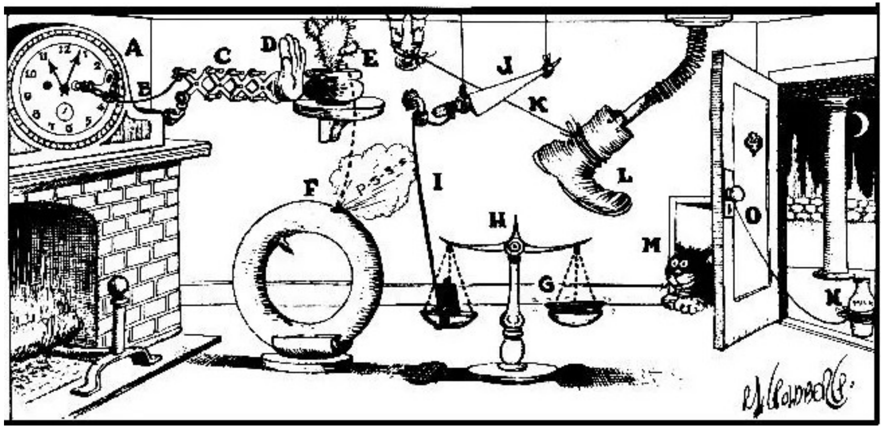
Building a 23cm SDR Based EME System

Dennis Rosenauer
GNU Radio Conference 2025

Summary



- EME or Earth Moon Earth communications has a lot of moving parts
  - High power transmitters
  - Sensitive receivers
  - Signal Processing
  - Tracking the Moon
  - Doppler correction
- All these components have to work together to make communications possible

EME System Analysis

- We can use the Radar equation to compute the path loss from a transmitted signal reflected from the moon.
- At 1296 MHz we get:

$$loss = \frac{\sigma r^2 \lambda^2}{64 \pi^2 d^4}$$

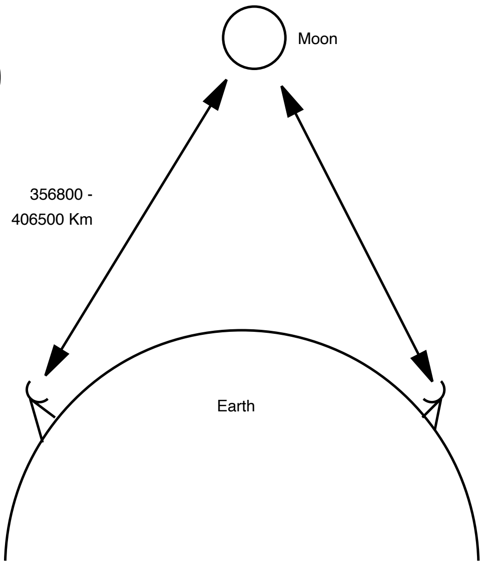
$$where:$$
$$\sigma = lunar\ reflection\ coefficient\ (0.065)$$
$$r = radius\ of\ the\ moon\ (1.738\ x\ 10^6\ m)$$
$$\lambda = wavelength\ (c/1296\ MHz = 0.2313\ m)$$
$$d = distance\ to\ the\ moon\ (3.844\ x\ 10^8\ m)$$

$$loss(dB) = 10 \log_{10}\left(\frac{\sigma r^2 \lambda^2}{64 \pi^2 d^4}\right)$$

$$loss = 7.618\ x\ 10^{-28}$$

$$loss(dB) = -271.1817\ dB$$

- The lunar coefficients are nominal values
- The moon orbit is elliptical, apogee is 406500 Km, perigee is 356800 Km



EME System Analysis

- Link Budget
  - Tx Power 900 W, Antenna Gain 26 dB (1.8m Parabolic Dish)
  - Rx Antenna Gain 28 dB (2.4m Parabolic Dish)
  - PathLoss 271.18 dB

Transmitter	Power	Total Power (dBm)	Total Power
Tx Power	900 W (59.5 dBm)	59.54	900 W
Tx Antenna Gain	26 dB	85.54	354000 W (EIRP)
Path Loss	-271.18 dB	-185.64	
Rx Antenna Gain	28 dB	-157.64	
Received Signal		-157.64	172.19 e-21 W

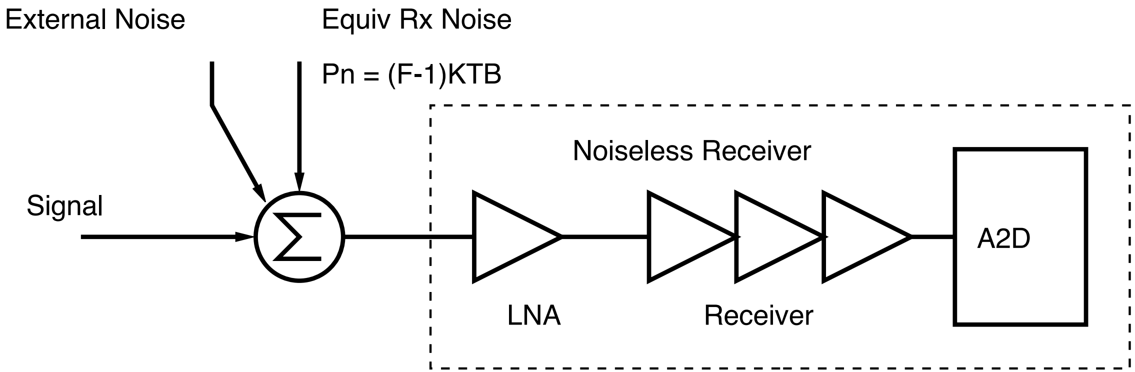
EME System Analysis

- The receiver sees the signal and all the other noise contributions in the system
- They can be all summed up as noise power at the input to the receiver
  - Receiver Noise Figure
  - Sky Noise (galactic and local noise)
  - Antenna noise (sidelobes picking up a warm ground)

$$\text{Equiv } Rx\ Noise\ Power = (F-1)\,KTB$$
$$\text{Sky Noise Power} = KTB,\ (T = Sky\ noise\ temperature)$$
$$\text{Antenna Noise Power} = KTB,\ (T = Antenna\ temperature)$$

$$\text{F} = \text{Noise Factor, not Noise Figure}$$
$$\text{F} = 10^{\left(\frac{NF_{dB}}{10}\right)}$$

$$SNR = \frac{Signal\ Power}{\sum Noise\ Power}$$



EME System Analysis

- Estimated Receiver Input Noise

Receiver	Noise Figure	
LNA NF	0.4 dB (35 dB gain)	
Receiver NF	7.17 dB	
Total Cascade Rx NF	0.405 dB	
Equivalent Noise Power	9.78 e -19 W	-180.1 dBm

$$F = 10^{\left(\frac{NF_{dB}}{10}\right)} = 10^{\left(\frac{0.405}{10}\right)} = 1.0978$$

$$P_{noise} = (F - 1)\, KTB$$

$$P_{noise} = (1.0978 - 1)\, 1.38\, e^{-23} * 290 * 2500$$

$$P_{noise} = 9.78\, e^{-19}\, W = -180.1\, dBm$$

- The Analog Devices 9361 datasheet shows a noise figure of 2.5 dB, it measured as 7.17 dB in the BladeRF.
- The overall receiver degradation is minimal because of the low noise figure and high gain of the LNA

EME System Analysis

- Estimated Received Signal to Noise Ratio (SNR) in 2500 Hz BW

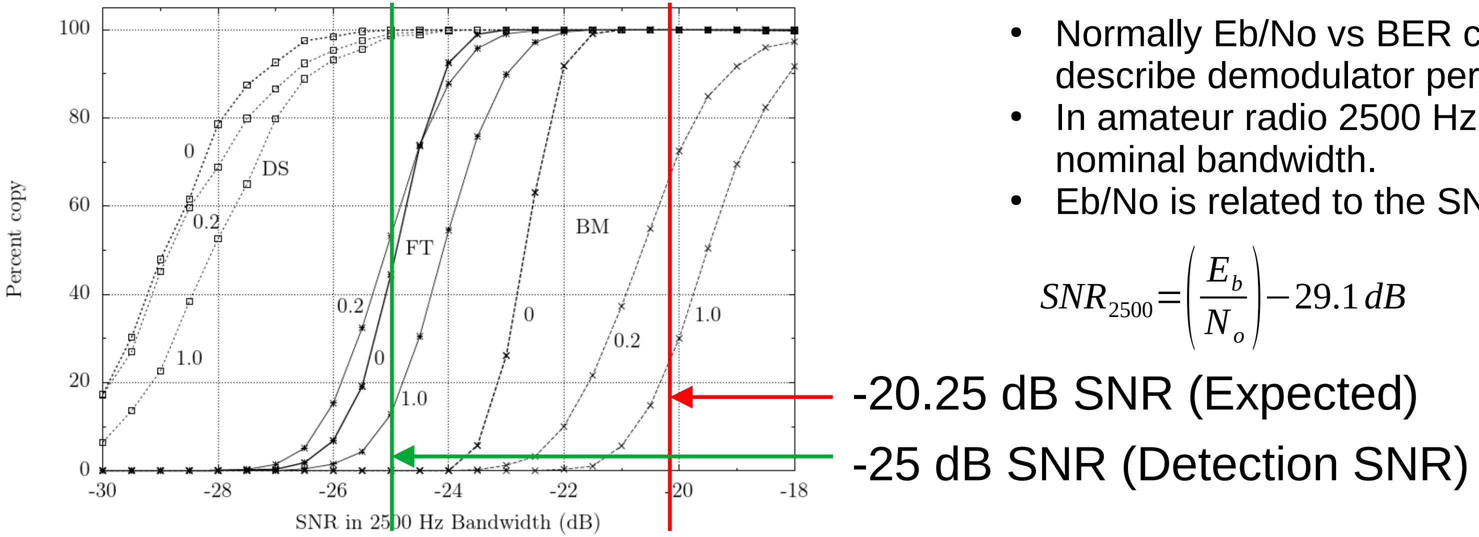
Noise Contributions	Power (dBm)	Power (Watts)
KTB Noise	-140.0 dBm	1.001 e-17
Receiver Noise	-180.1 dBm	9.78 e-19
Sky Noise (Sky Temp 10 K)	-154.6 dBm	3.45 e-19
System Noise Temp (200K)	-141.6 dBm	7.92 e -19
Total Rx Noise Power	-137.4 dBm	1.823 e-17

$$SNR = \frac{Signal\ Power}{\sum Noise\ Power} = Signal\ Power\,(dBm) - \sum Noise\ Power\,(dBm)$$

$$SNR = -157.64\,dBm - (-137.4\,dBm) = -20.25\,dB$$

WSJT-x Modem

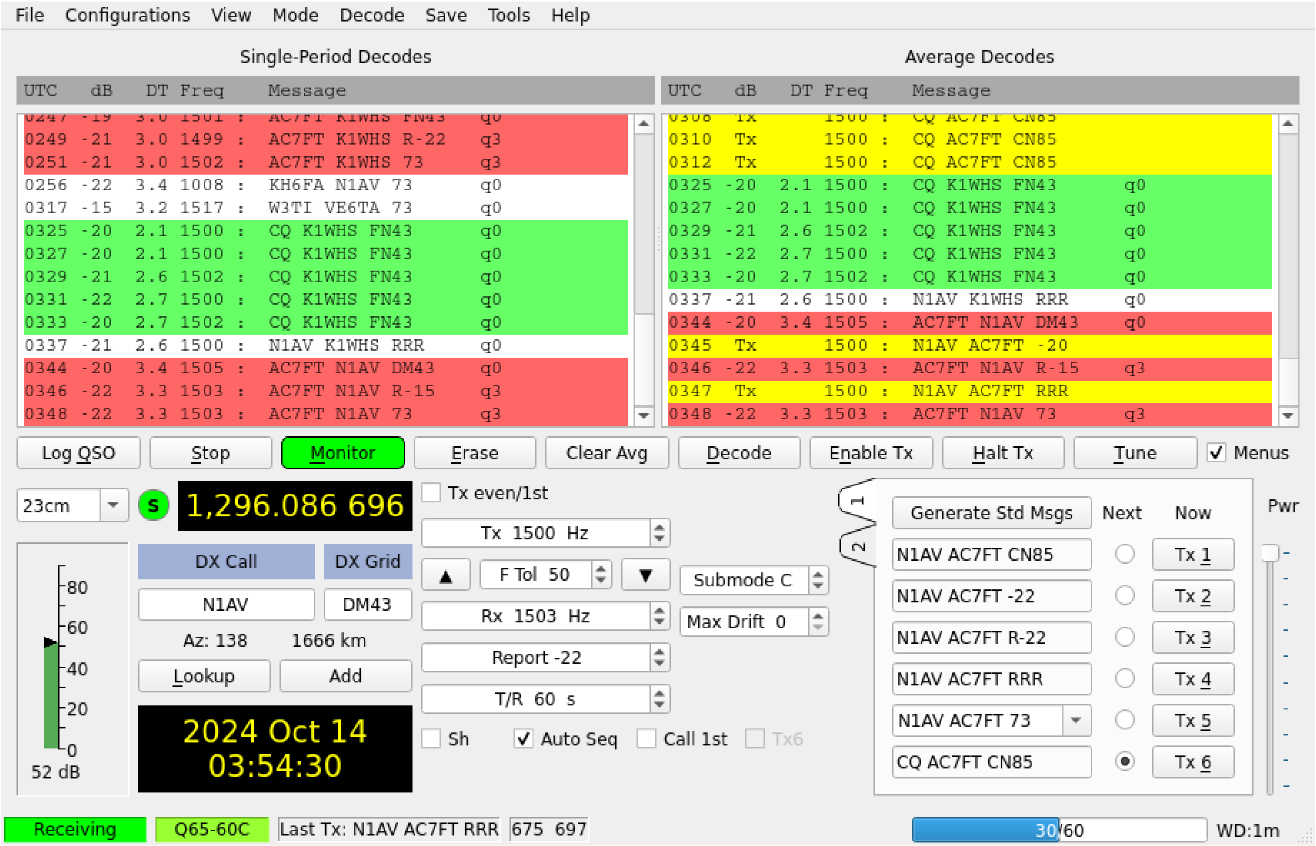
- JT65 decoder is part of the WSJT-x software defined modem that is used in the amateur EME community.
- It uses 65 tone frequency shift keying with constant amplitude and no phase discontinuities. It compresses a message into 72 bits and uses robust forward error correction.
- The detection SNR is about -25 dB in a 2500 Hz channel



- Normally Eb/No vs BER curves are used to describe demodulator performance.
- In amateur radio 2500 Hz is often the nominal bandwidth.
- Eb/No is related to the SNR in 2500 Hz by:

$$SNR_{2500} = \left(\frac{E_b}{N_o}\right) - 29.1\,dB$$

EME System Analysis

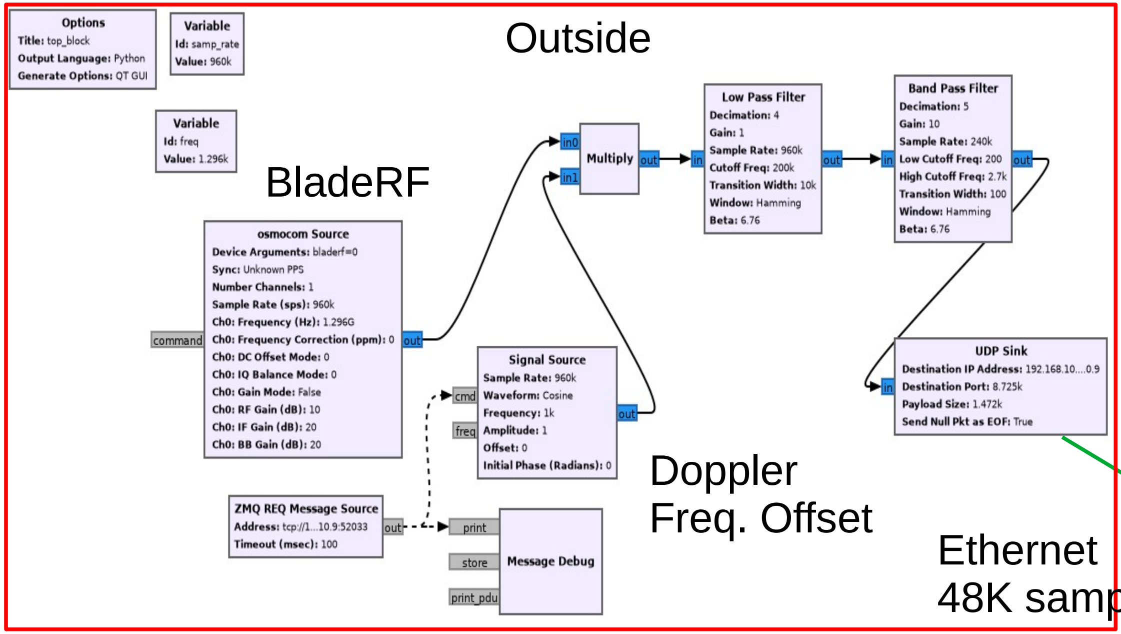


- WSJT-x is the “de-facto” modem used for EME
- It is designed to work with an audio soundcard and simple serial or Hamlib radio control
- EME commonly uses Q65 submode C
- We have to build some software wrappers to use it with an SDR

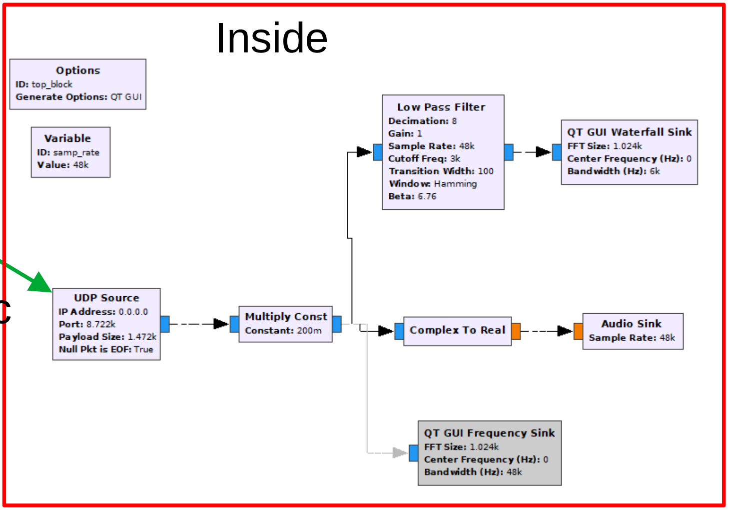
First Receive using GnuRadio

- The first receive test was done using GnuRadio as an SSB converter from a BladeRF SDR down to 48 Ksamples/sec audio
- The BladeRF was set to output samples at 960K samples/sec
- Two stages of decimating filters were used, the final being a 2.5 KHz wide complex SSB filter
- The audio samples we sent via UDP over Ethernet to another instance of GnuRadio for display and to WSJT-x via an audio cross-connect.

First Receive using GnuRadio

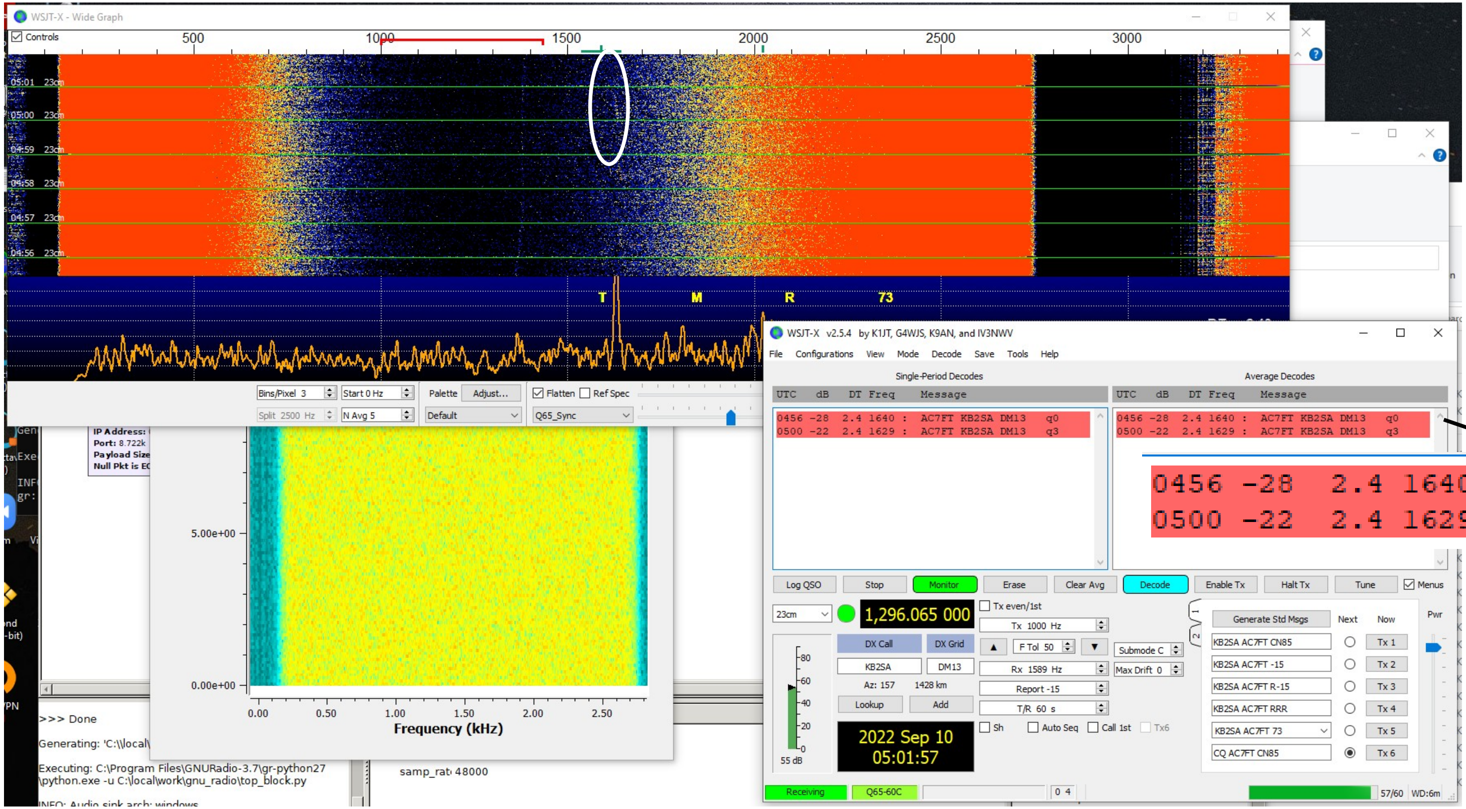


- Inside
  - Waterfall display
  - Audio cross-connect to feed audio to WSJT-x



- Outside
  - Doppler Frequency correction
  - BladeRF outputs 960Ksamples/sec.
  - Decimate and complex filter to 48Ksamples/sec (SSB 2.5 KHz)
  - Send 48K audio over Ethernet (UDP)

First Decode via EME at 1296 MHz



- Copied KB2SA
- SNR -22 dB
- 2.4 sec round trip delay

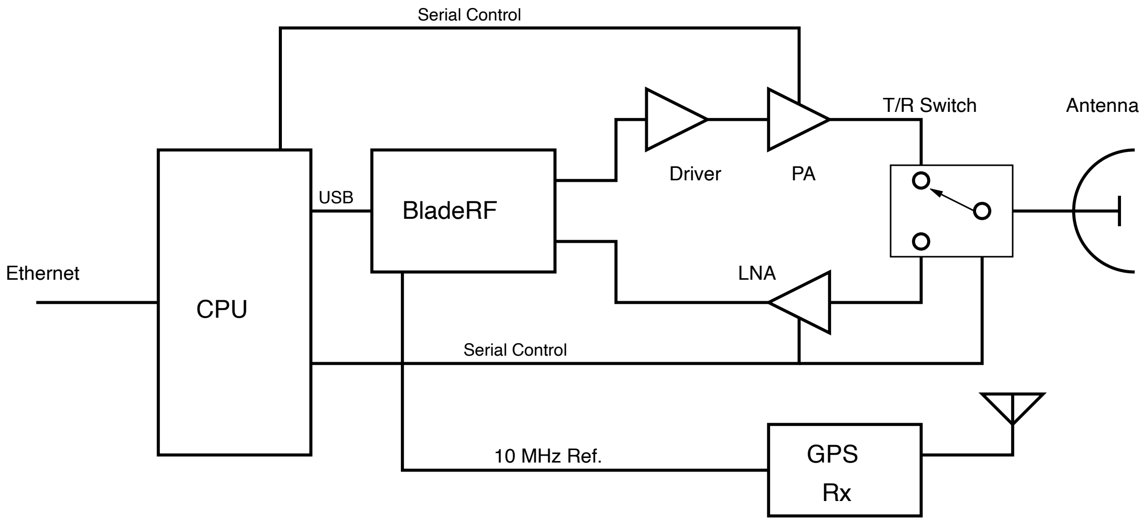
```
0456 -28  2.4 1640 :  AC7FT KB2SA DM13   q0
0500 -22  2.4 1629 :  AC7FT KB2SA DM13   q3
```

Lessons

- Doppler correction needs fine frequency tuning in real time
- GnuRadio makes a great initial test bed, but doesn’t handle real time frequency corrections and transmit-receive switching very well
- Keep the antenna pointed at the moon
- Telemetry from the RF hardware (LNA, PA, T/R relay)
- Only a digital connection via Ethernet (TCP/IP) between outside hardware and indoor hardware

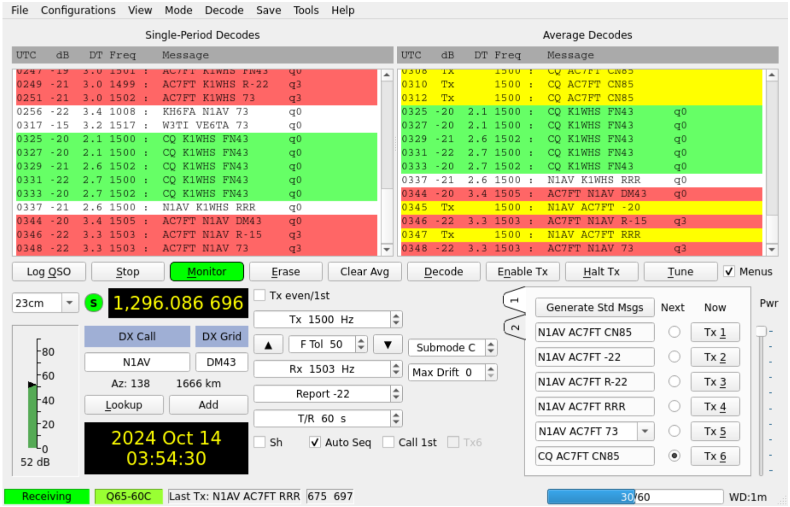
Outside System

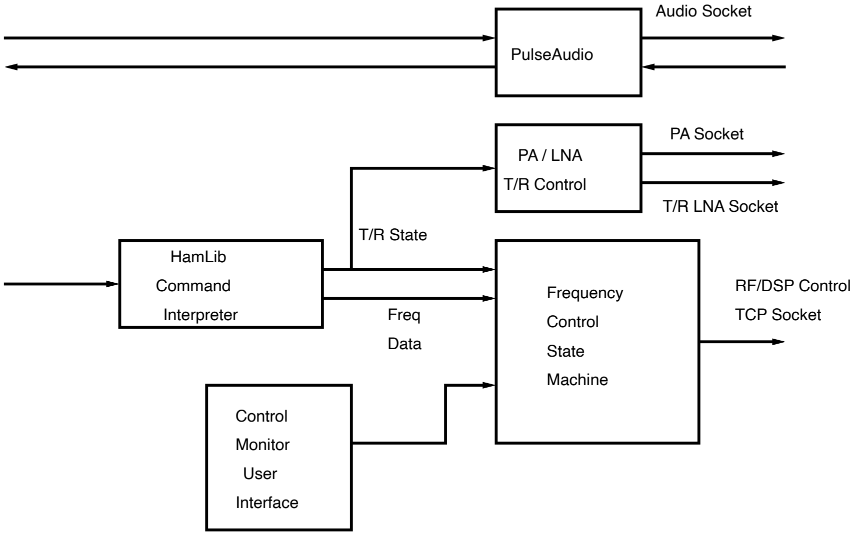
T/R and PA control over a TCP socket



- The BladeRF uses an Analog Devices AD9361 and directly receives and transmits on 1296 MHz
- Sample rate is 960k I/Q samples/sec
- Frequency reference and sample clocks are locked to GPS derived 10 MHz

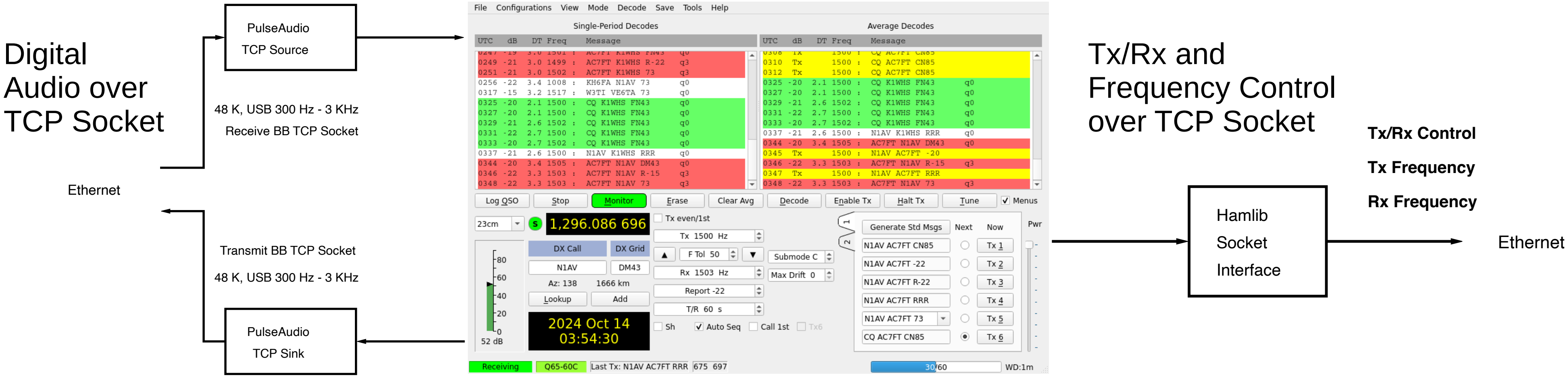
Inside System





- Frequency and state information is separated
  - Frequency data is forwarded to the RF/DSP via a control socket
  - State information is sent to the T/R control and PA control socket
- A listening socket is available for control and monitoring functions

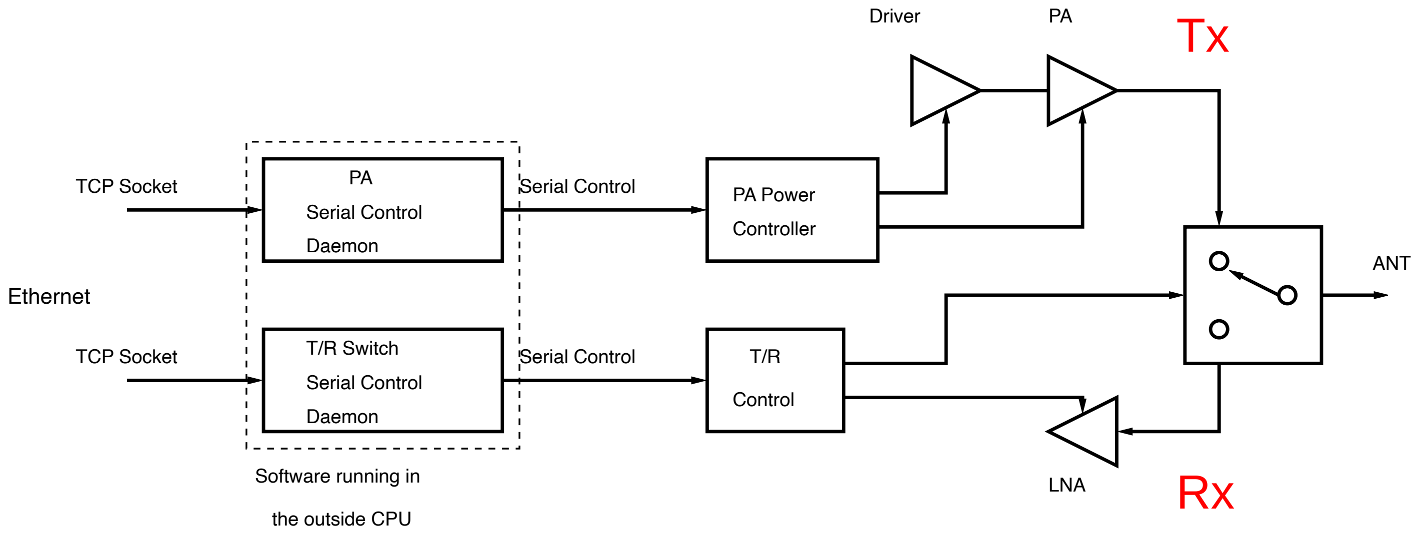
WSJT-x Interface



- WSJT-x has no audio or baseband socket interface
  - PulseAudio “module-simple-protocol-tcp” was used to mimic a 48 Ksample/sec audio device and bridge the samples to a TCP socket
- WSJT-x has a “Hamlib” socket interface which is not well defined
  - Custom code was written to extract Tx/Rx and frequency control information

Tx/Rx and PA Control

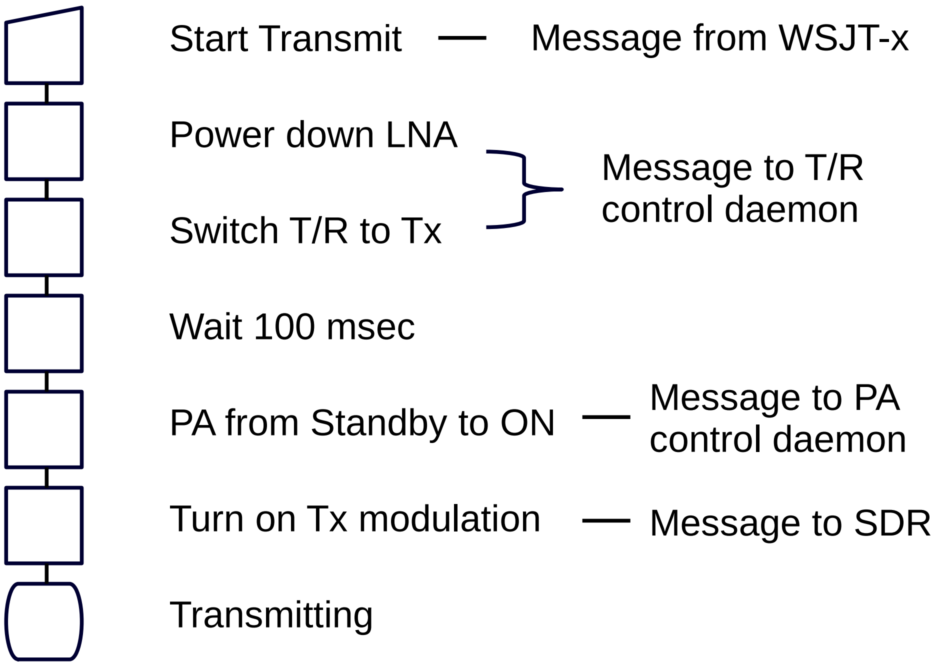
T/R and PA control over a TCP socket



- The T/R controller is an 8 bit AVR CPU with power switching and monitoring
- The PA controller is actually 2 x 8 bit AVR CPUs
  - Manages and protects the PA
  - Manages main power supply, cooling and monitors RF output

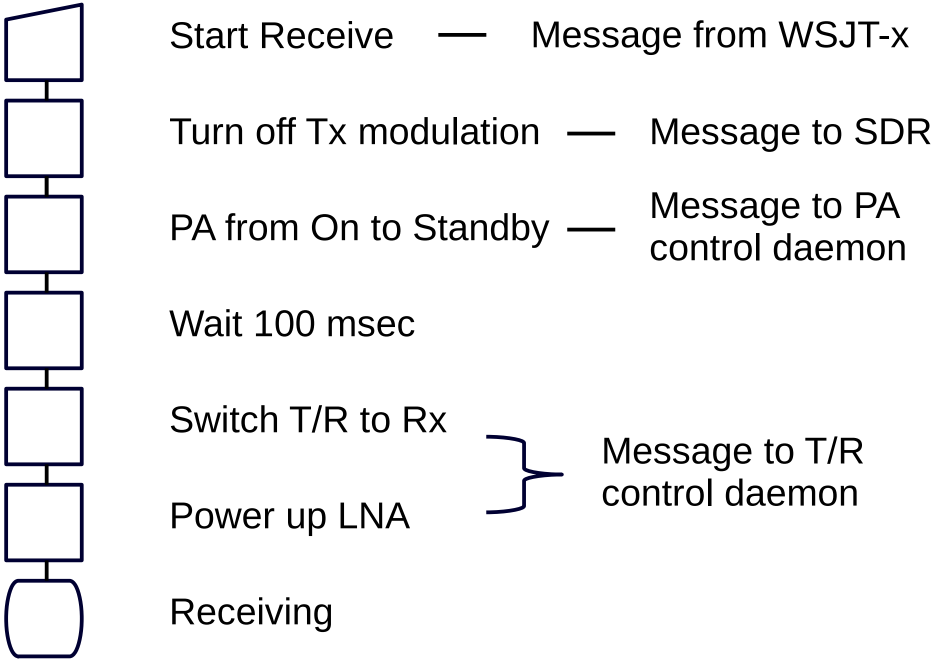
Transmit Control Flow

- WSJT-x drives the EME communication timing
- A transmit session starts at the top of the minute and lasts for about 45 seconds
- Receive stations are time synchronized for frame sync.
- We need to make sure that we are not trying to transmit while receiving (we can damage things with 500+W)

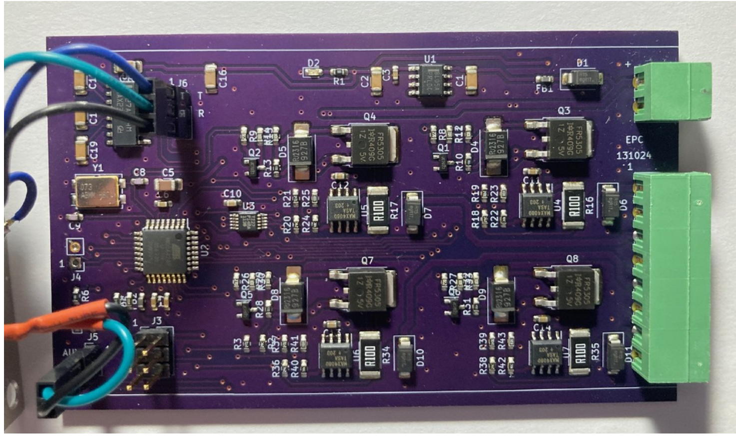


Receive Control Flow

- WSJT-x is nominally in receive mode
- It starts synchronization at the top of the minute
- When the frame is complete it will display the received message and signal SNR
- The T/R switch and LNA need to be in receive mode, Tx needs to be in standby mode

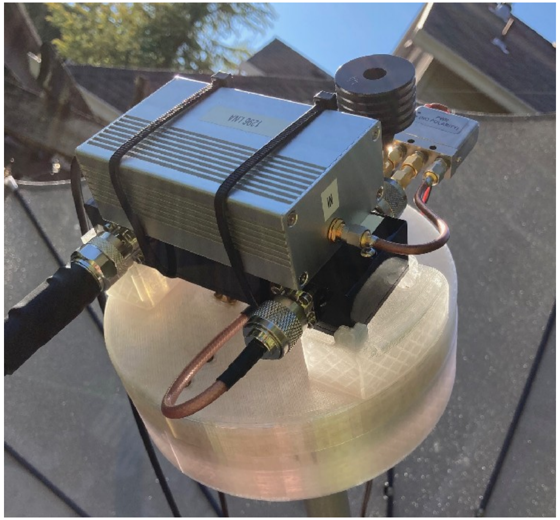


Tx/Rx Control



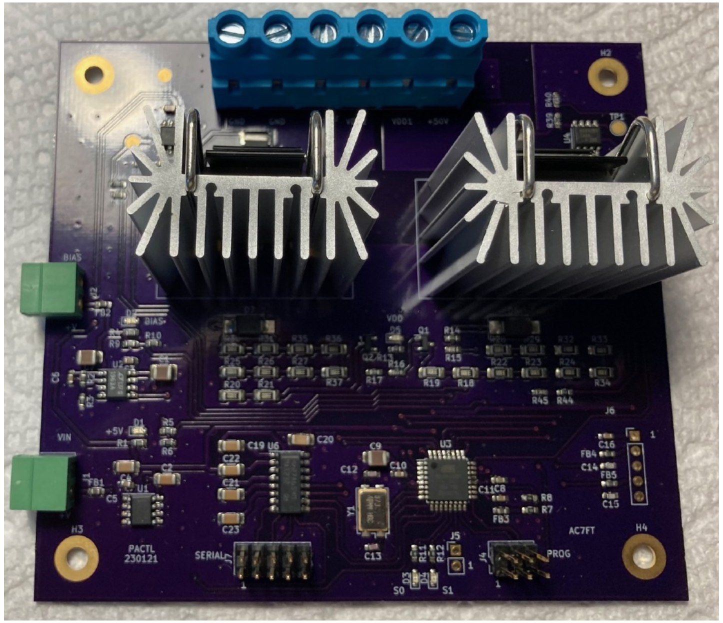
T/R Control

LNA Power



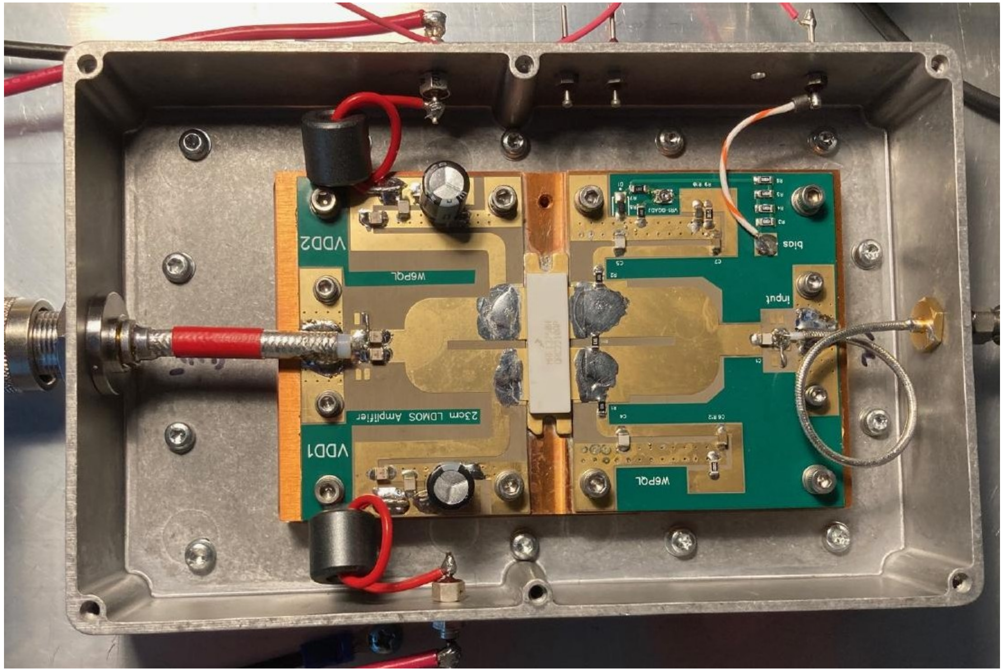
- 4 Channel power control over serial
- Monitors LNA and T/R relay voltage and current

PA Control



PA Control

PA Telemetry



- Controls PA on/standby/off
- Monitors drain voltage/current, bias, RF power out/reflection (SWR)

Control Receive

```
EME T/R Control

T/R Control                  PA Control                Status

LNA          ON              Status      Standby       Receive
T/R Relay    Receive         Vdd          15.158       Run
                             Idd           0.002
                             DC Pin          0.03
Vin          13.135          Vdd in       50.616
LNA V        13.135          Fan        1894.000
LNA I         0.191          Temp         26.200
T/R V         0.000          P Fwd        16.260
T/R I         0.000          P Refl       16.750

                             V12          11.972
                             Vbias         0.046

Rx Freq   1296.065000   Rx Synth  1295.990        Rx Offset     75000.0
Tx Freq   1296.065000   Tx Synth  1295.990        Tx Offset     75000.0


A - Abort, I - Idle, R - Run, X - Exit
```

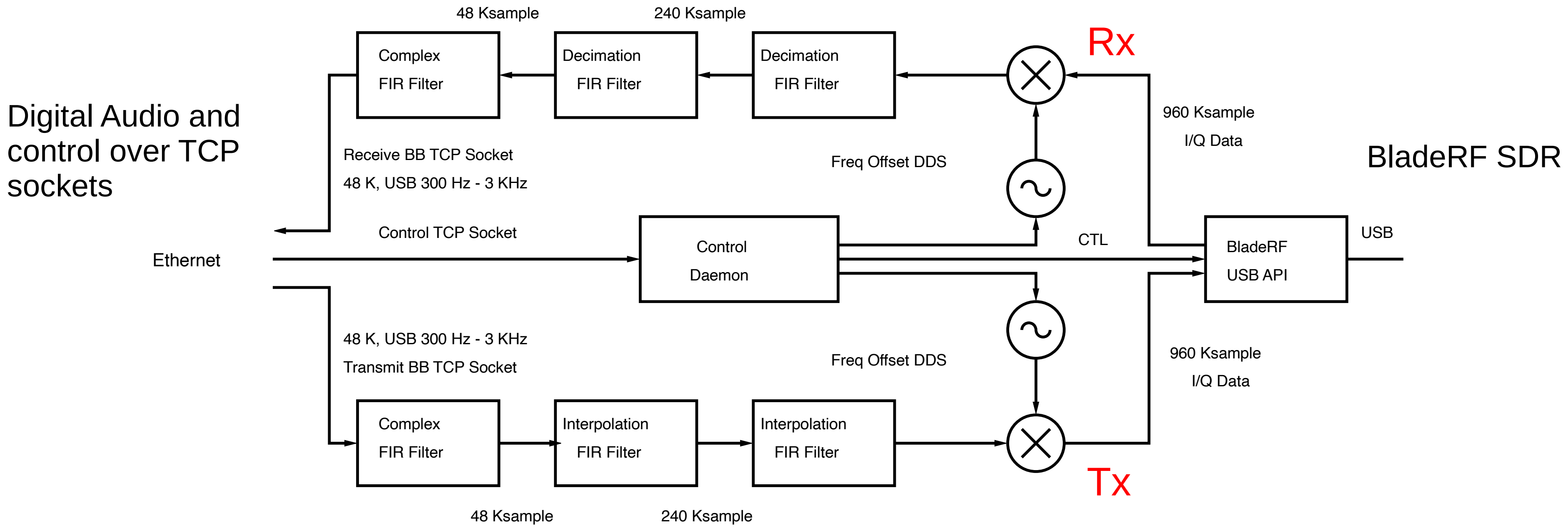
- Real time display of the EME control system
- We know state (Rx/Tx/Idle)
- PA is off
- Monitor DC and RF parameters
- Monitor the current Tx and Rx frequency

Control Transmit

```
EME T/R Control

T/R Control                    PA Control                Status

LNA         OFF                Status      PA ON         Transmit
T/R Relay   Transmit           Vdd          50.221       Run
                               Idd          21.720
                               DC Pin       1090.80
Vin         13.073             Vdd in       50.555
LNA V        0.000             Fan         1682.000
LNA I        0.000             Temp         26.200
T/R V       13.011             P Fwd        57.114
T/R I        0.291             P Refl       42.430

                               V12          12.049
                               Vbias        10.200

Rx Freq   1296.065000   Rx Synth  1295.990        Rx Offset      75000.0
Tx Freq   1296.065000   Tx Synth  1295.990        Tx Offset      75000.0


A - Abort, I - Idle, R - Run, X - Exit
```

- Real time display of the EME control system
- PA is on
- Output power is +57 dBm (500 Watts)
- T/R relay is Tx position

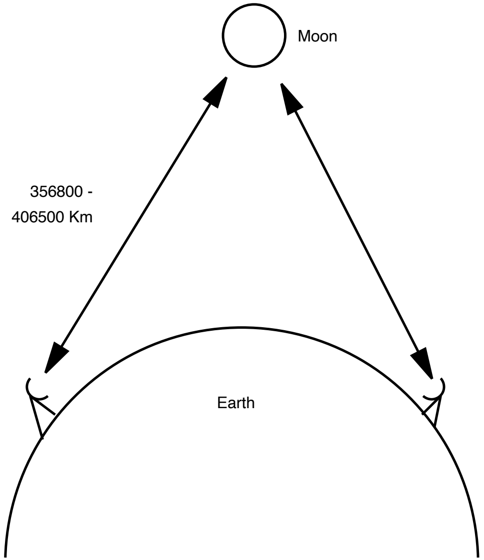
Software SSB Up and Down Converter



- The DSP Rx and Tx was based on the GnuRadio prototype, re-written in C with clean data and control methods over TCP sockets
- LiquidDSP libraries were used

Doppler

- The two stations on the earth are stationary with respect to each other, the Moon is moving due to its orbital velocity and the Earth rotation
- At 1296 MHz this can be up to 4 KHz. (worse as frequency increases)
- Convention is to keep the frequency constant to a Moon observer (Constant Frequency on Moon) CFOM
- The transmit station continually adjusts its transmit frequency to compensate the the Doppler shift on its uplink to the Moon
- The receive station continually adjusts its receive frequency to compensate for the Doppler shift on its downlink from the Moon
- WSJT-x computes this offset in real time
- Send the the current frequency information to the SDR via TCP socket

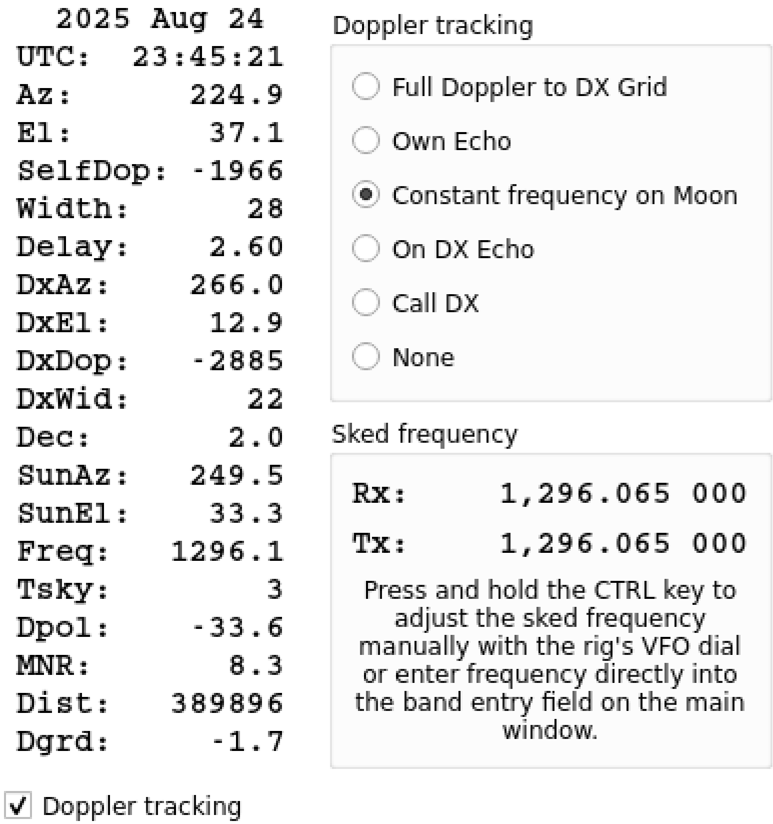


Control Frequency

```
EME T/R Control

T/R Control                  PA Control              Status

LNA          ON              Status       Standby    Receive
T/R Relay    Receive         Vdd           15.158    Run
                             Idd            0.002
                             DC Pin           0.03
Vin          13.151          Vdd in        50.616
LNA V        13.135          Fan         1894.000
LNA I         0.191          Temp          26.200
T/R V         0.000          P Fwd         16.260
T/R I         0.000          P Refl        16.750

                             V12           11.972
                             Vbias          0.046

Rx Freq   1296.064005   Rx Synth  1295.990       Rx Offset     74335.0
Tx Freq   1296.065994   Tx Synth  1295.990       Tx Offset     75664.0


A - Abort, I - Idle, R - Run, X - Exit
```

- Rx and Tx frequency offset is also shown
- The RF synthesizer does the coarse frequency set
- It takes a long time to lock and will cause an abrupt phase discontinuity when the frequency changes
- The DDS in the SDR, is phase continuous, fast and has very fine frequency resolution

Doppler Frequency Offset

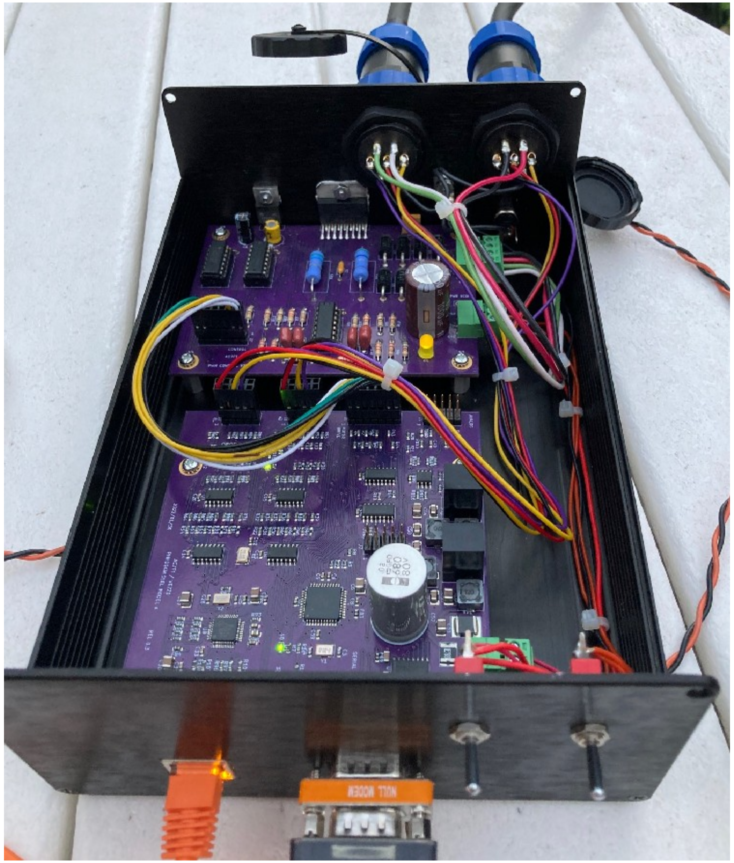


- The Rx and Tx need to agree on a frequency
- In this case we want to be at 1296.065 MHz on the moon, but it is receding
- The self Doppler is 1966 Hz, so we transmit 1966 Hz higher in frequency at 1296.066966 MHz
- The reverse occurs on receive, we receive at 1296.063034 MHz

Antenna Tracking

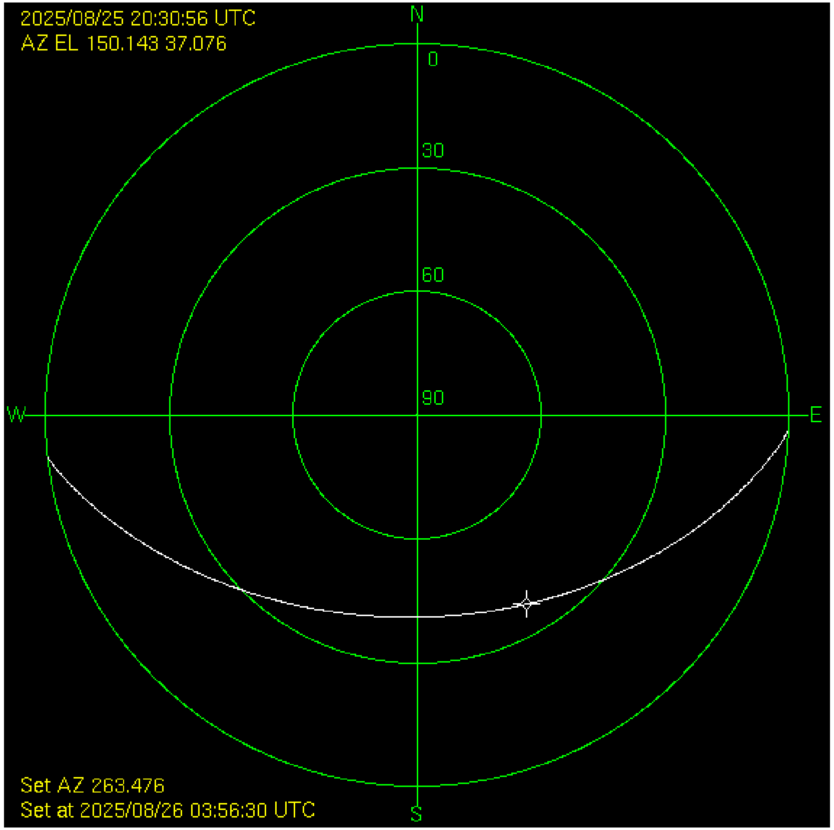
- We need to keep the antenna pointed at the moon
- WSJT-x calculates the Moon Az/El at the station location and updates it to a file
- You can also use a standalone tracking program
- You also need a sturdy positioner and the appropriate motor controls

Antenna Tracking



- Two DC motors with gear reduction are used to drive the antenna
- Driver is a PWM motor control with PID feedback control
- The CPU accepts Az/El info via a TCP socket over Ethernet

Antenna Tracking



- Moon position and Az/El are computed using the Py-Ephem library
- It communicates via a TCP socket to the antenna positioner
- Displays the current moon position, Az/El, time and moon rise/set time

Summary

- We showed that a complete communications system is more than just a receiver and transmitter, there are a lot of moving parts!
- Using an EME as an example there are other aspects that need to be included in the system design to make it work
  - RF system design
  - High power transmitters
  - Sensitive receivers
  - Signal processing
  - Modem
  - Doppler correction
  - Tracking the Moon

References

References:

Taylor, Joseph H., “WSJT-X User Guide”, https://wsjt.sourceforge.io/wsjtx-doc/wsjtx-main-2.6.1.html

LiquidDSP, https://liquidsdr.org/

PyEphem, https://rhodesmill.org/pyephem/

Rosenauer, Dennis, “Design of a 1296 EME SDR Radio System for EME”, GRCon 2023

Questions

"Shoot for the moon; You might get there"

– Buzz Aldrin