How to set up an ADS-B base station for FlightRadar24

What's ADS-B?

ADS-B is a radio protocol by which airplanes continuously transmit their identification, position and altitude. The transmissions are made **A**utomatically without any input from the pilots. The data is **D**erived from the airplane's own navigation systems, like its GPS receivers. It is a **S**urveillance tool used by Air Traffic Control because it provides much more data that ground-based primary radar. Lastly, it is a **B**roadcast that can be received by ATC, other airplanes and me.

All commercial aircraft are now required to have ADS-B transmitters. When an Air Traffic Controller looks at his radar screen, it is the ADS-B data that pops up on the screen beside each blip, identifying the airplane and, crucially, its altitude.

The frequency assigned to ADS-B signals is 1090 MHz. To put this in context,

the High Frequency (HF) range is 3 – 30 MHz;
the Very High Frequency (VHF) range is 30 – 300 MHz, which includes FM radio is 88 – 108 MHz; and
the Ultra High Frequency (UHF) range is 300 – 3000 MHz, which includes microwave ovens at about 2500 MHz.

The wavelength of ATS-B signals can be calculated as:

$$\begin{aligned} \text{wavelength } (\lambda) &= \frac{\text{speed of light } (c)}{\text{frequency } (\nu)} \\ &= \frac{2.9979 \times 10^{8} \text{ m/s}}{1.090 \times 10^{9} \text{ cycles/s}} \\ &= 275 \text{ millimeters} \end{aligned}$$

The driven element of a typical quarter-wavelength Marconi antenna at this frequency will be 68.8 millimeters, or about 2-3/4 inches.

ADS-B data is transmitted in "packets' each consisting of a stream of 112 bits called a squitter. The information is sent in plain text; it is not encrypted. A typical squitter contains four separate fields:

an 8-bit control field;
a 24-bit airplane address field;

a 56-bit data field; and
a 24-bit parity field.

The entirety of an airplane's data is not contained in a single squitter. A single squitter may contain an airplane's velocity, its position, its status, etc. Different data is transmitted when the airplane is on the ground than when it is airborne. The repetition rate for squitters depends on the type of data it contains.

<u>What's FligthRadar24?</u>

FlightRadar24 is one of the half-dozen or so websites which display airplane locations in real time. All of these websites consolidate ADS-B data received by hobbyists located around the world. The receiver each hobbyist maintains relays transmissions he receives over the internet to the website.

These websites make most of their money through advertising. Travelers log onto the website to track flights of interest and, as usual, have to navigate through ads to get the information they want. Frequent travelers can purchase subscriptions which provide enhanced data.

These websites "pay" their feeder hobbyists by giving them a business subscription. In the case of FlightRadar24, the retail value of the subscription is several hundred dollars per year. The little secret – don't tell anybody – is that these hobbyists do this mostly just for the fun of it.

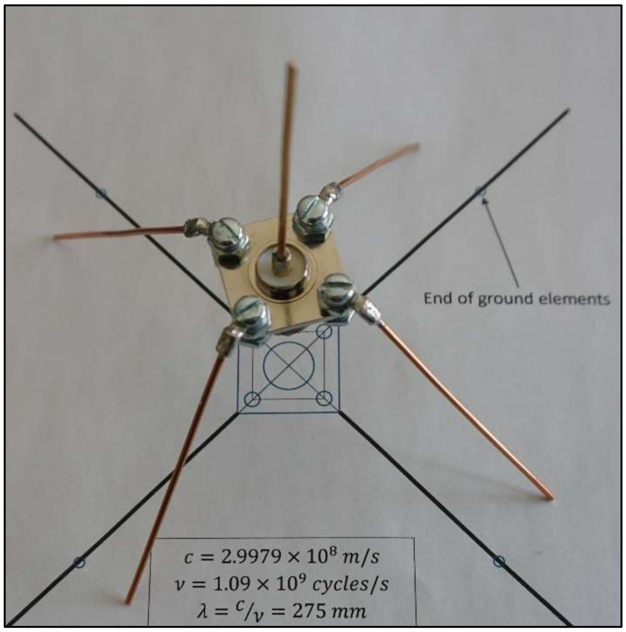
Yep, I'm a feeder. I'm one of these hobbyists and intend to use a Raspberry Pi 3B+ as my base station.

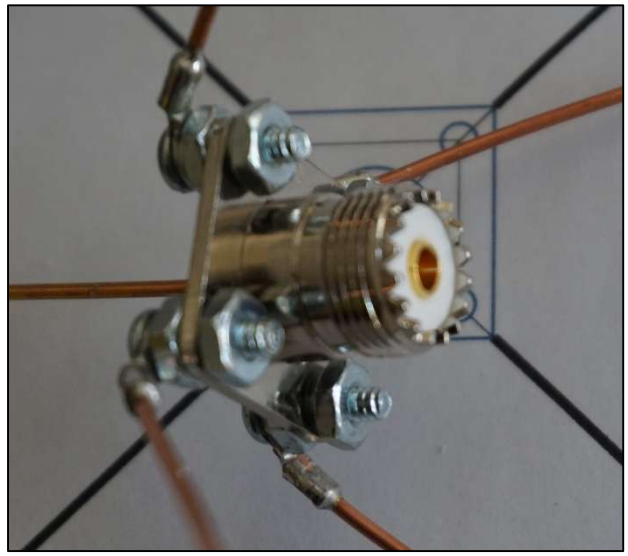
<u>The antenna</u>

I built a ground-plane antenna from an SO239 UHF four-hole flanged connector and a couple of feet of standard 14-gauge 2-conductor cable. This 14/2 cable is commonly used for residential wiring. The antenna is shown in the two photographs at the top of the next page.

I stripped the insulation off the cable and then cut five pieces about three and one-half inches long. Four of the pieces will be ground elements; the fifth will be the vertical element. I crimped a ring terminal (red size) to one end of each ground element and then soldered the ring in place. I used a #6 bolt to secure each ring to one of the corner holes of the SO239 flange and then bent the element down at a

45⁰ angle. When they are angled correctly, the ground elements outline the edges of a square pyramid.

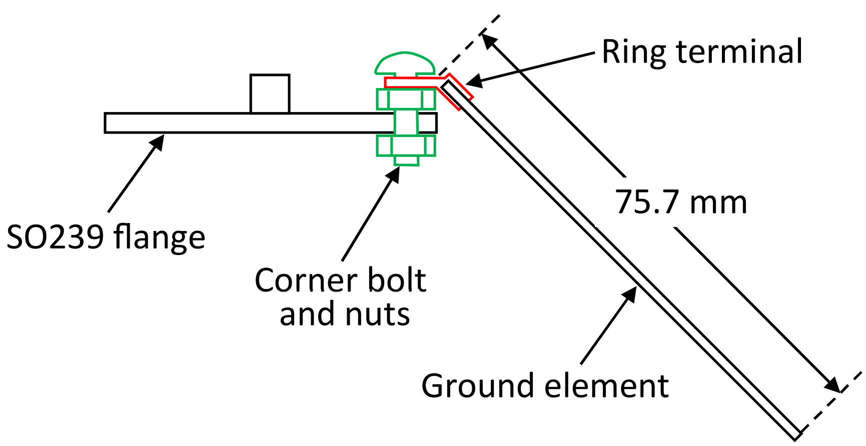




This photograph shows the bottom of the SO239 connector.

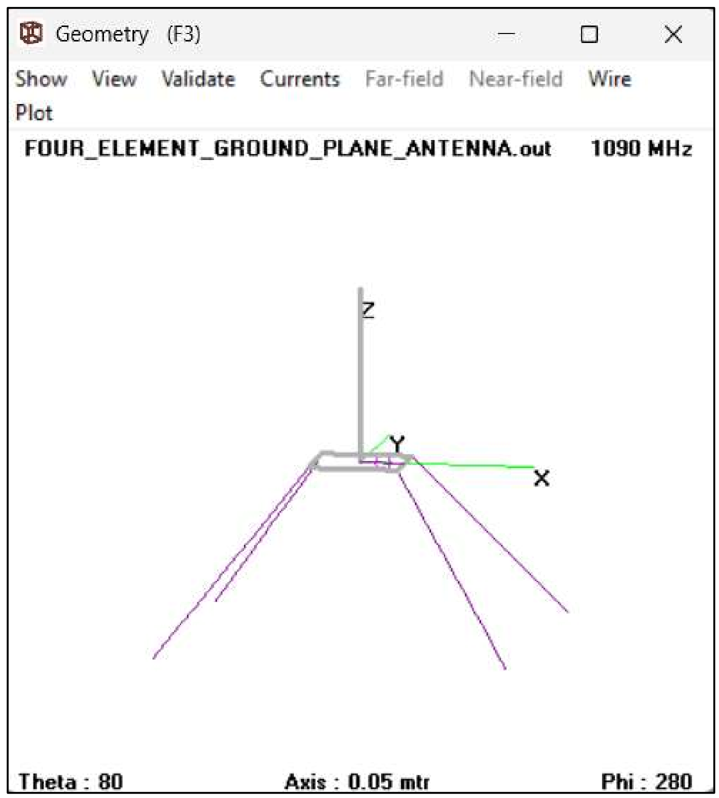
I soldered the fifth piece of wire into the top-side socket to act as the antenna's vertical element.

Antenna performance is highly dependent on the exact length of the vertical element. On the other hand, performance is much less sensitive to the length of the ground elements, which are often cut to a length of 110% or 120% of the quarter-wavelength. To cut the ground elements for my antenna, I measured 75.7 millimeters down each ground element from the head of the bolt. This distance is 110% of the quarter-wavelength. The following diagram shows how I made the measurements.



I have attached as Appendix "A" a template I used to adjust the angles of the four ground elements after they had been cut to the correct length. When the antenna is placed and centered on the template, the ends of the ground elements should be in the indicated positions on the template.

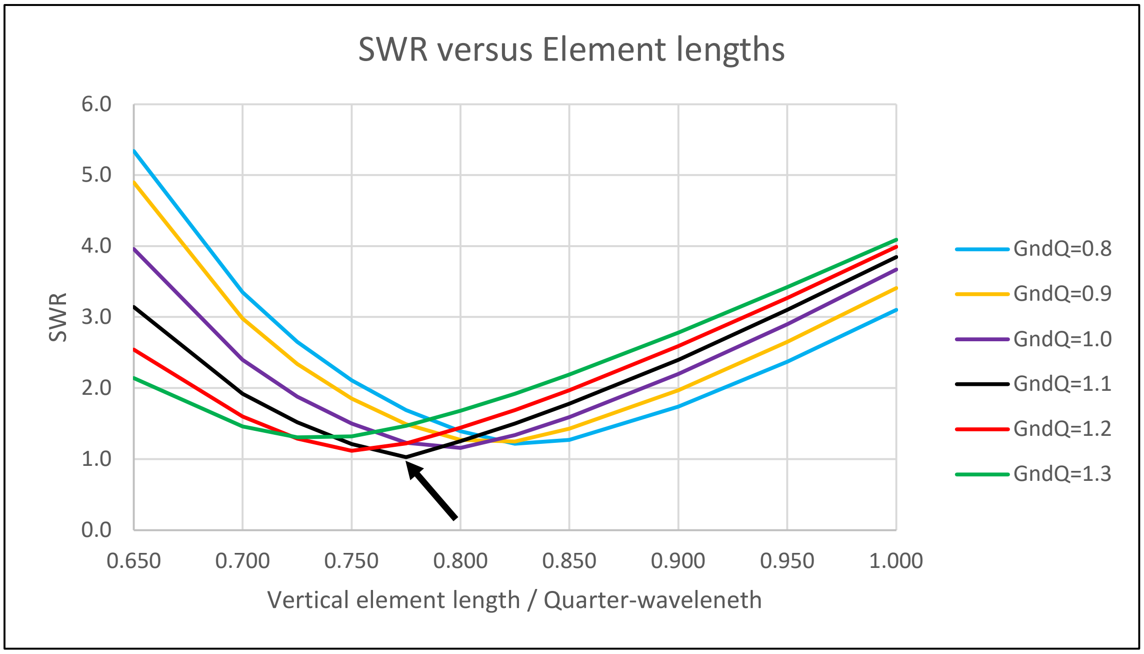
I modelled the antenna using the 4NEC-2 antenna software beloved of Ham radio operators. Appendix "B" is the input file, which describes the geometry and the wires and the required excitation at 1090MHz. The program is particularly helpful because it takes into account the physical diameter of the elements. In this case, the 14/2 wire used has a diameter of 0.815 millimeters. This is not trivial when compared with the lengths of the elements. In fact, the vertical and ground elements are divided into 11 segments for FEM analysis, where the minimum segment length is three times the wire diameter. The following figure shows the geometry used by the simulator.



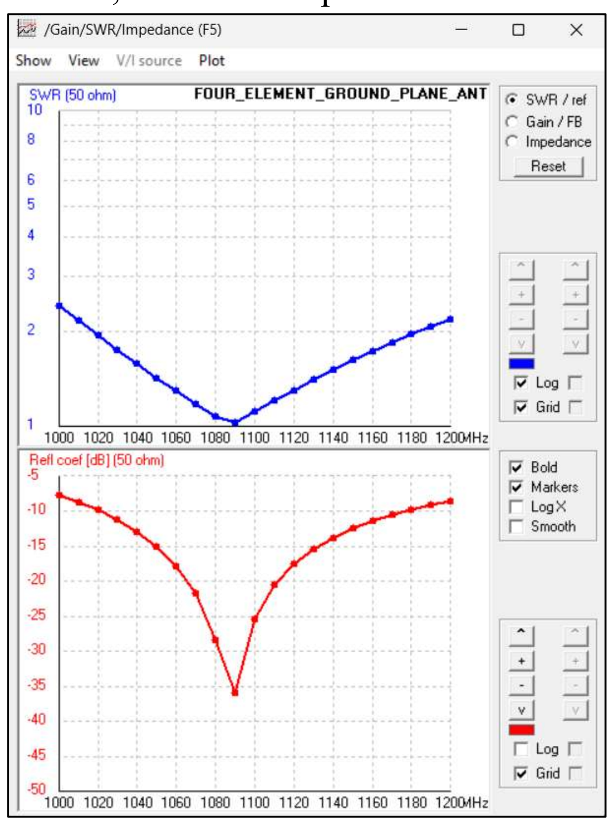
The SO239 connector is modelled by a square loop of wire – one inch on each side. The ground elements slope down at 45º from each corner.

In order to allow the lengths of the elements to be varied easily, I introduced two variables: `VertCoef` and `GndCoef`. These are the lengths of the vertical element and the ground elements, measured in units equal to one-quarter wavelength. For example, if `VertCoef=0.8`, then the physical length of the vertical element is 80% of a quarter-wavelength, or $0.8 \times 68.8 \text{ mm} = 55.04 \text{ mm}$.

My objective was to select the lengths of the elements which resulted in the minimum Standing Wave Ratio (SWR). If the antenna radiates perfectly at 1090 MHz, the SWR would be 1.0. I ran a number of simulations with differing lengths. The results are summarized in the following graph.

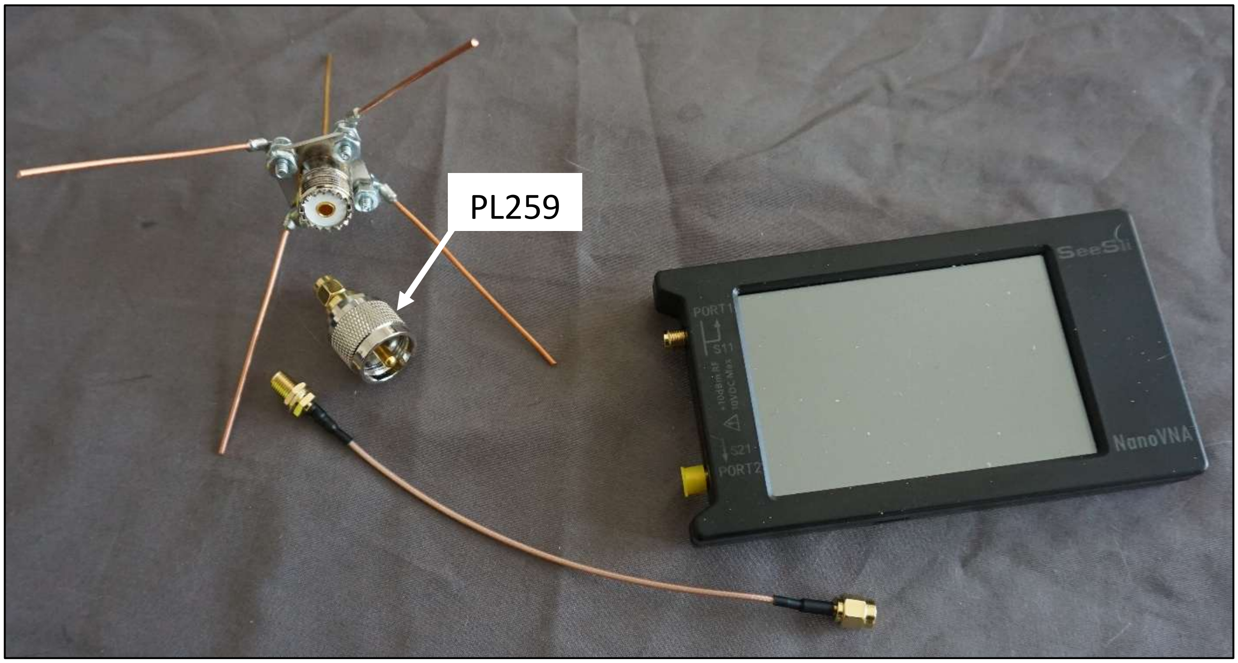


The graph plots the SWR (on the vertical axis) against the length of the vertical element (on the horizontal axis). All of these vertical lengths are relatively “short”, meaning less than a quarter-wavelength long. There are six separate traces, each corresponding to a different length of the ground elements. The black arrow points to the best, or lowest, SWR, of 1.03. It occurs when ground element coefficient is 110% and the vertical element coefficient is 77.5%, which correspond to 75.7 mm and 53.3 mm, respectively.



As I said above, I cut the ground elements 75.7 millimeters long after I bolted them to the connector. Trimming the vertical element needs more care. Since I will be using a Network Analyzer to do this, I thought it would be useful to see what a frequency sweep should look like. The prediction from the 4NEC2 model is shown here, with a sweep from 1000 MHz to 1200 MHz. The blue trace is the SWR. It has its minimum value (1.03) at 1090 MHz and rises to more than 2 at frequencies 100 MHz to either side. The red trace is the reflection coefficient, which also reaches its minimum at 1090 MHz.

The following photograph shows the equipment I used to trim the vertical element to length.

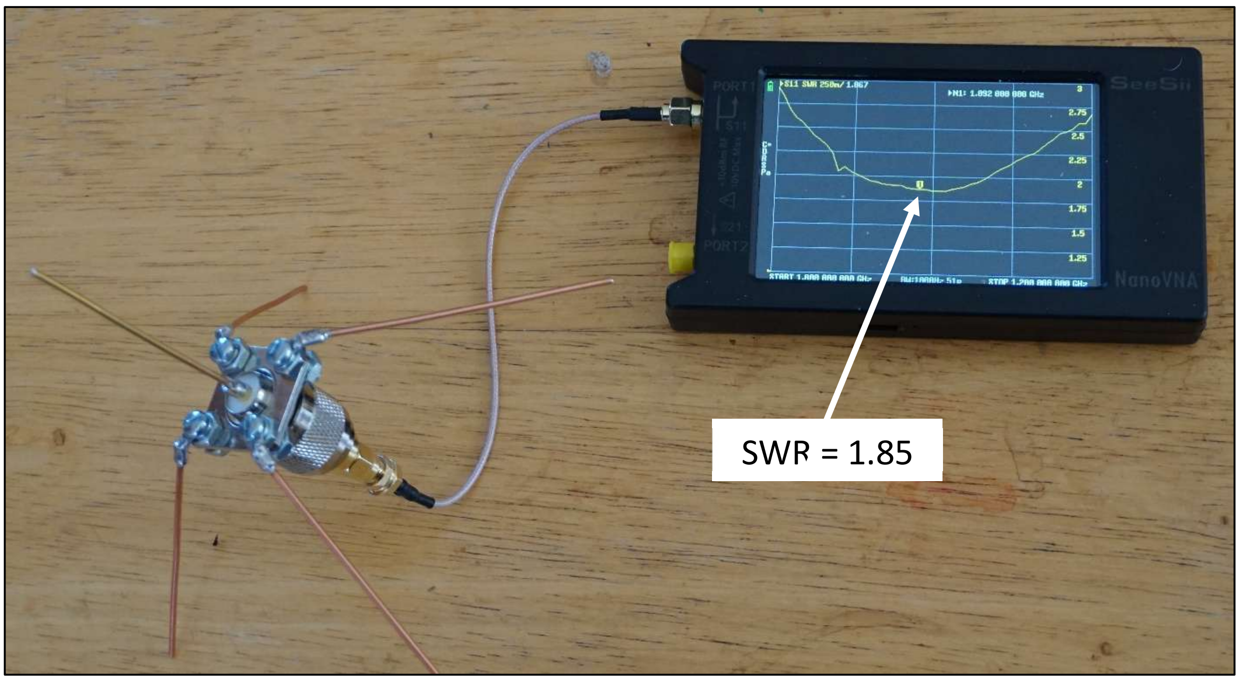


A UHF PL259 male plug (pin in center) is screwed onto the antenna's SO239 flanged connector. To be precise, the PL259 plug is an adapter with a male SMA plug (pin in center) on its other end. The 50Ω UHF coaxial cable has an SMA female connector on one end and an SMA male connector on the other. The free end of the coaxial cable is screwed into the reflection port (S11) of the Network Analyzer. (For those interested, the Network Analyzer is a NanoVNA-H4 made by the Chinese firm SeeSii.) The six-inch coaxial cable is necessary for physical clearance – without it, there is not enough room for the Network Analyzer inside the "pyramid" formed by the ground elements.

Before starting the test, it is necessary to calibrate the Network Analyzer. First, the desired endpoints of the frequency sweep are entered. Then, one-by-one, three test loads are screwed into the reflection port and the Network Analyzer instructed to make a measurement. The three test loads are: (i) a short-circuit connector, (ii) an open-circuit connector and (iii) a 50Ω connector. These test loads are included as accessories in the kit containing the Network Analyzer. The calibration settings can be saved for later use. I have listed in Appendix "C" the steps in the procedure to carry out the calibration.

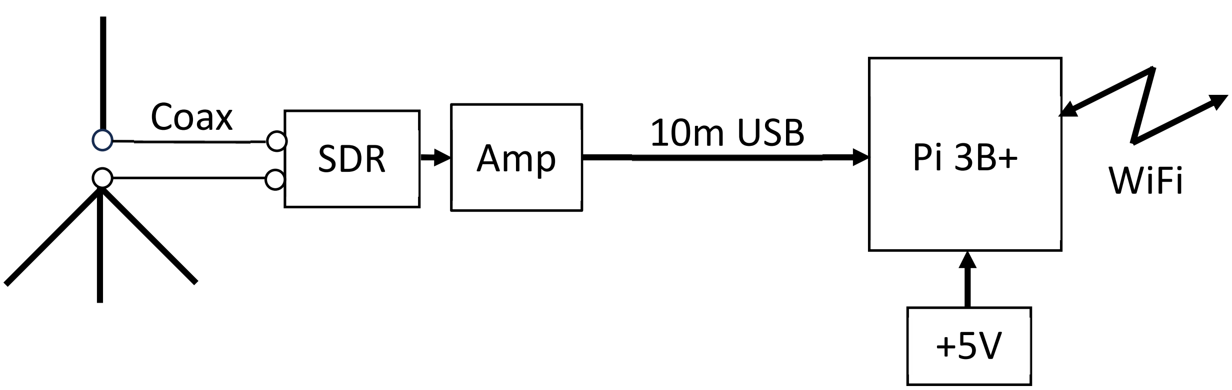
Finally, the last of the test connectors are removed and the antenna screwed into position. I configured the Network Analyzer to simultaneously display: (i) the SWR across the frequency range, (ii) the reflection coefficient across the frequency range and (iii) the Smith chart. Using a pair of wire cutters, I cut tiny bits off the end of the vertical element. As each little bit was removed, the display would show a very slight increase in the resonant frequency.

The next photograph shows the display when the resonant frequency at last reached 1090 MHz. In this photograph, only the SWR trace is displayed – that enables a scale to be shown along the right-hand edge, ranging from an SWR of one (1) at the bottom to three (3) at the top. The frequency sweeps from 1.000 GHz at the left to 1.200 GHz at the right, with the target frequency a little left of center. The SWR is approximately 1.85 at this point. That's not great but, on the other hand, it isn't bad for such a small antenna and such a "clunky" feed point.



Note that I ran the test on a wooden table. The measurement is quite sensitive to bits of metal in the vicinity, including on one's person.

An overview of the base station

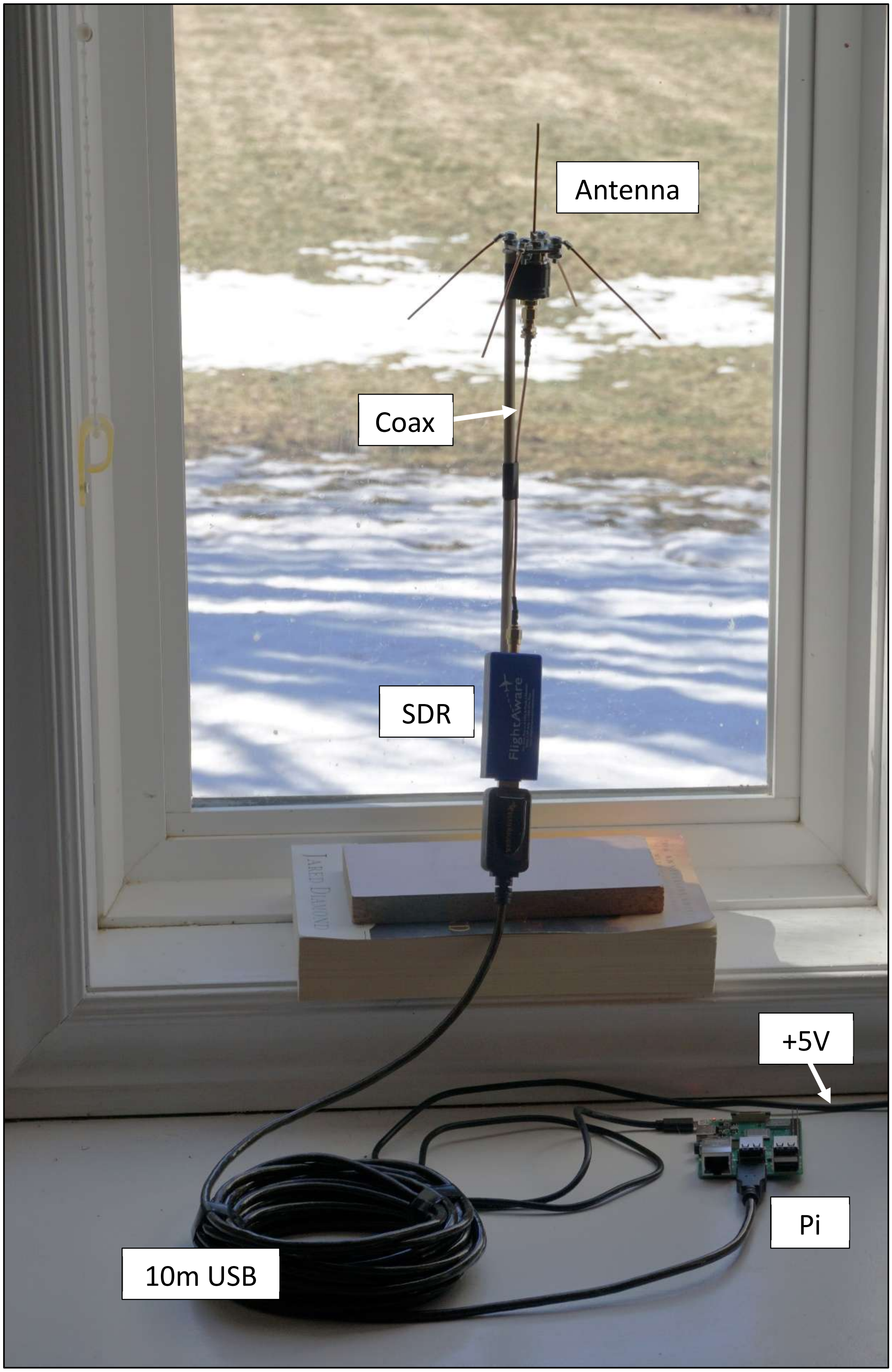


The antenna, with its SO239 flanged base, the PL259 adapter and the six-inch UHF coaxial cable form the input end to the FlightRadar24 base station. The coaxial cable feeds a Software-Defined Radio (SDR) dongle which converts the analogue UHF signal into digital packets. (The coaxial cable is needed to provide physical separation for the dongle, which should not be placed too close to the ground elements of the antenna.) The dongle is about the size of a large USB stick. Its input end is an SMA female connector; its output end is USB. This photograph shows the dongle attached to the coaxial cable. Keen-eyed readers will see that this dongle is a blue "FlightAware Pro" stick. FlightAware is a competitor of FlightRadar24. Nonetheless, the reviews I've seen on the web seem to show that this dongle is one of the best SDRs available.

Plugged into the bottom of the SDR in the photograph is one end of a 10-meter long active USB cable. The other end of the USB cable plugs into the Pi motherboard. The cable is "active", meaning that the signal is amplified before it is sent down the cable. Amplification is needed if the signal is to survive the attenuation it suffers passing through such a long cable. The amplifier is the black blob at the input end of the cable, just below the SDR dongle in the photograph. The amplifier needs a +5V power supply to operate. Conveniently, this power is supplied through the USB port of the Raspberry PI. There is no conflict between DC (direct current) passing up the cable while AC (the signal) passes down. The 10-meter length of the cable allows the antenna to be placed a considerable distance (and height) away from the motherboard.

The only other wire connected to the motherboard is the +5V power supply. WiFi carries all signals to and from the Raspberry Pi.

The following photograph shows the setup I used to test the entire system.


Antenna
Coax
SDR
FlightAware
+5V
Pi
10m USB

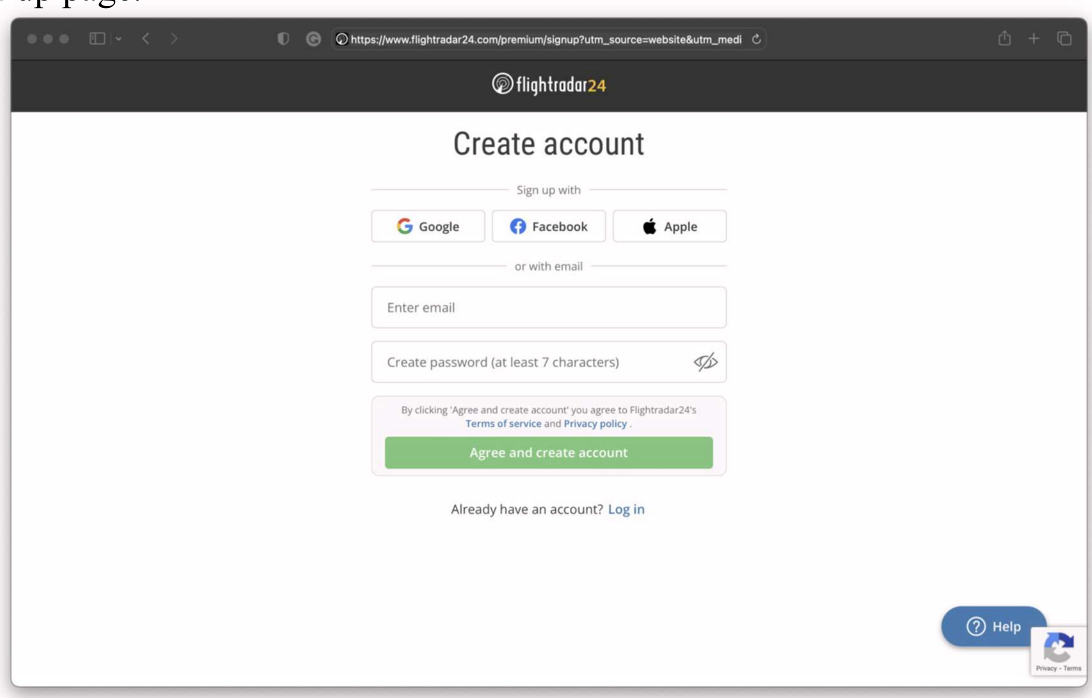
The antenna is mounted on a wooden dowel about 18 inches high. It is placed in a small window on the ground floor facing almost due west.

Creating an account on FlightRadar24

The first step on the software side is to open an account at www.flightradar24.com. This can be done from any computer. It probably makes most sense to sign up using the same computer you will use to monitor the base station on an on-going basis. Presumably, that will be the very same computer you will use to control the Raspberry Pi through an SSH ("Secure Shell") terminal, as I described in a previous paper.

FlightRadar's sign up screens give you several choices of paid accounts. You do not want any of those. You want to sign up for the Free account. Once your base station starts sending data to FlightRadar's head office, your account will automatically be converted into a Business account. This is the little perk which FlightRadar gives to feeders who use their own equipment.

Signing up requires an e-mail address and a password. Later, you can also select a username. These details have absolutely nothing to do with your Raspberry Pi and need not (better yet, should not) be the same as the username and password you chose when you set up the Pi. The following screenshot shows the FlightRadar sign-up page.

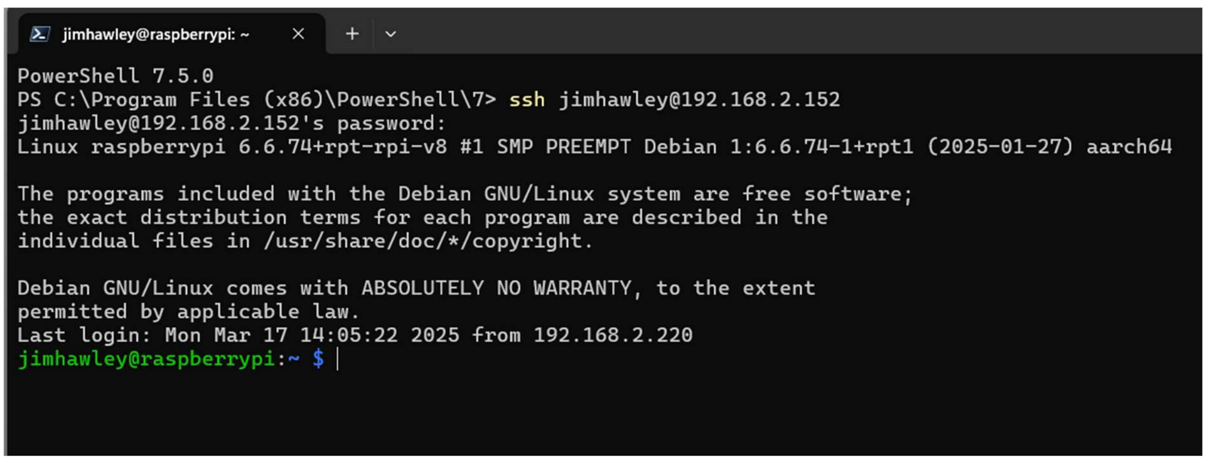


Downloading software for the Pi

It is best to connect the antenna to the Raspberry Pi, and then to turn it on, before running through the following procedure.

Use your monitoring computer to open a Secure Shell terminal window on the Raspberry Pi. When I run Power Shell on my laptop, I see this:

I then open the Secure Shell by typing `ssh jimhawley@192.168.2.152`, as shown in the following screenshot. After entering the password (the Pi's password, not the FlightRadar24's password), there is a legal dump, followed by the prompt from the Raspberry Pi itself: `jimhawley@raspberrypi:~ $`.



From this point on until we end the session, the commands we enter are executed by the Debian O/S running on the Raspberry Pi. The monitoring laptop is running like a dumb terminal.

The first step is to download the flight tracker program from FlightRadars4's website. The required command, to be typed in after the `:~ $` prompt, is as follows. (Unfortunately, the command is too long to be displayed on just one line in this paper, so it appears as two lines. But that is not the case. It is a single line and the character string `/repo-feed.fl` does not contain any blanks.)

```
sudo bash -c "$(wget -O - https://repo-
feed.flightradar24.com/install_fr24_rpi.sh)"
```

As well as downloading certain files, this command will also begin an interactive session through which you will give FlightRadar24 information it needs. These tidbits include:

1. Your email address. This must be the same as the e-mail address you gave when you opened your account at FlightRadar24.
2. The latitude and longitude of your antenna, to a precision of four decimal places. For example, my latitude and longitude here near Toronto are `43.8673` and `-79.9923`, respectively.
3. The altitude above sea level of your antenna, in feet. My altitude is 443 meters, or `1453` feet.

Some questions will not be relevant or, alternatively, you will not be able to answer them yet. Let me run through some of those.

Step 1.2 will ask you to enter your sharing key or (since one has not been assigned to you yet) leave the response blank.
Step 1.3 will ask you if you agree to participate in MLAT calculations. Answer yes. MLAT allows basic data to be calculated for older or private aircraft which do not have ADS-B transmitters. It compares the time delays experienced by several base stations to try to calculate the position and speed of such airplanes.
Step 4.1 will ask you to identify the type of radio receiver you have. The blue FlightAware stick, like virtually all 1090 MHz dongles, are `Type 1 – DVBT Stick (USB)`, so enter `1`.
Step 4.3 will ask you to enter additional arguments for the `dump1090` function. Leave this blank for now.
Step 5.1 will ask if you want to export raw data on port 30002. Answer no.
Step 5.2 will ask if you want to export base station data on port 30003. Answer no.
Step 6 will ask you to choose two-day or three-day cycles for logging data. Ignore the choice and enter 0.

The program will do a little more work and then report `Congratulations! You are now registered and ready to share ADS-B data.` It will also give you a Sharing Key (with the format `00013e5bf0d25b8d`) and a Radar Identification (with the format `T-EGTC8`). Make a note of these codes – they will be needed to access your data on FlightRadar24. FlightRadar24 will also send an e-mail with these codes.

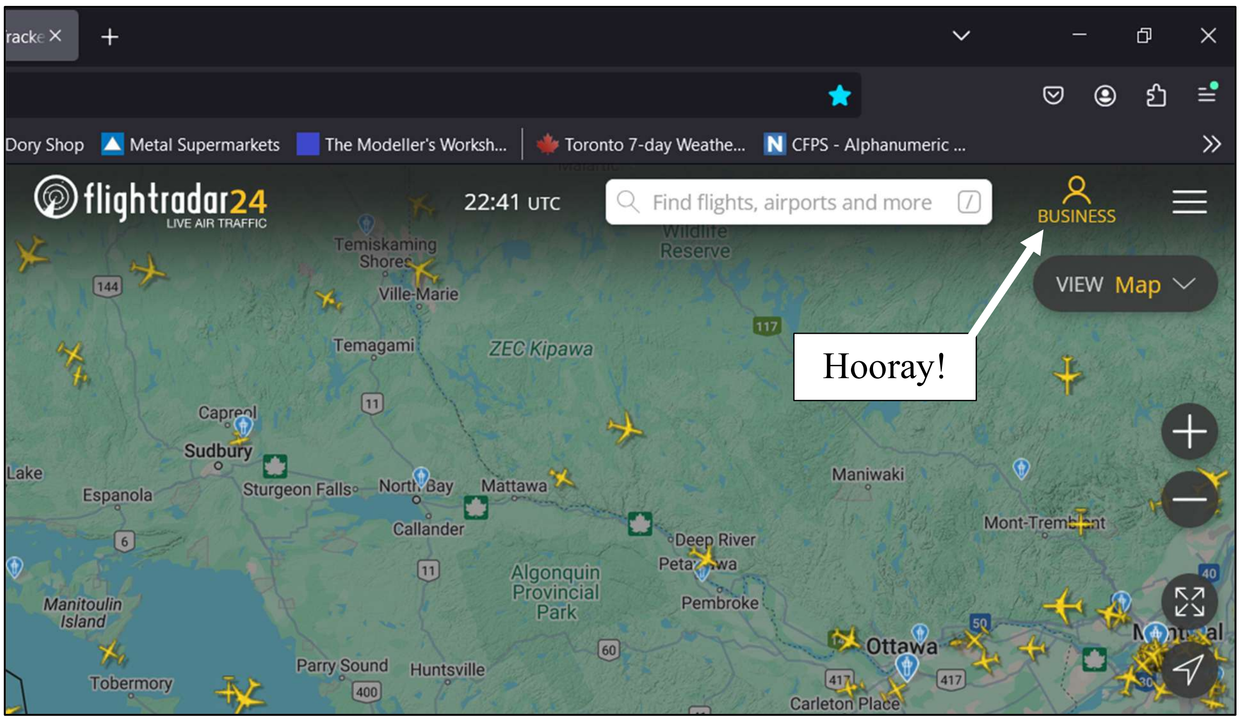
The program does not start sending data automatically. To start sending aircraft data, type the following command after the :~ $ prompt:

```
sudo systemctl start fr24feed
```

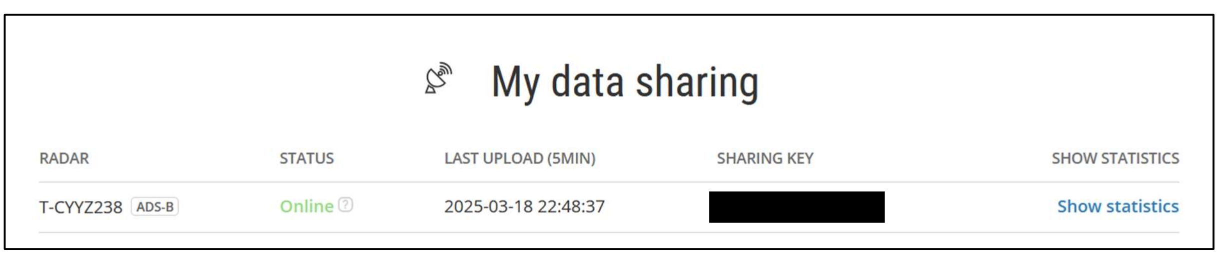
OK, good to go. Everything is now up and running.

Checking in with FlightRadar24 to monitor your performance

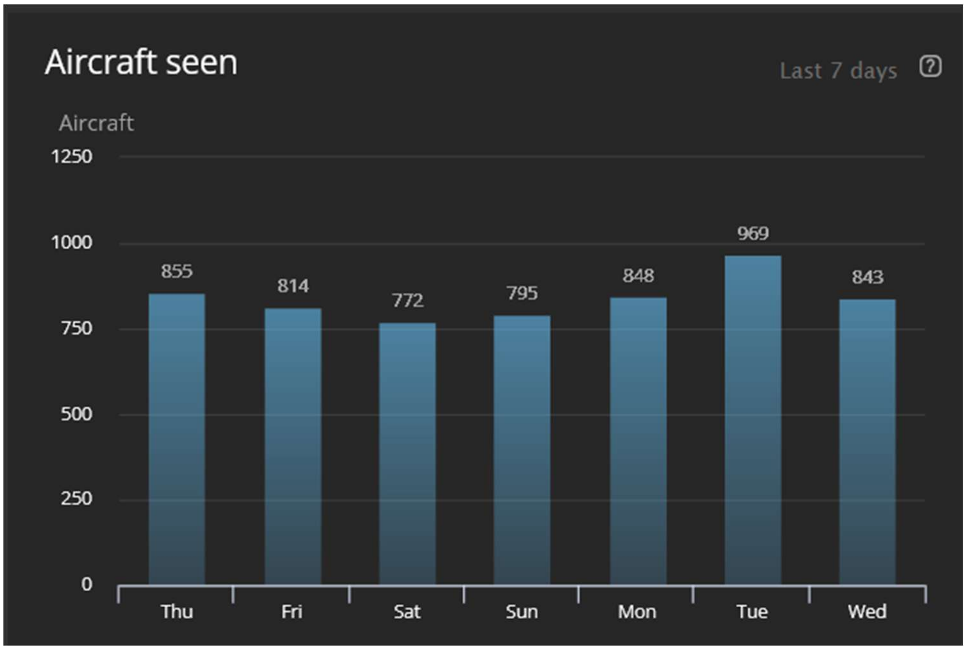
After a day or two, you will want to see what's going on. Go to the FlightRadar24 website. The first thing you will see, in the upper right-hand corner, is that you are now recognized as a Business account holder. (That doesn't mean much to me, but my wife likes it.)



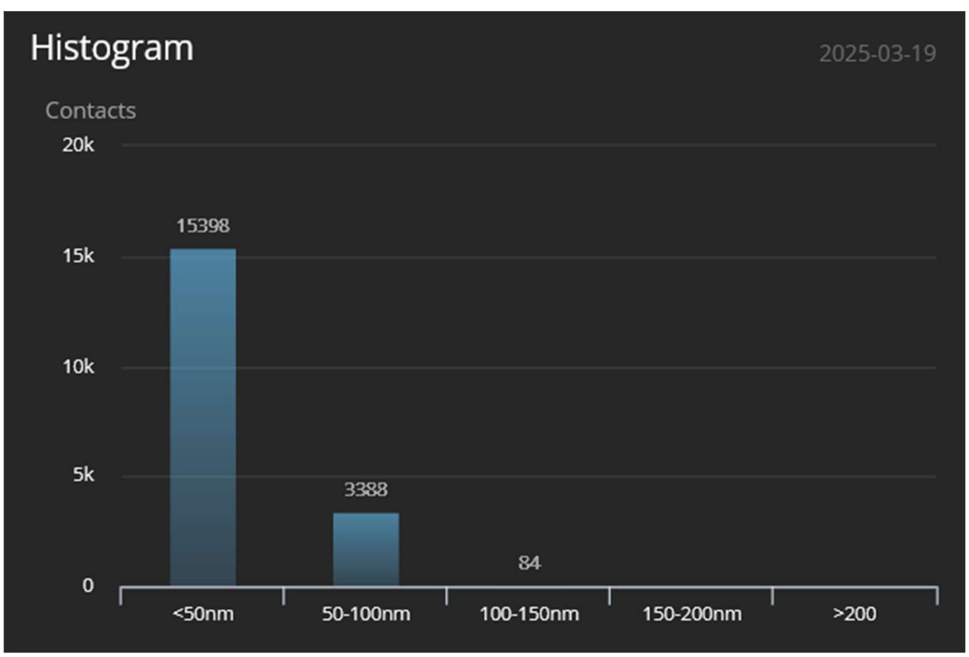
Clicking on the BUSINESS icon opens your Profile menu. That menu has several choices – the button you want to click to check your feeder status is the "My data sharing" one. Clicking will open a panel like this.



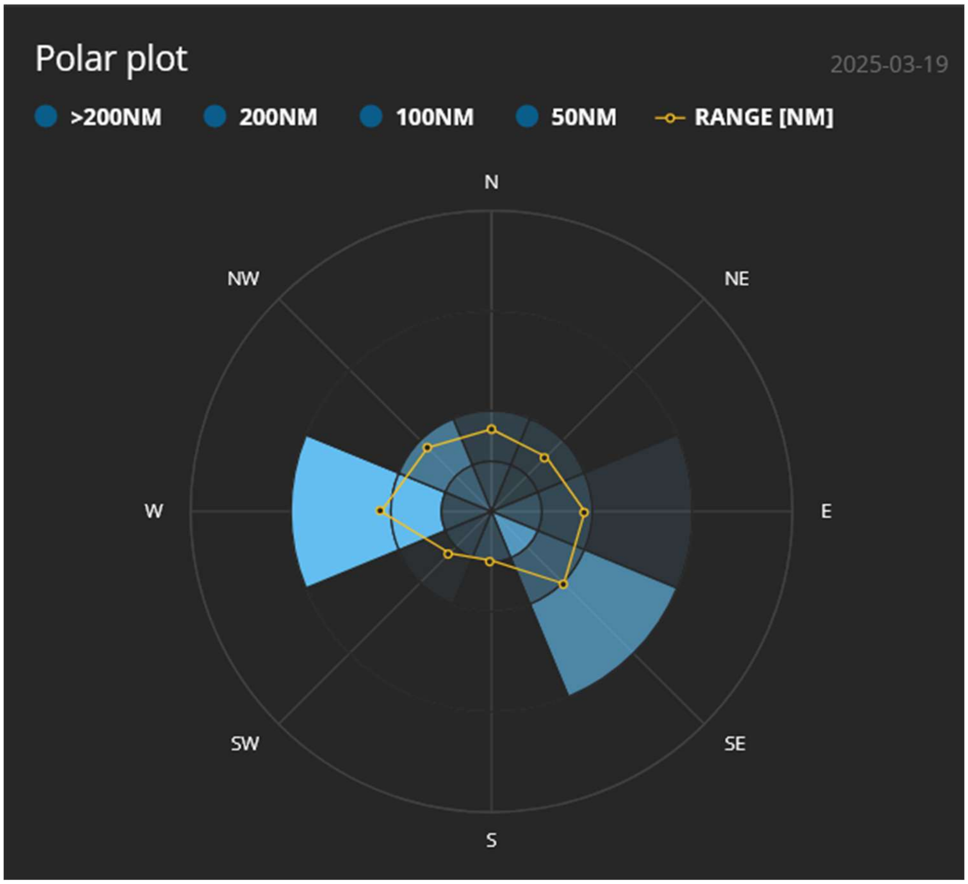
Then clicking on "Show statistics" will display a number of interesting measures. I will only point out a couple. The following is a daily histogram showing the number of aircraft tracked. Of course, multiple reports will have been sent during the time the airplanes were in range.



The following histogram shows the number of position reports sent as a function of the distance to the aircraft. My average range so far is 65 nautical miles. That's not too bad for an antenna looking through a ground floor window.



The following plot is interesting. It shows the horizontal distribution of sightings. Since my antenna is sitting right in front of a window facing to the west, most of its contacts are seen in that direction. But there's an east-facing lobe too because the room is open on the side opposite the window.

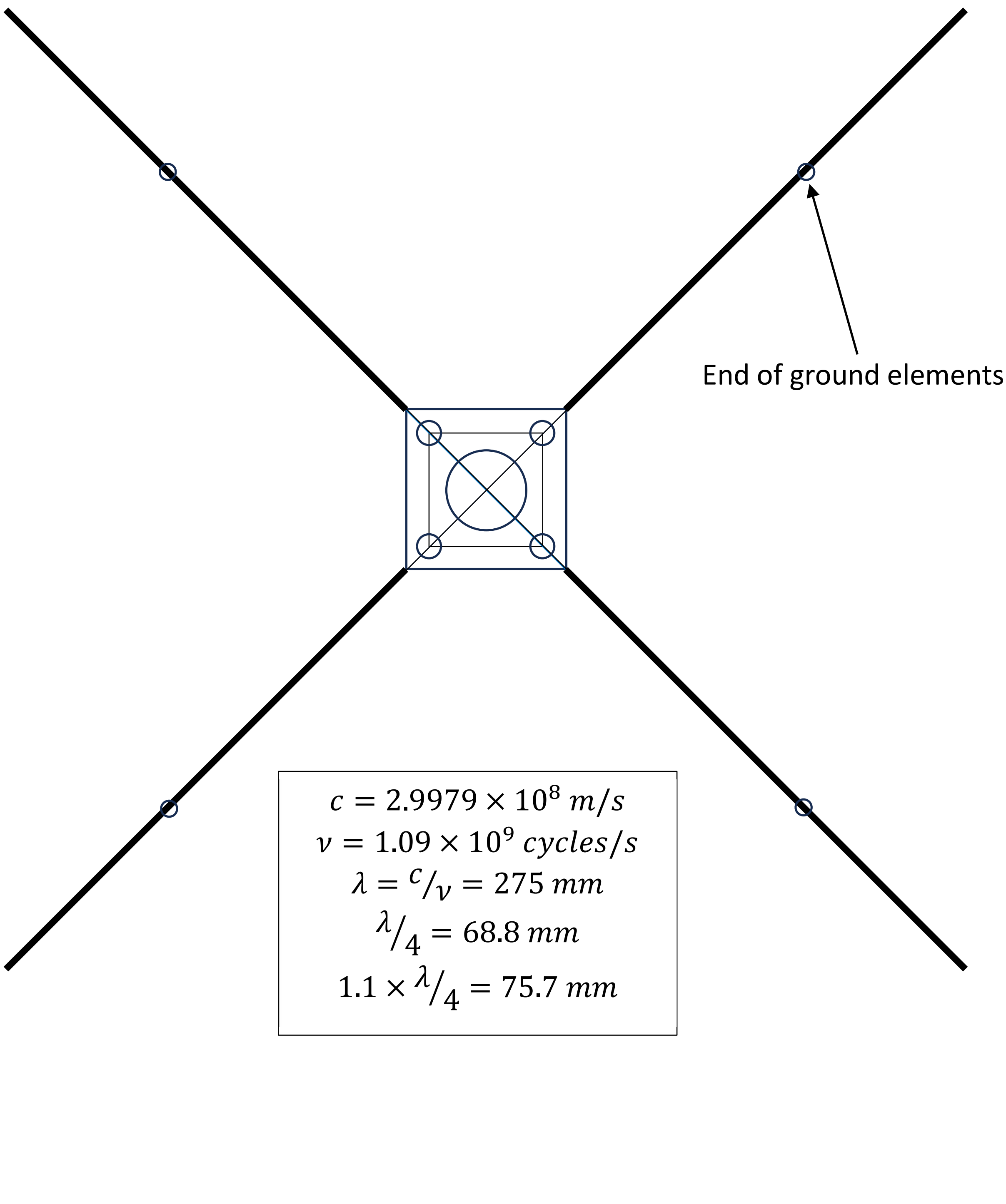


Height above ground is arguably the most important factor governing reception. The next step for me is to move the antenna up into the attic.

Jim Hawley
March 2025

Appendix "A"

Template for ground element adjustments



$$c = 2.9979 \times 10^{8}\ m/s$$
$$\nu = 1.09 \times 10^{9}\ cycles/s$$
$$\lambda = {}^{c}/_{\nu} = 275\ mm$$
$${}^{\lambda}/_{4} = 68.8\ mm$$
$$1.1 \times {}^{\lambda}/_{4} = 75.7\ mm$$

Appendix “B”

4NEC-2 input file

```
CM Ground-plane antenna with four ground elements
CM Frequency = 1090 MHz and Wavelength = 275 mm
CM Quarter wavelength = 68.8 mm
CM AWG #14 copper wire:
CM    Diameter = 0.0641" = 1.63 mm
CM    Radius = 0.03205" = 0.815 mm = 0.000815 meters
CM Minimum segment length = 4 * diameter = 6.5 mm
CE End of comments
'
' Antenna
SY VertCoef=0.775
SY GndCoef=1.1
SY LenVertElmt=VertCoef*0.0688            ' Length of vertical element (11 elements)
SY LenGndElmt=GndCoef*0.0688              ' Length of ground element (11 elements)
SY GndElmt2=LenGndElmt/1.414213562        ' Length of ground element / sqrt(2)
SY GndElmt4=LenGndElmt/2                  ' Length of ground element / 2
SY XYmin=0.5*0.0254                       ' X-Y displacement of corners is 0.5" = 12.7mm
SY XYmax=0.0127+GndElmt4                  ' X-Y displacement of ends of ground elements
SY Ztop=0+LenVertElmt                     ' Z at top of antenna
SY Zbot=0-GndElmt2                        ' Z at ends of ground elements
'
' Geometry of the antenna elements
GW 1 11 0 0 0 0 0 Ztop 0.000815                          ' Vertical element
GW 2 11 XYmin XYmin 0 XYmax XYmax Zbot 0.000815          ' Upper-right ground element
GW 3 11 XYmin -XYmin 0 XYmax -XYmax Zbot 0.000815        ' Lower-right ground element
GW 4 11 -XYmin -XYmin 0 -XYmax -XYmax Zbot 0.000815      ' Lower-left ground element
GW 5 11 -XYmin XYmin 0 -XYmax XYmax Zbot 0.000815        ' Upper-left ground element
GW 6 2 XYmin XYmin 0 XYmin 0 0 0.000815                  ' Upper half-loop on right edge
GW 7 2 XYmin 0 0 XYmin -XYmin 0 0.000815                 ' Lower half loop on right edge
GW 8 4 XYmin -XYmin 0 -XYmin -XYmin 0 0.000815           ' Loop on bottom edge
GW 9 4 -XYmin -XYmin 0 -XYmin XYmin 0 0.000815           ' Loop on left edge
GW 10 4 -XYmin XYmin 0 XYmin XYmin 0 0.000815            ' Loop on top edge
GW 11 1 0 0 0 XYmin 0 0 0.000815                         ' Driven element at base of antenna
'
' End of geometry -- no ground
GE 0
'
' Transmitter excitation
EX 0 11 1 0 1 0                           ' Voltage source (1+j0) on the driven element (wire #11)
'
' Frequency
FR 0 1 0 0 1090 0                         ' Set design frequency to 1090 MHz
EN                                        ' End of NEC input
```

Appendix "C"

Procedure to configure the NanoVNA-H4 for frequency sweeping

Four traces are named in a 2x2 block displayed along the top edge of the screen:

Trace 0 is Yellow in the upper-left
Trace 1 is Blue in the upper-right
Trace 2 is Green in the lower-left
Trace 3 is Purple in the lower-right

1. Assign functions to the traces

Set the Yellow trace to reflection coefficient
Set the Green trace to Smith chart
Set the Blue trace to SWR
The Purple trace is not used

These assignments are made by:

Tap anywhere on the screen to bring up the "Home" menu
Click on Display
Click on Trace
Click on Trace 3 to select the Purple trace
Click on Trace 3 a second time to hide the Purple trace
Click on Trace 1 to select the Blue trace
Click on Back
Click on Format S11 (REFL) to select the top input port
Click on SWR
Tap anywhere on the screen to hide all menus

2. Set up the frequency range for the test

Tap anywhere on the screen to bring up the most recent menu
Click on Back as required to bring up the "Home" menu
Click on Stimulus
Click on Start
Enter the lower frequency (1000M for 1000 MHz)
Tap anywhere on the screen to bring the menu up again
Click on Stop
Enter upper frequency (1200M for 1200 MHz)

3. Calibrate the device

Tap anywhere on the screen to bring up the most recent menu

Click on Back as required to bring up the “Home” menu
Click on Calibrate
Click on Reset (Note the calibration indicators on the left edge disappear)
Click on Calibrate
Screw the Open connector onto the top port
Click on Open
Remove the Open connector
Screw the Short connector onto the top port
Click on Short
Remove the Short connector
Screw the 50Ω Load connector onto the top port
Click on Load
Remove the Load connector from the top port
Click on Done
Click on Back
Click on Save
Click on any memory slot to save the settings as “1GHz 1.2GHz”
Turn off the device

4. <u>Make measurements</u>

Screw in the antenna
Turn on the device
Tap anywhere on the screen to bring up the “Home” menu
Click on Recall
Click on the “1GHz 1.2GHz” memory slot to retrieve those settings
Note that:

The Blue trace is the SWR
The Yellow trace is the reflection coefficient
The Green trace is the Smith chart

A. Move the markers using the jog wheel on the top edge of the device

B. Accurately identify a minimum value by:
Click on the marker (triangle) to select a particular trace
Tap on the screen to open the most recent menu
Click on Back as required to get back to the “Home” menu
Click on Marker
Click on Search
Click on Minimum