A Simple and Inexpensive CubeSat Ground Station

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Written by Bob and Jann Koepke

When we think of ground stations for satellites, large antenna arrays and dishes immediately come to mind along with a lot of expensive electronics. But you can receive transmissions from many satellites using very inexpensive equipment and listening to some of the easier satellites to hear. An inexpensive RTL-SDR (Software Defined Radio) USB dongle and an omnidirectional antenna is a good start.

This simple ground station consists of just a few components:

- A receiver – we'll use a $20 USB Dongle Software Defined Radio (SDR).
- Low Noise Amplifier (or LNA) is an optional component that will improve performance
- An antenna – we have used omnidirectional whips, discones, quadrafilar helix antennas, and directional yagis
- SDR software – we use SDR Console V2
- Satellite tracking software or web site – we use N2YO
- Websites to find the frequencies used by satellites – we use Amsat, PE0SAT, Zarya, and JE9PEL
- Data decoding software – we use WxtoImg for the NOAA weather satellites and the Funcube console for the Funcube CubeSat.
- A Personal Computer – laptop or desktop. Having more than one display helps
- Cabling to tie all of this together

Using these components and software, you should be able to hear transmissions from several different satellites. To decode the data will take a slightly better antenna than the collapsible whip that comes with most of the RTL-SDR dongles (Quadrifilar Helix, Turnstile, Yagis). Most of the frequencies of interest are below 500 MHz; weather satellites around 137MHz; many CubeSats use frequencies in the Amateur Radio 2 meter band(144 – 148 MHz) and 70cm band (420 – 450 MHz), and the ISS transmits data on the 2 meter ham band. One of the largest challenges is determining which satellites are still functional; especially with the CubeSats with their relatively short lives.

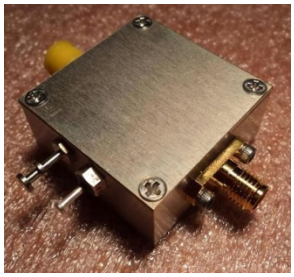
USB Dongle Software Defined Radio

A Software Defined Radio is a "radio communications system where components that have typically been implemented in hardware (e.g. mixers, filters, amplifiers, modulators/demodulators, detectors, etc.) are instead implemented by means of software on a personal computer or embedded system[1]. This can dramatically lower the cost of the radio for a simple system. Inexpensive software defined radios have only recently become available with

[1] Wikipedia, Article on Software Defined Radio: http://en.wikipedia.org/wiki/Software-defined_radio

the introduction of the Realtek RTL2832U in 2010[2]. Very informative websites exist on just the RTL-SDR with source links and tutorials.[3] And several books have been written on this subject[4]. Most of these will tune from about 30MHz to 1.7GHz; some go much further. You can purchase up converters and down converters to extend the range. More sophisticated SDRs can run several thousand dollars. Although any will do, NooElec is one company that offers customer support and still has a reasonably priced radio at about $24.00[5] (photo is also from Amazon).

Low Noise Amplifier



The Low Noise Amplifier is optional. The RF front end of the RTL-SDR radios is not the greatest (to some extent, you do get what you pay for). The LNA4ALL covers 28MHz to 2.5GHz providing a gain of over 20dB in the frequency range of most of the satellites we will be receiving[6] (photo is also from this web site). The LNA is particularly useful for amplifying the signals you are interested in while keeping noise down. And it is very useful to overcome coaxial cable loss if the antenna and receiver are located at some distance from each other. LNA 4 all is available for 20Euros without the case and 80 Euros with the case (at the time of this writing, that is about $23 and $91, respectively, plus 5Euro shipping ($6).

The Antenna

Most of the RTL-SDR radios will come with a collapsible antenna. This is sufficient to get started and verify that your radio is working. But as you try to tune in satellites, you will need a better antenna, especially as you receive data from the NOAA weather satellites and CubeSats. We built the Quadrifilar antenna and have been quite pleased with the performance. The Omnidirectional antennas are easiest to begin with, since you do not need to worry about pointing the antenna at the satellite while receiving. You will need to build an antenna for the frequency you wish to receive the satellite on, which is around 137MHz for NOAA satellites, and 2m (144 MHz) and 70cm (430 MHz) for many amateur CubeSats.

The Quadrifilar Helix Antenna is an excellent omni-directional antenna that can be built relatively easily for any of the frequencies of interest. This image is taken from http://homepage.ntlworld.com/phqfh1/qfh_diy_guide.htm. We have listened to NOAA weather satellites, several CubeSats, and the ISS successfully using this antenna.

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[2] Osmocom web site on RTL-SDR: http://sdr.osmocom.org/trac/wiki/rtl-sdr
[3] RTL-SDR web site: http://www.rtl-sdr.com/
[4] The Hobbyists Guide to RTL-SDR: http://www.amazon.com/Hobbyists-Guide-RTL-SDR-Software-Defined-ebook/dp/B00KCDF1QI
[5] NooElec USB Dongle SDR: http://www.amazon.com/NESDR-Mini-Compatible-Packages-Guaranteed/dp/B00P2UOU72/ref=sr_1_1
[6] LNA4ALL web site: http://lna4all.blogspot.com/

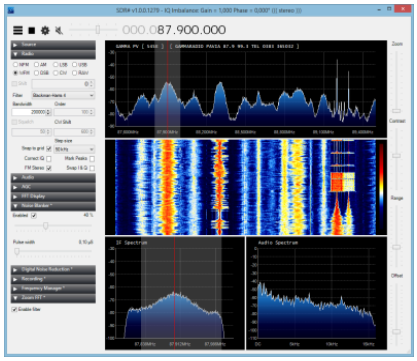
The Turnstile antenna is another excellent and slightly easier to build omnidirectional antenna for the frequencies for many of the weather and CubeSats. This image is taken from http://www.kr1st.com/na1ss.htm. We have not tried this antenna, but will.

The Lindenblad antenna is described by Amsat as the Ultimate Satellite Omnidirectional Antenna. It is constructed from four ½ wave diplose slanted 30 degrees to the horizon, placed 0.3 wavelength apart. The photo is from an article taken from http://www.amsat.org/amsat/articles/w6shp/lindy.html. We have not tried this antenna, but will.

SDR Software

With the Software Defined Radios, part of the radio is in the "radio" (or USB dongle), and the rest is in software running on your personal computer. There are several different software packages available; most you can download for free. These allow changing the receive frequency of the radio, you can change the modulation type, and many allow you to decode digital data or even help track satellites and handle the Doppler shift. Most also have a waterfall display – so you can see a piece of the RF spectrum around the signal you are listening to. Many modulations and data types have a unique look on the waterfall display; this helps not only identify the frequency, but what is being transmitted.

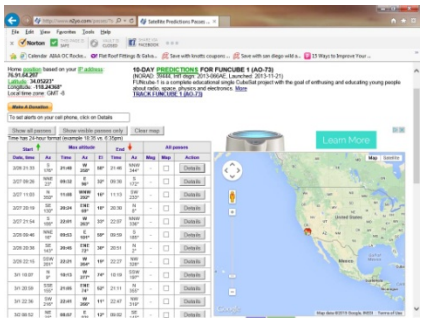
The SDR Console V2 software is available at http://v2.sdr-radio.com and is our favorite SDR radio software. You can store multiple favorite frequencies and it has multipleVFOs for tuning. The satellite tracking window will help identify satellites in range, and display altitude, azimuth, and distance during the pass. You can also set it up to help with the Doppler shift.



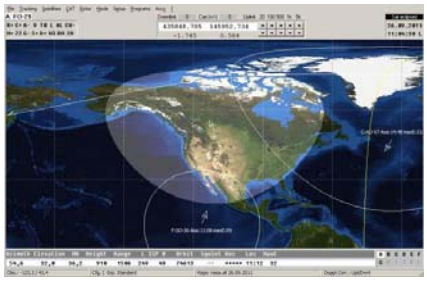
SDR Sharp is another very popular radio software, with many plug-ins available. It is not quite as feature rich as SDR Console, but still a very useful tool. You can find SDR Sharp at http://sdrsharp.com/#download.

Satellite Tracking Software

You need to know when the satellite will be in range of your ground station. There are web sites that can provide this information as well as programs that will not only tell you when the satellite is in range, but also help you track it (some of the SDR radio software programs also perform this function).



N2YO.COM will allow you to pick the satellite to track, list the passes where the satellite will be in range over the next few days, and provide real time location data. The web site is http://www.n2yo.com. Click on "Satellite on orbit" to select the satellite you are interested in. You will need to enter your latitude and longitude for accurate information, or it will estimate your location from your IP address. Heavens above is another site often used (http://www.heavens-above.com).

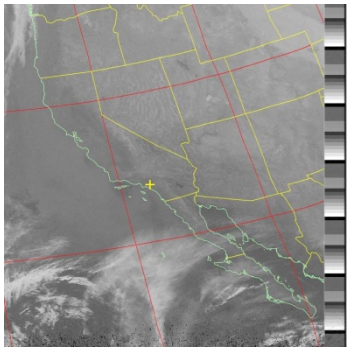


SATPC32 is a stand-alone software program that will also help track satellites. It is available for free, but you need to enter your location each time you start it. Or you can purchase a copy that helps fund Amsat.org. See http://store.amsat.org/catalog/product_info.php?products_id=50. You can also save a few dollars by joining Amsat at the same time that your order the product.

Satellite Frequencies

Once you have identified the Satellite that you want to track and when it will be in range, you will need to determine the frequencies that the satellite transmits on and what is being transmitted. There are good lists of frequencies at http://www.ne.jp/asahi/hamradio/je9pel/satslist.htm. The Zarya.info web site also lists satellite frequencies at http://www.zarya.info/Frequencies/FrequenciesAll.php. It also helps to Google the satellite name (many of the CubeSats and Amateur satellites have several names). We have had good luck with listings from Amsat (http://www.amsat.org) and PE0SAT (http://www.pe0sat.vgnet.nl).

Decoding Software



The software that you will need to decode signals you get from Satellites depends upon the data that you are expecting. A few of the easier satellites to receive and decode are the NOAA weather satellites NOAA-15, NOAA-18, and NOAA-19. These satellites transmit pictures of the earth with cloud cover and IR data. The WxtoImg software at http://www.wxtoimg.com will decode the NOAA weather satellite

images. It is free; there is also a paid-for version. We received the image shown to the left using the equipment in this article.

The Funcube web site has a console to decode the Funcube and Ukube transmissions at http://funcube.org.uk/working-documents/funcube-telemetry-dashboard.

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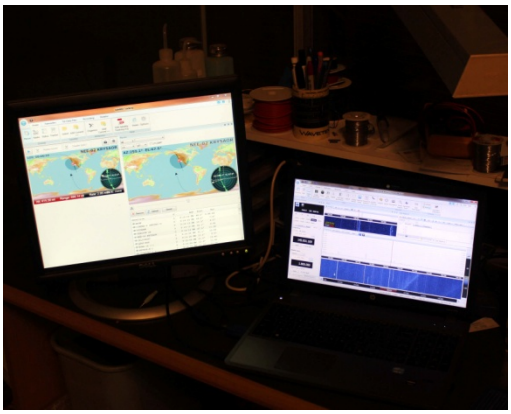
Putting it all together



We found it very convenient to use a roof-mount TV tripod with a 6 foot mast sitting in our yard. The mast has the antenna, Low Noise Amplifier, and Radio with very short coax lengths. We mounted the radio and LNA on a section of PVC pipe that we could slide over the mast to make it easy to take back inside out of the weather, and to modify as we tried various combinations. We then ran a long (three 5 meter) active USB cable back to our PC in the house. To power the LNA, we have a regulated 9VDC wall power supply in the house with two 25 foot cables to carry the power out the LNA on the mast.

You will need to purchase:

- An RTL-SDR such as this one from Amazon: http://www.amazon.com/gp/product/B00P2UOU72
- An aluminum enclosure is optional: http://www.amazon.com/Extruded-Aluminum-Enclosure-Select-RTL-SDRs/dp/B00NZ2I6QA
- An ACTIVE USB 2.0 extension cable from Amazon (don't get a USB 3.0 active cable as 3.0 is much noisier) – there are many brands, this one from Tripp Lite is available in 5, 10, and 20m length: http://www.amazon.com/Tripp-Lite-U026-016-Extension-Repeater/dp/B0002D6QJO

If you DON't use the LNA:

- If you don't use the LNA you'll need a MCX to UHF SO 239 PL-259 female cable (or MCX to whatever connector you use on your antenna): http://www.amazon.com/gp/product/B00C20FV78

If you DO use the LNA add (it is a lot to add, but well worth it):

- The Low Noise Amplifier is optional – if you choose to use it: http://lna4all.blogspot.com
- An MCX to SMA cable from the radio to the preamp: http://www.amazon.com/gp/product/B00ISTDOOO
- A cable from the LNA to the antenna – we used PL-259 on the antenna (SMA to UHF SO239 PL-259): http://www.amazon.com/gp/product/B004280GQ4
- You will also need a 9VDC regulated power supply (LNA for all takes 6VDC to 12VDC in – be careful of the inexpensive non-regulated "wall-wart" power supplies as even a 9VDC unregulated supply can be more the 13VDC under light loads): https://www.sparkfun.com/products/298. A similar one is available from Amazon at: http://www.amazon.com/650mA-Wall-Adapter-Power-Supply/dp/B007R9TJTU (I believe it is the same, but did not order the Amazon power supply)
- A short power cable with 2.1mm x 5.5mm connector. Cut the cable and connect a short cable with the female connector to the LNA: http://www.amazon.com/2-1mm-5-5mm-Extension-Cable-Adapter/dp/B00FTH6WNS
- One or more extension cable for LNA power (25ft with 2.1mm x 5.5mm connectors): http://www.amazon.com/2-1mm-5-5mm-Extension-Cable-Adapter/dp/B00FTGAJW4

Installing the software Defined radio and Drivers

In addition to the SDR software, you will need a program called Zadig. It comes along with SDR Sharp (or you can download if from the Zadig web site: http://zadig.akeo.ie).

- Download the SDR Sharp radio software: http://sdrsharp.com/#download
- Follow the instructions on http://www.rtl-sdr.com/rtl-sdr-quick-start-guide to install SDR Sharp as well as the drivers

You can start SDR Sharp with your dongle plugged in and the telescoping antenna on your desk and verify you can tune to an FM station like K-EARTH at 101.1MHz. The RTL-SDR radio does not tune below 27MHZ, so don't try to tune to AM stations or listen to "short wave radio" – the dongle does not cover those frequencies even though you can tune to them. If you move your PC and antenna outside, or move the antenna and dongle outside and connect to your PC inside with an active USB cable, you can tune around and find many more stations to listen to. Your PC generates a lot of RF noise, so getting the RTL-SDR dongle away from the PC helps. You can also use the metal case around the dongle to lower some noise. USB 3.0 is much noisier than USB 2.0 so it helps us use USB2.0 from your PC. You may need a ferrite bead on the USB cable as well. Some easy-to-hear frequencies are

- FM Broadcast from 88 – 108 MHz
- Aviation frequencies from 118 to 136 MHz
    - John Wayne: http://www.radioreference.com/apps/db/?aid=4749
    - LAX: https://www.radioreference.com/apps/db/?aid=5824
- NOAA weather reports: http://www.nws.noaa.gov/nwr/coverage/stations.php?State=CA. Knowing these frequencies is also a good method to calibrate your radio frequency.
    - Santa Ana on 162.45 MHz is easy to hear
    - Los Angeles on 162.55 MHz is easy to hear
- 2M Amateur Radio Band: 144 to 148 MHz
    - The K6JSI repeater on 147.210 is easy to hear, and very active. It is on the WINsystem that ties many repeaters together, so you will hear stations from many states through the local repeater: http://www.winsystem.org/index.html

We prefer and use the SDR Console software available at: http://v2.sdr-radio.com/Download.aspx. SDR console has several VFOs as well as satellite tracking support and some data decoding built in. It is much more feature rich than the SDR Sharp program, although SDR Sharp has plug-ins for a variety of functions as well. You will still need to install the drivers via Zadig – once you followed the instructions under SDR Sharp you have the drivers installed for SDR Console as well. The quick start guide for SDR Console is here: http://v2.sdr-radio.com/Support/QuickStart.aspx. There is additional information for the RTL-SDR radios here: http://v2.sdr-radio.com/Support/RTLSDRs.aspx. If the RTL-SDR USB options does not appear, you can download the support package .zip here: http://m3ghe.blogspot.com/p/adding-support-for-rtl-sdr-usb-dongles.html

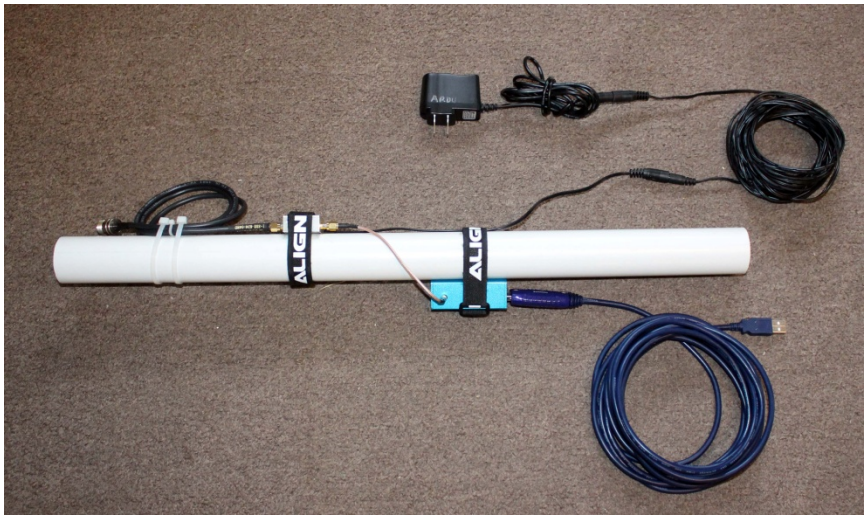
Moving the radio outside for better reception

To receive satellites you need an outdoor antenna. Traditional radio installations use an outdoor antenna and a long coaxial cable to a radio inside. The problem is that the coaxial cable adds a lot of loss. You can overcome this by putting the radio near the antenna and connecting the radio to the PC inside using an active USB cable. We found that the LNA improved reception substantially with the inexpensive RTL-SDR dongles. We did not weatherproof the radio and LNA; we also made it very simple to install and remove electronisc by using Velcro straps to secure everything to a piece of PVC pipe that we can easily slide on and off our 6 foot mast on tripod – all on our lawn – then bring it back inside:

The outside antenna assembly consists of four separate parts:

- The tripod – really meant for mounting a TV antenna on a roof
- A 6 foot or so mast
- A 2 foot long PVC pipe with radio and LNA that slides over the mast
- The antenna; the bottom slides over the top of the mast.

We have had excellent results with a Right Hand Circularly Polarized Quadrifilar Helix antenna. We used the plans from: http://homepage.ntlworld.com/phqfh1/qfh_diy_guide.htm. It is made of ½" copper pipe (about $8 for a 10 foot section at Home Depot, and some 90 degree elbows. We added the PVC support in the center



LNA with Radio, cables, and LNA power supply mounted on the 2 foot long PVC pipe

Top of PVC with LNA and Radio coax at top goes to the antenna

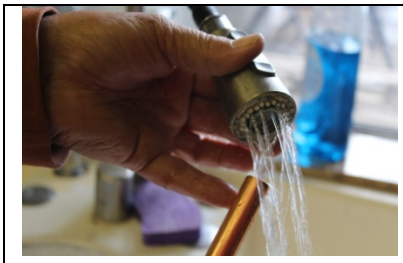
Center of PVC with LNA and Radio connected by a short piece of coax

Bottom of PVC with LNA and Radio – active USB cable goes to PC and cable with barrel connectors goes to 9VDC

The Quadrifilar Helix (QFH) Antenna

You will need to build (or purchase) an antenna – we chose the Right Hand Circularly Polarized Quadrifilar Helix antenna. We have built one for 137MHz and it works OK for receiving not only the NOAA weather satellites, but also the satellite transmissions on the 2M amateur band. It would be best, of course, to build one for each range of frequencies of interest. We made this design out of ½" copper pipe since it appeared to be quite sturdy and would not be deformed when moving it around. Virtually everything is available at home depot. The pipe is quite easy to bend, but if you are not careful it kinks easily. We filled it with water, then froze it. While the water was still ice, we slowly bent it using a conduit bender – it takes patience.

- You can purchase a QFH antenna here: http://www.nationalrf.com/satellite-tenna.htm
- Instructions to make the antenna can be found in links on this home page: http://homepage.ntlworld.com/phqfh1/qfh_diy_guide.htm
    - The antenna instruction .PDF is here: http://homepage.ntlworld.com/phqfh1/qfh.pdf
    - The balun instruction .pdf is here: http://homepage.ntlworld.com/phqfh1/phbalun1.pdf

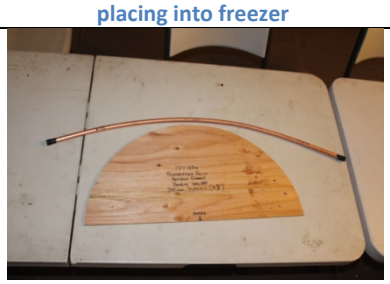


Fill the copper pipe with water, then freeze before bending

Tape on a copper end cap before placing into freezer

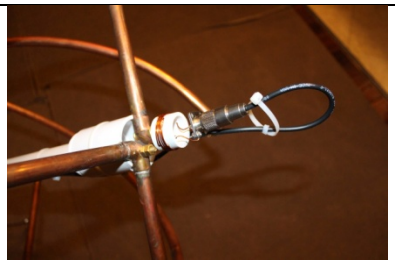
Freeze before bending to help prevent kinks in the pipe

Use a conduit bender and bend the pipe a little at a time

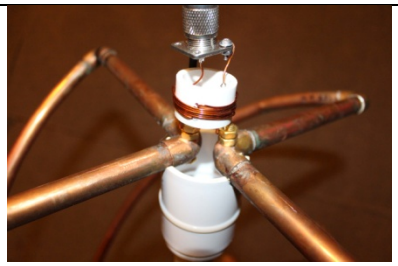


Use the template to adjust the bend

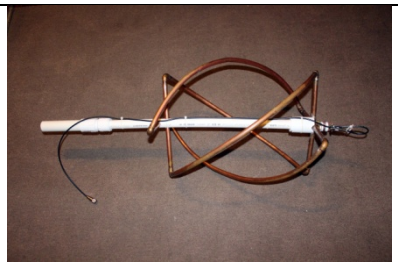
Solder the 90 degree elbows to form the antenna



Adding the Balun



Detail of the balun attachment and female PL-259 with coax attached



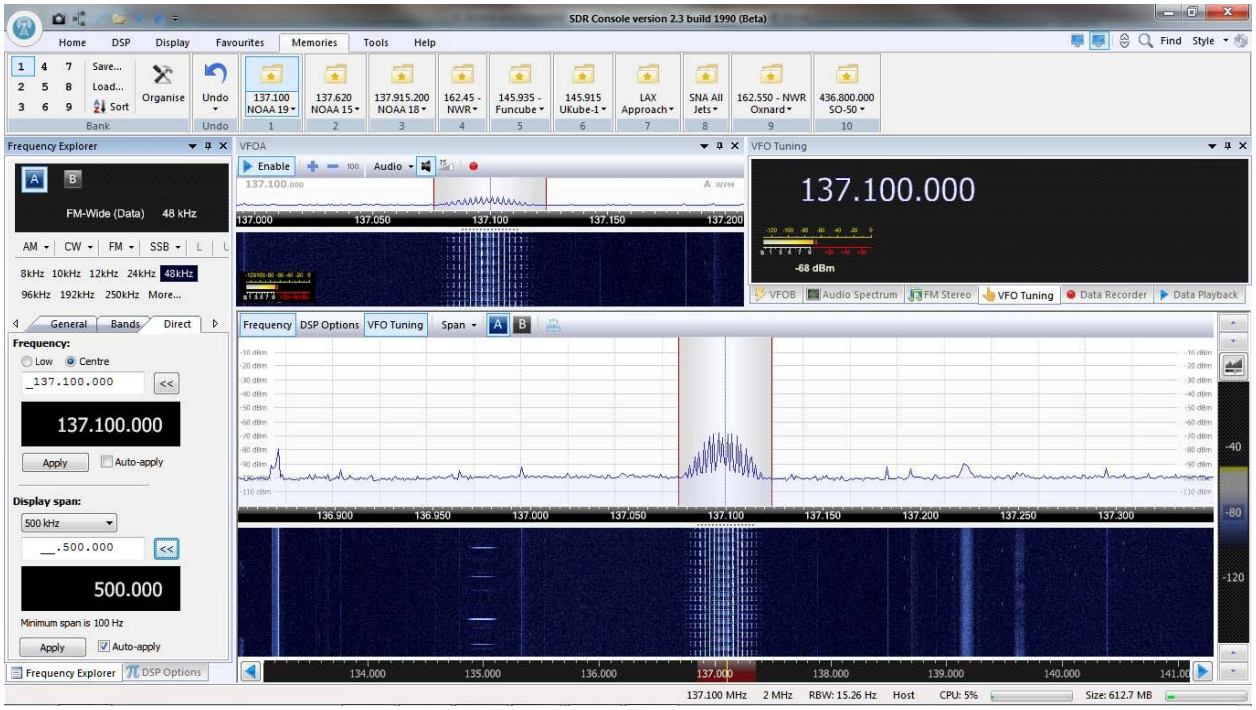
The final antenna

Easy Satellites to start

It is helpful to have several screens running simultaneously on your PC – three would be ideal, two is OK.

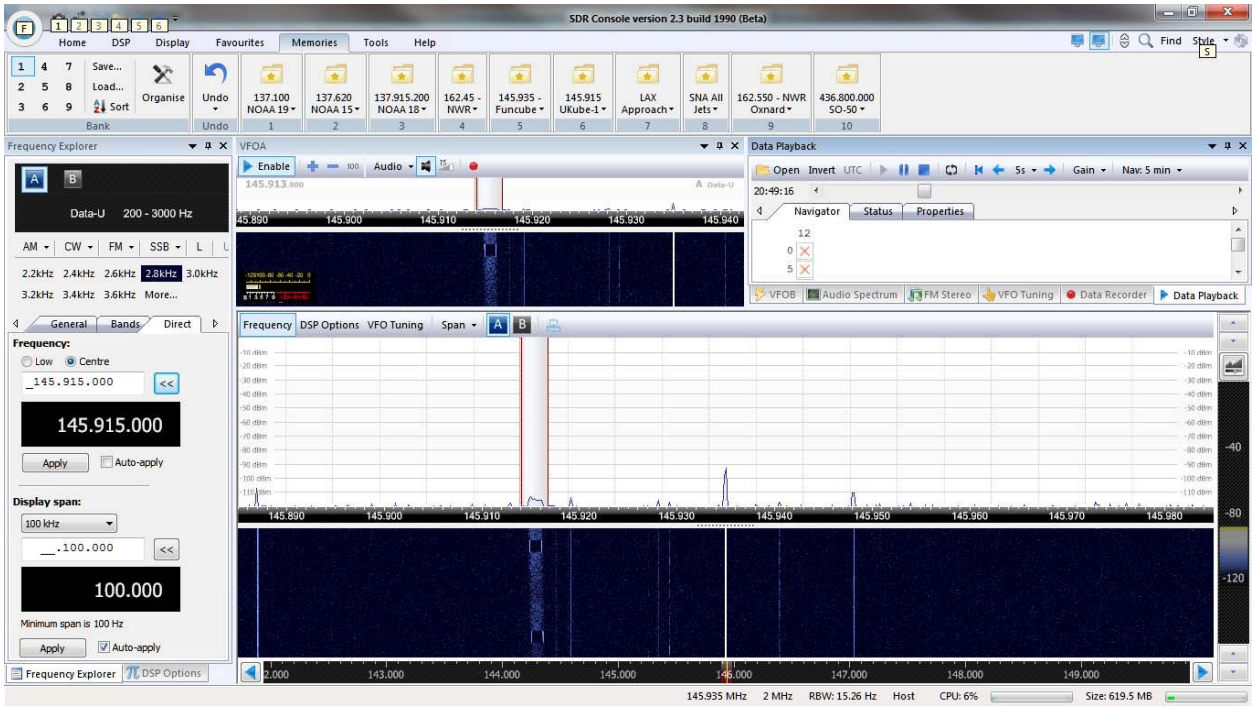
- One screen would be for the SDR console radio software, such as SDR Console V2
- One screen would be for tracking, such SDR Console V2 tracking screen, or N2YO
- One screen would be for the decoding software

One of the easiest satellites to hear is the NOAA weather image satellites. The NOAA satellites are well powered and easy to hear – they have a distinctive tick-tock sound and look unique on the SDR console. Use the PCs internal mixer to route the audio from the SDR radio software to WxtoImg, or use an external cable. The volume needs to be relatively high. You do not need to worry about Doppler shift as you can set the bandwidth of the radio wide enough to track OK



Satellite Name	NORAD ID	Frequency	Modulation & BW	Decoding S/W
NOAA-15	25338	137.620 MHz	FM Data Wide 24 KHz	WxtoImg
NOAA-18	28654	137.9152 MHz	FM Data Wide 24 KHz	Wxto Img
NOAA-19	33591	137.100 MHz	FM Data Wide 24 KHz	WxtoImg

The Funcube satellite is also relatively easy to hear – and it has a distinctive look on the SDR radio software as well as sound. Like many of the CubeSats, it has several names (Funcube-1, AO-73). Funcube-2 is also known as Ukube-1. Sometimes the only way you know for sure you are looking up tracking information for the correct satellite is through the NORAD ID.



Satellite Name	NORAD ID	Frequency	Modulation & BW	Decoding S/W
Funcube-1 (AO-73)	39444	145.935 MHz	USB Data (24KHz)	Funcube Telemetry Dashboard
UKUBE-1 (Funcube-2)	40074	145.915 MHz		Funcube Telemetry Dashboard