University of Toronto

Faculty of Applied Science and Engineering

ECE422H1 Radio and Microwave Wireless Systems

Project: Antenna and Radio for VHF Communications

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1.0 Introduction

This project focuses on the design and assembly of a Yagi-Uda antenna and the radio frequency (RF) front-end for a VHF radio system for the purposes of making contact with the International Space Station (ISS). This receiver is aimed to be used to receive a variety of terrestrial and satellite transmissions in the VHF band, including narrow-band FM broadcasts from commercial- and government-operated stations, aviation-band transmissions, and extraterrestrial amateur radio-band communications. The aforementioned broadcasts are then demodulated using ACARS (Aircraft Communications Addressing and Reporting Systems) Black Cat [1]. The team was able to receive from CBC, Weather Radio, Toronto Pearson International Airport, and the ISS. Future work includes recording received messages from the ISS and decoding these signals encoded in APRS (automatic packet reporting system), as well as making contact with the HERON Mk. II satellite (University of Toronto Aerospace Team).

2.0 Materials and Methods

The receiver itself comprises:

- An antenna tuned for the VHF band, designed for maximum gain endfire in the E and H plane at 142 MHz
- An RF front-end, comprised of a binocular balun, third-order band-pass filter, and an LNA to improve selectivity and sensitivity in links involving large distances
- A software defined NooElec radio, which provides DC power to receive, convert, and do DSP on the received signal
- A waterfall display to demonstrate the received signal as a function of power intensity, time and frequency,
- A demodulating program called Black Cat, which is “A full featured program that decodes and displays VHF ACARS transmissions directly from SDR I/Q recording files”. It takes digitized samples from the SDR to perform decoding of digital signals. [1][2]

The materials provided for the project include an unpopulated printed circuit board (PCB) for the radio front-end, a comprehensive set of electronic components necessary for building the RF front-end, a NooElec software-defined radio (SDR) dongle, and a coaxial cable to connect the SDR to the RF front-end, and construction materials for building the Yagi-Uda antenna (as well as our ECE422 knowledge!).

The methodology for the project is structured by three distinct lab sessions, as well as worksessions outside of class. The initial session focuses on the construction and tuning of a half-wave dipole antenna and a preliminary test of the SDR's functionality. The focus of the second session shifts towards terrestrial radio transmissions, with an emphasis on the assembly of a Yagi-Uda antenna to enhance the system’s gain for satellite experiments, making the antenna increasingly directional. The final session is dedicated to the assembly and testing of the RF front-end module, integrating it with the antenna and SDR to complete the radio system and attempting contact with the ISS. Throughout these sessions we have soldered, characterized, done measurements using a vector network analyzer (VNA), and witnessed digital signal processing by the SDR, culminating in a comprehensive understanding and practical skill set for building and operating a VHF radio system.

3.0 Session 1: Half-wave Dipole Construction and Antenna/SDR Testing

This first session was focussed on the initial steps of assembling a VHF radio system, with a specific focus on constructing and tuning a half-wave dipole antenna and an introduction to the software-defined radio (SDR) interface application, called HDSDR [3].

In this session, we constructed a half-wave dipole antenna from copper tubing. To tune the antenna to 142 MHz, we narrowed the VNA spectrum to 100-200 MHz. We shortened the antenna to the length that gave us the minimum S11 value at this frequency. For our case, this corresponded to approximately -7.7 dB at a length of 73 cm of each dipole arm with a spacing of 1.7cm. The impedance of the antenna changed as we moved in front of the antenna, therefore a slightly higher gain of 6.97 dB was captured in *Figure 1*.

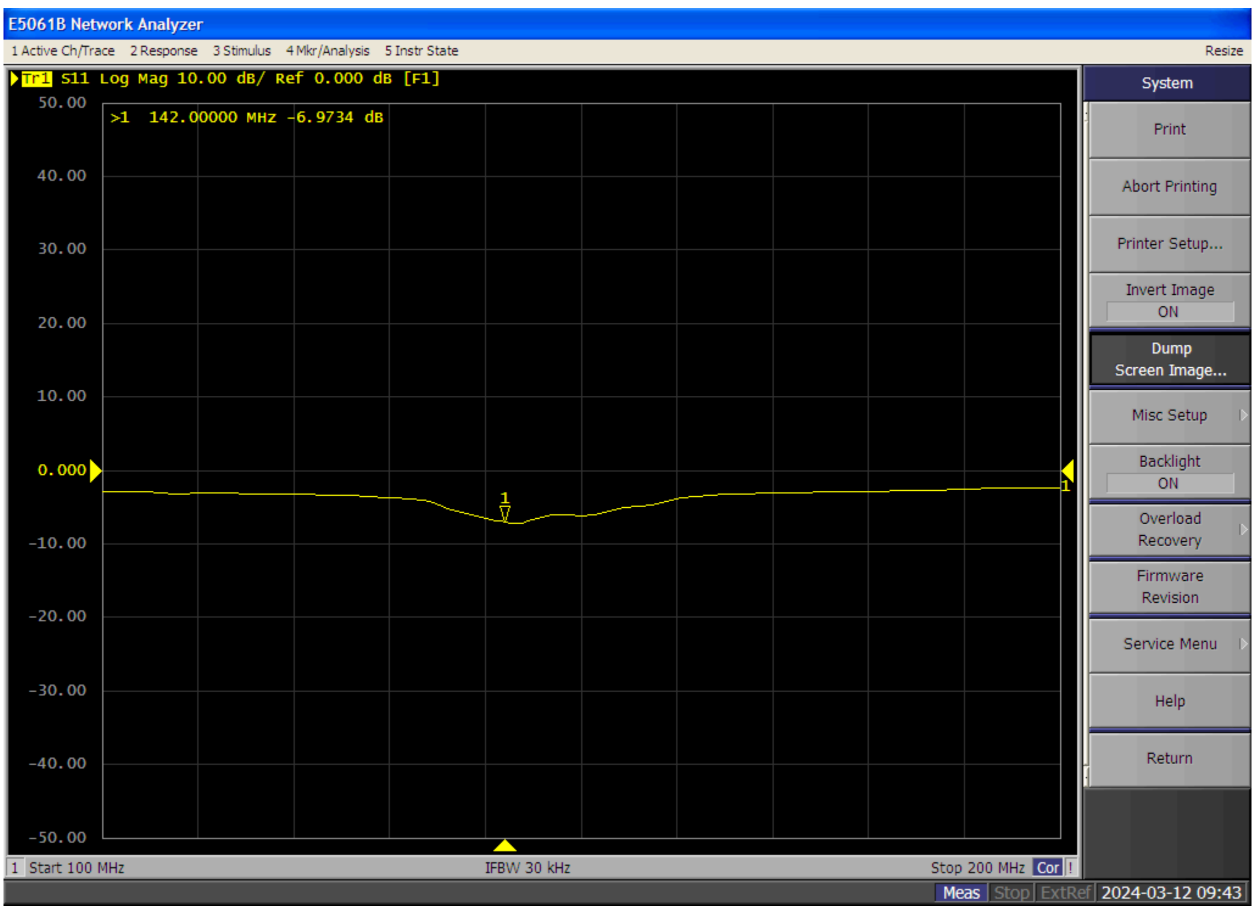

Figure 1: Frequency of operation & input reflection coefficient of the half-wave dipole at 142 MHz

After the construction of the half-wave dipole antenna, the NooElec SDR dongle was explored for its capabilities in receiving, downconverting, and digitizing signals. The antenna was connected to the SDR, and basic FM receiving operations in the VHF band were conducted using the HDSDR software. Calibration of the SDR was achieved by tuning to known broadcast signals, such as CBC Canada (see *Figure 2*) and Weatheradio Canada (see *Figures 3 and 4*). We adjusted the frequency correction factor in the "SDR Device" menu to +1 ppm to mitigate the inaccuracies of the local oscillator (see *Figure 5*). A video of us tuning into the Weatheradio station using our half-wave dipole antenna is also available here: https://youtube.com/shorts/6G6Ir6bzPB8?feature=share.

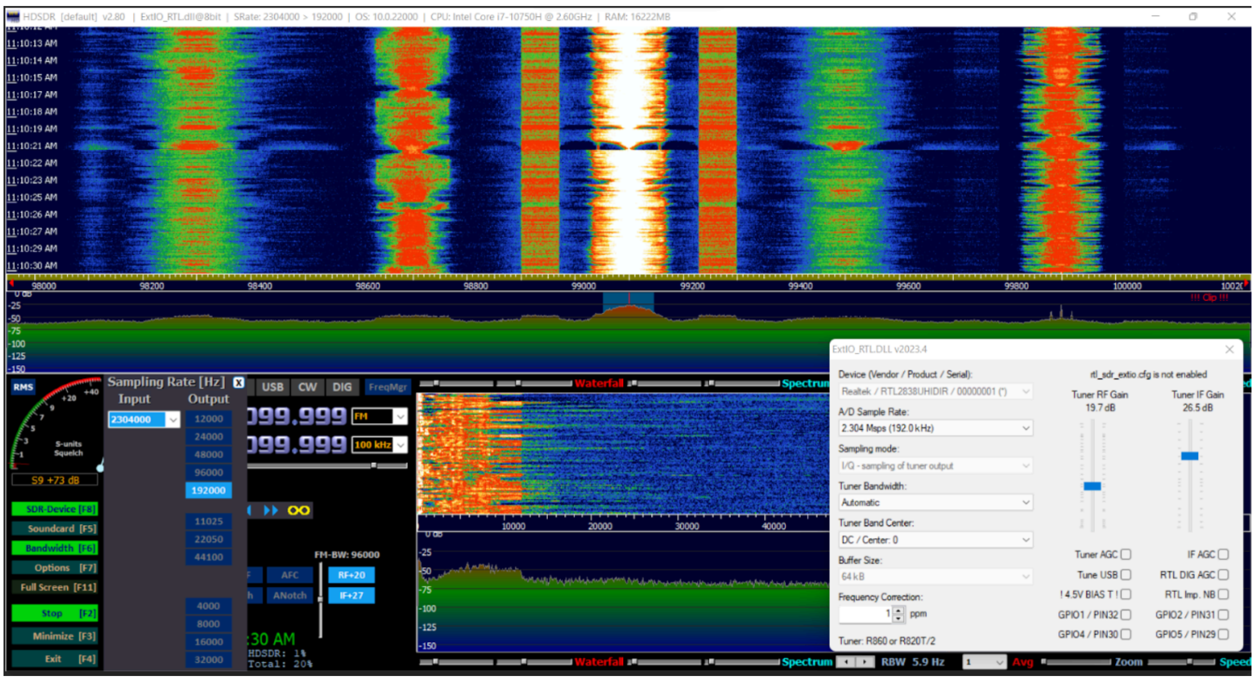

Figure 2: Screenshot from the HDSDR software. The radio is tuned to receive CBC Radio One in Toronto at 99.1 MHz

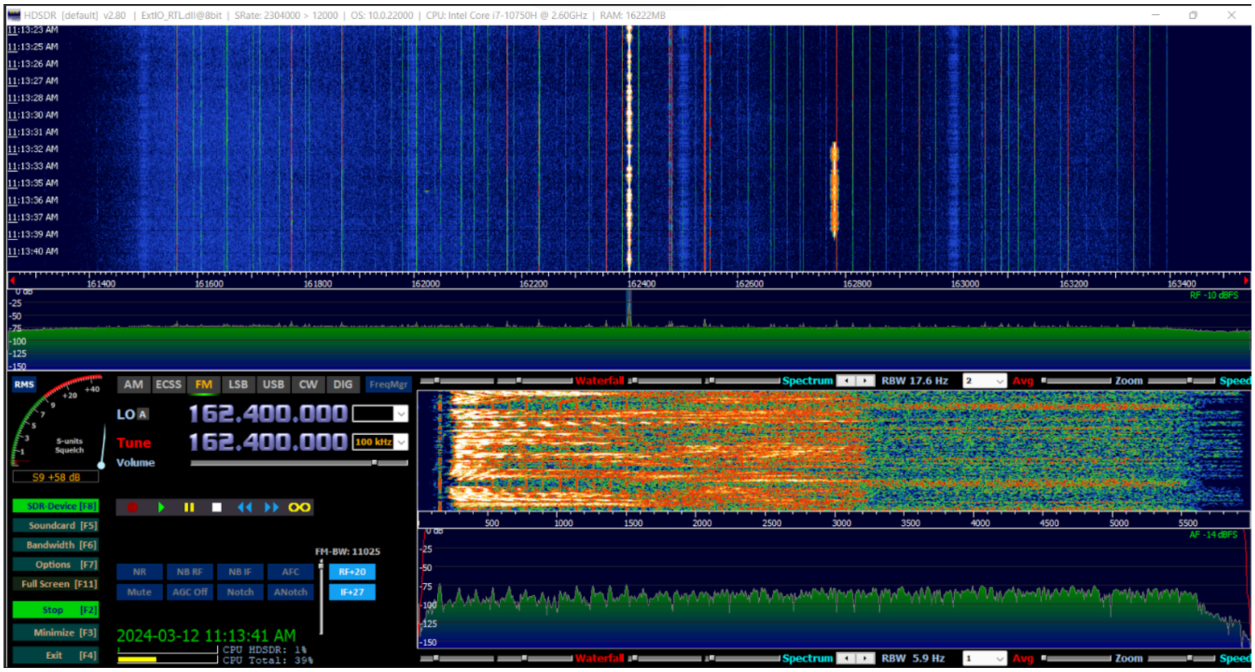

Figure 3: Screenshot from the HDSDR software where the radio is tuned into 162.4 MHz, Weatheradio Toronto, narrowband FM. Bandwidth was adjusted accordingly.

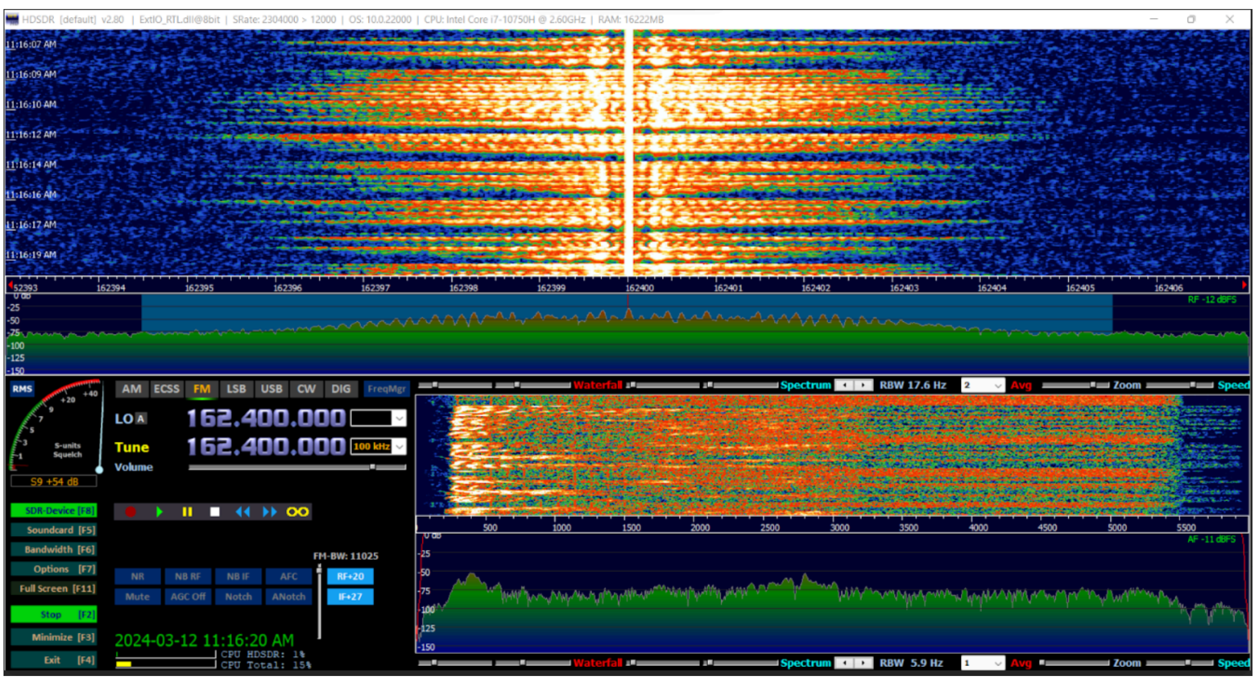

Figure 4: Zoomed in view of HDSDR in Figure 3, where the radio is tuned into 162.4 MHz, Weatheradio.

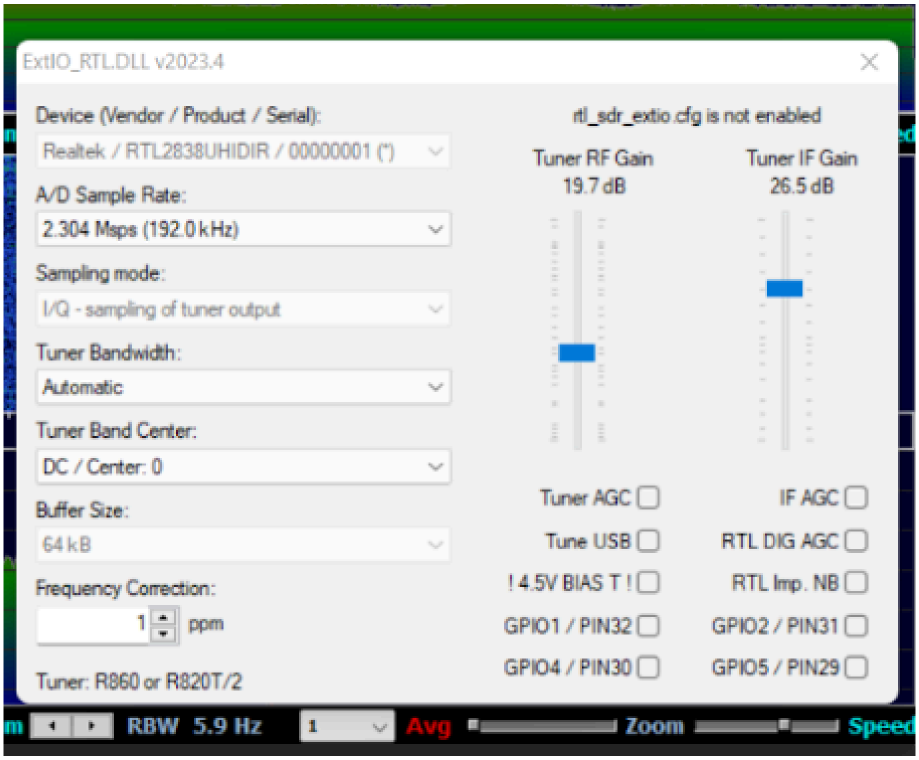

Figure 5: Settings from showing the ppm value of 1 for frequency correction

Using the HDSDR software, we engaged in a rudimentary exploration of the effects of bandwidth (BW) and gain adjustments to the quality of the received signal, along with the distinctions between wideband FM (WFM) and narrowband FM (NBFM) and the corresponding setting required for each to attenuate received noise. We learned that adjusting the BW is crucial to accommodating the signal's entire spectrum without introducing excessive noise. In WFM, typically used for broadcasting, a wider BW is necessary to capture the full signal, while NBFM, used for communication services like amateur radio or aviation, requires a narrower BW, reducing background noise and enhancing signal clarity. Gain adjustments further refined our signal reception, balancing between amplifying the signal strength and minimizing the parasitic amplification of noise. This experience illustrated the intricate balance between BW, gain settings, and their impact on the signal-to-noise ratio (SNR), enhancing our practical understanding of receiver optimization.

Tuning to different stations across the VHF spectrum, we observed varying power levels in the waterfall diagram, particularly noting that 99.1 FM exhibited significantly higher transmit power compared to other nearby WFM stations. This observation not only demonstrated the variability in broadcast strength across different channels but also the practical application of the waterfall diagram in visually assessing signal strength and quality.

Our investigation into the antenna's S11 parameter, which measures reflection coefficient or return loss, provided insights into the antenna's efficiency and the resonance of our antenna at our desired frequency. By analyzing the S11 measurements, we optimized the antenna design for maximum power transfer and minimal signal loss, thereby enhancing the overall performance of our radio system. This analysis was crucial for understanding the antenna's performance characteristics and ensuring optimal reception and transmission capabilities in our VHF radio system.

3.1 Session 2: Terrestrial Radio Transmission and Yagi-Uda Antenna Assembly

In the second session, we assembled a Yagi-Uda antenna (see *Figure 6*) to enhance our VHF radio systems' capability for terrestrial radio transmission. We added a reflector with the longest possible length of copper, and calculated the lengths of our three directors D1, D2, D3 based on a boom length of 0.8λ. Spacing between directors was measured based on the guideline of 0.2λ [4].

With our Yagi-Uda antenna we observed improvement in signal strength and clarity for transmissions received from specific directions. For example, by pointing our antenna towards the Pearson Airport in Toronto, and tuning our radio to the ACARS frequency of 131.475 MHz (used by Air Canada) (see *Figure 7*), we were able to receive messages from the planes which were transmitting signals to the tower using the Black Cat software. By using the Flight Radar website, we were even able to locate a plane which we were receiving a signal from, as shown in *Figure 8*. By using the flight number "CGCJZ", we were able to figure out that the signal was coming from an Air Canada Express flight, operated by Jazz Aviation, travelling from Atlanta to Toronto. At the time of the transmission, the aircraft was about to land at Pearson Airport. Other messages recorded during this session are presented in *Appendix A*.

Figure 6: Our Yagi-Uda antenna

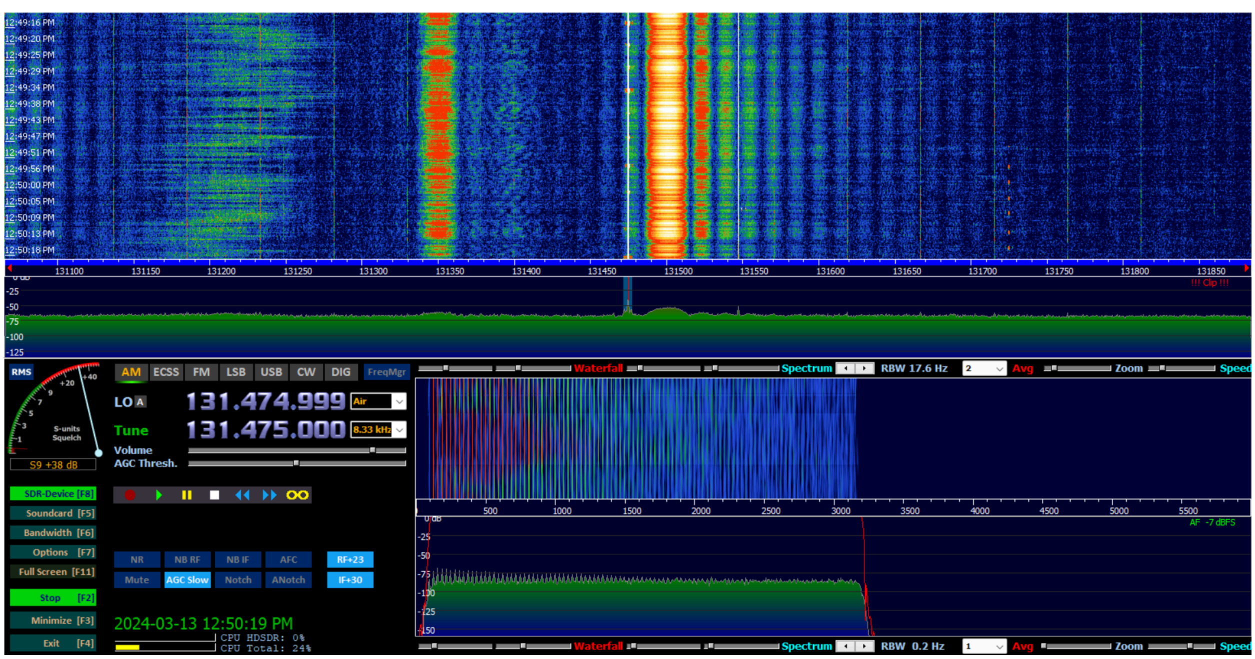

Figure 7: Screenshot of the HDSDR waterfall when the radio was tuned to 131.475 MHz

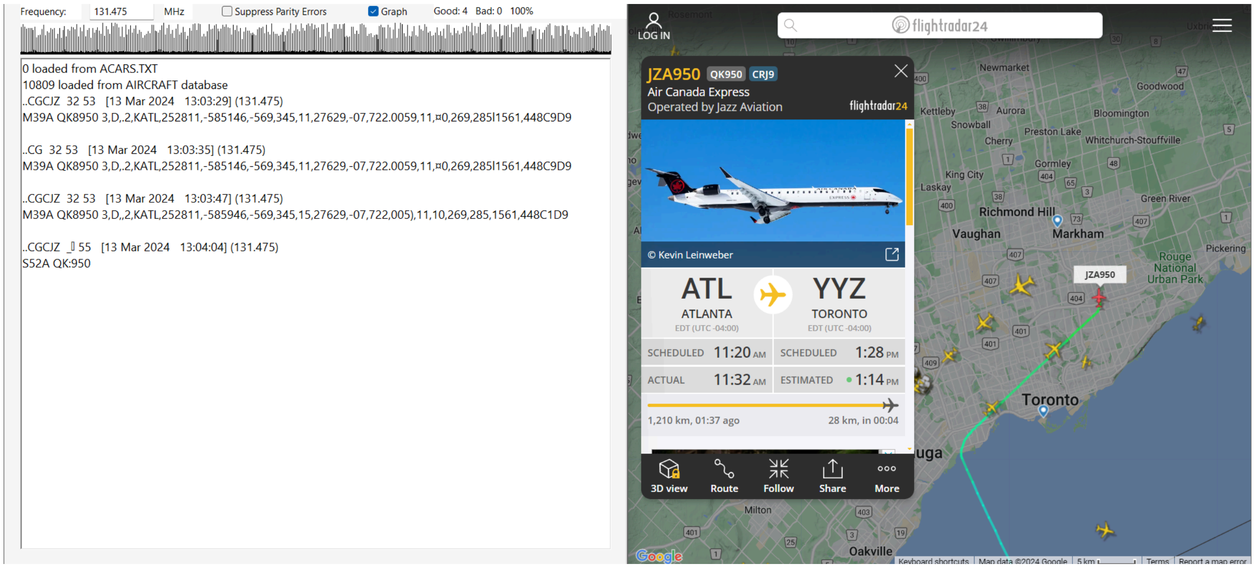

Figure 8: Screenshot from the Black Cat software (on the left) and Flight Radar website (on the right), showing the received signals and the location of the plane transmitting it side by side

3.2 Session 3: Radio Front-End Assembly

In the third and final session, we completed the assembly of our antenna and front-end module, and performed a comprehensive testing of the RF front-end module. After soldering the electronic components onto the PCB outside of the lab session, we completed characterization in-lab using the VNA and validated the functionality of our module, ensuring that it provided the necessary gain across the targeted VHF band. When we connected our board to the power supply the LED illuminated as seen on *Figure 9* and we ensured that the current draw was around 100 mA as seen on *Figure 10*. As seen on *Figure 12,* upon connecting a 20 dB attenuator between the bias tee and the VNA (*Figure 11*), we measured the peak S21 value at 146.498 MHz to be -23.478 dB. This value is unexpected, since with the attenuator we should have seen 26-20=6 dB of gain measured on the VNA, since the output power from the VNA is set to 0 dB. The VNA error mode was triggered without the attenuator.

We did measure cutoff frequencies as a result of the bandpass filter at around 114 MHz and 150 MHz, close enough to the expected values of 130 MHz and 160 MHz for the bandpass filter to be effective at our target frequency. We verified the functionality of the system by tuning into Weatheradio Canada as seen on *Figure 13* and noticed the signal quality seemed to be much clearer when the antenna was connected to J2 as opposed to J1 (see Figure 14 for reference [1]).

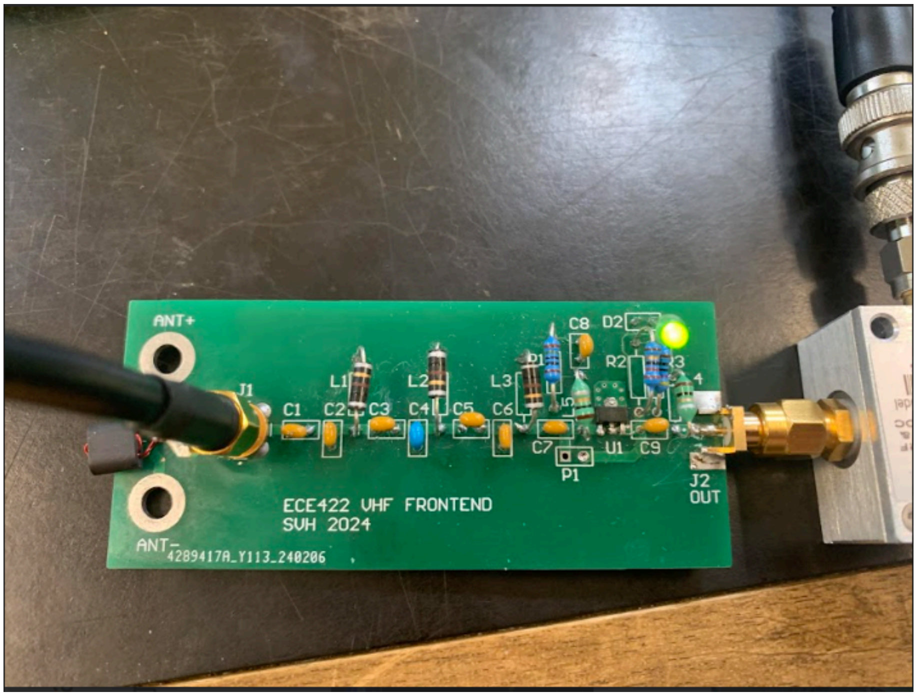

Figure 9: Populated PCB connected to the DC power supply with the illuminated LED

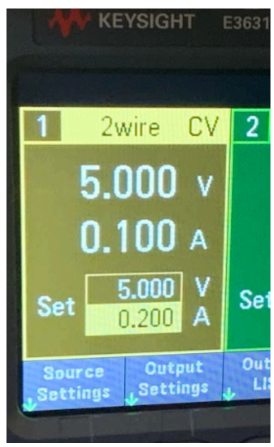

Figure 10: DC power supply connected to the PCB, showing the current draw is around 100 mA as expected

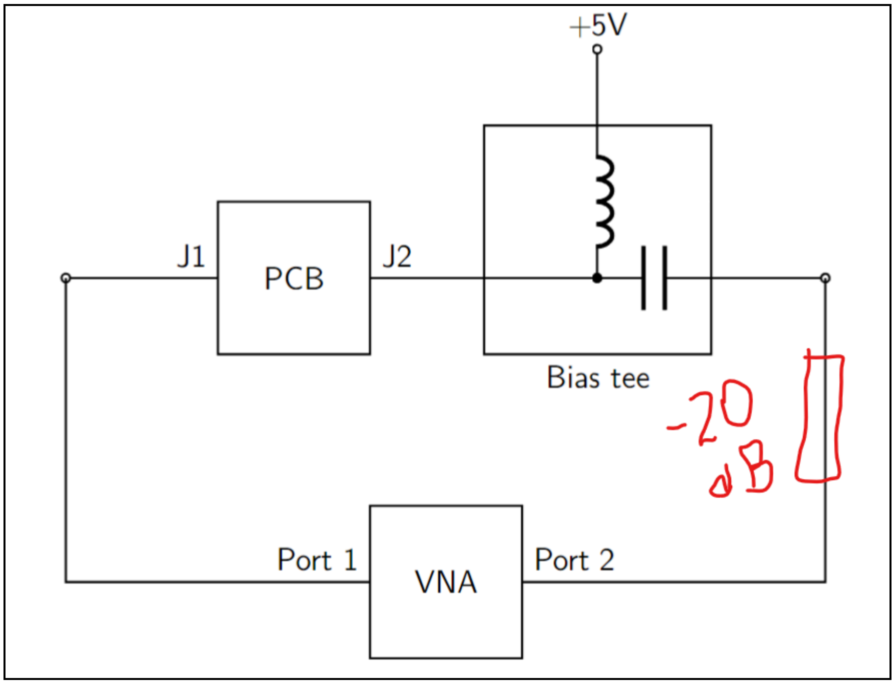

Figure 11: Schematic of the Front-end PCB with Bias Tee and -20 dB attenuator pictured also.

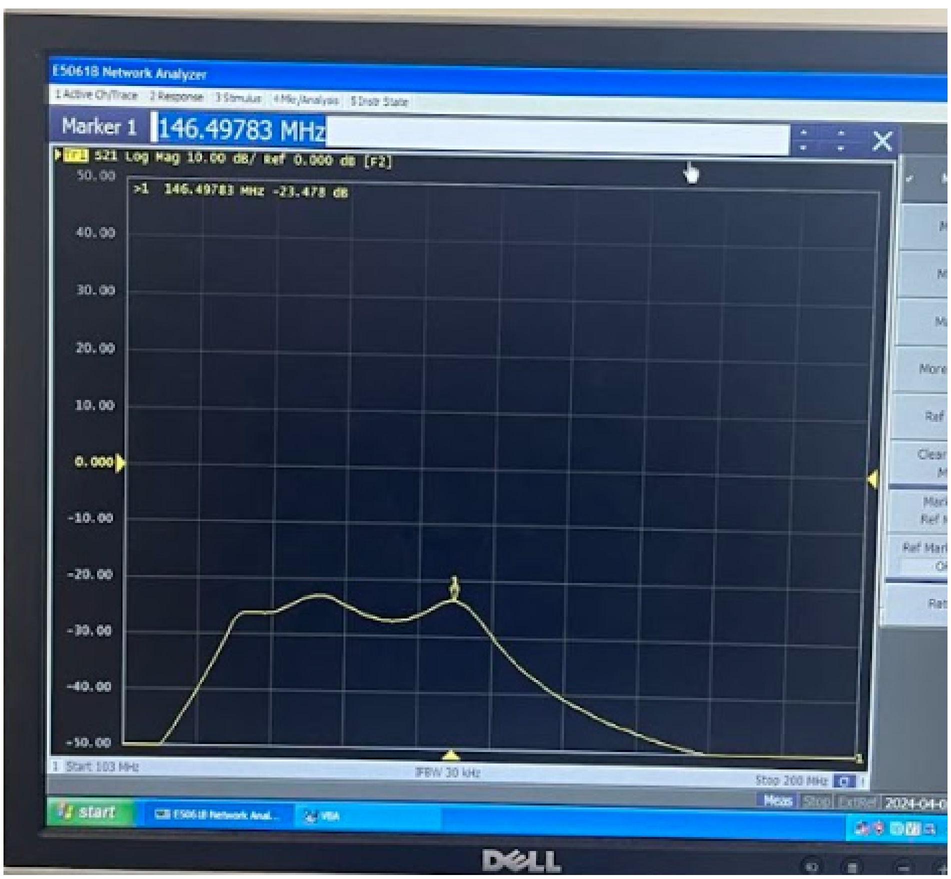

Figure 12: RF front-end S21 at 146 MHz frequency

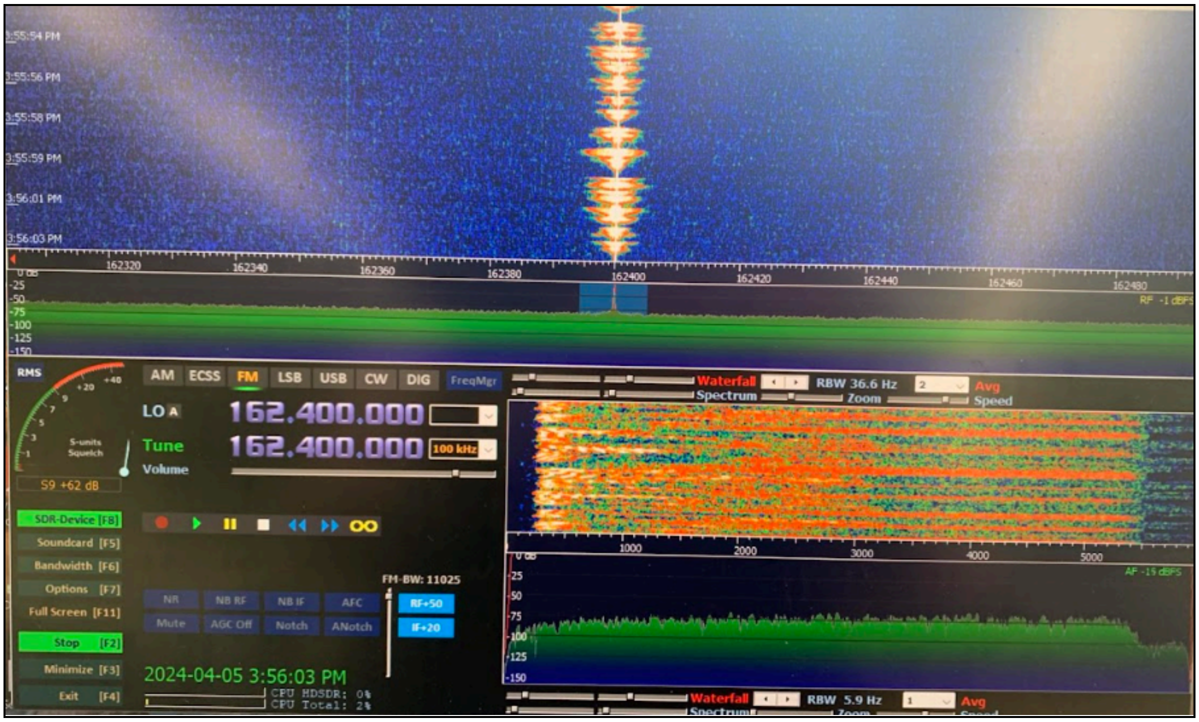

Figure 13: Verification of functionality using the SDR to receive Weatheradio signals

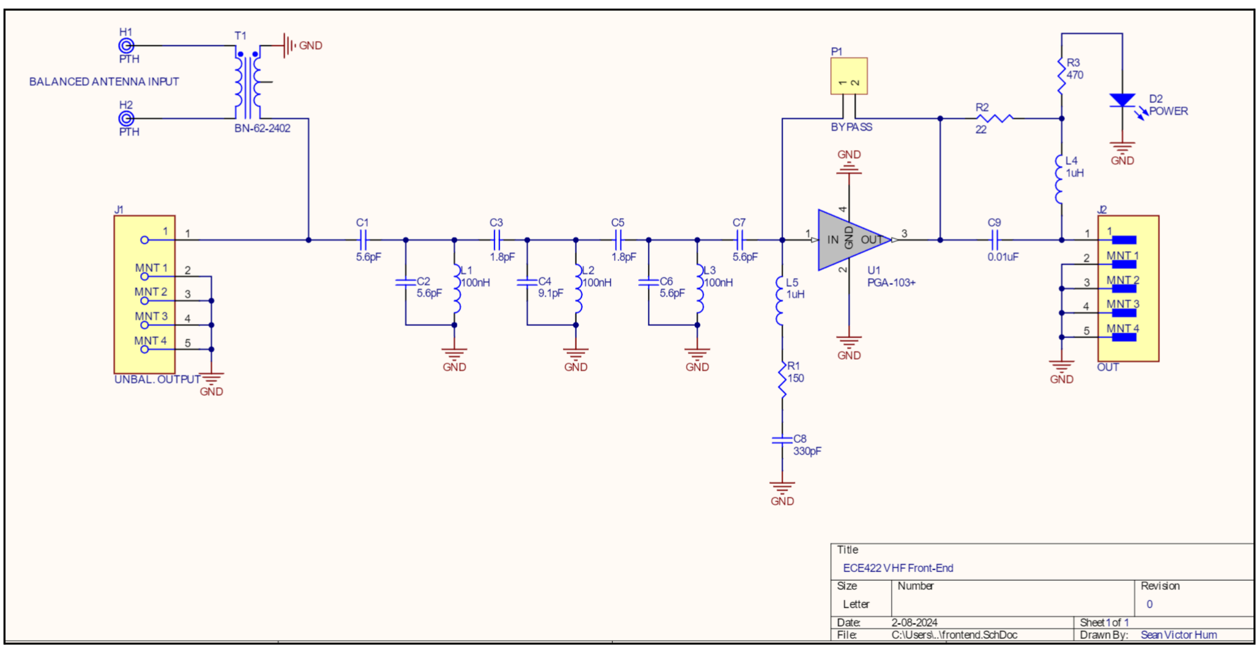

Figure 14: Schematic of the VHF Front-End [1]

3.3 Bonus Session - Making Contact

On April 10th, 2024, several groups went out to King's College Circle to obtain measurements for the antenna. See video below. We were able to make contact with the ISS and were able to hear some blips, lots of static, and lots of yelling directions and each other to tilt the antenna. We were unable to decode the received packets. See video here: https://youtube.com/shorts/KE72HXVNrzU?feature=share .

4.0 Conclusion

In this project, we have designed, assembled and tested a VHF radio system, including the construction of a Yagi-Uda antenna and an RF front-end module, enhancing the reception of terrestrial and satellite transmissions in the VHF band. In the first session, we constructed and tuned a half-wave antenna and verified our design by receiving signals from wide and narrow band FM radio stations. In the second session, we focused on enhancing the system's reception capabilities for terrestrial and extraterrestrial receiving via the construction of the Yagi-Uda antenna. By pointing our antenna towards the Pearson Airport and tuning into specific frequencies, we were able to receive and decode ACARS messages. Lastly, we have assembled and tested the RF front-end module to improve our system's selectivity and sensitivity, and used the added gain and filtering capabilities of the front-end along with the SDR to make contact with the International Space Station.

5.0 References

1. S. V. Hum, "ECE422 Project: Antenna and Radio for VHF Communications," ECE422: Radio and Microwave Wireless Systems, pp. 1-19, Mar. 25, 2024.
2. “Black Cat Absolute ACARS,” *blackcatsystems.com*. https://blackcatsystems.com/software/black_cat_absolute_acars_decoder_sdr_iq_file_decoding.html (accessed Apr. 12, 2024).
3. “HDSDR Homepage,” *www.hdsdr.de*. https://www.hdsdr.de/
4. “Yagi-Uda Antenna,” *www.antenna-theory.com*. https://www.antenna-theory.com/antennas/travelling/yagi3.php

6.0 Appendices

Appendix A: Recording of ACARS Messages Using the Yagi-Uda Antenna

```
0 loaded from ACARS.TXT
10809 loaded from AIRCRAFT database
.C-FNVU  4R 54   [13 Mar 2024   14:16:07][ACA Airbus A320 0403] (131.475)
M40A AC0414 C32CCC         1OSCFL AC0414/13/13 YY[ YUH 41501007Z 02¤/2054

.C-GIUF  H1 52   [13 Mar 2024   14:16:12][ACA Airbus A321 1638] (131.475)
D03D AC0102
#DFB81,22222222222111/V8042,074,00061,222¤222r222111/X103191,N101,0024,N000,N0¤0
7,0803/Y20312%,N2pr,202¤.¤¤00<N0¤00,0013?x3N008-0404,¤003,^005,N011,N012,0020/X4
N004,0000,0000,0000,0000,0000/X5N000,N000,0000,000

.C-FNVU  H1 55   [13 Mar 2024   14:16:17][ACA Airbus A320 0403] (131.475)
D61A AC0414
#DFBA04/A32004,1,1/CCC-FNVU,MAR13,181543,CYYZ,CYUL,0414/C105,76331,4000,43,0
010,0,0100,46,X/CE0187,01634,160,250,6491,376,C13006/EC731902,72256,17847,29680,23/E
E731584,84725,02183,

.C-FNVU  H1 56   [13 Mar 2024   14:16:23][ACA Airbus A320 0403] (131.475)
D61B AC0414
#DFB33171,23/N101,00,00,00,01,00,00,00/N201,00,00,00,01,00,00,00/S10908,0908,0970,7500
,3618,3227,0952/S20907,0908,0970,7450¤3511,3#11,09}b
v¤¤s-p):!+¤&,-¤¤q#¤S*I(¤\De¤n¤¤c¤¤2<¤¤¤0."'n

.C-FNVE  I1 57   [13 Mar 2024   14:16:30] (131.475)
D61C AC1414 #DVB101,20w,13
¤,-o%,1¤1.¤¤8/V1;6¤4¤.r1#5¤1,)<0¤2,071d082l412.:¤0/F215285,u352(0,1l053-075¤810,¤05
 64'X100200,000¤¤-00010,067l051<0968/X200400,00080,00050,067,052,0958/C¤=
k/Q?Q}NY96¤z¤Y2@¤!N|9Q0¤@%K-E¤¤kOyM ¤d¤

.C-WiuF  6Z 39   [13 Mar 2024   14:17:14] (131.475)
M6$A AC010# C32AAA     `   1o¤AFL AG2102-33/13 YWR yXZ 055 1815Z 100/¤042-0127
A`     !  ¤

..CFRQW  H1 51   [13 Mar 2024   14:17:18] (131.475)
C23B QK8876 #CFB----
```

1, 1, 0, 0, 0, 0, 156.855, 7, 560, 7, 560, 0, 1- 0, 0¤ 1, 19.6718< u:6.75,J46¤9.62, 850, 86.0156, 08.8593, (2.5714, 75.47, 75.2812, 85.3125, 0.542968, 82.J4937, 0.773437, 20, 292, 476.937, 0.9375, 0, 5

..CFrQW H1 52   [13 Mar 2024   14:17:26] (131.475)
C23C QK8876 #CFB26.625, 19.7187, 4713.62, 849,
86.0468, 89.4687, 77.1746, 73.0305, 74.4687, 85.2812, 0.519531, 83.1406, 1.
4746, 20, 289.625, 485.25, 0.125, 0, 0, 0, 0, 0.241687, 0, 39.6953, 0, 48.2109,
995.52, 0, 0, 17.6

..CFRQW H1 54   [13 Mar 2024   14:18:10] (131.475)
C24A QK8876 #CFBMM1817520313ABP
18154203 219 156
18155213 219 156
18155403 219 156
18155814   8 21
18155814 127 30
18155814 128 26
18155814 206 48
18155814 999 38
18160414 219 156
18160804 219 156
18163015 219 156
181

..CFRQW H1 63   [13 Mar 2024   14:18:18] (131.475)
C24B QK8876 #CFB70205 219 156
18171315 219 156
18¤72205 219 156
¤g/~.¤;K¤Z-¤9¤}I2¤B/¤N¤M¤]Rg=5¤¤mK.6?.¤]¤(+O
/ S+)U¤¤%_!¤¤)¤c¤'¤aD¤3]^1vAaS¤¤¤K¤]>
3uWZ¤`woDMl@!;b+Yr+>e
d¤0F¤ kq¤{zWjG\aPlYHw.k5¤&5Z¤X¤S~`¤¤3¤¤¤O7¤ZA¤U"¤$B%7¤eh2¤/]*{ t