Maximum Theoretical Interference Mitigation Capability of a GNSS Receiver as Limited by the GNSS Frontend

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BIOGRAPHY (IES)

Thomas Kraus graduated with a M.Sc. in Electrical Engineering from the University of Darmstadt, Germany. In 2008, he joined the Institute of Space Technology and Space Applications of the "Universität der Bundeswehr München". He's been working as a research associate on several projects of the German Space Agency (DLR) and European Space Agency (ESA-ESTEC). His main research focus is on future receiver design offering a superior detection and mitigation capability of intentional and unintentional interferences.

Prof. Thomas Pany is with the Universität der Bundeswehr München at the faculty of aerospace engineering where he teaches satellite navigation. His research includes all aspects of navigation ranging from deep space navigation over new algorithms and assembly code optimization. Currently he focuses on GNSS signal processing for Galileo second generation, GNSS receiver design and GNSS/INS/LiDAR/camera fusion. To support this activities, he is developing a modular GNSS test bed for advanced navigation research. Previously he worked for IFEN GmbH and IGASPIN GmbH and is the architect of the ipexSR and SX3 software receiver. He has around 200 publications including patents and one monography.

Prof. Bernd Eissfeller is full professor of navigation and director of the Institute of Space Technology and Space Applications (formerly the Institute of Geodesy and Navigation, IGN) at the Universität der Bundeswehr München. He is responsible for teaching and research in navigation and signal processing. Until the end of 1993 he worked in industry as a project manager on the development of GPS/INS navigation systems. He received the Habilitation (venia legendi) in Navigation and Physical Geodesy, and from 1994-2000 he was head of the GNSS Laboratory of the Institute of Geodesy and Navigation. From 2000 to 2008 he was vice director of the IGN until he became the director of the Institute which was formerly led by Prof. Guenter Hein. Eissfeller is author of more than 300 scientific and technical papers.

ABSTRACT

One key element for the performance of a GNSS receiver is the quality of the frontend. Each degradation occurring there can't be gained back by signal processing algorithms anymore. Typical parameters for GNSS frontends are the overall noise figure, group delay variation, clock stability, non-linearity and AGC control, which keeps the quantization noise a small as possible. Frontends are also designed for robustness against RF-interferences (RFI). The level of robustness depends on the application of the GNSS receiver.

Interference suppression within a GNSS receiver is often performed in the digital part of the receiver. Adaptive filters are used making use various signal processing techniques like time-domain methods (e.g. FIR, IIR, pulse-blanking) or transformation methods (e.g. Fourier). For all those methods it is important that the digital signal represents the analog received signal as close as possible. Only then a clear separation of the GNSS signal, RFI and thermal noise can be drawn. If this is achieved, then - for example - sharp notch filters can be used to eliminate a continuous wave interference. If, however, there is only one element in the frontend chain operating in the non-linear region, the mitigation algorithm will suffer in its performance.

Overall, the frontend limits the RFI mitigation capability of a GNSS receiver, regardless which digital signal processing algorithm is used. It is thus of interest to quantify this limit. This limit is then an upper bound of the RFI mitigation capability and will be reached if the best possible digital signal processing algorithm is used.

In this paper, we like to introduce a method to calculate the maximum theoretical mitigation capability (MTMC) based on the parameters of each element in the frontend. A good reason to use this figure-of-merit compared to the common ones like the maximum I/N_0 or I/S is, that the MTMC is more intuitively for the user of a receiver. It is easier to capture the SNR degradation and what he can gain back through mitigation, rather than understanding all the other effects like power, distance, angle of arrival of the RFI source and the antenna characteristics. With the MTMC it is understandable what the capability of the hardware is and later how effective the digital signal processing mitigation performs compared to the hardware performance.

INTRODUCTION

This paper starts with the introduction of a figure-of-merit (FoM), which is a little bit different to the conventional ones (I/N and I/S) used. The maximum theoretical mitigation capability (MTMC) is the maximum regain we can get, because of the hardware conditions. The calculation is based on the hardware parameter under the assumption of a perfect DSP-suppression of the RFI.

After presenting the theoretical derivations, we illustrate our method with an exemplary frontend. We use the USRP of National Instruments (USRP-2952R), which is equivalent to Ettus X310 with the RF-board SBX-120. This frontend has more than six elements in the signal chain, which needs to be considered for the calculations. One RF-channel consist of two amplifiers, one programmable attenuator, one demodulator, one ADC driver and one two-channel ADC. For each element, the datasheets are available providing the individual RF characteristics like noise figure, gain, compression and intermodulation points. With this information, the MTMC and I/N_{max} for the frontend can be determined. The performance of the frontend will be tested together with the geodetic antenna “Zephyr II” of Trimble. The calculated MTMC value will be validated with a GNSS receiver of Septentrio. Therefore, the USRP operates as an interference suppression unit (ISU) plugged in between the antenna and the receiver.

For the determination of the dynamic range two power levels needs to be known. The power level of the GNSS noise floor and maximum power of the RFI, when the saturation of the frontend leads to a loss of tracking for GNSS signals. The MTMC needs in addition the information about the threshold, when RFI starts to harm the GNSS signal with an unprotected receiver. These values will be evaluated by measuring the RF-characteristics of the USRP.

Finally, the results of the MTMC and $(I/N)_{max}$ will be presented, which shows us the optimum gain setting for the USRP to achieve a higher MTMC. Additionally, a detailed analysis of the inside of the USRP gives the dynamic ranges for each RF component.

MAXIMUM THEORETICAL MITIGATION CAPABILITY

The maximum theoretical mitigation capability (MTMC) is defined as the maximum regain we can get, when a lossless extinction of the RF-interference has been achieved, which is not at all affecting the GNSS signal with this filtering process. The unit of the MTMC is similar to a gain of an amplifier given as a lossless factor or as in the logarithmic interpretation (in dB). In case of the MTMC for the RF-frontend, we only consider the hardware conditions based on the hardware parameter under the assumption of a perfect DSP-suppression of the RFI.

An unprotected GNSS receivers suffers under the influence of RFI with a signal-to-noise ratio (SNR) degradation. The simplest interpretation is, that every increment of the noise floor by power of the RFI (P_I) leads to a degradation of the SNR. The so-called effective SNR is calculated by

$$SNR_{eff} = \left(\frac{\boldsymbol{P_S}}{\boldsymbol{N_0}}\right)_{\boldsymbol{eff}} = \frac{P_S}{N + P_I} \tag{1}$$

In fact, the effect of the RFI to the GNSS signal is depending on more than just the power of the RFI. It is important to consider the type of GNSS signal, the type of RFI and the parametrization of the RFI. To consider all that, a Q-factor is used to calculate the effective SNR for various situations, which is done by the equation of [1].

$$SNR_{eff} = \left(\frac{\boldsymbol{P_S}}{\boldsymbol{N_0}}\right)_{\boldsymbol{eff}} = \frac{1}{\frac{1}{\boldsymbol{P_S} / \boldsymbol{N_0}} + \frac{\boldsymbol{P_I} / \boldsymbol{P_S}}{\boldsymbol{QR_C}}} \tag{2}$$

In case of a perfect RFI mitigation the degradation of the SNR is equal to the gain, we get with the mitigation algorithm.

$$G(P_{RFI}) = \Delta SNR(P_{RFI}) = SNR_{noRFI} - SNR_{eff}(P_{RFI}) \quad \textbf{(3)}$$

Finally, the MTMC is then the maximum re-gain, which can be expected.

$$MTMC = \max\left\{G(P_{RFI})\right\} \quad \textbf{(4)}$$

Not only can the MTMC of the overall system ($MTMC_{SYS}$) be defined but also each of the sub-components. For a frontend ($MTMC_{RF\text{-}FE}$) with pre-correlation mitigation technology, the overall system consists of at least four elements as plotted in Figure 1. These elements are the active antenna ($MTMC_{ANT}$), the RF signal conditioning ($MTMC_{RFSC}$), the analog digital converter ($MTMC_{ADC}$), and the DSP for pre-correlation mitigation ($MTMC_{DSP\text{-}PM}$).

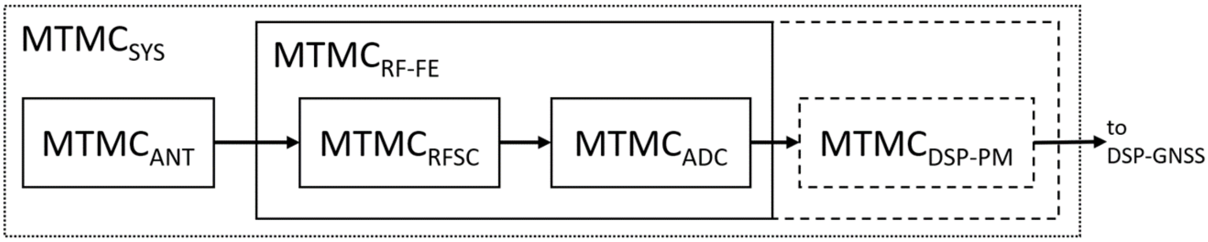


Figure 1: MTMCs in a signal chain of a GNSS receiver

The MTMC of the overall system ($MTMC_{SYS}$) is limited by the weakest element in the signal chain.

$$MTMC_{SYS} = \min(MTMC_{ANT}, MTMC_{RF-RE})$$

$$MTMC_{SYS} = \min(MTMC_{ANT}, MTMC_{RFSC}, MTMC_{ADC}, MTMC_{DSP-PM}) \quad \textbf{(5)}$$

The advantage of knowing each MTMC and the weakest one is, that we could optimize the signal chain in the right place. It could be for the enhancement of the overall dynamic or to reduce the quality of other elements for any reason, where not needed. Also the DSP for the RFI mitigation must not be better than the performance of the hardware part.

Dynamic Range Calculation

The dynamic range depends on the noise floor power level P_{noise} and the maximum power level P_{max}.

$$DR = \frac{I}{N} = \frac{P_{\max}}{P_{noise}} \quad \textbf{(6)}$$

Whereas P_{noise} is clearly defined by equation (9), P_{max} needs to be evaluated, which is part of this and future work. P_{max} might also depend on the type of applications, if GNSS degradation is accepted or not. The possible definition for P_{max} could be where: a) the GNSS receiver is losing abruptly tracking of the GNSS signals b) the GNSS signal starts to degrade irreparably because of distortion, c) the 3rd order product of the RFI begins to achieve the power level of the noise floor P_{noise} or d) the maximum input power of one RF-component has been reached before one of the other cases occurs.

Case a) is observed for our setup. It figured out that the ADC is the weakest element in our configuration and when the input power level of the 1dB compression point P_{1dB} is reached, the tracking of the GNSS signal stops immediately and abruptly.

$$P_{\max} = P_{1dB}$$

$$DR_{1dB} = \left(I/N \right)_{1dB} = P_{1dB} / P_{noise} \quad \textbf{(7)}$$

Case b) might occur, when an analog hardware is the limiting factor of the system. But this case, where not tested in this work. In the scenario c) the noise floor is increased next to the RFI itself with the 3rd order product of the RFI additionally. But this effect is highly dependent to the type of RFI, because of the fact that the measurement of the 3rd order intermodulation point (IIP3) is done by two continuous wave signals. The IIP3 is just a figure-of-merit, which must not behave in the same way for other signal types [2]. However, we can calculate for this scenario also the dynamic range, which is defined as

$$P_{\max} = P_{RFI,3\mathrm{rd}} = 10^{\frac{P_{RFI,3\mathrm{rd}}[dB]}{10}} \qquad P_{RFI,3\mathrm{rd}}[dB] = \frac{2 \cdot P_{IIP3}[dB] + P_{noise}[dB]}{3}$$

$$DR_{3rd} = \left(I/N \right)_{3rd} = P_{RFI,3rd} / P_{noise} \tag{8}$$

TEST-SETUP: USRP AS FRONT-END (OR ISU-UNIT)

To prove the concept of MTMC, we use a USRP as frontend. The USRP of National Instruments and Ettus is very transparent in terms of hardware design. So that, we have all parameter for the validation of the MTMC. The USRP has been used very often for GNSS applications like as GNSS frontend [3] [4] or as Interference Suppression Unit (ISU) [5].

The setup used within this paper is sketched in Figure 2. It consists of one GNSS antenna, an external programmable attenuator, one SDR as transceiver and a common GNSS receiver. Instead of the transceiver, the SDR could be used as frontend only, which is supporting a software receiver with the digital signal stream. The mitigation of the RFI happens in the SDR with a FPGA. The antenna used in this paper is the geodetic reference antenna of Trimble Zephyr II. The external programmable attenuator is from Mini-Circuits with the model number RCDAT 6000-90 and has an adjustable range from 0dB to 90dB in a 0.5dB step size. The SDR is a USRP from Ettus or National Instruments (NI). In this case we used the NI USRP-2952R, which is equivalent to the Ettus X310 with the RF-board SBX-120. They differ only with their firmware and using another driver and development environment. The given flexibility of the setup is the attenuation of the external attenuator $G_{att,ext}$, the gain of the USPR G_{USRP} and the bandwidth of the USPR BW_{USRP}. The optimum setting of this parameters will be evaluated in this paper later. Furthermore, we have the possibility to set the center frequency and the local oscillator of the USRP, but these parameters are not so important for the consideration of the maximum dynamic range. The GNSS receiver used for these tests was the PolaRx4TR PRO of Septentrio.

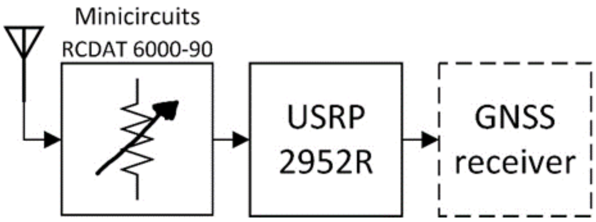


Figure 2: Schematic of the test setup

The design goals are set to the noise figure of 1.6 dB and the bandwidth of 10 MHz. The noise figure of 1.6 dB had been chosen, because of the reason that the noise figure of the Trimble antenna is already at 1.5 dB and for the calculation of the optimum settings of the USRP and the external attenuator, we accept an additional loss of 0.1 dB to the GNSS signal. The gain of the Trimble antenna is approximately G_{ant} = 50 dB.

RF-signal path of the USRP-2952R

One USRP has two RF-input and two RF-output channels working full-duplex. The channels are phase-coherent synchronized. One USRP is composed of one main-board and two RF-boards. The main-board includes two dual channel ADCs (one for each RF receiving channels), the fixed mounted TCXO and the optional pluggable GPS-disciplined OCXO. The hardware components of the USRP for one input channel are shown in Figure 3 and their RF-characteristics are listed in Table 1. This information has been extracted from the Ettus website [6], the datasheets from the individual RF-components and by opening the USRP.

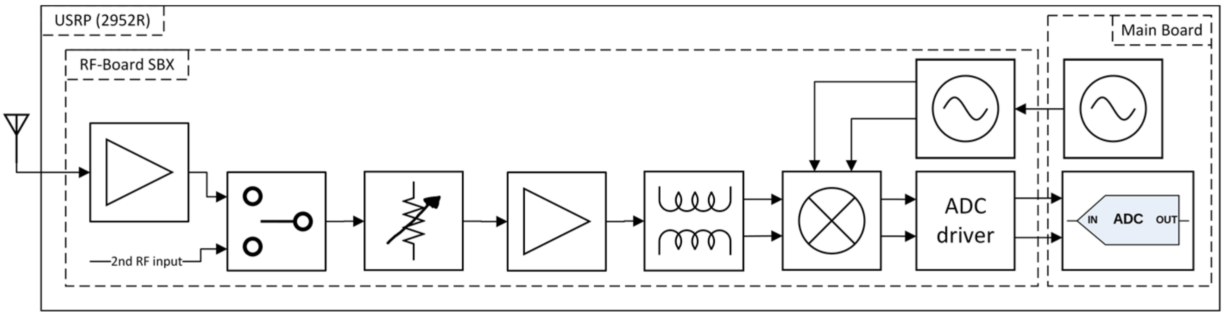


Figure 3: RF-signal chain of one RF-channel of the USRP-2952R

The first RF-element is the 13.2 dB amplifier MGA82563 of Avago Technologies, followed by the RF-switch AS225-313LF of Skyworks Solutions to select between the first and second RF-input. The internal programmable attenuator HMC624LP4E for the regulation of the USRP gain is from Hittie Microwave Corporation. The second amplifier is equal to the first one. Until this stage the signal is unbalanced and it will be transformed with the RF-transformer TC1-1-43A+ of Mini-Circuits to a balanced signal to feed the demodulator ADL5380ACPZ of Analog Devices. Finally, the signal will pass the ADC driver ADA4927 of Analog Devices and the 14-bit ADC ADS62P48 of Texas Instruments. The clock for the down-conversion is synthesized by the chipset ADF4350 of Analog Devices.

Table 1: RF-characteristics of each RF-element at the GNSS L1 band

	Amp	Switch	Attenuator	Transformer	Demodulator
Device No.	1, 4	2	3	5	6
Model-No.	MGA82563	AS225-313LF	HMC624 LP4E	TC1-1-43A+	ADL5380 ACPZ
G	13.2 ± 0.35	-	-31.5 to 0	-	6.8
NF [dB]	2.2 ± 0.2		1/G	-	11.7
P1dB [dBm]	17.4	30	-		11.6
IIP3 [dBm]	31	53	55		27.8
$P_{in,max}$ [dBm]			20		
Ins. Loss [dB]	0.37	0.4	1.8	0.5	

Because of the flexibility of the USRP, the USRP can be used for the entire GNSS frequency bands and is able to adapt the signal power level. The SBX-120 offers a frequency range from 0.4 to 4.4 GHz and has a bandwidth of 120 MHz. Even if a smaller bandwidth is selected, the analog bandwidth remains at 120 MHz. There is no analog filter within the signal chain. The bandwidth decimation happens in the DSP processing on the FPGA. The gain setting of the USRP can be set from 0 to 37.5 dB in a 0.5 dB set size. From 0 to 31.5 dB it is achieved by the internal programmable attenuator. The additional gain of 6 dB from 31.5 to 37.5 dB is done by the ADC. National Instruments applies very often the reference level instead of the gain value, which is commonly used for measurement equipments. The reference level defines the maximum input power until saturation is reach and it includes the individual offset of the gain for each USRP, which is stored in the firmware memory of the USRP device. Our reference level P_{ref} is from +1.346 to -28.654 dB with a step size of -0.5 dB, which corresponds to G of 0 to 30 dB with a step size of 0.5 dB, respectively.

$$G_{real} = G_{conf} + G_{offset} = G_{\max} - L_{Att} = 2G_{offset} - P_{ref} \quad \forall G_{conf}\,(G_{conf} \in \{0...30\})$$

$$\rightarrow P_{ref} = G_{offset} - G_{conf} \text{ or } G_{conf} = G_{offset} - P_{ref}$$

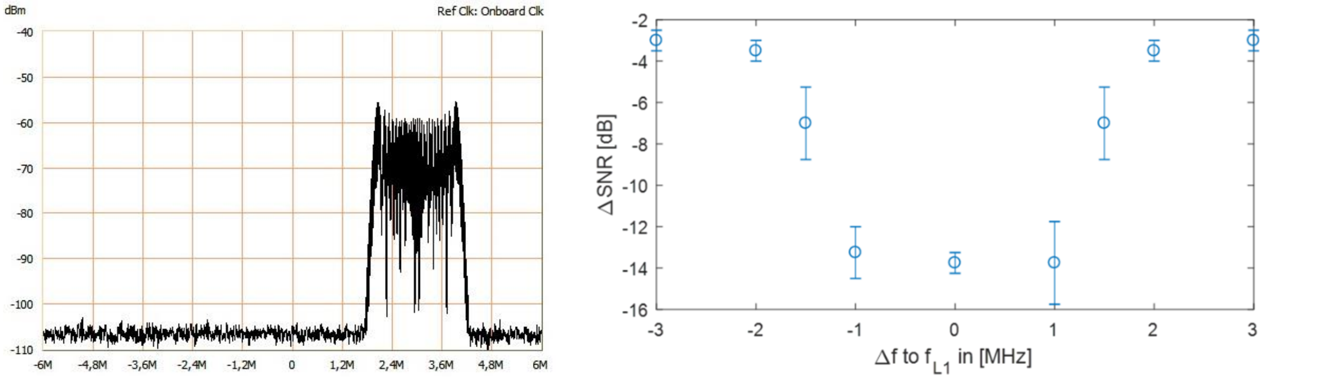
G_{real}: The gain value for one RF input signal channel
G_{conf}: The gain value for the configuration of the USRP (used by Ettus and NI). G_{conf} = 0…31.5dB when the gain of the ADC is not considered.
P_{ref}: The reference level for the configuration of the USPR (used by NI)
G_{offset}: The offset of the gain. It is different for each USRP (here: +1.346dB)
G_{max}: The maximum gain of the USRP defined by the gain of the two amplifiers and the demodulator minus the losses within the signal path (here: +32.846dB)
L_{Att}: The loss of the internal programmable attenuator

NI is not offering the gain of the ADC in combination with the reference level, because this additional gain brings no advantage in terms of performance and instead of that it suffers from a reduced dynamic range. The noise figure is not improving with the additional gain of the ADC (is keeping it constant) [7].

RFI used for these tests and the influence to an unprotected GNSS receiver

The radio-frequency interference (RFI) used for the tests is a FM-signal. The center-frequency has a three MHz offset to the GPS L1 C/A center-frequency. The signal was generated with a vector-signal-generator (VSA) of National Instruments (NI): PXIe-5673E. The signal waveform was set to “sine” with a waveform frequency of 25 kHz. The deviation was one MHz. The power spectrum of the signal is plotted in Figure 4 (a).

The selection of this RFI signal had two reasons. First this signal is leading to an abrupt loss of tracking when a certain input power threshold has been reached and second the offset of three MHz allows to use a simple filter for mitigation, which is similar to a lossless mitigation technology. RFI covering the main lobe of the GPS signal needs a more sophisticated mitigation approach to achieve a GPS lossless signal reconstruction.



(a) (b)

Figure 4: RFI (FM-signal) used for the tests: (a) spectrum and (b) different SNR degradation to the GPS L1 C/A when RFI power is constant

For the MTMC the effect of the RFI to a GNSS receiver needs to be well known. Compared to the interference to noise ratio, where the noise level is the lower reference signal, for MTMC the signal to noise (SNR) degradation to the GPS signal is important to know. Therefore, we measured the power level of the RFI signal when the SNR degradation was 10 dB. We know that after this signal level, the SNR degradation increases constant linear with the increase of the RFI power. With other words, every additional one decibel of RFI power leads to one decibel of SNR degradation.

Unfortunately, the influence of CW-RFI is dependent to the Doppler frequency of the GPS signal. A FM-signal is nothing else than a CW-signal with an alternating center frequency over time. That this dependency exists can be seen with our measurements in Figure 4 (b). The average SNR degradation is higher, if the center frequency of the FM-signal is within the main lobe of the GPS signal. The effect of CW-RFI to the tracking performance was investigated by [8] [9], where they demonstrated the highest degradation on a Doppler frequency offset. That's why, in Figure 4 (b) the variation of the SNR degradation is higher at frequencies far from the band center.

RF-CHARACTERISTICS OF THE USRP

Noise figure of the USRP-2952R

For the calculation of the maximum dynamic range we must know the power levels of the noise floor and the maximum allowed signal level for each RF-component. To understand the power levels of the noise floor on each RF-component, we need to calculate the noise figure (NF) of the GNSS frontend. The noise figure gives us information about the GNSS signal quality. A higher NF degrades the SNR of the GNSS signals linear.

$$\Delta SNR_{GNSS} = \Delta NF \tag{9}$$

The power of the noise floor is calculated by

$$P_{noise} = -174\, dBm/Hz + NF + G \tag{10}$$

The noise figure of concatenated components is calculated by the Fris-Equation:

$$NF_i = NF_1 + \frac{NF_2 - 1}{G_1} + \frac{NF_3 - 1}{G_1 \cdot G_2} + \ldots + \frac{NF_i - 1}{G_1 \ldots G_i} \tag{11}$$

The parameters for each components is listed in Table 1 and the insertion loss should not be neglect within the calculation. The same is true for the signal routing within the RF-design.

The noise figure of the USRP can be measured or if trusted it could be taken from the website of Ettus Research [7]. The datasheet of NI states that the NF is between 5 and 7 dB [10]. But this is just true for a certain gain of the USRP. The range of the NF for the USRP is between 5 and 28 dB. Even that you might think, it is the best to choose the lowest NF for the GNSS setup, you will see in the simulations of this paper, that this is not the optimum solution, if you like to get additionally a good performance in terms of signal dynamic for RFI. There are three methods to measure the NF of a device under test (DUT) [11]: a) Using a noise figure meter b) the gain method and c) the Y-factor method. The Y-factor method is the best choice for a SDR, because the expected NF values are usually higher than 4 dB and the digital samples can be used for the calculation of the power and the corresponding Y-factor. The power measurement needs not to be calibrated because of the differential power measurement of the Y-factor. The equation to calculate the noise figure is:

$$NF = 10 \cdot \log_{10}\left(\frac{10^{(ENR/10)}}{10^{(Y/10)} - 1}\right) \qquad \textbf{(12)}$$

In which ENR (Excess Noise Ratio) is the NF of the external noise source. Y is the difference between the output noise power density when the noise source is on and off [11]. As ENR can be used a calibrated noise head like HP346A/B or any noise source, which will be calibrated with a VSA before using it. We used the noise source NC1111A of Noisecom with external attenuators to achieve a NF of 32.7dB, which is equivalent to a power level of -71.3dBm at 10 MHz bandwidth.

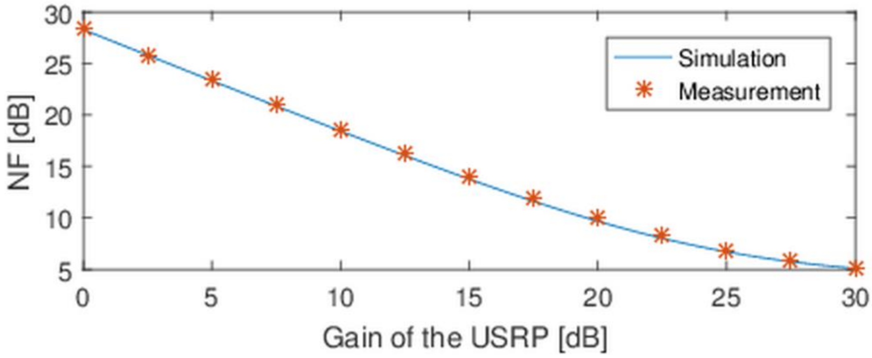


Figure 5: Noise figure (NF) of the USRP-2952R

Figure 5 shows the measured results and that the simulation matches with them.

1dB Compression Point and 3rd order Intermodulation Point of the USPR-2952R

The calculation of the dynamic range depends very much on the 1dB compression point and 3rd order intermodulation product. Therefore, the input power level for the 1dB compression point P_{1dB} and third order intercept point (IIP3) were measured with the single-tone and two-tone measurement.

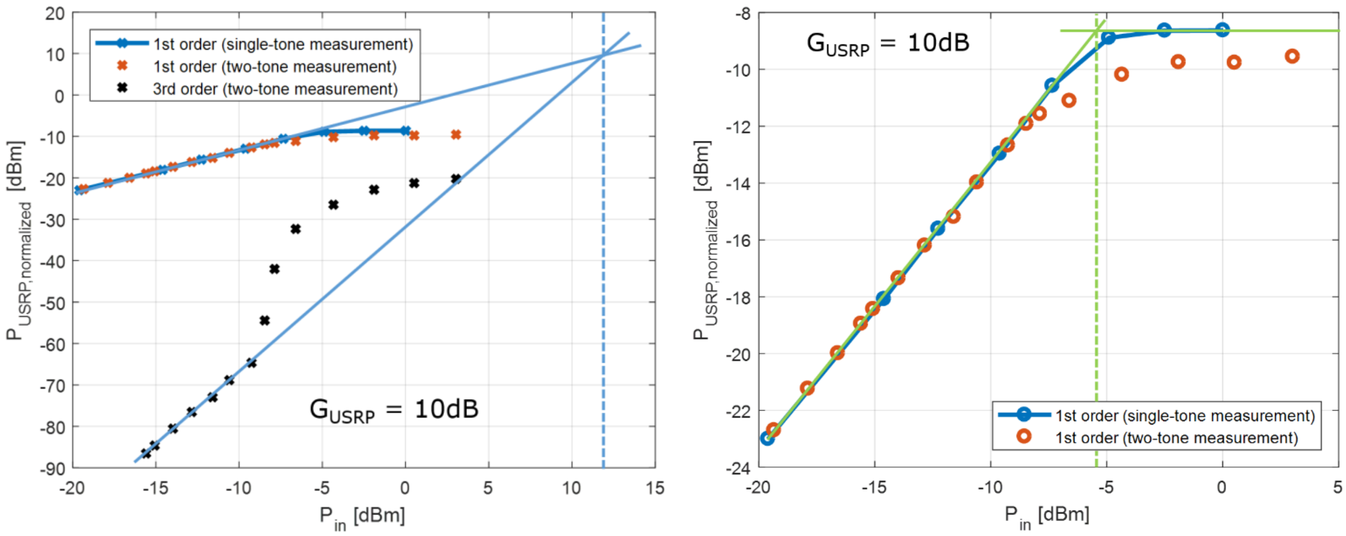
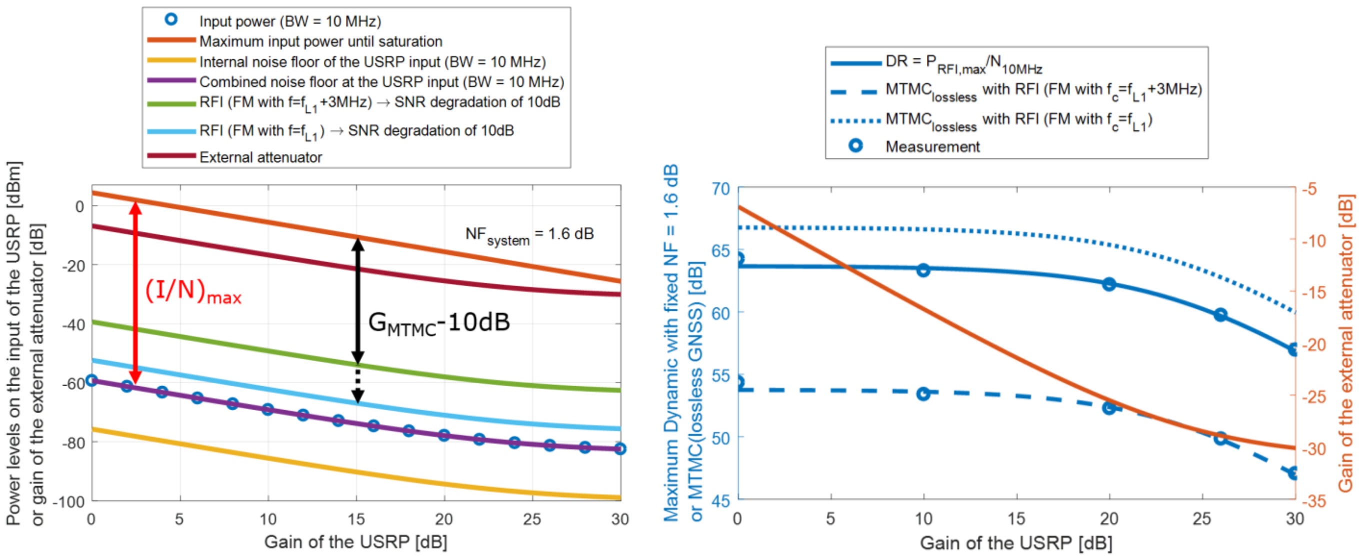


Figure 6: 1st and 3rd order signals of the USRP-2952R

The P_{1dB} and the IIP3 can be both extracted from Figure 6. The P_{1dB} is equal to -5.76 dBm. When the power of the RFI reaches exactly this value, the GNSS receiver will have a loss of tracking for all GNSS signals completely and abruptly. The IIP3 is equal to 12 dBm for the RF-board of the USRP. The measurement of Ettus Research has the same value [7]. Furthermore, it can be seen that after an input power P_{in} of approximately -9 dBm, the signal power of the 3rd order intermodulation product increases faster as from the RF-board expected, which ends later into a saturation state. This effect is assumed to come from the ADC.

RESULTS: DYNAMIC RANGE AND MTMC

The dynamic range and MTMC is calculated according to equations (4)(7)(8). Before that, the power levels needs to be well known. The power levels on the input of the USRP are plotted in Figure 7 (a). The maximum input power level P_{max} is equal to the 1dB compression point P_{1dB}. This value can be measured by increasing the RFI power level until the tracking of the GNSS stops abruptly or by a single-tone measurement as given in Figure 6. The power level of the noise floor P_{noise} can be determined by measuring the power level when it starts to degrade the SNR slightly or more accurately by equation (10) and using the noise figure of Figure 5. With this information the maximum interference-to-noise ratio (INR_{max}) is already known, which is in case of values expressed in decibel just the difference between P_{max} and P_{noise}. Finally, the INR_{max} is plotted in Figure 7 (b) and shows that there is a dependency to the gain of the USRP G_{USRP}. This can be explained by the fact, that P_{max} is constant linear dependent to G_{USRP}, but P_{noise} is not constant linear because of the shape of noise figure. For other SDRs or frontends this could be different. Here, the limiting factor in the RF-chain of the USRP is always the ADC whatever gain G_{USRP} is selected.



(a) (b)

Figure 7: Power levels and dynamic range (DR) of the USRP-2952R: (a) input power levels and (b) the DR/MTMC

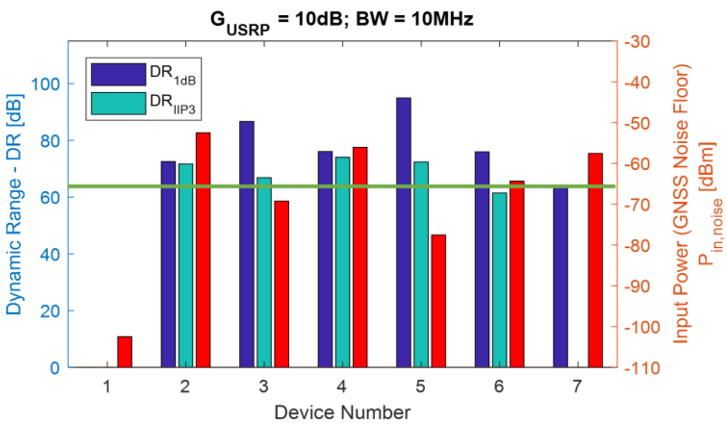


Figure 8: Dynamic ranges of each RF-component in the signal chain (Dev.-No. 1: Antenna; 2: Attenuator (external); 3: Amp No.1; 4: Attenuator (internal); 5: Amp No.2; 6: Demodulator; 7: ADC

For the MTMC, the lower reference is not the noise floor. Instead of that, the effect of RFI to the SNR is important. In a section before and in Figure 4 we've already discussed, that the influence is dependent to the type of RFI. In case of a lossless MTMC, where we expect no additional degradation of the GNSS signal because of hardware by keeping the noise figure of the system constant, there is an offset to P_{noise} and finally also to the INR_{max}.

The USRP must not be seen as black box only. With the knowledge of the input power levels, the structure of the RF-signal chain of the USRP (Figure 3) and the RF-characteristics of each RF-element, the dynamic range of each RF-component inside of the USRP can be calculated. Therefore, the equations (7) and (8) are used to get the dynamic ranges for the linear operation mode DR_{1dB} and for the 3rd harmonic influence to the noise floor DR_{3rd}, respectively. Both values are given in Figure 8. It can be seen that the ADC is the limiting factor of the USRP.

Ettus Research and National Instruments designed the USRP so well, that in each configuration the analog hardware of the RF-chain is never the limiting factor in terms of linearity. Furthermore, the noise floor of the GNSS signal is almost kept spurious free for the maximum input power of the RFI with our setup, which can be seen by the value DR_{3rd}. Only the demodulator is slightly below of the lowest DR_{1dB} of the ADC with the DR_{3rd}.

Comparison of the different dynamic values

Finally, it is worth to have a short look to the dynamic range values determined in this paper. The ADC of the USRP is a 14-bit ADC from Texas Instruments (ADS62P48). If we could use the entire dynamic of 14-bit, then we should get a dynamic range of 84.3 dB, calculated by

$$DR[dB] = 20 \cdot \log 2^n = 6.02 \cdot n \tag{13}$$

Looking to the datasheet of the ADC the signal-to-interference ratio including noise and distortion (SINAD) is only at 72.8 dB, which brings us to an effective number of bits (ENOB) of 11.8 bits.

The dynamic range of our setup with a noise figure of 1.6 dB and a bandwidth of 10 MHz is 63.7 dB for $(I/N)_{max}$, which is equivalent to an ENOB of 10.3 bits. The maximum theoretical mitigation capability (MTMC) is lower or higher, which depends on the type and parametrization of RFI and the type of GNSS signal. In case of a FM-signal with a one MHz bandwidth as RFI and GPS L1 C/A, the maximum regain is 53.8 dB or 66.8 dB with three MHz or no offset to the center frequency of GPS L1, respectively.

CONCLUSION AND OUTLOOK

In this paper the dynamic ranges for GNSS with RFI were simulated and measured for a SDR (USRP) to find a method to calculate this value for any other frontend by knowing the schematic of the frontend and the corresponding datasheets of the RF-components. We concentrated only on the maximum dynamic range, when the system kept in a state where no GNSS degradation occurred by keeping the noise figure of the system constant (GNSS lossless). Increasing this overall noise figure would lead to an irrecoverable GNSS loss because of the hardware, but it could bring an additional room for the signal dynamic of the RFI.

A further figure-of-merit were introduced called “maximum theoretical mitigation capability” (MTMC). Compared to traditional ones, which are strictly related to the power of the interference, the noise floor or the GNSS signal itself, the MTMC is looking for the direct influence to an unprotected GNSS receiver and the maximum re-gain, which can be achieved by the overall system or each individual element in the signal chain. In a GNSS lossless situation the MTMC has an offset to the maximum interference-to-noise ratio $(I/N)_{max}$, which is defined by the type of GNSS signal and RFI. It has been shown, that the maximum allowed power of the RFI is the 1dB compression point, at least when the ADC is the weakest element in the signal chain. It is still an open question, if this behavior is also valid for analog RF-components.

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