A DVB-T-Stick With An E4000 Tuner As A Measuring Receiver

Procurement, characteristics, conversion and operation using the software SDR#

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First published in the German UKW Berichte journal 3/2013

Digital receiver DVB-T Sticks are very popular at the moment and need to be investigated. It is worth mentioning the two-part article by Dirk Müller [1], [2]. They are very good and can be recommended as required reading on this topic. These articles inspired me to take a close look at these devices. This article should show what they are capable of and help others to get started.

1 Introduction

After reading both articles [1, 2] it was clear that such a Stick must be played with extensively. This means that it must be installed, connected to an SMA input in a shielded enclosure and connected to a PC using the highest quality USB cable available. This is the only way to obtain reproducible and exact information from a disturbing computer using a professional signal generator. Because the objective was to investigate the use of a Stick as an amplifier, receiver or spectrum analyser up to a maximum of 2 or even 2.2GHz, only a version with an E4000 tuner was considered.

2 Procurement

This should really be no problem because these Sticks are widely available. Unfortunately the information about the chip set used very poor! There are lists on The Internet [5], [6] but these are not always completely up-to-date. Unfortunately some companies have a nasty habit of “secretly” changing the chip set in a product. Therefore The Internet search engine “Google” was used with the search term "RTL2832U E4000" and lo and behold, the first 4 or 5 hits were from sellers in China selling on eBay. The price including postage was less than €20. The pictures with the listing of the PCB and the ICs used were beautiful. The eBay policy of monitoring and reporting "Top rated sellers" greatly reduces the risk. Payment was made using PayPal and a few days later there was a delivery from China. As well as the Stick this included a small rod antenna (a TerraTec version), feet, a short USB cable and software on CD. A twin shielded USB cable fitted with a ferrite ring (5m for about €6 on the Internet) should not be forgotten.

3 Preparation and Installation: a difficult task

The first task is to remove the plastic casing and expose the circuit board. That is easy using a knife or screwdriver because there are only four little lugs to overcome. However, there is a serious warning required:

You should take ESD protection measures (protection against damage by static charges), the CMOS

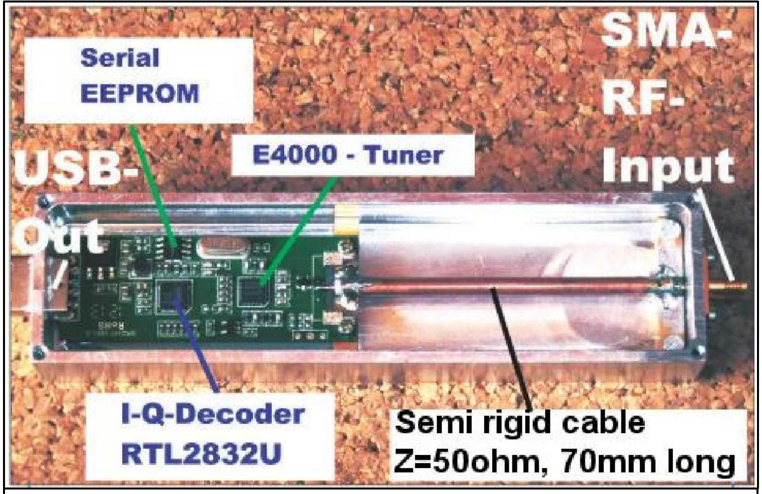

Fig 1: The goal is to prepare the stick in the milled aluminium housing for the measurements

devices are easily destroyed! The result is shown in **Fig 1:**

First a 30 x 130mm machined aluminium housing was made for the printed circuit board from stock material with a rectangular cut out on the a narrow side for the USB connector. The other end of the Stick (now out of its plastic housing) rests on a polished brass block attached to the housing with two M2 screws. The PCB can therefore be fitted and kept parallel to the bottom of the housing. At the other end of the housing another brass block with a depressions filed in the centre was fitted. A 70mm length of semi rigid coax cable was soldered to this block and attached to the antenna input of the Stick and to an SMA connector on the outside of the housing.

A problem arose when the cable sheath was being soldered to the two brass blocks. It proved nearly impossible because of the enormous heat dissipation through the aluminium housing and the semi rigid cable was destroyed. So the blocks were removed, tinned carefully (after heating with a very small, but extremely practical gas burner from PROXXON). The excess solder was removed with a brass wire brush. After reassembly an old 250 Watt soldering iron was used that had enough stored heat to make the solder joints quickly. The white patches in **Fig 1** around the USB connector are conductive silver used to fill the gap around the connector to make a good electrical seal.

4 The Program "SDR#": Purchase and installation

From [1] and [2], the decision on software was easy. SDR# was chosen for using the Stick mainly as a universal receiver or as a spectrum analyser up to 2GHz. This software is continuously developed so the best place to download it is from the homepage for "SDR#". There is an option to download an installation package for the latest program at www.sdrsharp.com [4]. The option to choose is in the middle of the download page is:

> *You can use this quick installation script to test the latest development version: http:/sdrsharp.com/downloads/sdr-install.zip*

After downloading and unpacking the installation is no problem. There are many improvements so be sure to delete any older versions.

A tip:

You should make this new installation once per month to get the benefit from the latest tricks and subtleties. In case of problems you can always store the previous SDR# installation in a "backup folder".

After a successful installation operation continues as follows:

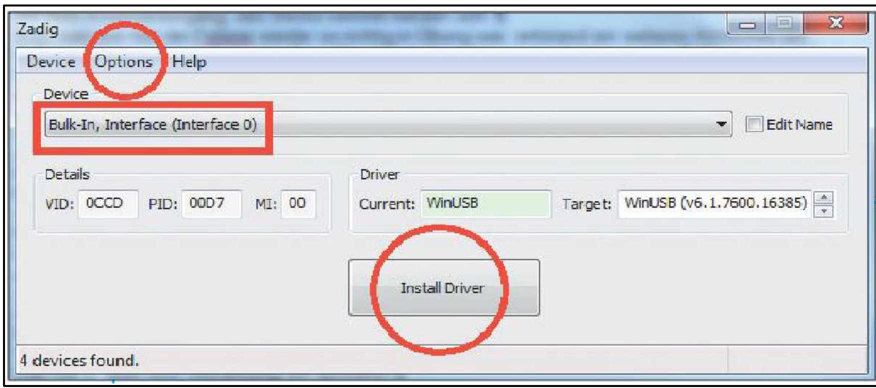

Fig 2: Without installing the correct driver, nothing works (see text)

a. Connect the stick to the computer, change to the newly created SDRinstall folder and navigate to the subfolder "sdrsharp". Start the program "zadig.exe" and open the "Options" menu (**Fig 2**). This “Lists all Devices" that work with USB, from this list select "BuIk In, Interface (Interface 0)" for the Stick. The program should accept this; now select the prompt "Install Driver" to execute. A sure sign is the final message "Driver installed".

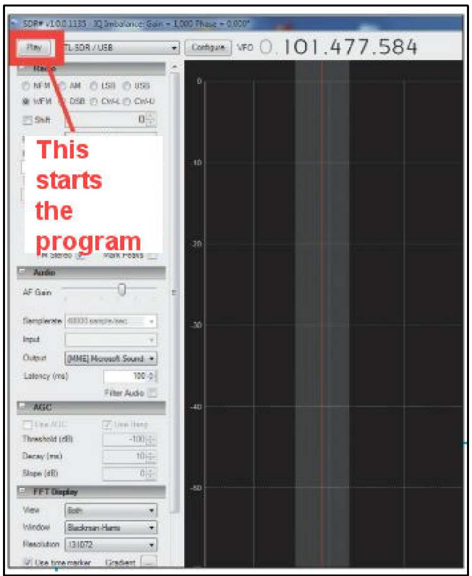

Fig 3: This is the start screen but nothing is happening yet

b. Now the actual program “SDR#” can be started from the same subfolder by clicking on "SDRsharp.exe" and the screen shown in **Fig 3** should be displayed.

Nothing should happen but that should change in the next chapter (if something does happen, be aware of the "PIay / Stop" button in the upper left corner of the screen.

5 Installation Confirmation and Function Test: FM radio reception

A small antenna was made from a 25cm long piece of semi rigid cable with the copper jacket and Teflon inner insulation removed and fitted to an SMA angle plug. The inner conductor consists of high strength silver plated steel wire and is therefore a fairly robust rod antenna (**Fig 4**). Shortly before the end of a presentation the E4000 tuner IC was destroyed by a static over voltage from the touch of a visitor. Therefore a HAM Radio solution was used to replace this with an improved version. Only the copper outer of semi rigid cable was removed and the inner insulation remained on the silver plated inner conductor.

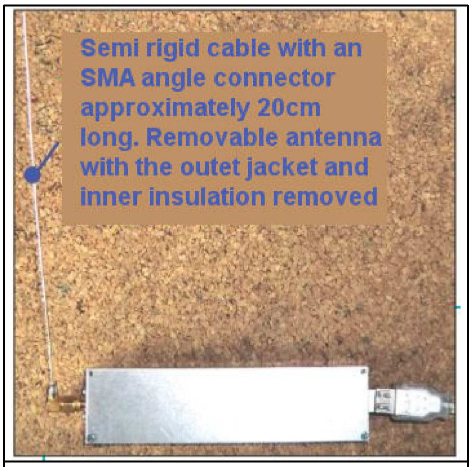

Fig 4: The first attempt at a removable antenna

5.1 The Basic Settings

On the screen with everything quiet you can look in the upper left corner of the screen. In addition to the "Stop / Play" button there is access to the available USB devices. It should be "RTL-SDR / USB". If this is not the case (for example, the message "Others (sound card)" is shown), go to this menu and switch to

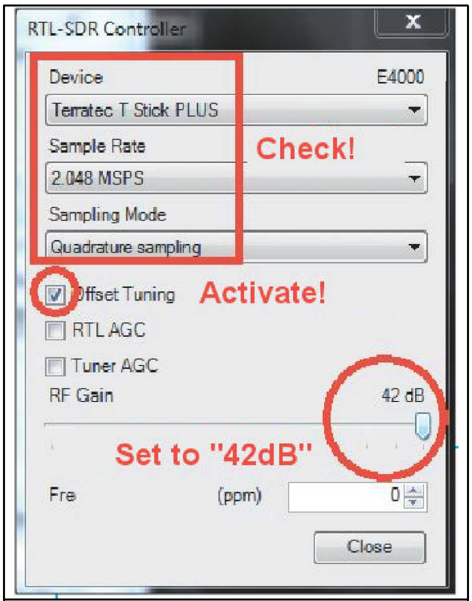

Fig 5: These settings in the "Conf-igure" menu must be correct

"RTL-SDR / USB".

Now click on "Configure" (in the upper left corner) because you must adjust the settings according to **Fig 5.** In the upper half of the menu check that the Stick was correctly detected and a sample rate of 2,048 Mega Samples is set. Set the sampling mode to "Quadrature Sampling" to suit the demodulator of the RTL2832U.

Important:

These changes to the driver selection, sampling mode, or the sample rate are only possible, if the program is stopped!

Next switch "offset tuning" on (this shifts the zero point of the spectrum view) and set the amplification (RF gain) to full = 42dB. Now close the menu and go to the "Radio" menu in the upper left corner (**Fig 6**). Viewed from the top downwards:

a. The SDR stick detected is displayed.

b. Enable "WFM" = wideband FM.

c. The filter type, you can't go wrong with "Blackman-Harris".

d. A filter bandwidth of 180kHz is perfect for listening to the radio.

e. A step size of 50kHz is the standard channel spacing of FM broadcasting.

f. Finally put a tick next to "Correct IQ" (and if you want: even "FM Stereo").

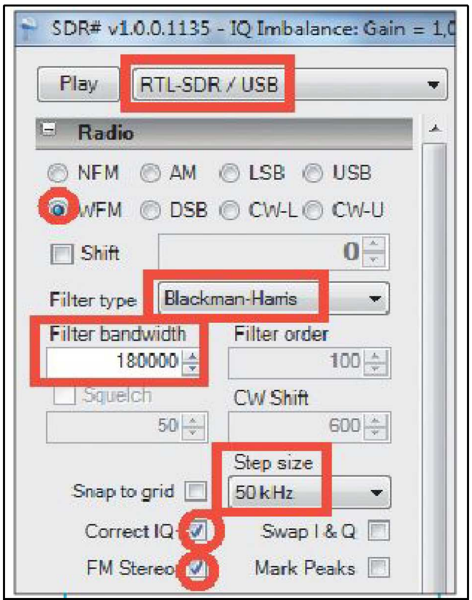

Fig 6: After the program has star-ted you can use these settings for FM stereo sound

Now the FFT display should be viewed at the lower left of the picture (**Fig 7**); Here are the setti-ngs from top to bottom:

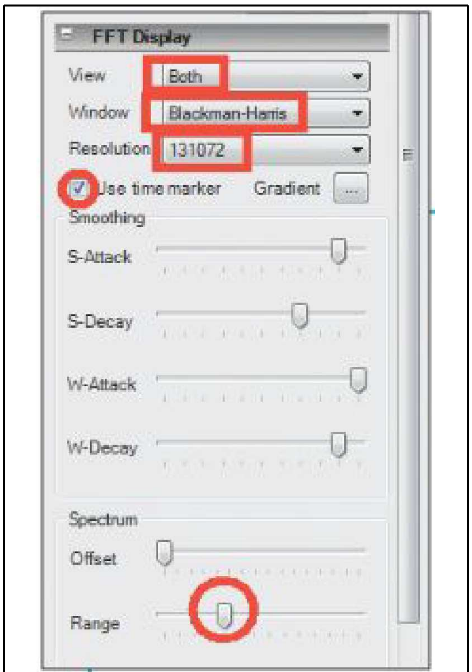

Fig 7: The FFT setting should be chosen to suit the PCs power

1. "Both", switches on the simultaneous display of spec-trum and waterfall (use the mouse to lift the bottom of the spectrum display because it hides the waterfall)
2. Blackman-Harris FFT filter.
3. "Resolution" is related to the number of sample values used for each new spectrum calculation this means: the more samples, the finer the frequency resolution and the clarity of the PC screen. As the number of samples increases, the demands on compu-ting power increase enormously and the demand for

memory increases correspondingly. It is best to test which setting gives no jerks. For computers with a clock frequency of more than 2GHz 131,072 samples should be possible, which results in a pleasant spectrum display.

4. If you want some fun, time markers can be shown in the waterfall display.
5. "Range" sets the range of the vertical axis, the setting "Zero to 70dB" has proved very successful because the noise level runs between 50 and 60dB. This high noise level has a simple reason: the circuit works with an 8 bit AD converter. The relationship in dB between the wanted signal and quantisation noise is given by:

$$S/N = 1.76 + 6.02 \times (\text{number of bits})$$

For 8 bit this is unfortunately only about 50dB

5.2 FM Reception

5.2.1 Here we go!

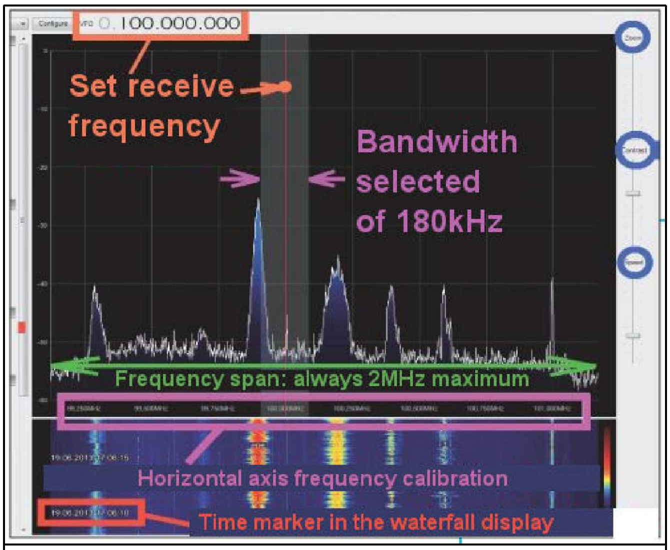

Fig 8: This image should be compared with your own PC screen in order to understand the options

When the antenna is connected, click on the play button in the upper left corner of the screen to start. The screen should show the noise with some transmitters appearing as spectral lines. Move to one of these and the transmission should audible in the loudspeaker. If not there is a slider for the volume (AF Gain) in the audio menu on the left. The preset frequency does not matter at first because the spectral representation needs to be described, the details of the spectrum in **Fig 8.**

a. The current frequency is marked by a thin red vertical line and shown with a resolution of 1Hz above the spectrum as "VFO".

b. This thin red line is framed by a greyish green area showing the selected range (here: 180kHz).

c. The frequency range ("frequency span") displayed on the horizontal axis is always exactly 2MHz, without the zoom, using the "2,048 Mega Samples" setting in the "Configure" menu. An additional division of the frequency axis into 10 sections allows a better overview of the frequency range which has just been swept.

d. The zoom slider is located in the upper right of the spectrum (in the blue circle). It is nice that when zooming the selected section around the red vertical line is ALWAYS automatically moved to the centre of the diagram - even if the red line is already close to the edge of the spectrum!

The waterfall display does not need much guidance. The activated "Time marker" is shown in **Fig 8** and there are two more (also marked in blue) sliders for contrast and feed ("speed").

5.2.2 Testing the frequency setting

Several different cases must be distinguished and discuss separately.

Case A: Choose a different frequency in the currently displayed 2MHz range:

This is extremely simple but also fun. Move the mouse in the displayed range to the desired frequency, this is shown as a thin red line. In addition to the thin red line, the current cursor position i.e. the currently frequency is displayed. A left mouse click is enough for the VFO to be tuned to the new frequency and it will be shown with 1Hz resolution above of the spectrum as "VFO". If you want you can also use the zoom to constrain the tuning range.

A tip:

If you are not satisfied with the absolute accuracy of the frequency display (the crystal in the PLL may not be completely accurate). If the received frequency is known with full accuracy and the display differs, open the “Configure” menu next to the VFO display and use the "frequency correction" in ppm (parts per million) to adjust the VFO frequency.

Case B: Selecting a different frequency range:

If only the selected section of the spectrum is to be moved, the cursor is moved to the frequency scale on the horizontal axis, there is just enough free space anywhere along the axis. When the left mouse button is held the image can be "dragged" left or right while the thin red line (for the VFO frequency) remains on the screen. Of course this will only move the frequency for a maximum shift around the displayed spectrum width of 2MHz. With several such steps the entire FM broadcasting band can be covered. The thin red vertical line on the screen always indicates the currently VFO frequency.

Note: This procedure will be looked at more closely in the next chapter in a practical example of an operating mode like "LSB" or "USB" because it is there that you need such a deliberate tuning method!

It is really interesting if you want to jump quickly into a completely different frequency range - as an example while listening at 101.5MHz you can jump to the 2m band at 145MHz or the 70cm band at 438MHz. This can be done as shown in **Fig 9**:

Fig 9: The method to adjust the VFO frequency

Move the cursor to the VFO frequency display (the number "1" in the display of 101.5MHz). A small red box will appear located in the upper half of the digit. Clicking in the box increments the number to "2". After two more clicks the first digit becomes "4". The receiver is now on the new frequency. In the same way the next digit can be changed to "3" and the third digit to "8". A zero is needed in the fourth position; placing the cursor in the lower half of this position displays a small blue box. A mouse click decrements that digit so it can be made "Zero". The remaining digits are changed in the same way. Do not forget that in the amateur bands "WFM (wideband FM)" is not used so the desired operating mode such as AM, SSB, or "NFM (Narrowband FM") must be selected. The bandwidth is adjusted automatically by the program and you can zoom out to the desired frequency.

5.3 Practical receiving exercises

5.3.1 FM stereo reception at 101.5MHz

As a summary of the operation and the information obtained, the step by step instructions are:

1 Step:

The following should be set in the Configure menu:

Offset “tuning”

RF Gain = 42dB

Frequency correction = 0ppm

Tuner AGC off

2 Step:

The following should be set in the Radio menu:

WFM (wide band FM)

Filter type = Blackman-Harris

Bandwidth = 180kHz

Shift = 0

Step size = 50kHz

Correct IQ

FM stereo

3 Step:

Set the VFO frequency to 101.500.000Hz (see above)

4 Step:

Now check the FFT menu. The following settings must be displayed:

View both (Spectrum + waterfall)

Blackman-Harris window

Resolution 131 072 samples

Use time marker range on the vertical axis 0 to -70dB

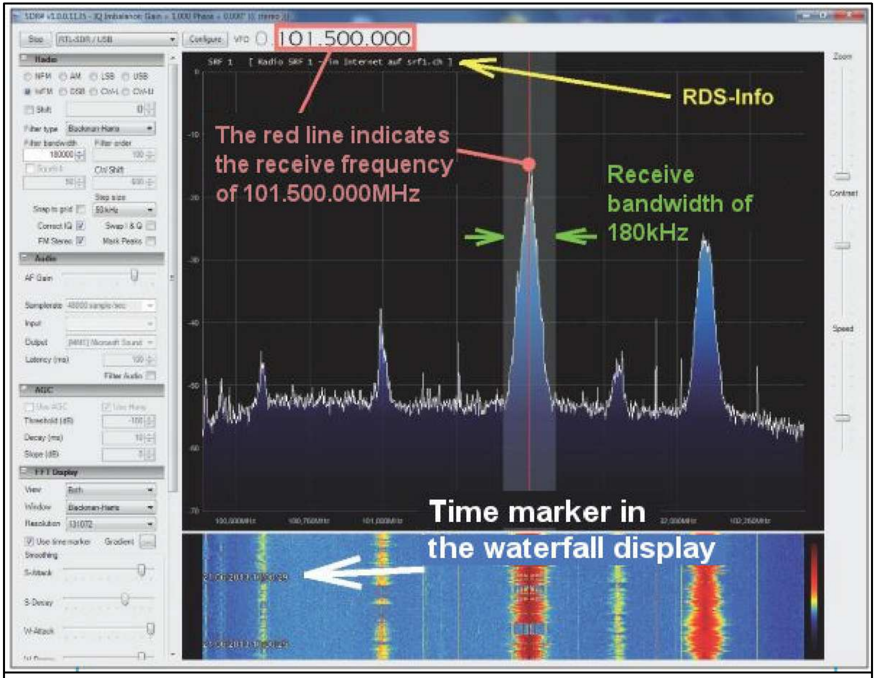

Fig 10: This shows FM reception at 101.5MHz, but select your own station

Now you have **Fig 10** on the screen (if there is no station on this frequency simply set the thin vertical line to the nearest neighbour in the spectrum!). Everything is marked and expl-ained in **Fig 10.** Now use the zoom function to bring just this channel on the screen and listen to the music from the stereo speakers.

5.3.2 AM and SSB reception in 2m band

To get an overview of the band click the left mouse button on the middle of the spectrum. The thin vertical red line is placed in the centre and after entering 145.000.000 as the VFO frequency this is selected with a width of 2MHz.

Unscrew the antenna from the Stick and replace it with an SMA terminator. This will allow you to see what the tuner chip itself produces as unwanted lines therefore new signals can be identified more easily (**Fig 11**).

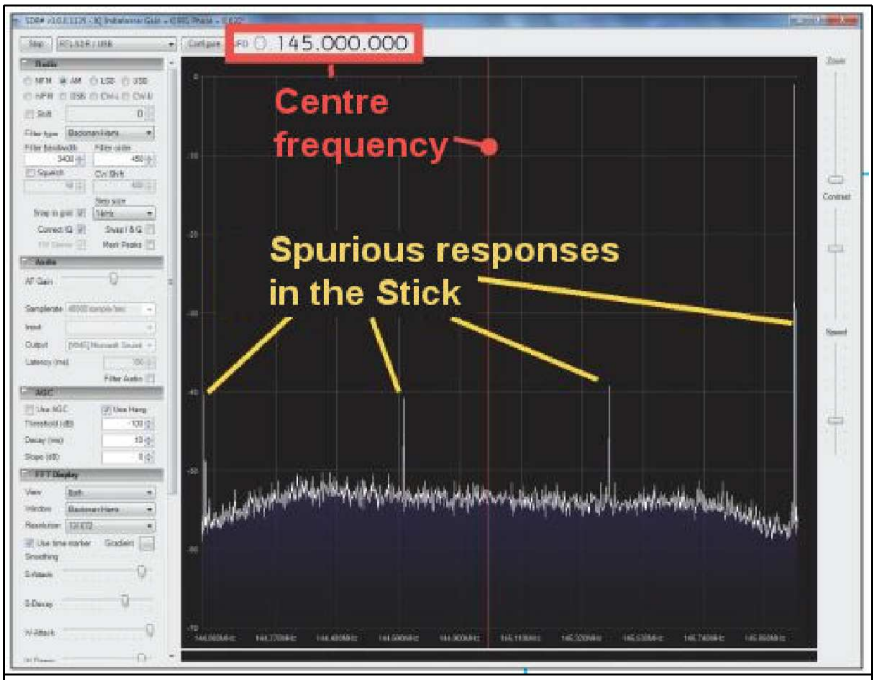

Fig 11: The entire 2m band in one display. The antenna input is terminated with a 50Ω load so the individual spurious responses generated by of E4000 tuner can be seen

5.3.2.1 AM reception at 144.5 MHz

An HP8657B signal generator with digital tuning, frequency resolution of 1Hz and an output level range from +14 to -143dBm (1.2V to 0.016µV) at 50Ω was used for this test. It has FM and AM modulation and is the perfect instrument for this purpose. The consistency and accuracy of the frequency is impressive. The input level to the Stick was set to -120dBm at 144.5MHz with 1kHz and m = 30% amplitude modulation. AM reception with an LF band-width of 6800Hz was selected in the Radio menu which results in the screen shown in **Fig 12** (if

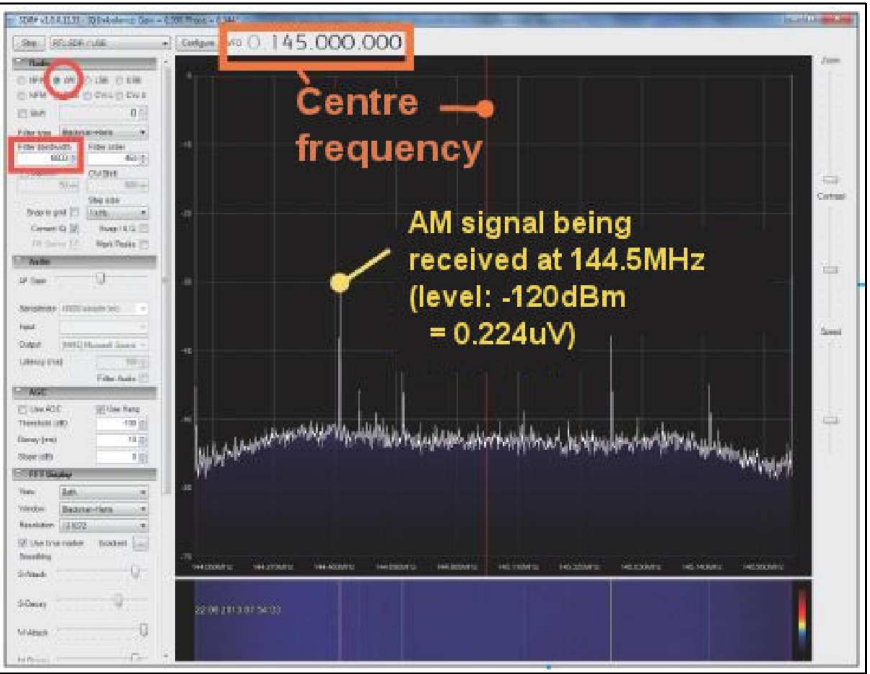

Fig 12: AM reception at 145.5MHz and an input level of 0.2µV. It is amazing how good this Stick is

you are surprised about the LF bandwidth selected: in commercial communications with a telephone or radio channel an LF bandwidth of approximately 300 to 3400Hz is used and for pure AM double that is required).

Now it's fast:

The mouse was clicked as accurately as possible on the new spectral line and then zoomed. The VFO frequency was not exactly on the frequency of the signal generator at 144.500.000Hz. It looked good but there was a frequency error of the PLL and most of the signal did not coincide with the bandwidth selection. To correct this the "Configure menu" at the top of the screen was used to check:

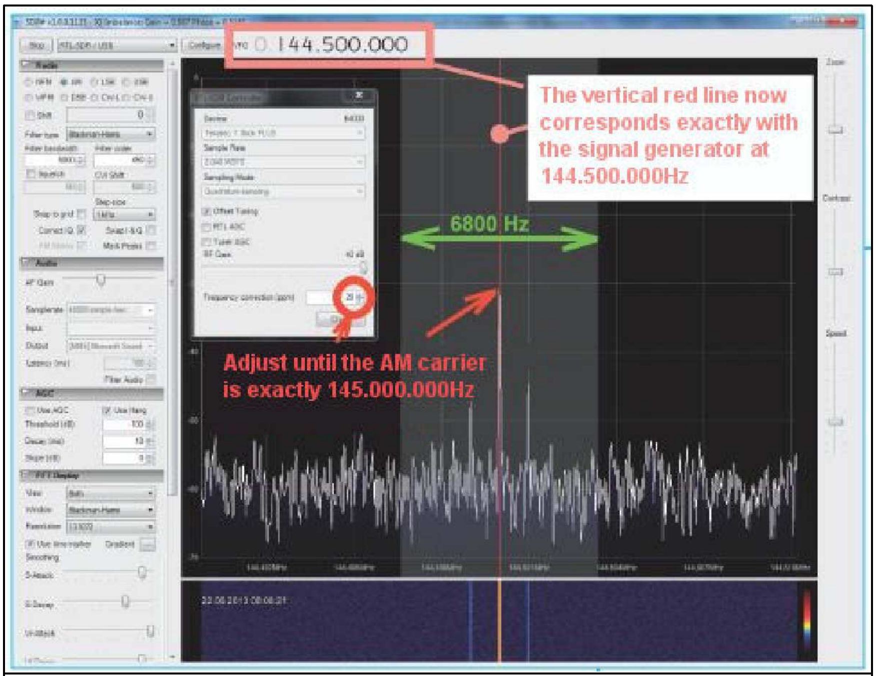

Fig 13: With a good frequency source you can correct the frequency on the screen

a. "Offset Tuning" is set?

b. The "tuner" gain is 42dB?

c. The "tuner AGC" is turned off?

This was all true so the "Frequency correction (ppm)" arrow was used until the AM signal carrier was exactly on the vertical line at 144.500.000Hz as shown in **Fig 13.**

The Stick is very sensitive and despite the small input signal of 0.224µV the signal is more than 20dB above the noise floor!

5.3.2.2 LSB reception

This is a very simple, select "LSB" together with a 3400Hz LF bandwidth (the program selects 2400Hz by default). If you increase the VFO tuning by 1kHz from 144.500.000 to 144.501.000Hz, you receive the 1kHz tone in the loudspeaker (**Fig 14**). It is just as easy for receiving USB.

6 Measurement of the Tuner Parameters

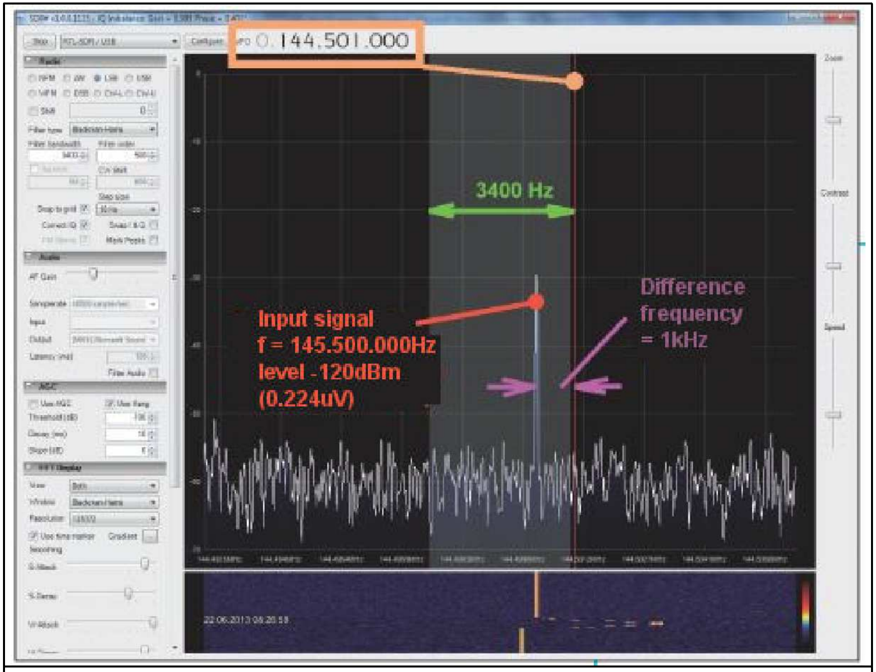

Fig 14: It is easy to use for LSB reception

6.1 The input reflection S11

The Stick was connected to a Network Analyser. The frequency and mode settings of the Stick do not matter. The "Tuner Gain" in the "Configure" menu must be set to 42dB. The Tuner AGC is turned off. The measured values from 200MHz to 2GHz (the range specified on the data sheet) are not too bad and not far away from the datasheet values as shown in **Fig 15.** The increase in reflection below 300MHz is probably caused by an increase of the input resistance of the input FETs with decreasing frequency. An improvement can be made using a Smith Chart to evaluate this and design a small circuit to add into the semi rigid cable at the input of the Stick (e.g. a resistor between 50 and 100Ω in series with a small inductor).

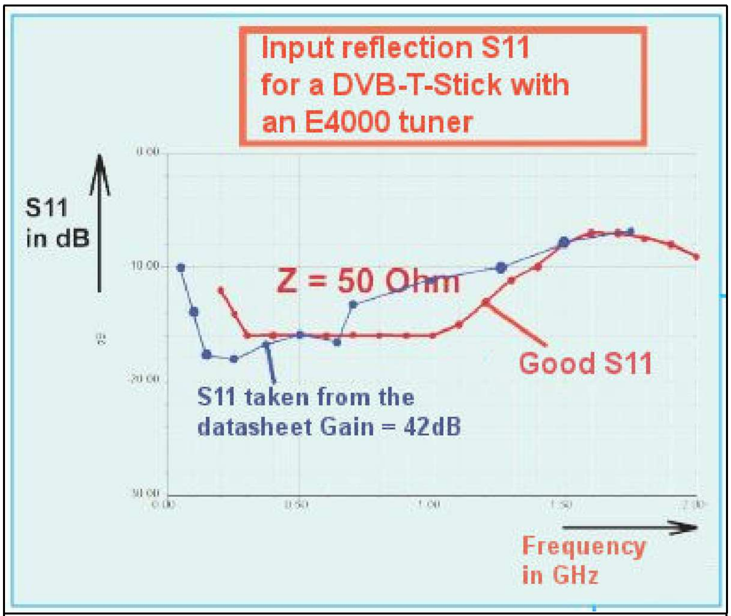

Fig 15: The measured input reflection S11 and the values from the datasheet

6.2 The input sensitivity

This was measured with an HP8657B up to 2GHz and an HP8616 up to 2.2GHz. An AM signal was fed into the Stick (modulation with m = 30% and f = 1kHz), the signal was seen in the spectrum at a level of -120dBm.

The receiver settings were:

AM / 6800Hz bandwidth / offset tuning / 42dB Tuner Gain / No Tuner AGC / frequency correction = 0 ppm

The FFT used "Blackman-HarrIs Window" with 131 072 samples.

The vertical axis range from 0 to 70dB.

The result is shown in **Fig 16.** The ranges from 0 to 50MHz and 1100 to 1235MHz are not receivable because the PLL tuning is locked but the data sheet says that from 1236MHz up to a maximum of 2200MHz is possible.

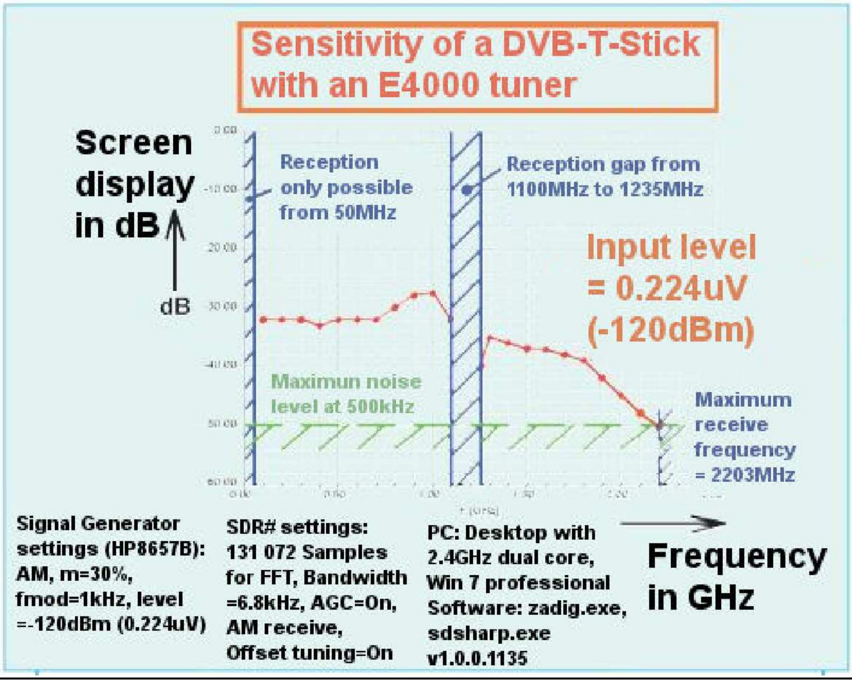

Fig 16: The input sensitivity measured with an input voltage of 0.2µV over the frequency range of 50MHz to 2200MHz

6.3 Determining the dynamic range as a spectrum analyser

That turned out to be a pretty hard nut to crack (unexpectedly!). It took quite long time to look through the behaviour of the Stick including the AGC. But because the Stick will be used as a measuring receiver or Spectrum Analyser (my friends have asked about this), the data to do this is needed so the following steps were taken:

1. The Radio menu was set as follows:

AM / Filter Bandwidth = 6800Hz / Blackman-Harris Window / Correct IQ - stream preserve.

2. The FFT was menu set as follows:

View = both

Filter = Blackman-Harris

Resolution = 131 072

Range = 0 to 70dB

3. The Configure menu was set as follows:

"Offset Tuning" and maximum RF Gain of 42dB.

Very important:

Both the RTL-ACG and Tuner-AGC must be turned off when all these measurements are made! A "frequency corrections" of +25ppm was also required.

4. A signal with the frequency 145MHz (modulation: AM / 1kHz / m = 30%) and a level of -120dBm = 0.224µV was connected to the Stick. This gave a carrier amplitude of about -30dB on the spectrum display after tuning the receiver and zooming. The AF Gain (in the "Audio" menu) was turned up slightly to increase the quality of the demodulated signal (**Fig 17**).

5. The level of the signal generator was increased (in steps of 10dB) by a total of 30dB up to -90dBm. As a result the carrier amplitude touched the zero line in the display and the

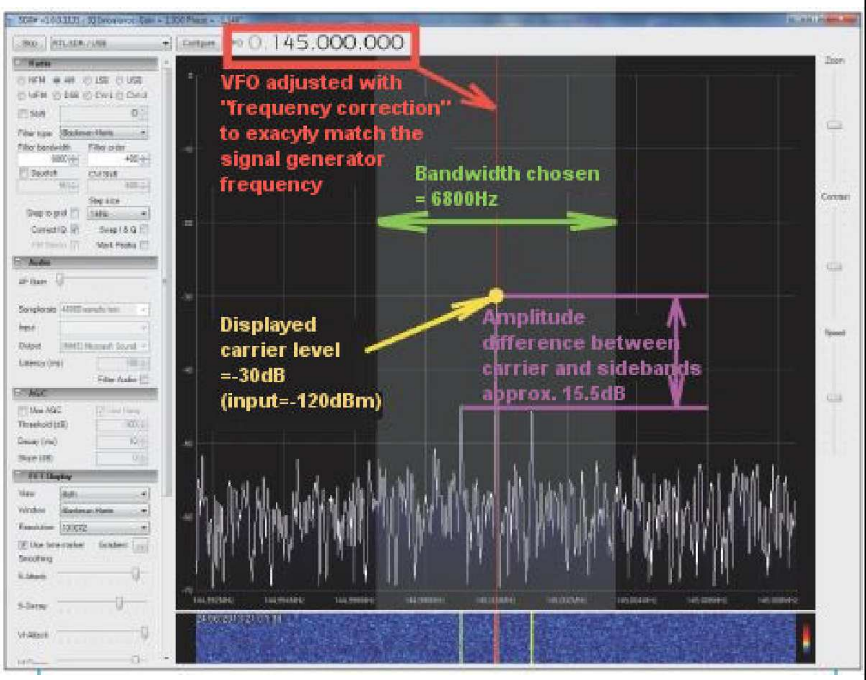

Fig 17: This is the starting point for the linearity measurement at 145MHz: an AM Signal of -120dBm (0.22µV). The display is zoomed and full amplification without AGC used (see text)

amplitude difference of 15.5dB between the LSB or USB signal and the carrier caused by the 30% AM modulation was correctly displayed.

6. The RF Gain slider in the “Configure” was adjusted to "-1dB" that theoretically should have reduced of the gain by a total 42dB + 1dB = 43dB but it was simply no more than 35dB. This was examined closely. Therefore we must unfortunately say: You cannot believe everything the "RF Gain" slider says. Neither the total amount of gain change nor the intermediate steps are correct. The program needs to be improved.

7. Therefore this measured gain reduction of 35dB, caused by setting the RF Gain to -1dB, was accepted. The reduction could be seen as a decrease in the carrier amplitude on the spectrum display. So the signal generator level was increased again and the displayed carrier amplitude increased again by an increase of this 35dB to the zero line of the display. This was for an input level of -55dBm corresponding to an input voltage of 400µV.

The zoom was then switched off briefly. This makes it possible to check whether new noise lines were generated in the spectrum due to the powerful signal. Unfortunately this is regularly found on the screen while tuning without an input signal. This was not the case and so you can actually use a spectral display range of 55dB at the maximum RF gain of 42dB (with a visible noise level of -55dB as the lower limit). As with a real spectrum analyser the linear range can be extended from 55dB to 55dB + 35dB (approximately 90dB) using the internal prescaler (with the RF Gain = -1dB). Not bad for €20 great!

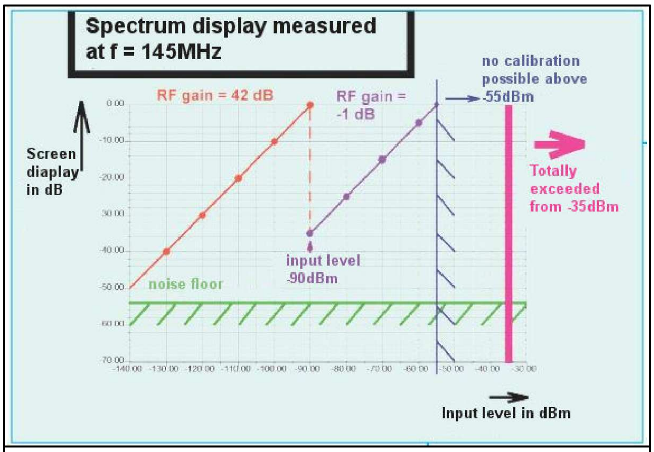

Fig 18: The usable signal level range with and without an additional 35dB gain reduction at 145MHz (see text)

But how does it perform above the maximum input level? The answer is: not very good because the displayed amplitude range of the spectrum does not go beyond zero dB. The display shows nothing beyond 0dB. In addition clipping begins incredibly quickly above by -50dBm and despite the RF gain set to minimum there are countless new spectral lines at -35dBm. **Fig 18** shows the above measurements for future use.

A question comes to mind that is easy to answer:

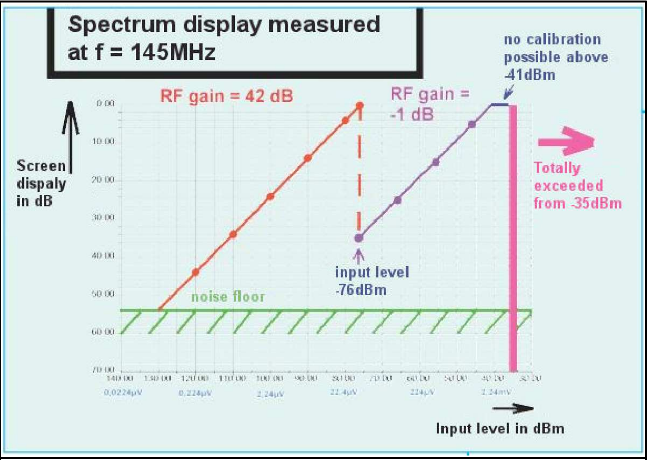

Fig 19: The usable signal level range with and without an additional 35dB gain reduction at 2000MHz (see text)

How does the Stick behave at other frequencies? Especially when it is above 1700MHz (official upper limit) or about 2000MHz?

According to the sensitivity curve over the frequency (see **Fig 16**) The values given in **Fig 18** for 145MHz need to be adjusted by the sensitivity difference at a different frequency. This causes the curve to shift to the right in the diagram. A test is shown in **Fig 19** showing the behaviour at 2000MHz.

6.4 The AGC

There is problem here because the Stick receiver was designed as an RF receiver for DVB-T, DAB, etc. but never as a spectrum analyser. Therefore you must be very careful when using the AGC and distinguish the following cases. These are all for a carrier frequency of 145MHz.

Case a) The RTL AGC in the “Configure” menu is off and the RF Gain is 42dB:

If the RF gain has been turned on (42dB) the Tuner AGC is ineffective and you can observe exactly that described in chapter 6.3. Turning the tuner AGC on or off does not have any effect. However the maximum display range is only up to an input level of -90dBm. If it is increased beyond this value overdriving begins at about -70dBm.

Case b) The RTL AGC in the "Conflgure" menu is turned on, the RF gain is 42dB, the Tuner AGC will remain off.

This activates an additional gain of approximately 15dB that not only raises the useful level but also the noise on the screen. Therefore the control limit of 0dB is reached with a correspondingly lower input level compared to chapter 6.3 (somewhere between -105 and -107dBm).

Case c) The RTL AGC in the “Configure” menu is switched off, the RF gain is turned back to -1dB, the Tuner AGC is turned on

Now it gets interesting because without Tuner AGC the signal completely disappears into the noise at an input level of -120dBm (The gain was reduced about 35dB. The tip of the carrier found previously at about 30dB on the screen, with a reduction of 35dB, is pushed down to approximately -65dB. With a noise level of about -55dB it is gone). Now turn the Tuner AGC on: the signal appears from the noise and it is audible and the tip is once again about -30dB on the screen! Increasing the input by 30dB to -90dBm also increases the carrier on the screen by 30dB. So you are back on the display limit of the screen (zero dB).

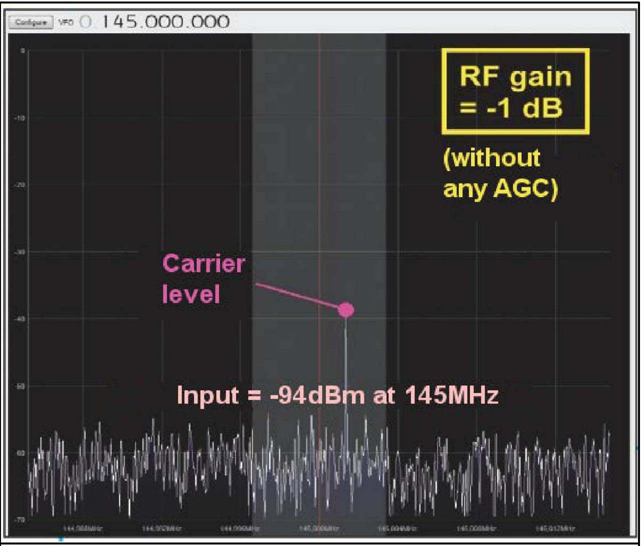

Fig 20: At first sight this is frightening: With minimum gain (35dB gain reduction), a signal of -94dBm almost disappears in the noise

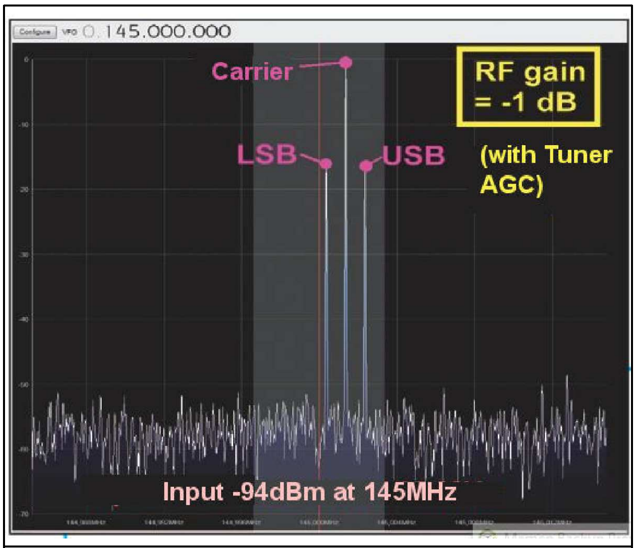

Fig 21: But with the Tuner AGC switched on the display is perfect

Therefore there is a different development concept: normally a receiver uses full gain with weak signals and is adjusted with increasing input level. In the E4000 tuner only 35dB attenuation is inserted in Tuner AGC mode and then checked to see how much can be taken away in order to receive weaker signals cleanly and noiselessly. This concept benefits the overload performance.

Also increasing the input signal reaches full level very quickly:

From -80dBm (approximately 22µV) it slowly becomes more level dependent with spurious lines in addition to the useful signal getting worse and with signals greater than -70dBm you no longer see the wood for noisy lines.

Case d) The RTL AGC in the "Configure" menu is on, the Tuner AGC is turned on, the RF gain is turned back to -1dB

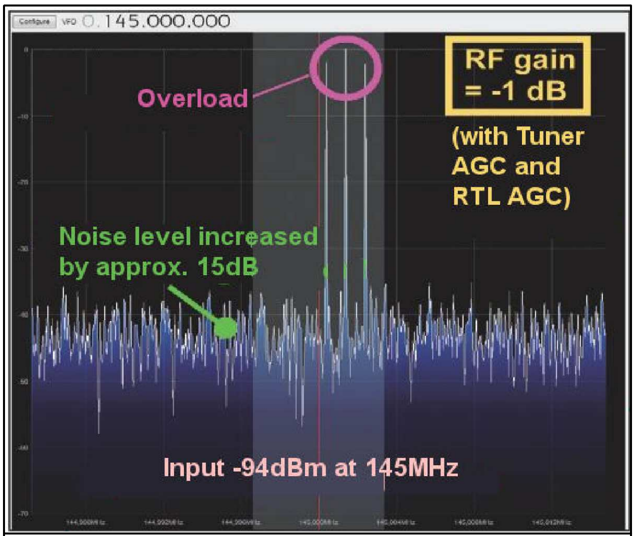

Fig 22: The RTL AGC should be be used very carefully as shown in this spectrum display (see text)

Now what was to be feared: the "basic gain" is raised by approximately 15dB. Not only does the noise increase by this value but input levels from -90 to -100dBm are already in the overload region and partially trigger "hysterical reactions".

Three examples are intended to vividly demonstrate this behaviour. The zoomed spectrum for a carrier level of -94dBm at 145MHz is shown in **Fig 20.** The Tuner AGC and the RTL AGC are switched off and the RF Gain is at the minimum value of -1dB. The peak of the carrier is only about 15dB above the noise and therefore the sidebands are not visible (there is only noise from the loudspeaker).

The Tuner AGC has been switched on in **Fig 21.** Very nice and clean display with good adjustment because the tip of the carrier now reaches just zero dB and the USB and LSB signals are clearly recognisable at approximately 16dB down. Also the signal-to-noise ratio is splendid. It's a pity that overload limits the display.

Fig 22 shows the effect of an additional 15dB of basic gain when the RTL-AGC is switched on: now the trouble with the overload starts. The amplitudes can no longer be processed correctly and the noise has increased by 15dB.

6.5 The AGC menu on the screen

An additional AGC menu is on the screen and below the "Audio" settings with “Threshold / decay / slope" adjustment that you can test out occasionally using the speaker on a received signal. These are pure software options that are effective only after the IQ decoder and have no influence whatsoever on the Stick properties or on the displayed spectrum. Therefore the results of the measurements in chapters 6.1 to 6.5 remain valid without change.

6.6 Temperature sensitivity and variation

Of course the tuner will warm up in the aluminium housing after 1 to 2 hours and the housing itself will get to about 45°C after one day of "HAM Radio" use. This means that you have to make a correction in the "Configure" menu by a maximum of -3 ppm (that is approximately -6kHz at 2000MHz), so that the frequency display of "SDR#" is correct. If the Stick gets very hot the spectrum display amplitude is reduced by approximately 1 to 2dB

From samples taken over several of the same Stick type their data and results differ by less that 1dB as shown by "SDR #".

7 Some technical information

7.1 The block diagram

The internal structure (**Fig 23**) of the Stick comes from the 60 page data sheet for the E4000 (found without problems on The Internet). It is amazing what the developers have made from a fairly simple concept. Here are the components in detail:

1. A tuner always starts with a preamplifier known here as the LNA (low noise amplifier). It must be low noise and have controlled amplification (via RF Gain) in this case 35dB adjustable – it has succeeded.

2. This is a filter that is adjusted via software for cut off frequency and characteristics in the selected frequency range. This is provided for DVB and DAB reception.

3. This is a "Direct Conversion Receiver". The conversion oscillator works at the receive

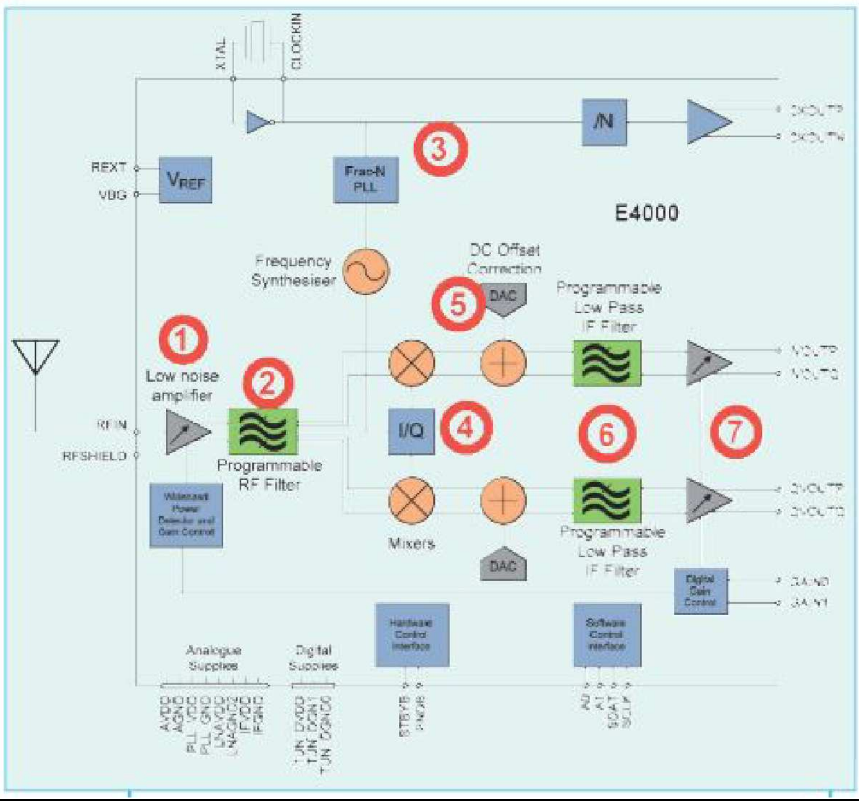

Fig 23: Block diagram of the E4000 Tuner, see text

frequency (or only very slightly offset). A "FractionaI N Synthesizer" is used for this because of the high resolution required for the step width (down to 1Hz). It is a "strange" construction that should be looked at in more detail - it is truly an interesting area. The following information is taken from the original E4000 data sheet. The VCO and thus the LO frequency is determined by the I^2C bus:

"The divider and sigma delta values need to be set as per the formulae

$$f_{VCO} = f_{Oscillator} * (Z + X / Y) \quad \text{(equation 1)}$$

and

$$f_{LO} = f_{VCO} / R \quad \text{(equation 2)}$$

Where Y = 65536 and $f_{Osillator}$ is the crystal frequency (e.g. 26MHz). Values R, X, Y and Z are configurable using the tuner serial interface (by I^2C bus control)"

4. The "IQ" interface. This requires two separate mixing stages and two oscillator signals with the same frequency but with a 90 degree phase difference. This is examined in Chapter 7.2.

5. The "direct conversion" produces a DC signal at the output generated by the oscillator and received signal at the same frequency. In this system drift effects etc. can lead to signal components that in reality are not present. So a DC offset correction is required following each mixer

6. The filters following the mixers are programmable according to the requirements of the selected receive operation.

7. Before the IQ signals leave the chip they are set to the correct levels by an AGC amplifier.

7.2 The secrets of the IQ signals

These are "state of the art" so you should know what they are so a short and clear explanation follows. *(UK translator G8ATD, I found two more useful explanations on The Internet, see [7] and [8])*

7.2.1 Real, Imaginary and Complex Signals

All electrical signals that you see (e.g. on an oscilloscope) or can hear (e.g. microphone and speaker) are "real world signals".

Signals that you can only guess about based on their impact or uncover indirectly are referred to as "imaginary". A mixture of these two signals one are "complex signals".

The ratios of sine and cosine signals can be represented as a stationary pointer on a crossed axis known as a phasor. Such a pointer or phasor has the two properties: pointer length or signal amplitude and instantaneous phase position in a reference system. It looks like a clock and is fixed in time so that you cannot see a temporal waveform (this would be seen if the x axis was rotated clockwise at the signal frequency).

The horizontal axis of the diagram is the real axis and the vertical axis is the imaginary axis (only conceivable). The path of a signal in a circuit is then nothing more than the real part of the corresponding "complex signal". This leads to the definition:

a. If such a phasor rotates counter clockwise the complex signal has only "positive frequencies". Consequently phasors that rotate clockwise have a "negative frequency" and produce a spectrum for the complex signal with spectral lines that can only be found in the negative frequency range.

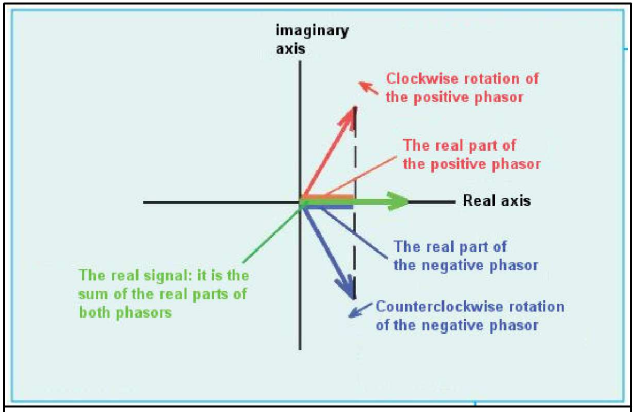

Fig 24: This diagram shows that there are things that we cannot see (see text)

b. A complex signal is nothing more than a phasor with its sum of the real part and the imaginary part rotating at its natural frequency.

This can be seen in **Fig 24** using the example of a simple 1kHz tone from a signal generator. It consists of two phasors rotating in opposite directions with a rotation frequency of f = 1kHz but with pointer lengths only half the amplitude of the measured signal. This is because both phasors sum to the peak value of the signal generator on the horizontal axis. The mathematical description is not very difficult thanks Mr Euler it can be seen clearly that:

The "positive phasor" is described by the expression

$$U_{positiv} = U_{positiv\_max} * e^{+j\omega t} =$$
$$= U_{positiv\_max} * [\cos(\omega * t) + j * \sin(\omega * t)]$$

and for the negative phasor is described by the expression

$$U_{negativ} = U_{negativ\text{-}max} * e^{-j\omega t} = \quad U_{negativ\_max} * [\cos(\omega * t) - j * \sin(\omega * t)]$$

Adding the two phasors in this example the quadrature imaginary parts are apparent while the two real parts sum to the peak amplitude of the cosine oscillation.

$$U_{gesamt\_max} = U_{positiv\_max} + U_{negativ\_max} =$$
$$= 2 * U_{positiv\_max}$$

producing the frequency f = 1kHz.

The corresponding frequency spectrum of the real signal must also encompass the negative range and there is the negative phasor with the frequency f = -1kHz.

If this seems strange or unbelievable remember what happens in an analog RF mixer. When two different real cosine signals (e.g. RF = 1MHz, LO = 10MHz, and 1V amplitude) are multiplied together (both in the negative and the positive frequency range) the output contains the RF signal split symmetrically about the LO frequency divided into a LSB and an USB component with half amplitude. The frequency multiplication of the pair of "positive and negative RF phasors" by the LO frequency has produced the mysterious negative RF phasor as a LSB signal even displayed on the screen of a spectrum analyser. **Fig 25** shows both the positive and the negative frequencies clearly. For people who enjoy complex maths the formulae for two real cosine signals (with frequencies f1 and f2) multiplied with each other is:

$$(\cos\omega_1 t)\cdot(\cos\omega_2 t) = \left[\frac{(e^{j\omega_1 t}+e^{-j\omega_1 t})}{2}\right]\cdot\left[\frac{e^{j\omega_2 t}+e^{-j\omega_2 t}}{2}\right] =$$

$$= \frac{\left[e^{j(\omega_1+\omega_2)t}+e^{-j(\omega_1+\omega_2)t}\right]+\left[e^{j(\omega_1-\omega_2)t}+e^{-j(\omega_1-\omega_2)t}\right]}{4} = \frac{1}{2}\cdot[\cos(\omega_1+\omega_2)t+\cos(\omega_1-\omega_2)t]$$

7.2.2 Analytic pairs

It sound very mysterious but it is not. Normally this is not done with a single frequency such as a sine tone but rather like music with a variety of individual frequencies and their harmonics that change their values continuously. To halve the bandwidth of such a signal either the positive or negative frequency range is chosen i.e. from a real signal to a complex signal. It works like this:

The real output signal is regarded as an "I" signal (in phase signal) and is processed unchanged.

This real "I" signal also feeds a special circuit called a "Hilbert Transformer". At the output you find the same amplitudes in all spectral parts but a phase shift of 90 degrees is performed for each spectral line and at each frequency! This artificially generated signal is named "Q" (quadrature signal).

Working with digital signal processing such as an SDR radio two digital data streams "I" and "Q" are available at the output that represent the two components of a complex signal:

$$U_{Complex} = I + j * Q$$

This is the famous "analytic pair" (*or analytic signals – see [8]*) that contain either only positive or only negative frequencies so that they occupy only half the bandwidth depending on the sign of the imaginary part! (+90 degree leading phase is often used thus there are only positive frequencies). Radio amateurs know this as an "SSB Signal".

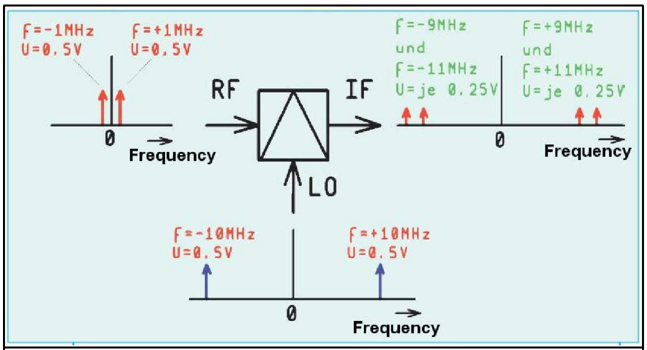

Fig 25: But an RF mixer rejects these "invisible things"!

The E4000 tuner uses a very simple technique to produce the required 90 degree phase. It uses two identical mixers connected in parallel fed with two separate LO signals. These have exactly the same frequency but 90 degree phase difference to generate the two IF signals, this elegant solution can be seen in **Fig 23.** On the "SDR #" screen the

"IQ Gain and Phase Imbalance" is measured which is nothing more than the deviations from the ideal state (equal IF amplitudes and exactly 90 degrees phase difference). Please take a look!

7.2.3 What can you do with an Analytic Pair?

There are countless applications for the Analytic Pair i.e. two digital data streams. Here are some examples from The Internet:

a. A receiver can be designed to supress the mirror frequency or "negative frequency part". This can be found using the keyword "Image Rejection".

b. The phasor length and thus the useful signal amplitude can be calculated easily using the famous "Pythagorean theorem" because the signals are is quadrature.

$$\ddot{U} = \sqrt{I^2 + Q^2}$$

This can be used to drive an AGC, a broadband volt meter, an RSSI (Received Signal Strength Indicator) or for AM demodulation using a digital signal processor.

c. For SSB demodulation by multiplying the "Analytic Pair" with a digital "complex oscillator" and a filter (also digital) to remove the difference frequency. The complex oscillator must be on the centre frequency as the SSB signal to recreate the information which is exactly how an analog transceiver works for SSB reception.

d. If a whole frequency band has to be received or filtered the first step (according to the image rejection principle) is to convert the band centre frequency "zero hertz". The negative frequency components are suppressed by this action. This is followed by a low pass filter with a cut off frequency of half the width of the frequency band being converted but will pass the negative frequency portion down to "$-f_{cut\text{-}off}$". The lower operating frequency allows steeper low pass filter sides. Only half the low pass bandwidth is required. The filtered band can be converted back to its original centre frequency. This technique is often used for sensors that emit signals in the MHz range. Digital signal processing can be used to replace analog circuits (mixers, filters, etc.) by almost ideal digital solutions.

e. FFT (Fast Fourier Transformation) is used to calculate frequency spectra in real time with high frequency resolution. The number of samples being processed in a “packet” defines the smallest frequency step in the output. The limits are the maximum sample rate and the computing power of the PC or DSP and the "tricks" used such as interpolation and oversampling

Etc. - more applications can be found on The Internet. But by using the "SDR#" you can already see what a clever programmer can get out of two data streams.

8 Summary

A completely new experience is available when you enter the SDR world and there is much to be observed, to puzzle, to tinker and to ask. Of course not everything is straightforward and the computer crashes frequently. But for many purposes this Stick is just perfect. It is not an overload proof receiver with very broadband input and a very high IP3 value (It was never meant for these purposes and it has its limits - see the measurements in [2]). But it is ideal for the processing and demodulation of narrow band signals e.g. weather satellite images or aircraft signals or following converters etc.

The unwanted effects of the high input sensitivity and the large signal-to-noise ratio with input signals as low as 0.2µV can be reduced by good preselection, even if there are a few dB of insertion loss and S/N increase.

Following my successful experience (finally everything works) I have some quiet thoughts on further developments of the tuner ICs and the complete Sticks. Desirable things would be:

- No gaps in the receive band
- A lowest possible receiver start frequency, preferably 1kHz.
- Two A to D converters with 16 bit resolution instead of the existing 8 bit converters to increase the dynamic range. The formula in Chapter 4 shows the maximum signal to noise ratio in dB is: S/N = 1.76 + 6.02 x (number of bits). For 8 bit converters this is about 50dB but for 16 bit converters you will get 97dB.
- The maximum sample rate should be increased (you can buy the “Funcube” dongle that uses the E4000 tuner but has two 16 bit converters) But it only has a maximum sample rate of 96 kHz).
- A higher upper frequency limit for the complete SDR receiver (5GHz would be not bad).
- Even greater signal strength of the tuner input and mixer would be ideal. And / or an additional preselector.

Let's see how long it takes until reality catches up with us or is even obsolete.

9 Literature

[1] Dirk Müller, DB6FM, “Der RTL SDR. Arbeiten mit dem USB-Stick, Tell 1”, UKW Berichte, issue 4/2012, page 201 to 212

[2] Dirk Müller, DB6FM, “lmpressionen zum RTL-SDR, Teil 2” UKW Berichte, issue 1/2013, page 47 to 60

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