

LightWork Memo 6: LNA Config. - Rev 6

Subject: Radio Astronomy Low Noise Amplifier Configuration Sketch-Rev 6
Date: 2015 December 5
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This note is a sketch of an amplifier chain for citizen-science radio astronomy projects. A fully functional implementation would be convenient for those wishing to make astronomical observations on their own, or as a part of a National (or International) coordinated program.

A Radio Astronomy Telescope is built from a number of major parts:

- Enthusiastic Scientist
- Telescope surface and support structure
- **Feed and Low Noise Amplifier chain**
- High speed data sampler
- Data Acquisition computer

This note addresses the **Feed and Low Noise Amplifier (LNA) chain**, which is one of the major costs for the citizen scientists. The skills needed for effective design of these components are not held by many (citizen) scientists. See LightWork Memo 4 for a systems performance overview.

The components were selected based on experience with a home-built telescope system that used the Mini-Circuits Incorporated [PSA4-5043+](#) amplifier with SMA connectors. An additional, ultra lower noise amplifier, is needed for the first stage amplification. Tentatively the Mini-circuits [SVA-541+](#) amplifier is identified. For neutral hydrogen observations near the 21cm line at 1420.406 MHz, a high pass filter is needed to protect the amplifier chain from saturation due to interference at lower frequencies.

The suggested RF amplifier board design consists of two sets of two amplifiers, with SMA input and outputs (See Figure 1). The goal is to have greater than 45 dB of gain before the input to the data sampler and digital spectrometer subsystem. Figure 1 shows the sketch with annotations and suggested part numbers.

The relatively low voltage of the amplifier biases were chosen to improve the Noise Figure of performance of these devices, at the cost of slightly lower gain. An additional benefit of the +3V bias voltage is the reduced power used by the amplifiers. The power splitter/combiner part suggested is Mini-circuits part [TCP-2-272+](#). The High pass filter, [HFCN-1200+](#) was selected, as it allows a fairly large frequency range near 1420 MHz to be sampled. These are all surface mount parts. The input and output connections are all via female SMA connectors. The combined current draw for the board, when operating at +3V is 160mA. Well below the 200mA limit for [TCBT-14+](#).

This design does not include temperature stabilization of the board. Limited experience did not suggest strong variation in gain with temperature, however, with such high gain as this design has, temperature stabilized components might be needed. That would add a significant complexity and component cost.

The input of power via the coaxial cable is not required and perhaps a direct power connection is preferred. Some systems use micro-USB connectors for power. This adds some flexibility and convenience, but at the cost of an extra power cable when in operation. Perhaps the

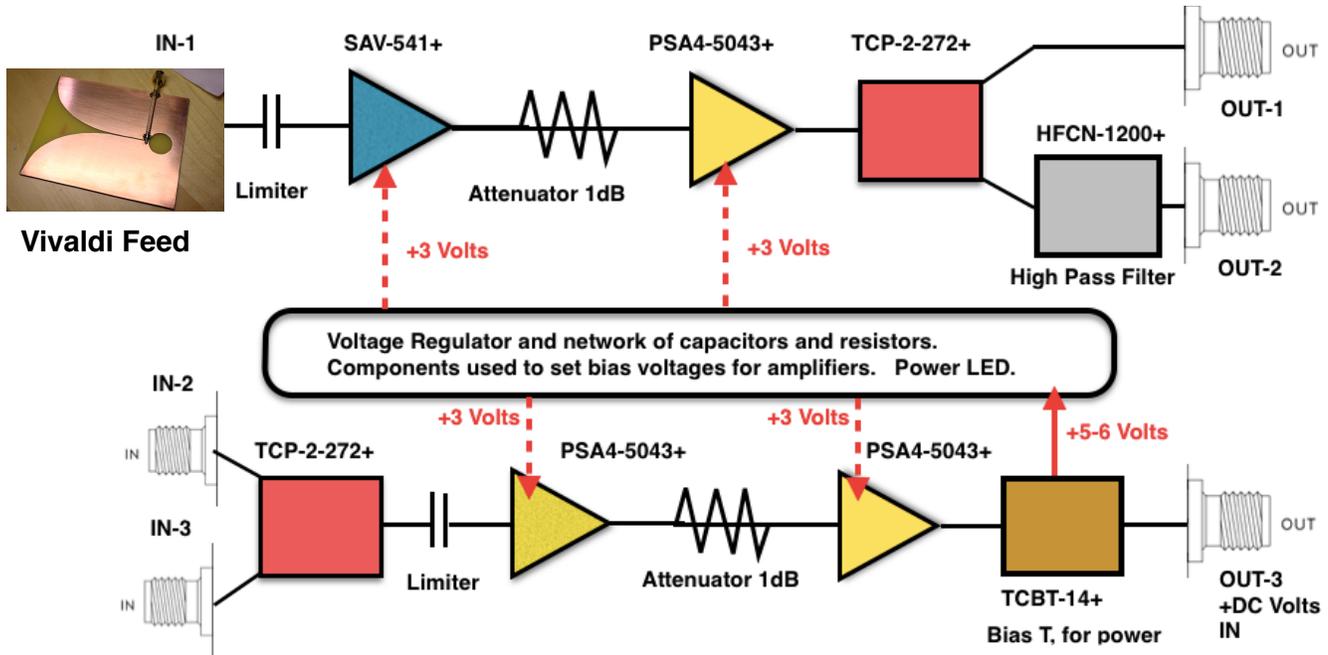


FIGURE 1: ULTRA-LOW-NOISE-AMPLIFIER BOARD FOR ONE INPUT FREQUENCY BAND. THE FOUR AMPLIFIERS (TRIANGLES) PROVIDE GREATER THAN 45 DB OF GAIN. THE NORMAL CONFIGURATION HAS THE ANTENNA CONNECTED TO INPUT 1 (IN-1), AMPLIFIED AND OUTPUT, FOLLOWING A HIGH PASS FILTER, AT OUTPUT-2 (OUT-2). A SHORT CABLE WILL CONNECT OUT-2 TO INPUT 3 (IN-3) FOR FURTHER AMPLIFICATION. THE OUTPUT TO THE DATA ACQUISITION IS VIA OUTPUT 3. THE OUTPUT 1 AND INPUT 2 ARE FOR CALIBRATION AND TESTING. INPUT POWER WILL BE VIA THE RF CABLE.

first version of the system should be constructed without Bias-T to simplify prototyping. The attenuators in the chain are included to reduce ringing in the amplifiers. The 1 dB values are suggested, but perhaps higher attenuation values are required. Circulators are not included in this sketch, but perhaps these should be added as well for frequency stability.

The design includes dual outputs on the first stage pair of amplifiers, so that the board can be used at lower frequencies that allowed in the presence of the high pass filter. The second stage pair of amplifiers includes dual inputs to allow combining a lower frequency source or a test signal source to be added before the final gain stages. The test signal might be either a noise source or calibration test tone. The test signal is discussed elsewhere.

The design should include electrostatic protection of as many components as possible. The PSA4-5043+ amplifiers seem to be relatively robust, in comparison to other devices I have tested. This protection is not included on the SAV-541+. Hopefully the lower noise figure of this device is worth the risk of using this device.

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| MicrowaveSystem Level Analysis | | | | | | | | | |
|--------------------------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|-------------------|--------------|
| L-Band Feed Horn | | | | | | | | | |
| Glen Langston 2015 Oct 2 | | | | | | | | | |
| | Input 1 | | Optional | | | | | | Output 2 |
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
| | feed horn | Coax | Limiters | Amplifier | Attenuator | Amplifier | Splitter | Filter | Coax |
| Gain (dB) | -0.10 | -0.10 | -0.30 | 15.00 | -1.00 | 14.00 | -4.00 | -1.00 | -0.10 |
| Cum. Gain (dB) | -0.10 | -0.20 | -0.50 | 14.50 | 13.50 | 27.50 | 23.50 | 22.50 | 22.40 |
| Gain (ratio) | 0.98 | 0.98 | 0.93 | 31.62 | 0.79 | 25.12 | 0.40 | 0.79 | 0.98 |
| Cum. Gain (ratio) | 0.98 | 0.95 | 0.89 | 28.18 | 22.39 | 562.34 | 223.87 | 177.83 | 173.78 |
| Noise Figure (dB) | 0.10 | 0.10 | 0.30 | 0.45 | 1.03 | 0.95 | 4.09 | 1.03 | 0.10 |
| Cum. Noise Figure (dB) | 0.10 | 0.20 | 0.50 | 0.96 | 1.00 | 1.04 | 1.05 | 1.05 | 1.05 |
| Noise Figure (ratio) | 1.02 | 1.02 | 1.07 | 1.11 | 1.27 | 1.25 | 2.56 | 1.27 | 1.02 |
| Cum. Noise Figure (ratio) | 1.02 | 1.05 | 1.12 | 1.25 | 1.55 | 1.56 | 1.62 | 1.56 | 1.62 |
| Noise Temp (K) | 6.75 | 6.75 | 20.74 | 32.75 | 77.68 | 73.35 | 453.57 | 77.68 | 6.99 |
| Cum. Noise Temp (K) | 6.75 | 13.67 | 35.39 | 72.13 | 74.89 | 78.17 | 78.97 | 79.32 | 79.36 |
| Physical Temperature | 290 | 290 | 290 | 300 | 300 | 300 | 300 | 300 | 300 |
| | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 |
| | Input 3 | | Optional | | | | | Optional Output 3 | |
| | From Above | Combiner | Limiters | Amplifier | Attenuator | Amplifier | | BIAS T | Coax |
| Gain (dB) | 0.00 | -1.00 | -0.30 | 15.00 | -1.00 | 14.00 | -0.01 | -1.00 | -0.10 |
| Cum. Gain (dB) | 22.40 | 21.40 | 21.10 | 36.10 | 35.10 | 49.10 | 49.09 | 48.09 | 47.99 |
| Gain (ratio) | 0.98 | 0.79 | 0.93 | 31.62 | 0.79 | 25.12 | 1.00 | 0.79 | 0.98 |
| Cum. Gain (ratio) | 173.78 | 138.04 | 128.82 | 4073.80 | 3235.94 | 81283.05 | 81096.11 | 64416.93 | 62950.62 |
| Noise Figure (dB) | 0.00 | 1.00 | 0.30 | 0.95 | 1.03 | 0.95 | 0.01 | 1.03 | 0.10 |
| Cum. Noise Figure (dB) | 1.05 | 1.06 | 1.06 | 1.06 | 1.06 | 1.06 | 1.06 | 1.06 | 1.06 |
| Noise Figure (ratio) | 1.02 | 1.26 | 1.07 | 1.25 | 1.27 | 1.25 | 1.00 | 1.27 | 1.02 |
| Cum. Noise Figure (ratio) | 1.02 | 1.03 | 1.03 | 1.03 | 1.03 | 1.03 | 1.03 | 1.03 | 1.03 |
| Noise Temp (K) | 0.00 | 75.09 | 20.74 | 73.35 | 77.68 | 73.35 | 0.69 | 77.68 | 6.99 |
| Cum. Noise Temp (K) | 79.36 | 79.79 | 79.94 | 80.51 | 80.53 | 80.55 | 80.55 | 80.55 | 80.55 |

FIGURE 2: TABLE OF CONTRIBUTIONS TO THE SYSTEM TEMPERATURE FOR DEVICES IDENTIFIED IN FIGURE 1. THE CONTRIBUTIONS ARE ADDITIVE FROM LEFT TO RIGHT THROUGH THE TOP ROW. THE BOTTOM ROW OF CONTRIBUTIONS ASSUMES A CONNECTION BETWEEN OUTPUT 2 AND INPUT 3 OF THE AMPLIFIER BOARD. IN THIS CALCULATION, THE -0.3 DB ATTENUATION OF THE FIRST LIMITER IS INCLUDED. THE CRITICAL ROW IS THE RED CUMULATIVE NOISE TEMPERATURE, WHICH MUST BE MINIMIZED BY THE DESIGN.

Notes on individual components follow.

Amplifier: SAV-541+

The Mini-circuits data sheet advertises the following features:

- Low Noise Figure, 0.5 dB
- Gain, 17 dB at 2 GHz; Figure shows +20 dB at 1.5 GHz.
- High Output IP3, +33 dBm
- Output Power at 1dB comp., +20 dBm • High Current, 60mA
- Wide bandwidth
- External biasing and matching required

The device frequency range is 0.45 to 6 GHz. This is the highest low frequency limit of any devices in the amplifier chain.

The device is fairly low price, only \$1.39 each, in quantities of 20. For the Radio Astronomy application the low noise figure is critical for the first stage amplifier. For +3V operation, the data sheets show noise figure as low as 0.5 dB (Corresponding to 35K) at 2 GHz. This would

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provide very good performance for the system, if the connection to the feed horn may be properly made. This noise figure is obtained with a current of 30 mA.

Amplifier: PSA4-5043+

The Mini-circuits amplifier has wide bandwidth, 0.05 to 4 GHz and Ultra Low Noise Figure, 0.75 dB typ. at 1 GHz. The main reasons for using this device are it's good electrostatic rating (Class 1B ESD rating (500V) and low noise when operating at +3V. My measured gain is 14.5 dB at 1.42 GHz, and the data sheet shows gain of 18.4 dB typical at 1GHz. They note different currents for a range of supply Voltages, +3V, Id=33mA, +5V, Id=56mA.

High Pass Filter: HFCN-1200+

The high pass filter prevents saturation of the amplifiers later in the chain. These devices are low cost, (\$2 per unit in quantities of 20 or more) and operate at up to 4.6 GHz.

Limiter: RLM-33+

Broadband Power limiter to protect against static discharge, which has wide bandwidth, 0.3 to 3.0 GHz. Insertion loss at 1.6 GHz is roughly 0.3 dB. These devices might reject very fast transients, having a (fast) recovery time of 10nsec. These are relatively expensive, \$10 per unit in quantities of 20.

The limiter before the first amplifier will make a significant contribution to the system temperature. No limiters are needed as the PSA4-5043+ devices include ESD protection. However these amplifiers will be in the hands of students so some consideration of device protection is needed.

Power Splitter/Combiner: TCP-2-272+

The device is used both on the output and input of the amplifier chain to allow testing of components. This device has broad bandwidth, .005 to 2.7 GHz and 1 dB insertion loss above the 3dB loss due to power splitting. These devices cost \$2.50 in quantities of 20. The two arms have good isolation, of better 20 dB.

Bias T: TCBT-14+

The Bias T is used to extract DC power from the coaxial output, simplifying wiring. The Bias Ts have wide bandwidth, 0.01 to 10 GHz and modest insertion loss, roughly 0.5 dB. This device can support 200mA power. If no bias T is included, the placements for the power line soldering should be generous, allowing amateur solderers to complete the wiring task.

| MicrowaveSystem Level Analysis | | | | | | | | | |
|--------------------------------|------------|----------|----------|-----------|------------|-----------|----------|-------------------|----------|
| L-Band Feed Horn | | | | | | | | | |
| Glen Langston 2015 Oct 2 | | | | | | | | | |
| | Input 1 | | Optional | | | | | | Output 2 |
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
| | feed horn | Coax | Limiters | Amplifier | Attenuator | Amplifier | Splitter | Filter | Coax |
| Gain (dB) | -0.10 | -0.10 | 0.00 | 15.00 | -1.00 | 14.00 | -4.00 | -1.00 | -0.10 |
| Cum. Gain (dB) | -0.10 | -0.20 | -0.20 | 14.80 | 13.80 | 27.80 | 23.80 | 22.80 | 22.70 |
| Gain (ratio) | 0.98 | 0.98 | 1.00 | 31.62 | 0.79 | 25.12 | 0.40 | 0.79 | 0.98 |
| Cum. Gain (ratio) | 0.98 | 0.95 | 0.95 | 30.20 | 23.99 | 602.56 | 239.88 | 190.55 | 186.21 |
| Noise Figure (dB) | 0.10 | 0.10 | 0.00 | 0.45 | 1.03 | 0.95 | 4.09 | 1.03 | 0.10 |
| Cum. Noise Figure (dB) | 0.10 | 0.20 | 0.20 | 0.66 | 0.70 | 0.74 | 0.75 | 0.75 | 0.75 |
| Noise Figure (ratio) | 1.02 | 1.02 | 1.00 | 1.11 | 1.27 | 1.25 | 2.56 | 1.27 | 1.02 |
| Cum. Noise Figure (ratio) | 1.02 | 1.05 | 1.05 | 1.17 | 1.45 | 1.46 | 1.51 | 1.46 | 1.51 |
| Noise Temp (K) | 6.75 | 6.75 | 0.00 | 32.75 | 77.68 | 73.35 | 453.57 | 77.68 | 6.99 |
| Cum. Noise Temp (K) | 6.75 | 13.67 | 13.67 | 47.96 | 50.54 | 53.59 | 54.35 | 54.67 | 54.71 |
| Physical Temperature | 290 | 290 | 290 | 300 | 300 | 300 | 300 | 300 | 300 |
| | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 |
| | Input 3 | | Optional | | | | | Optional Output 3 | |
| | From Above | Combiner | Limiters | Amplifier | Attenuator | Amplifier | | BIAS T | Coax |
| Gain (dB) | 0.00 | -1.00 | -0.30 | 15.00 | -1.00 | 14.00 | -0.01 | -1.00 | -0.10 |
| Cum. Gain (dB) | 22.70 | 21.70 | 21.40 | 36.40 | 35.40 | 49.40 | 49.39 | 48.39 | 48.29 |
| Gain (ratio) | 0.98 | 0.79 | 0.93 | 31.62 | 0.79 | 25.12 | 1.00 | 0.79 | 0.98 |
| Cum. Gain (ratio) | 186.21 | 147.91 | 138.04 | 4365.16 | 3467.37 | 87096.36 | 86896.04 | 69023.98 | 67452.80 |
| Noise Figure (dB) | 0.00 | 1.00 | 0.30 | 0.95 | 1.03 | 0.95 | 0.01 | 1.03 | 0.10 |
| Cum. Noise Figure (dB) | 0.75 | 0.76 | 0.76 | 0.76 | 0.76 | 0.76 | 0.76 | 0.76 | 0.76 |
| Noise Figure (ratio) | 1.02 | 1.26 | 1.07 | 1.25 | 1.27 | 1.25 | 1.00 | 1.27 | 1.02 |
| Cum. Noise Figure (ratio) | 1.02 | 1.03 | 1.03 | 1.03 | 1.03 | 1.03 | 1.03 | 1.03 | 1.03 |
| Noise Temp (K) | 0.00 | 75.09 | 20.74 | 73.35 | 77.68 | 73.35 | 0.69 | 77.68 | 6.99 |
| Cum. Noise Temp (K) | 54.71 | 55.11 | 55.25 | 55.78 | 55.80 | 55.82 | 55.82 | 55.82 | 55.82 |

FIGURE 3: TABLE OF CONTRIBUTIONS TO THE SYSTEM TEMPERATURE FOR DEVICES IDENTIFIED IN FIGURE 1. THE SAME CONTRIBUTIONS INCLUDED AS FOR FIGURE 2, EXCEPT THAT THE FIRST LIMITER IS NOT INCLUDED IN THIS DESIGN.

Attenuators and Miscellaneous Components.

The surface mount attenuators in this series are used to reduce ringing of high gain amplifiers. The GAT- series operate in the frequency range 0 to 8 GHz. They have a flatness of roughly 20% over the band. They are moderate cost, \$2.35 per part in small quantities.

In addition, resistors and capacitors will be needed for the power network. Complete amplifier boards, integrating a single PSA4-5043+ are available for roughly \$25 plus shipping, including 2 SMA connectors and a set of capacitors and resistors. These boards, produced by Adam Alicajic (adam9a4qv@yahoo.com, <http://lna4all.blogspot.com>) are of very good quality and have proven fairly reliable. Adding an LED is convenient for diagnosis of problems. The design presented here includes 4 amplifiers and three times as many connectors, so miscellaneous parts may cost roughly \$30, including connectors. Additionally a fuse for current limit bias T might also be valuable. The relative difficulty of adding these components is outside my expertise.

Frequency Range

The bandwidth of the system is limited by the narrowest upper and lower limits of the components in the chain. On the low frequency side, the first stage amplifier has the highest low-frequency limit, 0.45 GHz. On the high frequency side, the second stage amplifiers have a 4.0 GHz upper limit. The power splitter/combiners have a 2.7 GHz upper limit, but may function above this range, with inferior performance. The high pass filter will limit the performance below 1 GHz in the normal configuration.

Performance

For radio astronomy applications the primary three characteristics of performance are 1) low system temperature, 2) high gain and 3) reliability. Based on my experience developing home grown amplifier chains, some precautions should be taken to protect the amplifier chain, at the cost of some performance.

Based on a National Radio Astronomy Observatory Receiver performance spreadsheet, I've modified it for the proposed configuration and computed the net gain and expected receiver temperature. The standard formulas for gain calculations are used. For reference see Agilent "Fundamentals of RF and Microwave Noise Figure Measurements" Application Note 57-1, <http://cp.literature.agilent.com/litweb/pdf/5952-8255E.pdf>, 2015 October 2.

Figure 2 shows the spreadsheet of contributions to the system temperature for the amplifier chain shown in Figure 1. In Figure 2, the limiter is included in the chain. The resulting system temperature is 81 K.

Figure 3 shows the same spreadsheet, except the limiter is not included in the chain. The resulting system temperature is 56K, a significant improvement, but is potentially risky. A good alternate solution is to separately include a limiter with SMA connections that might be removed for actual observations, but included for development and testing.

The values in these spreadsheets are based on +3V operation of the amplifiers, where the noise figures are lower, but also the gains are lower.

Summary

A sketch of a configuration of 4 amplifiers for a low cost Radio Astronomy applications is presented. This chain is intended to completely implement the electronics ahead of the high speed samplers. This chain will have superior performance to an already functioning system I have implanted with discreet components.

The total cost of the components is \$80., if all limiters and bias Ts are included. If the simplified circuit is first implemented (no limiters or bias T), the parts cost is \$50. By making this available at low cost, many school and college groups would have access to a high performance system for research in Electronics and Astronomy.