Open Source Radio Telescopes

Ellie White WHITE728@MARSHALL.EDU
Marshall University, 1 John Marshall Drive, Huntington, WV, 25755, USA

Richard Prestage RICHARD.PRESTAGE@GMAIL.COM
West Virginia University, White Hall, Box 6315, Morgantown, WV 26506

Evan Smith ETSMIT12@GMAIL.COM
West Virginia University, 1220 Evansdale Drive, PO Box 6109, Morgantown, West Virginia 26506

Pranav Sanghavi PRNV.SNGHV@GMAIL.COM
West Virginia University, 1220 Evansdale Drive, PO Box 6109, Morgantown, West Virginia 26506

Abstract

Open Source Radio Telescopes (OSRT) is a new educational program which aims to inspire students of all ages to pursue science, technology, engineering and mathematics (STEM) by providing them hands-on opportunities to construct and observe with simple radio telescopes. OSRT makes open source software, hardware, instructions, and curricula available online at www.opensourceradiotelescopes.org, and is in the process of developing kits of radio telescope construction supplies to distribute to classrooms for students ranging from middle-school to undergraduate-level. OSRT has developed two simple projects to date: the small loop antenna, which can detect solar flares by monitoring changes in the signal strength of VLF submarine transmission signals, and the horn antenna, which can detect and map the neutral hydrogen (HI) gas distributed throughout the Milky Way. Both of these projects make use of GNU Radio for their digital signal processing (DSP) pipelines. The straightforward and visual nature of GNU Radio Companion (GRC) flowgraphs makes GNU Radio an ideal teaching tool to show students how signal processing and computer science works, and therefore it is a vital tool for helping OSRT achieve its goal: showing students that technical topics – like engineering, programming, physical science, and mathematics – are accessible to them, therefore opening doors for students to find their passions and pursue a future in these rewarding and lucrative fields.

1. Introduction

There are many reasons to pursue science, technology, engineering and mathematics (STEM) outreach programs. One is that, as STEM advocates and professionals, we find these subjects fascinating, and we wish to share our enjoyment of them. Another is that a highly-developed STEM workforce is required for the US to be competitive in the global economy: STEM outreach programs are required to attract students to these areas, and to help them develop the skills they need to be successful in them. Educators have been using robotics as a mechanism to attract middle and high school students to STEM fields for over fifteen years (Mauch, 2001; Shin et al., 2017), and competitions, camps, and after-school robotics clubs have become extremely popular (Welch & Huffman, 2011; Nugent et al., 2016). But, while aerial drones and autonomous vehicles are becoming a reality, as yet few students regularly encounter them in their day-to-day lives. In contrast, how many students do not have a cell phone in their pocket, and a streaming device in their bedroom? How many adults do not use a wireless key-fob? The advanced digital signal processing (DSP) algorithms running in these commodity devices are a fundamental part of modern life. Such signal processing techniques are vital across a wide range of areas, including not only communications, but also vision-based navigation, remote sensing, computerized tomography, bio-medical engineering, radar and sonar, and signal processing for security. Yet, while the majority of the general public are aware of robotics as an idea, the concept of “digital signal processing” is extremely esoteric. One aim of the OSRT program is to address this lack of familiarity by developing STEM outreach projects which use cheap ($100 - 200), readily available (from a local hardware store) materials, and which have direct and compelling STEM outcomes, such as observing solar flares, or making maps of our own Galaxy. We provide the DSP components –

Proceedings of the 8^{th} *GNU Radio Conference*, Copyright 2018 by the author(s).

hardware and software – initially as one simple and (hopefully) accessible component of the complete system. Once students have become interested in, and familiar with the basic DSP building blocks that they are using, we can introduce progressively more advanced concepts. Rather than, or as well as, a robotics club, our vision is a DSP club – which might be called the "radio telescope club"– in every high school.

2. The OSRT Projects

As part of the OSRT program, we envisage a series of progressively more complex projects, including:

A simple FM Radio. A simple aerial, RTL-SDR[1] dongle, and a laptop running existing software and is the most basic introduction to software defined radio (SDR) which includes a hardware component.

Small Loop Antenna. A magnetic loop antenna can be used to detect VLF submarine communication signals and, via their effects on the ionosphere, solar flares.

Neutral Hydrogen (HI) Horn Antenna. A simple horn antenna – including a low noise amplifier (LNA) and all other electronics components – can be constructed for a few hundred dollars and is powerful enough to detect 21cm radiation from neutral hydrogen (HI) in the plane of the Milky Way. By measuring the Doppler shift of the HI line emission in different directions, it is possible to trace the spiral arm structure of the Milky Way galaxy, and by comparing observations with simple Newtonian theory, infer the existence of dark matter.

Dish Antenna. Old $\sim$ 10-ft satellite dishes can be used for a wide variety of projects.

Two-element Interferometer. The basic interferometer is a pair of radio telescopes whose voltage outputs are correlated (multiplied and averaged). Interferometers now play a dominant role in observational radio astronomy; a simple two-element system can be used to investigate the key concepts.

Large transit telescopes. Designs exist for large ($\sim$ 15m), comparatively cheap ($\sim$ \$5-10k) cm-wave transit radio telescopes. These might be used to detect new classes of radio transient, such as the so-called "fast radio bursts" (Petroff et al., 2016).

None of these projects are new. The simple FM radio is a staple of SDR projects. Sudden ionospheric disturbance monitors have been distributed by the Stanford Solar Center (Scherrer et al., 2008), while the MIT Haystack Observatory have developed a number of small radio telescopes (Patel et al., 2014). Our goal with OSRT is to make these projects as accessible as possible, including comprehensive parts lists (and in some cases, complete kits) and constructions manuals. In particular, we are developing lesson plans and other teaching material, suitable for use from middle school classrooms up to undergraduate level, as well as for self-directed study.

Two of these projects, the small loop antenna and the HI horn antenna, are described in more detail below.

2.1. Small Loop Antenna

The small loop antenna is very simple to construct and is therefore well-suited for use by students from middle school upwards. The loop antenna is capable of detecting solar activity by monitoring changes in the signal strength of Very Low Frequency (VLF) submarine communications signals at 24 kHz (similar to the Stanford SuperSID antenna). The antenna itself is made up of several turns of magnet wire wound around a square PVC or wooden frame (Figure 1). The magnetic field component of the VLF radio signal induces a current in the coiled loops of wire, which is then processed by a printed circuit board (PCB) designed by engineers at the Green Bank Observatory (GBO), which tunes and amplifies the signal. This circuit is essentially an LC circuit, and so is ideal for demonstrating resonant circuits and the relationship between inductors and capacitors. By connecting the antenna to a spectrum analyzer and function generator, it is possible for students to learn to measure the Q effect of the antenna and quantify how well-tuned the LC circuit is. The output of the PCB is transferred via a coax cable to a "Ham It Up" upconverter available commercially from NooElec, which increases the frequency of the VLF signal by 125 MHz, so that it is within the working frequency range of an RTL-SDR dongle. The RTL-SDR creates digital I/Q samples which are then processed and recorded by a GRC flowgraph. The flowgraph is supplemented with a secondary, separate Python program which

Figure 1. A small loop antenna

---

[1] https://www.rtl-sdr.com/

displays spectral line (Figure 2) and time series (Figure 3) plots from the recorded data. By analyzing these plots, the student can learn what VLF stations are being detected, and how the station's signal levels are changing over time. Features in the time series plot can be caused by a number of different effects – sunrise and sunset can cause dips or spikes in intensity, interference can cause spikes, and solar activity can cause distinctive intensification of the VLF signal. By analyzing the data students record themselves, they can learn about the physical properties of the ionosphere, the reflection and propagation of radio waves, and how to troubleshoot and isolate sources of interference.

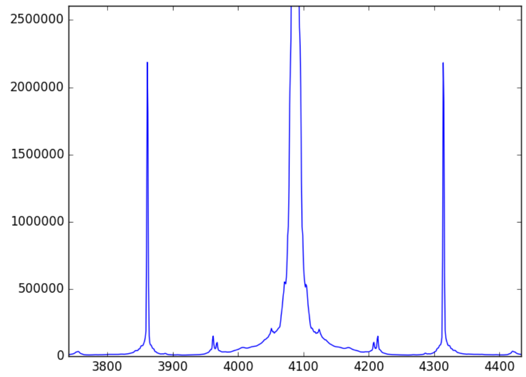


Figure 2. A loop antenna spectral line plot

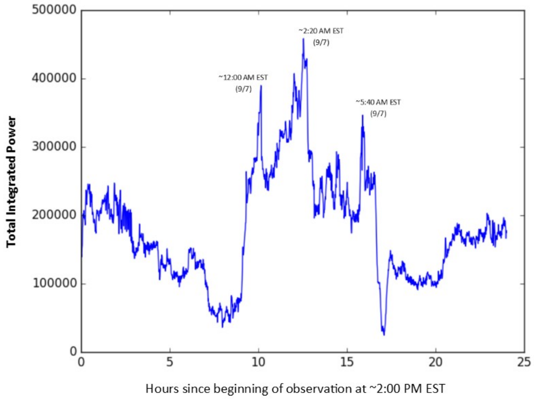


Figure 3. A loop antenna time series

2.2. The HI Horn Antenna

A fully functional radio astronomy observatory system (Figure 4) comprises an inexpensive horn antenna (Figure 5) tuned for neutral hydrogen detection, a low noise amplifier (LNA), an SDR dongle to act as a mixer and digitize the signal, and a GRC back-end flowgraph. As part of the OSRT project, we are distributing kits including all of the electronics components, including the SDR dongle and, most importantly, a state-of-the-art room-temperature LNA designed by Dr. Kevin Bandura of West Virginia University[2]. The remaining components for the antenna are cheaply available from any hardware store.

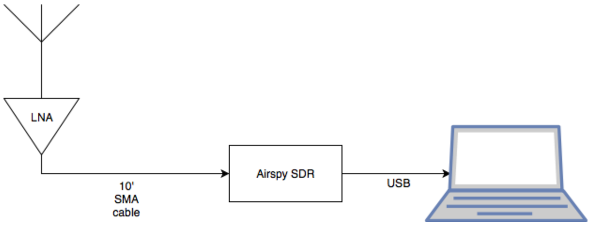


Figure 4. A radio astronomy observatory system

The design of the horn is reminiscent of the design Ewen and Purcell used for the initial detection of Galactic neutral hydrogen – the first spectral line ever observed in radio astronomy (Ewen & Purcell, 1951). Our design was driven two critical constraints – portability and cost. The antenna should be portable enough such that at its fully assembled configuration it can fit through a standard door, and it should be constructed out of easilt obtainable tools and material. The collecting horn is a four-sided open pyramid made out of home insulation Styrofoam boards with a metallic reflective lining. It is capped by a rectangular "L-band waveguide" made from a rectangular paint thinner can (which could be an old used one or a new empty can). The radio frequency signal is picked up by a quarter wave probe from within the can. The horn is mounted on a wooden base which is capable of adjustment in elevation (Figure 5). The signal from the horn is amplified using the custom-designed LNA. The amplified signal is sent to an SDR dongle where the signal is mixed down and digitized to be interpreted by the DSP software.

2.2.1. SOFTWARE

The digital signal processing of the digitized radio frequency signal is imperative for the OSRT program. The open source nature, the flexibility and the visual programming aspect of GNU Radio makes it an ideal platform. One can use several user designed radio astronomy software packages based in GNU Radio, for example `simple_ra` among others, to facilitate acquisition and processing of the radio signal. However, we make use of the software developed as part of the Digital Signal Processing in Radio Astronomy (DSPIRA) program, described in more detail in Section 3.1. This software allows users to build a radio astronomy software package from first principles, while also

---

[2] `https://github.com/WVURAIL/os_radio_astro_hw`

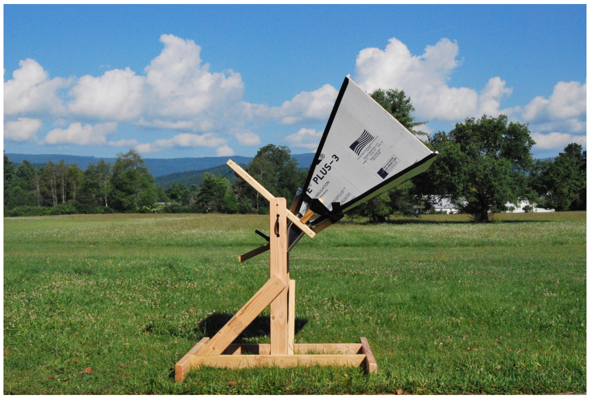


Figure 5. The HI Horn antenna

exploring the required DSP concepts along the way.

The core of the flowgraph is a Fourier Transform spectrometer (Figure 6). Salient features include a polyphase filter bank to improve channelization and custom designed "out-of-tree" modules to help with data display and data reduction[3]. These horns can be used for a slew of radio astronomy experiments including mapping the neutral hydrogen (HI) in the Galaxy, as demonstrated in Figure 8.

3. Educational Activities

One of the main aims of the OSRT program is not simply to provide open source hardware designs, but also to provide a rich set of accompanying educational material, including lesson plans and classroom activities.

3.1. Research Experience for Teachers – Digital Signal Processing in Radio Astronomy

Digital Signal Processing in Radio Astronomy (DSPIRA) is a National Science Foundation (NSF) Research Experiences for Teachers (RET) in Engineering and Computer Science at the West Virginia University Lane Department of Computer Science and Electrical Engineering. It is a six-week summer program, followed by in-class academic year activities, that leverages the ease and flexibility of the open source GNU Radio software to systematically dispense DSP concepts at a level accessible to high school teachers. This allows them in turn to demonstrate these concepts to their students, within the context of radio astronomy. This program has been in effect since 2017 and has had two sessions since then. The hands on approach to DSP training, and the broader context of radio astronomy, equip teachers to conduct several lessons and activities in their classrooms. Astronomy projects like the aforementioned Galaxy mapping, measuring the rotation curve of the Milky Way Galaxy and tangible demonstrations of red/blue shifted spectral lines, can be implemented out-of-the-box.

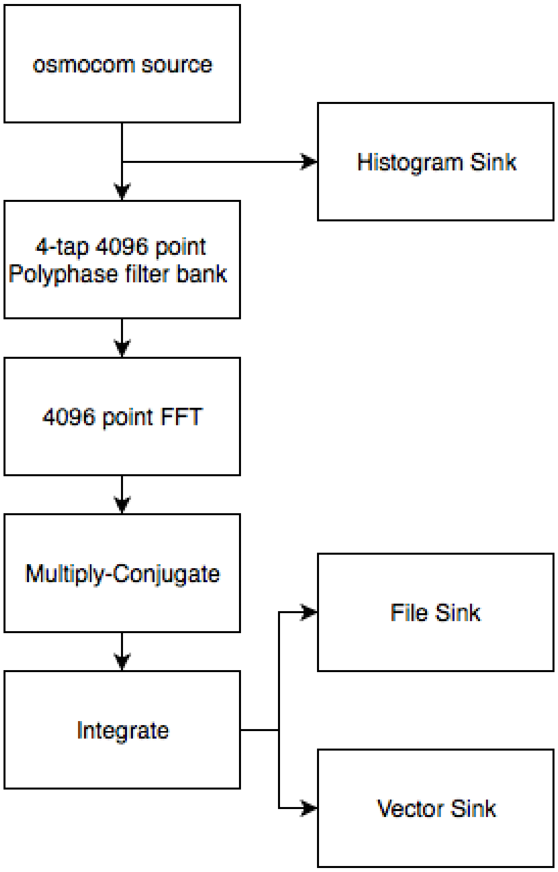


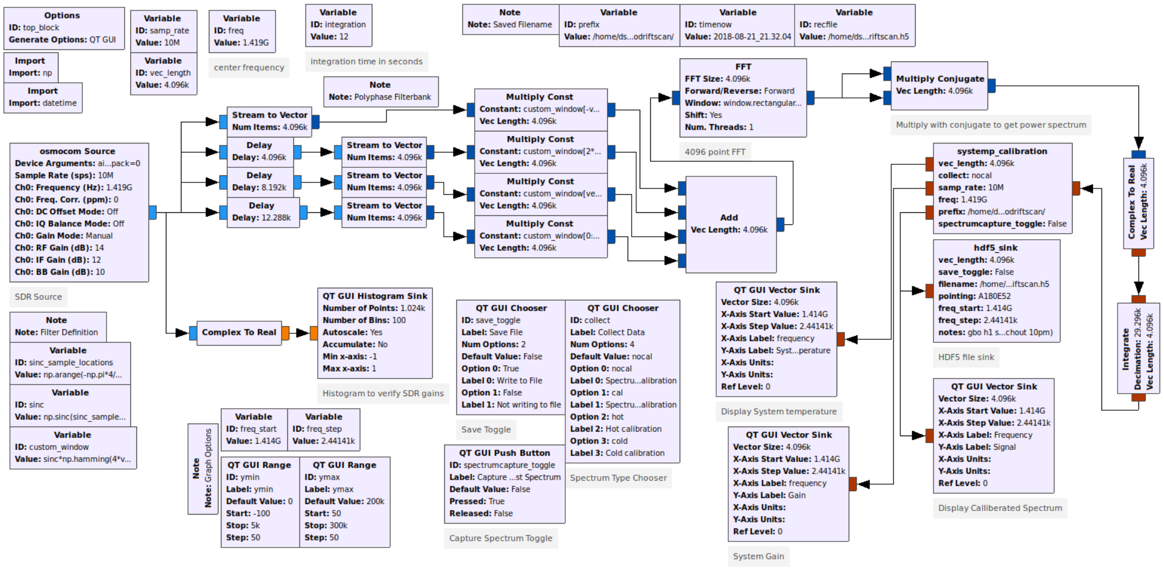
Figure 6. The Signal flow of the DSP backend

This program also brings the expansive tool-set offered by GNU Radio to high school through the participating teacher. They could adapt the contents of the DSPIRA training labs. This would allow them to explain complicated mathematical concepts using interactive GNU Radio demonstrations. Figure 9 shows an example of such a program developed by teacher Howard Chun of DSPIRA to demonstrate the basic fundamentals of Fourier analysis. In the context of radio astronomy such an activity proves extremely beneficial as a mechanisms to gain an intuitive understanding of spectroscopy. The visual programming aspect of GNU Radio Companion allows for the implementation of several DSP projects without imposing the burden of advanced mathematics on high school students.

Moreover, the entire telescope system comprises of projects from numerous engineering domains including electronics, radio frequency engineering, digital signal processing, computer science, mechanical engineering and shop work, all of which can be implemented in a classroom

---

[3] https://github.com/WVURAIL/gr-radio_astro



Options
ID: top_block
Generate Options: QT GUI

Import
Import: np

Import
Import: datetime

Variable
ID: samp_rate
Value: 10M

Variable
ID: vec_length
Value: 4.096k

Variable
ID: freq
Value: 1.419G

center frequency

Variable
ID: integration
Value: 12

integration time in seconds

Note
Note: Saved Filename

Variable
ID: prefix
Value: /home/ds...odriftscan/

Variable
ID: timenow
Value: 2018-08-21_21.32.04

Variable
ID: recfile
Value: /home/ds...riftscan.h5

Note
Note: Polyphase Filterbank

osmocom Source
Device Arguments: ai...pack=0
Sample Rate (sps): 10M
Ch0: Frequency (Hz): 1.419G
Ch0: Freq. Corr. (ppm): 0
Ch0: DC Offset Mode: Off
Ch0: IQ Balance Mode: Off
Ch0: Gain Mode: Manual
Ch0: RF Gain (dB): 14
Ch0: IF Gain (dB): 12
Ch0: BB Gain (dB): 10

SDR Source

Stream to Vector
Num Items: 4.096k

Delay
Delay: 4.096k

Delay
Delay: 8.192k

Delay
Delay: 12.288k

Stream to Vector
Num Items: 4.096k

Stream to Vector
Num Items: 4.096k

Stream to Vector
Num Items: 4.096k

Multiply Const
Constant: custom_window[-v...
Vec Length: 4.096k

Multiply Const
Constant: custom_window[2*...
Vec Length: 4.096k

Multiply Const
Constant: custom_window[ve...
Vec Length: 4.096k

Multiply Const
Constant: custom_window[0:...
Vec Length: 4.096k

Add
Vec Length: 4.096k

FFT
FFT Size: 4.096k
Forward/Reverse: Forward
Window: window.rectangular...
Shift: Yes
Num. Threads: 1

4096 point FFT

Multiply Conjugate
Vec Length: 4.096k

Multiply with conjugate to get power spectrum

Complex To Real
Vec Length: 4.096k

Integrate
Decimation: 29.296k
Vec Length: 4.096k

systemp_calibration
vec_length: 4.096k
collect: nocal
samp_rate: 10M
freq: 1.419G
prefix: /home/d...odriftscan/
spectrumcapture_toggle: False

hdf5_sink
vec_length: 4.096k
save_toggle: False
filename: /home/...iftscan.h5
pointing: A180E52
freq_start: 1.414G
freq_step: 2.44141k
notes: gbo h1 s...chout 10pm)

HDF5 file sink

QT GUI Vector Sink
Vector Size: 4.096k
X-Axis Start Value: 1.414G
X-Axis Step Value: 2.44141k
X-Axis Label: frequency
Y-Axis Label: Syst...perature
X-Axis Units:
Y-Axis Units:
Ref Level: 0

Display System temperature

QT GUI Vector Sink
Vector Size: 4.096k
X-Axis Start Value: 1.414G
X-Axis Step Value: 2.44141k
X-Axis Label: frequency
Y-Axis Label: Gain
X-Axis Units:
Y-Axis Units:
Ref Level: 0

System Gain

QT GUI Vector Sink
Vector Size: 4.096k
X-Axis Start Value: 1.414G
X-Axis Step Value: 2.44141k
X-Axis Label: Frequency
Y-Axis Label: Signal
X-Axis Units:
Y-Axis Units:
Ref Level: 0

Display Calliberated Spectrum

Note
Note: Filter Definition

Variable
ID: sinc_sample_locations
Value: np.arange(-np.pi*4/...

Variable
ID: sinc
Value: np.sinc(sinc_sample...

Variable
ID: custom_window
Value: sinc*np.hamming(4*v...

Complex To Real

QT GUI Histogram Sink
Number of Points: 1.024k
Number of Bins: 100
Autoscale: Yes
Accumulate: No
Min x-axis: -1
Max x-axis: 1

Histogram to verify SDR gains

Note
Note: Graph Options

Variable
ID: freq_start
Value: 1.414G

Variable
ID: freq_step
Value: 2.44141k

QT GUI Range
ID: ymin
Label: ymin
Default Value: 0
Start: -100
Stop: 5k
Step: 50

QT GUI Range
ID: ymax
Label: ymax
Default Value: 200k
Start: 50
Stop: 300k
Step: 50

QT GUI Chooser
ID: save_toggle
Label: Save File
Num Options: 2
Default Value: False
Option 0: True
Label 0: Write to File
Option 1: False
Label 1: Not writing to file

Save Toggle

QT GUI Chooser
ID: collect
Label: Collect Data
Num Options: 4
Default Value: nocal
Option 0: nocal
Label 0: Spectru...alibration
Option 1: cal
Label 1: Spectru...alibration
Option 2: hot
Label 2: Hot calibration
Option 3: cold
Label 3: Cold calibration

Spectrum Type Chooser

QT GUI Push Button
ID: spectrumcapture_toggle
Label: Capture ...st Spectrum
Default Value: False
Pressed: True
Released: False

Capture Spectrum Toggle

Figure 7. GNURadio Flow graph of a Radio Astronomy Spectrometer backend – built ground up from first principles. There exist two out-of-tree modules: `hdf5_sink`, a file sink to save data in a standard `hdf5` format and `systemp_calibration`, a block developed by DSPIRA member Dr. John Makous to take hot and cold load calibration readings to display and save the calibrated signal on the fly.

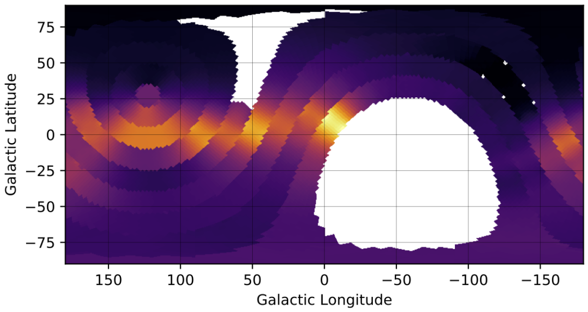


Figure 8. A drift scan map of the neutral hydrogen in the Galaxy made from data collected from DSPIRA horn antennas

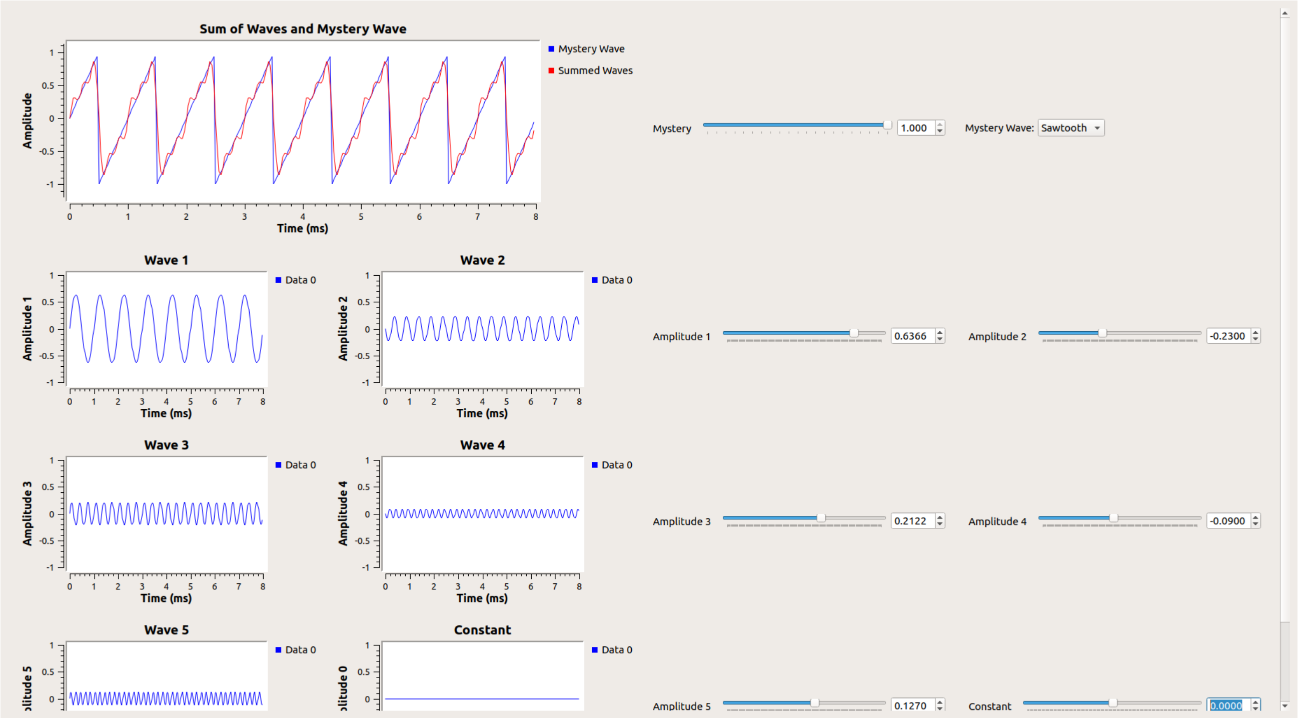
setting, exposing students to cutting edge science and engineering at an early stage, with minimal cost. A simple DSP classroom lesson can be prepared, as seen in Table 1, complying with education standards such as the West Virginia Next Generation of Content Standards and Objectives.

3.2. Loop Antennas in West Virginia Schools A Pilot Project

The loop antenna project is very well-suited to a classroom environment, and another way OSRT is implementing its educational goals in addition to the RET program is through a collaborative effort with Marshall University to bring radio astronomy to public middle schools and high schools in West Virginia. Lesson plans and supplementary materials are being prepared which will educate students on the topics needed to understand how to build and observe with a loop antenna and how to interpret their scientific results, and these curricula as well as loop antenna kits will be provided to science teachers who will use these materials in their classrooms. Students who are taught from the loop antenna curriculum will gain exposure to topics including but not limited to: the electromagnetic spectrum, multi-wavelength astronomy, elements of circuits, basic programming, analog-to-digital conversion, digital signal processing, stellar evolution, properties of the Sun, data analysis, science writing, and presentation skills. The pilot project described here will lay the groundwork for later incorporating the loop antenna curricula and kits into more West Virginia public schools science classrooms.

4. Conclusions

The Open Source Radio Telescopes project is a new educational and public outreach endeavour to inspire students to explore math, science, engineering and technology. We have several astronomy projects available, including a very low-frequency loop antenna that can measure the disturbances of the ionosphere and a horn antenna capable of collecting the radio emission of neutral Hydrogen in our Milky Way Galaxy. We collaborate with DSPIRA, which hosts a six-week long digital signal processing themed RET for high school teachers, using GNU Radio as the DSP development environment. This experience equips the teachers with engineering and astronomy based lesson plans and activities, which in turn provides a rich source of educational material for the OSRT project.



Mystery 1.000
Mystery Wave: Sawtooth
Amplitude 1 0.6366
Amplitude 2 -0.2300
Amplitude 3 0.2122
Amplitude 4 -0.0900
Amplitude 5 0.1270
Constant 0.0000

Figure 9. A DSP activity designed in GNU Radio to demonstrate Fourier Analysis in a simple interactive fashion.

Table 1. Class learning objective analysis for a classroom DSP unit prepared by DSPIRA member Alexis Emch `https://v2.overleaf.com/project/5b6b26018244444b037a2c13`

WV.s.9.ESS.2 **Space Systems**	Construct an explanation of the Big Bang theory based on astronomical evidence of light spectra, motion of distant galaxies, and composition of matter in the universe.
NGSS.HS.ETS.1-4 **Cross Cutting Concepts Engineering .and Technology**	Models (e.g., physical, mathematical, computer models) can be used to simulate systems and interactions – including energy, matter, and information flows – within and between systems at different scales.
Classroom Learning Objectives	Identify astronomical evidence (composition of matter) in the universe. Evaluate observed radiation for ordinary matter (universe) for HI.

5. Acknowledgements

The ORST project builds on the work of many of predecessors including, amongst others, the MIT Haystack Observatory and the work of Dr. Glen Langston. We happily acknowledge the support of Dr. Kevin Bandura and the West Virginia University Radio Astronomy Instrumentation Laboratory[4] for the development of the LNAs used in these projects, and Steve White, J.D. Nelson, and Bob Simon for designing and producing the PCB for the loop antenna, DSPIRA is supported through the National Science Foundation RET EEC 1611114. Financial support for the horn antenna electronics kits has been provided by the West Virginia University Center for Gravitational Waves and Cosmology[5], and components for the loop antenna kits have been provided by Nooelec Inc[6].

References

Ewen, Harold Irving and Purcell, Edward Mills. Observation of a line in the galactic radio spectrum: Radiation from galactic hydrogen at 1,420 mc./sec. *Nature*, 168 (4270):356, 1951.

Mauch, Elizabeth. Using technological innovation to improve the problem-solving skills of middle school students: Educators' experiences with the lego mindstorms robotic invention system. *The Clearing House*, 74(4): 211–213, 2001.

Nugent, Gwen, Barker, Bradley, Grandgenett, Neal, and Welch, Greg. Robotics camps, clubs, and competitions: Results from a us robotics project. *Robotics and Autonomous Systems*, 75:686–691, 2016.

Patel, Nimesh A, Patel, Rishi N, Kimberk, Robert S, Test, John H, Krolewski, Alex, Ryan, James, Karkare, Kirit S, Kovac, John M, and Dame, Thomas M. A low-cost 21 cm horn-antenna radio telescope for education and outreach. In *American Astronomical Society Meeting Abstracts# 224*, volume 224, 2014.

Petroff, E, Barr, ED, Jameson, A, Keane, EF, Bailes, M, Kramer, M, Morello, V, Tabbara, D, and van Straten, W. Frbcat: the fast radio burst catalogue. *Publications of the Astronomical Society of Australia*, 33, 2016.

Scherrer, Deborah, Cohen, Morris, Hoeksema, Todd, Inan, Umran, Mitchell, Ray, and Scherrer, Philip. Distributing space weather monitoring instruments and educational materials worldwide for ihy 2007: The awesome and sid project. *Advances in Space Research*, 42(11):1777–1785, 2008.

Shin, Robert, Karaman, Sertac, Ander, Ariel, Boulet, Michael T, Connor, Jane, Gregson, Kenneth L, Guerra, Winter, Guldner, Owen R, Mubarik, Mohamound, Plancher, Brian, et al. Project based, collaborative, algorithmic robotics for high school students: Programming self driving race cars at mit. Technical report, MIT Lincoln Laboratory Lexington United States, 2017.

Welch, Anita and Huffman, Douglas. The effect of robotics competitions on high school students' attitudes toward science. *School Science and Mathematics*, 111(8):416–424, 2011.

---

[4] `http://wvurail.org/`

[5] `https://gwac.wvu.edu/`

[6] `http://www.nooelec.com/store/`