Initial Results from VLF and LF Observations at Cohoe Radio Observatory

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1. Introduction

During June 2018 I temporarily installed a loop antenna and a software defined radio (SDR) receiver at Cohoe Radio Observatory on the Kenai Peninsula in southcentral Alaska. My main purpose was to determine if the site is viable for receiving VLF and LF transmissions in the frequency range 10 to 40 kHz. If so, the work would be a prelude to building a permanent installation for observing sudden ionospheric disturbances (SID) and other low frequency propagation phenomena. Since these tests and measurements were done near the minimum of the current solar cycle, I was not expecting SID activity and I did not record any.

A secondary purpose of this project was to determine if a particular receiver, the SDRPlay RSP2Pro receiver and its associated SDRUno software, are suitable for observing with the above loop antenna. This paper describes the temporary setup and also the reception results and operation details. Because software is very important to an SDR receiver's performance, considerable detail is provided on my application of SDRuno.

2. Equipment

The basic equipment setup was relatively simple (figure 1). Each major component is described following.

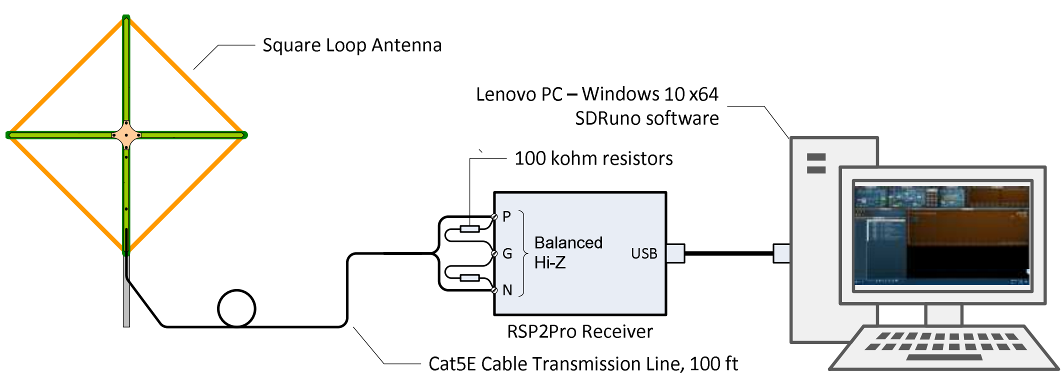

Figure 1 ~ System block diagram showing major components of the temporary installation. Image © 2018 W. Reeve

Antenna: Untuned square loop, 1.2 m diagonal (figure 2). I built this antenna in late 2009 (see {Reeve18-1} for mechanical and electrical details) but could not use it at my Anchorage observatory because of strong low frequency radio interference. The antenna was stored for nine years and then moved to Cohoe. The only change for the Cohoe tests was to add a 4 ft long PVC mast to the antenna for support.

Note: Internet links and references in braces { } and parentheses ( ) are provided in **section 9**.

Transmission line: Cat5E unshielded twisted pair (UTP) waterproof (gel filled core) cable rated for outdoor and direct buried applications: Vertical Cable 350 p/n 059-485/CMXF, LLDPE jacket, 4 twisted pairs, 24 AWG, solid copper {VertCable}. No connectors were used in the temporary setup; all connections were to screw-type terminal blocks. Pair 1 (white-blue/blue-white) was connected to the loop and the remaining 3 pairs were shorted together. I temporarily laid 100 ft of this cable on the ground with the unused portion coiled near the cable entrance.

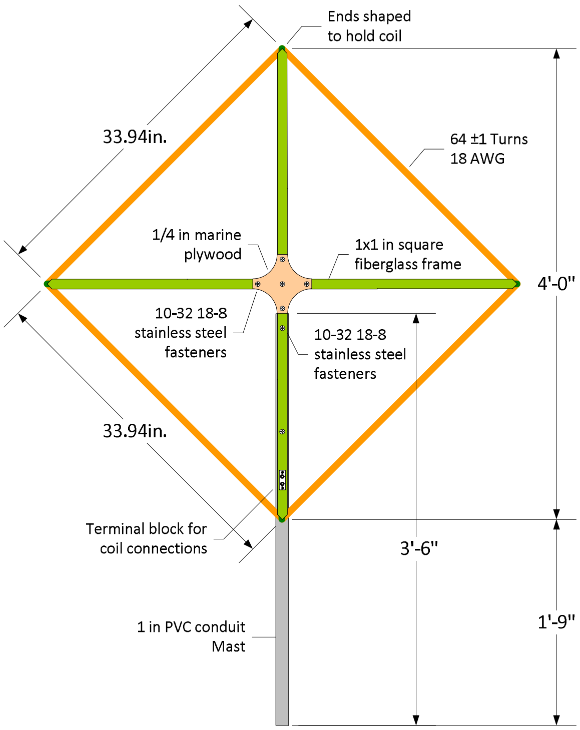

Figure 2 ~ Loop mechanical drawing. The main components are a frame made from square fiberglass tube, marine plywood braces, stainless steel fasteners and coated copper magnet wire. The loop originally was wound in 2009 with 96 turns but 32 turns were removed to reduce its distributed capacitance and increase its self-resonant frequency. The 1 in PVC conduit mast was added in 2018. Dimensional units are USA trade sizes with metric in ( ).

Loop diagonal: 4 ft (1.2 m)
Loop area: 7.9 ft^2 (0.733 m^2)
Loop perimeter: 11.2 ft (3.4 m)
Loop side length: 2.8 ft (0.853 m)
Windings: 64 ±1 turns of 18 AWG coated magnet wire
Wire length: Approximately 720 ft (218 m)
Measured inductance: 12.3 mH
Measured self-resonant frequency: 46 kHz
Measured dc resistance: 4.535 ohms at 20.6 C
Tuning: None

Image © 2018 W. Reeve

Receiver: SDRPlay RSP2Pro software defined radio (figure 3) {RSP2Pro}. The receiver's advertised frequency range is 9 kHz to 1.8 GHz and it costs about 200 USD. The antenna was connected to the receiver's balanced high-impedance antenna interface (1000 ohms, marked *HI Z*) through the balanced twisted pair transmission line. To control common mode currents I connected a 100 kohm resistor from each antenna terminal (P and N) to ground (G).

Figure 3 ~ SDRPlay RSP2Pro software defined radio receiver. Dimensions are 99 x 87 x 33 mm, 0.3 kg. The balanced high-impedance antenna interface is the green pluggable connector on far-left. The receiver is powered through its USB connection and draws about 170 mA at 5 Vdc. Images source: SDRPlay, used with permission.

Impedance matching: Above about 100 kHz the characteristic impedance of the twisted pair cable is 100 ohms (resistive, angle near 0°) but rises to about 125 ohms (capacitive, angle about –20°) at 50 kHz and 240 ohms (capacitive, angle about –40°) at 10 kHz. The impedance of the loop antenna varies almost linearly from approximately 800 ohms at 10 kHz to 3200 ohms at 40 kHz and is primarily inductive (angle near +90°). The receiver impedance as noted above is 1000 ohms (assumed to be resistive). I made no attempt to match the impedances of the antenna, transmission line and receiver and am satisfied that highly balanced twisted pair cable is far better than unbalanced 50 ohm coaxial cable in this application.

Software: SDRPlay SDRuno version 1.22 {SDRuno}. When it is opened, SDRuno fills the entire monitor screen with individual windows that are used to operate the receiver (figure 4). The software is designed to group related receiver functions in a window that can be minimized if not needed – I believe this is a good concept but it takes some getting used to. The larger windows can be resized. The pixel width of the Main Spectrum (SP1) windows may be selected from preset values in a popup window (528, 1024, 1280, ..., 3840) or adjusted to any other value by dragging with the mouse. The window sizes and positions are not remembered when the program is closed.

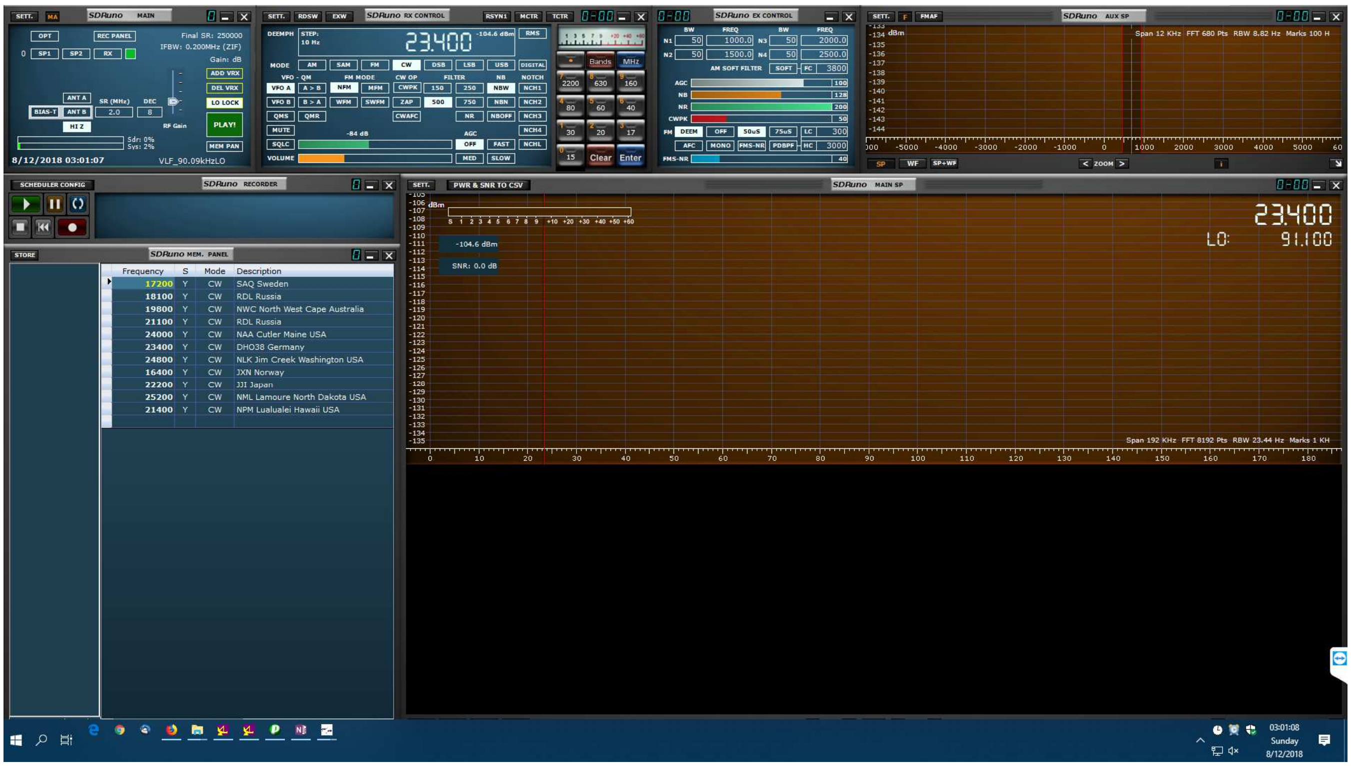

Figure 4 ~ SDRuno startup screen on a 24 in 1920 x 1080 pixel HD monitor before receiver has been started. At first glance it appears to be a jumble of large and small windows that completely fill the screen but each window has a specific purpose. They consist of a Main window (upper-left), one or more virtual receiver windows (to right of Main window) and associated Main Spectrum and Auxiliary Spectrum windows (upper- and lower-right), EX Control window (upper-middle), Memory Panel window (lower-left) and Recorder window (middle-left). The Memory Panel window shown here has a list of VLF stations and their frequencies that I entered during the tests. Just above the Memory Panel is the Recorder window (described later). The windows associated with only one virtual receiver (0-00) are visible in this image; the windows for additional virtual receivers are automatically stacked and can be selected from the taskbar. The background color of the spectrum windows SP1 and SP2 can be individually tailored for easy identification.

PC: Lenovo M910 SFF ThinkCentre with 8 GB RAM and Intel Core i7-6700, 3.4 GHz, 4-core processor, Windows 10 Pro x64 (figure 5) {Lenovo}. This PC was purchased new in April 2017. The RSP2Pro receiver connects through one of several USB 3.0 interfaces on the PC but the receiver itself uses USB 2.0, which is automatically detected by the PC. This PC has plenty of CPU power to simultaneously run multiple spectrometer and utility software applications including SDRuno.

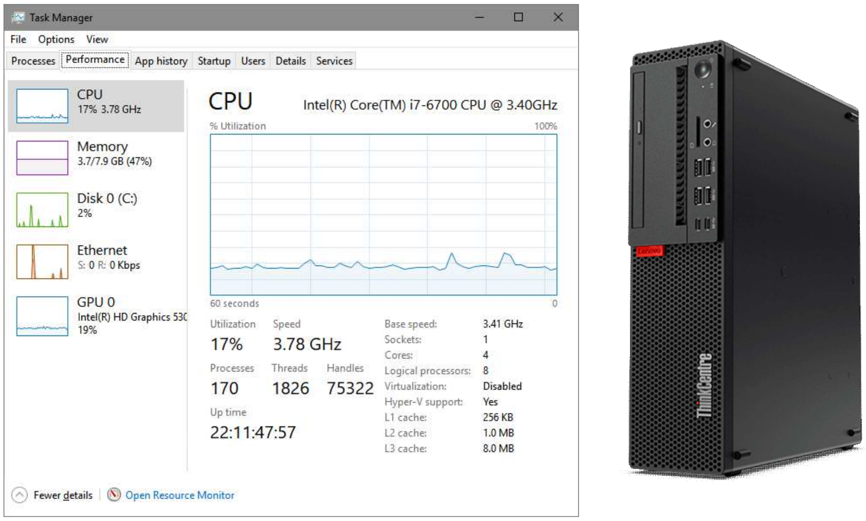

Figure 5 ~ Lenovo M910 Small Form Factor (SFF) ThinkCentre PC. The Windows 10 Task Manager (far left) shows CPU usage performance (17%) while running SDRuno, two instances of Callisto software and a few other applications including a UPS monitor. The memory usage is about 1.7 GB of 7.9 GB available. Memory was later increased to 12 GB.

3. Antenna Location

I investigated two antenna locations, both within 15 m of the CRO building and separated from each other by about 25 m, one south of the building and one northeast. I temporarily installed the loop antenna on a modified bar stool with the loop center about 1.8 m above the ground (figure 6). Prior to the survey, I installed outriggers on the bar stool legs to prevent the wind from tipping it over (everyone knows it is easy to *tip over* a top-heavy bar stool). This setup allowed easy relocation and manual rotation of the loop. I temporarily laid the transmission line on the ground and brought it through the cable entrance panel to the receiver inside.

Figure 6 ~ Temporary installation of the square loop antenna on a modified bar stool. The loop frame is fastened to a 1 in (trade size) PVC conduit mast, which is inserted in the stool for easy rotation. The bar stool is equipped with braces for the mast and outriggers to prevent upset in the wind. The whole assembly is very easily relocated. The loop locations investigated are in a heavily wooded area mostly with quaking aspen and black spruce trees and some open spaces frequented by rampaging moose (the permanent installation places the antenna high enough to prevent moose interference). Image © 2018 W. Reeve

I tuned the receiver to display the frequency range 10 to 41 kHz and then manually rotated the loop through 180° in 15° increments. I used the *Sight 'N Go* compass function (reference true north) in a Garmin 680T GPS receiver to establish the direction with 1° resolution. At each increment I saved a Main Spectrum SP1 screenshot. I then viewed each screenshot in sequence to subjectively determine if the two test locations differed in noise and signal amplitudes. This method was much faster and simpler than data recording and processing. Both locations yielded very similar results so, for the permanent installation, which I built before the end of June, I chose the south location where I could see the antenna from an observatory window. The permanent installation includes a rotator and RF and control cable interfaces and will be described in a future paper.

4. Software Setup

Prior to this project I had used the SDRuno software only at HF and VHF, so I had to spend considerable time learning how to use if at lower frequencies. The SDRuno user guide does not provide any application information for low frequency operation and is minimalist in nature. I had some problems with inconsistent mouse operation and found it far too easy to accidentally change the frequency and other settings; this was especially annoying while recording station signal level data. The settings cannot be locked and it took a while to learn how to move the mouse cursor without accidentally disturbing the settings and ruining the data. I found the best method is to not touch anything while saving data but this is impractical with a PC that is shared across multiple applications.

Once setup I could save the basic software configuration (called *Workspace* in SDRuno) and then run a new session later with relatively minor adjustments. However, usability features such as window size, position and zoom level are not saved in the workspace, so some adjustments are needed when opening the software and using a given workspace. The software is not bug-free, and it seems that most of the bugs are associated with the way the mouse interacts with the program. I reported a list of bugs to SDRPlay support and received a very fast acknowledgement but it remains to be seen if future software releases correct the deficiencies noted.

The lowest basic sampling rate available in SDRuno is 2 MHz. For VLF and LF observing, the 2 MHz rate is much too high because it does not provide adequate frequency resolution in the spectrum display. However, decimation by a factor of 8 is available at the 2 MHz sampling rate (figure 7). This gives an effective sampling rate of 250 kHz, which allows much better displayed resolution. This decimation simply discards seven of every eight samples of the digitized RF spectrum and through the use of buffers recombines the remaining samples of the In-phase and Quadrature-phase (I and Q) bit streams for processing.

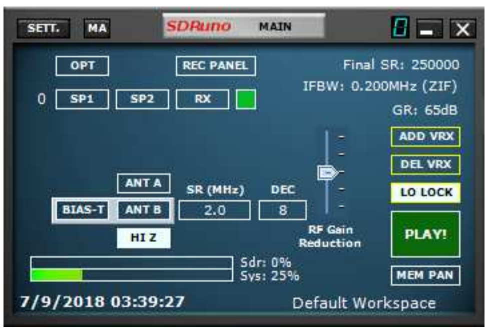

Figure 7 ~ SDRuno Main window. The Sample Rate (SR) is set to 2.0 MHz and Decimation (Dec) to 8 (both controls near middle of window) to provide an effective sample rate of 250 kHz. The RSP2Pro has three antenna ports, which may be selected near the lower-left and are marked ANTA, ANTB and HI Z. As mentioned previously, I used the balanced, HI Z interface. The local oscillator (LO) frequency is set by unlocking the LO LOCK button (middle-right) and tuning the receiver from the virtual receiver control window (described later). Once the desired LO frequency is set, it is locked as shown here. The receiver can then be tuned as needed. The Play button starts and stops the receiver.

For the observations reported here, I operated the receiver in *zero IF* mode (also called direct conversion and homodyne) (figure 8). One theoretical advantage of zero IF is image cancellation, which allows the spectrum both above and below the local oscillator (LO) to be viewed on the spectrum display. For example, if the receiver sampling rate is set to 250 kHz and the LO is set to 125 kHz, the viewable spectrum is 0 to 250 kHz (although it is unusable below about 9 kHz). However, with these settings there will be a strong oscillator signal displayed at 125 kHz. Depending on the quality of the receiver's oscillator there will be a certain range around the LO that is unusable due to oscillator noise (this will be apparent in a spectrum display image shown later). It should be noted that image cancellation in a zero IF receiver is never perfect so vestiges of frequency inverted signals may be apparent on each side of the LO; these are often very difficult to distinguish from real signals.

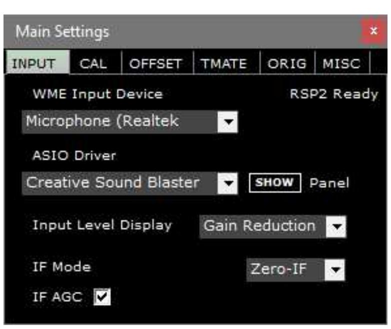

Figure 8 ~ Main Settings window. The IF Mode is set to zero-IF from the drop-down menu at the bottom-right (a *low-IF* mode also is available but I found it unsuitable for VLF). The SDRuno software allows the receiver gain setting to be displayed on the Main window in terms of Gain Reduction (shown here) or, alternately, simply Gain. With Gain Reduction, moving the gain slider upward in the Main window reduces the receiver gain (introduces attenuation); Gain Reduction is not intuitive. If set for Gain, raising the gain slider increases the receiver gain. Like almost all SDR receivers, the RSP2Pro is quite sensitive to the gain setting especially when strong signals are present in its frontend passband.

I initially set the receiver LO to a frequency in the 10 to 13 kHz range. Although I achieved good overall results, this LO setting range resulted in a strong oscillator signal at the lower end of the frequency range I was observing. For example, with the LO is set to 12 kHz, a strong spectral indication is located at 12 kHz. I later increased the LO frequency to a setting in the range 70 to 100 kHz (figure 9), which moved the oscillator signal out of the way above my observed frequency range. It turned out there were no signals at the low end of the observed frequency range, anyway, and my low end of 10 kHz was very close to the advertised 9 kHz lower frequency limit of the RSP2Pro.

The SDRuno software can operate up to sixteen simultaneous virtual receivers. A virtual receiver is simply a group of software settings that allow the user to specify and display a particular frequency and spectrum and use a particular demodulation mode and associated filters. The frequencies of the virtual receivers can be different but must fall within the spectral width, or span, determined by the sampling rate and decimation, and all must use the same LO frequency. Each virtual receiver has its own uniquely numbered control window or VRx and has associated with it unique Main Spectrum (SP1) and Auxiliary Spectrum (SP2) windows.

The received power in dBm and signal-to-noise ratio (SNR) in dB for the selected receiver frequency in the VRx is displayed in its associated Main Spectrum SP1 window. When using the high impedance (HI Z) input, the reference for the internal dBm calculation is 1 milliwatt into 1000 ohms (for the ANT A and ANT B inputs the impedance is 50 ohms). These data may be saved in a Comma Separated Variable (CSV) file during a user-specified time interval. In response to my inquiry about how the power and SNR are calculated in SDRuno, SDRPlay technical support said "*The SNR is calculated using the noise bandwidth defined within the SP2 window, whereas the spectrum display shows the noise power integrated across the FFT resolution bandwidth. The difference between the two will be* $10 \cdot Log\left(SP2BW/RBW \right)$".

The mouse cursor changes to cross-hairs when it is over the Main Spectrum (SP1) window and displays the frequency and power in dB relative to the receiver's analog-digital converter (ADC) full scale. When the cross-hairs are placed at the peak of a signal at the receiver frequency, the dBm power reading and cross-hairs dB reading differ by 10 dB, indicating that ADC full scale corresponds to an input power of +10 dBm. The mouse cross-hairs also display frequency and relative power in dB when placed over the Auxiliary Spectrum (SP2) window. Demodulated signals are displayed in SP2 with a dB scale but there is no apparent relationship with its dB scale to the SP1 dB scale.

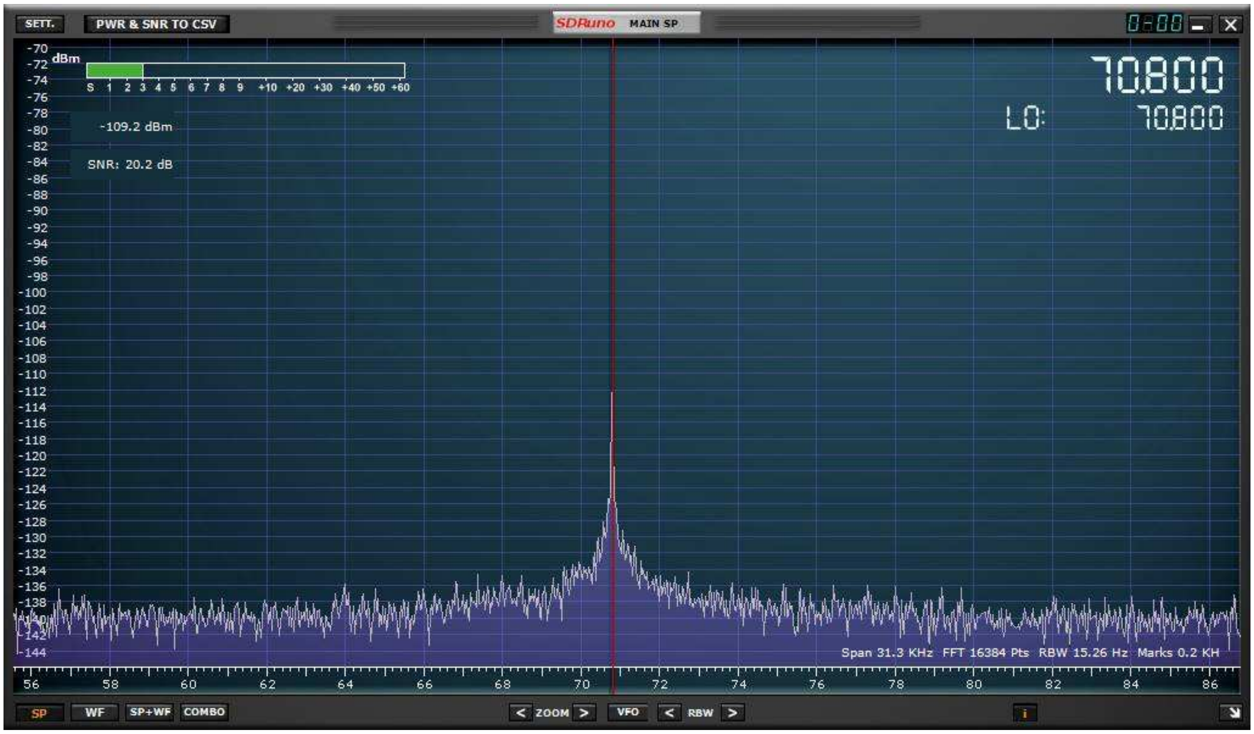

Figure 9 ~ Main Spectrum window. The LO is set to 70.800 kHz as seen at the upper-right of this example. The receiver also is tuned to 70.800 kHz as seen just above the LO setting. A red cursor indicates the receiver frequency on the spectrum display. Note the large spectral spike at 70.8 kHz and the relatively higher noise around it; this is the undesired LO signal and its associated phase noise. The type of Main Spectrum display can be selected by clicking on the SP (spectrum only), WF (waterfall only) or SP + WF buttons at the bottom-left of the window. The SP display is shown in this example. The displayed frequency range can be changed within limits set by the sampling rate and decimation by dragging the frequency scale with the mouse and by using the < Zoom > buttons.

For initial familiarization I experimented with short data recordings on station NLK in Washington USA on 24.8 kHz and a few others. For longer tests I setup three virtual receivers (figure 10) to allow simultaneous data saving at three different frequencies in the 10 to 41 kHz band: 19.8 kHz, NWC (North West Cape) in Australia, 23.4 kHz, DHO38 in Rhauderfehn, Germany, and 24.0 kHz, NAA in Cutler, Maine USA. I adjusted each virtual receiver Main Spectrum window to display the frequency range 10 to 41 kHz (figure 11). Various other adjustments such as displayed amplitude range, noise floor position, color scheme and contrast are made in the respective Main Spectrum Settings window (figure 12).

Received power and SNR data are saved at an interval determined in the Time Mark Interval dropdown menu in the Main Spectrum Settings window. I initially used 5 seconds for the DHO38 and NAA data and 10 seconds for the NWC data. These sample intervals produce a lot of data over a 24 h period but these settings are comparable to the interval used in the SuperSID software, which is the benchmark software for SID observing {SuperSID}.

Figure 10 ~ Three RX Control (VRx) windows shown tiled. These are numbered consecutively 0-00, 0-01 and 0-02 as seen in the upper-right corner of each window. The VRx window is used to set the desired receiver frequency. This frequency also will be displayed in the corresponding Main Spectrum window SP1 as the receiver frequency. The LO frequency displayed in all virtual receiver Main Spectrum windows will be the same.

As shown here the virtual receivers are set to CW mode and 150 Hz bandwidth. The VLF signals cannot be demodulated in any useful way by SDRUno but a CW audio tone can be monitored when the demodulation is set to the CW mode. The default offset in SDRUno for the CW mode is 700 Hz but this may be changed if desired. When in CW mode, the IF spectrum is centered at this offset and the display has different shading to indicate the demodulation bandwidth. For example, if the receiver is tuned to 19.8 kHz in CW mode, the IF spectrum is centered at 700 Hz offset. The demodulation mode in no way affects the overall displayed IF spectrum. With other demodulation modes, such as AM and SSB, the IF spectrum is centered on the receiver frequency (no offset).

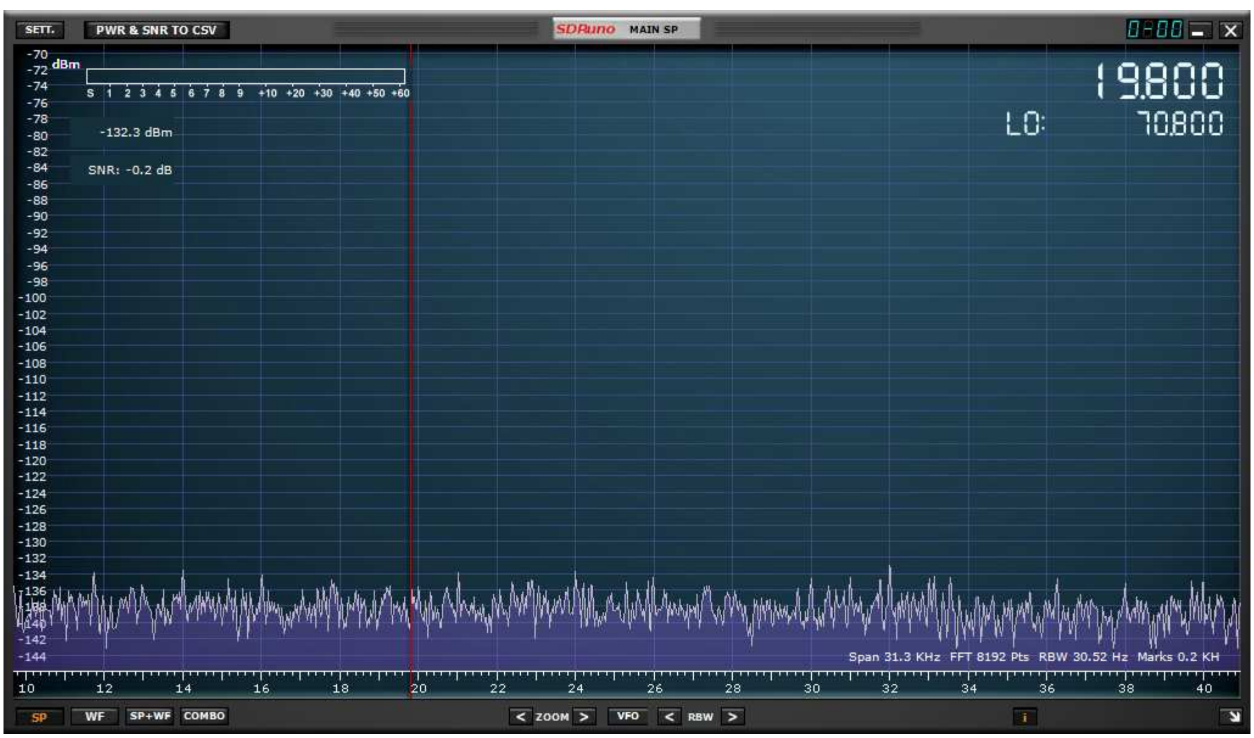

Figure 11 ~ Main Spectrum window corresponding to VRx 0-00. No antenna was connected for this image. To set the displayed frequency range to 10 to 41 kHz, it is necessary to press the increase zoom button > until the displayed frequency span is 31 kHz wide. The Span will be displayed in the Info text on the lower-right of the spectrum along with the FFT frame size (8192 bits shown here), resolution bandwidth RBW (30.52 Hz) and frequency scale tick interval (0.2 kHz). The left-mouse button is then used to grab the frequency scale and drag it until it starts at 10 kHz.

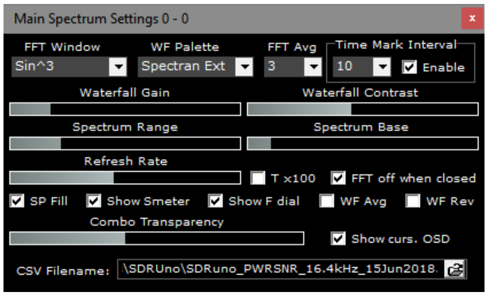

Figure 12 ~ Main Spectrum Settings window. The Spectrum Range slider is adjusted to display the desired amplitude range. The noise floor may be moved up or down using the Spectrum Base slider. The Range and Base settings interact. Many other settings are available in this settings window including FFT averaging, time stamp (or Time Mark) interval, color palette and the file path for the saved CSV data. FFT averaging is very handy for bringing out weak relatively steady-state signals, and I often used a setting of 256.

The SDRuno software also has built-in Waveform Audio File Format (*.wav) file record and playback capability. WAV recording is different than the CSV files recorded for individual frequencies previously described. It records the entire spectrum as determined by the sampling rate and decimation. WAV file recording results in even more data than the channel CSV files. An individual WAVE file cannot exceed 2^{32} bytes, or about 4 GB. SDRuno allows the user to specify a maximum WAV file size up to that limit. Since many programs that can process WAV files limit the file size to 2.1 GB, I set my recordings to that maximum. I found that for the spectrum setup used here, a 2.1 GB WAV file was produced about every 30 minutes. A 24 h recording session results in about 100 GB (0.1 TB) of data and 10 days of data will fill a 1 TB hard drive.

WAV recording may be scheduled for a user-specified time and date. The time and date schedule for a recording session is entered in a popup Recorder Configuration window from the main Recorder window. However, only one recording session can be scheduled at a time – multiple recording schedules are not possible in the SDRuno version I used. The entire spectrum contained in the files can be played back later for detailed analysis. In this regard, SDRuno has an annoying limitation: It cannot be opened without a receiver attached so WAV file playback is not possible without a receiver (I did not attempt playback with any other application).

5. Stations Received by Temporary Loop Antenna Setup

I received all US government VLF stations except NAU in Puerto Rico (possibly off the air) with the initial setup on 7 June (table 1). I received station NPM in Hawaii on 7 June but it went off the air after those first tests until 14 September. The station details including the correlation between frequency and station ID were taken from various online lists, including {ReeveVLF}, {VLFList-1}, {VLFList-2} and {VLFList-3} (all lists, including my own, are cross-dependent and have out-of-date or incorrect information but are the best I could find). Additional details are provided for CRO and the stations selected for data saving as CSV files (table 2 and figure 13).

Table 1 ~ Stations received during initial tests at Cohoe Radio Observatory on 7 June 2018
Azimuths and distances are calculated from coordinates given in the online sources cited in the text

Frequency (kHz)	Station ID	Country	Azimuth (° True North)	Distance (km)	Remarks
16.4	JXN	Norway	007	5773	
18.1	RDL	Russia	Unknown	Unknown	Intermittent, see text
19.8	NWC	Australia	263	12386	
21.1	RDL	Russia	Unknown	Unknown	Intermittent, see text
21.4	NPM	Hawaii, USA	190	4390	Off air later
22.2	JJI	Japan	277	6297	
23.4	DHO38	Germany	014	7224	
24.0	NAA	Maine, USA	068	5464	Superposed spur
24.8	NLK	Washington, USA	113	2272	
25.2	NML	North Dakota, USA	090	3661	
30.0	Unknown	Unknown	Unknown	Unknown	Superposed spur

Table 2 ~ Cohoe Radio Observatory and selected stations
Coordinates are from the online sources cited in the text

Station	Location	Frequency (kHz)	Geographical coordinates	Remarks
CRO	Cohoe, Alaska USA	N/A	60° 22’ 06” N, 151° 18’ 55” W	Receiver
NWC	North West Cape Australia	19.8	21° 49’ 01” S, 114° 09’ 58” E	Transmitter
DHO38	Rhauderfehn, Saterland, Germany	23.4	53° 04’ 46” N, 07° 37’ 01” E	Transmitter
NAA	Cutler, Maine USA	24.0	44° 38’ 35” N, 67° 16’ 52” W	Transmitter

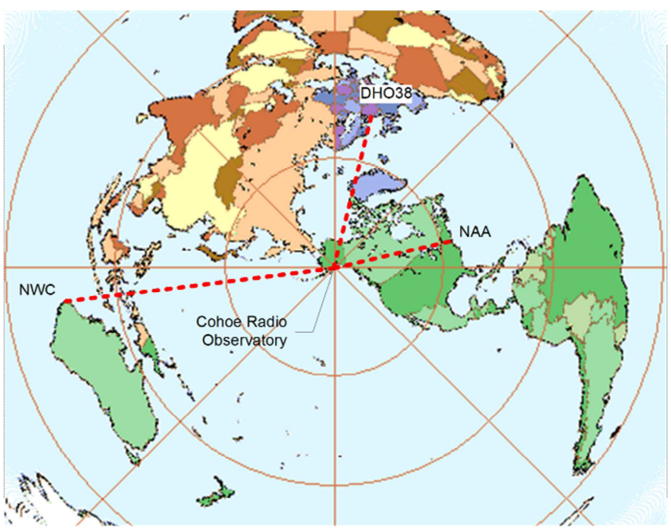

Figure 13 ~ World view showing Cohoe Radio Observatory (center) and stations selected for data saving: NWC, DHO38 and NAA. Top is true north. This map was produced with Aziworld software {Aziworld} and annotated in MS Visio.

6. Description of Received Signals

I was surprised by the low noise levels at Cohoe compared to my Anchorage observatory and the number of stations that I received with the temporary setup (figure 14). Each station showed a different pattern throughout the day and night depending on its location with respect to CRO. By rotating the loop I was able to determine the general direction to each station (with 180° ambiguity) and could compare that to the online VLF and LF frequency lists that show station coordinates.

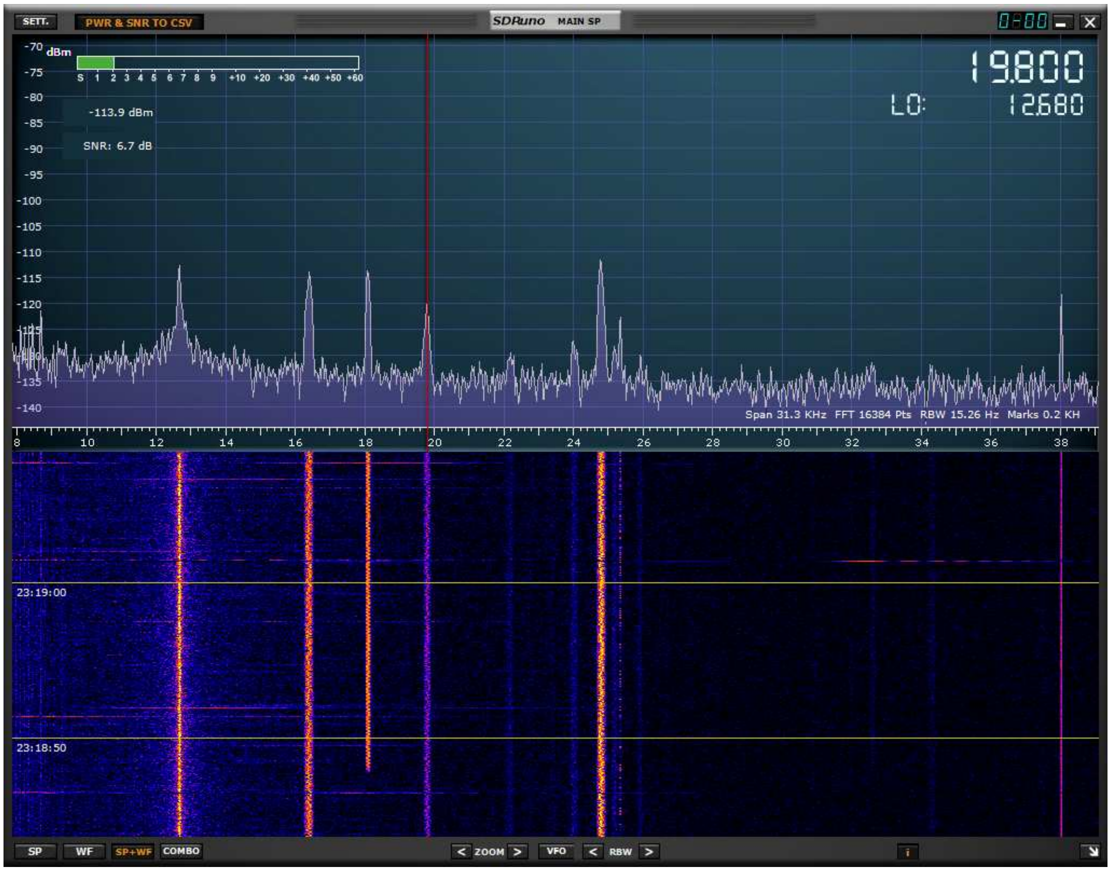

Figure 14.a ~ Main Spectrum window for reception on 16 June 2018 showing the frequency range 8 to 39 kHz. Several stations are visible including 16.4 kHz, 18.1 kHz, 19.8 kHz (red cursor location), 22.2 kHz, 24.0 kHz, 24.8 kHz and 25.2 kHz. The LO can be seen at 12.680 kHz and a receiver artifact is seen at 38 kHz. When FFT averaging is used, the noise floor smooths out and receiver spurs appear at 8 kHz intervals but they are not visible here.

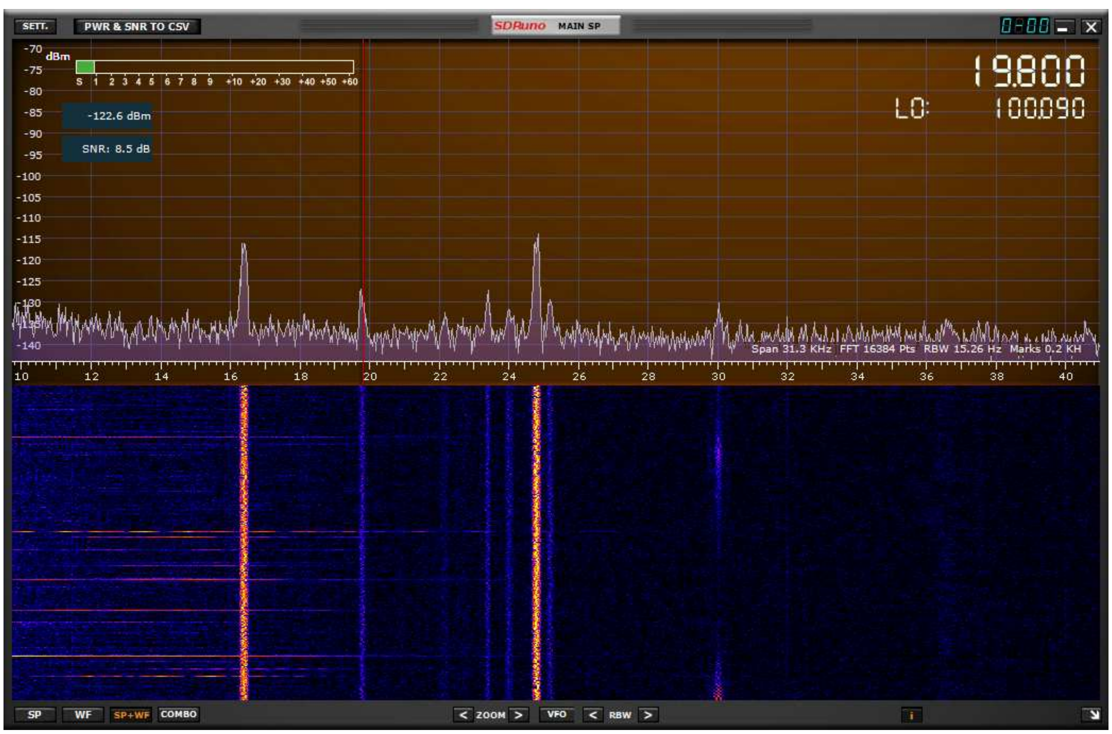

Figure 14.b ~ Main Spectrum window for reception on 16 June 2018 showing the frequency range 10 to 41 kHz. Most of the stations seen in the previous figure are visible here with an added station at 30.0 kHz. The main difference is the LO frequency, which was set to 100.090 kHz and moved out of the displayed frequency range.

The antenna plane was oriented north-south during most of the tests described here; this placed the pattern null east-west (figure 15). I did change directions when measuring the approximate station directions and to locate stations that might be in the direction of the loop east-west pattern null (for example, NML in North Dakota USA).

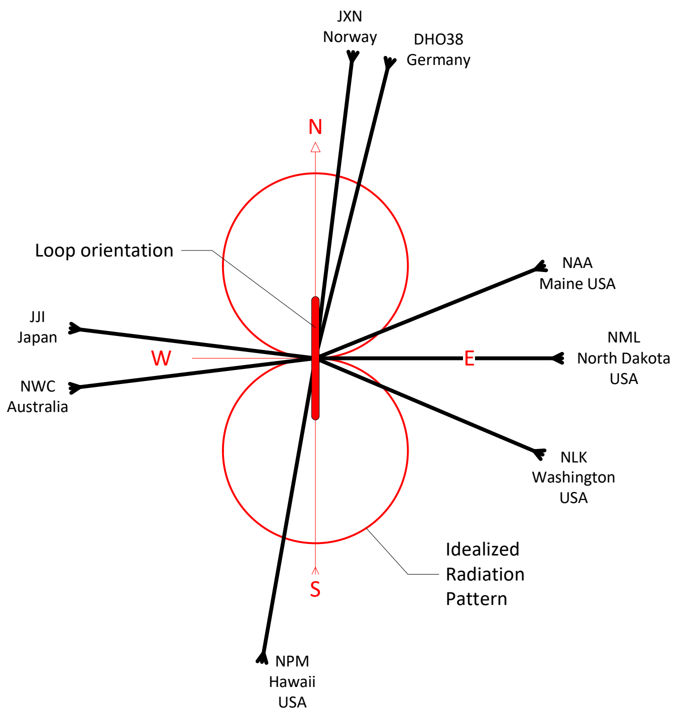

Figure 15 ~ Idealized loop radiation pattern for the loop plane oriented north-south and received station relative directions. This view is from above the loop looking down on it and shows the maximum (N-S) and null directions (E-W). The stations received on the initial tests are shown. Station NML in North Dakota USA (90°) was not detected until the loop was rotated away from north-south, and station JJI in Japan (277°) was weak but detectable when the loop plane was in the north-south direction. Station NWC on the west coast of Australia (263°) generally was strong even with the loop plane oriented north-south but would be enhanced when rotated. Received signal strength of all stations varied over a 24 h period. Image © 2018 W. Reeve

The low frequency stations generally can be recognized by their relatively wide spectrum compared to a single carrier or a single receiver spur or artifact, which appear as spectral spikes. By expanding the frequency scale (zooming) on the Auxiliary Spectrum SP2 window, the resolution bandwidth is lowered and the individual spectral components of multi-carrier transmissions and the shapes of continuous spectra are revealed.

The received spectrums from all stations that are operated (or paid) by the USA have a smooth Gaussian shape (figure 15.a) and are transmitted continuously for long periods. The exception, noted during my relatively limited observation times, is NWC, which occasionally breaks into multi-carrier and other modulated transmissions. The two Russian stations I received on 18.1 and 21.1 kHz often appear to use multiple carriers (figure 15.b) and I never observed continuous spectrums. The groups of multi-carriers are irregularly turned on and off. These two stations often operate together but not at exactly the same time. One will turn on and a few seconds later the other will turn on. When one turns off the other turns off a few seconds later. Transmissions can last a few minutes to several hours and periods between transmissions usually last a few minutes or less. The signals from the Russian stations variously consist of one or more carriers and other times have a low-speed frequency shift keying modulation (FSK) that demodulates as warbling tones.

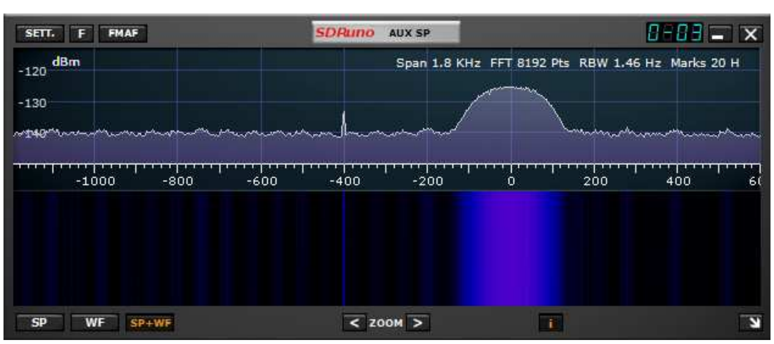

Figure 15.a ~ Auxiliary Spectrum window showing the IF spectrum for the received signal at 16.4 kHz, which is centered at 0 Hz on the frequency scale. FFT averaging was used to smooth out the visible noise floor and accentuate the signal. Note the smooth Gaussian shaped spectrum indicative of VLF transmissions used by the US Navy. The resolution bandwidth indicated is 1.46 Hz.

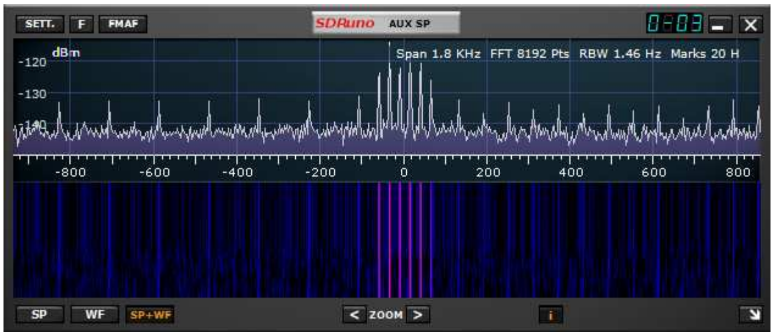

Figure 15.b ~ Auxiliary Spectrum window showing the IF spectrum for the received signal at 18.1 kHz, purportedly a Russian station, and centered at 0 Hz. Note the multiple carriers separated by 10 Hz. This is only one of several types of signals seen on 18.1 and 21.1 kHz. Also present in this image but only occasionally seen are spectral spikes at 60 Hz intervals, probably from intermittent powerline interference.

The received signal levels over long periods reflect the changing propagation characteristics between the transmitting and receiving stations. Generally, the received signal levels increase at night and decrease during the day (figure 16). However, because CRO is a higher latitude station, the summertime propagation is complicated by the long days and short nights. Propagation is also affected by the mix of land and water or ice along the propagation path, among other things.

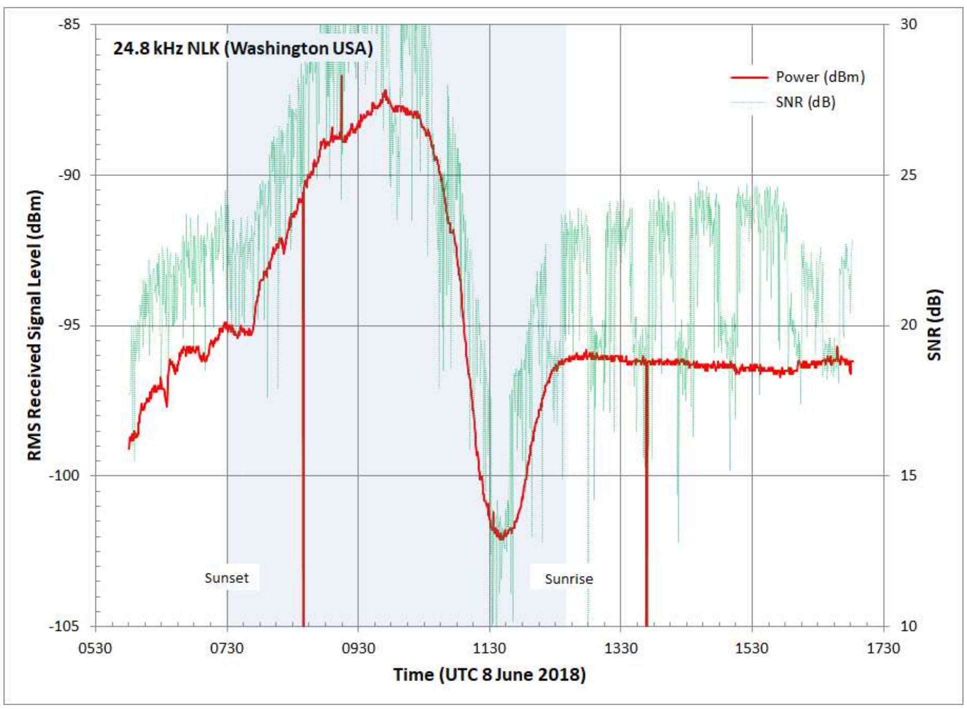

Figure 16 ~ Example of night and day propagation from station NLK as received at Cohoe Radio Observatory covering approximately 12 h. The signal level (red trace) rises after sunset, in this case near sunset at the transmitter site, and then falls rapidly the next morning as the Sun rises and has a characteristic dip before leveling off for the day. The signal-to-noise ratio (light green trace) is quite variable at all times and shows periodic noise increases (reduced SNR) during the day, probably powerline noise. Image © W. Reeve 2018

During my tests in early- and mid-June near the summer solstice, the nights at CRO from the end of civil twilight as the Sun sets to the beginning of civil twilight the next day as the Sun rises lasted only about 1 h 45 min (the opposite occurs during winter). Depending on the relative location of the transmitting station, the propagation path may traverse nighttime or daytime ionospheres, or both. For example, station NWC on the west coast of Australia is in the southern hemisphere near latitude 22° S at a (short path) distance of 12 400 km from CRO. The great circle propagation path is almost entirely over water. During the late-afternoon at CRO the propagation path not only crosses the equator but is completely in daylight (figure 17.a). The propagation path to the German station DHO38, which is near latitude 53° N, is over the North Pole and traverses a distance of 7200 km over water, ice and land. This path is mostly in daylight (figure 17.b). The propagation path to station NAA in

Maine USA, which is near latitude 45° N and about 5500 km, is entirely over day lit land although the Sun is near setting at that location and time (figure 17.c).

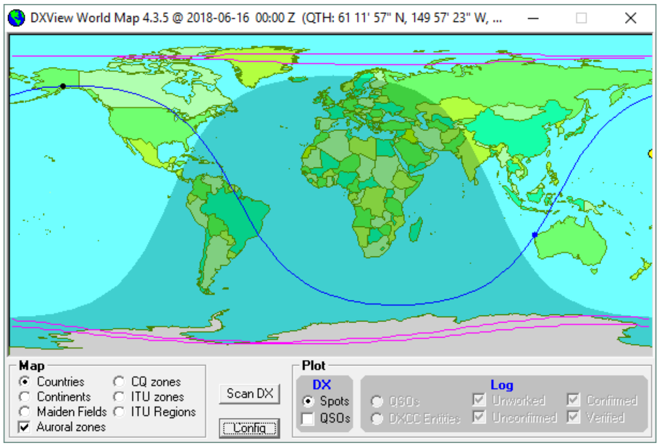

Figure 17.a ~ Solar terminator (gray line) plot showing the great circle propagation path (blue line) between CRO in Alaska and NWC in Australia at 0000 UTC. The station's locations are indicated by blue dots. Local times at the stations corresponding to UTC are 4:00 PM at CRO and 8:00 AM at NWC. The Sun's location is indicated by the (partial) yellow circle on the far right edge. This and the following two images were produced from DXView, a component of the DXLab software {DXLab}.

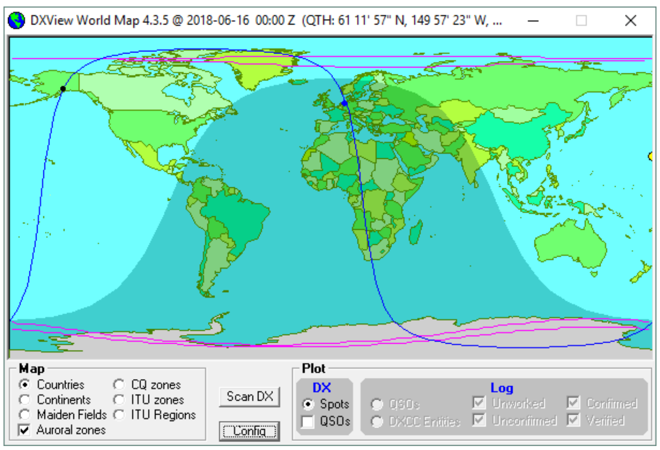

Figure 17.b ~ Solar terminator plot showing the propagation path between CRO and DHO38 in Germany at 0000 UTC. Corresponding local times at the stations are 4:00 PM at CRO and 2:00 AM at DHO38.

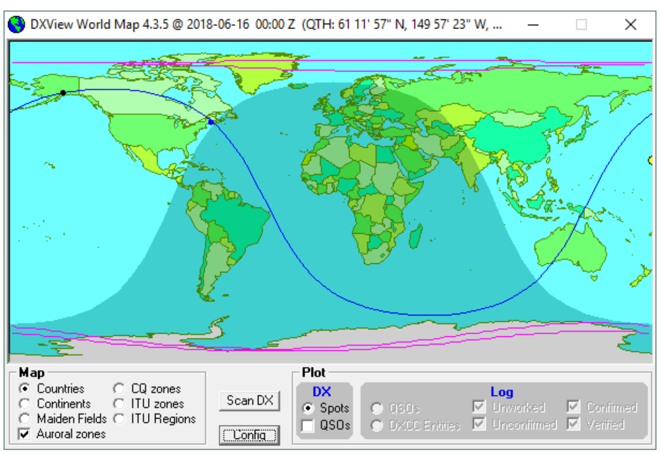

Figure 17.c ~ Solar terminator plot showing the propagation path between CRO and NAA in Maine USA at 0000 UTC. Corresponding local times at the stations are 4:00 PM at CRO and 8:00 PM at NAA.

Of course, the mix of day and night along the paths changes over a 24 h period as well as with the seasons. Longer daylight hours at CRO correspond to shorter daylight hours in the southern hemisphere. Stations at mid- or low-latitudes experience a more even split of day and night throughout the year than stations at higher latitudes. Higher latitude stations experience long days during summer and short days during winter. Earth's magnetic field also significantly influences the ionosphere and propagation. The field lines have a low angle with respect to Earth's surface at lower latitudes but sharply dip at higher latitudes. These differences affect the path propagation characteristics at VLF and LF. The propagation characteristics can be studied with plots of received signal levels with respect to time.

As previously mentioned, the data for three selected stations were saved as Comma Separated Variable files by SDRuno. The CSV files were then imported to Excel, saved as *.xlsx files and plotted using Excel's built-in chart functions (figure 18). Data were saved for 46 h, which resulted in CSV files sizes of approximately 0.7 MB (10 s data saving interval) and 1.7 MB (5 s interval).

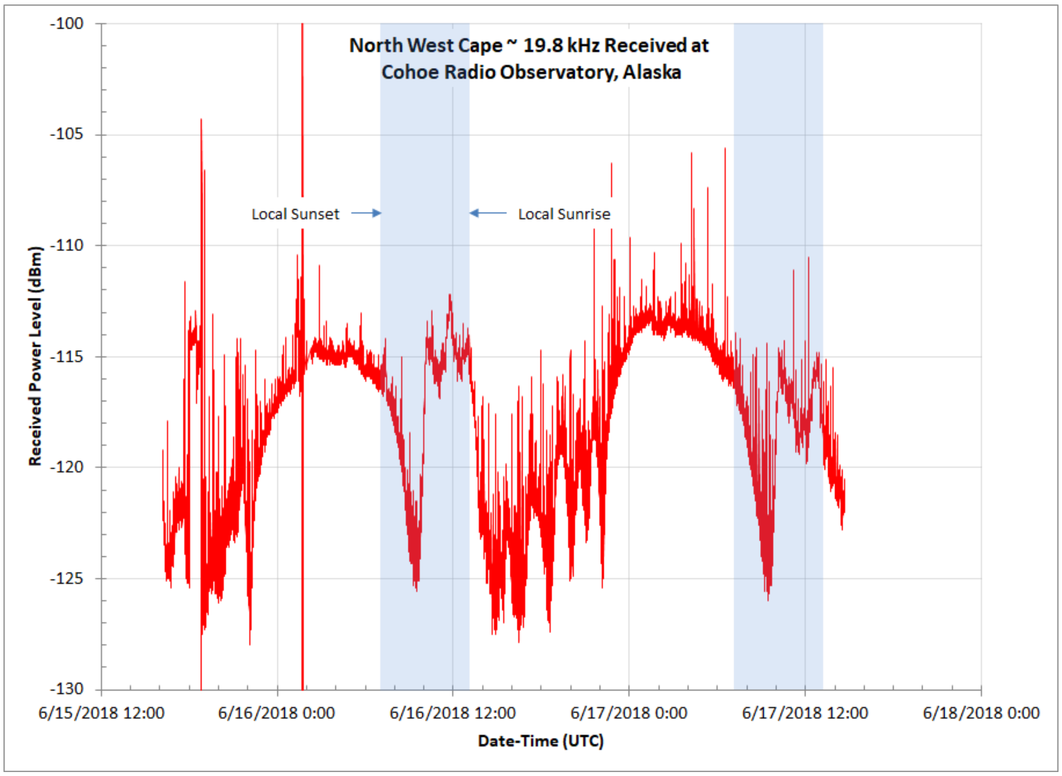

Figure 18.a ~ Received signal levels saved at 19.8 kHz for station NWC from 1600 UTC on 15 June 2018 to 1400 UTC on 17 June 2018. The shaded areas indicate the period between sunset and sunrise at CRO.

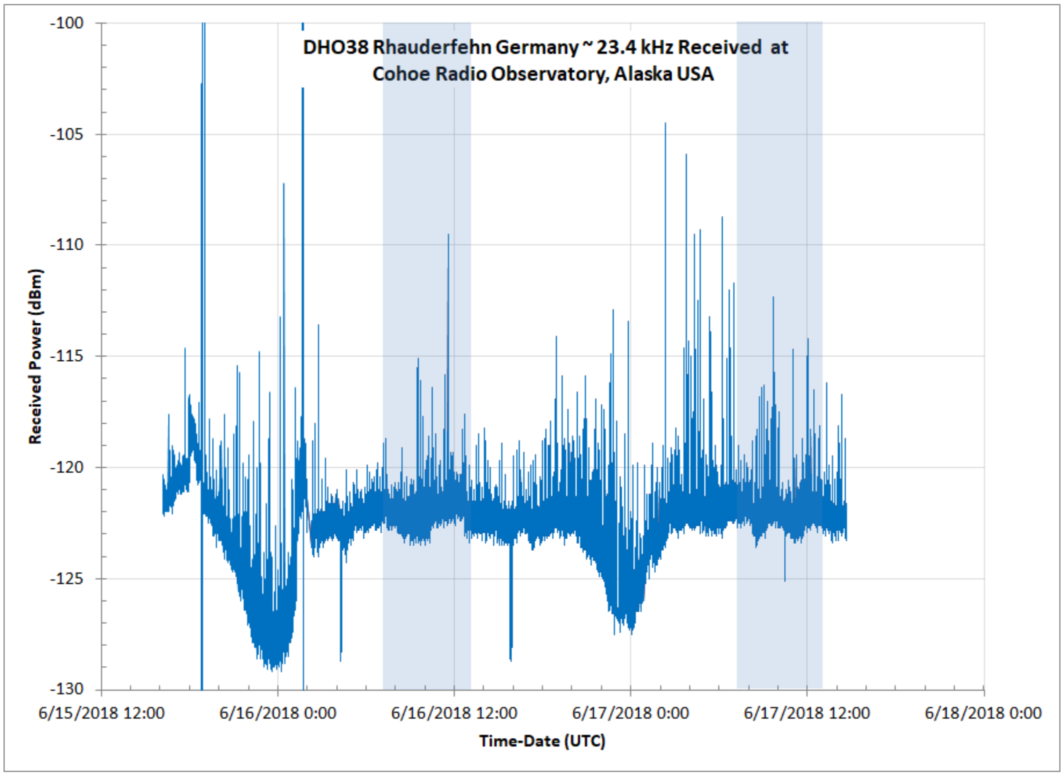

Figure 18.b ~ Received signal levels saved at 23.4 kHz for station DHO38 from 1600 UTC on 15 June 2018 to 1400 UTC on 17 June 2018. The shaded areas indicate the period between sunset and sunrise at CRO.

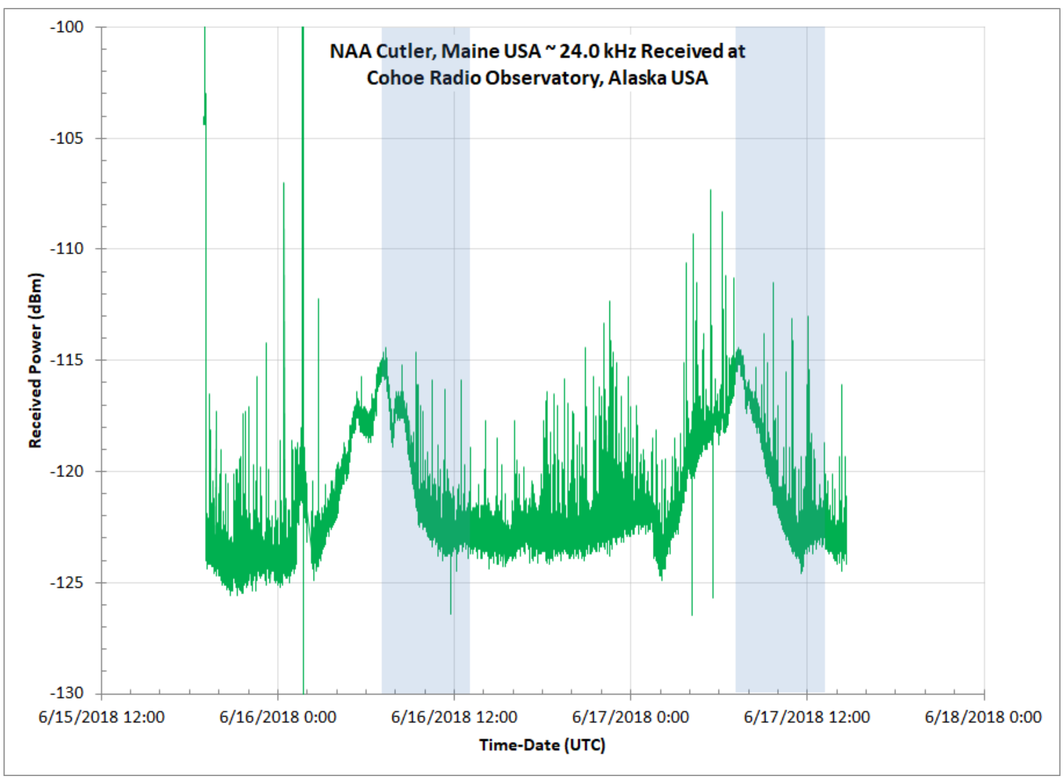

Figure 18.c ~ Received signal levels saved at 24.0 kHz for station NAA from 1600 UTC on 15 June 2018 to 1400 UTC on 17 June 2018. The shaded areas indicate the period between sunset and sunrise at CRO.

7. Discussion

The plotted received signal levels throughout a 24 h period show day-night patterns similar to what would be expected for VLF and LF propagation – higher levels during the night and lower levels during the day. However, because the propagation paths are long and the change in proportion of local day and night throughout the seasons, it is necessary to analyze the day-night aspect of each path to determine how the propagation is affected. Clearly, additional data are needed.

The plots also indicate a considerable amount of impulse noise. The temporary installation used Unshielded Twisted Pair (UTP) cable transmission line and, thus, no shield bonding and grounding. Later, when I permanently installed the loop, I replaced the UTP with Shielded Twisted Pair (STP) and bonded the shield at both ends to Earth ground. This considerably reduced the impulse noise. Using the software noise blanker may help control the impulse noise effects on the data, and it may be necessary to use a larger loop antenna to increase the signal-to-noise ratio.

One drawback to using the RSP2Pro and SDRuno software for SID detection and monitoring is that the data are not directly compatible with the SuperSID data that is archived by Stanford Solar Center {SSCData}. I did not investigate adapting or converting the data so that it is compatible. Nevertheless, the received signal plots automatically generated from the SuperSID data may be easily compared to the SDRuno data that has been manually plotted in Microsoft Excel.

8. Conclusions

The main purpose of the temporary loop antenna Installation was to determine if Cohoe Radio Observatory is a viable location for receiving VLF and LF transmissions. The site proved to be quite satisfactorily, and a permanent installation has since been built. A secondary purpose was to determine if the SDRPlay RSP2Pro receiver and associated SDRUno software are suitable for this type of observing. These also appear to be satisfactory but I plan to do more analyses.

As the days get shorter at Cohoe additional data will be collected for analyzing the day-night propagation characteristics and possibly capturing a SID. Low frequency radio enthusiasts who are more interested in modulation methods or simply monitoring the encrypted transmissions of governments worldwide than detecting SIDs and related phenomena will find that the receiver system described in this paper is worth considering.

9. References and Weblinks

{Reeve18-1} Reeve, W., Square Loop Antenna, 1.2 m Diagonal ~ Mechanical and Electrical Characteristics and Construction Details, 2018, available at: http://www.reeve.com/Documents/Articles%20Papers/Reeve_SquareLoopAntenna1.2m.pdf

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{VLFList-3} https://www.smeter.net/stations/vlf-stations.php

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