Basic RTL-SDR Tests, Stability of a new RTL2838U/R820T2 Dongle*

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Abstract

Technology in radio astronomy is gradually changing. Software controlled devices begun about 10 years ago to replace correlators and analog receivers. The new technology, termed often "Software Defined Radio" (SDR), was made possible by a technology boost in wireless communications. Mass production allowed cheap but sophisticated hardware.

The aim of this project is to check whether simple SDR technology might be applicable to radio astronomical observations for amateurs, in particular for educational purposes. Hard- and software should be affordable and easy to use. Modern RTL-SDR devices based on the Realtek 2838U chip appear to be particularly interesting. RTL2838U/R820T dongles are very cheap (10 to 20 Euros) but powerful. Recent hardware upgrades, using the Rafael Micro R820T2 tuner, are coming on the market and it appears timely to test these dongles in detail. Here I report about such tests, emphasizing radio astronomical needs, in particular sensitivity and stability.

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1 Introduction

The RTL2838U/R820T USB dongles are intended for use as DVB-T TV, FM and DAB receivers. However they can also be programmed as general SDR devices, allowing a broad range of applications for frequencies between about 24 MHz and 1.7 GHz. For an overview see osmocomSDR.

Since a few years software for these devices got developed. There is Gnuradio, the free and open software radio ecosystem. Unfortunately I failed to get a working environment under Ubuntu 12.04 and 14.04. For RTL-SDRs a specific rtl-software is available which is sophisticated but at the same time easy to use, it even runs well on older and less powerful PCs. I'll use these programs, supplementing them with own data reduction software. This post-processing follows strategies that have been developed in radio astronomy for bandpass calibration and elimination of spurious features such as radio frequency interference (RFI). Data can also be stacked to improve sensitivity by repeated observations.

I report about two Newsky dongles. The older is identified by rtl_test as RTL2832U, SN: 77771111153705700; the second as

RTL2838UHIDIR, SN: 00000001. Well, I never before have got a device with serial number one. I once tried to buy a SN-1 lithography, but the gallery owner refused to sell this piece; I had to take SN-2. rtl_test also found “Rafael Micro R820T tuner”, nothing about “R820T2”, so at the beginning I was a bit skeptical. But let’s see how this works out...

Outline First we test the broadband performance, next we explore the performance for frequencies above 1 GHz in more detail. After a brief introduction to radio astronomical fundamentals and reduction methods we study bandpass and stability issues. Most important for radio astronomical applications is the long term stability, usually tested by determination of the Allan variance.

2 Test setup

The setup is as simple as possible. I do not aim here to do astronomical observations, I just want to test the performance of the SDR devices. The antenna is a simple whip antenna as usually sold with DVB-T dongles. The only modification is that I supplement a 28 cm metal baking dish, functioning as ground plane. The monopole antenna needs this for proper performance. The dongles are connected to a Lenovo E530c Thinkpad. It is unknown, how far this PC causes RFI problems but I found no indications for serious problems. As operating system Ubuntu 14.04 is used.

3 Broadband performance

We start to survey the entire tunable frequency range, 24 MHz to 1.7 GHZ. Fig. 1 compares the old R820T dongle (top) with the new R820T2 (bottom). On the first glance these spectra are similar but a close look to frequencies above 1 GHz shows some remarkable differences. The older dongle shows some strong spurious features for frequencies above about 1.45 GHz. Here the R820T frequently tends to oscillate, observations are completely unreliable. The R820T2 behaves much better, but still there appears to be a tendency for instabilities and oscillations at about 1.7 GHz, close to the upper useful frequency. The vendor of the R820T2 claims operation up

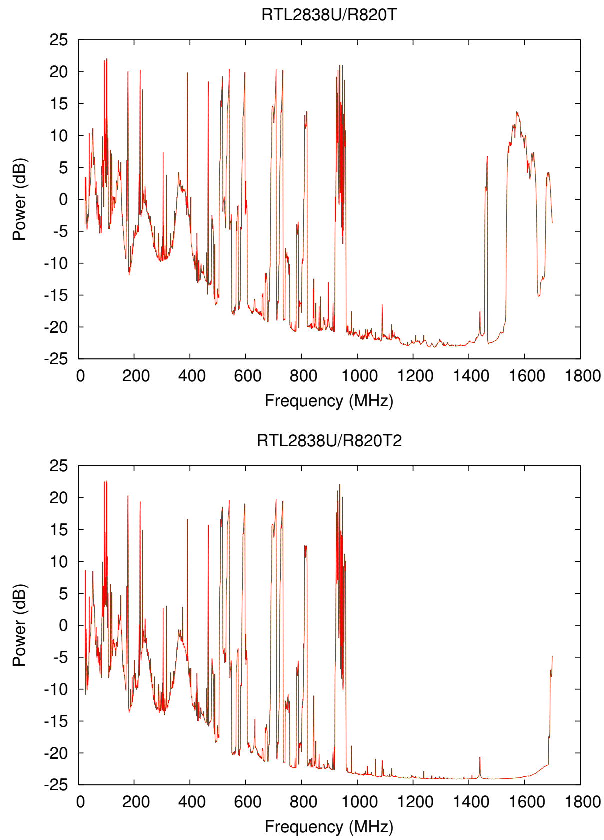

Figure 1: Broad band performance of the R820T dongle (top) and R820T2 (bottom).

to 1.864 GHz, but I found phase lock problems above 1.84 GHz. It is further claimed that the R820T2 can be used for frequencies as low as 700 kHz. The dongle is prepared to be run in direct sampling Q branch mode. No attempt was made to verify this. A closer look to frequencies above 1 GHz (Fig. 2) shows a number of spurious features for the old R820T version but a much cleaner image for the R820T2. Repeated tests verified that these spurious features are no RFI but caused by the dongle. A very strong birdie is observed for both dongles at 1.44 GHz, caused by the 28.8 Mhz oscillator. In both cases some more nasty features are found, spreading out up to 20 MHz on both sides of this peak (see Fig. 2).

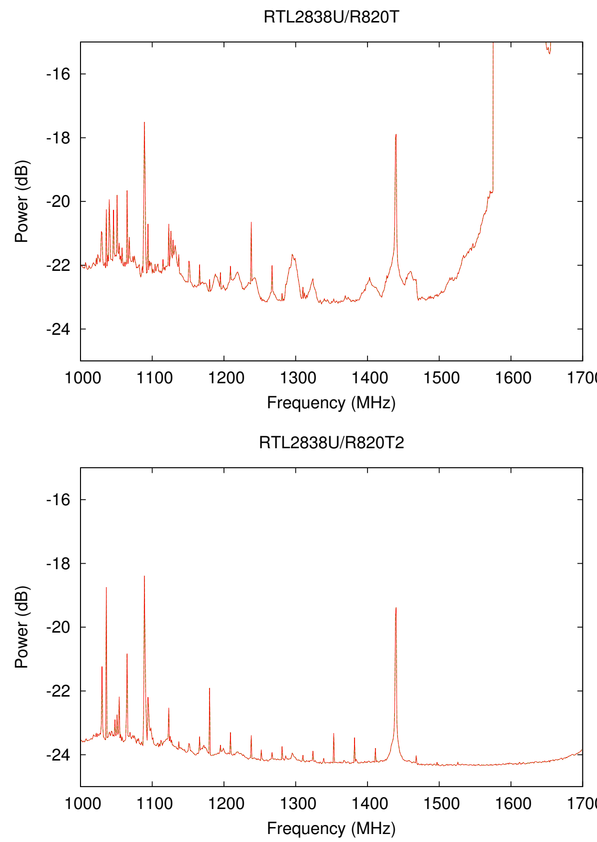

Figure 2: A closer look to high frequencies for the R820T dongle (top) and R820T2 (bottom).

4 Stability tests

As mentioned before, the R820T dongle was found to get sometimes unstable at higher frequencies. To test, how far the SDR devices are useful for deep integrations, the frequency range 1.415 to 1.430 GHz was chosen. This range includes the interesting protected frequencies where the 21 cm line emission of the neutral hydrogen (HI) is found. I also deliberately included frequencies around 1.430 GHz that are affected by the 1.44 GHz birdie.

The stability tests were made with the same setup as mentioned before. At these frequencies no significant emission is expected and the insensitive whip antenna is only used to generate thermal noise.

4.1 Frequency stability

The R820T2 dongle comes with an active SMD crystal oscillator which should provide “near to perfect frequency reading and minimal or no drift”. Frequency stability was tested using kalibrate-rtl against frequencies of GSM base stations. After a few minutes of warming up, systematic errors of about 3.6 ppm and -9 ppm were found for the R820T2 and the R820T dongle respectively. Warming up means that the dongle needs to be in operation, not only just connected to the USB port.

4.2 Radio astronomical fundamentals

The spectra in Figs. 1 and 2 display the relative power of the signal in logarithmic presentation (dB). To get meaningful physical quantities we need first to remove instrumental effects. Most important is the instrumental bandpass, representing the frequency dependent transfer function. Next we need to convert the relative gain, given in dB by the rtl_power tool, to noise temperatures T. The noise power P per unit bandwidth generated by a resistor of temperature T is $P = kT$, here k is Boltzmann constant. It is essential that for such a conversion any automatic gain control of the receiver is switched off, the gain was set to the maximum, 49.6 dB.

We apply exactly the same concept that can be used for a resistor in a thermal environment to our antenna signal, amplified by the receiver. These observed temperatures are called antenna temperatures. Observing hot objects like the Sun results in an increase in the measured antenna temperature, proportional to the temperature of the object. For a very comprehensive overview about radio astronomical fundamentals we refer to the course essential radio astronomy.

4.3 Data reduction

The total bandwidth of an RTL-SDR is limited. Testing both dongles with rtl_test we determine a maximum sampling rate of 2400000 IQ Samples/s, corresponding to a theoretical maximum bandwidth of 2.4 Mhz. A larger range in frequencies is covered by hopping in frequency. Important for the determination of the internal RTL-SDR bandpass is the fact that the internal bandpass of the SDR can be assumed to be similar for each of the individual hops. The bandpass function represents the gain of the receiver, hence it is an amplification factor that needs to be determined.

To get the internal bandpass we stack all individual frequency hops. Since we are dealing with gain factors we use the direct signal outputs from rtl_power, given in dB, but subtract the average gain for each hop. We are interested to determine the receiver response to a pure thermal (white) noise signal. Therefore we need to take care that only noise signals are stacked. We determine the average noise power and reject all signals exceeding the system noise significantly. Frequency hops with known signals can be blacklisted. From all the stacked data we determine for each individual frequency channel the median gain as the most robust estimator for the internal bandpass response.

After determination of the internal bandpass we apply a gain correction for all observed data, subtracting simply the gain in dB from the data delivered by rtl_power. Now we are ready to convert the dB values to antenna temperatures $T_a(\nu) = 10^{(P(\nu)/10.)}$, where $P(\nu)$ is the power measured in dB. Strictly, dealing with antenna temperatures T_a (in Kelvin) demands a careful intensity calibration of the observed signal. Such a calibration is quite elaborate but not needed for our current investigations. So we are going to deal here with intensities $I(\nu) = 10^{(P(\nu)/10.)} \cdot 1000000$, uncalibrated but comparable for all individual observations to be discussed here. The factor 1000000 is arbitrary, we use it to get nice numbers.

We are interested in spectroscopy, hence we subtract the continuum background. Most of this background is anyhow caused by instrumental effects.

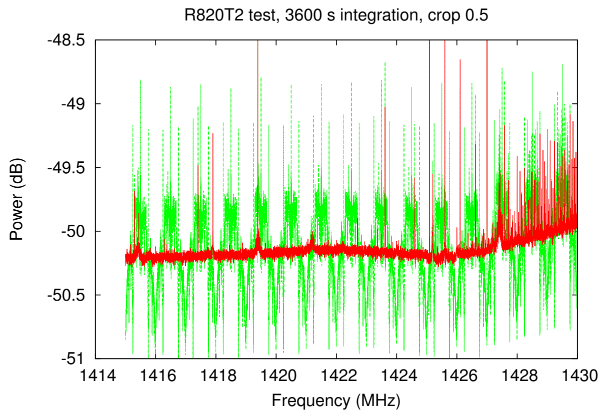

Figure 3: Long integration using the R820T2 dongle. Green: raw data, red: data after correction for the internal bandpass.

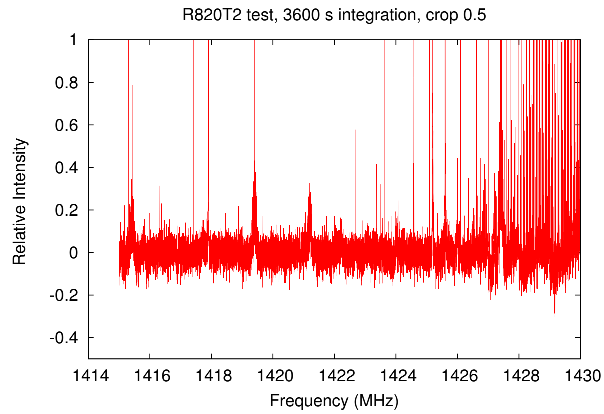

Figure 4: Long integration using the R820T2 dongle. Same as Fig. 3 but intensities in lineal scale.

4.4 Observed spectra

In the following we are going to inspect a few spectra with the aim to compare data obtained from the two dongles. Figure 3 shows data observed by the R820T2 device after integrating 3600 s. The green spectrum shows raw data, bandpass effects are obvious. We can count 15 frequency hops that are necessary for a total observed bandwidth of 15 MHz. An individual frequency hop has 1000 channels, each with 1 KHz width. To minimize internal bandpass ripples, we have chosen to use only 50% of the available bandwidth (the rtl_power crop parameter was set to -c 0.5, see discussion in Sect. 5 for more details). The red lines in Fig. 3 show the same data after bandpass correction. For bandpass determination hops 13 to 15 have been discarded.

After bandpass correction we may convert the data to intensities, correcting also for the continuum contribution. Figure 4 shows the result. This is a useful measurement and we are ready to compare this result with R820T observations, using exactly the same setup, also applying the same code for data reduction.

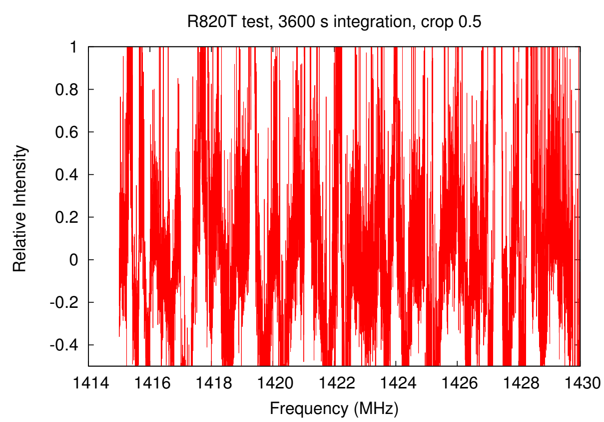

Figure 5: Long integration using the older R820T dongle. The setup is identical to observations displayed in Fig. 4

Figure 5 displays the result. Obviously this spectrum is just rubbish. Next we explore the reason for such a bad performance.

4.5 Allan variance

As mentioned earlier, at high frequencies the R820T dongle tends frequently to oscillate, independent of the gain settings. In some cases it is necessary to switch the dongle off for a few seconds to allow the R820T to settle down. However, during the observations discussed here no obvious failures were detected.

Aiming a good signal-to-noise ratio for observations, we need to study the the radiometer equation.

$$\sigma = T_{sys}/\sqrt{B\tau} \tag{1}$$

σ is the statistical uncertainty of the observation and T_{sys} is the noise of the receiver system. Obviously, to improve performance, it is useful to have a low noise figure for the receiver. It is also possible to improve the quality of observations by increasing the integration time τ, however long integrations get increasingly inefficient because of $\sqrt{\tau}$. The same relation, $\sqrt{B}$, holds for the channel bandwidth B, but this is usually limited by observational needs.

Equation 1 demands ideal observational conditions. The best way to test the receiver performance is the Allan variance test, this is simply the determination of the statistical uncertainties σ as function of integration time τ.

Figure 6 summarizes Allan variance tests for the SDR dongles. The red line shows observations with the R820T2 dongle. Figure 4 gives the spectrum with integration time $\tau = 3600$ s. The green line in Fig. 6 represents a perfect instrument as expected from the radiometer equation. We see that the R820T2 dongle behaves almost perfect for integration times between 2 and a few hundred seconds. Long integrations get inefficient, but from our test we found no indications for a degradation of the data, even after 4 hours. In practice, for radio astronomical observations integration times of 3600 seconds are sufficient. In one hour the earth rotates 15 degrees.

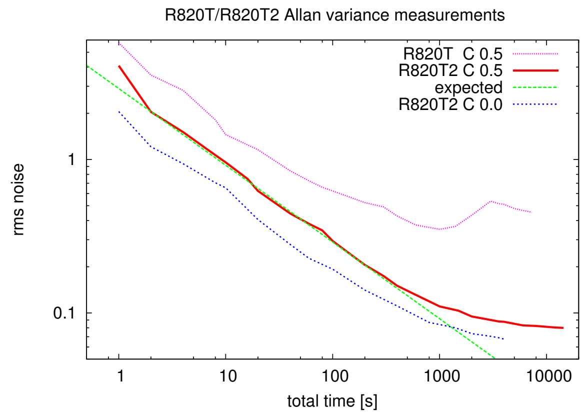

Figure 6: Allan variance plot. The straight green line shows the radiometer equation for comparison. The slope shows how white noise is integrated down by an ideal device. Receiver with stability problems tend to drift away after some time, as visible for the upper curve in case of the R820T device. The red line is valid for the R820T2 dongle and shows a much better performance.

Quite different the performance of the R820T dongle. The uncertainties are larger but, most important, the spectra degrade after $\tau > 1000$s. Figure 5 corresponds to the data point at $\tau = 3600$. This device has obvious stability problems.

To compare the Allan variance obtained for the R820T2 dongle, we add here a comparison with a more professional device. About ten years ago SDR technology became available to radio astronomy. In Fig. 7 we reproduce an Allen plot that was derived for a prototype field programmable gate array spectrometer for radio astronomy (FPGA). The Allan curve is comparable to the red line in Fig. 6. So, with a lag of

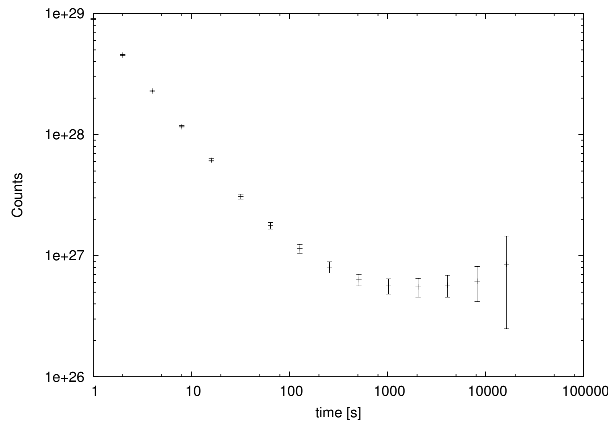

Figure 7: Allan variance for a prototype SDR spectrometer developed in radio astronomy about ten years ago.

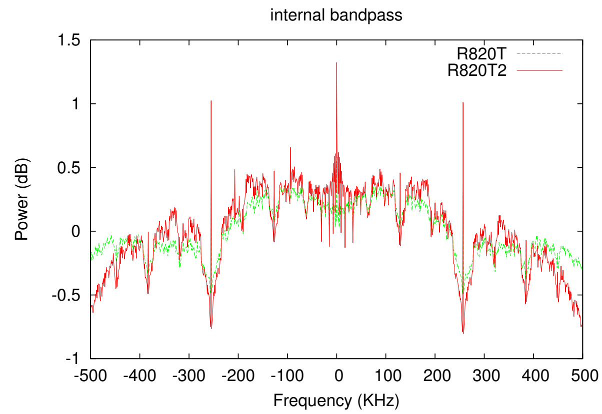

Figure 8: Internal instrumental bandpass determined for the observations from Fig. 4 (R820T2, red) and Fig. 5 (R820T, green).

about ten years, quality observations got feasible also for amateurs. What a chance! Of course, recent professional FPGA devices are much more sophisticated, they can be programmed for various different tasks, but at the same time the costs are higher by a factor of at least a few thousand.

5 The internal bandpass

Figure 3 demonstrates the importance of a reliable bandpass determination. Figure 8 shows the bandpass for the observations discussed above, the gain curves are very similar. In both cases we used only 50% of the available bandpass, the rtl_power crop parameter was set to -c 0.5. In this case bandpass ripples are mostly below 1 dB.

To study, how far bandpass issues affect observations, we repeat our tests with a zero crop parameter. This means for the test setup a dongle bandwidth of 1.875 MHz. Figure 9 shows

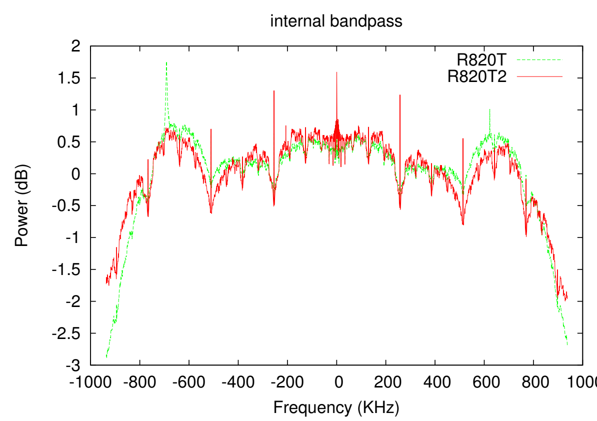

Figure 9: Internal instrumental bandpass for a zero crop parameter. Red: R820T2, green: R820T dongle.

that in comparison to Fig. 8 at the band edges the gain of the R820T2 dongle is now lower by 1 dB but performance of the R820T bandpass is worse by another dB.

It is interesting to analyze R820T2 test observations with such a bandpass setting. The

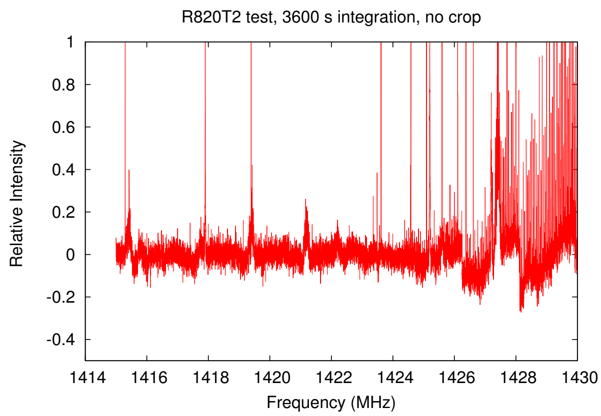

Figure 10: Long integration using the R820T2 dongle with zero cropping. This plot should be compared with Fig. 4.

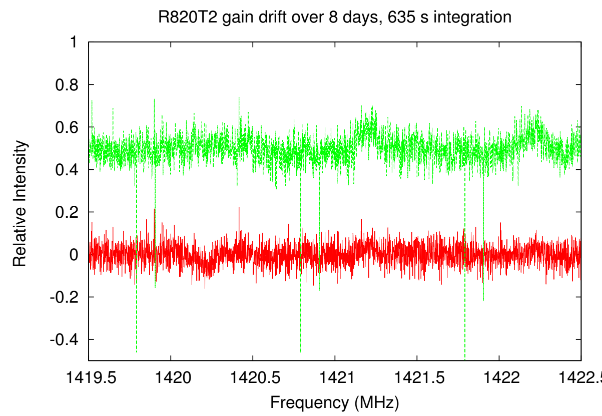

Figure 11: Testing stability over 8 days.

corresponding Allan variance is plotted in Fig. 6 in blue. This line appears similar well behaving like the red line, the noise is even better. To understand this diminished noise we need to consider that the time plotted in Fig. 6 is the total observing time. The integration time per individual pixel in the spectrum is the total time divided by the number of hops, hence it is larger in this case. For that reason it appears favorable, not to use cropping.

Well, let us investigate the resulting spectrum at the end of the integration, plotted in Fig. 10. Here we see that the noise, derived formally as the median over the spectrum, is not the most important quality criterion. We see that the baseline of this spectrum has significant ripples that could not be removed. The spectrum from Fig. 4 is much cleaner. To avoid rough baselines, we do not recommend to use zero cropping for deep observations.

Pushing our tests to an extreme, we present in Fig. 11 data that were observed 8 days after the Allan test. Here we compare the new spectrum (red) with what is obtained if we use the old gain curve from Fig. 8 for reduction (green, shifted).

6 Conclusions

Two Newsky RTL2838U dongles were tested, the R820T2 device against the R820T. The evaluation results in a clear preference for the new RTL2838U/R820T2 dongle. In the L-band the new dongle is at least 2.7 dB more sensitive. According to the radiometer equation the effective system temperature is reduced by almost 50%. Most important for reliable radio astronomical observations are stability issues. Allan variance tests have shown that the R820T2 dongle is far better then the older version. The stability is comparable to that of professional radio astronomical devices. The tests have shown that using the full bandwidth of the RTL-SDR devices results in spurious baseline ripples. For a good performance it is recommended to use the dongles at reduced bandwidth. rtl_power with the crop option -c 0.5 appears to be a good choice.

Ah yes, one final note: the tested RTL2838U dongle has really a Rafael Micro R820T2 tuner, though rtl_test doesn't realize that. But I wonder still whether or not I really have got the first of these devices, SN-1. Anyhow, it was fun to test this dongle, a nice cosy R820T2.

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