Software Defined Radio Telescope Receiver

Functional Specification

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Abstract

This document contains the functional specifications for a portable software defined receiver and spectrum analyzing software. The receiver is intended to be used in conjunction with an antenna provided by the Grand Valley State University physics department for radio astronomy to receive RF radiation from the sun and Jupiter. The signals from those celestial bodies are typically approximately 1MHz bandwidth with a center frequency of 20.1 MHz. The receiver is to be powered by rechargeable batteries, have an audio output jack with adjustable volume, and be easily transported by a single person to remote locations for field study use. The receiver will stream the processed data to a personal computer via USB 2.0 where it can be analyzed in real time or be stored for analysis at a later time.

Section 1.0: INTRODUCTION AND BACKGROUND

Section 1.1: Radio Astronomy Background

Radio astronomy is the study of celestial objects that emit radio waves. With radio astronomy, scientists can study astronomical phenomena that are often invisible in other portions of the electromagnetic spectrum. Using radio astronomy techniques, astronomers can observe the cosmic microwave background radiation, which is considered the remnant signal of the birth of our universe.

The properties of electromagnetic radiation depend strongly on its frequency. Electromagnetic radiation is produced whenever electric charges change either the speed or direction of their movement. In a hot object like the sun, molecules are continuously vibrating or bumping into each other, sending each other off in different directions and at different speeds. Each of these collisions produces electromagnetic radiation at frequencies all across the electromagnetic spectrum.

Electromagnetic radiation is also generated as the result of free electrons or protons spiraling around magnetic field lines as show in Figure 1.1. The electrons and protons become energized in the magnetic field and begin to accelerate. As the electron and protons accelerate they release electromagnetic waves. It is observed that the shorter the wavelength (and higher the frequency), the more energy the radiation carries. It is this radiation which can be detected by radio telescopes.

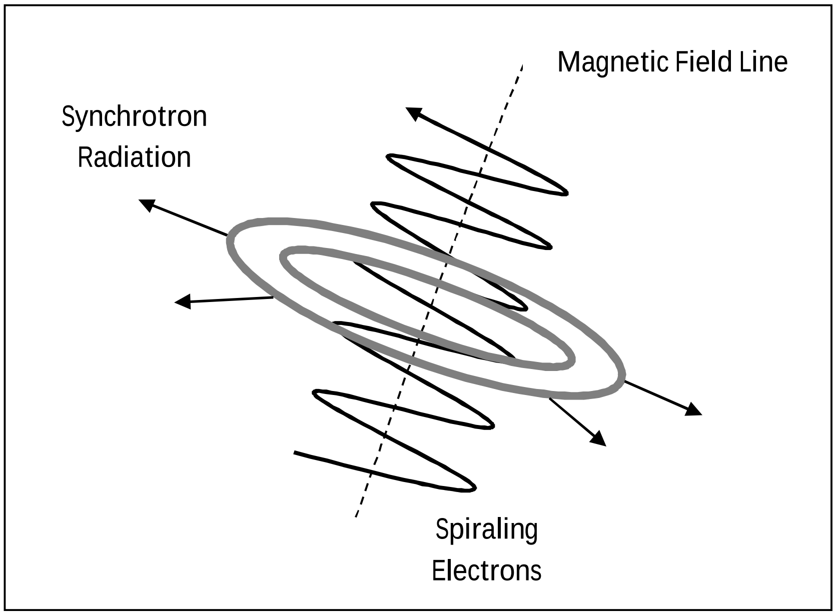

Figure 1.1: Synchrotron Radiation

Earth's atmosphere acts as a barrier to much of the electromagnetic spectrum. The atmosphere absorbs most of the wavelengths shorter than ultraviolet, most of the wavelengths between infrared and microwaves, and most of the longest radio waves. This leaves only visible light, some ultraviolet, infrared, and short wave radio to penetrate the atmosphere and bring information about the universe to the surface of our planet. One of the largest frequency ranges allowed to pass through the atmosphere is referred to as the radio window. The radio window is the range of frequencies from about 5 MHz to over 300 GHz (wavelengths of almost 100m down to about 1mm). Although these wavelengths have no discernable effect on the human eye, they do induce a very weak electric current in a conductor such as an antenna. Electronic filters in a receiver can be tuned to amplify a small frequency range at a time or, using sophisticated data processing techniques, thousands of separate narrow frequency bands can be detected. With this method we can find out what frequencies are present in the RF radiation and what their relative strengths are.

Section 1.2: Software Defined Receiver Background

A software-defined radio system, or SDR, is a radio communication system where components that have typically been implemented in hardware are instead implemented by means of software on a personal computer or embedded computing devices. The ideal receiver scheme would be to attach an analog-to-digital converter to an antenna. A digital signal processor would read the digitized data from the converter, and then its software would transform the stream of data from the converter to any other form the application requires. Most present day receivers use a variable-frequency oscillator, mixer, and filter to tune the desired signal to a common intermediate frequency or baseband, where it is then sampled by the analog-to-digital converter.

In some applications it is not necessary to tune the signal to an intermediate frequency and the radio frequency signal is directly sampled by the analog-to-digital converter (after amplification). Real analog-to-digital converters lack the dynamic range to pick up sub-microvolt, nanowatt-power radio signals. Therefore a low-noise amplifier must precede the conversion step and this device introduces its own problems. For example, if spurious signals are present (which is typical), these compete with the desired signals within the amplifier's dynamic range. They may introduce distortion in the desired signals, or may block them completely. The standard solution is to put band-pass filters between the antenna and the amplifier, but these reduce the radio's flexibility - which some see as the main purpose of a software defined radio. A simple block diagram of an SDR receiver is shown in Figure 1.2.

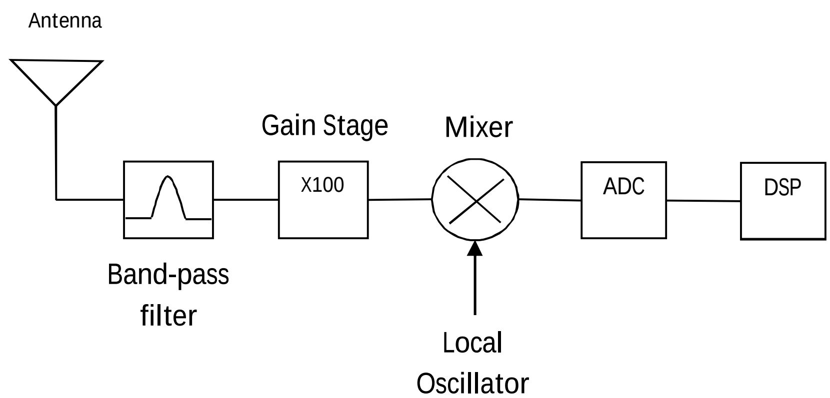

Figure 1.2: Simple Generic SDR Receiver Diagram

The receiver performance of this line of SDRs is directly related to the dynamic range of the analog-to-digital converters used. Radio frequency signals are down converted to the audio frequency band, which is sampled by a high performance ADC. The newer software defined radios use embedded high performance ADCs that provide higher dynamic range and are more resistant to noise and RF interference. The SDR software performs all of the demodulation, filtering, and signal enhancement.

SECTION 2.0 – HARDWARE REQUIREMENTS

The design will be comprised of three main sections. The first of these sections will be the receiver RF Front End. The second section will be the pre-processing section that will handle the conversion of the analog signal to a digital signal and send the data to the PC. The final section is the software front-end, which handles further signal processing of the samples as well as functioning as a user-interface.

Section 2.1 – Receiver Hardware

The goal of the receiver hardware will be to take the incoming 20.1 MHz signal and downshift it into a spectrum that can be processed. The hardware will downshift a 1 MHz bandwidth of the frequency content of the signal centered around 20.1 MHz down to the baseband. The receiver will also have an audio output so that the signal can be further downshifted into the audio spectrum and listened to by the user, for system testing purposes in the field. Thus, the system has a single input: the RG-6 (75Ω) cable input using a female F-connector that will connect directly to the antenna. The system has two outputs: a 3.5mm "headphone jack" for direct audio output, and the output that will connect directly to the PC. The audio output should be able to drive a 30Ω load at 100mW. The receiver will connect to the PC through a USB 2.0 connection. Figure 2.1 shows a block diagram of the receiver.

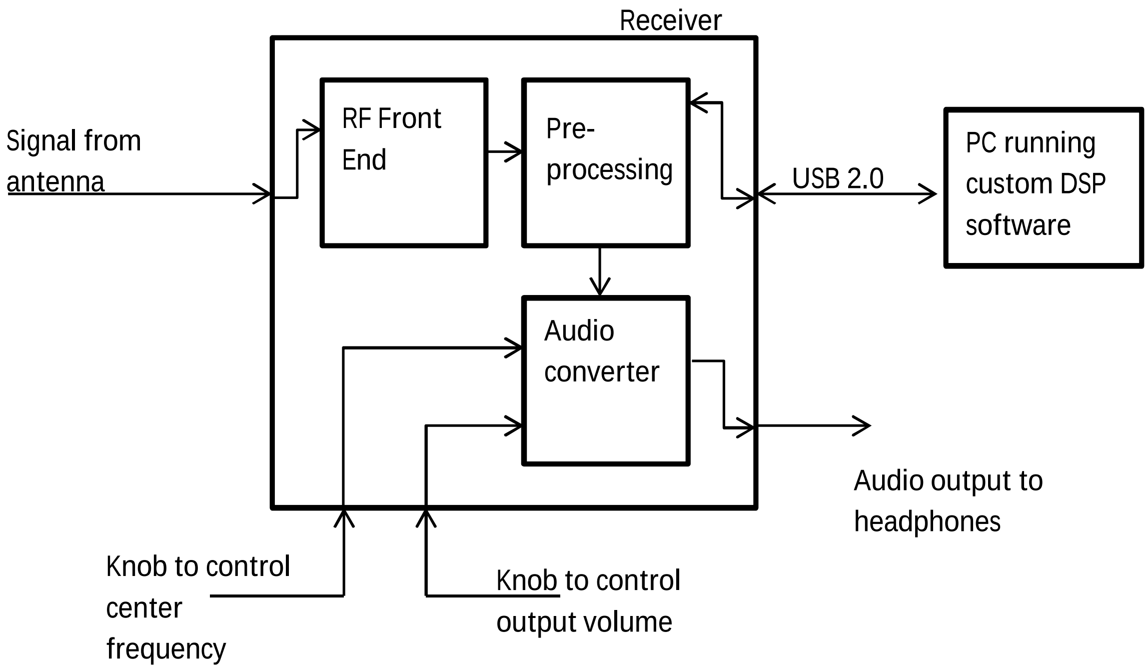

Figure 2.1: Block Diagram of Receiver

Section 2.3 – Power

The system is designed to be portable. Therefore, it will be designed to be battery-powered, and the battery will be rechargeable. The battery life is expected to be greater than or equal to two hours. Furthermore, the battery is required to charge from an AC to DC "wall wart" power supply with a voltage of 9-15V. There will also be two status LED's that will be visible through the case. One of these LED's will indicate whether the receiver is receiving power, and the other will indicate when the battery is charging. It is required to not receive any power from the USB port in order to avoid putting excessive drain on the laptop battery.

Section 2.2 – Casing

A prefabricated aluminum case is required to enclose the receiver hardware. The case shall be lightweight and easily portable. The case shall also be capable of acting as an RF ground. Holes in the case are required for the USB connector, indicator LED's, antenna F-connector, audio output 3.5mm jack, a knob for adjustable gain of the audio amplifier, power switch, and DC connector for charging. The system will not be designed to withstand inclement weather; coating and protection of the case will not be required. However, the system should be able to operate from -20°C to 40°C.

Section 2.4 – Audio Output

As previously mentioned in Section 2.1, the system will have an audio output via a separate built in direct conversion receiver. The purpose of this output is to listen to the signal level being output from the system, and will have to be mixed down to a range of frequencies audible to the human ear. The user will be able to select which frequency to listen to through a control knob on the case. The user should be able to select a signal between 19.6 MHz and 20.6 MHz. The bandwidth of the selected frequency will be fixed at 10kHz. Because this feature of the system will only be used for debugging the system (ie. making sure the antenna is connected properly and a useable signal is being fed into the receiver), the accuracy of the direct conversion receiver is not an important design requirement.

Section 2.5 – Analog/Digital Conversion

In order to transform the incoming audio signal into a digital signal that can be processed by the computer, an analog-to-digital converter (ADC) is required. The ADC must have sufficient resolution in order to detect a large dynamic range of signals. There should be enough quantization levels to allow for good distinction between incoming voltage levels. This resolution is largely determined by the number of bits the ADC can sample.

$$number\ of\ quantization\ levels = 2^N, where\ N = number\ of\ bits$$

A 14 to 24-bit ADC was recommended for use by the sponsor. A 14-bit ADC would give 16,384 quantization levels whereas a 24-bit ADC would give 16,777,216 quantization levels. The voltage resolution of the ADC can be determined using the formula shown below.

$$Voltage\ Resolution = Amplitude / Quantization$$

Using this reasoning, given a 3.3V maximum signal amplitude, a 14-bit ADC would give a voltage resolution of 201.4 µV/code and 24-bit ADC would give a voltage resolution of 196.7nV/code.

Section 2.6 – Dynamic Range

Dynamic range is defined as the ratio between the largest and smallest possible signals the receiver is able to detect. The dynamic range of the receiver is required to be a minimum of 100dB. The dynamic range of an analog to digital converter with N-bit uniform quantization is defined by:

$$DR_{ADC} = 20 \log \left(\frac{2^N}{1} \right)$$

A 16-bit ADC would have a dynamic range of 96.3dB and would be considered the minimum quantization needed to achieve an overall dynamic range of approximately 100dB.

Assuming a minimum signal voltage of 1µV and dynamic range of 100dB, the maximum signal detectable with saturation of the ADC would be:

$$1\mu V \times 100dB = 100mV$$

Assuming a reference voltage of 10V on the ADC, the maximum signal can be amplified by a gain of 100 before saturation of the ADC occurs. The minimum signal would then be 100µV after amplification. With a 16-bit ADC, the voltage resolution is:

$$\frac{V_{ref}}{2^N} = \frac{10}{2^{16}} = \frac{152\mu V}{code}$$

While ideally the voltage resolution should be smaller than the minimum signal, this resolution should be sufficient to give a dynamic range of approximately 100dB.

SECTION 3.0: SOFTWARE REQUIREMENTS

One of the main advantages to implementing a software defined radio system is the ability to do all signal processing in the digital realm. This not only allows for a variety of different digital signal processing algorithms to analyze the radio signal quickly, but also provides the ability to capture RF signals from across a large spectrum and disseminate the data in that spectrum immediately or at a later time. A disadvantage doing this is that it requires a large amount of processing power in order to analyze a signal with a large bandwidth. Current hobbyist SDR kits include software designed specifically with amateur radio (HAM) users in mind. Currently, no known software has been developed with radio astronomy as its primary focus. Because of this, several specifications have been proposed to develop SDR software with the radio astronomer in mind.

Section 3.1: General Specifications:

The software must be able to run on a mid-range laptop running Microsoft Windows. The software should have compatibility with Windows XP, Vista, and 7. Because of the amount of data being transferred, a USB 2.0 port will be required on the laptop (see Section 3.4). The software should be able to run smoothly and process live data on a laptop running a 2GHz, dual-core processor with 2 GB of RAM. The software should be able to either run as a standalone executable or be installed with an installer package.

Section 3.2: Software Modes of Operation Specifications:

To aid amateur radio astronomers, the software will have four basic modes of operations. Those modes are as follows:

- Real Time
- Radio Astronomy
- Full Record
- Data Analysis

In “Real Time” mode, live or previously recorded data is processed into an audio signal and played in real time. The user should be able to select what portion of the total 1MHz bandwidth should be mixed to audio. This means the user should be able to adjust the center frequency and bandwidth of the audio signal, as well as the resulting audio bitrate. Also, the processed audio streams can optionally be recorded and saved to the hard drive or other storage media. While in “Real Time” mode, the software should also plot frequency vs. time vs. signal strength. Time will be plotted on the x-axis, frequency will be plotted on the y-axis, and signal strength will be shown in color on the resulting plot. The user should be able to save the plots as a picture (ie. JPEG, bitmap, etc.).

The “Radio Astronomy” mode gives the user the ability to plot a live or previously recorded data by taking the integrated RMS average over the entire 1MHz bandwidth and plotting this average over time. The integration time should set at a constant 10ms. The user should also be able to export the averaged data in a parsable format (ie. CSV).

The “Full Record” mode will save all unprocessed, digitized I and Q streams to a WAV format. Channel 0 of the WAV file will contain the I stream, channel 1 will contain the Q stream. The user should be able to configure how much data the program should store. The user should be able to select whether a buffer should be used to only store a certain amount of data, or whether the program should continue to record until out of disk space. Also while in “Full

Record” mode, a plot should be displayed showing time on the x-axis, frequency on the y-axis, and signal strength in color.

The “Data Analysis” mode will give the user the ability to analyze previous recorded I/Q data recorded in “Full Record” mode in “Radio Astronomy” mode.

Section 3.3: Time Stamp Specification

If any astronomical events are recorded with this system, it is critical that the events are time stamped to accurately report the event. Therefore, it is required to time stamp data within 1 second of UTC. The software should prompt the user to determine if the system clock is accurate. If the user selects that the time is inaccurate, the software will prompt the user to correct the system clock, and will exit. The software should time stamp the first and last data sample and by knowing the data rate, extrapolate all other time stamps as needed.

Section 3.4: USB Connection

The software will need to communicate with the receiver over a USB 2.0 connection. USB 2.0 is required over USB 1.0 due to the high amount of data being transferred. The theoretical maximum data transfer rate of a single USB 2.0 controller is 480 Mbps. This transfer data applies to the controller, not individual devices. Therefore, each additional device attached to the controller will reduce the speed available to the receiver. The theoretical speed of the USB bus is further reduced due to the fact that 10%-15% of the peak data transfer rate goes to overhead in the USB protocol. Assuming a 16-bit analog to digital converter is used running at the minimum sample rate required (Nyquist frequency of 2MHz), data will have to be sent to the PC at a rate of 32Mbps. USB 1.0 cannot be used because the theoretical maximum data transfer rate of USB 1.0 is only 12 Mbps.

Section 3.5: GUI

It is required to implement a graphical user interface in order to present the user with different modes of operation, different ways of capturing the data, and options for what data should be captured or displayed. The GUI should have a file menu, toolbar, options area, and pane for displaying plots. Figure 3.1 shows a mockup of the GUI in "Real Time" mode. The user will be able to change the current mode of operation in the "Mode" file menu option. The options pane will be used to change various aspects of the plot and/or data stream, such as filtering, bandwidth, sample rate, etc.

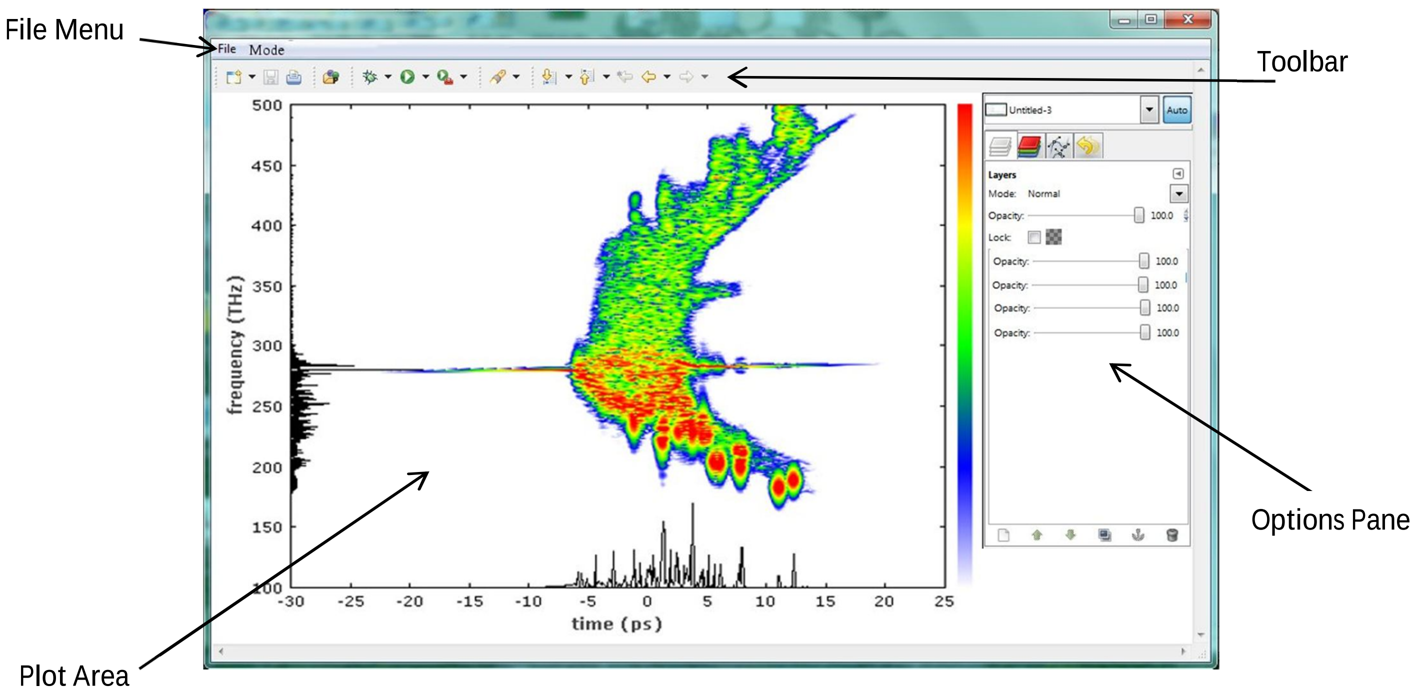

Figure 3.1: GUI Mockup in "Real Time" Mode

Appendix A: Summary Table of Requirements

Functionality	Target Value
Metal case	• Small enough to fit into a backpack. • Holes for USB shield, indicator LED's, antenna F-connector, audio out jack, adjustable gain, power switch, DC connector for charging. • Use Prefabricated Aluminum Case. • Not Required to be Weather Proof.
Antenna cable and connector	• RG6 75Ω impedance cable • Use female F-connector. • No material or impedance concerns.
Battery	• Must charge battery from 9V, 500mA AC to DC "wall wart" power supply. • Hold a charge for 2 hours minimum. • No power off of USB.
USB connection	• USB 2.0 • Should not provide power.
Time Stamps	• Time stamp first and last data point within 1 second of UTC. Extrapolate other time stamps.
Frequency measuring	• Receive signal with center frequency of 20.1 MHz • 1MHz Bandwidth
Audio output jack for testing operation	• Convert 10 kHz width signal directly to audio before ADC. • Head phone jack, tuning knob to change center frequency. • Center frequency can change from 19.6 MHz to 20.6 MHz with constant bandwidth of 10 kHz. • No accuracy requirement for center frequency or bandwidth. • Audio output is required to drive 30Ω load.
Adjustable gain for audio amplifier	• Both the center frequency and volume of the audio output should be adjustable by the user.
High dynamic range	• Minimum dynamic range of 100dB for RF front end.
Send time domain signal to PC for processing	• Send both I and Q components of signal to PC for processing.
Store unprocessed data as 2 channel WAV files	• Channel 0: I • Channel 1: Q
Automatic Gain Control	• Not allowed
Software must be able to plot received data.	• Must be able to plot frequency vs. time with intensity in color (waterfall chart). • Must be able to plot RMS average of signal power over 10ms window of entire 1MHz bandwidth versus time.

Software must be able to process signal to audio	• User must be able to select center frequency and bandwidth of audio output • Save audio output to uncompressed WAV.
Public release	• Must submit commented source code, schematics, gerber files, and board files at the end of the project.
Total cost of hardware	• <$200
Save output of radio astronomy mode	• User should be able to save picture of current plot. • As parsable format (ie. CSV or binary format).
Power indicator LED and power switch	• An LED is required to indicate power is being applied to the receiver. • An LED is required to indicate the battery is being charged.
Analog to Digital Converter	• Use of a 16-bit ADC running fast enough to sample 1MHz wide signal (at least 2Msps).