

Implementation of a Total Power Radiometer in Software Defined Radios

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My wife, Jennifer and my family for their support

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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.

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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 and benefits of this system.

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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.

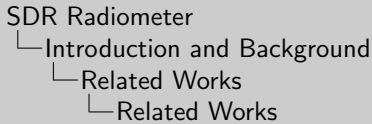
Related Works

Radio Astronomy

- Radiometers are used in a variety of remote sensing applications such as soil moisture and ocean salinity
- Radio Astronomy is one method of using radiometers for remote sensing
- There are current setups using Software Defined Radios for Radio Astronomy

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SDR Radiometer



Related Works

Radio Astronomy

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Radiometers are used in remote sensing of soil, ocean and deep space. SMOS is an excellent example of a working soil and ocean measurement system.

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 GNURadio[Leech, 2007].

- Tuned to the hydrogen line at 1420.4058 MHz
- Marcus Leech is the Principal Investigator
- Mr. Leech has made contributions to GNURadio related to radiometry



SDR Radiometer

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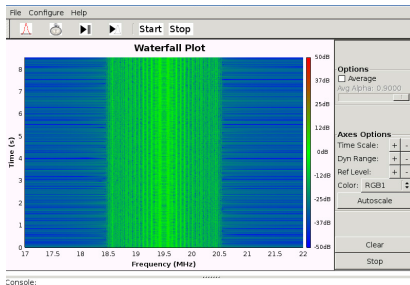


Marcus is the Principal Investigator at SBRAC and also a contributor to the radiometer branch in GNURadio. Although this branch is no longer maintained, he still answers questions about using radiometers with GNURadio

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[Behnke, 2013] 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.



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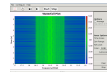
- └ Introduction and Background

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Related Works

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While the students in this paper built their own hardware, GNURadio was still used to develop the software. Another goal of this project was to produce a low cost solution using GNURadio.

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. In order to accurately measure power, we need to keep the following in mind.

- Total system noise
- Bandwidth of the signal
- Stability of the system



SDR Radiometer

- └ Radiometer Theory of Operation
 - └ Traditional Radiometer
 - └ General Theory

General Theory

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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

A very simple and ideal radiometer is an antenna that amplifies a signal with a gain of G and is within a bandwidth of B . A device then measures the power from this system. The total power received by the is the noise temperature of the object it is pointed at. 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 [Ulaby, 1981].



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General Theory

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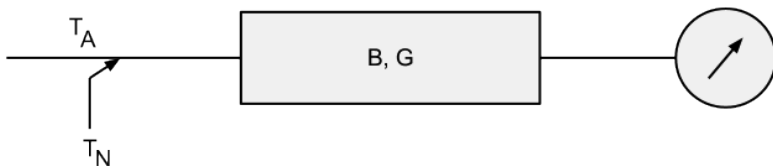


To measure power we begin with the noise signal coming from the antenna. Our antenna is assumed to be looking at our target of interest and it is assumed that we can relate the antenna noise to the noise from the source. It is often easier to refer to this noise as the brightness temperature. Therefore 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

General Theory

Measuring power

A more realistic model is a system that includes the noise that is generated by the radiometer itself. This noise is added to noise from the antenna.



SDR Radiometer

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 - └ Traditional Radiometer
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General Theory

Measuring power

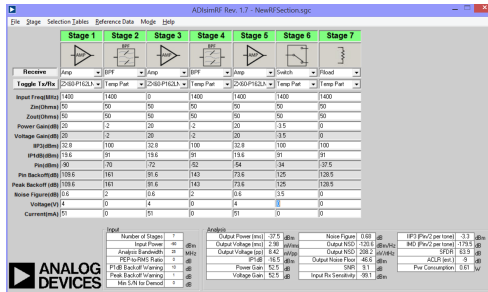
A more realistic model is a system that includes the noise that is generated by the radiometer itself. This noise is added to noise from the antenna.



The antenna itself also adds noise. Our greatest contributor to noise is from the LNAs. However mismatches in the RF chain and other factors can also increase this noise. This noise covers up or obscures the noise that we are interested in so we want to keep this to a minimum.

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. This is where Low Noise Amplifiers (LNAs) come in to play, they amplify the signal while keeping the noise they contribute as low as possible.



SDR Radiometer

- └ Radiometer Theory of Operation
 - └ RF Front End
 - └ RF Front End Design

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. This is where Low Noise Amplifiers (LNAs) come in to play, they amplify the signal while keeping the noise they contribute as low as possible.



The image shown is Analog Devices program for analyzing gain, noise temperature and losses in a RF chain. This program was used to analyze ours and other RF Front end systems. The system shown is a simplified version of the RF front end used in testing. Although filters were included in this image, a SDR does not require filters as we can filter in the SDR itself.

While LNAs attempt to keep the noise they add as low as possible, they are usually still our largest contributor to the total system noise that we see. However LNAs are often a vast improvement over other amplifiers that may be used in more general communication equipment.

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.

SDR Radiometer

- └ Radiometer Theory of Operation
- └ Software Defined Radio

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.

Software defined radios have been used in a number of applications, but usually related to communication systems. Changes to modulation and encoding/decoding is very easy for a SDR and this is why SDRs have grown in recent years. Use in remote sensing applications, as far as I know, is a relatively new application of SDRs.

Software Defined Radiometer

To build a radiometer in software, we need to know what components are key to the radiometer and build them in software. There are four key components we can build in software.

- Filter to the bandwidth we desire
- Total power measurement
- Integrate
- Record the data

SDR Radiometer

└ Radiometer Theory of Operation

└ SDR Radiometer

└ Software Defined Radiometer

Software Defined Radiometer

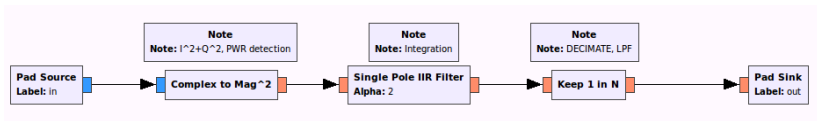
To build a radiometer in software, we need to know what components are key to the radiometer and build them in software. There are four key components we can build in software.

- Filter to the bandwidth we desire
- Total power measurement
- Integrate
- Record the data

Filtering can be done by limiting the sampling rate of the SDR, but we can also add additional filtering if desired.

Software Defined Radiometer

Total power measurements is accomplished by squaring the the phase and magnitude information provided by the SDR. Integration is a simple mathematical operation on the signal. Recording the data is also trivial for the program to accomplish.



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SDR Radiometer

- └ Radiometer Theory of Operation
 - └ SDR Radiometer
 - └ Software Defined Radiometer

Software Defined Radiometer

Total power measurements is accomplished by squaring the phase and magnitude information provided by the SDR. Integration is a simple mathematical operation on the signal. Recording the data is also trivial for the program to accomplish.



The block shown is the TPR block we used in GNURadio. This combines the total power measurement and integration and low-pass filter into one block that we can call in other programs.

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.

SDR Radiometer

- └ Comparison of Software Defined Radiometer to Traditional
- └ SDR vs Traditional
- └ Comparison

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.

SDRs can filter in two ways. First, by limiting the sampling rate we effectively put a bandwidth filter on the system. Two, we can also filter by constructing a filter in software, although there is some cost with this option in terms of CPU and memory requirements on the system

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

Since we have both magnitude and phase information we can recreate the signal or manipulate it as needed. This allows for more in-dept analysis such as RFI and also using Stokes parameters on the signal as well. We therefore have more information without any additional hardware[Ruf, 2010].

SDR Radiometer

- └ Comparison of Software Defined Radiometer to Traditional
- └ SDR vs Digital Radiometer
- └ Differences

Differences

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SDRs give us a lot more information to work with. At the core of a radiometer, this information is not needed which is why it was often discarded. However, several papers have now been written that bring to light the need for additional information in order to deal with known issues with radiometers such as interference or new methods for determining total power such as the Stokes method. A key thing with a SDR radiometer is that in many ways it is flexible enough to handle any future methods with either very little or no change in hardware.

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.

SDR Radiometer

└ Implementation of a Software Defined Radiometer

└ Implementation

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.

Unlike an analog radiometer, the magnitude information is there and a simple squaring gives us total power. A square-law detector however has to do just that, it detects the power and then extracts that as a voltage.

Implementation

Implementing a TPR

For the SDR, the incoming signal is sampled and converted to I/Q values. The I/Q 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:

$$I^2 + Q^2 = P_{out} \quad (1)$$

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.

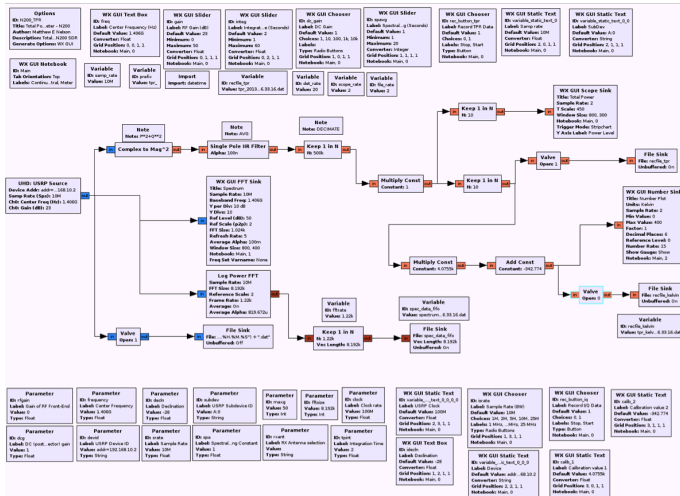
IIR as an integrator implementation

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.

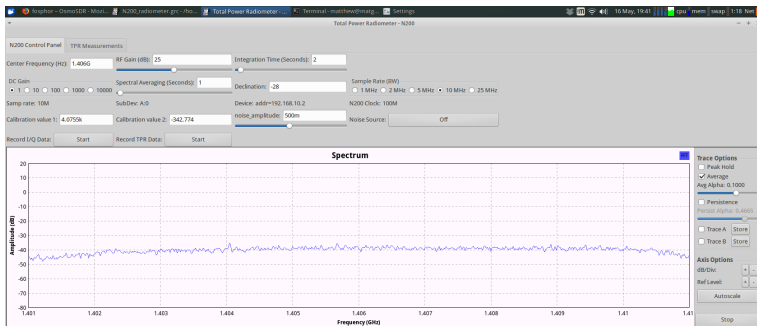
$$y_n = \frac{T}{T + RC} x_n + \frac{RC}{T + RC} y_{n-1} \quad (2)$$

Implementation of a total power radiometer in software



GNURadio Controls

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



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SDR Radiometer

- └ Implementation of a Software Defined Radiometer
 - └ GNURadio Controls
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GNURadio Controls

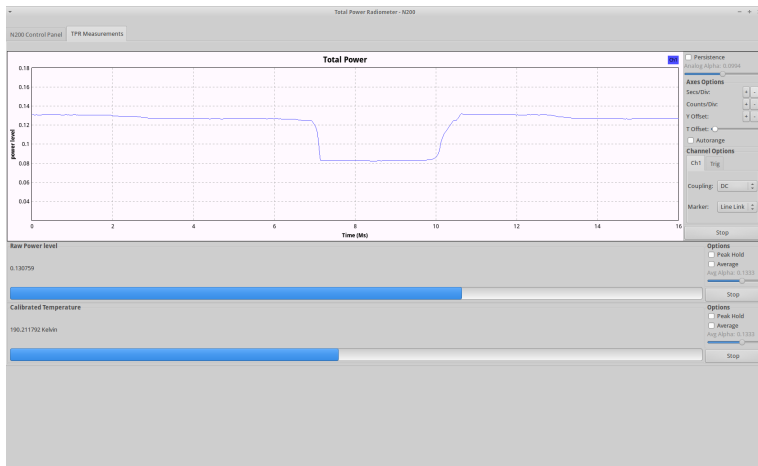
GNURadio exposes GUI controls through wxGUI which allows us to implement a GUI system



The controls allow us to control a number of key features of the radiometer. This includes bandwidth or sampling rate, the frequency, integration time and also the filter.

GNURadio Display

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



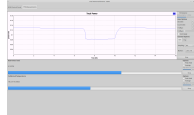
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SDR Radiometer

- └ Implementation of a Software Defined Radiometer
 - └ GNURadio Display
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GNURadio Display

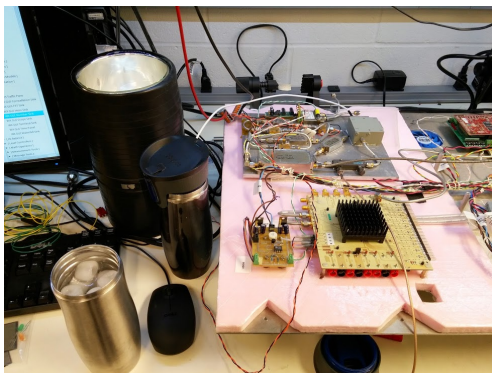
As well as controls, we can also display information such as spectrum, total power and even a calibrated result.



The display can show both frequency information as well as total power. Additional information such as calibrated noise temperature can also be shown

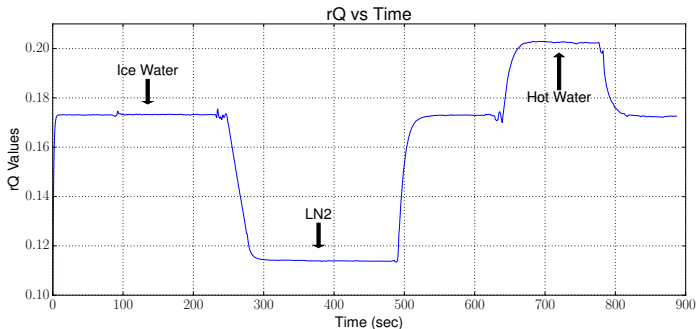
Experimental Data

Experimental data was collected to verify the operation of software defined radio as a radiometer. In addition, we performed an experiment that demonstrated an additional benefit of using a SDR over a more traditional radiometer.



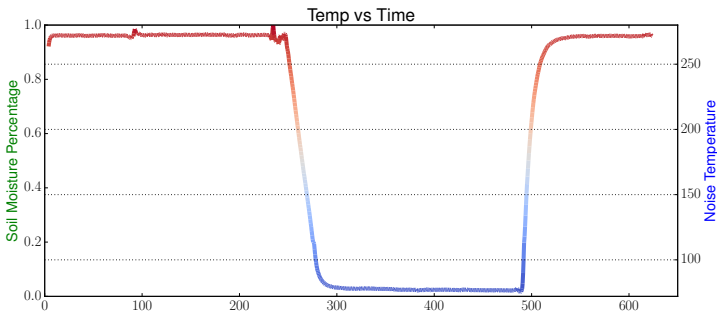
Normal operation

Experiment 1 is designed to compare the operation of the SDR radiometer and compare it to a traditional radiometer using a square-law detector. This was accomplished by using a common RF front end and splitting the signal to both the SDR and the square-law detector.



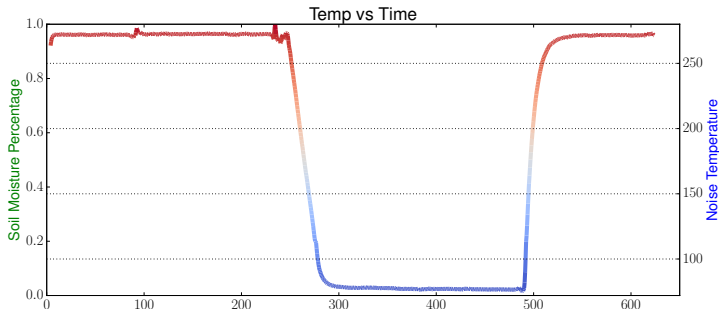
Normal operation

Finally, we can do a hypothetical where we calibrate the radiometer to say that LN2 is "dry soil" and our ice water bath is our "wet soil". We can now interpolate the data to a soil moisture percentage.



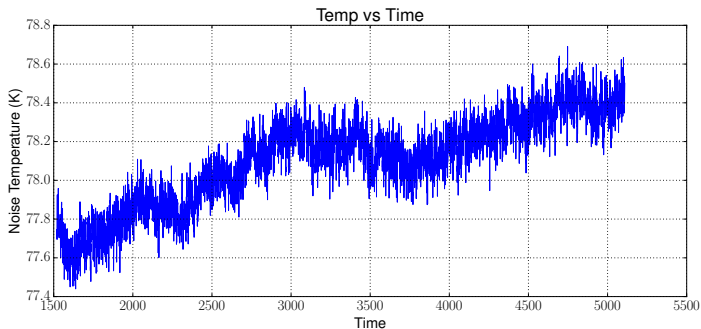
Normal operation

Experiment 2 is designed to again compare the SDR radiometer to a traditional radiometer but now have an unwanted signal present. The SDR is able to filter this signal out, where the square-law detector is not able to do so.



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 $NE\Delta T$.

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

Performance

Accuracy

blah blah blah

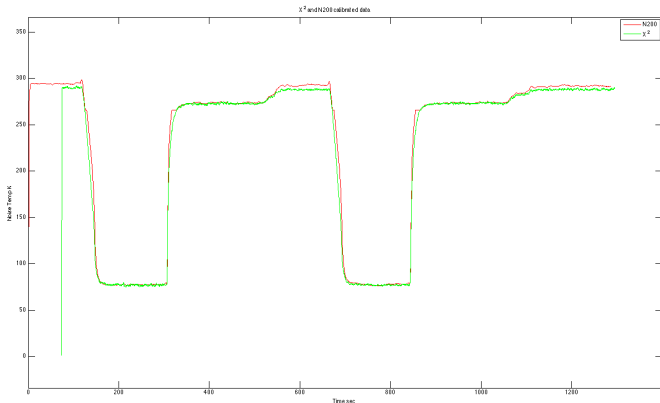
Experimentation

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.

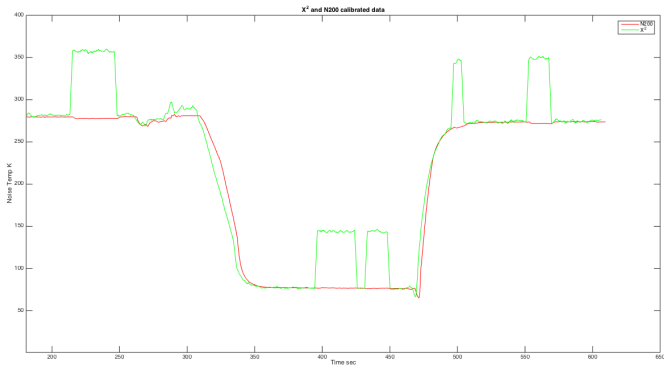
LN2 Tests

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 replacing the Rabbit uC with PIC32
- Correlation
- Noise Injection
- Stokes parameters

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SDR Radiometer

└ Future Work

└ Future Work

Future Work

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- Make improvements to the ISU RF Front End
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- Noise Injection
- Stokes parameters

Fix issues with SWR and interferenceR

References



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Artech House



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

Microwave Remote Sensing

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

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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 15 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.

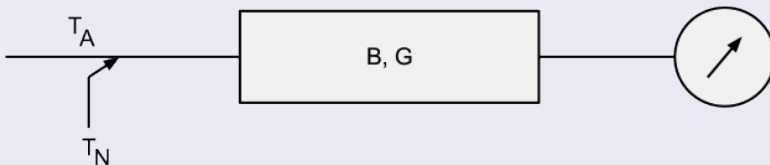
Power

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 4

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

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 5.

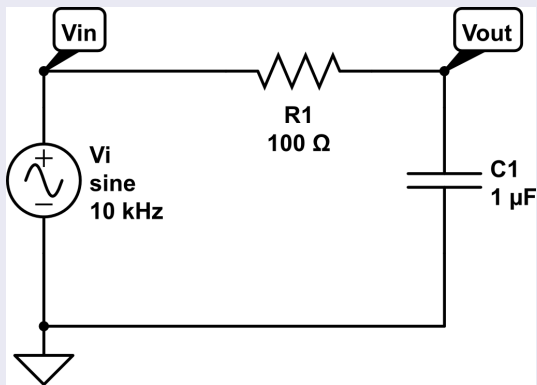
$$P = k * \beta * G * (T_A + T_N) \quad (5)$$

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.

$$\frac{V_{in} - V_{out}}{R} = C \frac{dV_{out}}{dt} \quad (6)$$

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:

$$y_n = \sum_{i=0}^{P-1} c_i x_{n-i} \quad (7)$$

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.

$$y_n = \sum_{i=0}^{P-1} c_i x_{n-i} + \sum_{j=1}^Q d_j y_{n-j} \quad (8)$$

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.

$$H(f) = \frac{\sum_{j=0}^{P-1} c_j e^{-2\pi i j f T}}{1 - \sum_{k=1}^Q d_k e^{-2\pi i k f T}} \quad (9)$$

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 6, 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.

$$T = \text{timebetween samples} = \frac{1}{\text{samplingrate}} \quad (10)$$

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.

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

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

Rewrite difference eq

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

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

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.

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

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}
```