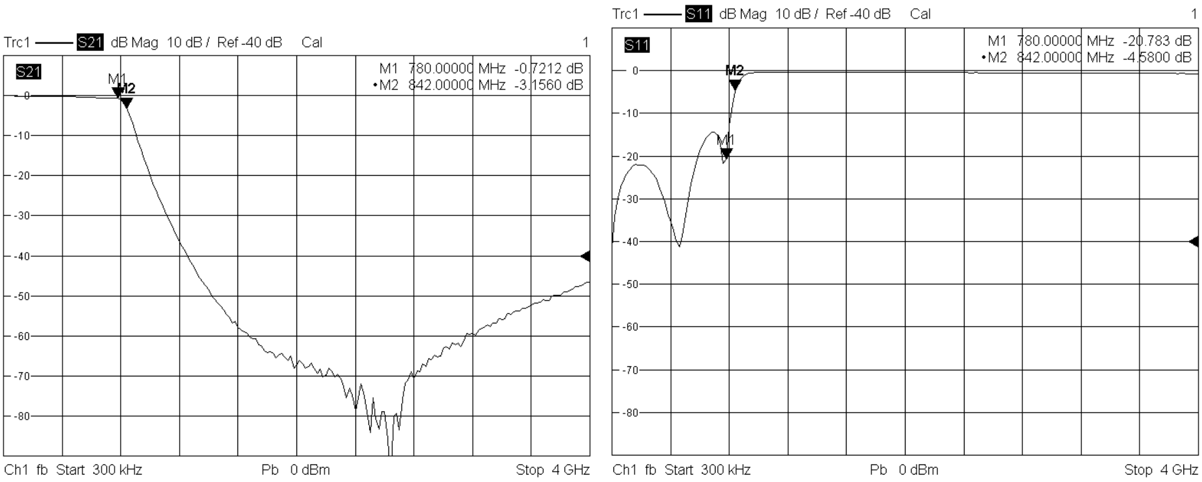
(a) S21 (b) S11

Figure 29: 225 MHz filter



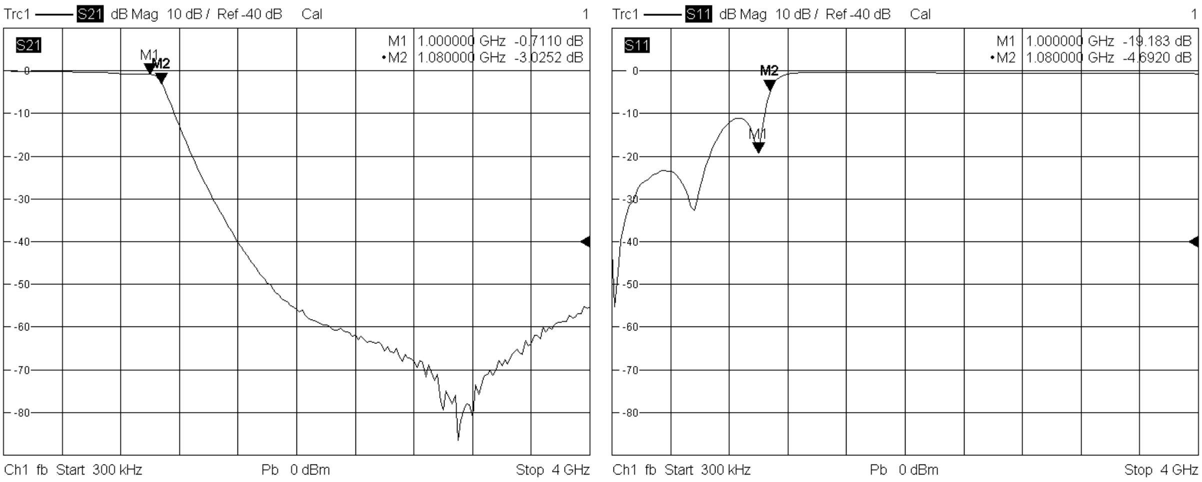
(a) S21 (b) S11

Figure 30: 400 MHz filter



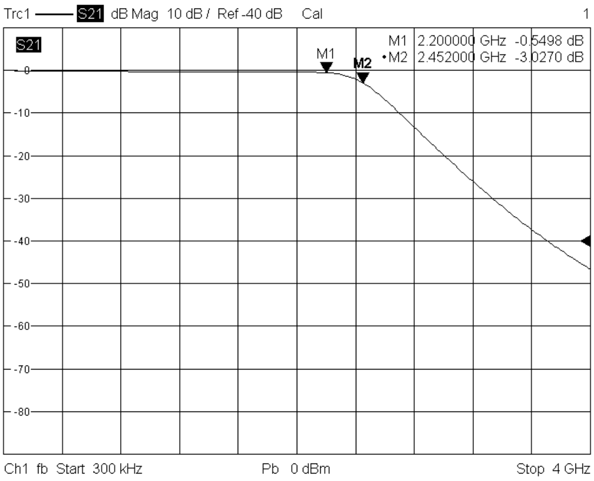
(a) S21 (b) S11

Figure 31: 780 MHz filter

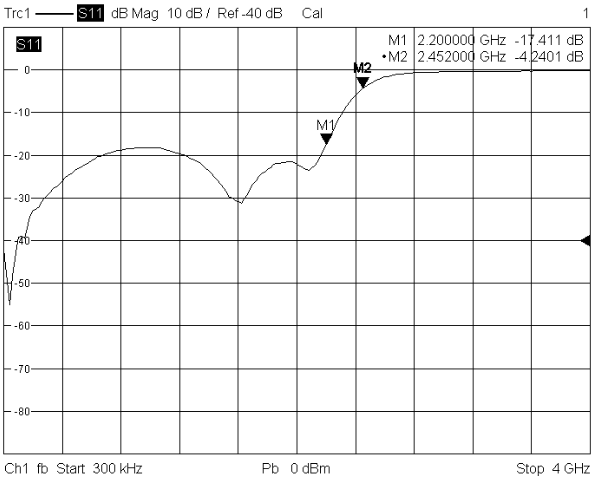


(a) S21 (b) S11

Figure 32: 1000 MHz filter

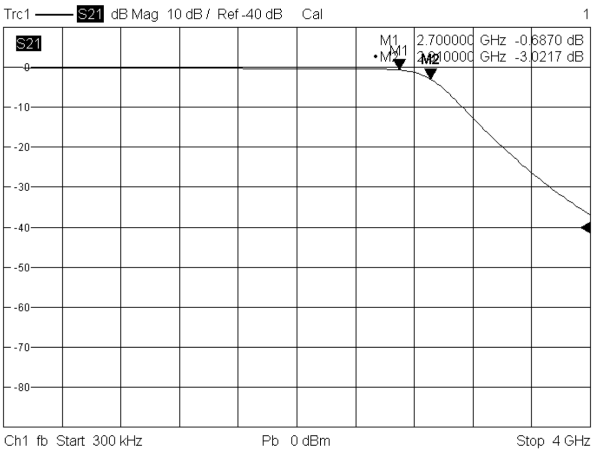


(a) S21

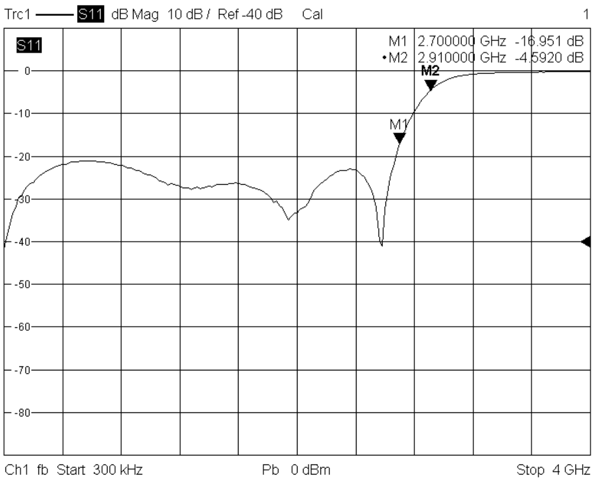


(b) S11

Figure 33: 2200 MHz filter



(a) S21



(b) S11

Figure 34: 2700 MHz filter