Implementation of a Total Power Radiometer in Software Defined Radios

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Introduction

Presentation Goals

The goal of this presentation is to present my research into implementing a total power radiometer using low cost hardware and software used in software defined radios.

Introduction

Presentation Goals

The goal of this presentation is to present my research into implementing a total power radiometer using low cost hardware and software used in software defined radios.

Questions Asked

This thesis looks to explore the following questions:

1. Can we use a SDR to recreate a radiometer in software?
2. If so, what performance can we get from the system?
3. Can we create a low cost SDR Radiometer that is effective?
4. What benefits do we obtain by using a SDR Radiometer?

About the thesis

Thesis Overview

The goal of this thesis is to explore a low cost method for implementing a total power radiometer using software defined radio and to demonstrate the effectiveness of this system.

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The goal of this thesis is to explore a low cost method for implementing a total power radiometer using software defined radio and to demonstrate the effectiveness of this system.

Why a SDR?

A software defined radio infrastructure provides a highly flexible system that is able to adapt to different scenarios more quickly and at a lower cost than traditional radiometers.

Related Works

Radio Astronomy

- Radiometers are used in a variety of remote sensing applications
- Radio Astronomy is one method of using radiometers for remote sensing
- There are current setups using Software Defined Radios for Radio Astronomy

Related Works

The Shirleys Bay Radio Astronomy Consortium (SBRAC) located in Smiths Falls, Ontario is currently using a USRP software defined radio in conjunction with GNU-radio. SBRAC has successfully used this configuration to obtain radio astronomy data by looking at the hydrogen line at 1420.4058 MHz [**?**]. The person in charge of this facility, Marcus Leech, contributed software to the GNURadio specifically for radio astronomy applications. It was this software branch that was used as the base for the GNURadio program that was used in this thesis.

Related Works

Students at the University of Illinois and Grand Valley State University built a software defined radio to listen to emissions from Jupiter[?] by building their own RF section and using GNURadio for the software. This software defined radio was built using an Analog Devices AD9460 and a Xilinx Spartan-3E-500 FPGA to build the SDR itself.
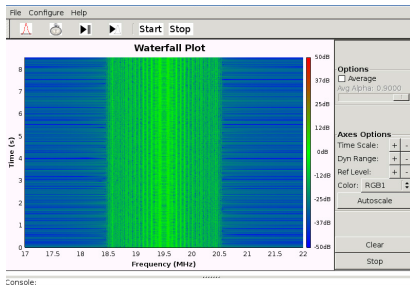
General Theory

Traditional Radiometer

The primary goal of a radiometer is to measure power. While that statement sounds easy, there are in fact many factors that go in to how well a radiometer can measure the power it sees. A better statement would be that a radiometer's primary goal is to accurately measure power within a certain degree of accuracy. In order to accurately and within a high degree of precision measure power, a radiometer must take into account various factors such as the system noise, the bandwidth of the signal and the stability of the system as a whole.

General Theory

Measuring power

To measure power in a radiometer, several factors are taken into consideration. To begin with we have the noise signal coming from the antenna. Our antenna is assumed to be looking at our target of interest and it is assumed that we can relate the antenna noise to the noise from the source. It is often easier to refer to this noise as the brightness temperature. Therefore the brightness temperature of the source can be related to the brightness temperature at the antenna. We will refer to this brightness temperature as T_A.
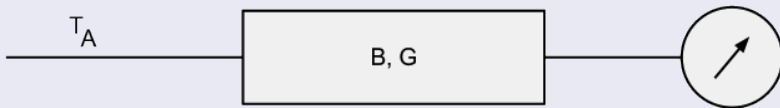
RF Front End Design

The RF front end is one of the most critical components in a radiometer. Although we have moved most of the functionality in to software with the SDR, we still need to amplify the signal. Unlike other RF front ends though, we can use a fairly simple setup using 3 Low Noise Amplifiers (LNAs) and some basic filtering.

SDR
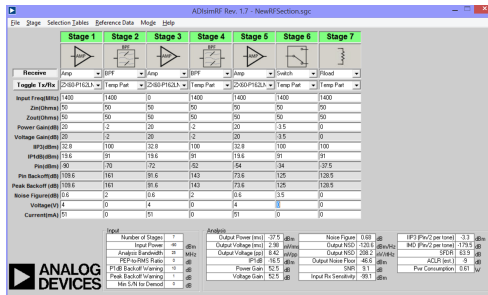
A software defined radio (SDR) is designed to mimic radio functions in software instead of using dedicated hardware. A radiometer is a radio that can detect changes in power. Therefore the SDR needs to be able to measure power coming from the source that we are looking at.

Comparison

Traditional Radiometer

A traditional radiometer uses Low Noise Amplifiers, hardware based filters and a square-law detector to measure the power detected.

SDR Radiometer

A software defined radiometer eliminates the filters and the square-law detector and replaces this with their mathematical equivalents that is emulated in software.

Differences

Traditional Radiometer

Most total power radiometers do not retain any frequency information, this information is lost and in most cases can not be recovered.

SDR Radiometer

A software defined radio captures both phase and magnitude of the signal. This information allows us to recreate the signal and manipulate the signal any way we wish. This allows for more in-depth analysis of the signal and gives us the ability to detect things, such as an interfering signal, that might otherwise be missed with a traditional radiometer.

Implementation

Implementing a TPR

A total power radiometer in software requires us to extract the magnitude (or amplitude) information from the I/Q data captured. This is equivalent to what a square-law detector does in determining the power measured.

Implementation

Implementing a TPR

For the SDR, the incoming signal is sampled and converted to IQ values. The IQ values represent the amplitude and phase information of the signal. In GNURadio we are then able to square these values within software. This block in GNURadio mathematically performs the following:

$$I^2 + Q^2 = P_{out} \tag{1}$$

Filtering

Filtering requirements in a software defined radio is different from a hardware based or traditional radiometer.

- The bandwidth setting of the SDR only samples data within that bandwidth
- Additional filters can be added at a cost of additional processing requirements
- Because filtering is a simple software change, filters can be added and removed with no additional hardware

Integration

The data we get from these power measurements fluctuate very quickly. We want to smooth out or filter this data by integrating this over time. In a traditional radiometer a hardware integrator is often used. In software, we can use an Infinite Impulse Response (IIR) filter as an integrator.

IIR as an integrator implementation

IIR and RC filter

It can be seen that an IIR filter can have the same frequency response as we would expect from an analog RC filter. As our sampling rate approaches infinity, the approximation gets closer to the original response from the analog RC circuit.
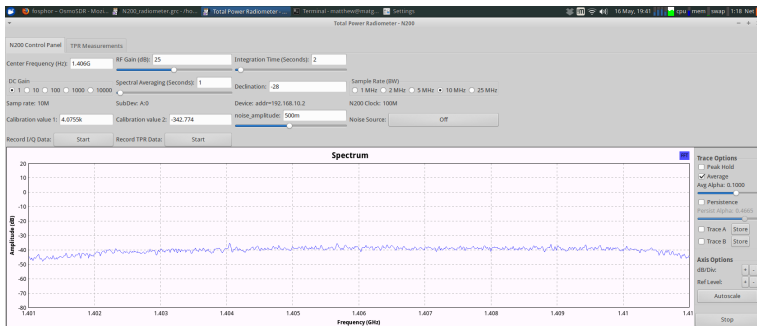
$$y_n = \frac{T}{T + RC} x_n + \frac{RC}{T + RC} y_{n-1} \qquad (2)$$

Implementation

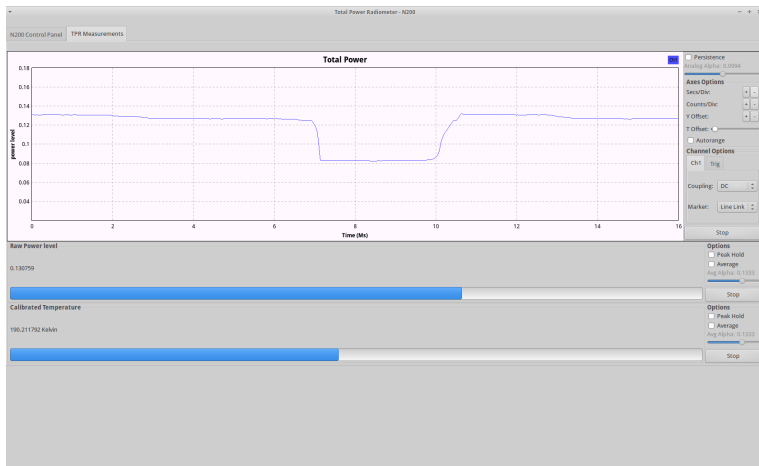Implementation of a total power radiometer in software
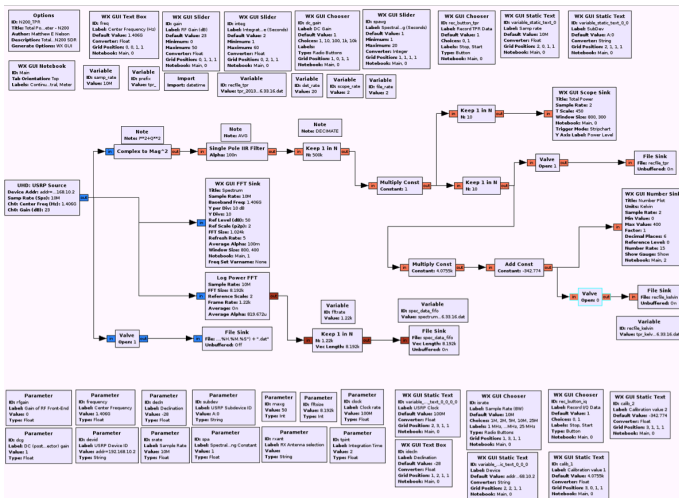
GNURadio Controls

GNURadio exposes GUI controls through wxGUI which allows us to implement a GUI system
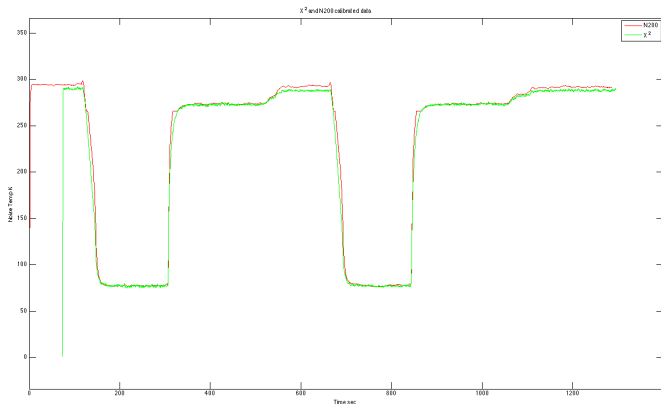
GNURadio Display

As well as controls, we can also display information such as spectrum, total power and even a calibrated result.

Stability

Stability testing was accomplished by placing the matched load into a constant temperature bath and looking at amount of change over time. A 4 hour soak test was done using Liquid Nitrogen.

Performance

Sensitivity

The ability of a radiometer to detect these small changes is the radiometer's sensitivity, or the standard deviation of the output signal from the radiometer. This sensitivity is also referred to as the Noise Equivalent Δ Temperature or NEΔT.

$$NE\Delta T = \frac{T_A + T_N}{\sqrt{\beta * \tau}} \qquad (3)$$

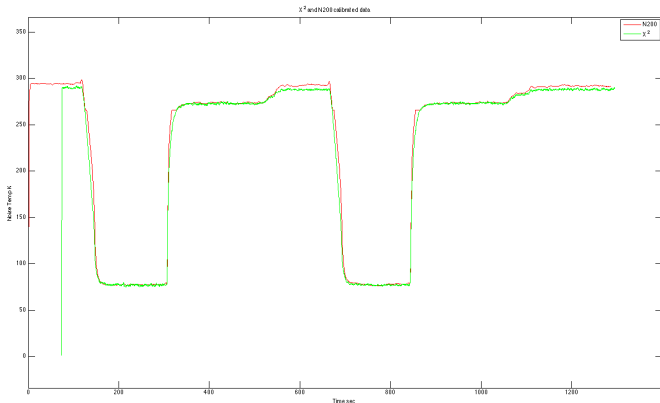# Performance

Accuracy

blah blah blah

Experimentation

To verify that a software defined radio based radiometer can perform the same or better as a traditional radiometer, experiments were run to compare data captured from the SDR and data collected from a square-law detector, typically used to detect power in radiometers.

In addition, we also wanted to test how a SDR can perform better than most traditional radiometers since frequency information is retained. To do this, we tested with the ability to filter out an unwanted signal and compared the results.

LN2 Tests

Calibration and testing of the radiometer was conducted by using two reference temperature points. The two points selected was Liquid Nitrogen at 77 K and Ice Water at 273.15 K.

Unwanted signal filter

Another experiment was conducted, but this time with a signal injected that interferes with the radiometer.

Conclusion

Final Thoughts

In this thesis we have shown that an off the shelf SDR can be used to perform as a radiometer. Using a SDR has several advantages such as a more flexible system and can result in a less expensive system. Since a SDR offers high flexibility, changes to the system can be done very quickly and helps in future proofing the system.

Future Work

Future Items

- Make improvements to the ISU RF Front End
- Rebuild the ISU radiometer eplacing the Rabbit uC with PIC32
- Correlation
- Noise Injection
- Stokes parameters

References

📄 Niels Skou and David Le Vine (2006)

Microwave Radiometer Systems Design and Analysis

Artech House

📄 F. T. Ulaby, R. K. Moore and A. K. Fung (1981)

Microwave Remote Sensing

Artech House

📄 Marcus Leech and David Ocame (2007)

A year of Gnu Radio and SDR astronomy: experience, practice and observations

http://www.sbrac.org/documents/gnuradio_at_one_year_20070401.doc

📄 Behnke, P. and Soberal, D. and Bredeweg, S. and Dunne, B. and Sterian, A. and Furton, D. (2013)

Senior capstone: A software defined radio design for amateur astronomy

Interdisciplinary Engineering Design Education Conference (IEDEC), 2013 3rd

The End

Extra Slides

Secondary goal

A secondary goal was to use off the shelf components and components that are generally more accessible. This would allow radiometers to be more accessible to a wider scope of researchers in this field.

Tertiary goal

And finally a tertiary goal was to ensure that the system as a whole is fairly easy to use. This ties to our secondary goal of making radiometers more accessible to a wider range of researchers and research topics.

Ideal Radiometer

Figure on slide 9 shows us an ideal radiometer. That is a radiometer that has an input from the antenna, T_A, a known bandwidth denoted as B and a known gain denoted as G. At the end of the block is the detector, which measures the power from the radiometer.

Bandwidth

Only a certain selection of the radio spectrum is observed by the radiometer. This is referred to as the bandwidth of the radiometer and is denoted as B or as β. This bandwidth is then centered around a center frequency. In our case, we center around 1.405 GHz as this falls in a protected frequency range often used for radiometry.
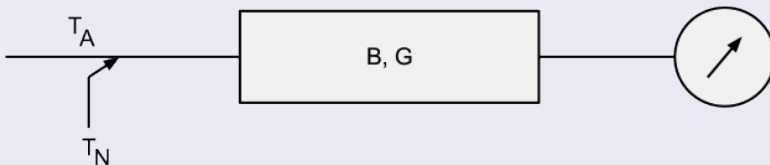
Power

The power coming from the antenna is amplified so it is easier to determine changes in the brightness temperature. The overall gain of the radiometer system is referred to as G in this case. Finally, we need to apply Boltzmann's constant, referred to as k. With these values, we can now compute the power the radiometer will see for an ideal radiometer. This can be shown in equation **??**

$$P = k * \beta * G * (T_A) \qquad (4)$$

Noise

However, since we do not have an ideal radiometer, we have another key component that needs to be addressed and that is the noise added to the system from the radiometer itself. Most of the additional noise is from the Low Noise Amplifiers (LNA) that are used to increase the signal while attempting to keep the noise added to a minimum. The Figure below shows the additional noise that is injected into the system.

Antenna Noise

As it can be seen, this additional noise is added to the noise coming from the antenna source. Therefore T_N is added to T_A and our final equation for the power measured is shown in equation **??**.

$$P = k * \beta * G * (T_A + T_N) \tag{5}$$

IIR Filter

This signal will fluctuate rapidly and to improve the sensitivity of the radiometer we wish to integrate this signal. A RC filter is analogous to an integrator where the R and C values determine our time constant and our integration time for the filter. A SDR however operates in the digital domain at discrete intervals. One type of filter that can be used in the Infinite Impulse Response (IIR) filter.

RC Filter

To begin with, we look at what an analog RC filter looks like.
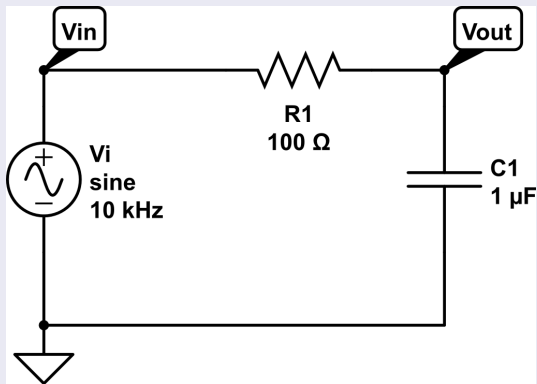
RC Filter Eqs

This circuit can be represented by the following equation.

$$\frac{V_{in} - V_{out}}{R} = C\frac{dV_{out}}{dt} \tag{6}$$

FIR Filter

A Finite Impulse Response (FIR) filter is a digital filter that can take an impulse signal and decays to zero after a finite number of iterations. This type of digital filter can be represented by the following equation:

$$y_n = \sum_{i=o}^{P-1} c_i x_{n-i} \tag{7}$$

IIR Filter

An Infinite Impulse Response (IIR) filter is the same as the FIR filter, except that we add an additional summation term which feeds back the previous output.

$$y_n = \sum_{i=o}^{P-1} c_i x_{n-i} + \sum_{j=1}^{Q} d_j y_{n-j} \tag{8}$$

It can be seen that a FIR filter is really a IIR filter except that $Q = 0$.

IIR and RC Filter

To get a better understanding on how our digital IIR filter relates to our RC filter analog, we can look at the Fourier Transform and the relationship of the input to the output in the frequency domain.

$$H(f) = \frac{\displaystyle\sum_{j=o}^{P-1} c_j e^{-2\pi ijfT}}{1 - \displaystyle\sum_{k=1}^{Q} d_k e^{-2\pi ikfT}} \tag{9}$$

Here f is our frequency in Hz and T is the time between samples in seconds.

Link between RC and IIR

We now want show the link between our analog RC circuit and the IIR filter. Looking at equation **??**, which represents the differential equation relating the input voltage V_{in} to the output voltage V_{out}, we can substitute for input and output of our IIR filter. Since we are now in the time domain, we need to define what T is.

$$T = timebetweensamples = \frac{1}{samplingrate} \qquad (10)$$

input voltage to IIR

We can now relate our input voltage to the input to our IIR filter and the output voltage to the output of our IIR filter.

$$x_n = v_{in}(nT) \tag{11}$$

$$y_n = v_{out}(nT) \tag{12}$$

Rewrite difference eq

We can now rewrite our difference equation with x_n and y_n.

$$\frac{x_n - y_n}{R} = C\frac{y_n - y_{n-1}}{T} \tag{13}$$

Now, we can solve for y_n which results in our final equation for showing how a IIR filter is related to an RC filter.

$$y_n = \frac{T}{T + RC}x_n + \frac{RC}{T + RC}y_{n-1} \tag{14}$$

Multiple Columns

Heading

1. Statement
2. Explanation
3. Example

Lorem ipsum dolor sit amet, consectetur adipiscing elit. Integer lectus nisl, ultricies in feugiat rutrum, porttitor sit amet augue. Aliquam ut tortor mauris. Sed volutpat ante purus, quis accumsan dolor.

Table

Treatments	Response 1	Response 2
Treatment 1	0.0003262	0.562
Treatment 2	0.0015681	0.910
Treatment 3	0.0009271	0.296

Table: Table caption

Verbatim

Example (Theorem Slide Code)

```
\begin{frame}
\frametitle{Theorem}
\begin{theorem}[Mass--energy equivalence]
$E = mc^2$
\end{theorem}
\end{frame}
```