Some Measurements on DVB-T Dongles with E4000 and R820T Tuners: Image Rejection, Internal Signals, Sensitivity, Overload, 1dB Compression, Intermodulation

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1. Motivation

After having read quite a few posts in the user group *http://uk.groups.yahoo.com/group/SDRSharp* about the sensitivity or "deafness" of these dongles, but not having come across any figures, I feel constrained to post the results of my tests. I have measured two types of dongles:

- a Terratec dongle, containing an E4000 tuner and the RTL2832, VID + PID = 0CCD 00D7, designated *E4000* further down.
- a "no name" dongle marked "DVB-T+DAB+FM ", containing an R820T tuner and the RTL2832, VID + PID = 0BDA 2838, designated *R820* further down.

2. Test Setup

Instruments used:
- HF Signal Generators HP8657A (0.1…1040MHz) and HP8640B (0.5…520MHz)
- AF Voltmeter HP333A.

Software used: SDR# v1.0.0.135
Settings:
- *Configure*: 2.048MSPS, RTL AGC off, Tuner AGC off, RF Gain max (49dB for the R820, 42dB for the E4000)
- *Radio*: CW-U, Bandwidth 500Hz, Filter Order 300
- *AGC* off
- *FFT Display*: Window Blackman-Harris, Resolution 262144.
- In the spectrum display the noise floor appears at about -40dBm. In order to display the levels of received signals closer to reality, in *SDRSharp.exe.Config* I modified the value -40.0 in line *<add key="fftOffset"value ="-40.0"* to *"-120.0"*.

Having been an HF engineer and a ham radio operator for over 40 years, I am used to measure receiver sensitivity in dBm. I am aware of those UHF enthusiasts who are used to rate their receivers by Noise Figure (NF). It is easy to go from dBm to NF, however, by using the formula:

NF = Power of the MDS (dBm) + 174dBm - 10log(Bandwidth) - Measured S/N.

Example:
MDS (Minimum Discernible Signal) = Signal giving an (S+N)/N of 3dB (measured with the AF Voltmeter).
10log(Bandwidth) in my measurements is 10log(500) = 27dB.
For (S+N)/N = 3dB, S is equal to N. Thus, S/N is 0dB.
So, for an MDS of, say, -140dBm: NF = -140 + 174 - 27 - 0 = 7dB.

Remark 1: The dongles have a nominal input impedance of 75 Ohms, whereas my signal generators have output impedances of 50 Ohms. My dBm figures take account of the difference of 1.6dB.

Remark 2: The measurements were carried out on one dongle of each type only. Of course, the results may vary by several dBs between individual dongles.

Remark 3: In such measurements uncertainties of +/-1…2dB are common.

3. Image Rejection

The E4000 is a direct conversion receiver*;* therefore, a "hump" is clearly visible in the center of the spectrum display. It is mostly due to noise on the power source of the dongle, and could probably be reduced by a well filtered, external power supply (I did not try this). ***The R820 first mixes down to an IF of a few MHz***, and, therefore, does not show such a hump.

Both dongles present a peak in the center of the spectrum display of SDR#, which for the *E4000* can be reduced, and for the *R820* can be (almost) eliminated by marking *Correct IQ*.

For the *E4000*, marking *Correct IQ* improves the image rejection by about 30dB. Without *Correct IQ* the image rejection of the *E4000* is a poor 21dB (measured on 435MHz), with *Correct IQ* it reaches a more or less acceptable 50dBs. This means that for signals lower than about -90dBm no image will be visible any more in the spectrum display.

Because of the different technology, the *R820* does not have the same image rejection problem. Therefore, marking *Correct IQ* has no effect (except for the peak in the center of the spectrum display).

4. Internal signals

In digital receivers clock signals, poor shielding (space requirements!) and digital processing produce internal signals actually not present at the antenna input ("birdies" in ham speak). Since the dongles are not shielded, I wrapped them in aluminum foil connected to the PC ground. Figures 1 and 2 show typical examples. Harmonics of the clock frequency are quite strong and clearly visible up to at least 1GHz. Regarding birdies, the *R820* is much cleaner than the *E4000*.

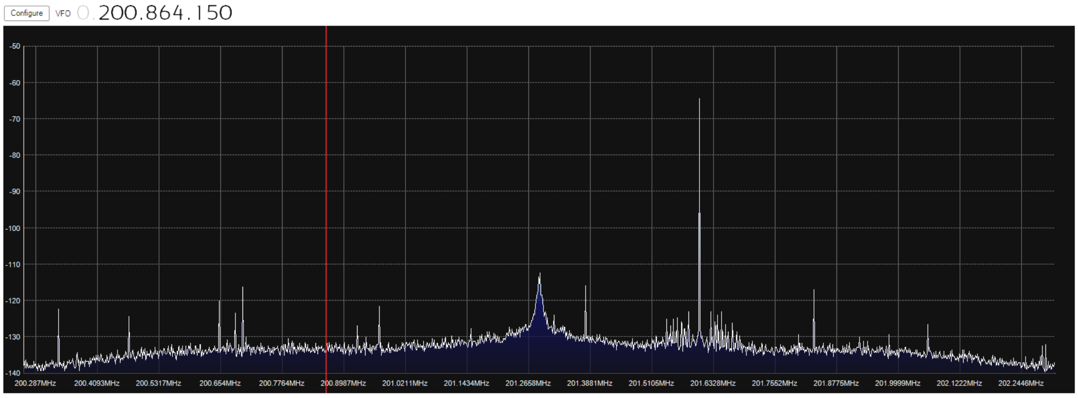

Figure 1 *E4000*: 7th harmonic of the clock frequency 28.8MHz and other "birdies".

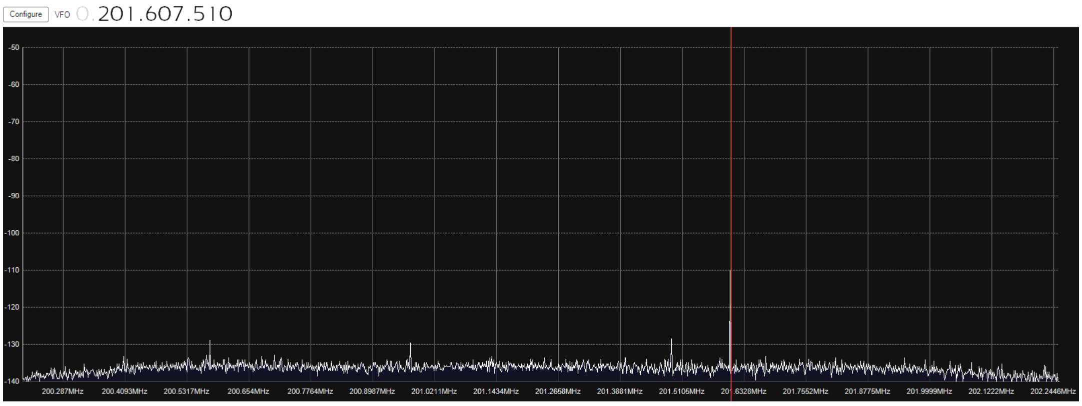

Figure 2 *R820*: 7^{th} harmonic of the clock frequency 28.8MHz and a few, weak birdies. Also note the missing "hump" in the center.

It is easy to recognize birdies: most of them (except the harmonics of the clock, of course) vary their frequency when moving the spectrum window in frequency. Many of them even move up if you move the window down in frequency.

5. Sensitivity

Definition of sensitivity:
MDS (Minimum Discernible Signal) = 3dB (S+N)/N, measured with the HP333A.

My signal generators only go up to 1040MHz, therefore no measurements were possible on higher frequencies. Using harmonics of the generators, I was able to verify that my E4000 had a range of 51.850…>2080MHz, with a gap of 1105…1268MHz. My R820 had a range of 24…1766MHz without a gap.

Frequency MHz	Sensitivity *E4000* dBm	Sensitivity *R820* dBm
24	n.a.	-127
52	-139	-134
110	-139	-134
145	-141	-134
435	-139	-135
700	-136	-136
1000	-129	-137

Table 1 Sensitivity

Remark: The figures are for signals about in the middle between the left edge and the center of the spectrum display. At the edges the sensitivity is a few dBs less.

Both dongles are very sensitive. Between 50 and about 500MHz the *E4000* is about 5dB more sensitive than the *R820*, but at 1000MHz the *E4000* is about 8dB less sensitive compared to the *R820*.

6. Overload and 1dB Compression

6.1 Overload

Figures 3 and 4 show the effects of a single, strong signal within the window of the spectrum display:

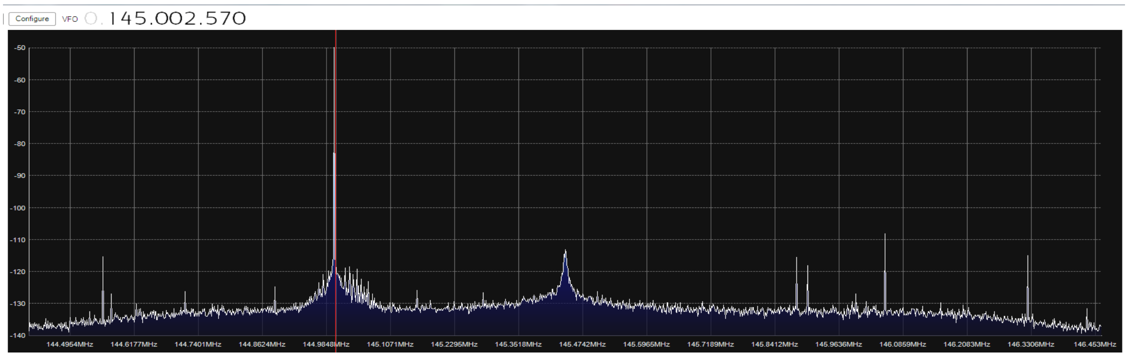

Figure 3 *E4000:* Just before overload at 145MHz/-64dBm (the other signals are "birdies" and aliasing products)

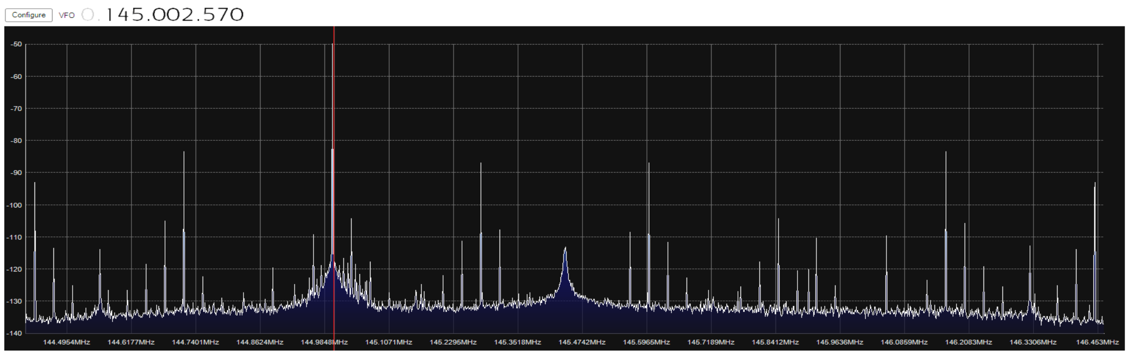

Figure 4 *E4000*: Overload at 145MHz/-63dBm: a multitude of "phantom signals" pop up

The "phantom signals" pop up suddenly, within an increase of the level of the strong signal of only 1dB.

At 145 MHz turning on *RTL AGC* surprisingly degrades the overload limit by about 5dB. Then reducing the gain improves the overload limit, but not by the same amount the gain is reduced. Turning on *Tuner AGC* and maintaining full gain has no effect on the overload limit. And if the gain is then reduced, the overload limit does not improve at all. At 435MHz the behavior is the same.

The effects of overload of the *R820* are similar to Figure 4. At 145MHz turning on *RTL AGC* and maintaining full gain degrades the overload limit by 1…2dBs. Then reducing the gain improves the overload limit by about the same amount the gain is reduced. Turning on *Tuner AGC* is to be avoided: it degrades the overload limit by about 10dBs, independent of the gain setting.

At 435MHz turning on *RTL AGC* and maintaining full gain improves the overload limit by 1…2dBs. Then reducing the gain improves the overload limit by about the same amount the gain is reduced. Turning on *Tuner AGC* is to be avoided: it degrades the overload limit by about 10dBs, independent of the gain setting.

For both dongles it seems there is nothing to be gained from activating *RTL AGC* or *Tuner AGC*.

6.2 1dB Compression

The block diagrams of both dongles show an RF filter after the preamplifier. These filters (and also the subsequent digital signal processing) should help to improve the overload limit as the strong signal is moved away from the center frequency of the spectrum display.

But the level of such a strong input signal cannot be increased without limits, because the preamplifier will saturate at some point (and, ultimately, will give smoke signals), hence reducing the S/N ratio of a desired signal. It is common practice to determine the level of a strong signal that causes a reduction of the S/N ratio of a desired signal by 1dB.

I tried to measure the overload limit and/or the 1dB compression limit for two center frequencies of the spectrum display, 145MHz and 435MHz. The desired signal was close to the center frequency with a level of -80dBm. If overload occurs like in Figure 4, the limit can be determined quite accurately (within 1…2dB). For strong signals further away from the desired signal, the limit is not that well defined anymore, because then the effect of overload becomes weaker, and finally only a handful of "new" signals pop up in the display. In these cases I chose the 1dB compression as the limit. The following figures show overload and/or 1dB compression limits for both dongles, and for center frequencies of 145MHz and 435MHz.

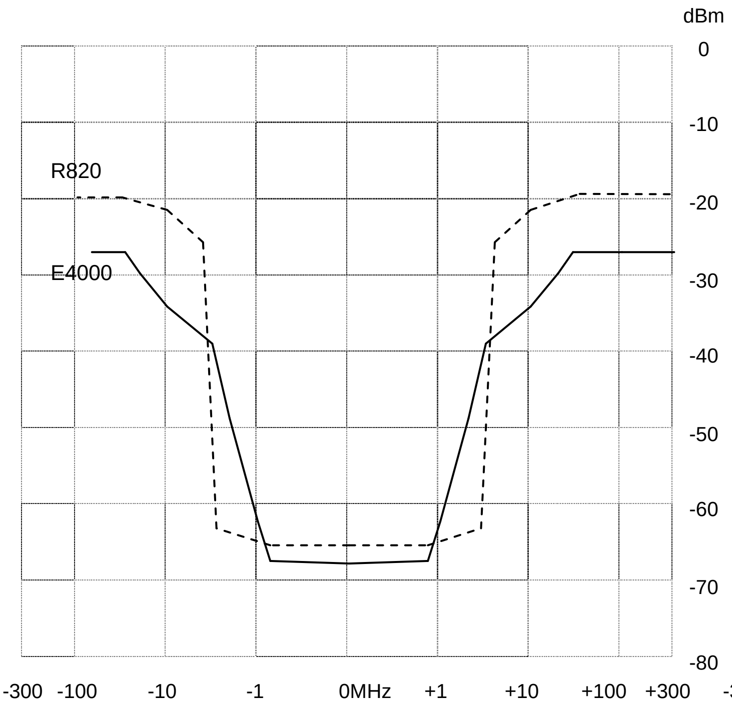

Figure 5 Overload/1dB Compression at 145MHz
Desired signal -80dBm at 145.03MHz
E4000 = ——— *R820* = - - - - -

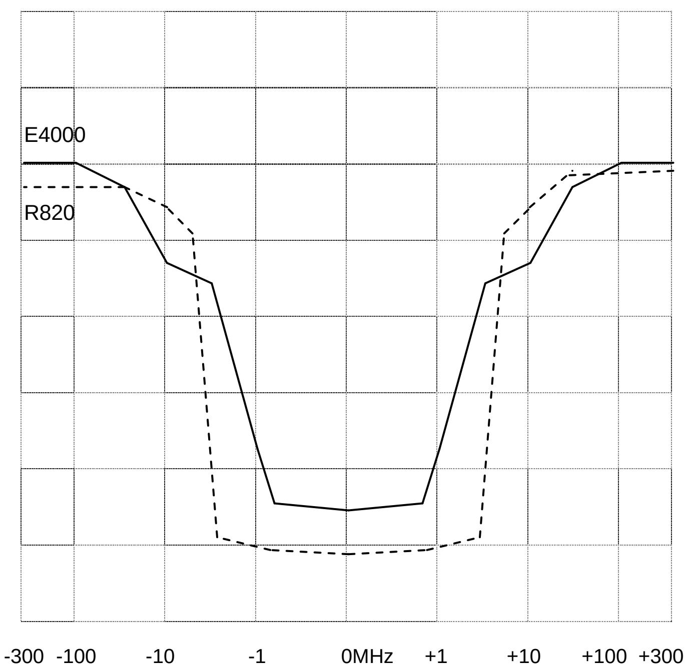

Figure 6 Overload/1dB Compression at 435MHz
Desired signal -80dBm at 435.03MHz
E4000 = ——— *R820* = - - - - -

For a weaker desired signal of only -120dBm the measured values differed by only about +/-1dB for both center frequencies and for both dongles. I was very surprised by these results; I had expected the preamplifier to overload at much lower signal levels.

The figures show that the digitally tuned filters (and the subsequent digital signal processing) of both dongles improve the overload/1dB compression limit considerably. The filters are more or less symmetric.

The filter of the *E4000* is about +/-0.8MHz wide, but less steep than the filter of the *R820*. Surprisingly, at 435MHz the filter is a bit steeper than at 145MHz. Within this bandwidth a signal of about -64…-62dBm causes overload. At about +/-5MHz 1dB compression becomes the limiting effect.

The filter of the *R820* is about +/-3MHz wide, but steeper than the filter of the *E4000*. Up to about +/-1MHz the effects of overload caused by a signal of about -62…-68dBm are very similar to those of the *E4000*. Up to about +/-3MHz the effects of overload are still the same, but getting weaker. At about +/-10MHz 1dB compression becomes the limiting effect.

For the *E4000* the overload/1dB compression limit is not linearly dependent of the gain set in *Configuration* of SDR#: if the gain is reduced by 13/20/30dB, the overload limit is improved by only 7/14/25dB (measured on 145MHz only).

For the *R820* the overload/1dB compression limit is nearly linearly dependent of the gain set in *Configuration* of SDR#: if the gain is reduced by 11/20/30dB, the overload limit is improved by 12/20/30dB (measured at 145MHz only).

7. Intermodulation

If strong signals are fed to a nonlinear amplifier (they all are nonlinear to a certain extent), intermodulation products are generated.
Their general form is: $f_{IM} = +/-n \bullet f_1 -/+m \bullet f_2$ where n+m is called the order of the intermodulation.

Example for Intermodulation of third order (IM3) with f_1 = 145.1MHz and f_2 = 145.2MHz:

f_{IM3} = 2 • 145.1 - 1 • 145.2 = 145.0MHz and -1 • 145.1 + 2 • 145.2 = 145.3MHz
and for IM5: f_{IM5} = 3 • 145.1 - 2 • 145.2 = 144.9MHz and -2 • 145.1 + 3 • 145.2 = 145.4MHz

So, if the two signals are spaced by x kHz, the IM products are appearing every x kHz to the left and to the right of these signals.

IM3 is the strongest. IM levels decrease as their order increases.

7.1 Intermodulation in the *E4000*

Figure 7 shows intermodulation products generated in the *E4000* by two signals at 145.1 and 145.2MHz. The many signals to both sides of the IM products are due to overload occurring at the same time: The signals at 145.1 and 145.2MHz each have a level of -67dBm. Thus, both signals together exceed the overload level at 145MHz. The highest signal at the far left is the 5^{th} harmonic of the clock, and is always present.

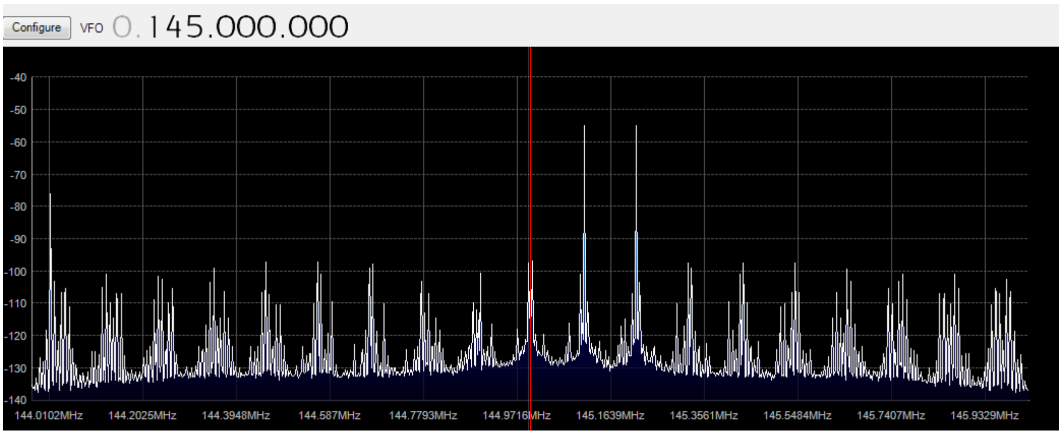

Figure 7 *E4000,* Intermodulation products and overload caused by two signals of -67dBm at 145.1 and 145.2MHz

Figure 8 shows what happens with two strong signals at 147.5 and 147.6MHz, i.e. outside the bandwidth of the filter of the *E4000*. The IM products, evenly spaced at 100kHz are clearly visible. At the same time additional signals pop up, because the two strong signals together reach the overload limit. The same happens if the two strong frequencies are even further away from the center frequency: IM products become visible at about the same level overload occurs.

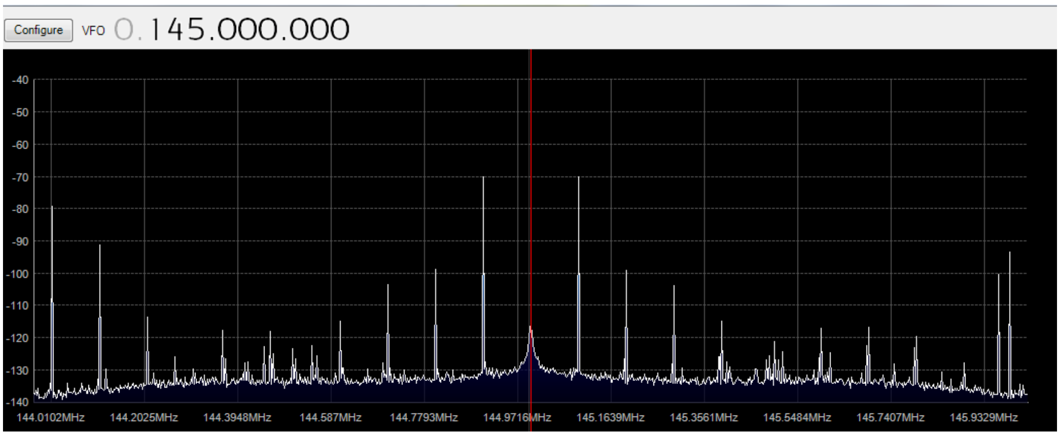

Figure 8 *E4000,* Intermodulation products and overload caused by two signals of -42dBm at 147.5 and 147.6MHz (outside the spectrum display and the filter bandwidth)

Figure 9 shows what happens if the two strong signals are far away (+50MHz) from the center of the spectrum display: IM products begin to appear already at levels of about -40dBm each, i.e. at much lower levels than the overload/1dB compression limit of -24dBm.

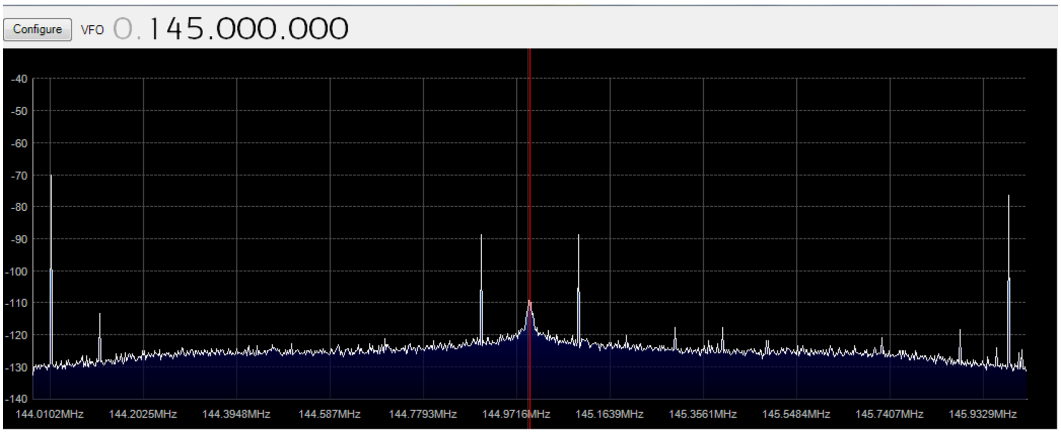

Figure 9 *E4000*, effects of two strong signals of -40dBm at 195.0 and 195.1MHz (far off the center frequency)

At 435MHz the IM in the *E4000* is similar to 145MHz (accounting for the differing overload/1dB compression limits).

7.2 Intermodulation in the *R820*

Figure 10 shows the *R820* with two strong signals of -65dBm each at 145.1 and 145.2MHz. IM products begin to appear, but at the same time both signals together exceed the overload limit. The highest signal at the far left is the 5th harmonic of the clock, and is always present.

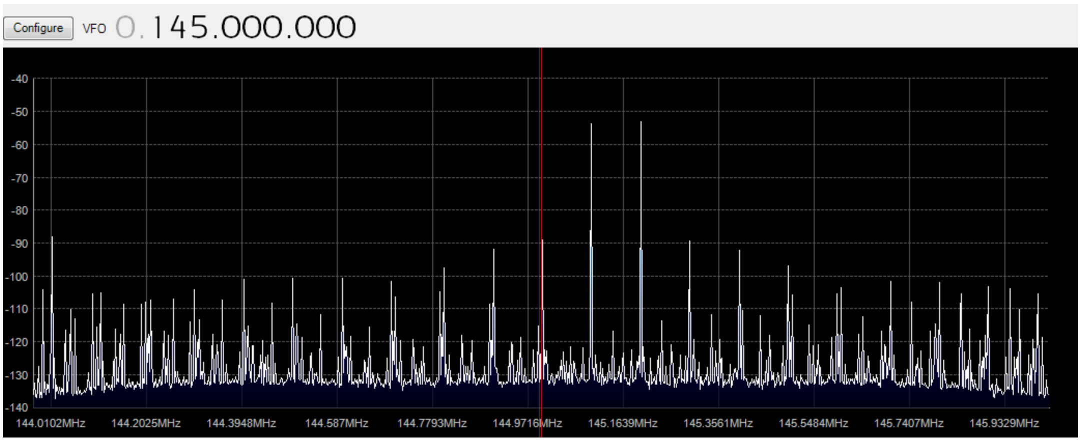

Figure 10 *R820*, intermodulation products and overload caused by two signals of -65dBm at 145.1 and 145.2MHz

Figure 11 shows how the *R820* copes with two strong signals of -37dBm each at 150.0 and 150.1MHz (outside the filter bandwidth): a few IM products begin to appear.

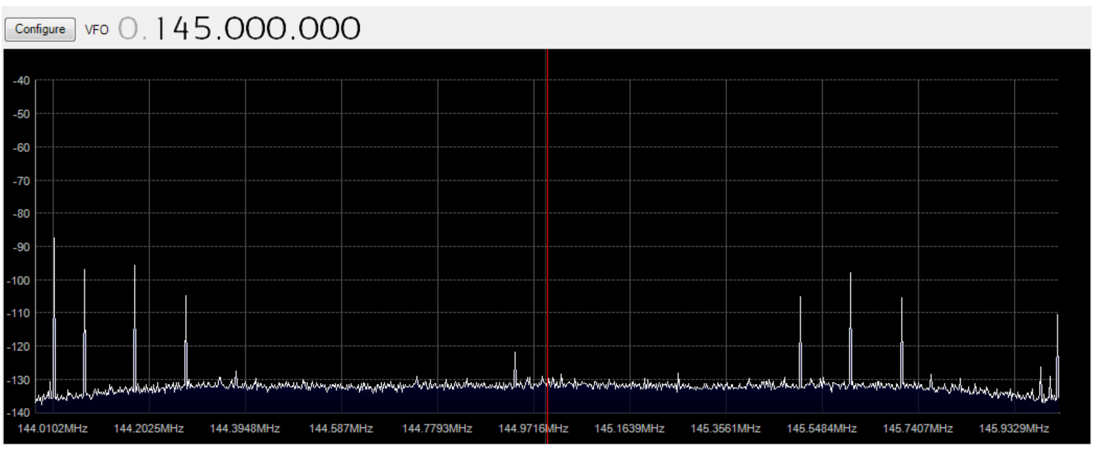

Figure 11 *R820*, effects of two strong signals of -37dBm at 150.0 and 150.1MHz (outside the spectrum display and the filter bandwidth)

Figure 12 shows what happens in the *R820* with two strong signals far away from the center of the spectrum display at the overload/1dB compression limit: the noise floor rises by about 3dB, and a few "new" signals appear.

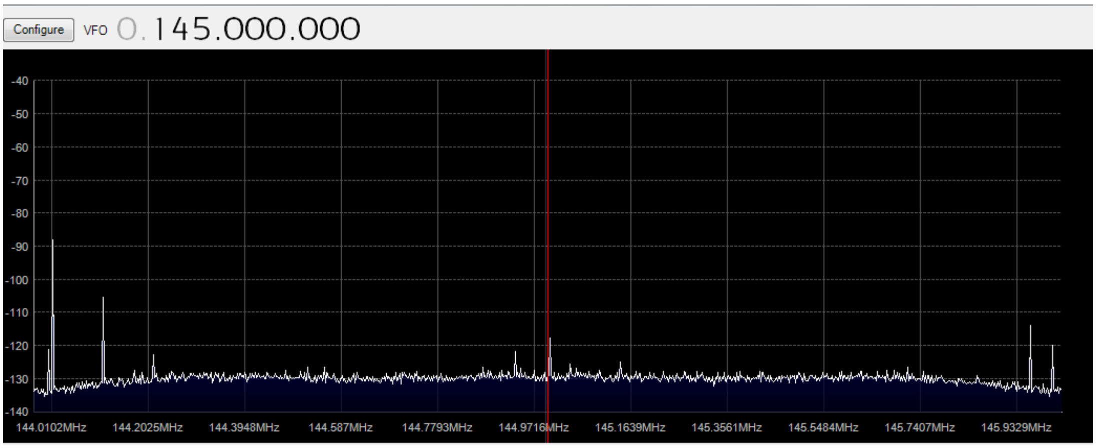

Figure 12 *R820*, effects of two strong signals of -20dBm (at the overload/1dB compression limit) at 195.0 and 195.1MHz (far off the center frequency)

At 435MHz the IM in the *R820* is similar to 145MHz (accounting for the differing overload/1dB compression limits).

It seems that for frequencies far off the center frequency the *R820* is less prone to IM than the *E4000*.

8. Aliasing

Aliasing always occurs if an insufficiently band limited signal is sampled, i.e. if the signal to be sampled contains frequencies above half the sampling frequency. Thus, aliasing is an effect showing up in many SDRs, not only in these dongles. In both types of dongles there is not much space for brickwall filters, hence aliasing is to be expected. As an example, Figure 13a shows a desired signal of -80dBm at the far left, and a corresponding aliased signal in the center. If the spectrum display is moved to higher frequencies (by sliding it to the left), the desired signal will disappear at the left, but at the right it will reappear as Alias 2, whereas Alias 1 moves to the right (see Figure 13b). If moving to still higher frequencies, Alias 2 will move more to the left, maintaining its frequency, while its level will decrease because of the effect of the (non-perfect) filtering. At the same time Alias 1 will slide more to the right, maintaining more or less its level, because the filter does not have better wide band attenuation, but increasing in frequency. So, some aliased signals can be recognized by the fact that they are not constant in frequency when the spectrum display is moved. Others are constant in frequency, but not in level. Both types will show the same modulation, e.g. no modulation at the same time.

Aliasing effects are similar in both types of dongles.

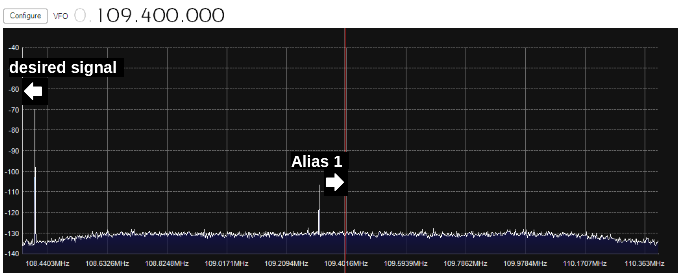

Figure 13b *R820*, Example for aliasing effects: desired signal and an aliased signal

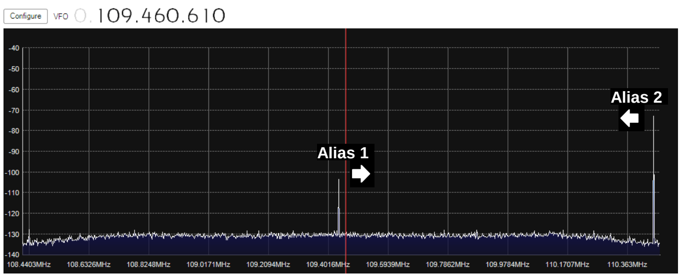

Figure 13b Tuned to a higher frequency, the desired signal disappears at the left and an aliased signal reappears at the right

9. Summary

General notes

- The measurements were carried out on one dongle of each type only. The results may vary by several dBs between individual dongles.
- In such measurements uncertainties of +/-1…2dB are common.

Image Rejection

Because the *E4000* is a Direct Conversion Receiver, it has an Image Rejection problem. By switching on *Correct IQ* in SDR# a more or less acceptable 50dBs are reached. For the same reason, a "hump" shows in the center of the spectrum display. By using a well filtered external power supply (not from the USB connector) the hump might be reduced.

Internal signals
The *E4000* shows many signals actually not present at its input ("birdies"). Birdies are easy to recognize: most of them (except the harmonics of the clock) vary their frequency when moving the spectrum window in frequency. Many of them even move up if you move the window down in frequency.

The *R820* is much cleaner in this respect: besides the harmonics of the clock (28.8MHz) only few birdies show up.

Sensitivity
Both dongles have a very high sensitivity. Between about 50 and 450MHz the E4000 is about 5dB better than the R820 (-139dBm vs -134dBm). At 1000MHz the E4000 is about 8dB less sensitive (-129dBm vs -137dBm). No measurements could be made above 1040MHz.

Overload and 1dB Compression
If a signal is strong enough, it may cause overload, i.e. many (unwanted) signals show up on the spectrum display that are not present at the antenna input. Also, if we listen to a desired signal, another signal (if strong enough) may cause a reduction of the S/N ratio of the desired signal.

Both dongles have a digitally tuned RF filter after the preamplifier that (together with the following digital signal processing) improves the overload/1dB compression limit considerably.

- The filter of the *E4000* is about +/-0.8MHz wide, but less steep than the filter of the R820.

- The filter of the *R820* is about +/-3MHz wide, but steeper than the filter of the E4000.

For the *E4000* the overload/1dB compression limit is not linearly dependent of the gain set in *Configuration* of SDR#: if the gain is reduced by 13/20/30dB, the overload limit is improved by only 7/14/25dB (measured on 145MHz only).

For the *R820* the overload/1dB compression limit is quite linearly dependent of the gain set in *Configuration* of SDR#: if the gain is reduced by 11/20/30dB, the overload limit is improved by 12/20/30dB (measured at 145MHz only).

For both dongles it seems there is nothing to be gained from activating *RTL AGC* or *Tuner AGC*.

Intermodulation
Intermodulation products in general show up close to the overload/1dB compression limits. However, if the strong signal is on the roll off of the filter, they appear well before this limit.

Aliasing
Aliasing always occurs if an insufficiently band limited signal is sampled, i.e. if the signal to be sampled contains frequencies above half the sampling frequency. Thus, aliasing is an effect showing up in many SDRs, not only in these dongles. In both types of dongles there is not much space for brickwall filters. Therefore, aliasing effects are well visible with both dongles.

10. What do we learn from these tests?

- Both types of dongles are very sensitive. The choice depends on which frequency range you are most interested in.
- Considering birdies and image rejection, the R820 is much cleaner than the E4000.
- Set the spectrum display to show a range of not more than 60db above the noise floor. If a signal is close to the top, you know you are close to overload.
- Both types of dongles are prone to overload by strong signals within their filter bandwidth: +/-0.8MHz for the E4000, +/-3MHz for the R820. Therefore, keep signals within this bandwidth to not more than about 60dB above the noise floor by reducing the gain. If increasing the gain does not audibly increase the signal to noise ratio of the desired signal any more, reduce the gain by one step. Do not switch on RTL AGC or Tuner AGC, as it seems there is nothing to be gained.
- Outside their filter bandwidth both types of dongles can live with much higher signals without showing serious degradation. Use the gain control as explained above to check a possible reduction of signal to noise ratio of the desired signal or the appearance of "new" signals not present at the antenna input.
- Intermodulation occurs if several strong signals are present within the bandwidth of the dongle. Their individual voltage levels add up (add 6dB per equally strong signal). Therefore, in frequency bands with many strong signals, e.g. broadcast bands, the gain must be reduced even further. Watch for "new" signals appearing when increasing the gain, and then reduce the gain by one step.
- If very strong signals are present at the antenna input (>-40dBm), they should be attenuated by bandstop or notch filters.

Of course these neat, little toys are no match for "real" software defined receivers. They do have some limitations, but you get a LOT of radio for almost no money! They are fun to experiment with, and to learn more about SDR technologies.