Hydrogen line observations: From frugal to advanced

Part 2: Low Noise Amplifiers and Filters

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1. Introduction

Observing the emission of neutral hydrogen from our galaxy has become a very achievable target for amateurs. Low cost components have become readily available over the recent years which substantially facilitate the observation possibilities. There are quite a few options to approach this goal, varying in technical and financial effort. Achievable results will be different, but as will be demonstrated some basic observations are possible with a very frugal approach.

This series of articles intends to give an overview of various options and to do a comparison between these. Each component of a receiving chain will be dealt with one by one: The antenna, the low noise amplifier, filter and the receiver itself (the "backend" in radio astronomy parlance). Once the individual components are covered, a comparison between various setups using these components is done. Actual observations are performed in order to allow an apples to apples comparison to the extent possible.

This second part of the series deals with amplifiers and filters.

2. Reminder: Basic setup of a hydrogen line receiving system

As a reminder from the previous article, the basic setup for hydrogen line observation consist of an antenna, a low noise amplifier (LNA), a filter, some more amplifier(s) and the receiver (backend) as shown in Fig. 1.

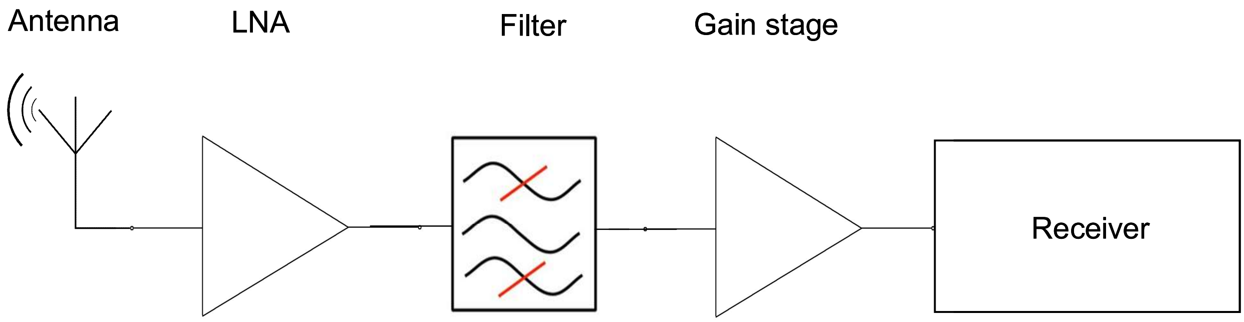

Figure 1: Generic setup

In the previous article we have dealt with various antennas. We will now look what options are available for the amplifiers and filters.

3. LNA and gain stage options

Low noise amplifiers are readily available these days as high quality devices are being produced in large quantities. These are typically based on High Electron Mobility Technology (HEMT). This is very beneficial for the amateur radio astronomer community: Unless one is shooting for the very best noise figures, they are also quite cheap.
We have investigated various low cost solutions to see which ones are best suited for the hydrogen observations. In doing so, we have determined the gain at 1420 MHz, the noise figure and the input return loss for each amplifier tested.

3.1. Test methods

Gain
The gain has been measured using a spectrum analyzer with tracking generator.

Noise figure (NF)
For measuring the noise figure, the Y-factor Method has been applied. This method requires a calibrated noise source and two accurate power measurements. The noise source is connected to the input of the amplifier under test and the power at the output of the amplifier is measured with the noise source turned on and turned off.
A good description of the method is available from Rohde&Schwarz at [1]

In our specific measurement we have used a calibrated noise source with an excess noise ratio (ENR) of 8.73 dB at 1420 MHz. We used a spectrum analyzer in channel power measurement mode to determine the power. This mode measures the integrated power in a channel of defined bandwidth. In our case we used 5 MHz of bandwidth centred at 1420 MHz. The signal was integrated over several minutes to get stable readings. In order to avoid that the noise figure of the spectrum analyzer itself affects the measurement, a preamplifier with 0.5 dB NF was used in front of the spectrum analyzer.

In this way the (linear) ratio of the signal *Y* with the noise source on and off is determined:

$$Y = N_{on} / N_{off} \qquad (1)$$

Since this is the ratio of two power measurements, the absolute calibration of the spectrum analyzer does not influence the result. Stability, though, is of importance and therefore the instruments need to be in good thermal equilibrium.

From this value of Y the noise figure NF can be calculated using the ENR value of the noise source:

$$NF_{dB} = ENR_{dB} - 10 \log(Y-1) \qquad (2)$$

Return loss
The input return loss has been measured with a spectrum analyzer with tracking generator and a reflection bridge. This is the same setup as used for the return loss measurement of antennas as described in the first part of this series of articles.

3.2. Triquint (Qorvo) evaluation boards

One of the options is to use LNAs which were developed for the mobile phone market. Such devices are available from various manufacturers. We have used evaluation boards from Triquint (today acquired by Qorvo and re-branded) for the devices TQP3M9036 and TQP3M9037. The data is available at [2] and [3]. The evaluation boards have SMA connectors and can therefore be easily connected., see fig.2 .

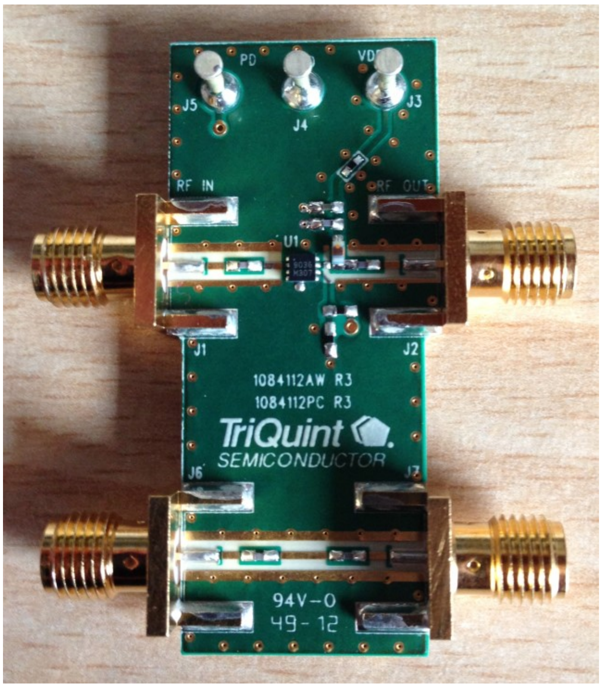

Figure 2: Triquint evaluation board

The board has a reference trace (the second lower trace) which we have later cut off as it is not needed for our purpose.

The performance was evaluated against the data sheet:

Device @ 1420 MHz	Gain		Noise figure		Return loss	
	Data Sheet	Measured	Data Sheet	Measured	Data Sheet	Measured
TQP3M9036	16.4 dB	15.9 dB	0.4 dB	0.4 dB	-10.4 dB	-11.4 dB
TQP3M9037	22.6 dB	22.8 dB	0.4 dB	0.4 dB	-11.4 dB	-10.4 dB

Table 1: Measurement vs. data sheet for Triquint devices

Essentially the data quoted could be confirmed. This makes these devices excellent choice as LNAs.

3.3. LNA4ALL

We have purchased two of these devices from [4]. They are based on a PSA4-5043+ E-PHEMT and come on a small PCB with optional SMA connectors, see fig. 3.

Figure 3: LNA4All (Image from supplier's website)

Our test results were:

LNA4ALL @ 1420 MHz	Gain	Noise figure	Return loss
#1	16.0 dB	0.7 dB	-11.2 dB
#2	15.4 dB	0.7 dB	-10.7 dB

Table 2: Measurement results for LNA4ALL

While not as good in terms of the noise figure compared to the Triquint devices, these LNAs are still a very reasonable choice.

3.4. "Chinese" products

There are a large number of various RF amplifiers which are sold by Chinese suppliers via eBay. Typically these are small PCBs with SMA connectors which makes them easy to use.
We have tested a number of these devices whether they can be used for amateur radio astronomy purposes. Here is the collection, ordered in the sequence of measured noise figure.

"50-4000 MHz SPF 5189Z"
The unit tested is marked with "50-4000 MHz SPF 5189Z" (see fig. 4) which indicates that it is based on the SPF 5189Z. It has a shielding cover so the details of the design cannot be seen. However, one can assume that it is closely following the reference design as published for example in [5].

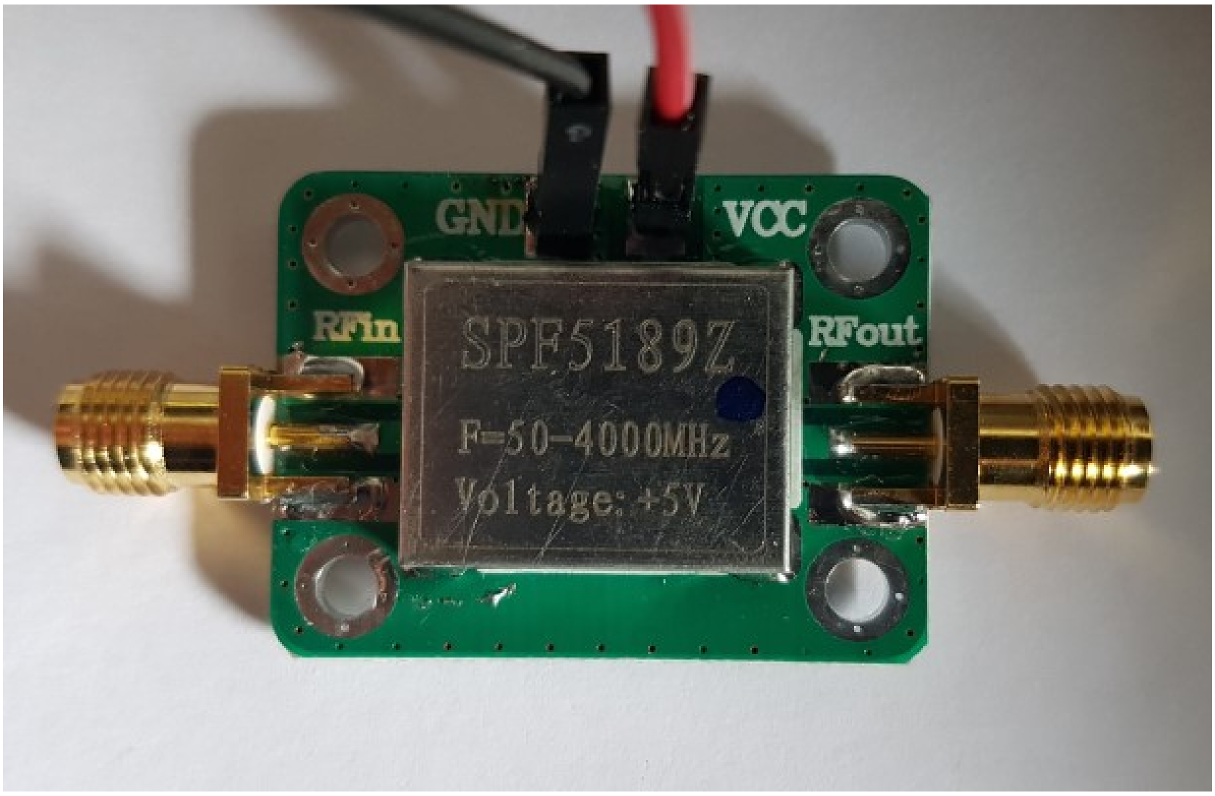

Figure 4: 50-4000 MHz unit

Four of these units have been measured with relatively consistent results as shown in table 3. The parameters are quite comparable to the LNA4ALL so it can be considered as more or less on even ground.

50-4000 @ 1420 MHz	Gain	Noise figure	Return loss
#1	14.6 dB	0.6 dB	-13.0 dB
#2	15.1 dB	0.6 dB	-14.1 dB
#3	14.8 dB	0.7 dB	-18.7 dB
#4	14.8 dB	0.7 dB	-16.5 dB

Table 3: Measurement results for "50-4000 MHz SPF 5189Z"

"RF AMP V 2.0"

The unit tested is marked with RF AMP V 2.0 on the board which has a black colour. It is also based on the SPF 5189Z (see fig. 5).

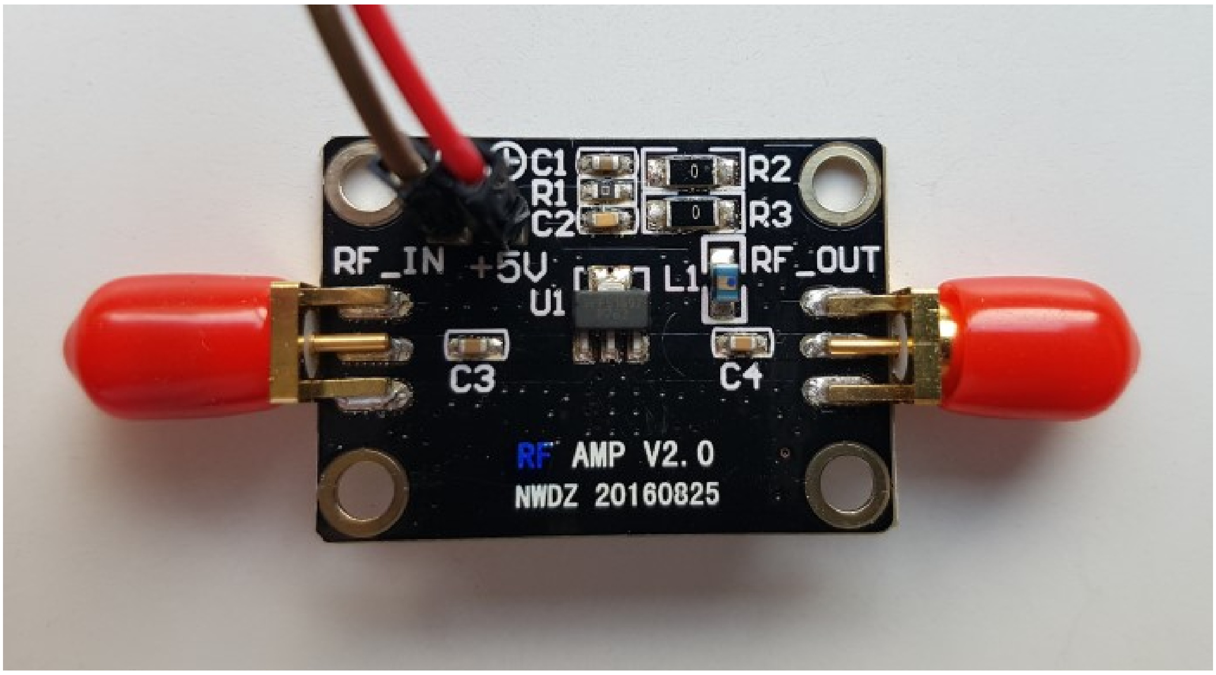

Figure 5: RF AMP V 2.0

Despite this similarity to the previous example, the noise performance is not quite as good as demonstrated by the test results in table 4.

AMP V2.0 @ 1420 MHz	Gain	Noise figure	Return loss
#1	14.6 dB	0.8 dB	-13.8 dB
#2	15.1 dB	0.8 dB	-18.2 dB

Table 4: Measurement results for "RF AMP V 2.0"

The difference in noise figure compared to the previous type may be just be variations in the SPF 5189Z rather than an effect of the board design.

"5-3500 MHz Gain 20dB"

This unit is marked with "5-3500 MHz Gain 20dB" (see fig. 6). It is mechanically very similar to the first of the "Chinese units" but it remains unclear what chip is under the hood.

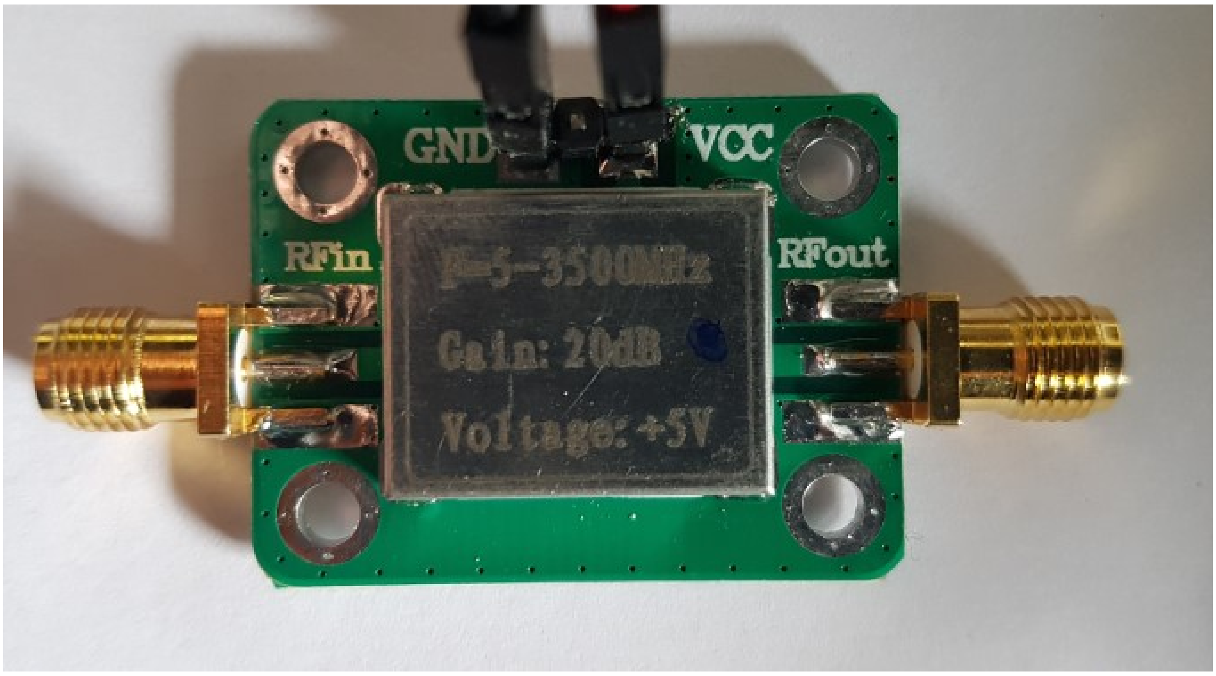

Figure 6: 5-3500 MHz unit

As it turns out, the units live up to the claim of having 20dB of gain. However, this goes at the expense of the noise figure compared to the previous devices, see table 5. Four units were measured.

"5-3500 MHz 20 dB" @ 1420 MHz	Gain	Noise figure	Return loss
#1	20.0 dB	1.1 dB	-15.1 dB
#2	20.6 dB	1.1 dB	-22.3 dB
#3	20.5 dB	1.2 dB	-18.0 dB
#4	20.2 dB	1.1 dB	-18.0 dB

Table 5: Measurement results for "5-3500 MHz 20 dB"

The higher noise figure does not make this one a prime choice for the LNA, however it will fare well as a gain stage given it's higher gain.

"1M-2GHz 64dB"

Marking on this unit is 1M-2GHz 64 dB", see fig 7. Indeed we have confirmed that this unit has a gain of about 65 dB, but only up to 400 MHz. But still at 1420 MHz the gain is 50.3 dB.

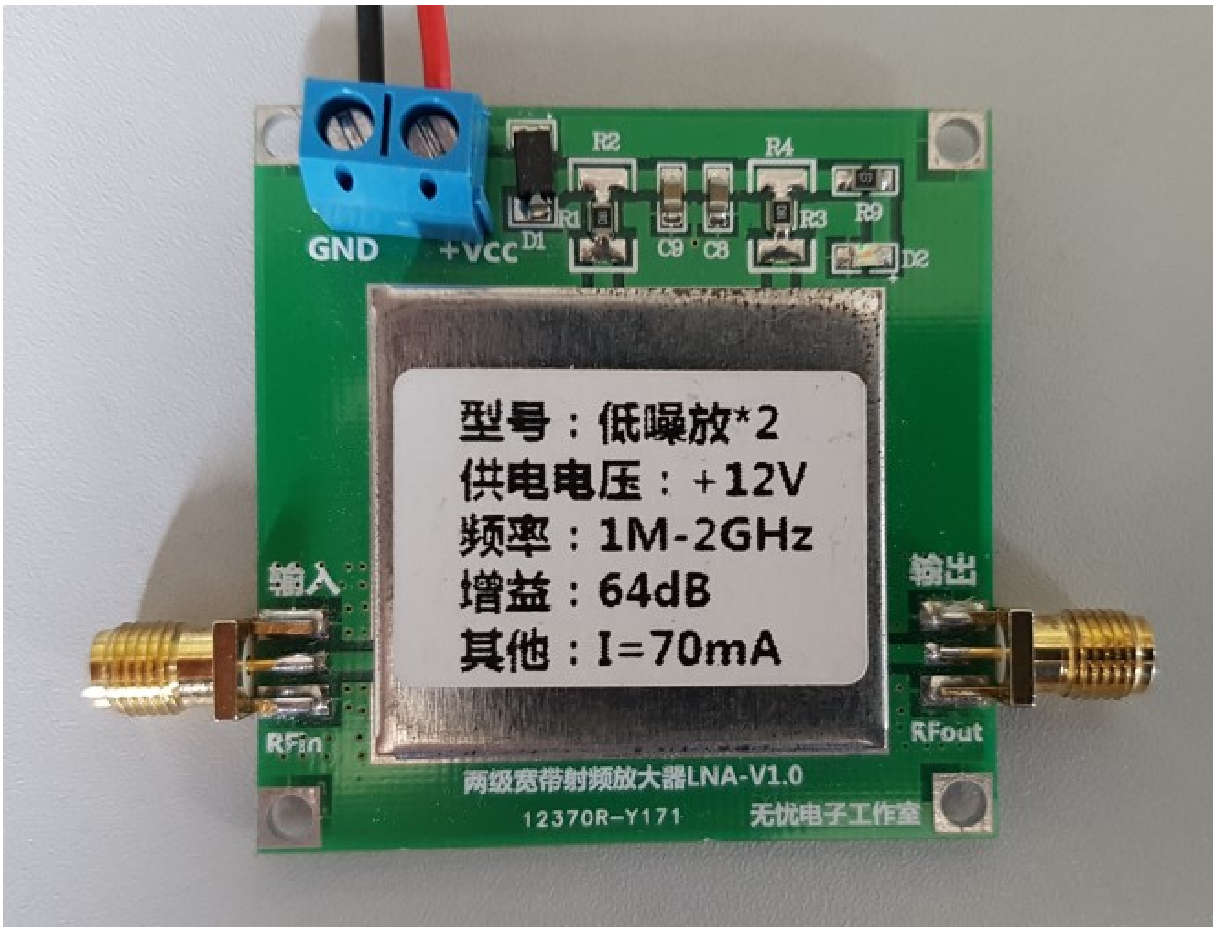

Figure 7: 1-2000 MHz unit with 64 dB gain

"1MHz-2GHz 64 db" @ 1420 MHz	Gain	Noise figure	Return loss
#1	50.3 dB	3.0	-6.3 dB

Table 6: Measurement results for "1 MHz-2 GHz 64 dB"

With a noise figure of 3 dB it is not well suited as a LNA, but it may be quite usable as a gain stage later in the chain. At such a high gain stability is a concern and care must be taken that oscillations doe not occur. The input return loss of only 6.3 dB is low so one might want to add a 3 dB attenuator in front to minimize reflections.

Another consideration to take into account is the maximum output power of the device. If a fairly wideband signal is supplied at the input, the aggregate power over the bandwidth at the output may become too large and non-linearity will be the result. Therefore care must be taken not to overload the device. We have not determined what level would still be acceptable.

"0.1-2000 MHz Gain 30 dB"

Marking on this unit is 0.1-2000 MHz, Gain 30dB, see fig. 8. We have not figured out which semiconductor component is used, it is marked with N02.

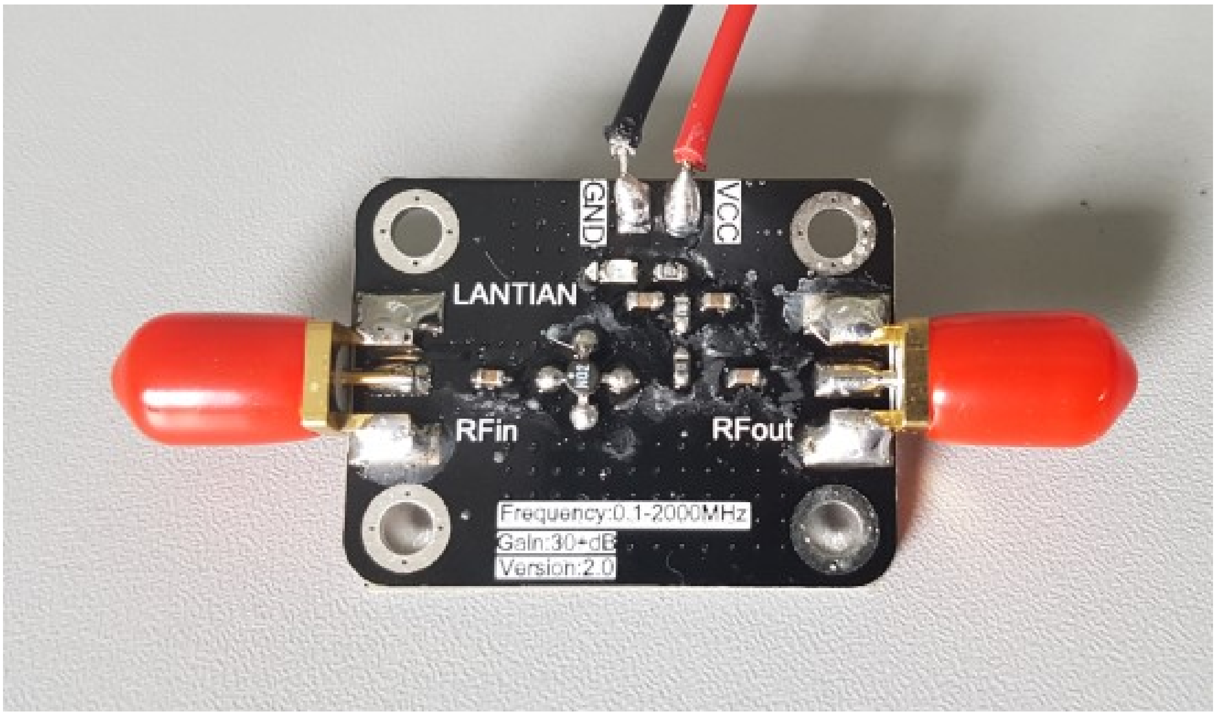

Figure 8: 0.1-2000 MHz unit with 30 dB gain

"0.1-2000MHz 30 db" @ 1420 MHz	Gain	Noise figure	Return loss
#1	23.1	3.1	-9.1

Table 7: Measurement results for "0.1 - 2000 MHz 30 dB"

Again, this one would not be a good choice for a first stage LNA due to its high noise figure but it would certainly work later in the chain for adding gain.

"50M-6GHz 20dB"

Marking on this unit is 50M-6GHz 20dB", see fig. 9. Since we are interested in the performance at 1420 MHz we have not checked whether this device is usable up to 6 GHz.

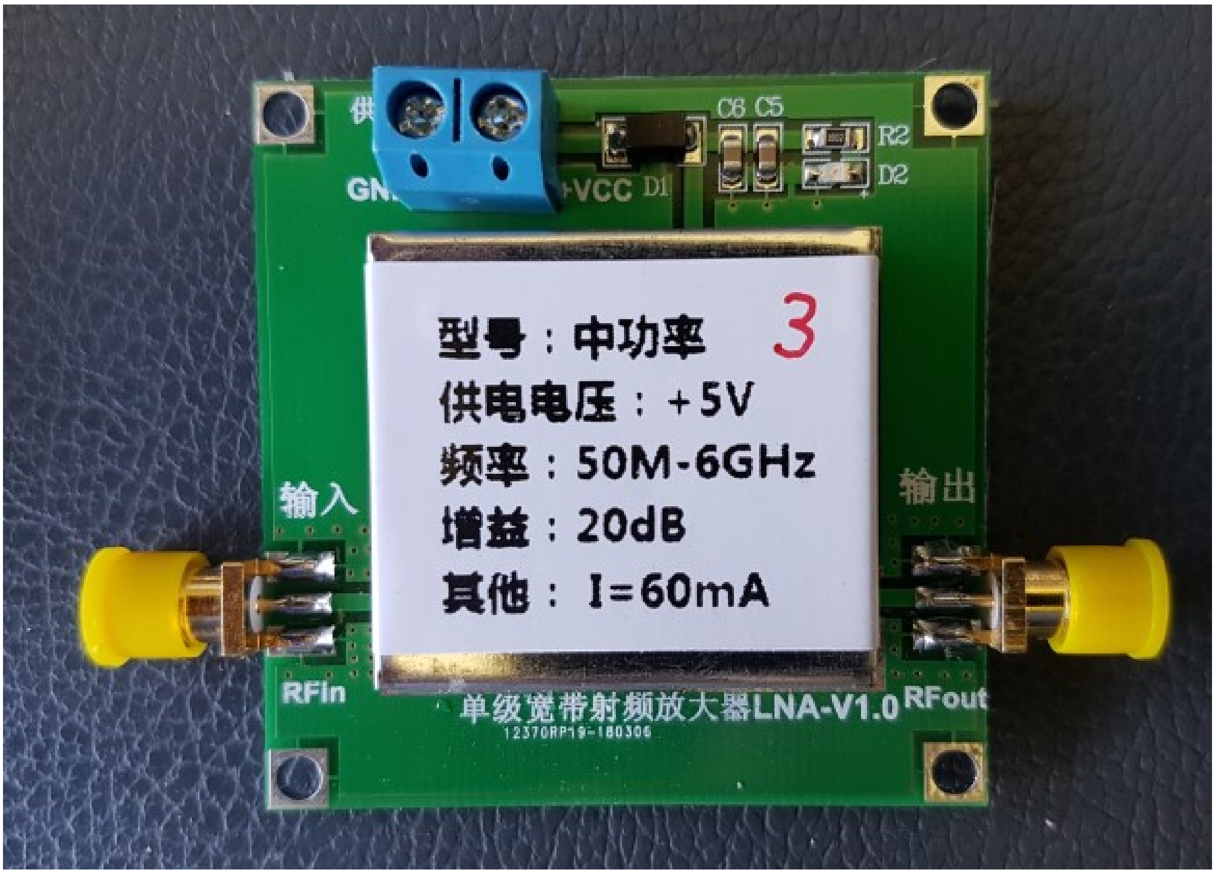

Figure 9: 50M-6GHz, 20 dB unit

We have tested three devices. All of them clearly fail the claim of 20 dB gain and all three have a relatively poor noise figure as listed in table 8:

"50 Mhz-6GHz 20 dB" @ 1420 MHz	Gain	Noise figure	Return loss
#1	15.6 dB	3.8 dB	-14.5 dB
#2	15.6 dB	3.5 dB	-12.5 dB
#3	15.6 dB	3.7 dB	-14.7 dB

Table 8: Measurement results for "5-3500 MHz 20 dB"

It might work as a gain stage, but it is not the prime choice for a hydrogen observation setup.

"1M-2GHz 32 dB"

Marking on this unit is "1M-2GHz 32dB", see fig. 10.

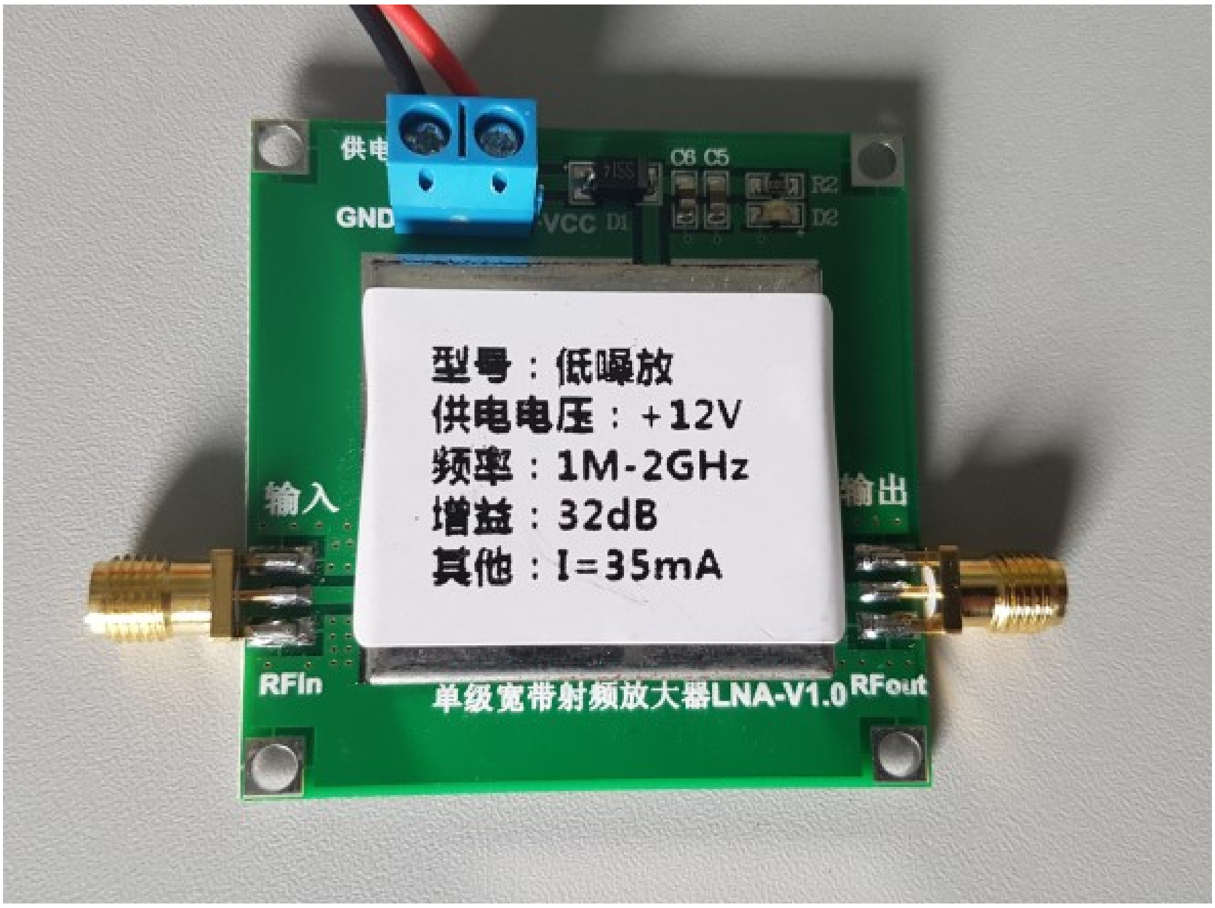

Figure 10: 50M-6GHz, 20 dB unit

"1M-2GHz 32 db" @ 1420 MHz	Gain	Noise figure	Return loss
#1	25.3	4.0	-9.4

Table 9: Measurement results for "1M - 2 GHz 32 dB"

Again, this one would not be a good choice for a first stage LNA due to its high noise figure but it would certainly work later in the chain for adding gain.

3.5. Down East Microwave Amplifiers

We gratefully acknowledge the donation of two DEM 1420LNA amplifiers by Dr. Alex Vrenios. He sent these to us when he dismantled his hydrogen observation setup. The LNAs come in a waterproof housing with N-connectors. There are two versions, a higher gain (1420LNAH) and a lower gain version (1420LNA) [6]. We have received one of each. The unit is depicted below in fig. 11.

Figure 11: DEM 1420LNAH

While these are certainly good amplifiers, they do not quite live up to the noise performance as quoted in the data sheet. One should note that these are older designs from times when P-HEMTs were not available.

Device @ 1420 MHz	Gain		Noise figure		Return loss	
	Data Sheet	Measured	Data Sheet	Measured	Data Sheet	Measured
1420LNAH	25 dB	27.9 dB	0.7 dB	0.8 dB	-6 dB	-9.5 dB
1420LNA	15 dB	11.1 dB	0.7 dB	0.9 dB	-6 dB	-8.3 dB

Table 10: Measurement results for Down East Microwave Amplifiers

3.6. SAT IF Inline Amplifier

Another option for a gain stage are inline amplifiers intended for the IF of satellite reception units (see fig. 12). These are mass products and are therefore relatively cheap. The disadvantage is that they are designed for an impedance of 75 Ohm and therefore some mismatch may occur when connecting with other components.
As an upside, these devices are remotely powered through the coax cable.

Figure 12: SAT inline amplifier

Due to the different impedance test results for these devices have to be taken with caution. In particular, the noise figure measurement will be impaired by the mismatch. For the same reason, no value is given for the return loss.

Inline Amp @1420 MHz	Gain	Noise figure	Return loss
#1	18.6 dB	2.8 dB	n/a
#2	19,2 dB	2.6 dB	n/a

Table 11: Measurement results SAT Inline Amplifiers

3.7. LNA Housing

Obviously, the open boards with SMA connectors are not suited to be put right at the antenna without additional protection. We found using ready made Aluminium die cast housings to be a good solution. Of course one could also make a specific housing if one has the right tooling.
In our case we used housings made by Hammond [7], in particular the 1550C type.
They were fitted with a flange male-N to female SMA adapter as input and with a female SMA to female N adapter as output. An example is shown below in fig. 13.

Figure 13: LNA housing

While this housing primarily provides a weather proof setup, it also gives shielding of the open boards against RFI to a certain extent.
In the setup shown, we have placed two amplifiers in the box, interconnected by a semi rigid cable. In many cases, however, one would put a 3 dB attenuator between the two stages in order to improve matching and avoid oscillation.
This particular example consisted of two boards of the "50-4000 MHz SPF 5189Z " type providing a gain of 28.6 dB with a NF of 1.0 dB.

3.8. Stability

No specific tests were made with respect to the stability of the amplifiers, i.e. whether they do not oscillate under certain conditions. No instabilities were observed under the test setups. However, this does not exclude that such instabilities may occur when an amplifier is connected to an antenna where matching conditions will vary.

Another aspect is gain stability. Again, this was not tested for the devices described. For a hydrogen observation setup this is of less importance unless one wants to do calibrated measurements. Since one in primarily interested in the shape of a spectrum, gain variations will not matter. However if one wants to do continuum observations where small variations in total power are to be observed, the gain stability (over time, temperature and other factors) becomes an important aspect.

3.9. Other options

Besides the amplifiers covered above there are quite a few more options which were not tried as part of this project.

There are two units specifically designed for the hydrogen band. Not being mass produced, they are in a different price bracket:

- Kuhne Electronic (1350-1450 MHz, 30 dB, NF 0.4 dB) [8]
- Radio astronomy supplies (Bandwidth n/a, 35 dB, NF 0.29 dB) [9]

These two devices would be superior to what we have described above if they live up to the specifications.

3.10. Which one to choose?

Unless one wants to go for the more expensive and high performing devices mentioned in 3.9, the best choices for an LNA directly at the antenna are the Triquint evaluation boards, the "best of the Chinese" and the LNA4ALL. For the gain stages after that, any of the other devices will do. It will depend on the required overall gain, which suits best.

4. Filters

Depending on the characteristics of the antenna various signals will be picked up from terrestrial transmitters. Such strong signals may overload one of the elements in the receiving chain, creating all sorts of side effects and spurious signals.
Therefore in most circumstances a filter will be needed to suppress such unwanted signals. The choice of a suitable filter will be influenced by the individual radio interference (RFI) situation.

The general rule is to put the filter behind the first LNA. Otherwise the noise figure is significantly affected due to the additional attenuation between the antenna and LNA. There are cases, however, when it may be necessary to put the filter in front of the LNA. This is when the interference situation is so severe that already the first amplifier gets overloaded.

4.1. Test method

We have investigated several filters with different characteristics suited for a receiving chain aiming at the hydrogen line frequency. Each filter has been measured using a spectrum analyzer with tracking generator as shown below in fig. 14 . The frequency range of the measurement has been from ~ 8 MHz to 3.2 GHz.

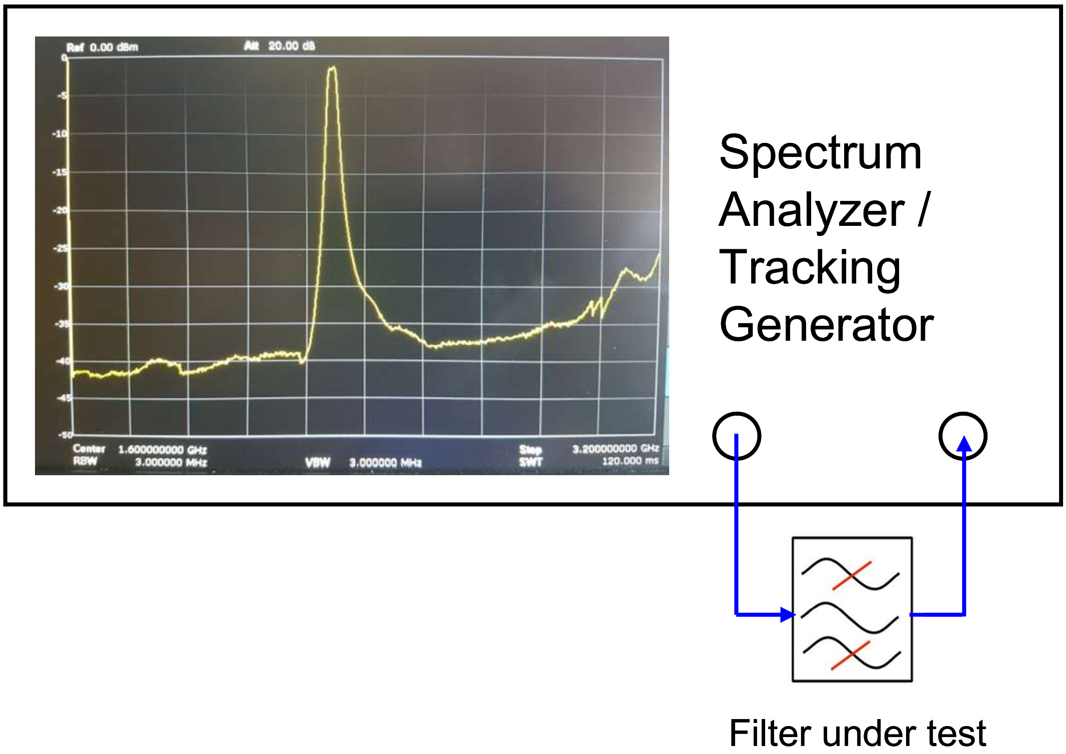

Figure 14: Filter test setup

4.2. Minicircuits VBFZ-1400-S+

Figure 15: Minicircuits VBFZ-1400-S+

The Minicircuits VBFZ-1400-S+ is a fairly wide band device with good suppression outside the passband, see fig. 16.

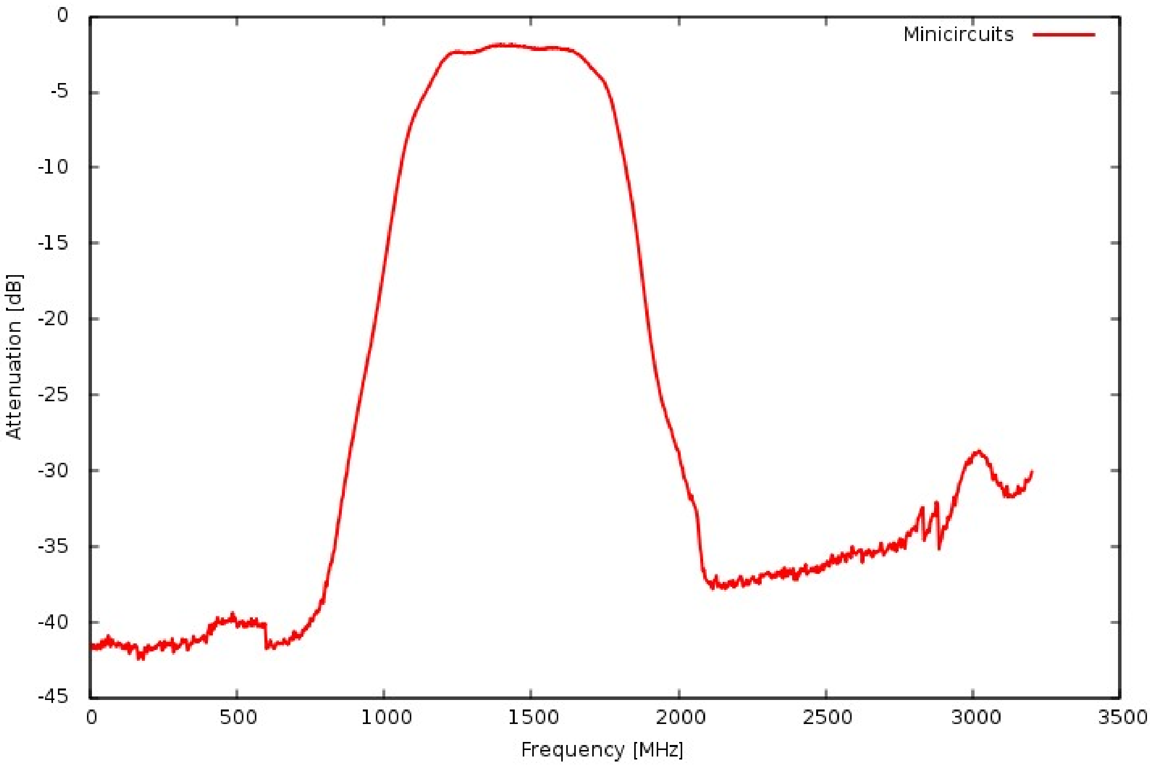

Figure 16: Minicircuits VBFZ-1400-S+ filter characteristics

3 units were measured with almost identical results

The filter loss at 1420 MHz is about 2.3 dB (slightly more than the 2 dB quoted in the data sheet), the 3 dB points are at 1139 MHz and 1784 MHz.

Since this filter is very wide band, it will be applicable where the interference is low in the bands immediately adjacent to the radio astronomy band, but where good attenuation of WiFi signals at 2.4 GHz is required.

4.3. "LNA4ALL" filter

The provider of the LNA4ALL described above [4] also makes filters. One of his designs is targeting the 1420 MHz suited for radio astronomy.
The filter is equipped with SMA connectors as shown in fig. 17.

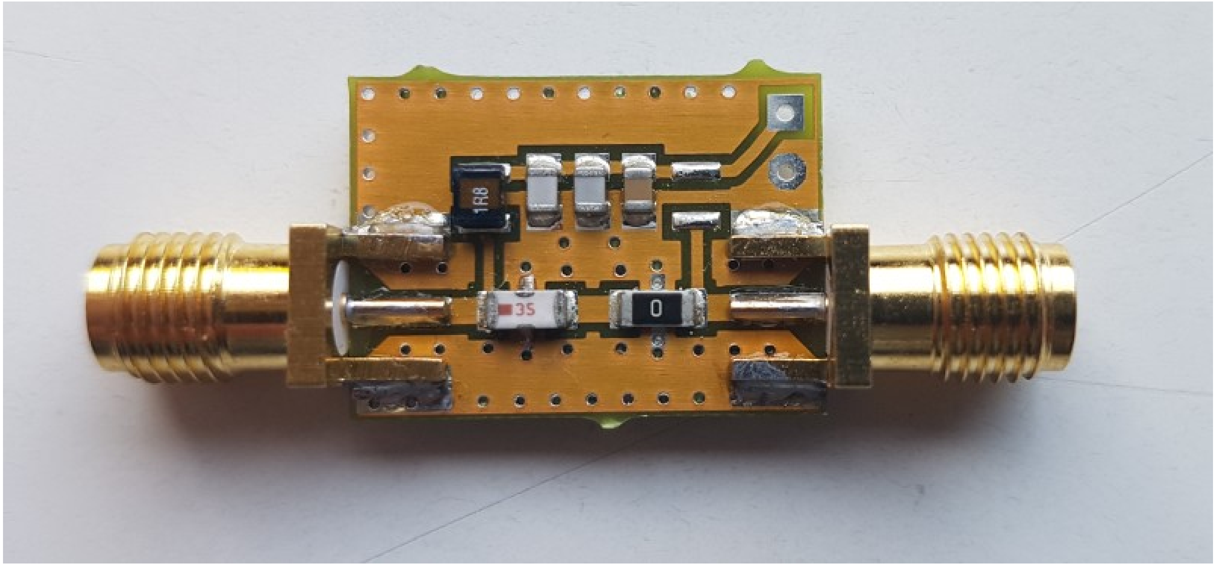

Figure 17: LNA4ALL filter

Also this filter is fairly wideband but not as wide as the Minicircuits filter. The drop towards higher frequencies however is not very sharp. As a result the attenuation of the WiFi band is about 10 dB less compared to the Minicircuits design. If the antenna used picks up stations in the FM band the lower attenuation in this range may be a concern.

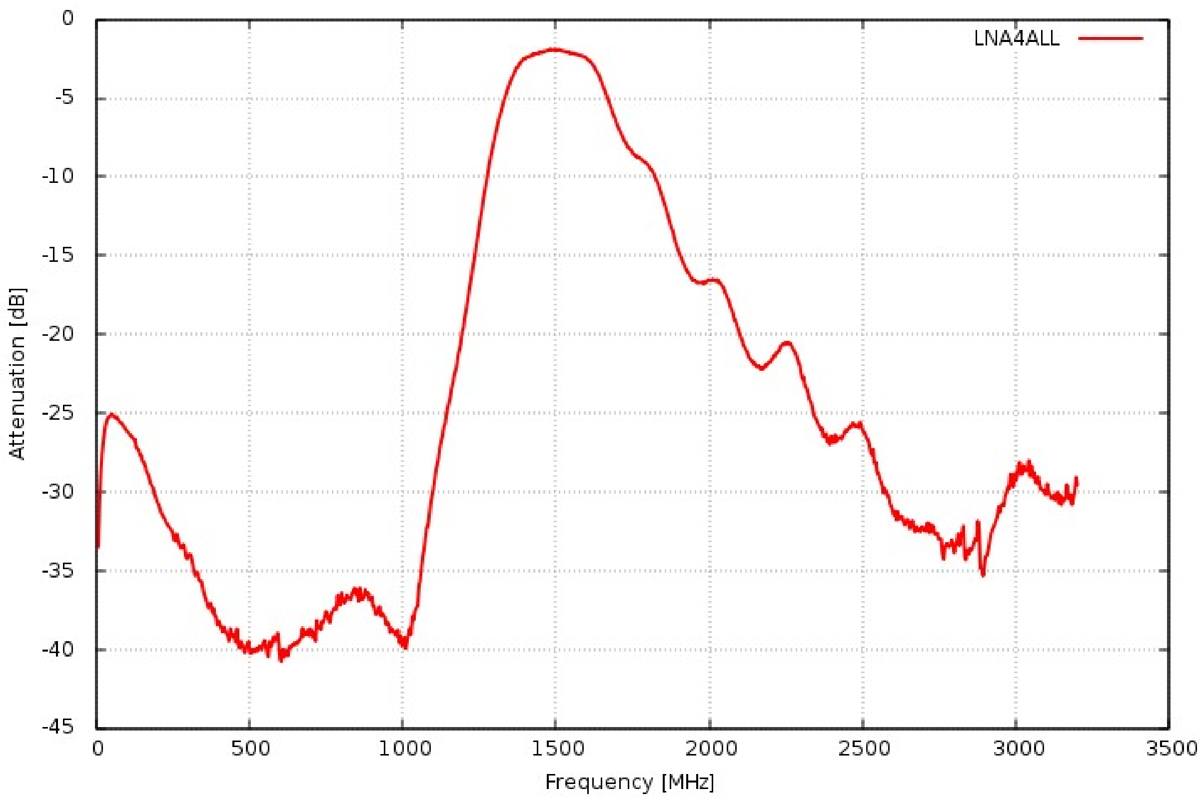

Figure 18: LNA4ALL filter characteristics

The filter loss at 1420 MHz is about 2.3 dB, the 3 dB points are at 1331 MHz and 1673 MHz.

4.4. Home made hairpin stripline filter

Hairpin stripline filters are fairly easy to make as they consist just of traces on a piece of double sided PCB. Paul Wade has a good writeup on this matter [10].

We have used a design created by Sven Brauch which he describes in his blog [11] with exact geometry [12]. As a side note: In his blog he also describes how he made a small telescope for hydrogen line observations.

Another variant (not tested by us) is described at [13].

Our finished result of this design is shown below in Fig. 19:

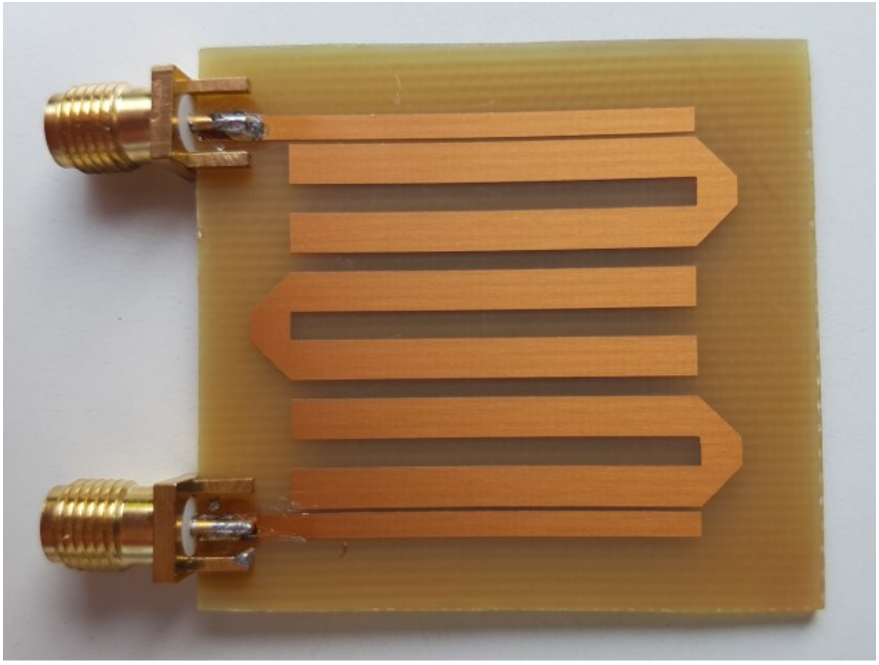

Figure 19: Hairpin hairpin stripline filter

This filter is fairly selective. The disadvantage, however is a second passband which falls into the region of 2.4 GHz so this may not be ideal in the presence of strong WiFi signals.

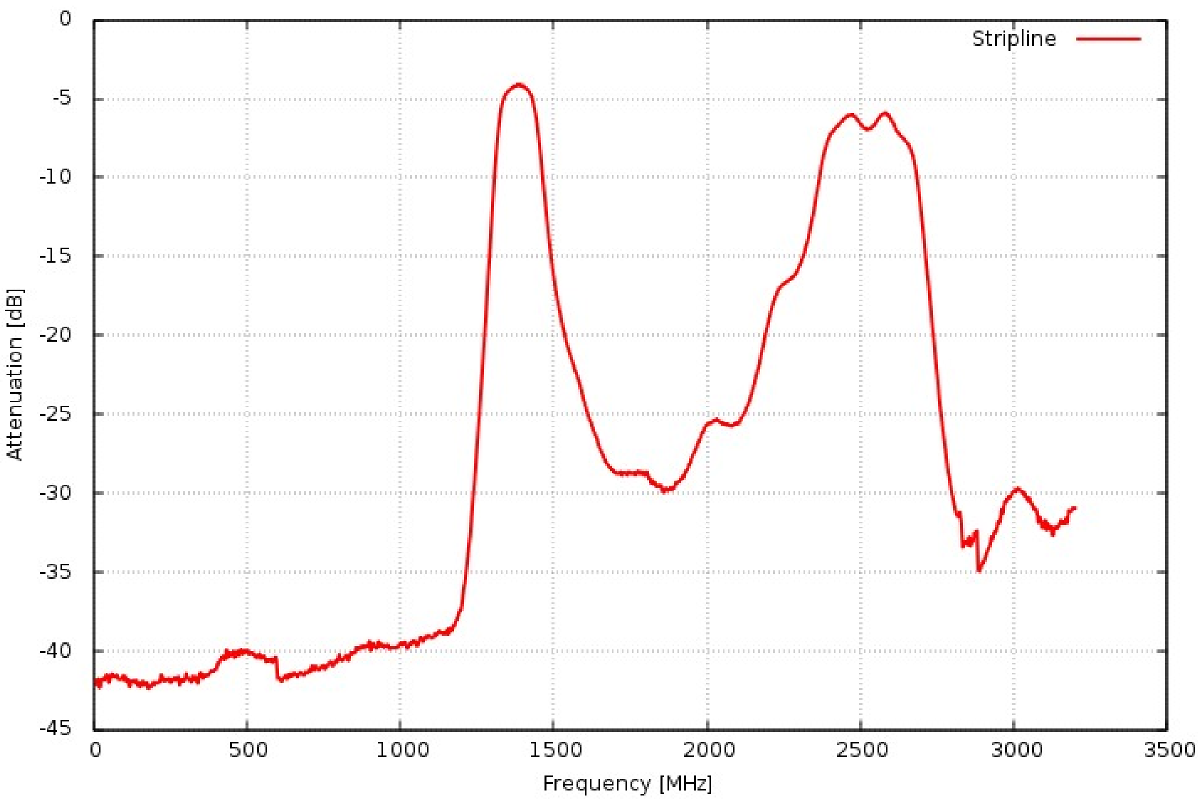

Figure 20: Stripline filter characteristics

The loss of the filter is 5 dB at 1420 MHz, and the 3 dB points are at 1326 MHz and 1462 MHz.

Several units were measured and the results were quite consistent. We found that there is some sensitivity if the filter is put into a housing. This can degrade the performance as shown in the comparison plot below in fig.21.

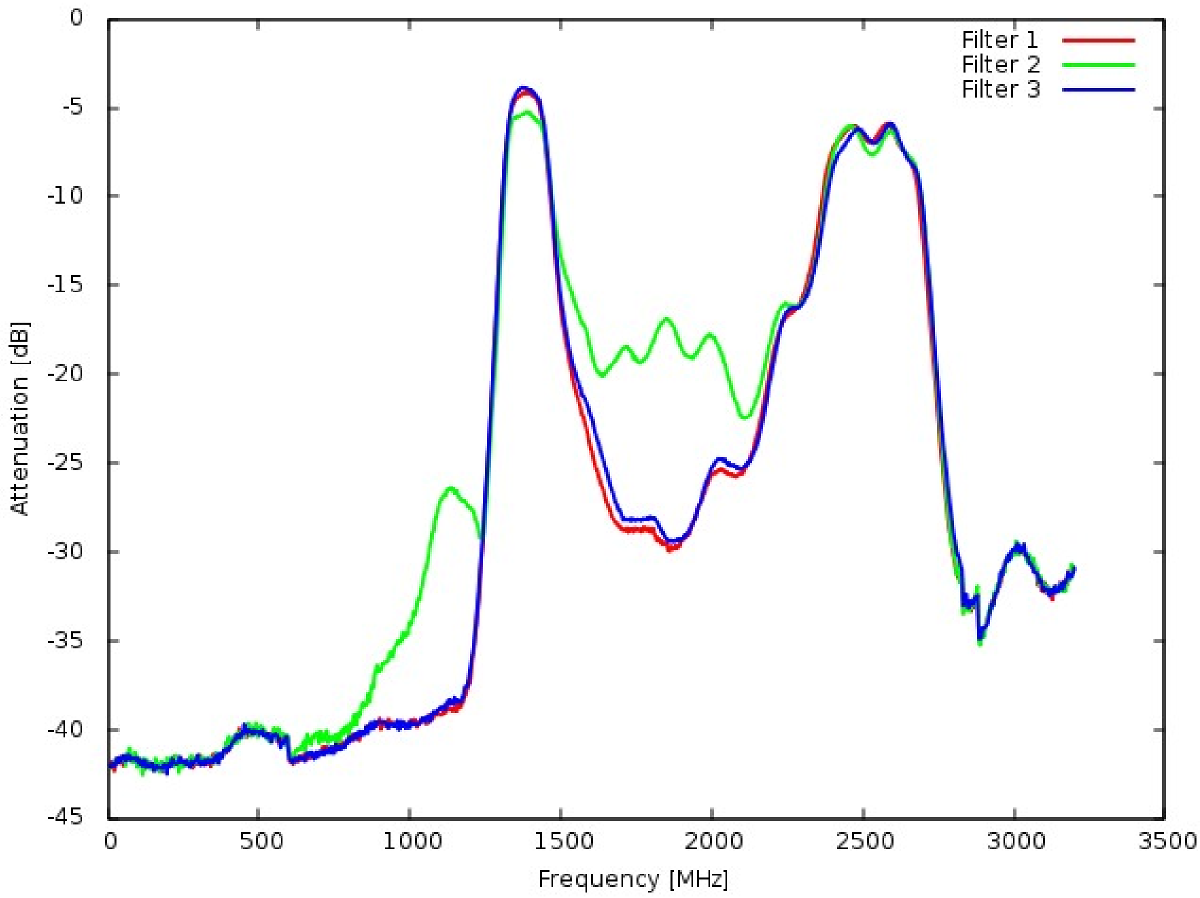

Figure 21: Comparison of three filters. Filter 2 is placed in a metallic box

4.5. Surface acoustic wave (SAW) filters

Marcus Leech from CCERA [14] has had a batch of SAW filters made. These are fairly selective and have a good suppression at the WiFi band. Their attenuation decreases towards the higher end of the measured range. This decrease is quite sensitive to the mounting of the device.

In our case we have put the filter on either a board supplied by Marcus or on a PTFE board. This board was the reference trace which was cut off from the Triquint LNA evaluation assembly described above. The resulting device is shown in fig. 22.

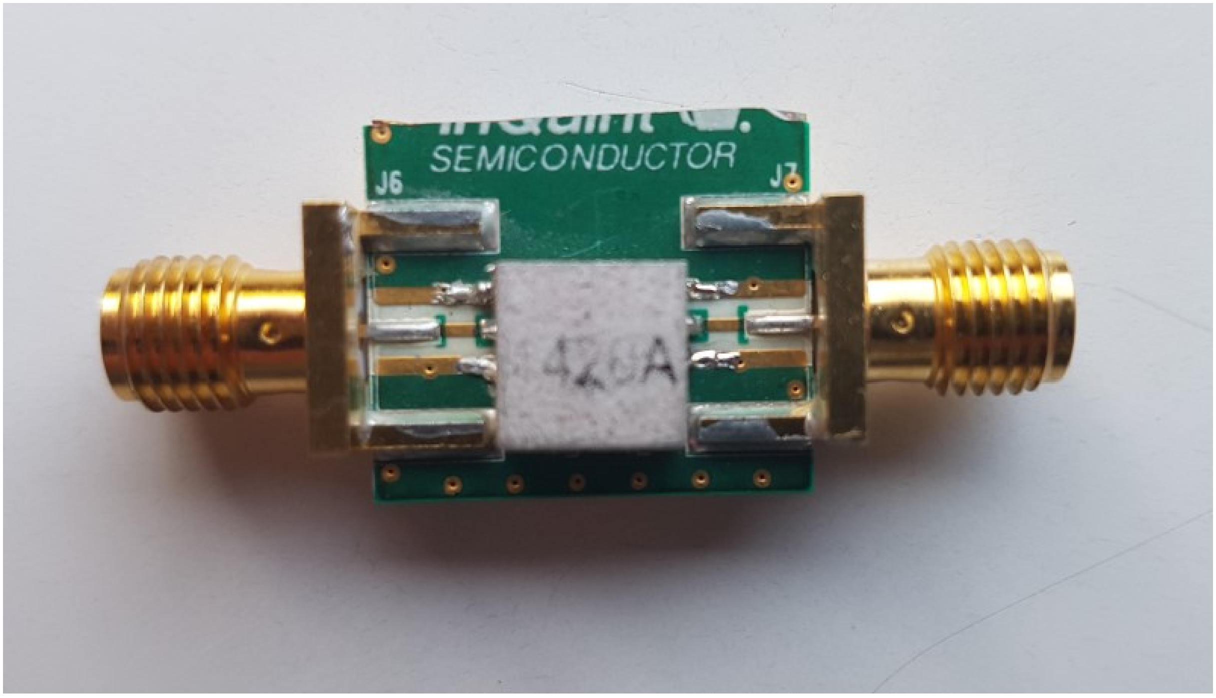

Figure 22: SAW filter

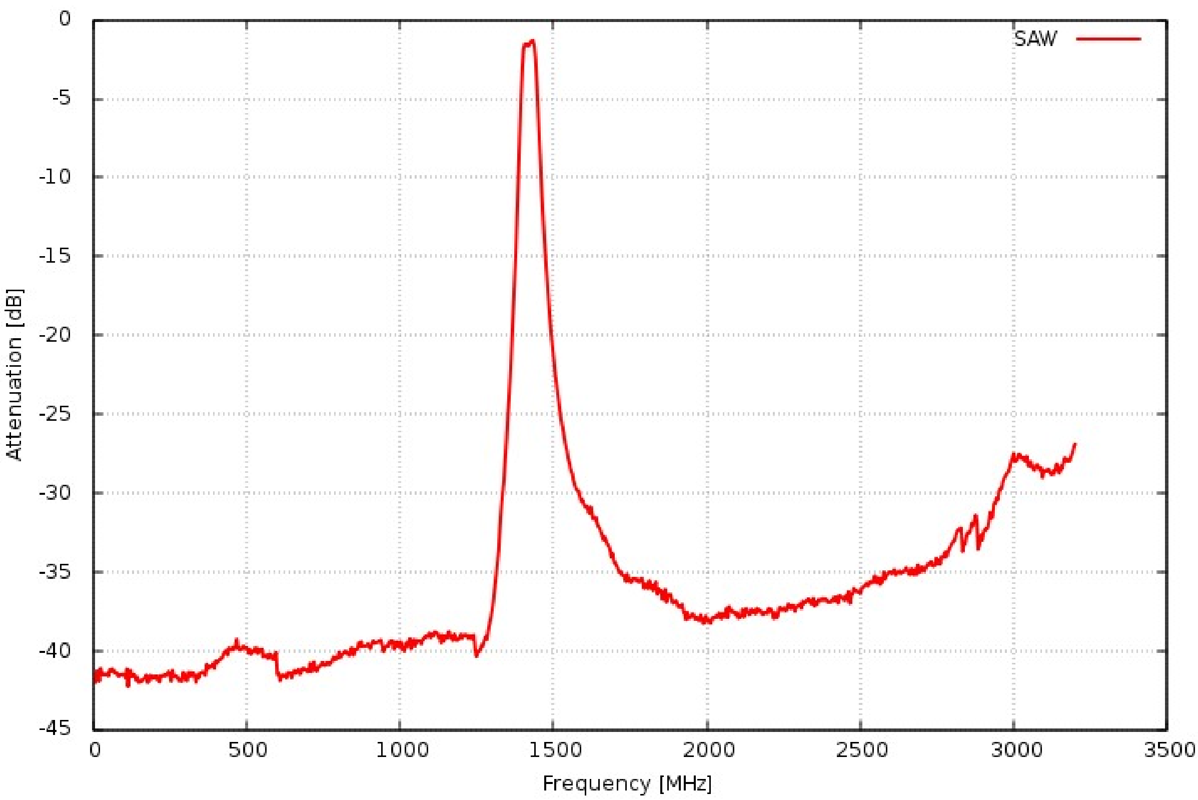

Figure 23: SAW filter characteristics

The loss of the filter is 1.7 dB at 1420 MHz. The 3 dB points vary a bit from device to device, typical values are 1400 MHz and 1446 MHz.

Marcus offered these devices for purchase, encapsulated in a small housing with SMA connectors. In our case, we received a batch of the filters and separate boards for self assembly.

4.6. Radio Astronomy Supplies filter

There is a filter available from Radio Astronomy Supplies (RAS) specifically for the hydrogen line [9]. It is provided in a housing with N-Connectors, see fig. 24. According to the website this filter is designed and built by Tommy Henderson (WD5AGO). Our unit was donated to us by Dr. Alex Vrenios.

Figure 24: Radio Astronomy Supplies filter

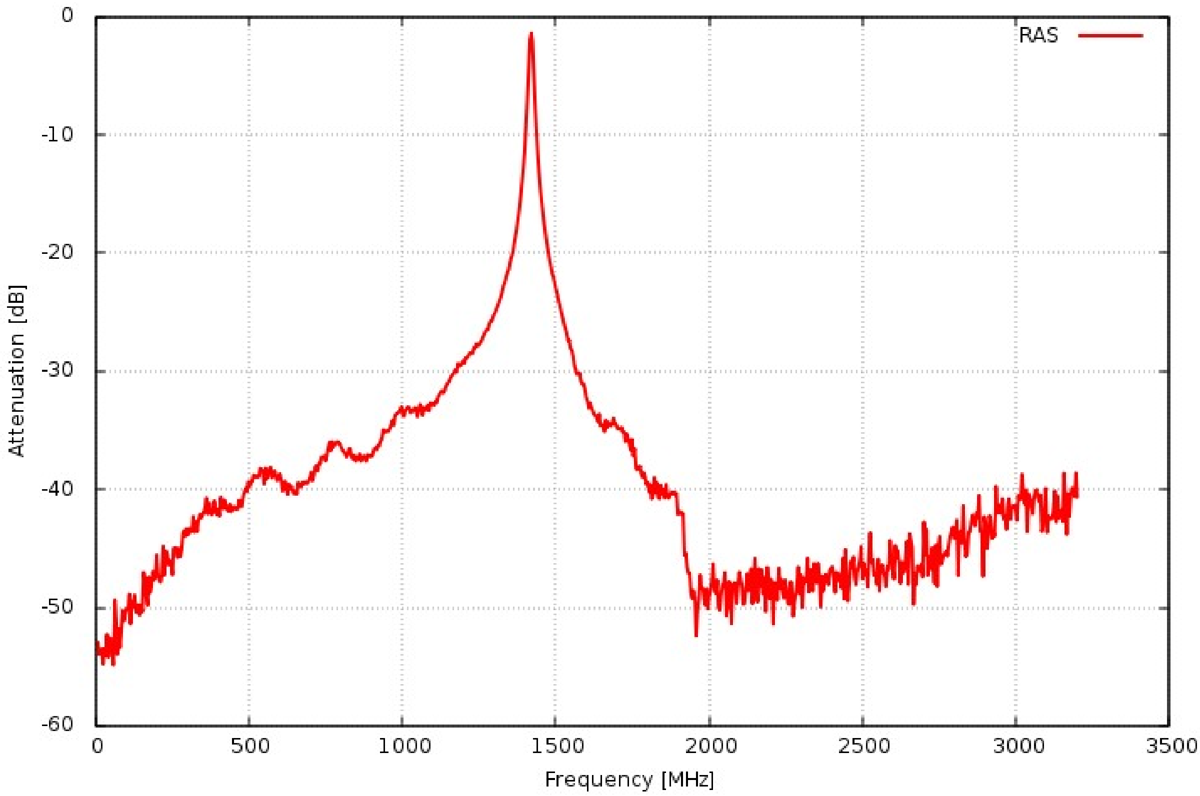

Figure 25: Radio Astronomy Supplies filter characteristics

This filter is very narrow and has good suppression of all frequencies outside the passband. The attenuation at 1420 has been determined to be 1.1 dB and the 3 dB bandwidth is about 8 MHz. Please note when comparing this measurement with the other filter measurements that in this case a lower attenuation has been used on the spectrum analyzer. Therefore the noise floor is lower.

4.7. Cavity filters

We have adopted the design of a 3-pole cavity comb filter by Matjaž Vidmar [15] and built two filters with excellent results. This design was chosen as it allows to use standard aluminium material for the waveguide housing and the fingers.

One of the filters was using the dimensions as described in Matjaž's paper for 1420 MHz. The second filter has a smaller distance between the fingers and therefore has a wider bandwidth. Both filters and their inside are shown below fig. 26.

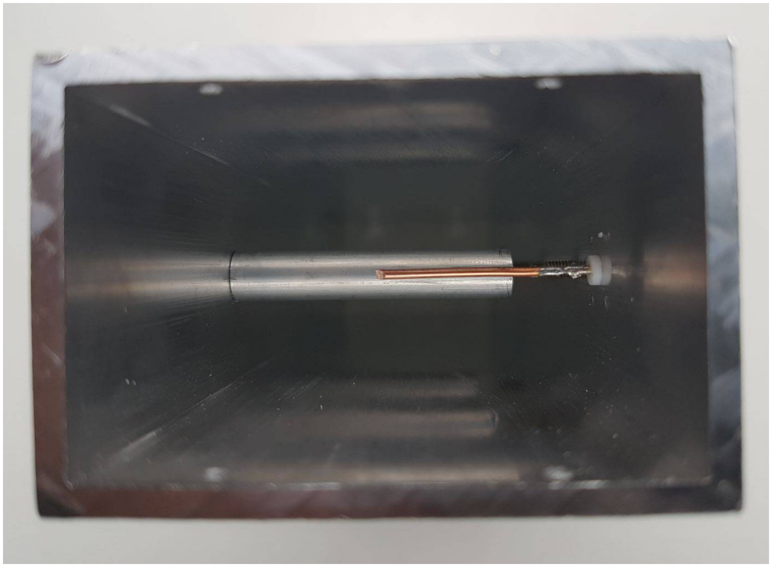

Figure 26: Cavity filters

The narrower filter "Cavity_1" has a 3dB bandwidth of 24 MHz and a loss of 0.4dB. There are some spurious resonances at higher frequencies, see fig 27.

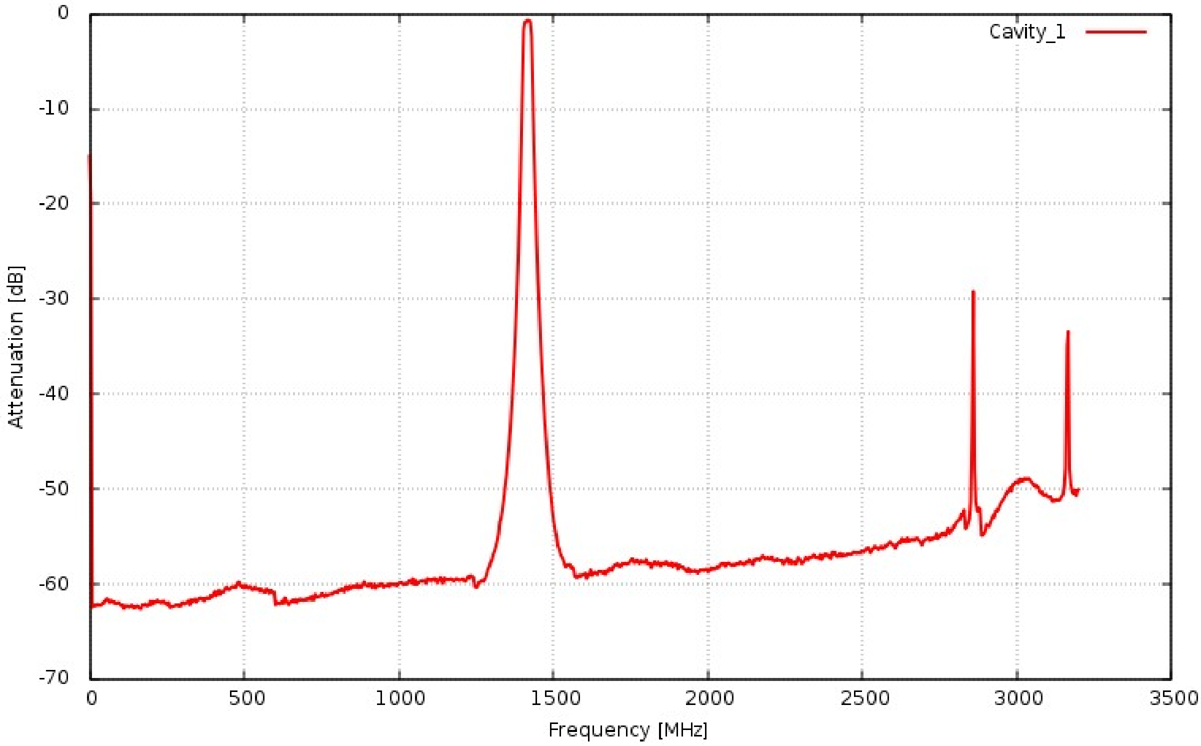

Figure 27: Narrow Cavity Filter "Cavity_1"

The wider filter "Cavity_2" has a 3 dB bandwidth of 54 MHz, the loss is 0.4 dB as well. The response is depicted in fig. 28.

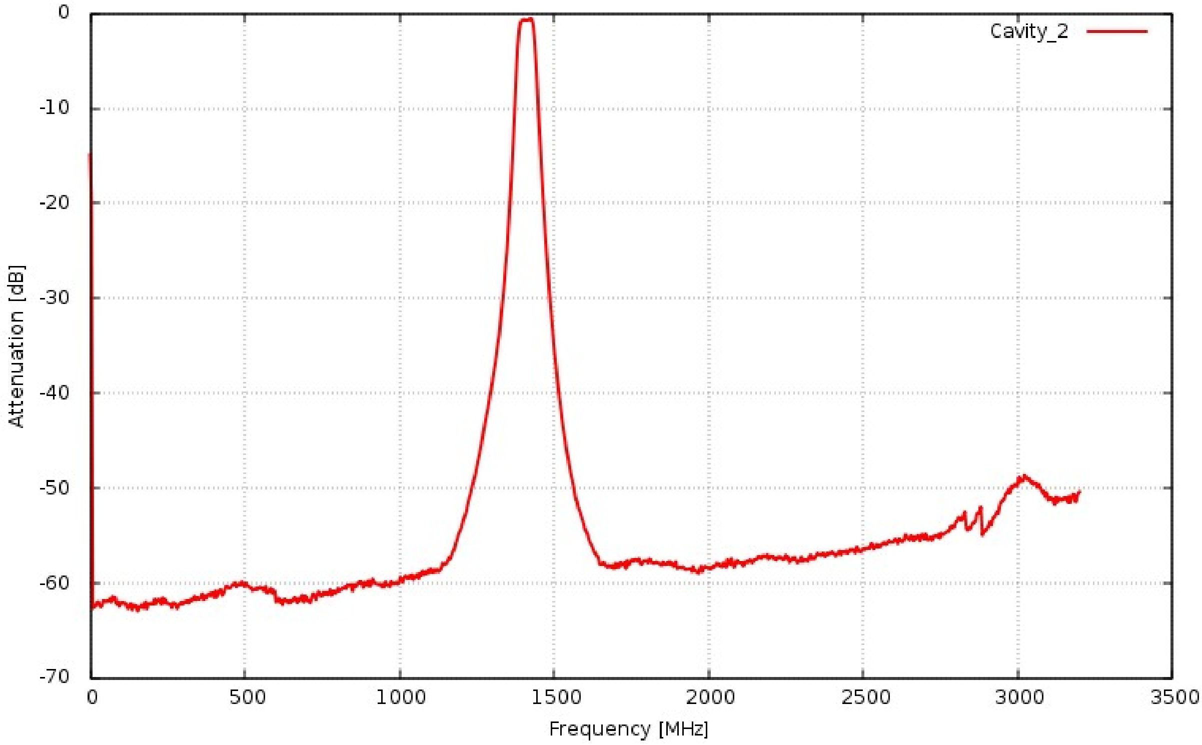

Figure 28: Wide Cavity Filter "Cavity_2"

4.8. Summary

Which is the best filter from the ones we have tested? There is no straightforward answer. If the aim is to observe the galactic hydrogen, the Radio Astronomy Supplies filter is an excellent choice. However, if one wants to observe continuum sources as well, more bandwidth is desirable. Ideally one would then use a cavity filter. Making such a device does require some skills/machinery for the mechanical construction. Marcus' SAW filter is an alternative. An easy to build "home made" filter is the stripline filter.

In case one is in the unfortunate situation that a filter is required in front of the LNA due to severe RFI, then the cavity filter offers the best solution due to its low loss.

The figure 29 below show a comparison of all filters in the 0 to 2 GHz range. A more detailed view is shown in fig. 30.

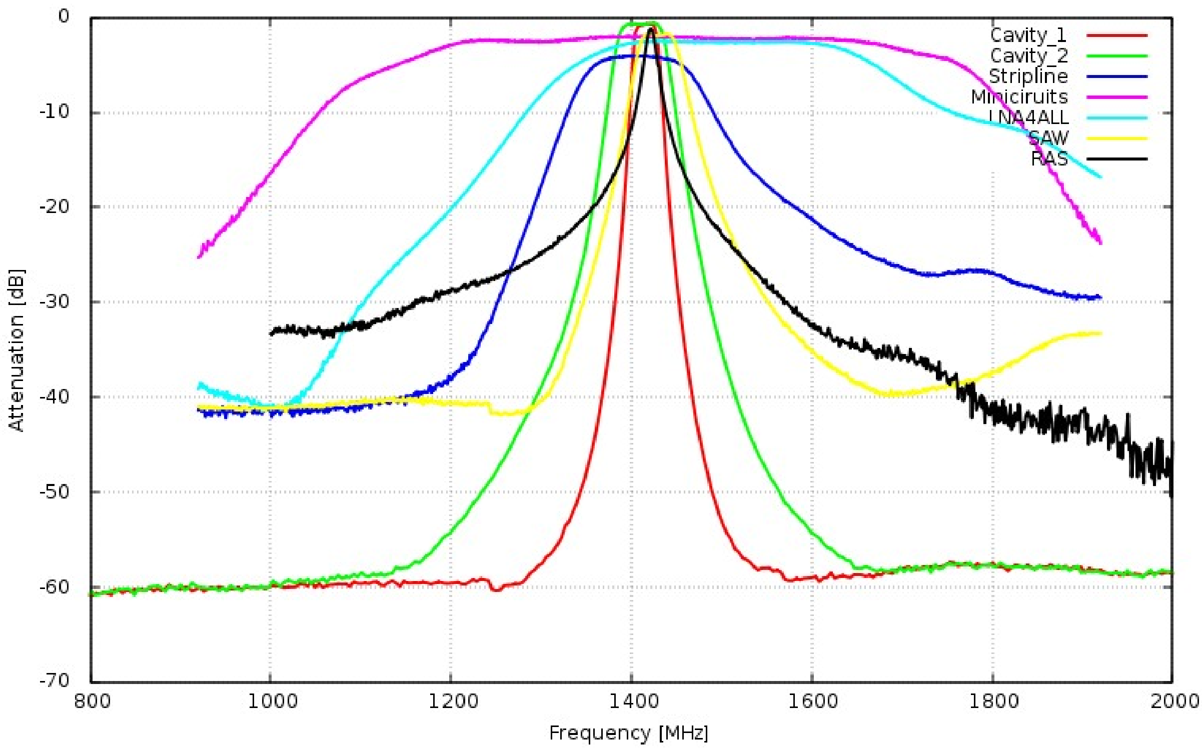

Figure 29: All filters in comparison, 0-2 GHz

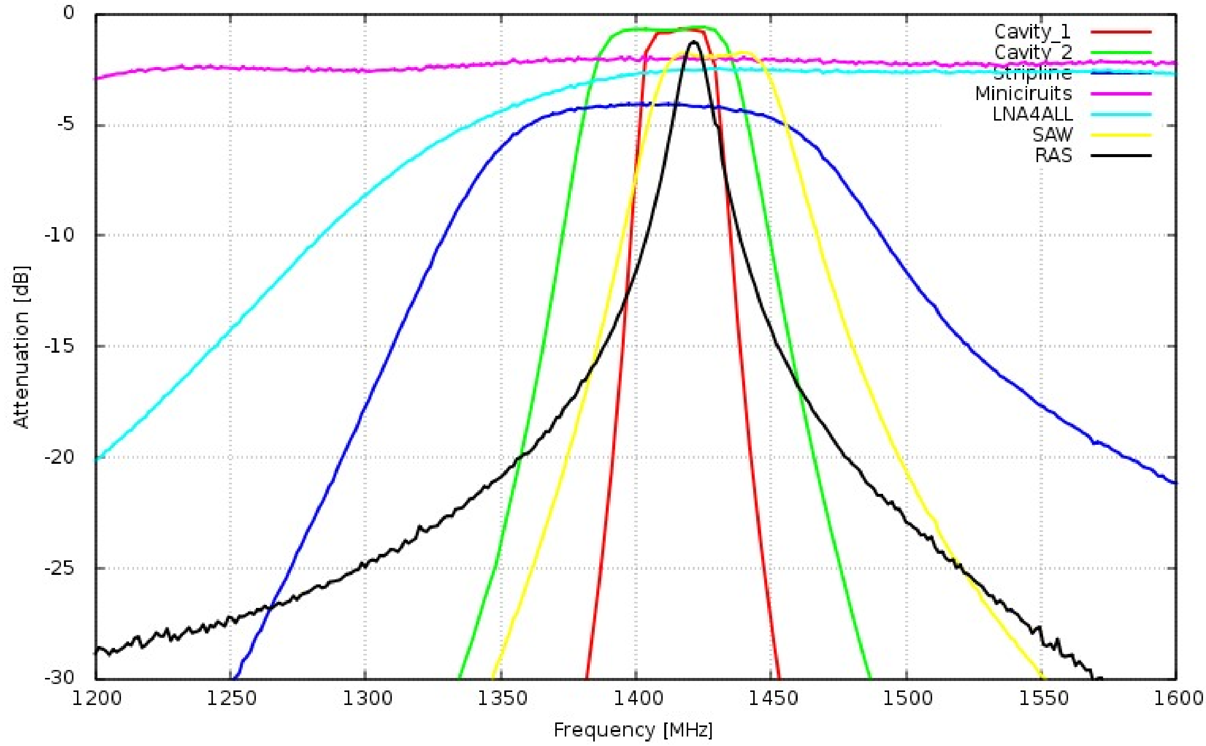

Figure 30: All filters in comparison, detail view

5. The "Hydrogen Team"

Several people from the Astropeiler team have contributed to this article. They have provided LNAs from their collections for the measurements. A special thanks goes to Gerhard Stramm who has built the cavity filters.

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