

# HEPCAT Dark Radio Day 1

June 21, 2023

## 1 Overview of Spectrum Analyzers

A spectrum analyzer displays frequency versus magnitude of an input signal. The origin of the signal is generally electromagnetic although it can be anything with the appropriate transducer. A spectrum analyzer can be used to do various analyses of the spectra of an incoming signal including measuring power, harmonics, distortion, etc. These measurements may not be easily made in the time domain. In general, spectrum analyzers appear physically similar to oscilloscopes. However, on a spectrum analyzer the y-axis shows the power and the x-axis shows the frequency while on an oscilloscope y-axis shows the voltage and the x-axis shows time. The spectrum analyzer will be at the heart of the data acquisition that we perform for this lab.

### 1.1 Types

There are two main types of spectrum analyzer: Swept-tuned and real-time.

#### 1.1.1 Swept-tuned analyzers

A swept-tuned analyzer is an automatically tuned frequency-selective voltmeter. Inside, a superheterodyne receiver down-converts a portion of the input signal to the center of a narrow

band-pass filter, whose instantaneous output power is displayed as a function of time.<sup>1</sup> A swept-tuned analyzer only displays magnitude information of the incoming signal not phase.

### 1.1.2 Real-time analyzers

As the name suggests, real-time analyzers are able to take in signals and display them in real-time. They do this by taking the discrete Fourier transform of the incoming signal [generally using the Fast Fourier Transform (FFT) algorithm]. Unlike swept-tuned analyzers, real-time analyzers can display both magnitude and phase information of the spectral components of the time-domain signal. However, for this lab, we will not be dealing with phase.

## 1.2 Units

Frequently, a spectrum analyzer will display the amplitude not in linear units (like volts or watts) but in logarithmic units. Displaying on a logarithmic scale resolves issues of displaying values that span many orders of magnitude, which can skew visualizations when displayed on a linear scale. Generally, amplitudes are given in *dB* or decibels. For power quantities, a decibel is defined as

$$P_{dB} = 10\log_{10} \left( \frac{P_{lin}}{1 \text{ watt}} \right) \quad (1)$$

where  $P_{dB}$  indicates the power quantity in dB and the  $P_{lin}$  represents the power in watts. Similarly, for voltage quantities,

$$V_{dB} = 20\log_{10} \left( \frac{V_{lin}}{1 \text{ volt}} \right) \quad (2)$$

where  $V_{dB}$  indicates the voltage quantity in dB and the  $V_{lin}$  represents the voltage in volts. Note that the 20 leading the  $V_{dB}$ . This comes about because  $P \propto V^2$  so  $\log_{10}(P) \propto 2\log_{10}(V)$ .

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<sup>1</sup>Superheterodyning is a process in which an incoming signal is mixed with a local oscillator to produce an intermediate frequency that is easier to process than the original signal.

It is also common to append prefixes onto the logarithmic quantities to reference powers to different values. For example, you will likely see  $dBm$ , which is defined by

$$P_{dBm} = 10\log_{10} \left( \frac{P_{lin}}{1 \text{ milliwatt}} \right) \quad (3)$$

Common reference values are  $dBm$  (milliwatt),  $dBmV$  (millivolt), and  $dB\mu V$  (microvolt). Note that it is also common to write  $dBV$  when describing voltage quantities to make it clear that the value is not a power quantity.

### 1.3 Comment on the Frequency Spectrum

A spectrum analyzer takes a time domain signal and converts it into the frequency domain. An example of such an operation is shown in Figure 1. Notice that the power of the signal in the time domain is equal to the power of the signal in the frequency domain. This is an example of Parseval's theorem, which says that the (discrete) Fourier transform is power preserving. This is a nice result because it means that the units in the frequency domain are the same as the units in the time domain.<sup>2</sup>

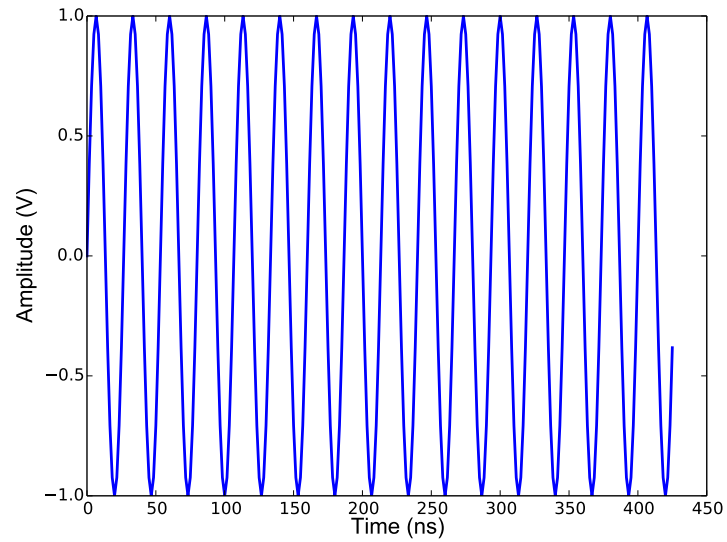
Notice that the discrete Fourier transform of a sine wave is a  $\delta$ -function. This is because the Fourier transform is taking a function and re-writing it in terms of a set of sinusoids. For more information about the discrete Fourier transform refer to [1, Chapter 8]. However, you will notice that the baseline on a spectrum analyzer does not just look like a  $\delta$ -function as you see in Figure 1. There is also a lot of baseline noise. The height of the signal of interest above the noise floor is called the signal-to-noise ratio or SNR.

This noise floor is a result of wide-bandwidth noise that gets combined with the signal of interest. A simulated example is shown in Figure 2 where additive white noise is added to the

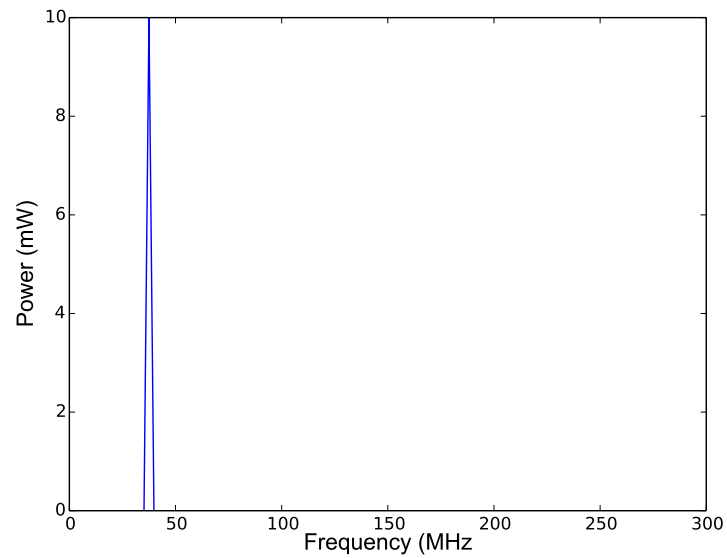
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<sup>2</sup>Specifically, Parseval's theorem says that for a discretely sampled signal  $x[n]$  of length  $N$ , that  $\sum_{n=0}^{N-1} |x[n]|^2 = \sum_{k=0}^{N-1} |X[k]|^2$ , where  $X[k]$  is the discrete Fourier transform of  $x[n]$  and also has length  $N$ .

sine wave. Notice how this compares to what you see on the spectrum analyzer.



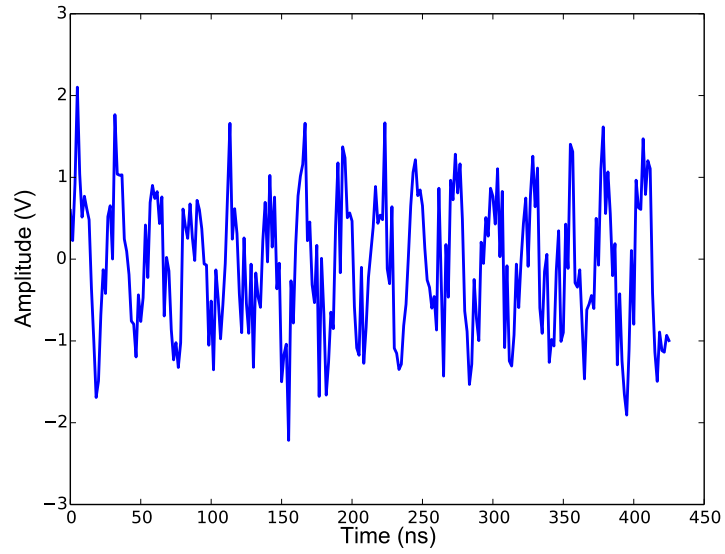
(a) Time domain



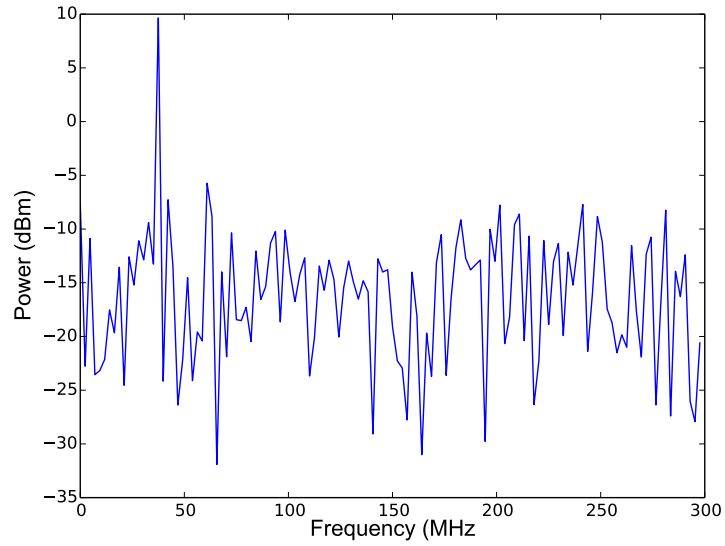
(b) Frequency domain

Figure 1: (a) Example of a 37.5 MHz sine wave sampled at 600 MHz. (b) A 256-point discrete Fourier transform of this sine wave. Notice that the power of the signal is preserved.





(a) Time domain



(b) Frequency domain

Figure 2: (a) Example of a 37.5 MHz sine wave sampled at 600 MHz with some additive white noise. (b) A 256-point discrete Fourier transform of this sine wave. Notice that the y-axis units are now in dBm. The signal-to-noise ratio of this signal is approximately 11.4 or 10.6 dB.

## **2 Important Spectrum Analyzer Quantities**

### **2.1 Resolution Bandwidth**

Qualitatively, resolution bandwidth (RBW) gives you the minimum separation between two frequency components in order to be able to visually resolve them. For a swept-tuned analyzer, RBW defines the bandwidth of the intermediate frequency (IF) filter that acts on the mixed down signal. For a real-time spectrum analyzer, the resolution bandwidth is defined by the length of the acquisition.

### **2.2 Video Bandwidth**

The video bandwidth is a property of swept-tuned analyzers. It sets the bandwidth of a low-pass filter that acts as a moving average to smooth the trace and reduce noise. It can be useful to improve the signal to noise ratio of weak signals.

### **2.3 Trace Type**

The trace type calculates a trace to be displayed from the sampled data. There are several trace types to choose from (not exhaustive):

#### **2.3.1 Clear Write**

Erases any data previously stored in the bucket and continuously updates any signals according to the trace detector during the sweep of the analyzer.

#### **2.3.2 Average**

Displays an average trace, by averaging the data from each displayed point on the trace.

### **2.3.3 Max Hold**

Shows the maximum value for each point in the trace. Only gets updated when a new maximum value is generated.

### **2.3.4 Min Hold**

Shows the minimum value for each point in the trace. Only gets updated when a new minimum value is generated.

## **2.4 Trace Detector**

A spectrum analyzer doesn't display all the points it acquires. Rather, it collects points into buckets and displays a certain number of buckets. The data that is displayed can be set as the following (this list is not exhaustive):

### **2.4.1 Positive Peak**

As suggested, sets the output to the largest data point in the bucket.

### **2.4.2 Negative Peak**

As suggested, sets the output to the smallest data point in the bucket.

### **2.4.3 Normal**

Displays both positive and negative peaks depending on the number order of the buckets (e.g. if the bucket is even display the negative peak and if it is odd display the positive peak)

### **2.4.4 Sample**

Displays the median of the data in each bucket.

### 2.4.5 Average

Displays the average of all data points in a bucket. Averaging can be done in a few different fashions:

- Power (RMS) averaging

Calculates the average of the root-mean-squared values of each data point measured during the bucket interval. This is then converted to a power by squaring and dividing by the input impedance of the analyzer (normally  $50\Omega$ ).

- Voltage averaging

Calculates the average of the values of each data point measured during the bucket interval.

### 2.4.6 Quasi-peak detection

Performs a weighted form of peak detection. This is used in electromagnetic compatibility testing. Specifics of the weighting function used are defined in CISPR (Comité International Spécial des Perturbations Radioélectriques) 16-1-1.

## 3 Transmit and Receive Testing

While Sections 1 and 2 are not exhaustive, they should give you a good basis to get off the ground. We're going to start this lab by getting acquainted to basic data acquisition and spectral analysis. We have enough equipment to split up into two groups. Each group is going to be given a spectrum analyzer to use - either the Rigol RSA5065-TG (Rigol) or the Anritsu MS2721B (Anritsu). See Figure 3 for a picture of both spectrum analyzers. While they are different spectrum analyzers, they have similar functionality especially for the testing that we will be doing.



(a) Rigol RSA5065-TG



(b) Anritsu MS2721B

Figure 3: Pictures of the front faces of the Rigol RSA5065-TG and Anritsu MS2721B spectrum analyzers.

## 3.1 Calibration Testing

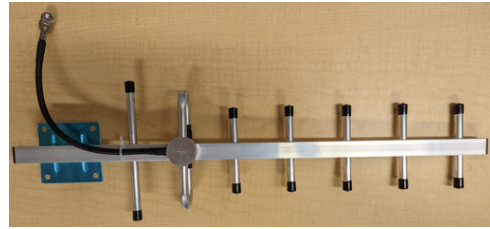
### 3.1.1 Measuring baseline power with terminated input

- Terminate the input to your spectrum analyzer with a  $50\Omega$  terminator.
- Set the center frequency to 200 MHz and the span to 100 MHz or set the start frequency to 150 MHz and the end frequency to 250 MHz
- Set RBW = VBW = 10 kHz
- Set the trace type to clear write on the Rigol / normal on the Anritsu
- Set trace detect to Sample
- Turn the RF preamp OFF
- Set the reference level to -80 dBm
- Set the scale per division to 5 dB
- Set the attenuation to 0 dB

- **Question 1: What is the average power level of the baseline (feel free to estimate)?**
- Now set the resolution bandwidth to 100 kHz
- **Question 2: What is the average power level of the baseline now? Does this make sense?**
- Now turn the RF preamp on.
- **Question 3: What is the average power level of the baseline now? Does this make sense?**
- Set the VBW to 10 kHz
- **Question 4: What was the effect of reducing the VBW?**
- Now set the VBW to 100 kHz
- Set the trace type to average
- Set the number of averages to 1
- If using the Rigol, set the average type to Log
- Now set the number of averages to 100 and note the difference in the standard deviation in the baseline
- **Question 5: What was the effect of averaging? How does it compare to setting the VBW?**



(a) Dipole Antenna



(b) Yagi Antenna

Figure 4: Pictures of the antennas that you will use to do your testing.



(a) Rigol DSG830



(b) Marconi 2022A

Figure 5: Pictures of the signal generators that you will use to do your testing.

### 3.1.2 Antenna Testing

Now that you have a better idea about the various settings on the spectrum analyzer, we can start to make some measurements. Each group will be given two antennas: A basic dipole antenna and a Yagi antenna. See [2, Chapter 5-2], [2, Chapter 11-9], and [3]. You will also be given a signal generator - either a Rigol DSG830 or a Marconi 2022A. For information on how to use these signal generators refer to Sections 4.3 and 4.4.

For these measurements, set the following on your spectrum analyzer:

- RBW: 10 kHz
- VBW: 10 kHz

- Attenuation: 0 dB
- RF Preamp: On
- Trace type: Average
- Trace detector: Sample
- Total averages: 10

Once you have done that, perform the following tests. Be careful when reporting the size of a signal that you correctly subtract the baseline from the signal. If dealing with logarithmic quantities, subtraction in log space is division in linear space. Specifically, given two powers  $P_{A/B}$  measured in logarithmic units,  $P_{A/B}^{\text{dB}}$ , or linear units,  $P_{A/B}^{\text{lin}}$ ,

$$P_A^{\text{dB}} - P_B^{\text{dB}} = 10 \log_{10} \left( \frac{P_A^{\text{lin}}}{P_B^{\text{lin}}} \right). \quad (4)$$

Subtraction of these quantities is given by

$$P_A^{\text{lin}} - P_B^{\text{lin}} = 10^{P_A^{\text{dB}}} - 10^{P_B^{\text{dB}}}. \quad (5)$$

At the end of these measurements, we'll discuss the results and see if they make sense. Do not worry about completing all the measurements. Pick ones that seem interesting and do those. Even feel free to try other things (e.g. set the spectrum analyzer to look for FM radio stations). The goal of this part of the lab is to give you a better sense of the equipment we are working with.

1. Separate the antennas by 1 m with their polarization axes aligned with each other. Set the transmit frequency around 915 MHz (don't overlap with the other group). Set the transmit power high enough that you see the signal at least 20 dB above the baseline. Set the span on your spectrum analyzer to see your signal. Record the measured power.



2. Repeat setting the RBW and VBW to 100 kHz
3. Set the RBW and VBW back to 10 kHz and repeat the above separating the antennas by 2 m.
4. Repeat the above for 3 m
5. Keeping the antennas 3 m apart, rotate the polarization of one antenna by 90°, and measure the received power.
6. Keeping the same polarization repeat for 1 m apart, and measure the received power.
7. Repeat step 1 with the same transmit power but with the transmit frequency set somewhere around 600 MHz (make sure not to overlap with the other group). Set the span to be 10 MHz.

Repeat all the above steps for two dipoles, two Yagis, and a dipole and a Yagi. For the dipole and Yagi test, switch transmit and receive for test number 1 and see if you get different results.

Figure 6 shows a plot of radiation intensity vs angle for a Yagi (red) versus a dipole (blue) antenna. Antenna gain is defined as the intensity (power per area) that would result if the same total power available at the antenna terminals were radiated isotropically over  $4\pi$  steradians. This is generally measured in dBi or *gain over isotropic*. For a half-wave dipole this is 2.15 dBi. The gain of a Yagi depends on the geometry of the antenna. In this figure, the numbers going vertically reflect the gain relative to the maximum gain of the Yagi antenna. Do your results support that a Yagi antenna is more directional than a dipole? Why might this be a useful feature for an antenna? Why might this not be desired?

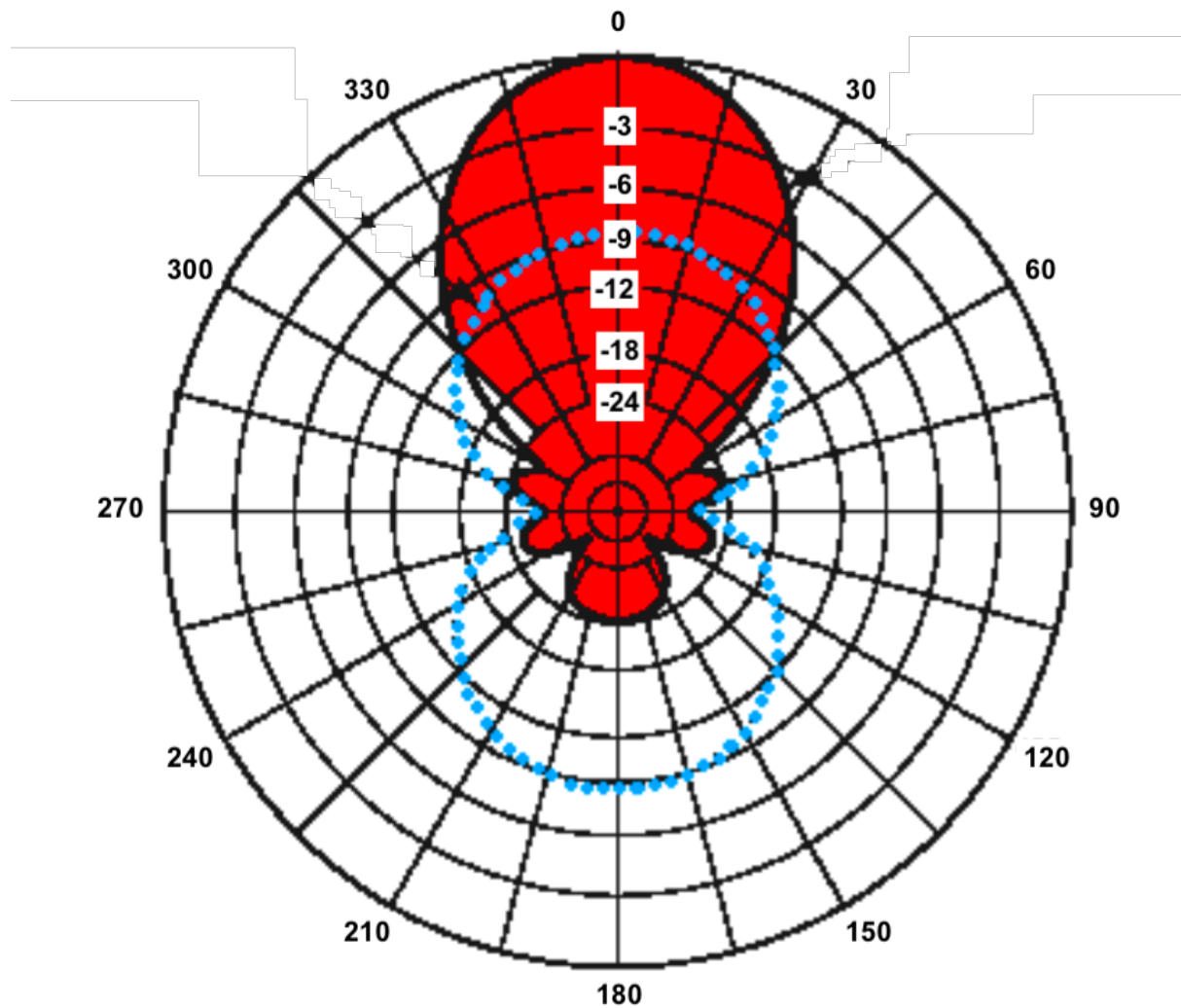


Figure 6: Radiation pattern of a Yagi antenna (red) overlaid with the radiation pattern of a dipole antenna (blue) showing the antenna gain as a function of angle (copied from [4]). Here, the numbers going vertically reflect the gain in dB relative to the maximum gain of the Yagi antenna. For more information see [5, Chapter 10.3].

Transmit antenna	Transmit polarization	Transmit Power (dBm)	Transmit Frequency	Receive antenna	Receive polarization	Receive power (dBm)	Distance between antennas

<b>Transmit antenna</b>	<b>Transmit polarization</b>	<b>Transmit Power (dBm)</b>	<b>Transmit Frequency</b>	<b>Receive antenna</b>	<b>Receive polarization</b>	<b>Receive power (dBm)</b>	<b>Distance between antennas</b>

<b>Transmit antenna</b>	<b>Transmit polarization</b>	<b>Transmit Power (dBm)</b>	<b>Transmit Frequency</b>	<b>Receive antenna</b>	<b>Receive polarization</b>	<b>Receive power (dBm)</b>	<b>Distance between antennas</b>

Transmit antenna	Transmit polarization	Transmit Power (dBm)	Transmit Frequency	Receive antenna	Receive polarization	Receive power (dBm)	Distance between antennas

## 4 Using the Measurement Equipment

### 4.1 Settings on the Rigol

Function	Page in Manual
Center Frequency (CF)	2-2 and 2-3
Resolution Bandwidth (RBW)	2-14
Reference Level	2-9
Video Bandwidth (RBW)	2-14 and 2-16
Span	2-8
Start/stop frequency	2-2 and 2-4
Trace type	3-15
Trace detector	3-15
Sweep points	2-18
Total averages	2-38
Average type	2-38
Peak	2-79
RF Preamp	2-9 and 2-11
Attenuation	2-9 and 2-10
Scale per division	2-9 and 2-12
Amplitude units	2-9 and 2-11
Scale type	2-9 and 2-12

### 4.2 Settings on the Anritsu

Function	Page in Manual
Center Frequency (CF)	3-4
Resolution Bandwidth (RBW)	3-5
Reference Level	3-6
Video Bandwidth (RBW)	3-5
Span	3-7
Start/stop frequency	3-4

Trace type	<ul style="list-style-type: none"> <li>• Press shift</li> <li>• Press Trace (5)</li> <li>• Select Trace A Operations</li> <li>• Select the appropriate trace type</li> <li>• Select back to navigate back through submenus</li> </ul>
Trace detector	<ul style="list-style-type: none"> <li>• Press shift</li> <li>• Press Sweep (3)</li> <li>• Select Detection</li> </ul>
Sweep points	Cannot modify, fixed at 551
Total averages	<ul style="list-style-type: none"> <li>• Refer to Trace type</li> <li>• Select # Averages</li> </ul>
Average type	Cannot change
Peak	<ul style="list-style-type: none"> <li>• Press Marker (bottom set of buttons on right)</li> <li>• Select Peak Search</li> </ul>
RF Preamp	<ul style="list-style-type: none"> <li>• Press Amplitude (second bottom from the left on bottom)</li> <li>• Press Pre Amp</li> </ul>



Attenuation	<ul style="list-style-type: none"> <li>• Press Amplitude</li> <li>• Select Atten Lvl</li> <li>• Type in attenuation using num pad and hit Enter to select</li> </ul>
Scale per division	<ul style="list-style-type: none"> <li>• Press Amplitude</li> <li>• Select Scale</li> <li>• Type in attenuation using num pad and hit Enter to set</li> </ul>
Amplitude units	<ul style="list-style-type: none"> <li>• Press Amplitude</li> <li>• Press Units</li> <li>• Select unit of choice</li> </ul>

### 4.3 Settings on the Rigol DSG830

For safe practices, make sure the the RF/on button is off when you are setting the power settings on the signal generator. When you are sure of your settings, press the RF/on button to turn the signal generator on. You will know that the signal generator is on because a green back-light will illuminate the button and also the *RF* indicator on the front display will illuminate.

Function	Page in Manual
Frequency	2-2
Power	2-4

### 4.4 Settings on the Marconi 2022A

For safe practices, make sure to press the *Carr On-Off* button (second button down on the far right) when changing the power settings. The output is off when the Off indicator on the bottom right panel of the screen is displayed. Output is on when you do not see this. When you are sure of your settings, press the *Carr On-Off* button again to turn the power on.

Function	Page in Manual
Frequency	<ul style="list-style-type: none"> <li>• Select <i>CARR FREQ</i> on the front panel</li> <li>• Type in the frequency of interest</li> <li>• Hit the corresponding unit (MHz, kHz, or Hz).</li> </ul>
Power	<ul style="list-style-type: none"> <li>• Select the <i>RF LEVEL</i> button</li> <li>• Type in the power that you would like to output. Note that if you want to put in a negative power, type in the negative sign first. If you make a mistake, hit the <i>RF LEVEL</i> button again.</li> </ul>

## References

- [1] A. V. Oppenheim and R. W. Scafer. *Discrete-time signal processing*. 3rd ed. Pearson Education, 2010.
- [2] J. D. Kraus. *Antennas*. 2nd ed. McGraw-Hill, 1988.
- [3] P. P. Vezbicke. *Yagi Antenna Design*. Tech. rep. NBS Technical Note 688. Boulder, Colorado: Time and Frequency Division Institute for Basic Standards, Dec. 1976.
- [4] *From Longwire to Yagi*. <http://www.astrosurf.com/luxorion/qsl-antenna4.htm>. Accessed: 2022-06-16.
- [5] D.H. Staelin. *Electromagnetics and Applications*. [https://phys.libretexts.org/Bookshelves/Electricity\\_and\\_Magnetism/Electromagnetics\\_and\\_Applications\\_\(Staelin\)](https://phys.libretexts.org/Bookshelves/Electricity_and_Magnetism/Electromagnetics_and_Applications_(Staelin)) (visited 2022-06-16). Massachusetts Institute of Technology, 2011. URL: <https://books.google.com/books?id=E37zswEACAAJ>.

# A Guide on the HEPCAT\* Dark E-Field Radio Experiment

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# 1 SpectranV6 Spectrum Analyzer

The SPECTRAN® V6 (Spectran) is a real-time spectrum analyzer (RTSA), which we will use to collect and analyze the data from a 24 hr run of the Davis Dark E-Field Radio (DR) Experiment. Here, we present a brief overview of the features, which are needed for the HEPCAT DR Experiment. More information about the Spectran can be found from the data sheet<sup>1</sup>. In addition, the Aaronia online forum provides technical support for Spectran users<sup>2</sup>. For other applications of the Aaronia receiver you can follow them on Twitter<sup>3</sup>.

## 2 Hardware Setup for DR Experiment

The DR Experiment hardware consists of the Spectran, two high-gain amplifiers, a DC source, a Vivaldi antenna, and cables. An overview of the pieces is presented here.

### 2.1 External Low Noise Amplifiers

Two Minicircuits (MC) low-noise amplifiers (LNAs) in series are used to detect weak signals well above the Spectran's noise level. The overall gain of the two amplifiers is  $\sim 47$  dB at 4 GHz. As we will describe in Section 3, we will also use the internal Spectran amplifier to increase the

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<sup>1</sup>[www.aaronia.com](http://www.aaronia.com)

<sup>2</sup><https://v6-forum.aaronia.de>

<sup>3</sup>[https://twitter.com/Aaronia\\_AG](https://twitter.com/Aaronia_AG)

gain of the system further. The noise temperature of the external amps are  $\sim 79$  K at 4 GHz. This corresponds to a noise figure of 1.0 dB.<sup>4</sup>. There are lots of resources to learn more about noise figure and noise temperature. For example, see the HEPCAT Electronics Lecture [1]. When working with LNAs, make sure you ground yourself to the chassis using the grounding strap. Furthermore, ensure that the output of LNA 1 is connected to the input of LNA 2. The output of LNA 2 should be connected to the Rx1 input of the Spectran. Use a wrench to gently tighten the SMA connectors. Once connected, make sure both LNAs are DC biased with +5V (**Red: Positive +** and **Black: Negative -**). When the power supply is on (do this by pushing the On/Off button), you should see  $\sim 132$  mA of current. For a picture of the setup, refer to Figure 1.

## 2.2 Terminated Load

As a first test of the system, we terminate the input of LNA 1 with  $50\ \Omega$ . See Figure 1 to see how this is set up. Doing this ensures perfect matching of the input when we set the parameters for the Spectran.

## 2.3 Vivaldi Antenna

Once the data are stable and the noise floor does not have huge variation, gently remove the  $50\ \Omega$  load with a wrench and replace it with the PCB Vivaldi antenna (RFSPACE TSA600). A picture of the antenna inside the room is shown in Figure 2). Use an SMA cable to attach the Vivaldi antenna to the input of LNA 1.<sup>5</sup>. The block diagram in Figure 3 shows the main RF components of the DR Lab.

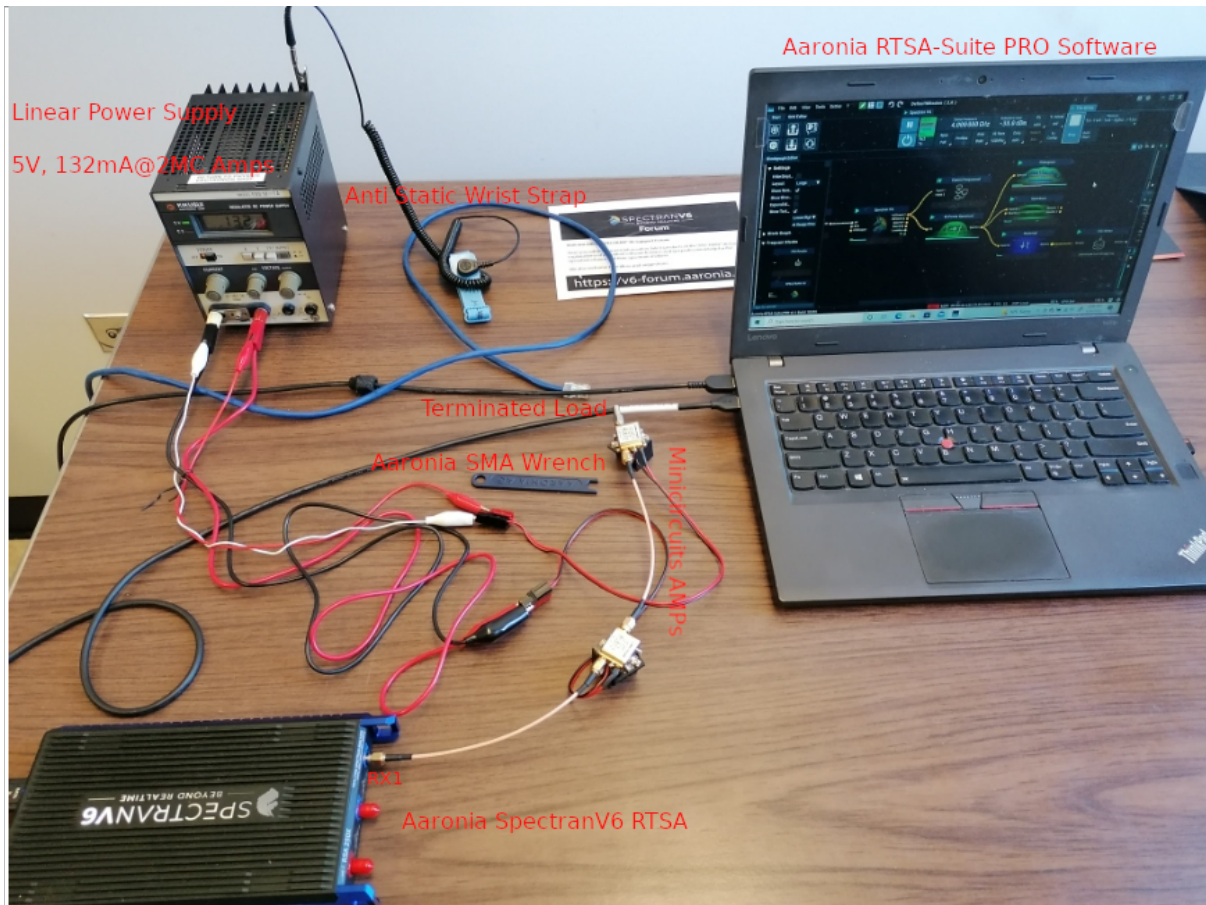


Figure 1: Annotated picture of the Spectran setup for the HEPCAT DR lab.

## 2.4 Setup Instructions for the Spectran

As illustrated in Figure 4, the black data cable is connected to the USB port of the laptop. AC power is supply via the red cable. Before touching the receiver, always ground yourself using the anti-static wrist band. Once plugged in, open the pre-installed RTSA-Suite PRO software. If powered off/on, the corresponding box on the display is red/green. If data are unstable it turns orange. Only use the Rx1 input for data taking. Rx2 and Tx are disabled for this device.

<sup>4</sup>The full specs of the MC LNAs in use can be found at [https://www.mouser.com/datasheet/2/1030/ZX60\\_63GLN\\_2b-1842821.pdf](https://www.mouser.com/datasheet/2/1030/ZX60_63GLN_2b-1842821.pdf)

<sup>5</sup>The specs of the antenna, including the voltage standing wave ratio (VSWR) and the gain can be found in [http://rfspace.com/RFSPACE/Antennas\\_files/TSA600.pdf](http://rfspace.com/RFSPACE/Antennas_files/TSA600.pdf)

Occasionally you will see a message that the device is in a critical state or that the FPGA (field programmable gate array) failed (see for instance [4]). If this happens, you should reset the receiver using the on/off box in the software.

Please note that there is no on/off hardware switch, so unplug and plug the Spectran in if the problem persists. Once powered on, a small green LED on the power line connector will turn on. For monitoring the data stream from the receiver, make sure the small blue LED on the data line connector is on (see Figure 5). For actual data taking, the Spectran will be placed in the DR Lab and will be connected via the patch panel to the external MC AMPs. Chokes on the SMA cables are for filtering electromagnetic interference (EMI). See Figure 6 for a picture of what the chokes look like.

### 3 Monitoring Data from the Spectran

This section gives an overview of some salient features of the RTSA-Suite PRO software used to control the Spectran.

- The averaged spectrum data are shown in the top window. These are the data that are saved to file for further analysis.

A snapshot of the Spectran display is shown in Figure 7. The total number of averages is set to  $10^6$  (the maximum value) in the spectrum adjustment block on the left. This is done because we need to average the noise as much as possible while not writing too much data to disk. The noise floor is approximately -130.3 dBm. You can change the scale of either axis by right clicking (set the zoom) or holding and dragging on the display.

- The middle window in Figure 7 is called a *density view*. It displays four-dimensional data on a two-dimensional display. The x-axis represents frequency, the y-axis represents amplitude, the z-axis, represented using color represents the number of hits in a certain



acquisition interval, and the time axis is represented via brightness of the trace. The current acquisition is shown in white. We will not use this block for the DR Experiment.

<sup>6</sup>.

- The calibration block in the middle window in Figure 7 won't be used for the DR experiment.
  - By clicking the icon, *Main*, you can find an option for data calibration when using external components (antennas, amplifiers etc). By default, several Aaronia products are listed in here. Other components can be added to the list by using Aaronia MCS Software <sup>7</sup>. For the DR Experiment, we use the pre-calibrated noise floor of the Spectran as the main reference. Once the antenna and MC amps are connected, the noise floor will be compared with the reference.
- In the bottom window in Figure 7, IQ Power Spectrum block, the instantaneous power spectrum of data is shown. Here, IQ refers to the I and Q components (real and imaginary) of the FFT spectrum. These are explained in [1]. The instant noise level and transient signals (as opposed to the steady state signals which remain visible even after averaging) can be traced in this window.

Next to the IQ Power Spectrum icon, there is the waterfall block (Figure 8). We write this data to a file and analyze it for the DR Experiment.<sup>8</sup>

- In the waterfall block, the signal variation, both in time and frequency, is illustrated using a 2D color-coded image. This block is especially useful for tracing spurious

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<sup>6</sup>More information about this block and its application can be found in <https://v6-forum.aaronia.de/forum/topic/histogram-block/>

<sup>7</sup><https://aaronia.com/software/mcs-software/>

<sup>8</sup>See RTSA-Suite PRO Manual/Waterfall

signals (spurs) so you know when, and at what frequencies, the spectrum is noisy. For instance, Figure 8, shows that strong signals at the level of up to -40 dBm exist in the range of 866-880 MHz.

- (Frequency) Profile
  - In the menu bar in Figure 7, there is the Profile icon. If you click on it, it shows well known RF signals such as those due to WiFi and Bluetooth. Once you observe a strong signal in the Waterfall block, you can use Profile to look up the corresponding signal (see Figure 9 for an example). For instance, according to the Profile, the strong signals in the frequency range of 866-880 MHz in Figure 8 could be related to WiFi and ISM (Industrial, Scientific and Medical) radio band based on the signal profiles in Figure 9. Additional frequencies can be added to the Profile using RTSA-Suite PRO software.

Using the Waterfall block it is clear that the span for the DR Experiment around 4 GHz has a spur-free spectrum and therefore is ideal for detecting very weak signals (see Figure 10).

## **4 Data Parameters for the HEPCAT DR Experiment**

- The receiver parameters for the DR lab are shown in Figure 7.
- In the menu bar, select Rx1 and enable both amps. The central frequency is 4 GHz with 1/4 span of IQ rate of 122MHz.
- In the top window, we only keep average data and remove the other data. The left panel in Figure 11 shows the other data, which can be removed by right clicking on it. Set the number of averages to  $10^6$ .

- Set the FFT window to Uniform (see lecture notes for a description of windowing) in the control block of the main IQ window. Set the RBW to 3.75 kHz. The RBW is shown in the legend at top of the window. At 4 GHz, this RBW equals the expected Q factor of  $10^6$  for dark photons. [1, 2]
- We write data from the Waterfall block to a file. Set the time compression in Figure 11 to  $10^5$  (the maximum value). This will ensure that there is plenty of hard drive space on the laptop for a 24 hr data run.

## 5 How to Write and Record Data for the Spectran

- Data are recorded in .rtsa file format using the File Writer block. The rtsa files are stored in a binary format. They contain meta-data including time, location, and frequency (for multi-stream) data from various blocks.<sup>9</sup>
- For the DR experiment, we use data from the Waterfall block. The time compression is set at  $10^5$ , which results in data being written every 27 s. This substantially reduces the disk space needed for the 24 hr data run. To write the data from the Waterfall block, click on the green icon in Figure 7 called *Write Data* on the left side of top menu bar.
- Next, you should be able to see the DAQ blocks in a separate window as illustrated in 12. For this experiment, the option *stream to the Histogram* won't be needed and can be removed. Make sure that the File Write block is connected (right click to connect/disconnect) to the Waterfall block and the data stream is running in the display.
- On the menu bar of the DAQ window, set the name of the file (which will be in .rtsa format) and click *Record*.

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<sup>9</sup>More information about the .rtsa format can be found at <https://v6-forum.aaronia.de/wp-content/uploads/asgarosforum/29/RTSA-File-Format-2.pdf>.

- Once you have clicked on *Record*, the icon will change to *Stop*. You should not click on the Stop icon if you want to keep recording data.
- On the laptop, find the directory where the data are being written and check that the data stream is running. (A sync icon will appear next to the name of the file).

## 6 How to Read data and Upload Files

- The .rtsa file created when writing data will be read by the Read Block in the DAQ window. Once the file is uploaded, a 2D image of the Waterfall data will be illustrated and data can be saved in .CSV format.
- Double click on a separate File Reader and in the Main block, find the *Upload Files* icon.
- For the 24 hr data run, the .rtsa file should be around 50-60 MB in size. Once you upload the file, on the menu bar of the File Reader, click on download which saves the data in .CSV format. The final .CSV file should be about 100 MB for the full 24 hr data run.

### 6.1 .CSV (Comma Separated Values) Format for Post-Processing

- A snapshot of the data in CSV format is shown in Figure 13. Column titles indicate the frequency bin. The row titles correspond to the time when the data were taken. Each data point shows the measured power (in dBm) for each frequency and time. For the data shown in Figure 13, data are taken every 0.67 s, which corresponds to a time compression of  $10^4$ . For the HEPCAT DR lab, the frequency range covers 22 MHz with a central frequency of  $\sim 4$  GHz and data are stored every 27 s corresponding to a time compression of  $10^5$ .

## 7 DR Data Post-Processing

Refer to the Jupyter notebook for a detailed overview of how the CSV data are processed.

## 8 Summary and Conclusion

In the first part of the DR Experiment, you get familiar with a basic RF setup, which can be used for the detection of radio signals in a broad frequency spectrum. Here, the key hardware components are the antenna, the LNAs and the Spectran spectrum analyzer (see [1]).

In the second part of the DR experiment you learned the basics of digital signal processing (DSP), which has numerous applications in science and technology. Extraction of a signal from the noise using filtering and data averaging are the key elements (see [2]).

The DR experiment is a proof of concept for the detection of EM radiation associated with dark photons, a candidate for dark matter. The basics of the theory are explained in [2] and [3].

### 8.1 Further Activities

- In the RTSA-Suite PRO software, choose various frequencies and see how the Waterfall data change. What frequencies are the signals the largest? Can you find the possible sources using the Profile? You can use your cellphone and activate Bluetooth to see the changes.
- With the help of lab supervisor, inject a signal and see if you can detect it in your data
- Zoom in on the spectrum data and move around the antenna in the shielded room. Monitor how the data change.

## Acknowledgment

We thank Joseph M. Levine for his great contribution in preparation of the HEPCAT DR Lab.

## References

- [1] RF Electronics Lecture, A. Aminaei, HEPCAT Summer Schoool, UC Davis, June 2022.
- [2] Dark E-Field Radio Hands on Activity, B. P. Godfrey, HEPCAT Summer Schoool, UC Davis, June 2022.
- [3] Search for dark photon dark matter: Dark E field radio pilot experiment, B. P. Godfrey et al., Phys. Rev. D 104, 012013, 2021.
- [4] FPGA Hands on Activity, Hensley, HEPCAT Summer Schoool, UC Davis, June 2022.



Figure 2: A picture of the Vivaldi TS600 Antenna on an antenna stand inside the shielded room. The antenna is attached to the two MC amps, which are connected to the patch panel.

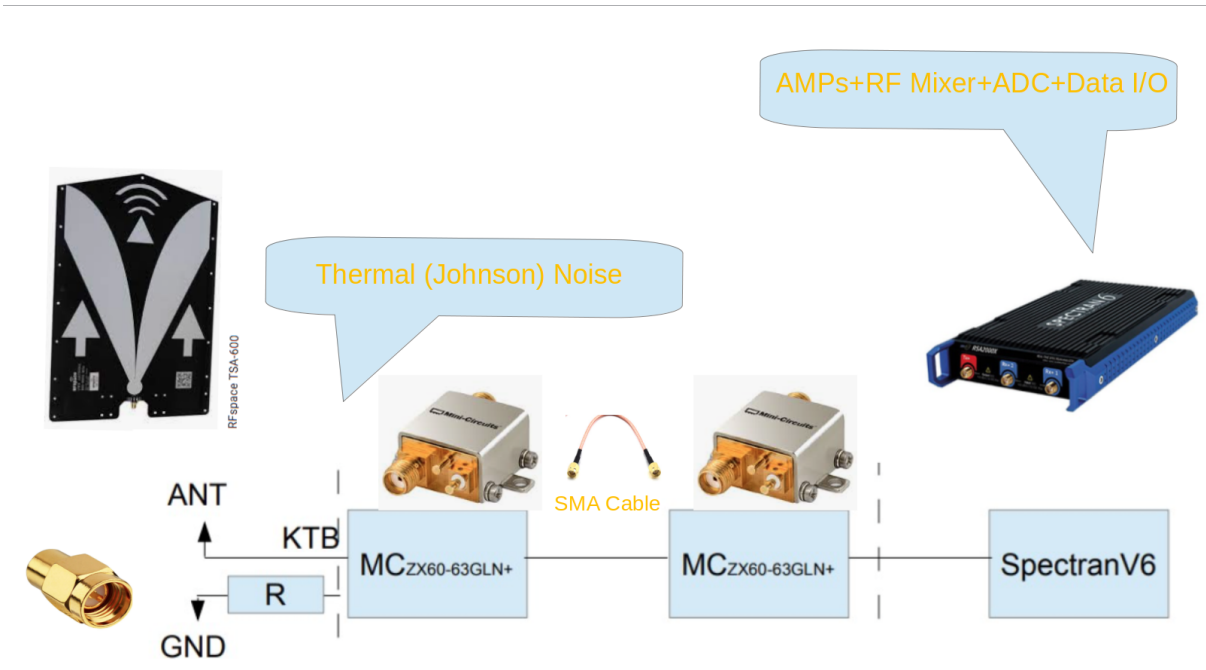


Figure 3: A block diagram of the main RF components for the HEPCAT DR Lab. The input of the first LNA is either a terminator or an antenna.

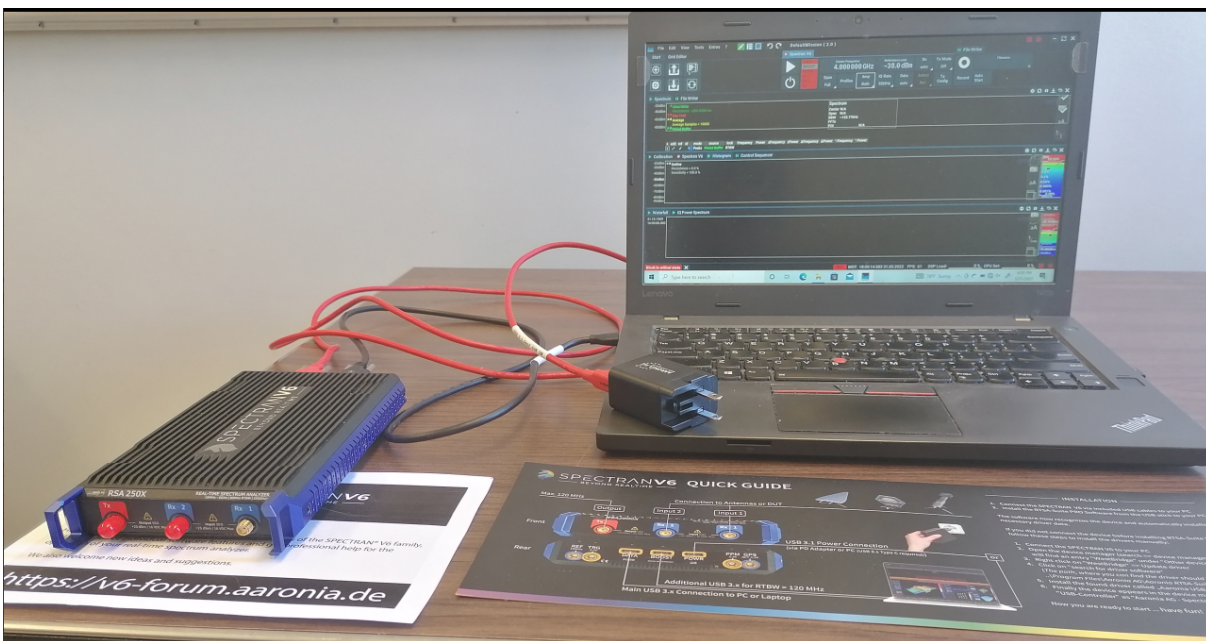


Figure 4: A picture of the Spectran spectrum analyzer connected to the laptop via the black USB cable. The red cable is for the AC power supply.





Figure 5: Once Powered on and connected, a small green LED on the power line and a blue LED on the data line turn on.

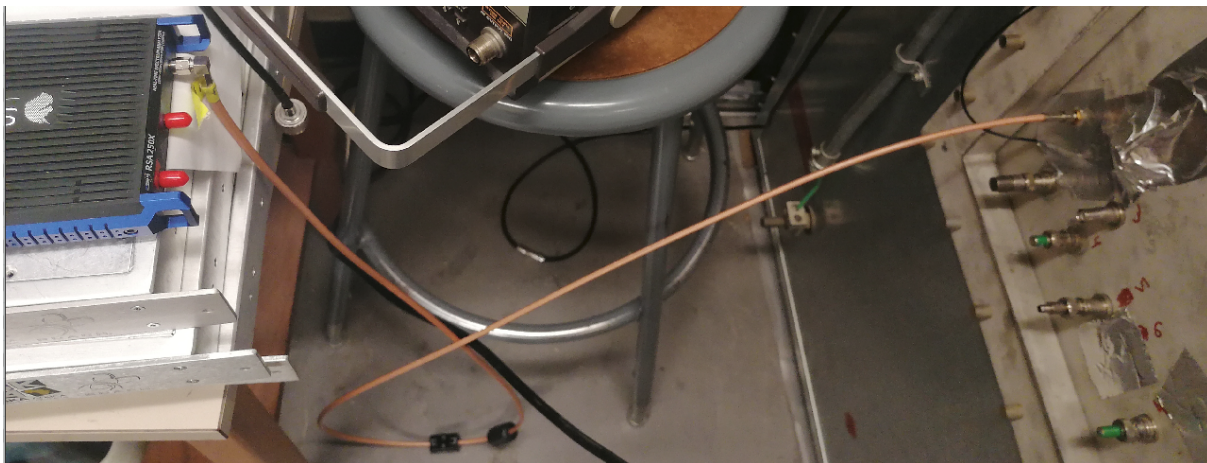


Figure 6: The Spectran is connected to the patch panel in the DR lab. EMI filter chokes are attached around the cable.

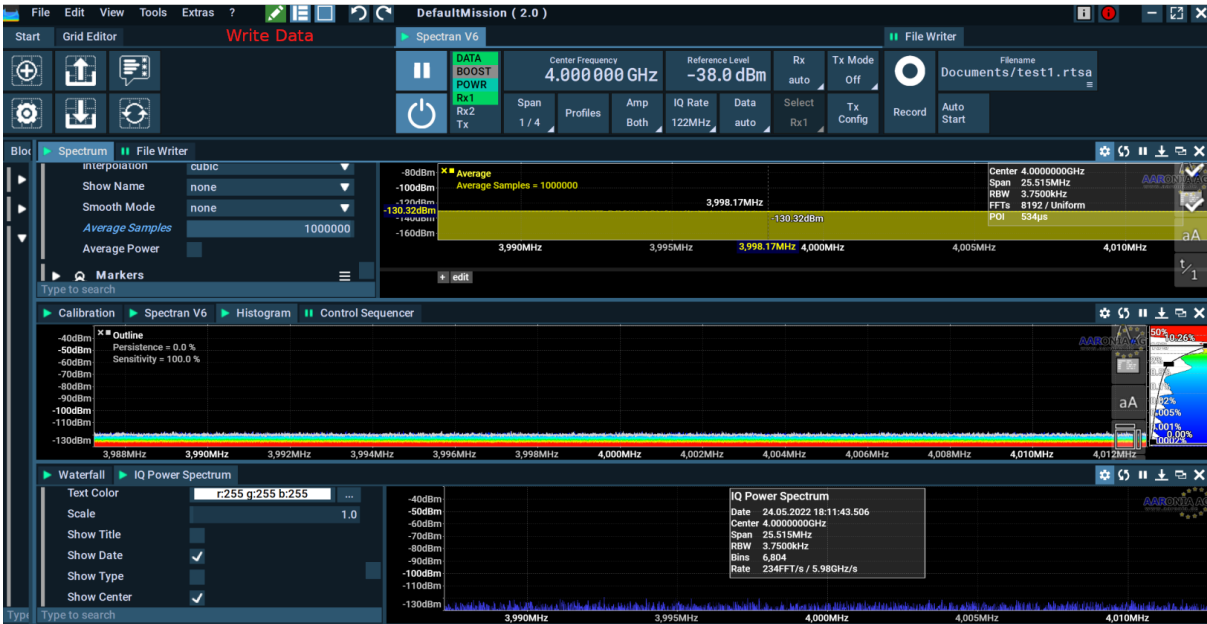


Figure 7: A picture of the main display window of the RTSA-Suite PRO software.

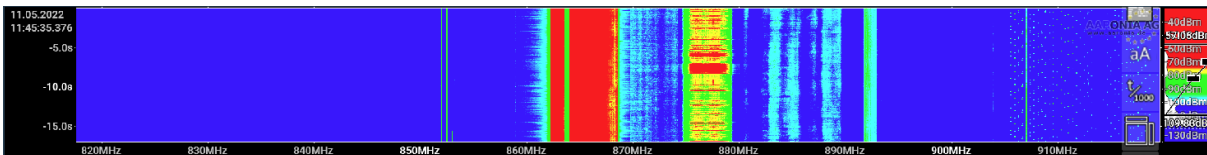


Figure 8: An illustration of data in the Waterfall block

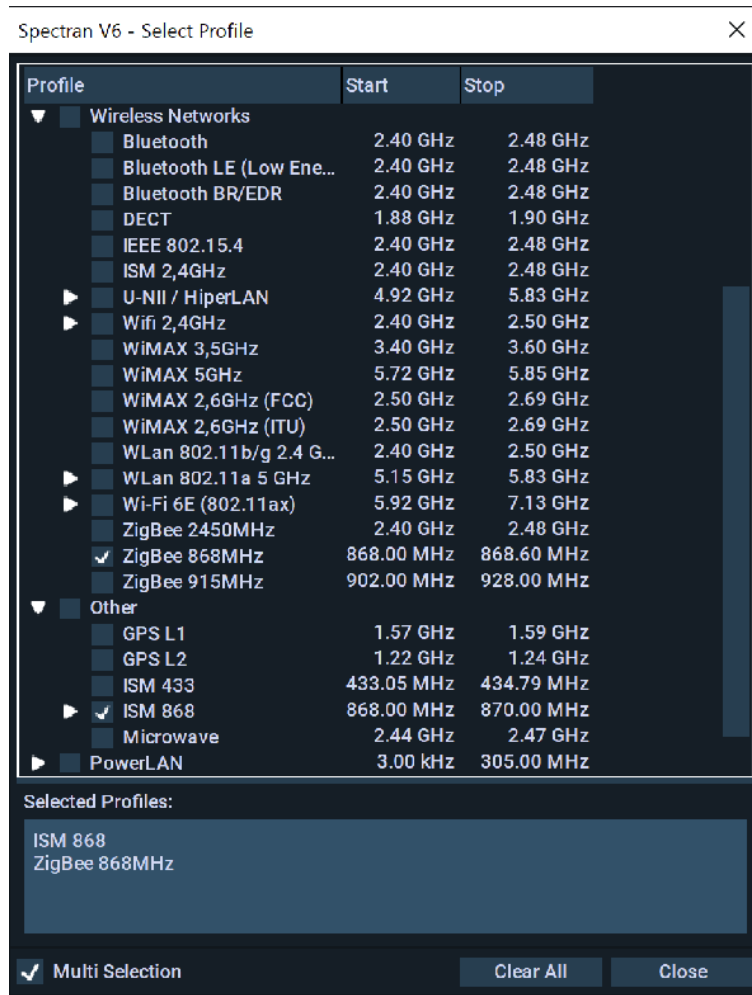


Figure 9: An illustration of the Profile block in RTSA-Suite PRO software

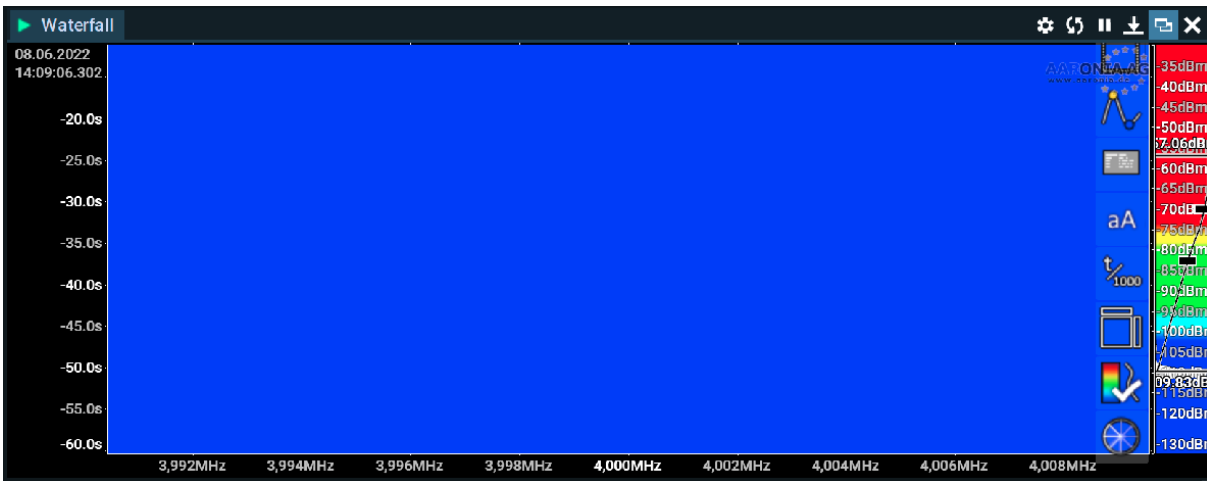


Figure 10: Waterfall plot showing spurs-free data around the central frequency of 4 GHz

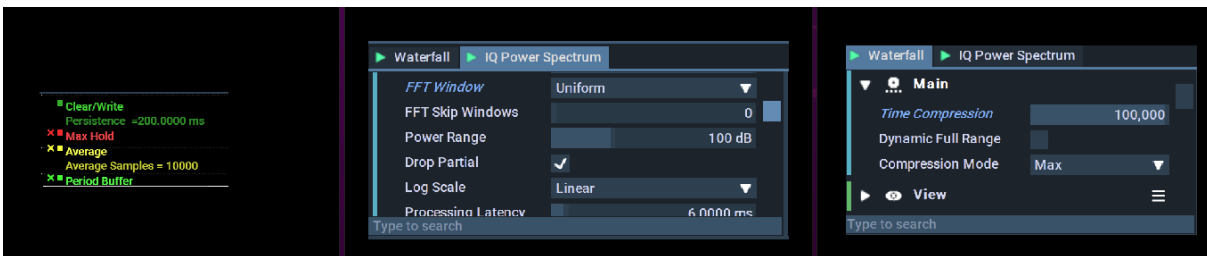


Figure 11: The data control screen in the RTSA-Suite PRO software

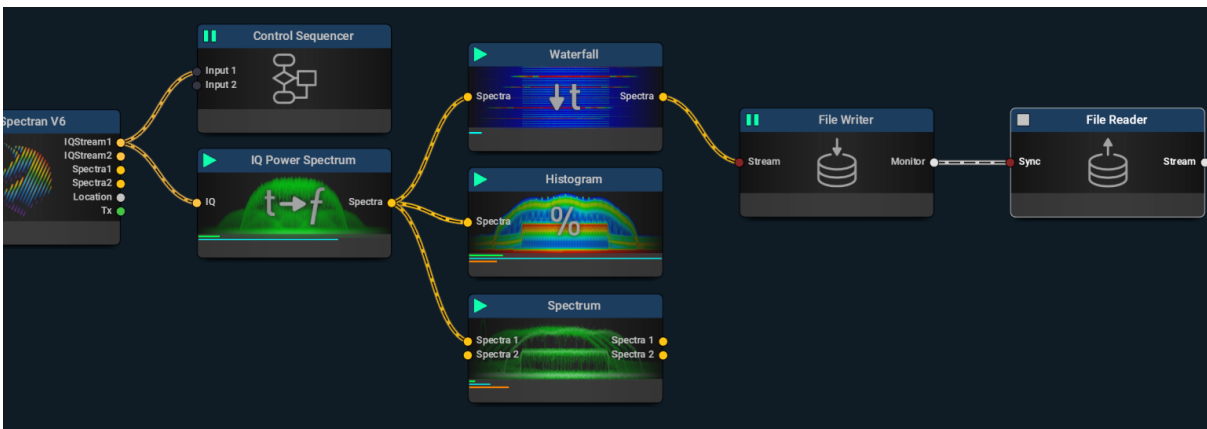


Figure 12: A block diagram of the Spectran DAQ.

Freq.) →

time	3.95E+09	3.95E+09	3.95E+09	3.95E+09	3.95E+09	3.95E+09	3.95E+09	3.95E+09	3.95E+09	3.95E+09	3.95E+09	3.95E+09
766.8932	-83.03	-83.1	-83.08	-83.07	-83.07	-83.09	-83.07	-83.04	-83.04	-83.04	-83.06	-83.06
767.5598	-83.09	-83.15	-83.1	-83.07	-82.98	-82.97	-83.02	-83.03	-83.07	-83.07	-83.09	-83.09
768.2265	-82.96	-83.15	-83.05	-83.05	-83.06	-83.03	-83.06	-83.1	-83.04	-83.06	-83.08	-83.08
768.8979	-83.15	-82.96	-83.11	-83.06	-83.14	-83.07	-83.12	-83.14	-83.03	-83.07	-83.15	-83.15
769.5646	-83	-83.05	-82.98	-83	-83.07	-83.11	-83.02	-83.07	-83.04	-82.98	-83.05	-83.05
770.2312	-83.2	-83.02	-83.11	-83.13	-82.99	-83.05	-83.09	-82.93	-82.96	-83.02	-82.99	-82.99
770.8979	-83.16	-83.09	-83.07	-83.11	-83.07	-83.08	-83.08	-83.05	-83.09	-83.09	-83.15	-83.15
771.6616	-83.1	-83.07	-82.99	-82.92	-83.04	-83.02	-83.02	-82.99	-83.03	-83.02	-83.01	-83.01
772.8024	-83.05	-83.06	-83.06	-83.07	-83.04	-83.08	-83.09	-83.02	-83	-83.05	-83	-83
774.1187	-83.1	-83.06	-83.01	-83.08	-83.07	-83.07	-83.03	-83.03	-83.07	-83.06	-83.07	-83.07
774.9362	-83.13	-82.94	-83.16	-83.2	-83.01	-83.02	-83.01	-82.96	-83.04	-83.06	-83.08	-83.08
775.6029	-83.04	-83.06	-83.03	-83.07	-83.05	-83.09	-83.13	-82.98	-83.08	-83.1	-83.04	-83.04
776.4136	-83.05	-83.05	-83.11	-83.04	-83.05	-83.07	-83.06	-83.1	-83.12	-83.06	-82.97	-82.97
777.0903	-83.01	-83.07	-83.06	-83.05	-83.03	-83.09	-83.06	-83.03	-82.99	-83.04	-83.01	-83.01
777.757	-83.07	-83.08	-83.01	-83.07	-83	-82.98	-83.11	-83.12	-83.1	-82.94	-83.01	-83.01
778.4237	-83.08	-83.01	-83.04	-83.1	-83.03	-83.05	-83.08	-83.07	-83.06	-83.07	-83.04	-83.04
779.1116	-83.09	-83.16	-83.07	-83.09	-83.07	-83.05	-83.04	-83.09	-83.14	-82.99	-83.06	-83.06
779.7783	-83.1	-82.91	-83.03	-83	-83.11	-83.05	-83.02	-83.05	-83.15	-83.1	-82.9	-82.9
780.445	-83.1	-83.03	-83.05	-83.1	-83.05	-83.04	-83.01	-83	-83.03	-83	-83.09	-83.09
781.1116	-82.9	-83.09	-83.02	-83.06	-83.08	-83.15	-82.99	-83	-83.1	-83.07	-83.04	-83.04
781.7783	-82.99	-83.19	-83.04	-83.07	-83.04	-83	-83.05	-82.98	-83.12	-83.06	-83.08	-83.08
782.4449	-83.08	-83.09	-83.05	-83.06	-83.08	-83.07	-83.06	-83.01	-83.07	-83.01	-83.04	-83.04
783.1116	-83.01	-83.03	-82.99	-82.98	-83.1	-83.05	-82.99	-82.93	-83.02	-83.09	-83.04	-83.04
783.7782	-83.06	-83.11	-83.06	-83.02	-83.01	-83.08	-83.17	-82.96	-83.02	-82.96	-83	-83
784.4449	-83.11	-83.08	-83.07	-83.03	-83.04	-83.1	-83.07	-83.07	-83.07	-83.07	-83.04	-83.04
785.1116	-82.92	-82.99	-83.07	-83.04	-83.14	-82.99	-83.02	-83.09	-83.08	-83.05	-83.05	-83.05

dBm

Figure 13: A snapshot of waterfall data in .CSV format. For this run the start frequency is 3.95 ,GHz. Data are taken every 0.67 s corresponding to a time compression of  $10^4$ .