Better Automated Reception of Transitory Satellite Images through Antenna Simulation and Pass Prioritization

James Monaco, Dartmouth Engineering, '21
Isaac Savona, HWS Computer Science '22

August 2020

Contents

Abstract

A software-defined radio (SDR) was used with V-dipole and double-crossed antennas to receive transient satellites in the 137MHz band, including Meteor M2 and NOAA 15, 18, and 19. Using a Raspberry Pi (RPi) to run bash scripts that coordinate open-source software, this became a headless and automated process that included recording signals, decoding data, and building images. For better scheduling, a python script was written to prioritize either the satellite with better visibility or with higher image quality when two satellites pass overhead at once. Two popular antenna designs were simulated, built, and compared. A cheap portable assembly was designed and 3D printed, with the final product able to continuously collect data for 4 days with little to no user input (see figure 1). A secondary goal was to make this project accessible and affordable for other student groups, hobbiests, or educators to use this to teach engineering and computer science.

Figure 1: Left: showing the final packing of the Raspberry Pi, its battery, fan, and SDR into the PVC antenna stand. Right: The fully assembled set-up with a V-dipole antenna. 3D printed guides keep the antenna at 120 degrees.

1 Introduction

This project aims to use a cheap software-defined radio (SDR) and a simply built or cheaply bought antenna to intercept weather satellite signals to provide near real-time images of the earth. Novel work has been done to automate satellite reception, prioritize satellites with stronger signals when two satellites are overhead, and make the system more reliable with or without network access. In addition, novel mechanical and electrical elements have been added to increase the mobility of the conventionally static antenna set-up.

Current weather satellites that are transmitting images are either in a transitory polar orbit or a geostationary orbit [14]. Geostationary satellites are at a fixed point in the sky, allowing continuous data acquisition but requiring a directional antenna to get a adequate signal to noise ratio

(SNR) for a picture [14]. Geostationary satellites include NASA's GOES series (16 and 17), and will be the focus of future work.

Transitory satellites obit north-south or south-north around the poles, and are generally close to earth resulting in a strong signal. Their signal can only be received when the satellite is within line-of-sight of the receiver at discrete windows throughout the day. By using an omni-directional antenna, the satellite signal can be received as soon as the satellite is above the observer's horizon [14]. Targeted transitory satellites include NOAA 15, 18, and 19 as well as the Russian Meteor M2 satellite. All NOAA satellites broadcast an analog signal (automatic picture transmission, APT) while the Russian Meteor M2 broadcasts a digitally encoded signal (low-resolution picture transmission, LRPT) [4, 5, 6, 7] and each type of signal requires slightly different post-processing, with the digitally encoded signals being more information dense resulting in higher resolution pictures. A table showing their transmission characteristics can be seen in table 1.

This project focuses on receiving, decoding, and automating the reception of transient satellite signals with two different omni-directional antennas. A headless system using single-board computer provides opportunity for an automated, low-cost, low-power design that could last for days with no user input. This paper will focus on the creation of the headless system run on a Raspberry Pi, as the GUI based system is well-documented online [1, 16].

2 Hardware Specification and Requirements

The chosen SDR needs to be able to receive the frequencies that the NOAA and Meteor satellites transmit, and have a large enough bandwidth to interpret the signals. Ideally, the SDR would be appropriate for future work such as radio astronomy observation or other satellite reception (see table 2). Additionally, an SDR with a bias tee would allow in-line low-noise amplifiers (LNAs) and filters with no external power lines needed.

The SDR that met the design requirements, was affordable, and widely accessible was the Nooelec NESDR SMArTee XTR [15]. Its extended tuning range up to 2350 MHz and maximum bandwidth of up to 2.4MHz makes it fine for all applications in the scope of this paper and future work. The only the concern for future work is that the hydrogen line center frequency overlaps with the NESDR SMArTee XTR's frequency reception gap, but with appropriate amplification, the frequency gap could be negligible.

The single-board computer chosen was the Raspberry Pi 4 Model B (RPi), again mainly due to its availability and affordability. While this project would be completely doable on older models of RPi, the newest model is significantly faster making these data-intensive tasks more manageable at a similar power consumption [9]. This SBC offers a good balance of performance, power consumption, and cost compared to others.

3 Automation and Headless Operation

3.1 New Contributions

While other people have already written bash scrips that can schedule, record, and process satellite transmissions, these scripts lack several key features. This work expands on widely-circulated previous scripts [13, 10] with the goal of refining the automation of scheduling, receiving, and processing weather satellite signals. This included creating directories for each day of data collection and for each satellite pass, overlaying maps with less distracting colors, saving more enhancements and image interpretations by default, and saving all information required to decode/demodulate the recorded signals in the future including as raw data and logging of TLEs and location at the time of capture. In short, we wrote scripts that logged more information about each pass, extracted more information by default, and organized the processed images in a clearer way than previous work.

Additionally, previous attempts at automation handle the problem of two simultaneous satellite passes poorly. When tracking four transient satellites, each having fly-over windows lasting approximately 10-15 minutes several times per day, conflicting fly over windows are a likely event and were observed early on in data collection. In the case of two conflicting fly-overs, it would be best only to record the signal from the satellite that will be passing at a higher elevation in the sky, giving a stronger signal, or prioritize the METEOR satellites which offer higher resolution images. A python script was written to do those prioritizations, structured to handle multiple simultaneous overlaps.

When prioritizing conflicting satellites, many edge cases exist. For instance, an early prioritization scheme that was improved upon was simply looking at two conflicting satellites and scheduling the ”better” one for recording and processing, and canceling the recording of the other. There is the concern that the two satellites being compared are actually a part of a chain of overlapping passes, where the first overlaps with the second, the second satellite overlaps with the first and third, etc, until the last satellite passes overhead. If, by bizarre circumstance, each satellite had increasing elevation with the last satellite having the greatest elevation (highest priority), all satellites except the last would be canceled. So, de-

Transient Satellite	Center Frequency	Bandwidth	Modulation Scheme
NOAA 15	137.6200 MHz	38 MHz	APT (Analog)
NOAA 18	137.9125 MHz	38 MHz	APT (Analog)
NOAA 19	137.1000 MHz	38 MHz	APT (Analog)
Meteor M2 Pathfinder	137.1000 MHz	150 MHz	LRPT (Digital)

Table 1: Center frequencies, modulation schemes, and bandwidth required for the targeted transient satellites (NOAA 15 [5], 18 [6], 19 [7], and Meteor M2 [4])

spite the last satellite only having a conflict with one other satellite, it would cause all other satellites in the chain to get canceled. This is obviously unacceptable, as overlaps and chains are likely when observing four satellites that each pass for 15 minutes four times per day.

The solution is to make decisions based not only on if a given satellite (A) overlaps with another satellite (B), but also to look if satellite B has further conflicts that should be taken into account. While complicating the scheduling, it makes sure the maximum amount of passes with relatively high resolution are being captured without conflict.

Other software improvements made include making the system more robust without a wireless network. This includes checking a real-time clock upon startup if there is no network connection, otherwise the RPi would not update its clock and miss the pass. This also includes changing the bash scripts to not attempt to update the two-line element files (TLE) if there is no network connection. These files contain information that is used to predict satellite times, and if updated without a network connection an error is thrown. If not handled, and none of jobs would start and no data would be collected.

4 Antenna Simulation and Fabrication

Several popular antenna designs exist for receiving signals in the 137MHz range, including quadrifilar helical antennas (QHF), double-crossed antennas, and V-dipole antennas with or without reflectors. Due to its low cost and ease of fabrication, a double-crossed antenna was built and was able to receive NOAA images (figure 2), but a cheap premade V-dipole antenna with reflectors (figure 1) was used to capture most images found here as it was found to have the best receptivity between the two. The built designs were simulated to provide better comparison of antennas.

4.1 Double-Crossed Antenna

A double-cross antenna (DCA) was the initial antenna choice, as a few groups had found DCAs to have a good balance of omnidirectional reception while still being easy and cheap to build [8]. A comprehensive guide to building a DCA is popular [12], including wiring diagrams and component characteristics.

Four dipoles, each a half-wavelength ($\lambda/2$) long with the feed in the middle, are placed evenly around a circle with radius of $\lambda/4$ and tiled by 30 degrees to receive the circularly-polarized signal. This design is meant to be tolerant of construction variations [12]. A receptivity diagram and picture of the completed can be seen in figure 2.

Figure 2: Left: The final built DCA antenna. Note how it uses the same PVC base as the V-dipole antenna, allowing for quick assembly and modularity with other antenna types. Right: A free space radiation pattern diagram for the double-crossed antenna as described by Martes guide [12], simulated in MATLAB.

From the simulated receptivity diagram, it is clear that this is a great omni-directional design that will not pick up on unwanted signals reflected from the ground.

Using PVC and wire clamps, the DCA was fabricated in what seems to be the simplest and cheapest way possible, built entirely out of materials bought at a local hardware store. Initial designs inspired by previous work had problems of inconvenient wiring, fragile connections, and poor portability [18]. This new design allows for the dipoles to be removed easily, the entire antenna to be popped on or off its stand for repairs and mobility, all wiring is accessible, and it is low-cost. See figure 2 for reference.

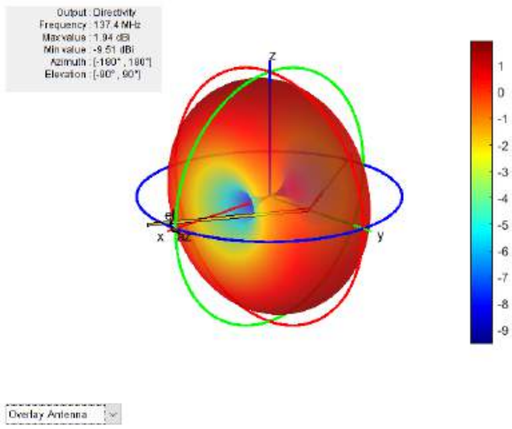

Figure 3: A free space radiation pattern diagram for a V-dipole tuned to 137.4MHz

4.2 V-Dipole

A V-dipole was bought [17] and configured for each side of the dipole to be $\lambda/4$ long at 120 °apart. The receptivity diagram can be seen in figure 3. While not omni-directional, it has good overhead receptivity around the plane perpendicular to both dipoles. As all transient satellites orbit north-south, the antenna can be oriented parallel to the ground and north-south would have good reception to the desired signals while cutting out unwanted signals from most other directions.

4.3 Novel Antenna Accessories

All antennas used stood on a PVC base that provided rigidity and durability, while still being cheap and accessible to hobbiests and student groups. This base allowed the design to be extremely modular, with antennas being switched out, heights easily changed, and accessories easily designed to snap on to the PVC pipes. See figure 1.

4.3.1 V-dipole guides

While the V-dipole set-up is common among satellite enthusiasts, several problems exist. It is tedious to set-up the V-dipole to exactly 120 degrees, and the v-dipole is not sturdy enough to keep its angle consistent against winds and weather for extended periods if left alone . As such, a 120 degree guide was designed and 3D printed (seen in figure 1) to fix the dipole in place. A compass mount was also built into it in order to attach a flat-pack compass to the guide, making it easier to orient the antenna north-south.

4.3.2 Compact and Portable Raspberry Pi Storage

A significant design hurdle was powering, storing, and weather-proofing the the Raspberry Pi to make extended outdoors data collection possible. The solution also had to be compact and cheap.

A case was designed for the Raspberry Pi that fits a standard power bank, a 30mm fan, USB accessories (including the SDR), and friction fits into 3” PVC stand by taking advantage of a compliant 3D printed spring mechanism. GPIO pins are accessible for other peripherals. Its ability to slide into the existing 3” PVC antenna mount means that all wires can be routed inside the antenna mount, increasing durability of the overall design. The RasPi is protected from the elements and able to take data as long as the power bank holds out. See figure 4 for reference, or appendix B, figure 13.

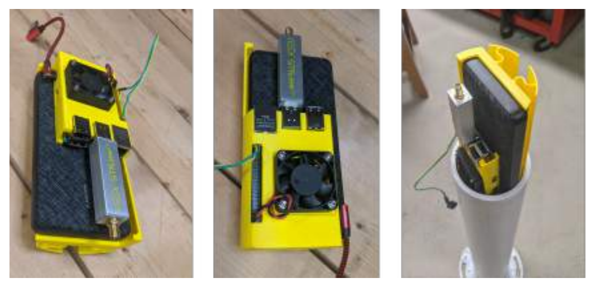

Figure 4: The final case for the Raspberry Pi, holding the power bank, SDR, and fan, all fitting within the 3” PVC pipe. The thick red wire transfers power from the battery to the Pi, while the red/yellow wires provide a shutdown switch for the Pi.

5 Results

This set-up lasts approximately four days on a 20Ah battery before losing power. During the initial test, it had access to wi-fi and could sync its data to a cloud service, and subsequent tests were done in a more remote area without service.

Despite simulations showing the DCA antenna having better receptivity, field tests showed the V-dipole to generally receive cleaner pictures than the double-crossed antenna. This could be due to the V-dipole rejecting unwanted signals from the sides, while the DCA would be more susceptible to noise from all directions.

On reflection, it would have been a better choice to build a QHF antenna rather than a DCA, as the DCA ended up not having great receptivity and was more complex to build than initially thought, and likely similar in complexity to a QHF antenna.

Satellite / Object	Center Frequency (MHz)	Bandwidth (kHz)
NOAA Series (APT)	137	38
NOAA Series (HRPT)	1,680	4,000
Meteor M2	137	150
GOES Series	1,694.1	1,000
Hydrogen Band	1,420	2,000 - 5,000

Table 2: NOAA Satellites [1], [5] (transitory), Russian Meteor satellite [4] (Transitory), GOES satellites [2, 3] (geostationary), and hydrogen band center frequencies and bandwidths required. The frequency is approximate, varying by satellite and Doppler shift.

5.1 NOAA Satellite Images

In addition to the false-color images below, maps of precipitation, temperature, sea surface temperature, and IR are created for these (and all) passes using data encoded in the satellites transmission. A selection of relatively low-noise images are seen below in figures 7 and 6. More images and enhancements can be seen in appendix A.

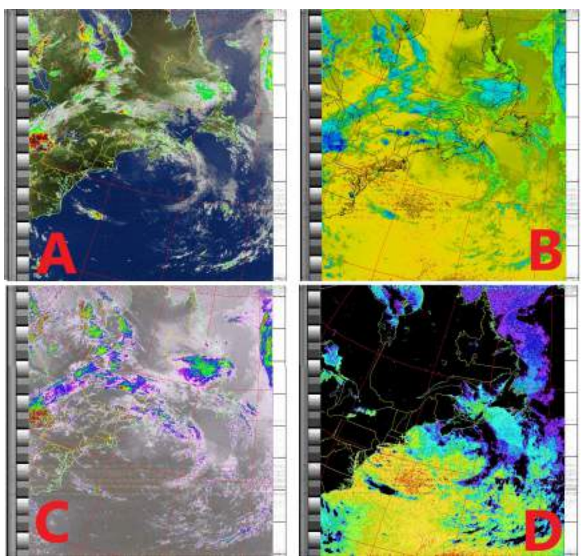

Figure 5: This is the same pass as seen in fig 6, without the metadata cut off from the sides and with other enhancements. NOAA 19 northbound pass at 27 Jul 2020 21:44:09 GMT on 137.10MHz, Normal projection, Channel A: 2 (near infrared), Channel B: 4 (thermal infrared). Picture A is MCIR enhancement with precipitation enhancement, B shows thermal enhancements, C is IR enhancements, and D is sea surface temperature enhancement.

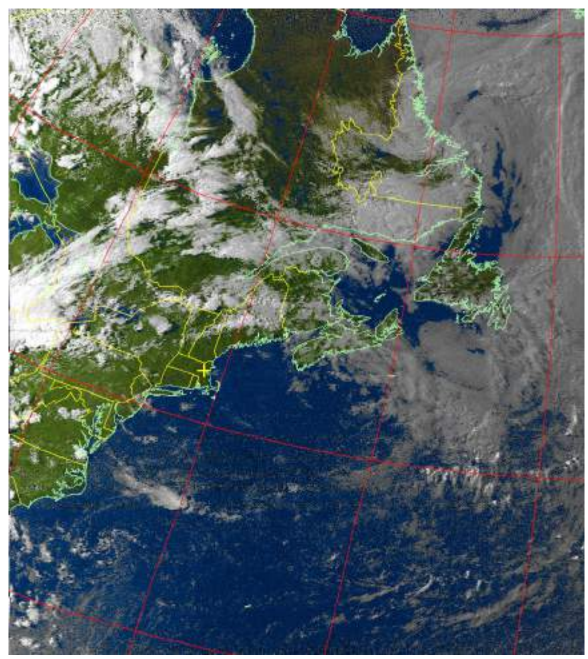

Figure 6: NOAA 19 northbound pass at 27 Jul 2020 21:44:09 GMT on 137.10MHz, MSA enhancement, Normal projection, Channel A: 2 (near infrared), Channel B: 4 (thermal infrared). Taken with a V dipole antenna. Maximum SNR for this picture was around 34dB.

5.2 Meteor Satellite Images

6 Future Work

An easy evolution of this project would be using a directional antenna and minimal changes in set-up to receive GOES satellite imagery, including continuous full-disk images of the earth. Further expansions of the project would use the SDR for radio astronomy, such as probing the hydrogen band to image the galaxy and using the Doppler shift of the hydrogen band to see different parts of the galaxy's movement relative to the observer [11]. With a big enough directional antenna/receiver, the radio signature of quasars could also be observed. Additionally, with a directional antenna with the ability to track transient satellites combined with an SDR with a wide bandwidth could receive high-resolution picture transmission (HRPT) [14]. A summary of future work can be seen in table 2.

UPDATE OSCAR LINKS, MAKESURE NO DEAD LINKS

References

[1] Rtl-sdr tutorial: Receiving noaa weather satellite images. 2013. https://www.rtl-sdr.com/rtl-sdr-tutorial-receiving-noaa-weather-satellite-images/.

[2] Observing Systems Capability Analysis and Review Tool (OSCAR). Satellite: Goes 16. Technical report, 2020. https://www.wmo-sat.info/oscar/satellites/view/152.

[3] Observing Systems Capability Analysis and Review Tool. Satellite: Goes 17. Technical report, 2020. https://www.wmo-sat.info/oscar/satellites/view/664.

[4] Observing Systems Capability Analysis and Review Tool. Satellite: Meteor-m n2. Technical report, 2020. https://www.wmo-sat.info/oscar/satellites/view/284.

[5] Observing Systems Capability Analysis and Review Tool. Satellite: Noaa-15. Technical report, 2020. https://www.wmo-sat.info/oscar/satellites/view/337.

[6] Observing Systems Capability Analysis and Review Tool. Satellite: Noaa-18. Technical report, 2020. https://www.wmo-sat.info/oscar/satellites/view/340.

[7] Observing Systems Capability Analysis and Review Tool. Satellite: Noaa-19. Technical report, 2020. https://www.wmo-sat.info/oscar/satellites/view/341.

[8] Justin Atkin. How to pull images from satellites in orbit (noaa 15,18,19 and meteor m2), 2017. https://www.youtube.com/watch?v=cjClTnZ4Xh4&t=175s.

[9] Raspberry Pi Foundation. Raspberry pi 4 tech specs. webpage, 2020. https://www.raspberrypi.org/products/raspberry-pi-4-model-b/specifications/.

[10] haslettj. Raspberry pi noaa weather satellite receiver. 2017. https://www.instructables.com/id/Raspberry-Pi-NOAA-Weather-Satellite-Receiver/.

[11] Marcus Leech. A 21cm radio telescope for the cost-conscious. 2013. https://www.sbrac.org/files/budget_radio_telescope.pdf.

[12] Gerald Martes. Double cross — a noaa satellite downlink antenna. 2008. https://web.archive.org/web/20160403221532/http://noaaport.poes-weather.com/download/jm-dca/MARTES_Double_Cross_Antenna.pdf.

[13] NateDN10. Raspberry pi noaa and meteor-m 2 receiver. 2020. https://www.instructables.com/id/Raspberry-Pi-NOAA-and-Meteor-M-2-Receiver/.

[14] NOAA. User's guide for building and operating environmental satellite receiving stations. 2009. https://noaasis.noaa.gov/NOAASIS/pubs/Users_Guide-Building_Receive_Stations_March_2009.pdf.

[15] NooElec. Nooelec nesdr smartee xtr sdr. Webpage, 2020. https://www.nooelec.com/store/sdr/sdr-receivers/nesdr-smartee-xtr-sdr.html.

[16] RTL-SDR.com. Rtl-sdr tutorial: Decoding meteor-m2 weather satellite images in real-time with an rtl-sdr. 2015. https://www.rtl-sdr.com/rtl-sdr-tutorial-decoding-meteor-m2-weather-satellite-images-in-real-time-with-an-rtl-sdr/.

[17] RTL-SDR.com. Buy rtl-sdr dongles (rtl2832u). Webpage, 2020. https://www.rtl-sdr.com/buy-rtl-sdr-dvb-t-dongles/.

[18] u/Oxffff0000. Double cross dipole antenna build. Webpage, 2020. https://www.reddit.com/r/RTLSDR/comments/7mg2gn/double_cross_dipele_antenna_build/.

A More Satellite Pictures

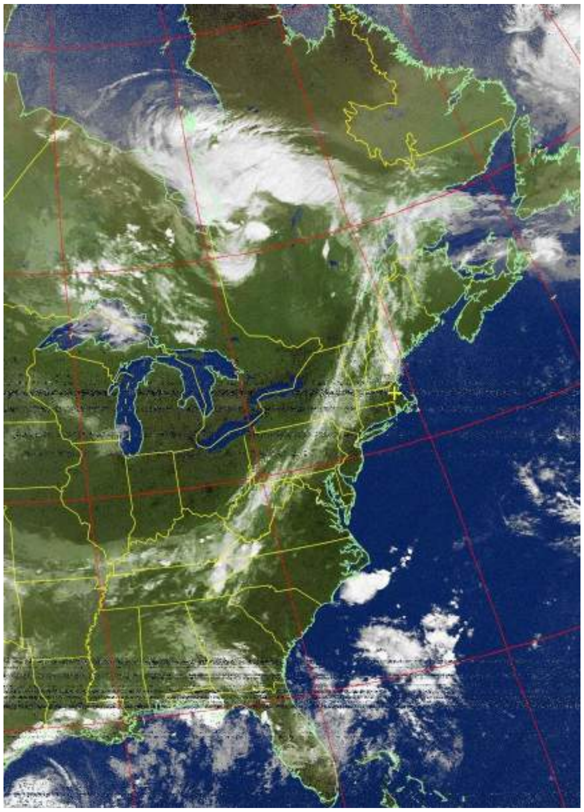

Figure 7: NOAA 18 northbound pass at 28 Jul 2020 14:58:09 GMT on 137.9125MHz, MCIR enhancement, Normal projection, Channel A: 2 (near infrared), Channel B: 4 (thermal infrared). Taken with a V dipole antenna. Maximum SNR for this picture was around 32dB.

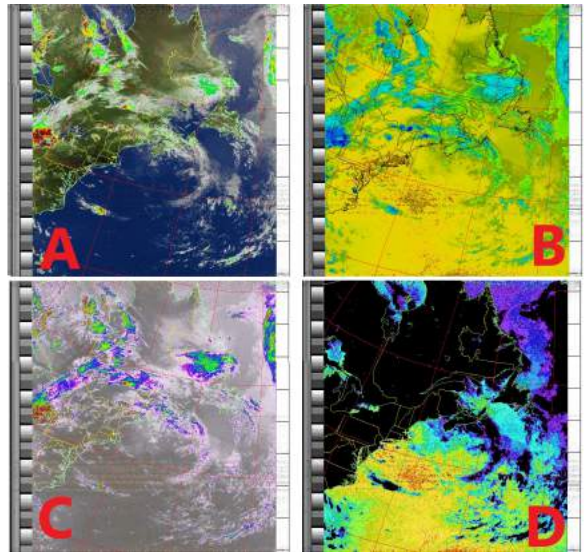

Figure 8: This is the same pass as seen in fig 6, without the metadata cut off from the sides and with other enhancements. NOAA 19 northbound pass at 27 Jul 2020 21:44:09 GMT on 137.10MHz, Normal projection, Channel A: 2 (near infrared), Channel B: 4 (thermal infrared). Picture A is MCIR enhancement with precipitation enhancement, B shows thermal enhancements, C is IR enhancements, and D is sea surface temperature enhancement.

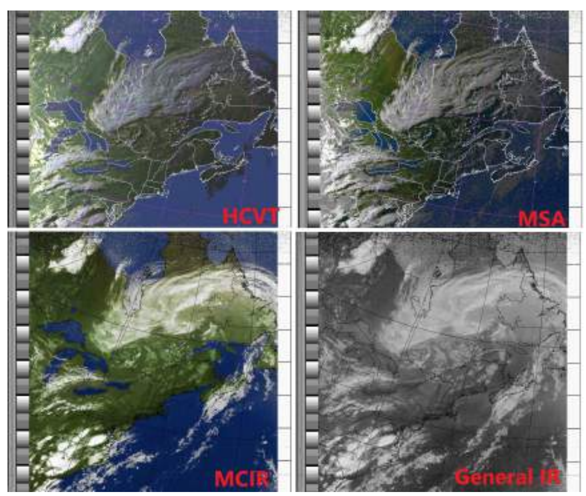

Figure 9: NOAA 15 pass at 05 Aug 2020 23:29 GMT on 137.620MHz, Normal projection, Channel A: 2 (near infrared), Channel B: 4 (thermal infrared). These are all the same pass under different false-color enhancements available.

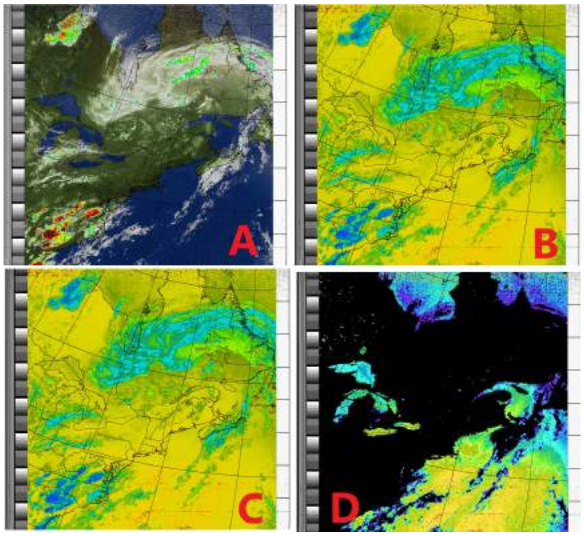

Figure 10: This is the same pass as seen in fig 9, showing different data enhancements available. Picture A is MCIR enhancement with precipitation enhancement, B is a thermal enhancements, C is IR enhancements, and D is sea surface temperature enhancement.

B CAD Drawings

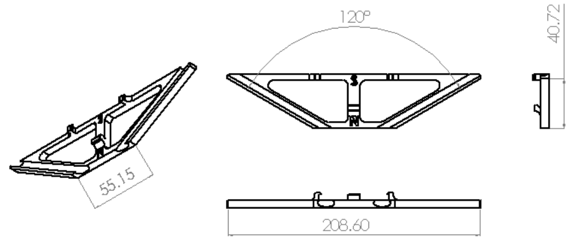

Figure 11: CAD Drawing of the V dipole guide, designed to fit the RTL-SDR V dipole [17]. All measurements shown are in millimeters.

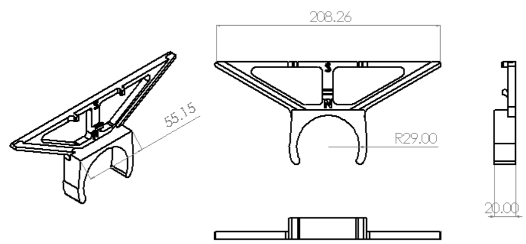

Figure 12: CAD Drawing of the V dipole reflector guide, designed to fit 2” PVC pipe. All measurements shown are in millimeters.

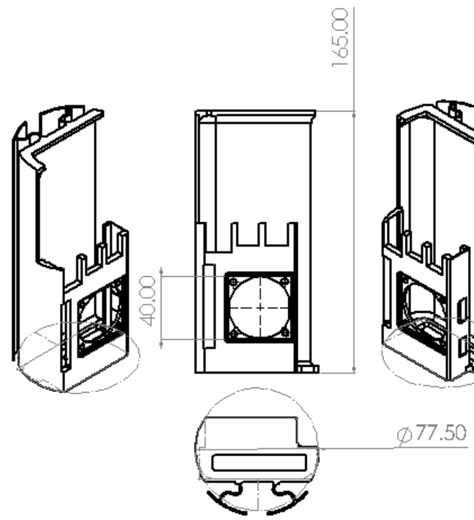

Figure 13: CAD Drawing of the Raspberry Pi case, designed to fit inside 3” PVC pipe. All measurements shown are in millimeters.