An Advanced Riometer platform based on SDR Techniques

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Abstract

We describe a new riometer (**R**elative **I**onospheric **O**pacity **Meter**) platform based on the latest *Software Defined Radio* techniques, and show how these techniques offer distinct advantages over traditional, analog, riometers.

Introduction

A *riometer* is an electronic instrument that is used to measure the relative opacity of the ionosphere by making precise measurements of the RF power incident on an antenna structure whose major lobe is generally oriented towards the zenith (overhead). The assumption (and indeed a fundamental requirement) is that the majority of the RF power incident on that antenna structure will originate in the galactic-background radiation of our own galaxy.

Galactic background radiation is dominated by synchrotron emissions and has a very broad spectrum, with significant equivalent noise temperatures spanning frequencies from a few MHz up to a few hundred MHz. Equivalent noise temperatures are generally in the range 1e3 to 1e6 Kelvin, depending on frequency.

Riometers generally operate in the 30MHz to 50Mhz region, since galactic background radiation is high enough to be measurable, and peak ionospheric absorption is not inconveniently large. While the background radiation at lower frequencies is generally much larger, daytime absorption of that radiation is generally quite high.

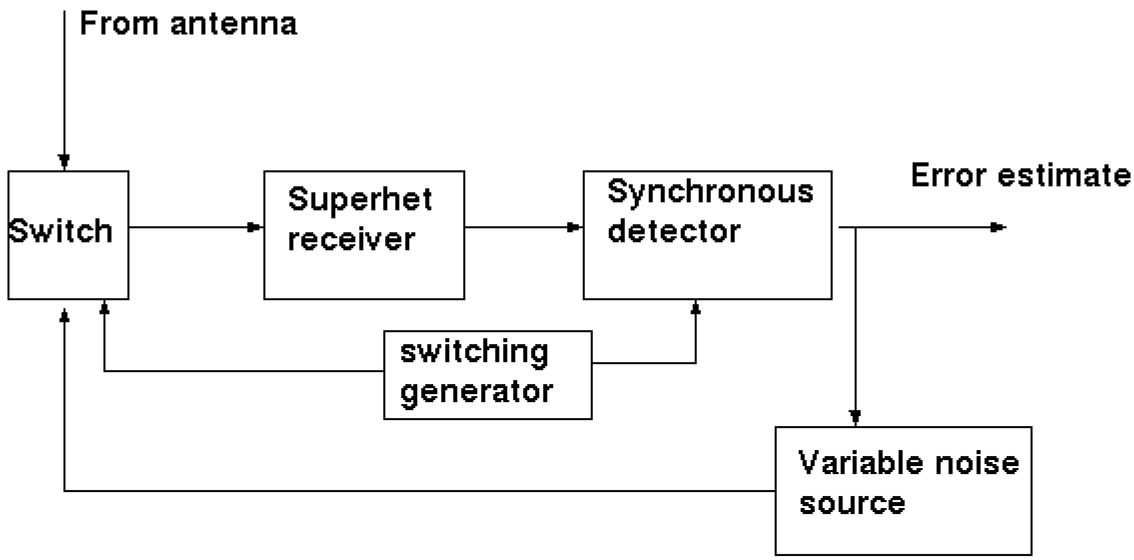
Absorptions estimates for any given time period are made by comparing instantaneous received RF power to a so-called *Quiet Day Curve* (QDC) which is a quasi-synthetic estimate of the diurnal variation in received RF power during a “perfect” sidereal day in which no unusual disturbances in absorption or emissions occurred[2].

A traditional riometer

A traditional (analog) riometer consists of a relatively-straightforward Ryle-Vonberg[3] radiometer,usually using a single-conversion superheterodyne receiver chain, generally constructed for a single observing frequency[4].

1 On loan from *Science Radio Laboratories, Inc.*
2 See, e.g. http://www.dcs.lancs.ac.uk/iono/iris/qdc.html
3 Machin, Ryle, Vonberg, 1952 *The design of equipment for measuring small radio frequency noise powers*
4 See, e.g.: http://www.lajollasciences.com/block.html

The diagram below illustrates this concept:



The measured-quantity in a Ryle-Vonberg receiver is the so-called e*rror estimate*, which acts as a kind of proxy for the incoming noise power. A *Ryle-Vonberg* receiver strives to balance the noise power offered by the noise source against the noise power coming from the antenna, and the magnitude of the *error estimate* signal is directly related to the magnitude of the incoming sky noise.

Receivers such as the *Ryle-Vonberg*, and the closely-related *Dicke-switched*[5], receiver were developed at a time when gain stability in RF amplifiers was insufficient to allow reliable measurements of small noise powers over modest measurement periods. By using a *differential* (either closed-loop as in *Ryle-Vonberg*, or open-loop as in *Dicke*) measurement technique, gain variability can be effectively excised from the measurements.

Switched systems are not without their drawbacks. For example, because the system only spends (usually) half its time connected to the "sky" and half its time connected to the noise source, the sensitivity is reduced for a fixed integration time, necessitating longer integration times to achieve the same sensitivity over a non-switched (and presumably perfectly-gain-stable) system.

A modern, digital, receiver

A modern radiometer for use in *riometry* can benefit greatly from advances in monolithic semiconductor amplifiers and digital-signal-processing technology that have occurred in the years since *riometers* were first deployed in the field.

In an approach that uses digital technology, we can first eliminate the superheterodyne approach to processing of the analog RF signal in favor of *direct-sampling* the incoming RF signal to allow digital

5 Dicke, R.H, 1946: *The Measurement of Thermal Radiation at Microwave Frequencies*, Review of Scientific Instruments 17:268-275

processing of the noise signal even prior to the detection phase.

Modern analog-to-digital converters (ADCs) can operate at sample rates of hundreds of MHz, and can do so cheaply and reliably. They offer excellent dynamic range, with 14-bit converters readily providing over 80dB dynamic range, and signal-to-noise ratios of better than 70dB.

Further, modern *InP*, *InGaP*, and *GaAs* monolithic amplifier ICs[6] are readily available as common, off-the-shelf items that offer stability, low-noise, and gain vs temperature coefficients as low as 0.004dB/C.

A digital radiometer (or riometer, they're the same thing) typically trades a much-simplified analog signal path, for a new, digital signal path that is not without its complexities. The complexities of a digital signal path, however, come with significant improvements in flexibility and functionality that would be impractical to implement using an analog signal path.

The front end

The front-end of a digital riometer begins with a strictly-analog signal processing chain, much like an analog riometer.

In the front-end of a digital riometer, however, we are concerned only with providing filtered, low-noise gain that is adequate to drive the analog-to-digital converter hardware. In the direct-sampled design contemplated here, there is no need to use any type of superheterodyne conversion on the analog signal. We thus eliminate the local oscillator, and mixers that are found in an analog superheterodyne receiver system.

Filtering is important both for the usual analog reasons, but also to provide a well-defined bandwidth that is sampled by the analog-to-digital converter at the output of our front-end gain chain. It is often the case that a so-called “anti-aliasing” filter is used in front of ADCs to eliminate or dramatically reduce frequency components outside of the so-called *first-Nyquist-zone*.

In our prototype design, we used a series of 3rd-order butterworth bandpass L-C filters with a 3dB bandwidth extending from 25MHz to 45MHz. That frequency range was chosen for a number of reasons:

- The first nyquist zone ends at 50MHz, due to the 100MHz ADC sampling rate, and setting an upper cut-off of 45MHz gives adequate roll-off up to the first Nyquist frequency of 50MHz.
- Most riometry observations occur over the 25Mhz to 45MHz frequency range
- Component values for such a filter were available readily off-the-shelf

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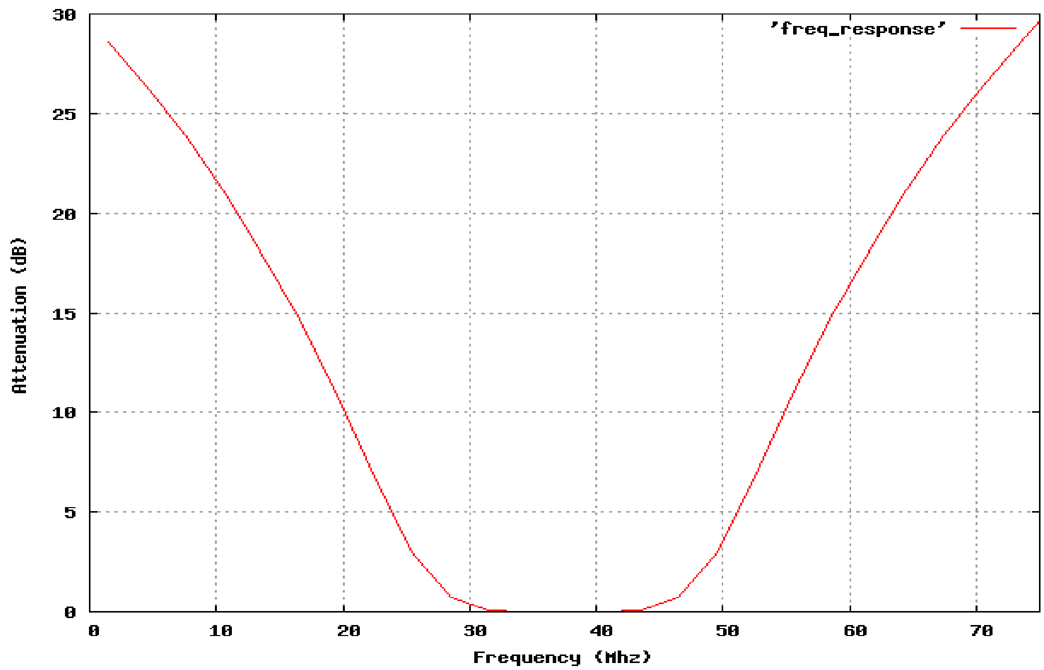
6 See, for example, Mini-circuits ERA, GALI, and PMA-series monolithic amplifiers. Http://www.minicircuits.com

Computer-modeled frequency response is shown below.



RF gain is provided by a combination of amplifiers from mini-circuits:

- GALI-39 is used as the first stage, due to excellent noise figure (< 2.3dB at the design frequency), p1dB (+12.5dBm), and OIP3 (+25dBm).
- Subsequent stages are ERA-3+, which offer good gain and noise figure.

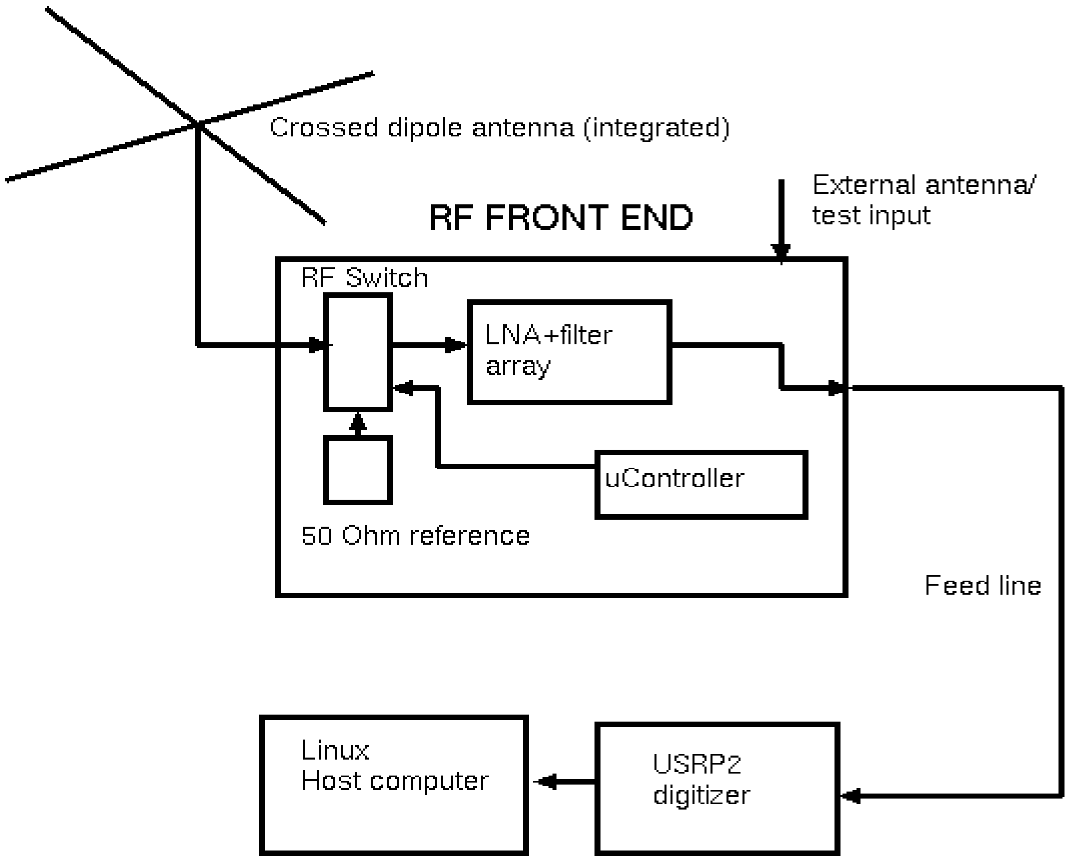
There are 3rd-order bandpass L-C filters (as described above) between each stage, and also in front of the first stage. Filter insertion loss is approximately 0.2dB. The first stage filter may be switched out-of-circuit to improve system noise figure, at the expense of higher susceptibility to inter-modulation products from strong out-of-band signals.

The total gain of the front-end is approximately 55dB, which is both adequate to drive the subsequent analog-to-digital converter and provide suitable small-signal dynamic range, and overcome the ADCs inherently-high noise figure. It is important to note that 55dB of gain is approximately 40-50dB **less** gain than would be used in an analog radiometer designed for a similar purpose.

The prototype front-end is also actively maintained at a fixed ambient temperature of 40C through the use of a commercial PTC (Positive Temperature Coefficient) heater which is a coarsely-self-regulating heater made from semiconductor material. This provides even better gain stability than the already-excellent 0.004dB/C offered by the MMIC amplifiers, since gain stability in semiconductor amplifiers is generally dominated by thermal effects, removing, or reducing, temperature variability is an effective method to achieve enhanced gain stability, with an only very-modest penalty in ultimate noise figure.

The front-end described here also includes an RF switch that switches the gain-chain between the antenna and a reference termination. That termination provides an equivalent noise temperature equal to its physical temperature, which is 310K when the PTC heaters are operational, and whatever the ambient temperature is when the heaters aren't operated. The RF switch may be optionally driven by a 20%-duty-cycle switching waveform at between 10Hz and 20Hz. This allows the downstream digital processing system to optionally provide a Dicke-switched type processing environment for detector data, further reducing any gain variability inherent in the system. A 20% duty cycle switching waveform reduces the impact of reference switching, since the gain chain spends more of its time looking at *sky*, and less of its time looking at the *reference*.

A high-level block diagram of the prototype system is shown below.



Digitizing: the USRP2 digitizer

The prototype system used an off-the-shelf high-speed RF digitizer, the *Universal Software Radio Peripheral,* manufactured by Ettus Research. This device performs some important functions in addition to straight analog-to-digital conversion. It has an FPGA (Field-Programmable Gate Array) inside that performs functions that allow further processing by a host-side *Software Defined Radio* architecture.

Analog data are sampled by the ADC at 100Msps, and presented to the FPGA for further processing. The FPGA performs a digital down-conversion (DDC) process on the incoming ADC samples that converts the desired spectral range to a complex base-band signal, and is then decimated (bandwidth reduced) and filtered appropriately, and presented to the 1gigabit Ethernet connection to the host.

Recall that the incoming analog signal spans from approximately 25MHz to 45MHz. The FPGA then, acts as a digital version of the local-oscillator and mixer in a conventional superheterodyne receiver.

Instead of using an *Intermediate Frequency* (IF) however, it converts the signal into a complex[7] base-band representation.

Once the complex base-band signal leaves the USRP2 via the 1gigabit ethernet port, the host software processes the resulting signal further. In our prototype system, that complex base-band signal consists of 400K complex samples/second delivered to the host computer.

A Software Defined Radiometer

The concept of digital-signal-processing has existed for many decades, and indeed it has been used in scientific disciplines for almost as long as it has existed as a practical technology. For example, most of the significant radio astronomy observatories in existence today use DSP techniques to process the signals from their radio telescopes, and indeed, the signals are digitized **very early** in the process to facilitate maximum flexibility for downstream operations.

Upon examination, it becomes clear that many of the functions in an analog signal processing chain (such as a radio) are approximations of strictly-defined mathematical functions. Some of those analog elements are "higher fidelity" than others, but they very often suffer from critical limitations. A mixer, for example, is nothing more than a multiplier. But an analog mixer must be operated over a fairly narrow range of input values in order to remain a reasonably-faithful approximation to a multiplier.

Similarly signal filters in the analog domain are merely hardware realizations of precisely-defined mathematical operations. Filters in the analog domain suffer from many "ugly real-world" problems such as component tolerance issues, and poor characterization.

It seems natural, then, to digitize analog signals as early as is practical, and then conduct operations on those signals in the digital domain with high mathematical fidelity. The fidelity of those operations has very few constraints, but there are a few:

- Resolution of the analog-to-digital conversion
- Linearity of the analog-to-digital conversion
- Dynamic range of the numerical representation

The USRP2 used in the prototype includes a modern analog-to-digital converter, in this case a **LTC2284** 105Msps dual-channel type made by Linear Technologies[8]. This converter includes:

- 14-bit resolution
- better than 85dB dynamic range
- better than 72dB SNR
- better than 0.6LSB linearity over the entire input range (~ -74dBm to +10dBm)

The SNR specified gives an equivalent noise figure that is only a few dB worse than many analog mixers extant in the market, and can be easily overcome by the addition of sufficient low-noise gain ahead of it, and indeed our design places approximately 55dB of low-noise gain ahead of the USRP2 input to the LTC2284 ADC, which both overcomes the ADC noise figure, and shifts the observed power levels of interest sufficiently above the ADC noise-floor to provide adequate small-signal

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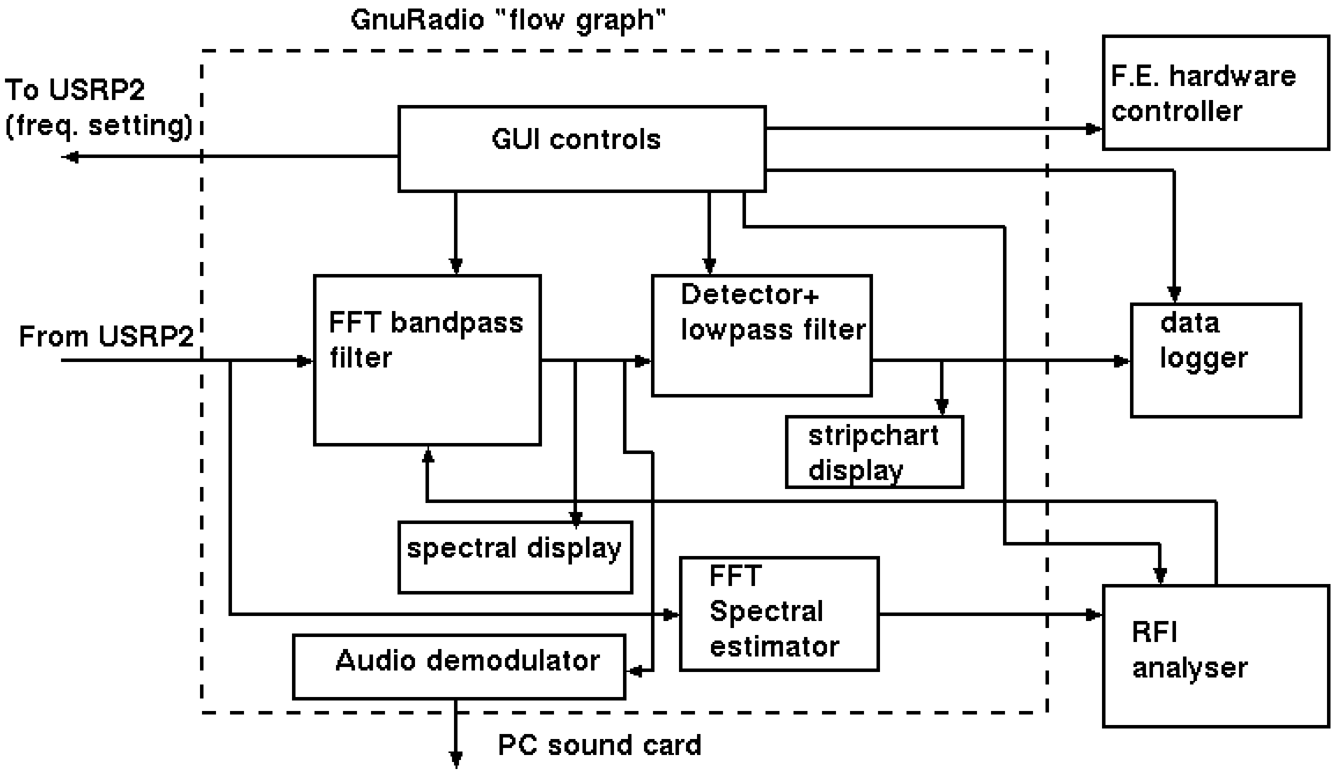
7 When we use the term "complex", we refer to the mathematical concept of complex numbers, rather than "complicated".

8 See: http://www.linear.com

dynamic range.



Software RF Signal Processing: GnuRadio

Prior to the late 1990s, the notion that digital-signal-processing for RF could usefully be accomplished on anything other than a dedicated and specialzed CPU known as a “DSP Engine” would be an largely-unsupportable proposition.

The breathtaking pace of general-purpose computing performance enhancement has meant that many of the functions typically found in a radio can usefully be provided purely in software executing on a general-purpose computer.

In the early part of the 21st century, a number of pioneers in the field of S*oftware Defined Radio* engaged in a project to produce a viable, flexible and *open-source* platform for the development of *Software Defined Radio* technology. That platform became known as *GnuRadio*[9]. The *GnuRadio* software architecture allows the rapid development and testing of signal-processing chains known as *flow-graphs*. The environment provides an extremely rich pallette of basic signal-processing blocks which may be strung together using a building-block approach.

We take ruthless advantage of the *GnuRadio* platform to construct most of the software pieces of our riometer/radiometer.

Recall that the signal arrives as a complex base-band data stream that is usually 400KHz wide, and centered on our desired frequency of interest, thanks to the FPGA in the USRP2.

Riometer observations are typically conducted over a range of bandwidths, depending on local

9 See: http://www.gnuradio.org

circumstance, between 5KHz and 250Khz. In an analog world, a hardware filter would need to be constructed for each of the desired bandwidths. In the digital world of *GnuRadio*, we simply present the 400Khz-wide signal to a programmable band-pass filter, which can be dynamically configured for any desired bandwidth between 5KHz and 390Khz. In our particular instance we use a band-pass filter with an FFT-based *core* for reasons that will be described later.

Once the signal has been filtered, it is presented to a power detector, which is nothing more than a complex squarer, followed by a low-pass filter that acts as an integrator. The low-pass filter is based on an FIR *core*, and is fully configurable, dynamically, at run-time.

In an analog receiver, the RF signal would be envelope-detected by a square-law diode detector. Such a detector produces an output voltage that is proportional to the power incident on the detector. Diode detectors have a limited dynamic range, aren't ever perfectly linear-in power, and have a proportionality constant that must be characterized quite carefully.

In our design, the squaring operation is perfectly linear-in-power, and has a dynamic range that is limited only by the allowable numeric range of the CPU upon which the operation executes, which in our case is double-precision floating-point on the x86 platform.

Once the detected signal has been low-pass filtered, it is presented to a logging function that logs the detected data to a file. In our implementation, the data are low-pass filtered to 500Hz, then an external data-logging function further filters the data according to the desired integration time, and logs at a rate appropriate to the integration time.

The detected signal is also presented to a graphical “stripchart” display in order to provide real-time display to an operator, and this display is updated at 2Hz, and presents the most recent 30 minutes of detector data to the operator.

Further the band-limited signal is also presented to an FFT spectral display to show the operator the local spectral environment.

Narrowband RFI excision

Recall that detector bandwidth is controlled by the use of a digital band-pass filter, which operates using an FFT-based filter *core*.

A copy of the *pre-filtered* signal is presented to a special analysis function that looks for the existence of persistent narrow-band spikes in the incoming computed spectrum, and augments the band-pass filter with notches to remove the spikes in the computed spectrum, which are presumed to be RFI. The implementation of such functionality in an analog receiver would be close to impossible, and yet with digital signal processing and software-defined radio, such functionality is relatively straightforward.

The method is simple and straightforward. The incoming “normal” spectrum is assumed to be flat, or near flat. The excision function looks for bins in the computed spectrum that persistently exceed the average spectral floor, and then issues commands to the *GnuRadio* flow-graph to augment the filter.

The user may control the threshold value that the excision function uses in order to “declare” a given spectral feature an “RFI” feature.

Audio demodulation

It has often been considered a “missing feature” in extant riometers the ability to demodulate the incoming bandwidth in one of several popular communications formats, and present the result to an audio output transducer, such as a speaker.

This can be used for a number of purposes, including:

- Gross sanity testing of the riometer receiver
  - Tune to amateur-radio or CB radio frequencies and listen for distant stations
- Assist in the identification of local RFI sources

Our implementation allows the demodulation of the filtered bandwidth under the following modulation modes:

- AM
- USB, LSB
- FM

Since the bandwidth of the filter can be reduced to 5Khz, individual narrow-band transmissions may be demodulated and evaluated.

Dicke switching

We earlier indicated that the front-end may be optionally configured to switch automatically at a several-hertz rate between the reference termination, and the antenna.

In a traditional analog riometer/radiometer the switching frequency is generally chosen to be at least several hundred hertz, and usually a kilohertz or more. The reasons for that included both the nature of short-term gain instabilities, and also the ease with with the switched waveform could be "synchronously detected" with the aid of appropriate filters.

In our implementation, a frequency of only a few hertz is required to provide adequate tracking of the already extremely stable gain. Further we operate the switching at a 20% duty cycle in order to reduce the sensitivity-reducing effects of switching. When switching is turned on, the receiver still spends 80% of its time looking into the antenna, rather than the reference.

The core of the software-defined receiver has no "knowledge" of the Dicke-switching function. The switching waveform is not synchronous to any part of the internal receiver structure, this is partially because doing so in the *GnuRadio* architecture is awkward, and partially because it isn't strictly necessary.

The only piece that's "aware" of the switching function is the data-logger, which alters its behavior when the switching function is enabled.

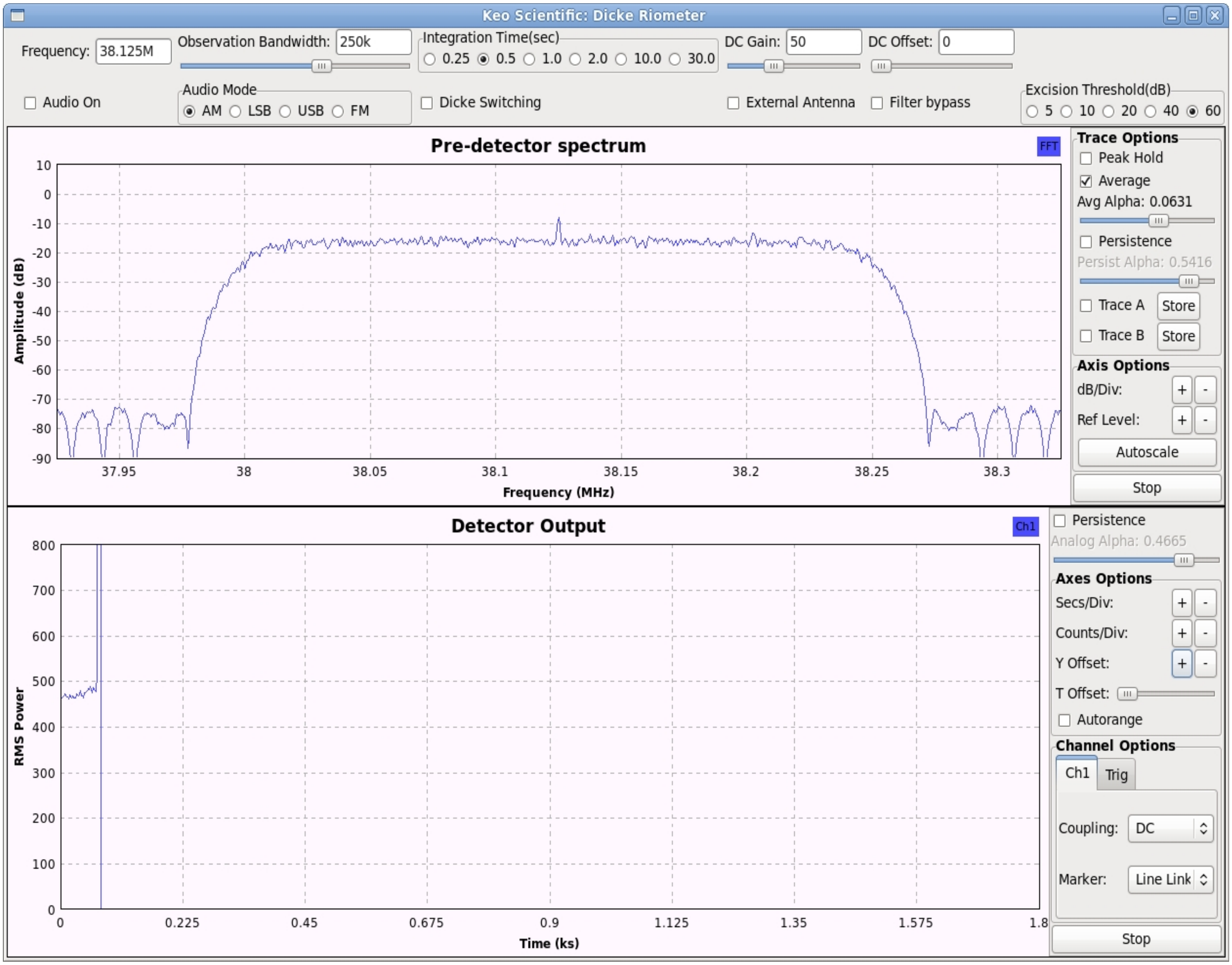
The data-logger applies a "data slicing" technique to the incoming samples using the simple observation that there will nearly always be a significant difference between the antenna-derived samples, and the reference-derived samples. The logger simply sorts the incoming samples into the two discrete categories, discards the outliers, and computes the delta between the averages of the two groups, and then logs this computed delta. Similar techniques have been used in the implementation of data-modems in the telecommunications industry for many decades, although application of the method to the processing of switched radiometer data is originally ascribed to K. Tapping.[10]

It is anticipated that in field use, Dicke switching will not generally be necessary, due to the already excellent gain stability inherent in the front-end design.

The riometer software application is shown below as implemented with *GnuRadio* and *Gnu Radio*

10 K. Tapping, private communications, and "A Multi-Frequency Riometer" Huberman, Steele, Tan, U. McGill graduate project

Companion—a graphical tool to assist in the construction of *GnuRadio* flow-graphs



Performance considerations

The performance of an RF radiometer, whether used for riometry, or other scientific applications is dependent on a number of important factors, including:

- Sensitivity
- Linearity
- Repeatability
- Stability
- Dynamic range

Sensitivity

The sensitivity of a radiometer is defined by the well-known radiometer equation, namely:

$$Tmin=\frac{Tsys}{\sqrt{bw*T}}$$

Where *Tsys* is the system noise temperature in K, *bw* is the bandwidth, in hertz, and *T* is the integration time, in seconds. In this case *Tmin* is the minimum detectable noise power change, in K.

It is clear from the above that for modest bandwidths and short integration times, sensitivity is dominated by *Tsys*, the system equivalent noise temperature. In most systems, the *Tsys* is further dominated by the noise temperature of the RF gain chain. In our prototype front-end, the measured noise figure was approximately 2.7dB, or roughly 250K noise temperature.

The typical observation bandwidth is 250e3 hertz, and integration times of 0.25 to 1.0 seconds are typical. Which means that the minimum detectable noise temperature change at the input in our prototype system, as configured, would theoretically be 1K, although in practice, one can expect sensitivity to be 2 or 3 times worse.

If we assume a 3K sensitivity, and divide that into the expected antenna noise temperature from peak galactic emissions at 38MHz—we assume approximately 6.0e3K antenna temperature due to galactic noise, then our sensitivity amounts to being able to detect an antenna noise temperature change of 0.002dB.

Linearity

The linearity of a radiometer depends on the linearity of its analog RF chain, and the linearity of the detector mechanism.

In an analog radiometer the gain chain is typically “longer” that in our prototype system, and also has many more opportunities for non-linear behavior, including the amplifiers and mixers.

Our gain chain operates well within its linear operating range, the MMIC amplifiers don't begin compressing their outputs until the output power is well above +9dBm. The final amplifier in our gain chain will produce signal power levels to the ADC of approximately -50dBm to -40dBm—well below the range where compression and other non-linear behaviors become an issue. Further, the input is typically filtered to reduce out-of-band signals and thus allow the first-stage gain element to operate well within its linear range.

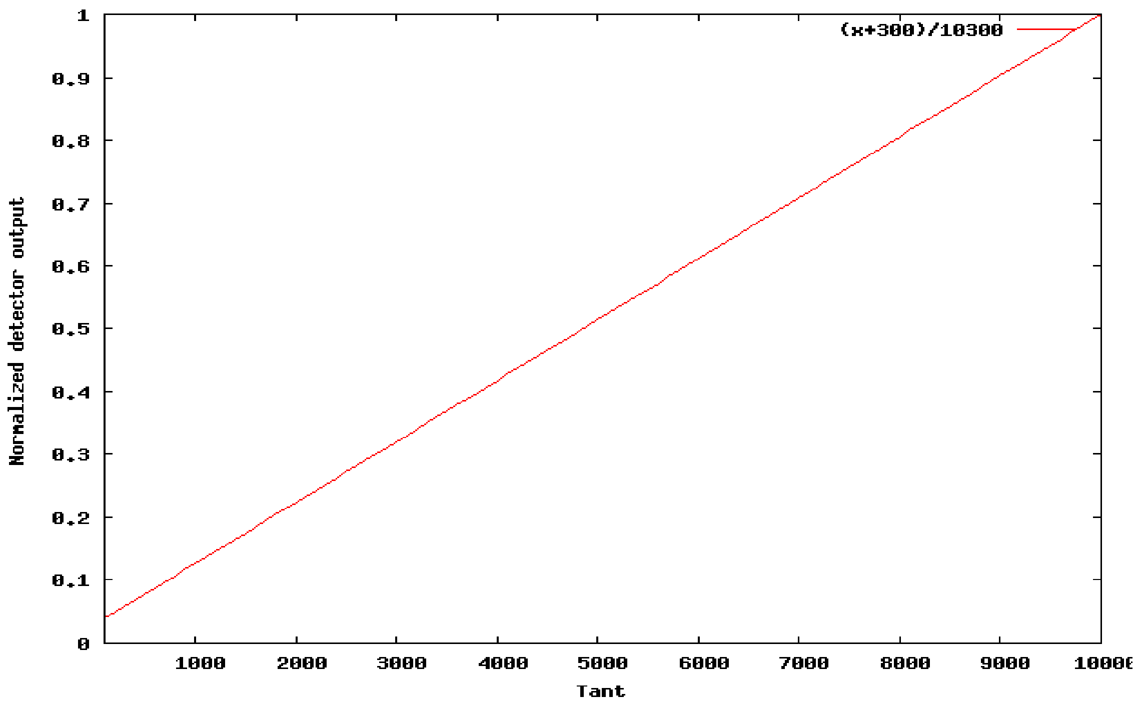
It has already been mentioned that the LTC2284 ADC has a linearity of better than 0.6LSB over the entire 85dB dynamic range of the ADC.

In any radiometer system, whether digital or analog, the power detector produces an output according to the following simplified proportionality relation:

$$Pout \propto G(Tsys+Tant)$$

Where *Pout* is the detector power level, *G* is the system power gain, *Tsys* is the system noise temperature and *Tant* is the incident antenna temperature.

We can see, from the plot below, that while such a system has linear slope, it does not have a zero intercept:

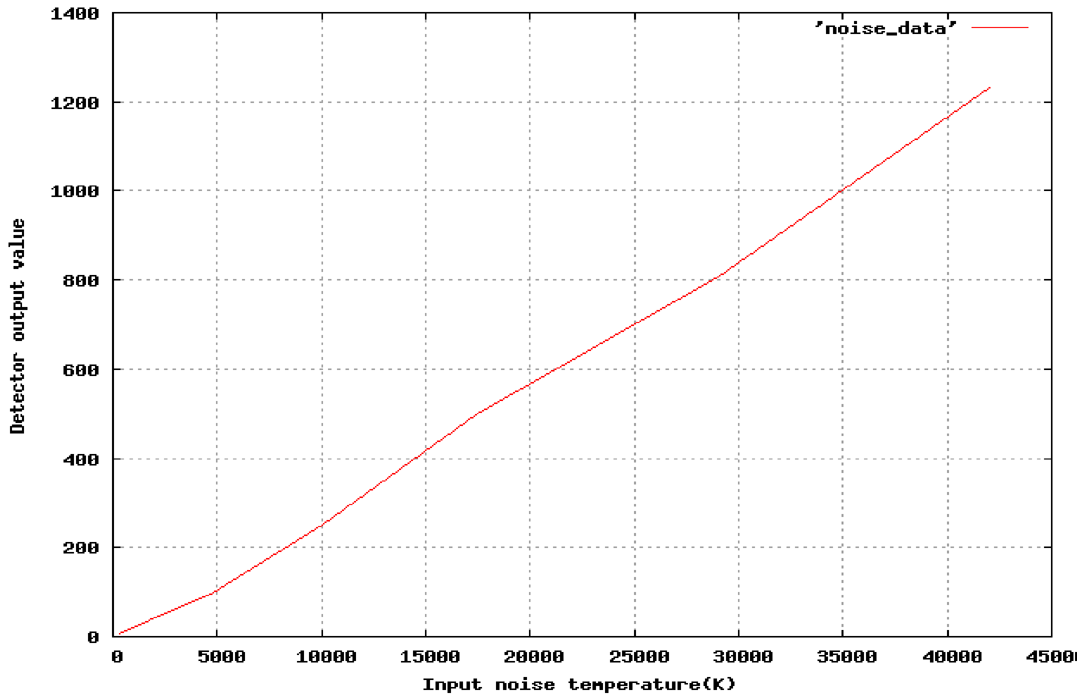


The smaller the value of *Tsys*, the closer to zero the detector output function intercepts the Y axis for zero input power.

In a practical radiometer used for riometry, expected values for *Tant* range from 100K to roughly 100000K.

Similarly in a practical radiometer for riometry, *Tsys* is expected to be in the range of 250K to 320K.

Through the use of a fixed noise-source and a step attenuator, we were able to measure detector response over an input noise range of 290K to 10000K, and were able to observe a detector output response that adhered to a linear-in power response function, within the uncertainty limits of our noise source and attenuator array:



Above a plot of actual detector output values vs input noise temperature, for a variable noise source capable of producing noise outputs over the range of 290K to 42000K. Minor excursions from linearity are due largely to uncertainty in the calibration curve of the noise source.

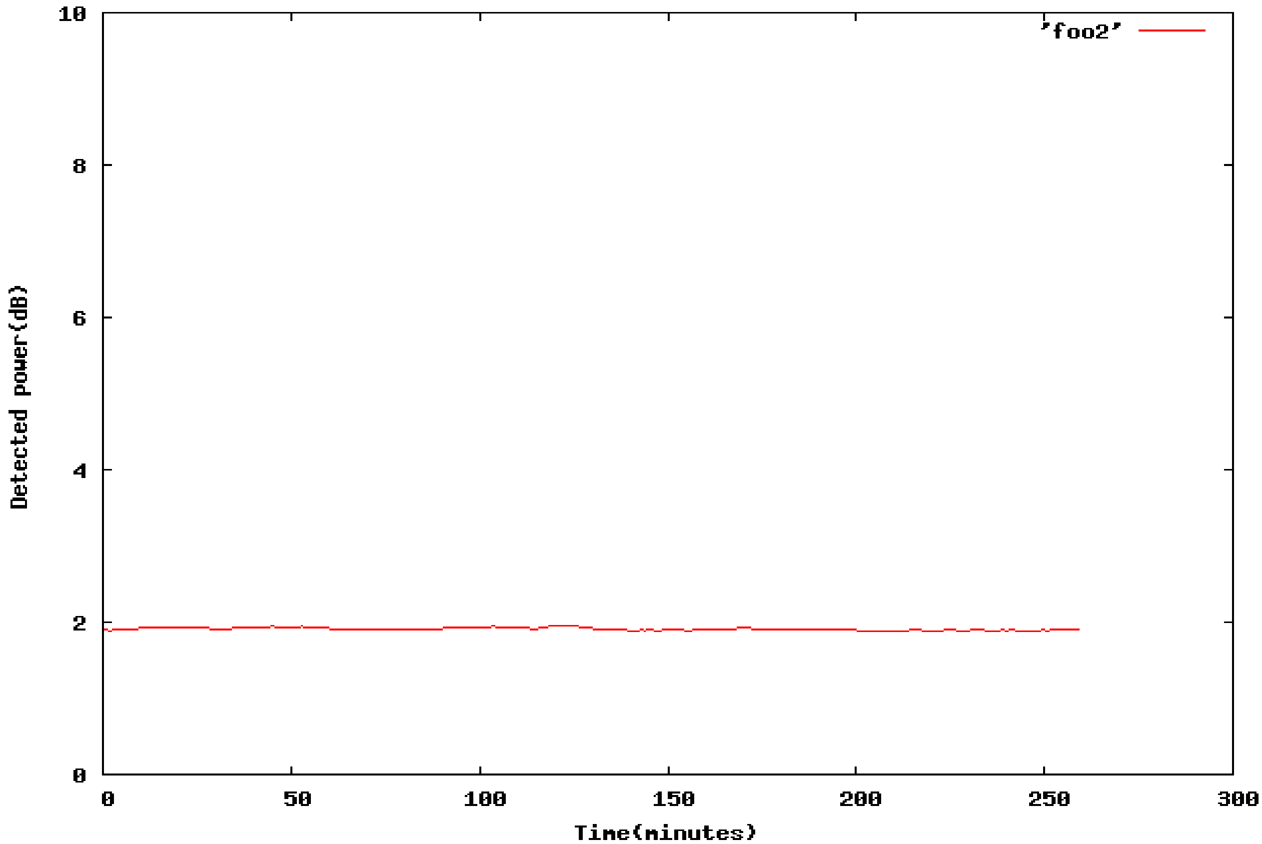
On the scale of the graph, it is difficult to see that this function actually doesn't have a zero intercept, but rather intercepts at an output level of roughly 1.8 units.

Repeatability and Stability

It is important for a radiometer that is to be used for riometry to produce repeatable results. Repeatability is intimately linked with stability. Stability refers to the ability of the radiometer to produce a constant output value when the input noise power is held constant.

In our laboratory tests for stability, we used a 50 ohm input termination held at ambient temperature for several hours, and observed only tiny variations in detected output power, amounting to less than 0.04dB variability, with an ambient temperature that varied by approximately 1C over the course of several hours.

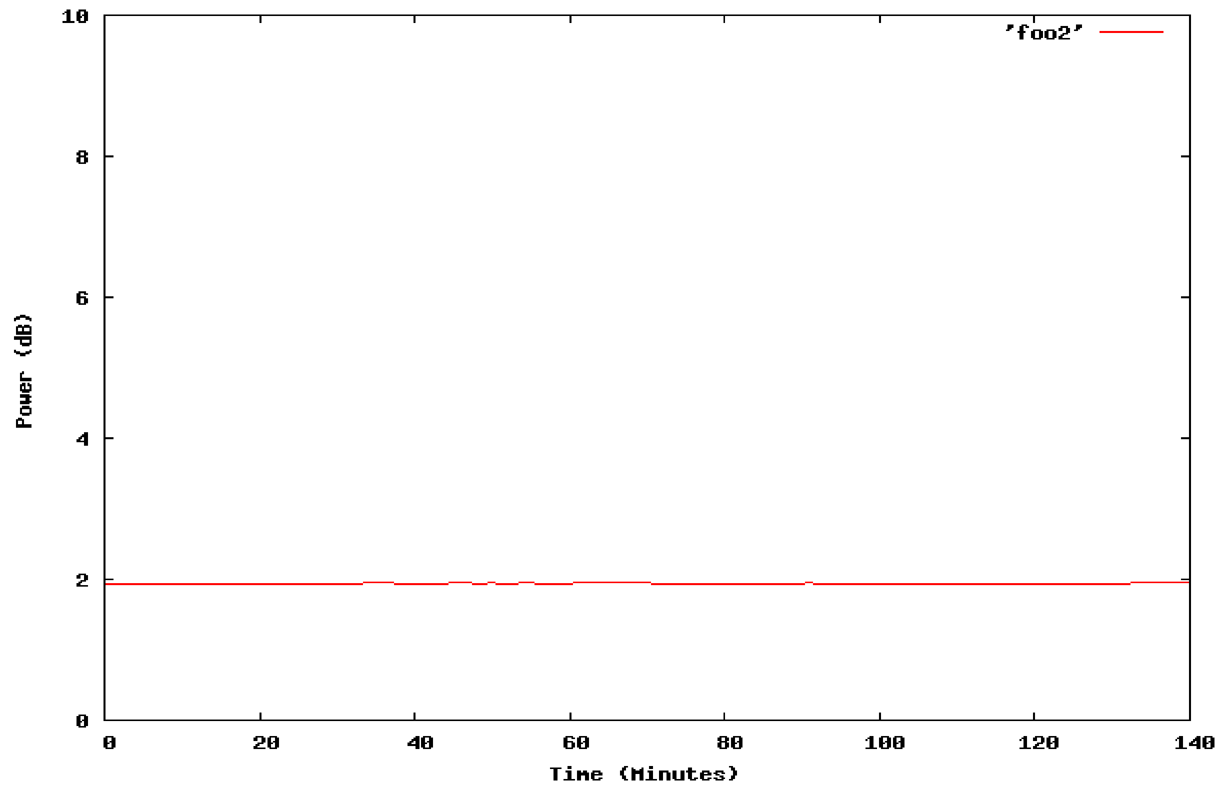
The plot shown below shows detector output over approximately 3 hours, with the input terminated in a 50 ohm reference termination. It should be noted that this test was conducted with Dicke-switching disabled, which shows the excellent inherent gain stability of the system.



In field deployment, the front-end unit will be held to a constant 40C, and surrounded in foam insulation to reduce temperature variability,which improves both gain stability and stability of the reference termination used for switching.

Repeating the same test several hours later after the unit had been turned off over that time produced closely comparable results—the detected average power level was identical to the test conducted several hours earlier, settling at approximately 1.9dB.

Shown below are data taken after several hours of the equipment being turn off and then back on again—that includes both the prototype front-end, and the USRP2 digitizer.



The system has repeatability within approximately 0.04dB.

Dynamic Range

The dynamic range of a radiometer describes its ability to reliably detect various input noise power levels without distortion or “clipping”.

Of particular importance in riometry is the ability to reliably “track” absorption events that may reduce the antenna temperature by a significant factor, sometimes as much as 10dB to 20dB.

Using simple laboratory equipment, we can easily show that the prototype system is able to “track” noise power all the way down to 290K, simply by using a reference termination on the “cold” end of the scale, and a variable noise source on the “hot” end of the scale. Without a cyrogenic termination, however, it is impossible to simulate noise powers below ambient (nominal 290K) in the laboratory.

However, the radiometer equation, shown earlier, gives us extreme confidence in being able to detect galactic noise power levels well below the noise power of an ambient-temperature termination. Recall that:

$$Pout \propto G(Tsys + Tant)$$

If we estimate a worst-case absorption event of 20dB, and a “normal” galactic background noise temperature of 10000K, then *Tant* would drop to 100K, which is below *Tsys* but still easily within the mathematical (and practical) grasp of the radiometer equation:

$$Tmin = \frac{Tsys}{\sqrt{bw * T}}$$

Which we've already shown gives our prototype system the ability to detect down to 3K. That is, we should be able to reliably distinguish between a power level of *Tsys+0K* and *Tsys+3K*, according to the radiometer equation, which means that distinguishing between *Tsys+0K* and *Tsys+100K* should be exceedingly easy.

Put another way, in the laboratory, we “track” detector output down to *Tsys*+290K using an ambient-temperature termination. We should easily be able to distinguish between a detector output due to *Tsys+290K*, and a detector output due to *Tsys+100K*, given constant *Tsys*. By observing over a non-zero bandwidth, and a non-zero integration time, we effectively make *Tsys* a constant. That is because variations in *Tsys* are reduced towards zero by integrating over both bandwidth and time.

Our LTC2284 ADC provides us with a dynamic range of approximately 85dB. The minimum signal power into the ADC is approximately -72dBm, and our gain change produces enough gain to cause the nominal unabsorbed galactic noise temperature to “appear” at approximately -45dBm into the ADC, and the maximum signal before clipping for the ADC is approximately +5dBm, which gives us a dynamic range **above** nominal galactic background noise of approximately 50dB. This easily allows clipping-free observation of both *deep absorption* events, and strong solar noise bursts.

Conclusions

We show a new digital riometer/radiometer system that is easily capable of meeting the requirements of a research-grade instrument for on-going riometric investigations in geosolar physics over the HF and low-VHF radio spectrum.

We leverage the considerable flexibility inherent in the *GnuRadio* open-source SDR environment, and make extensive use of off-the-shelf monolithic amplifiers to provide a stable, reliable, and repeatable source of RF gain at the 25Mhz to 45MHz RF frequency range of interest in riometry.

We show a system with significant flexibility in choice of observing frequencies and bandwidths, and easily usable over a range of desired post-detector integration times.

About the authors

Marcus Leech is CEO of *Science Radio Laboratories,* a small consulting company specializing in the development of scientific instruments at HF through L-band frequencies. He has been an avid amateur radio astronomer for many years, and is considered a pioneer in the application of SDR techniques to small-scale radio astronomy.

Trond Trondsen is a wily Norwegian physicist with a penchant for expensive Scotch, auroral cameras and obscure foreign-language films. He is also president of *Keo Scientific*.

Titus Matthews is a silicon gunslinger and head hardware honcho at *Keo Scientific*.