Measurement of Harmonics using Spectrum Analyzers
Application Note

Products:

- R&S®FSW

This Application Note focuses on measurement of harmonics using modern spectrum analyzers. It highlights the source of harmonics before focusing on their measurement using a spectrum analyzer. The Application Note also explains the benefits of the R&S FSW's high pass filter option for harmonic measurements.

ROHDE&SCHWARZ

Application Note

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1 Introduction

One of the key features of non-linear elements in any electronic circuit is the generation of harmonic signals. On the one hand side, harmonics resulting from the non-linear characteristic of a given component like a diode, are used intentionally to implement vital functions for today's RF world, such as e.g. harmonic mixers. On the other hand, not every harmonic signal generated by a DUT may be welcome. In an ideal world, amplifiers do not generate any harmonics, but simply amplify the input signal. One of the challenges in the real world therefore is to optimize a device to come as close as possible to its ideal, which means to make use of the wanted harmonics (e.g. of 3rd order) and suppress the unwanted harmonics (e.g. of 2nd order).
When it comes to measuring the harmonics of a device, not only the device under test (DUT) consists of non-linear elements. The measuring instrument - usually a spectrum analyzer – contains amplifiers and mixers, which also may generate harmonics and thus contribute to the measurement results. During the verification of the harmonic specifications of a DUT, extra effort therefore is necessary to differentiate harmonics generated by the DUT from harmonics generated by the measuring instrument.
This article briefly derives the generation of harmonics in non-linear elements, before highlighting the architecture of the high-end spectrum analyzer R&S FSW. The R&S FSW was designed to minimize internally generated harmonics to provide outstanding harmonic measurement performance.

2 Harmonics

2.1 Theory of Harmonic Signals

This chapter gives some mathematical background on the origin and behavior of harmonic signals. Readers who are familiar with the theory of Taylor series are welcome to skip this chapter and continue directly with chapter 2.2.

Harmonics, no matter of which order, are generated every time when a signal with frequency $f > 0$ passes through a non-linear component.
The output signal of a component can be derived from the input signal using a so-called transfer function, which provides a mathematical relation between the two signals. As known from mathematical theory, every transfer function can be described by a polynomial, a so-called Taylor-series.
Without going into details on how to calculate the individual coefficients a_n, this means that the behavior of any non-linear component can be described by a formula like

$$P(s) = a_0 + a_1 \cdot s + a_2 \cdot s^2 + a_3 \cdot s^3 + \cdots$$

with $P(s)$ being its transfer function and s being the input signal.
Assuming a CW input signal, the general formula for a signal s as a function of time t is

$$s(t) = B \cdot \cos(2\pi \cdot f \cdot t + \varphi).$$

In the output signal of the element the input signal appears within the term $a_1 \cdot s$, which is generally known as the fundamental signal.
The addition theorem for the cosine function

$$\cos(\alpha)\cdot\cos(\beta)=\frac{1}{2}\left(\cos(\alpha+\beta)+\cos(\alpha-\beta)\right)$$

can be applied to the terms $a_2 \cdot s^2$, $a_3 \cdot s^3$ etc., with α and β being replaced by $2\pi \cdot f \cdot t + \varphi$.

For $s^2(t)$ this results in a term

$$s^2(t)=\frac{1}{2}\cdot B^2\cdot\left[\cos\left(2\pi\cdot(2f)\cdot t+2\varphi\right)+1\right]$$

which is a signal with twice the frequency of the original CW signal, the so-called 2nd harmonic.

For $s^3(t)$ the resulting term is

$$s^3(t)=\frac{1}{4}\cdot B^3\cdot\left[\cos\left(2\pi\cdot(3\cdot f)\cdot t+3\varphi\right)+3\cdot\cos\left(2\pi\cdot f\cdot t+\varphi\right)\right]$$

which includes a term with 3 times the frequency of the CW signal, the 3rd harmonic.
Generally speaking the term $s^n(t)$ will include a term with n-times the frequency of the original CW signal, the nth harmonic.

The above equations lead to two basic conclusions:

1. Since a Taylor-series is infinite, the number of harmonics included in the output signal is also infinite in theory.
   In practice, higher order harmonics (e.g. n > 10) can usually be ignored, because the amplitude of the signal decreases with increasing order of the harmonic: the factor from the addition theorem (½ for the 2nd harmonic, ¼ for the 3rd harmonic etc.), or generally speaking, the n-th coefficient a_n, decreases with the order of n.
2. When decreasing the amplitude of the CW signal, the amplitude of the harmonic signals decreases exponentially, as expressed by the factor B^n. Practically on a logarithmic scale 1 dB less power of the fundamental means 2 dB less of second order harmonic, 3 dB less of 3rd order, and so on.

2.2 Specification of Harmonics

In technical specifications, harmonics are often specified using the so-called harmonic intercept point. The intercept point specifies a theoretical point, where a certain harmonic, e.g. the second for the second harmonic intercept, has grown as large as the fundamental itself. The intercept point is a theoretical point, because in real-life, non-linear effects, such as e.g. saturation, usually dominate before the intercept point is reached.

From the equations in chapter 2.1, the level difference between fundamental and harmonic signal can be calculated for any given level of the fundamental if the intercept point is known. As an example, a 2nd order harmonic intercept point of 80 dBm is given. The level difference between fundamental and 2nd harmonic distortion for a fundamental of 20 dBm is 60 dB, i.e. the 2nd harmonic level is -40 dBm in this case. This example corresponds to the graph in Figure 1. In short, the distance between fundamental and second harmonic D_2 for a given level P_1 can be calculated from a 2nd order harmonic intercept point *SHI* as follows:

$$D_2 = SHI - P_1$$

Note that the calculation is valid only for a logarithmic scale, i.e. D_2 is in dBc, P_1 and *SHI* in dBm.

Please note that the specification of the second (or higher) harmonic intercept differs from the intermodulation intercept points, called IP2, or IP3. The harmonic intercepts are measured in a single tone scenario, whereas the intermodulation intercept points are measured with in a two tone scenario. This application note focuses on harmonics of a single tone input signal. Therefore, the intersection with the third harmonic in Figure 1 is not marked, as the third harmonic intercept point (THI) is not common. In some documents, the harmonic intercepts are also abbreviated IPk2 or IPk3, with an additional "k" differentiating it from the intermodulation intercepts. The IP2 is always 6 dB below the SHI (IPk2), whereas the IP3 is 9.54 dB below the THI (IPk3) [Rau01].

Nevertheless there is a similar equation for the 3rd order harmonic distortion D_3 for a given level P_1, derived from the intersect point of the 3rd order harmonic distortion with P_1:

$$D_3 = 2 \cdot (THI - P_1)$$

Figure 1 shows fundamental and harmonic distortion of 2nd and 3rd order for a non-linear 2-port with gain 1. The intercept point of second order is indicated at 80 dBm.

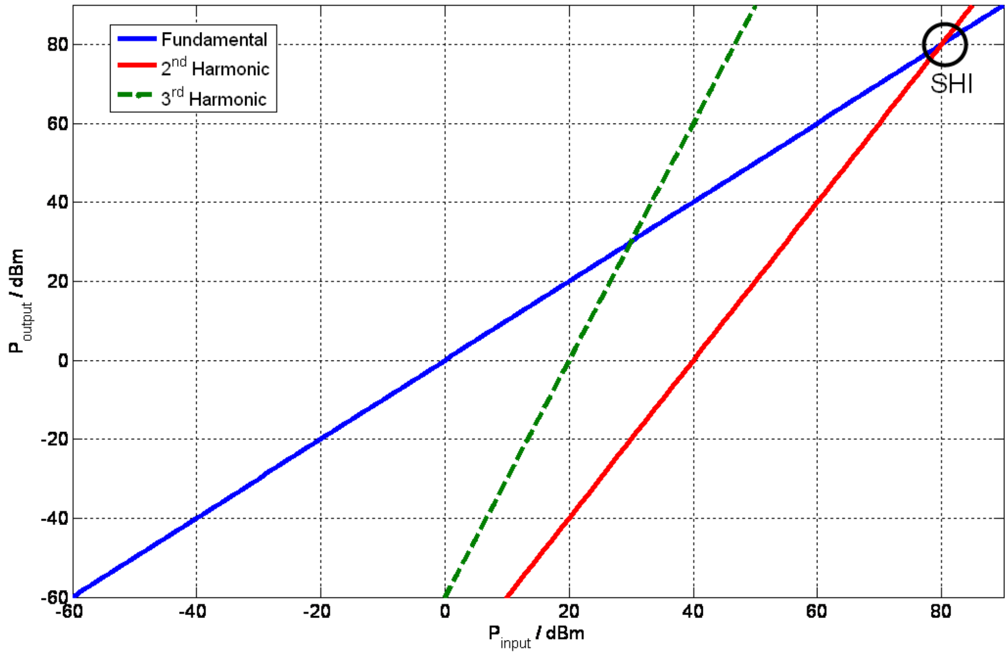

Figure 1: Input and output levels of a non-linear element with gain 1, for fundamental, 2nd and 3rd harmonics, single tone scenario

3 Measurement of Harmonics

To measure the harmonic signals of a DUT, a frequency selective measuring instrument is necessary to separate the fundamental from the harmonic signals. To avoid complicated setups of filters and power meters, harmonics are usually measured using spectrum analyzers. Spectrum analyzers are capable of displaying the fundamental signal and its harmonics at the same time – depending on the frequency range of the analyzer.

3.1 Spectrum analyzer design minimizing harmonics

Spectrum analyzers have different operating concepts, depending on the frequency range. The so-called RF path (path “1” in Figure 2) is used for frequencies e.g. up to 3.6 GHz, 7 GHz, or 8 GHz, depending on the spectrum analyzer model. Above this frequency limit (path “2”), a tunable preselection filter, in most cases using YIG technology (Yttrium Iron Garnet) is applied for image frequency rejection. [Rau01] discusses the details on spectrum analyzer design concepts.
As the frequency range of path “2” usually extends to 13 GHz and above, path "2" is often called the "microwave path". The R&S FSW switches from path “1” to path “2” at 8 GHz. For the following two sections, it is important to keep in mind that the critical element, creating the strongest harmonics, is the first mixer (non-linear element) in the signal path. This mixer is either the up-converting mixer to IF1 for path “1”, or the down-converting mixer to IF2 for path “2”. The subsequent mixers in the block diagram in Figure 2 do not contribute to the harmonic distortion, since they are operated as fixed frequency mixers (LO has always the same frequency), followed by band pass filters which block their harmonics.
The difference in terms of harmonics between the RF and the microwave signal path is the YIG filter in front of the first non-linear element in the signal flow.

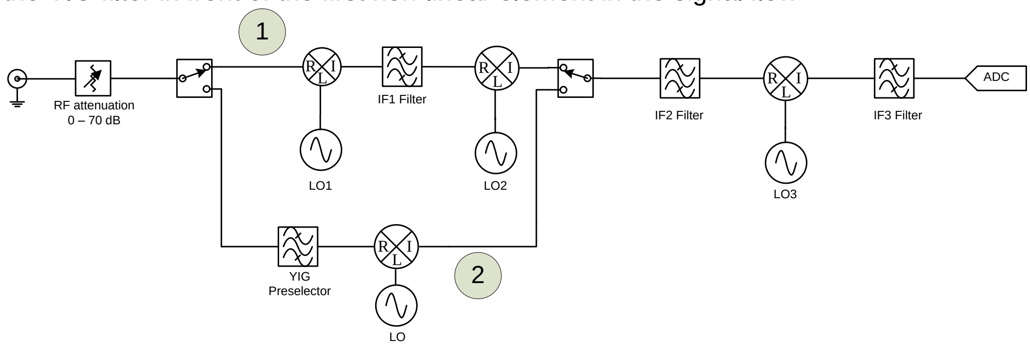

Figure 2: Simplified block diagram of a heterodyne spectrum analyzer, with RF path “1”, and microwave path “2”

3.1.1 Harmonics in the microwave range

As mentioned above, a tunable preselection filter is utilized for image frequency rejection in the microwave band. It is swept or tuned across the frequency range of interest and allows only a small band of frequencies to pass onto the mixer. The typical bandwidth of preselection filters is on the order of 30 MHz to 50 MHz.
For measurement of harmonic signals the YIG preselection filter is an advantage for the microwave signal path. When measuring harmonic distortion at 8 GHz or above with a 30 MHz band pass filter, the fundamental at e.g. 4 GHz will be suppressed by the filter and can therefore not create any harmonic signals. Practically speaking, if the spectrum analyzer is tuned to measure harmonic power at 8 GHz, the fundamental signal at the RF input port (4 GHz) does not reach a non-linear element, because the YIG preselector rejects it. Thus, the contribution of the spectrum analyzer to the measured harmonic power is negligible.

3.1.2 Harmonics below the microwave range

In contrast to the microwave signal path, the RF signal path of a spectrum analyzer usually does not have a tunable preselection filter. Consequently this means that without further precautions the signal power of the entire frequency band (e.g. DC to 8 GHz) will be applied to the first mixer. Assuming a CW input signal of 1.2 GHz, the first mixer in path “1” (Figure 2) also "sees" the 1.2 GHz signal when measuring the power at the harmonic frequency of 2.4 GHz. Therefore the harmonics created inside the mixer will be displayed on the analyzer screen as part of the measured signal power.

In order to optimize the performance in the RF frequency range, the R&S FSW uses several signal paths, each of them optimized for best performance within its frequency range.

In terms of harmonic measurements, an ideal spectrum analyzer would be equipped with a separate path for every octave, so that the fundamental and the harmonic signals always pass through different signal paths. Even though this looks like a straightforward concept, the number of switching points has a direct impact on the sweep speed, since every switching point costs additional settling time before the measurement can be continued. As in practice the "one octave per path" concept cannot be maintained for low frequencies, the R&S FSW starts to use it at 350 MHz.

Figure 3 shows the preselection concept of the R&S FSW for frequencies below 8 GHz. In the diagram, all parallel paths for the different frequency ranges are numbered from “1” through “5”. The signal flow chart is simplified, but contains all significant filters of the preselection concept.

Preselector (on Frontend)

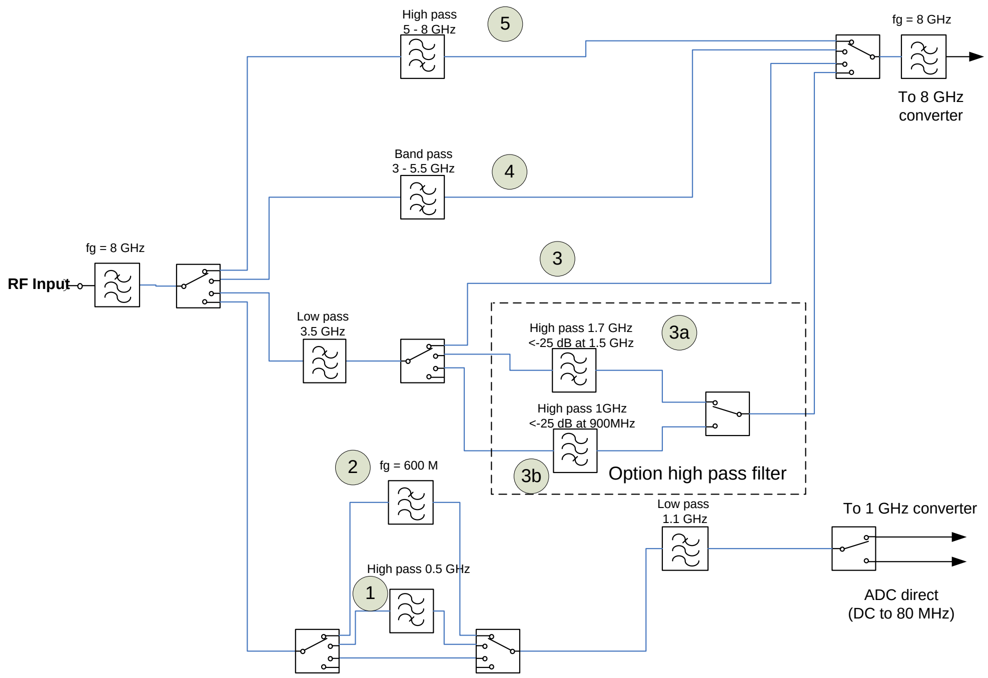

Figure 3: Signal Flow for f ≤ 8 GHz

In Figure 3, signal paths “1”, “4”, and “5” each comprise less than an octave. The frequency range limitation of each path is defined by low pass or high pass filters, as shown in the figure.

Signal path "2" is used for frequencies < 600 MHz. As discussed above, the concept to separate fundamental and harmonic, does not apply for this path.

Signal path “3” from 1 GHz to around 3.5 GHz requires special attention, as it covers the most popular frequencies for mobile communication standards, such as GSM, WCDMA, or LTE. Without additional measures this signal path will cover more than one octave.

By adding two different high pass filters, option R&S FSW-B13 "High pass filter for harmonic measurements", splits signal path "3" into two paths, “3a” and “3b”, which now comprise less than one octave each. Option B13 increases the second harmonic intercept point of the R&S FSW from 47 dBm (without option B13) to 62 dBm for fundamental frequencies in the range between 500 MHz and 1500 MHz.

The additional high pass filters added by option B13 can be activated on demand. In default operation (filters off) the R&S FSW provides maximum sweep speed, in harmonic suppression mode (filters on) the R&S FSW provides optimum harmonic distortion performance.

3.2 Differentiating between DUT generated and analyzer generated harmonics

During harmonic measurements, it is essential to make sure that the measured harmonic signals are generated by the DUT and not caused by the measuring instrument.

As already mentioned, the first mixer will cause a major part of the harmonic distortion contributed by the spectrum analyzer. This part of the distortion depends on the power the mixer “sees”, and is therefore influenced by the RF attenuation applied to the signal. Adding RF attenuation at the analyzer input will therefore reduce its residual harmonic distortion.

The harmonic distortion part coming from the DUT is independent of the level at the first mixer of the spectrum analyzer. Adding RF attenuation will have no influence on the level distance between fundamental and harmonic signal of the DUT.

This difference in behavior can be used to minimize the harmonic distortion contribution of the spectrum analyzer: By increasing the RF attenuation, the harmonic signals created by the 1st mixer will decrease, whereas the external harmonic signals will not change in level on the display, as the spectrum analyzer compensates for the additional attenuation applied to them by shifting their signal level numerically. The signal flow in Figure 4 shows this compensation mechanism:

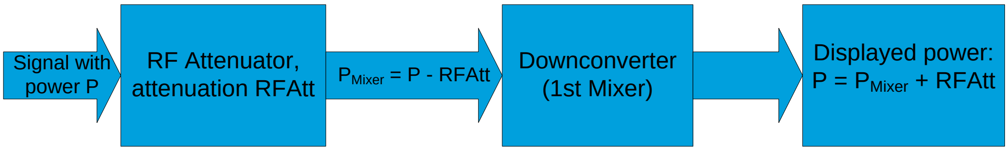

Figure 4: Signal Power Flow Chart through a Spectrum Analyzer, with signal power P, RF attenuation setting RFAtt, signal power at mixer P_{Mixer}, and displayed Power P (= signal power)

As an example, a CW signal at -10 dBm is assumed, with an initial attenuator setting of 0 dB. It is also assumed that the spectrum analyzer in use displays an inherent 2nd harmonic at -40 dBm. Increasing the attenuator setting to 10 dB still displays the fundamental at -10 dBm. Assuming an ideal DUT with no harmonics generated, the display of the 2nd harmonic caused by the 1st mixer of the spectrum analyzer will decrease by approx. 10 dB.

Due to this behavior, it is easy to differentiate between DUT generated harmonics and analyzer generated ones by using the variable RF attenuator of the spectrum analyzer.

In Figure 5 marker M2 shows the level of the harmonic signal with 0 dB attenuation, whereas marker M3 shows its level with 10 dB attenuation applied. The level difference is obvious, which means that a significant part of the harmonic power with 0 dB attenuation was generated by the spectrum analyzer.

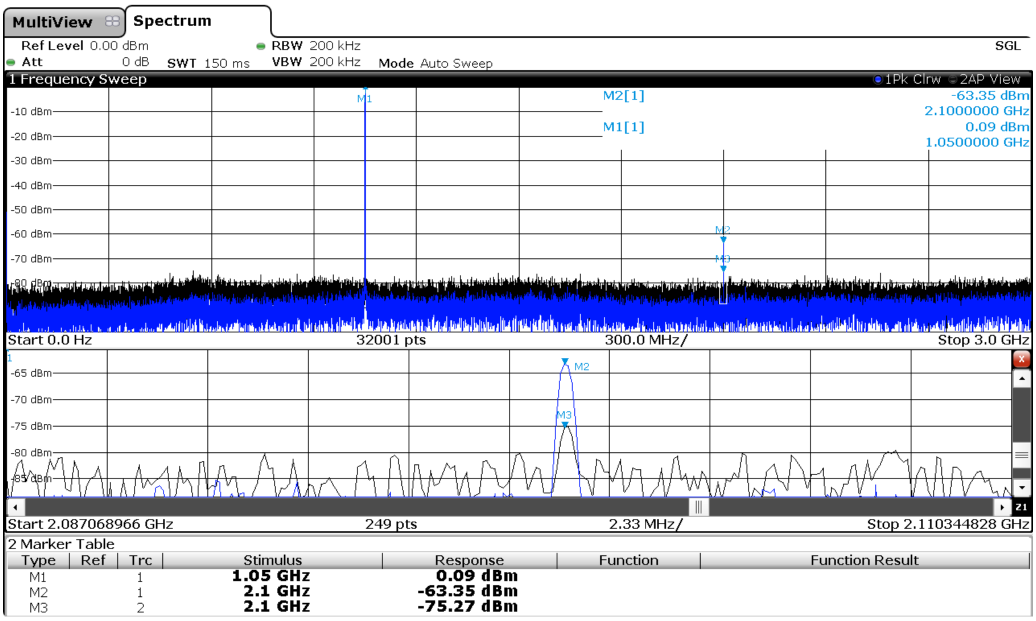

Figure 5: Fundamental and second harmonic, black trace with 10 dB RF attenuation, blue trace with 0 dB. The lower diagram shows the zoomed area around the 2nd harmonic

In the scenario used for Figure 5, the additional high pass filters of the R&S FSW-B13 option exhibit their full benefit. They provide a harmonic suppression for the given scenario of more than 20 dB, as shown in Figure 6, without having to increase the RF attenuation.

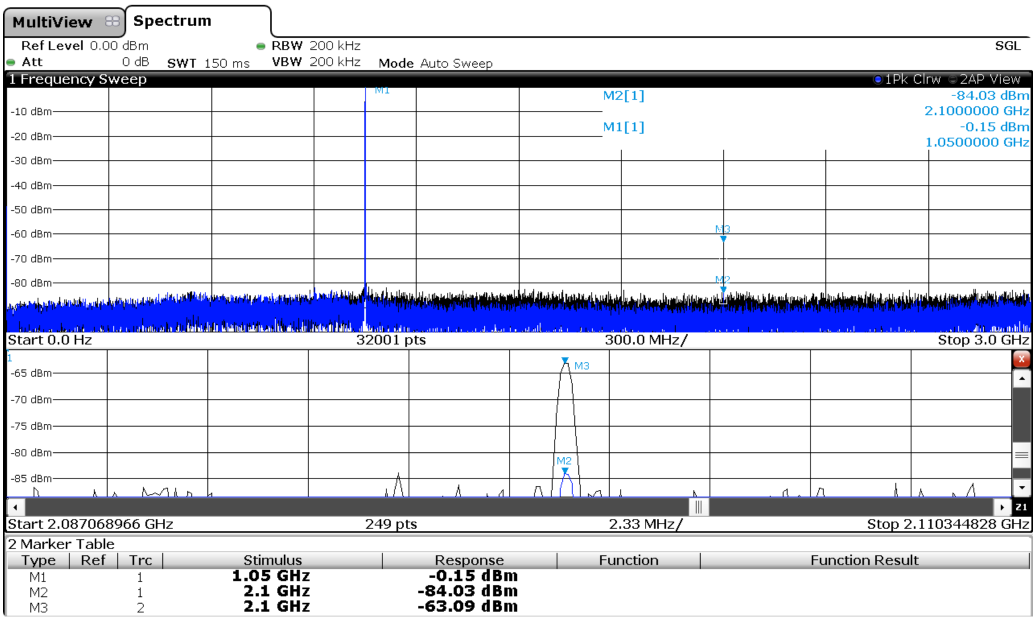

Figure 6: Fundamental and second harmonic, black trace with High Pass Filters Off, blue trace with High Pass Filters On, same RF attenuation. The lower diagram shows the zoomed area around the 2nd harmonic.

Other than in Figure 5, the noise floor does not increase, since no additional attenuation is used. A closer look even reveals a slightly lower noise floor, due to additional amplifiers in the high pass filter path. Clearly, using the high pass filters instead of additional attenuation allows more sensitive harmonic measurements when using the R&S FSW.

Figure 7 shows the *Input Source Dialog* (INPUT/OUTPUT – *Input Source Config*) used to activate the R&S FSW-B13 high pass filters.

Figure 7: Input Source Dialog providing the High Pass Filter On/Off selection

4 Conclusion

Whenever it gets to measuring harmonics on a spectrum analyzer, it is important to make sure that the DUT generated harmonics clearly dominate.

Increasing the RF attenuator setting is an appropriate way to minimize the analyzer generated harmonics at the cost of an increased noise floor, which means less sensitivity for the measurement.

The R&S FSW uses a design concept with high pass filters in the RF signal path up to 8 GHz, which minimizes the contribution of spectrum analyzer inherent harmonic signals. For harmonic measurements in the range from 1 GHz to 3.5 GHz option R&S FSW-B13 adds two more high pass filters, which allow harmonic measurements on cellular signals without sacrificing sensitivity.

5 Literature

[Rau01] Rauscher, Christoph. Fundamentals of Spectrum Analysis. 1st edition. Rohde & Schwarz.

6 Ordering Information

R&S FSW8	Signal- and Spectrum analyzer 2 Hz to 8 GHz	1312.8000.08
R&S FSW13	Signal- and Spectrum analyzer 2 Hz to 13.6 GHz	1312.8000.13
R&S FSW26	Signal- and Spectrum analyzer 2 Hz to 26.5 GHz	1312.8000.26
R&S FSW-B13	High pass filter for harmonic measurements	1313.0761.02

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