Wide-Band Antenna Pattern Mapping with an RFSoC on a Drone

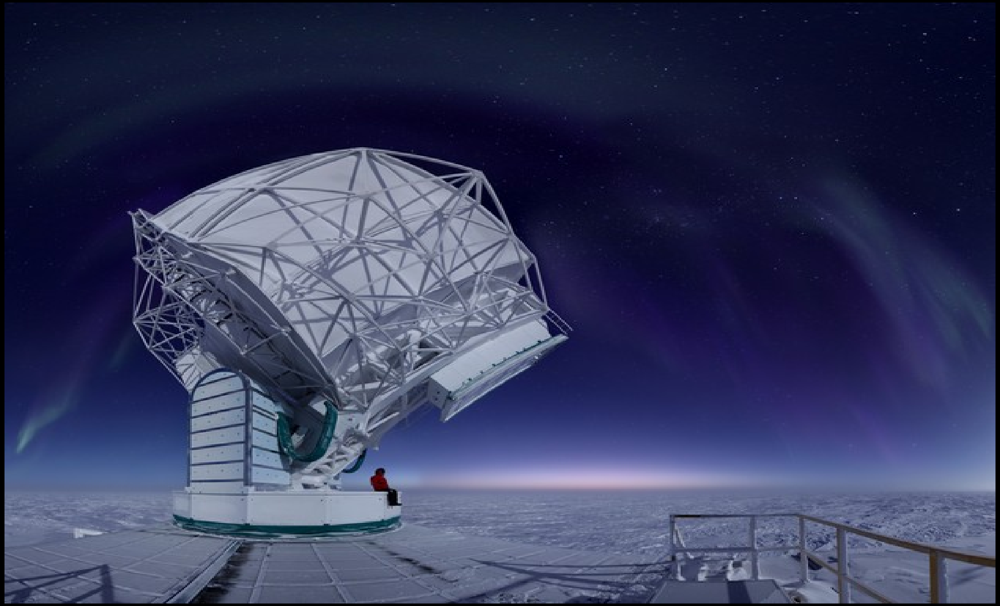
Jason Gallicchio (W3JQ)
jason@hmc.edu

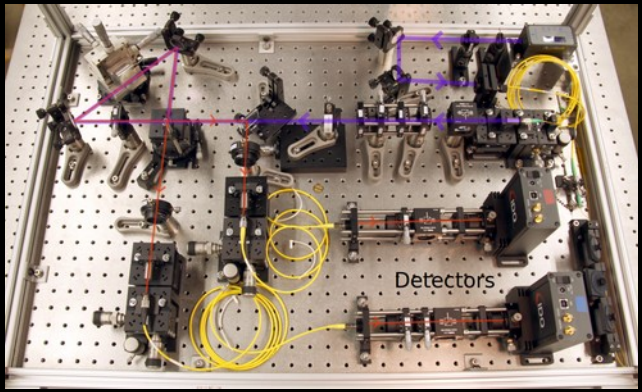
Physics Professor
Harvey Mudd College
Claremont, CA USA

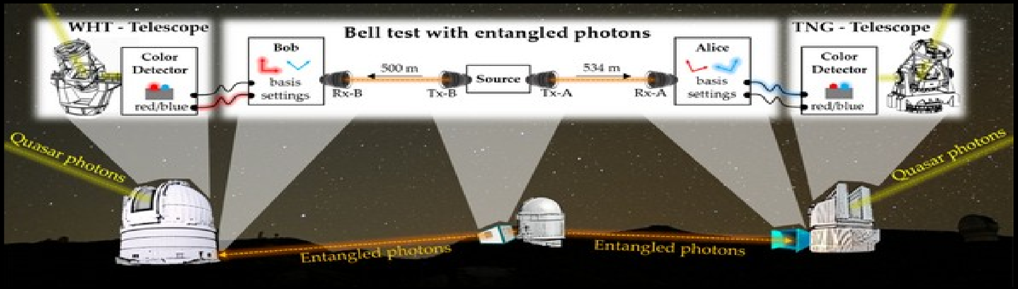
HARVEY MUDD COLLEGE

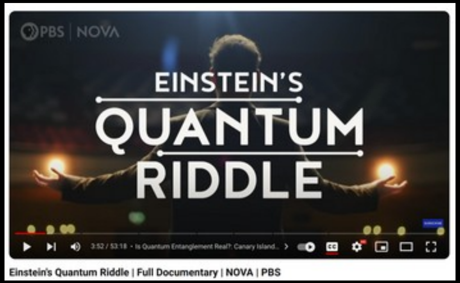
GRCon25
Everett, Washington

My (dis?) qualifications:

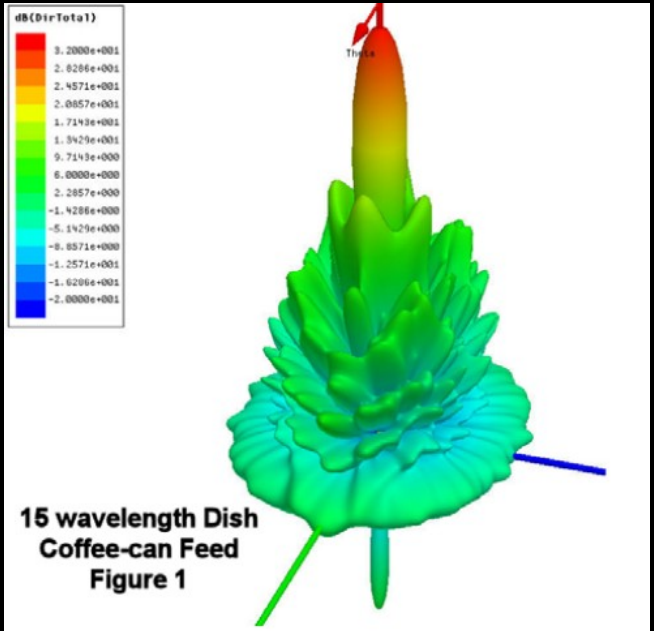






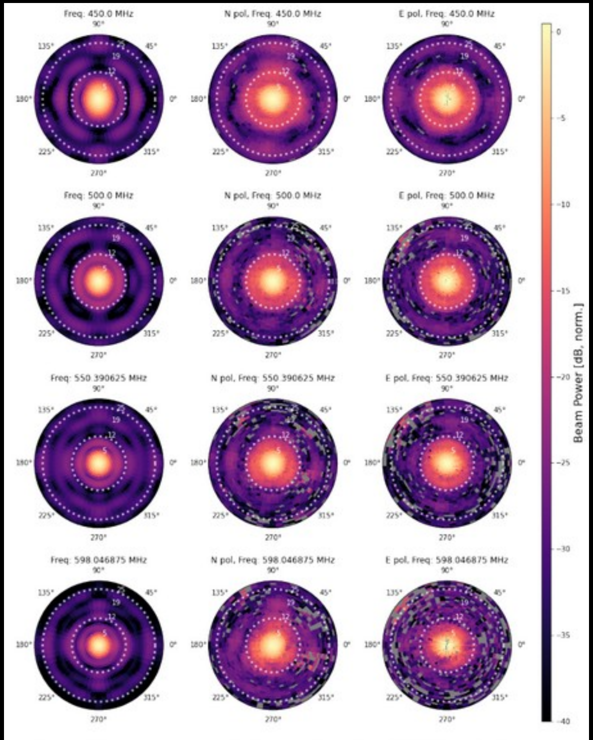


Antenna Patterns / Beam Maps



Paul Wade (W1GHZ) 2009

sidelobes and nulls
change with frequency



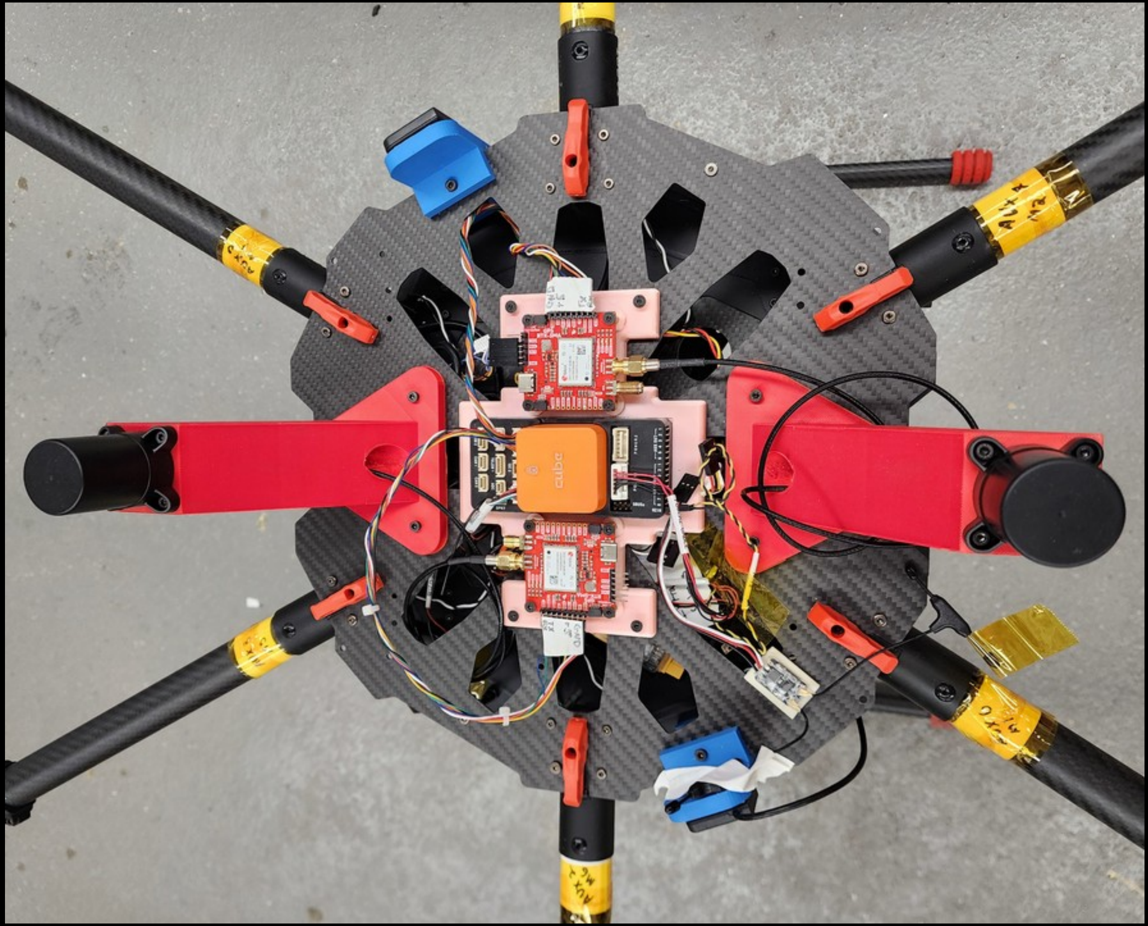
Simulated (left column) and measured (right columns) beams for the TONE dishes at four frequencies

Kuhn et al. Drone Beam Mapping of the TONE Radio Dish Array 2025
see also Tyndall et. al. 2024

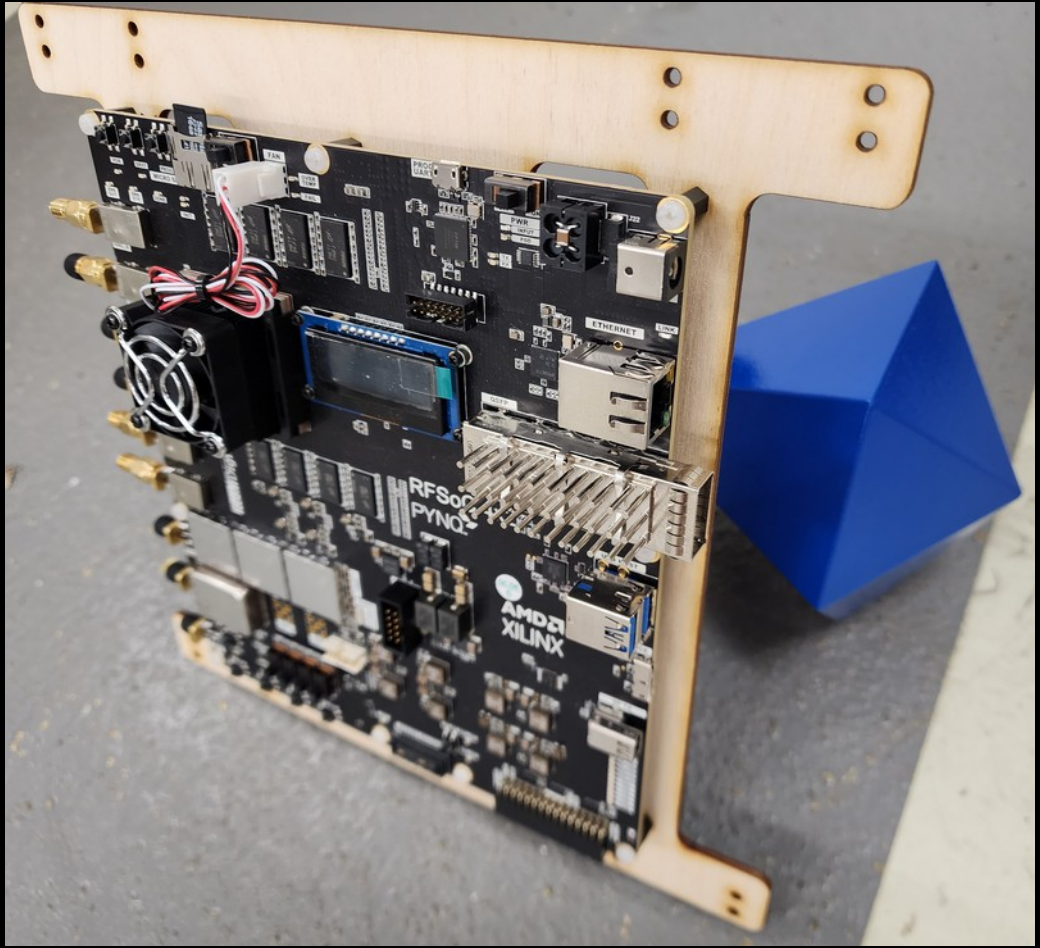
What We Built

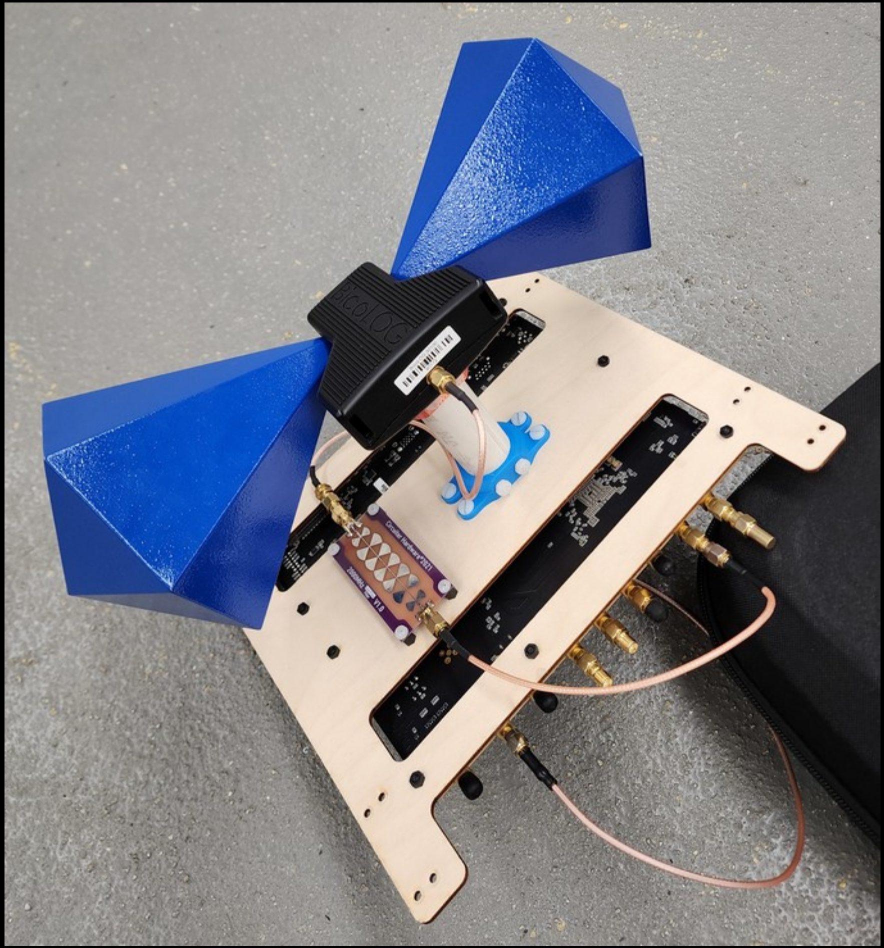
- We basically split a VNA in half
- for *complex* beam mapping (magnitude, phase, polarization)
- up to 2 GHz wide (4 GSPS)
- adjustable timing and spectral resolution

The Drone



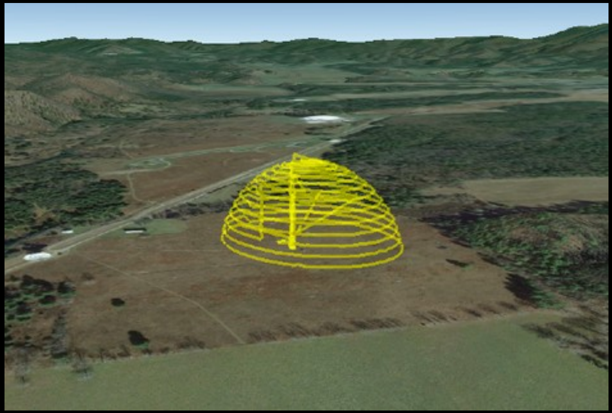
Transmitter RFSoC 4x2 under Drone





“Telescope”/Antenna, Mount, and Cart

Flight Paths and Testing Location

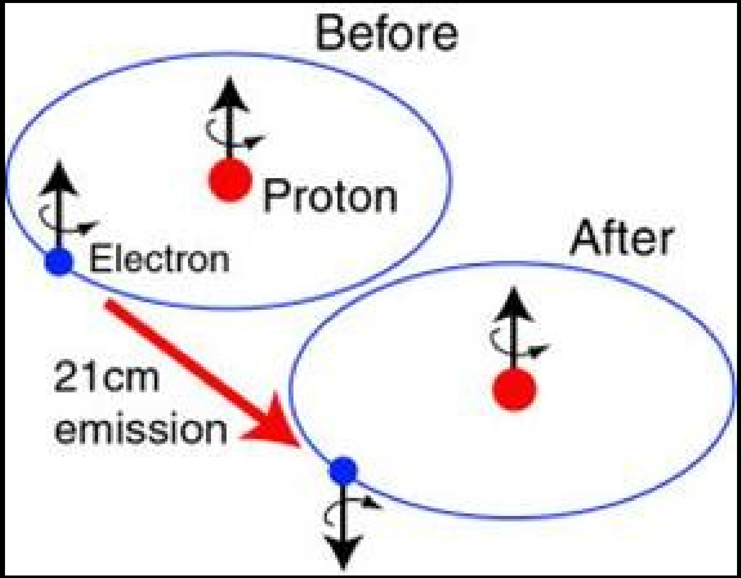


Daniel C. Jacobs and the
ECHO Team at ASU

Simple Flight Plan on Google Earth

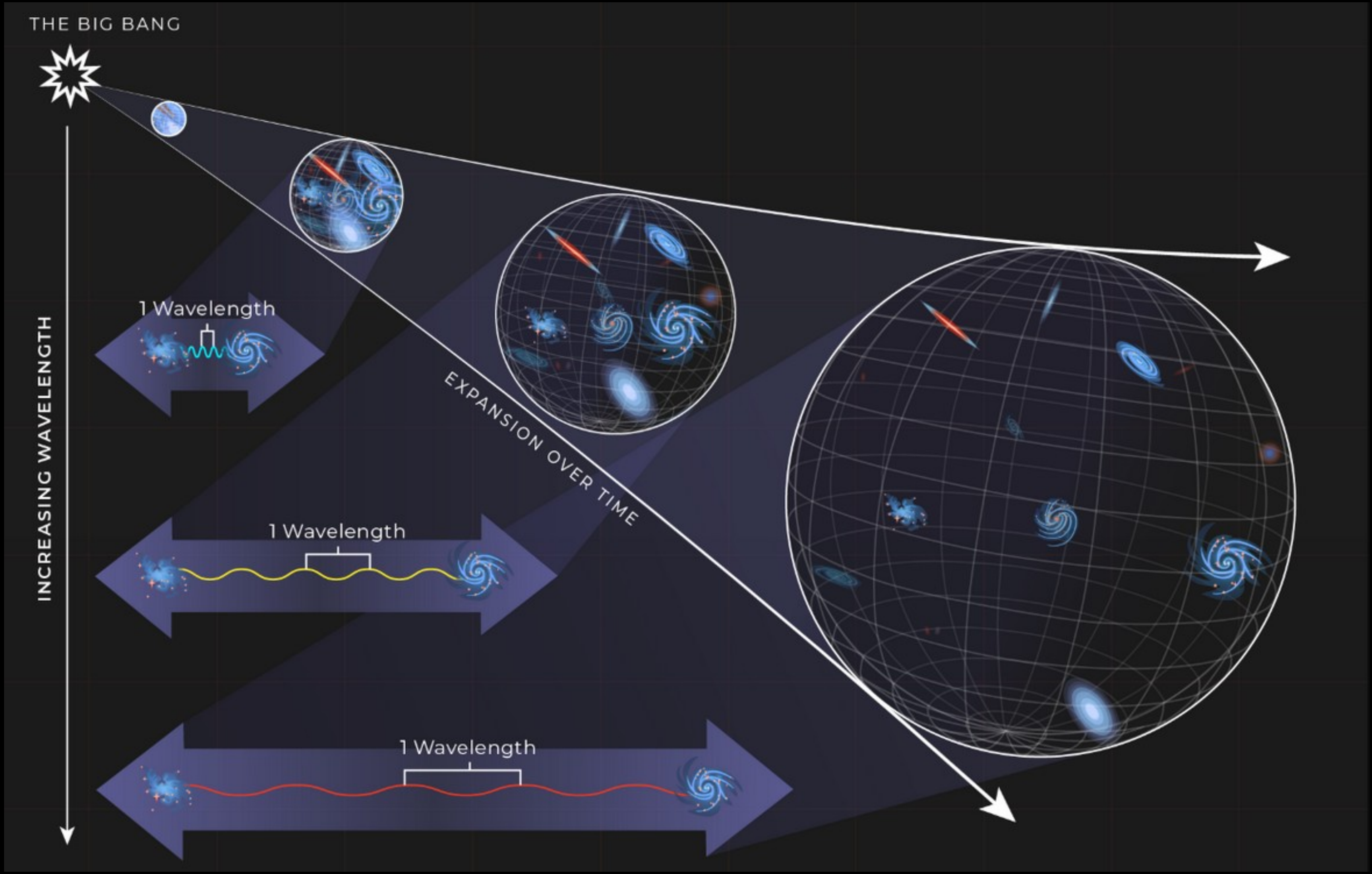
Why? Radio Astronomy / Cosmology

Hydrogen is most common element.
“Spin-flip” transition
→ 21cm (1420 MHz) emission



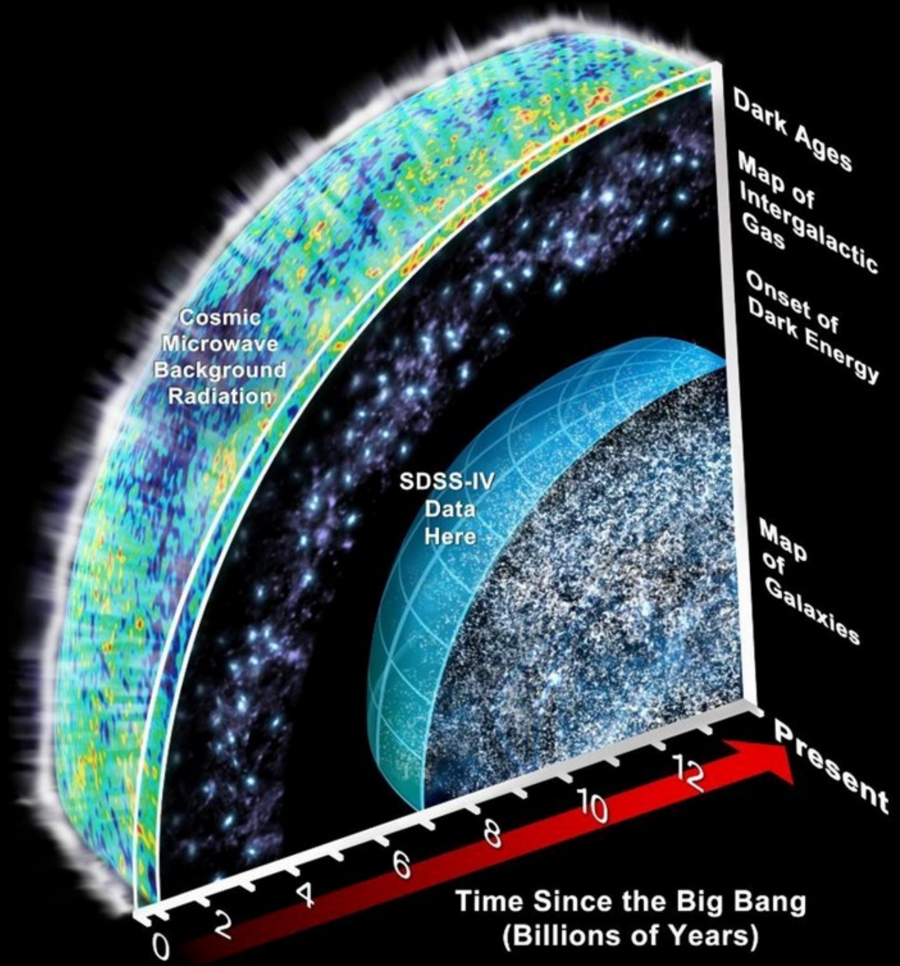
Credit: Jodrell Bank

Cosmological Redshift Stretches It



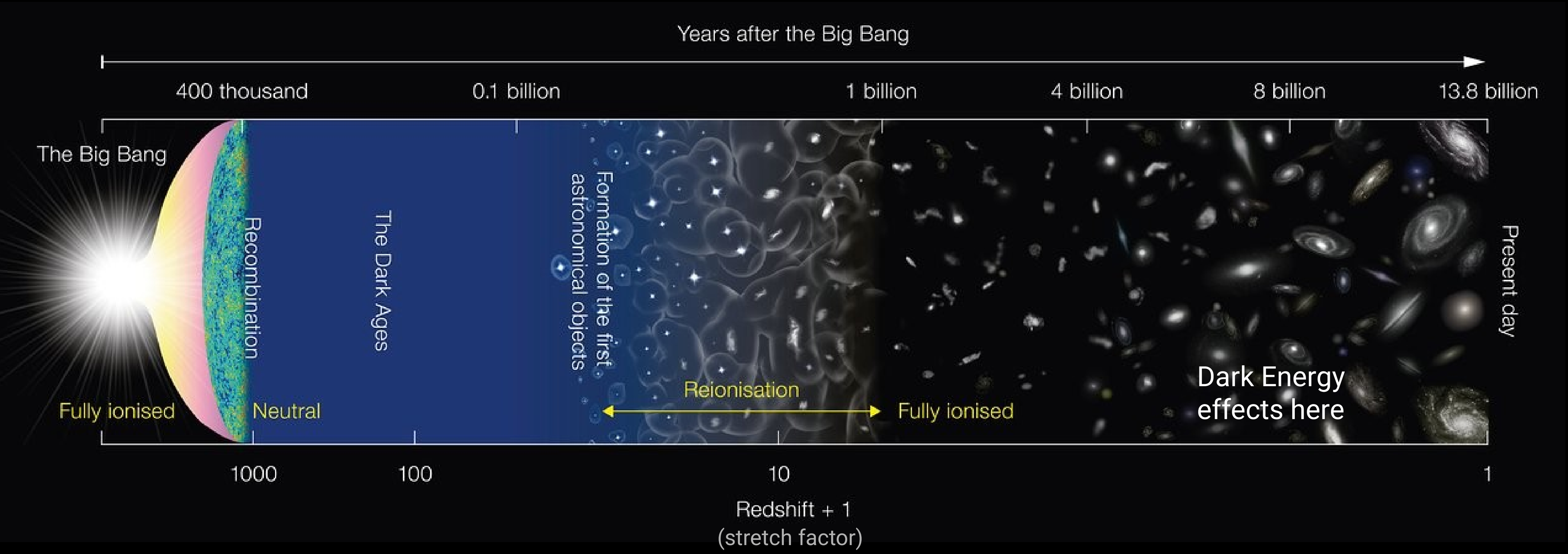
Credit: Roman Space Telescope/NASA

Looking out is also looking back in time



Credit: Sloan Digital Sky Survey (SDSS)

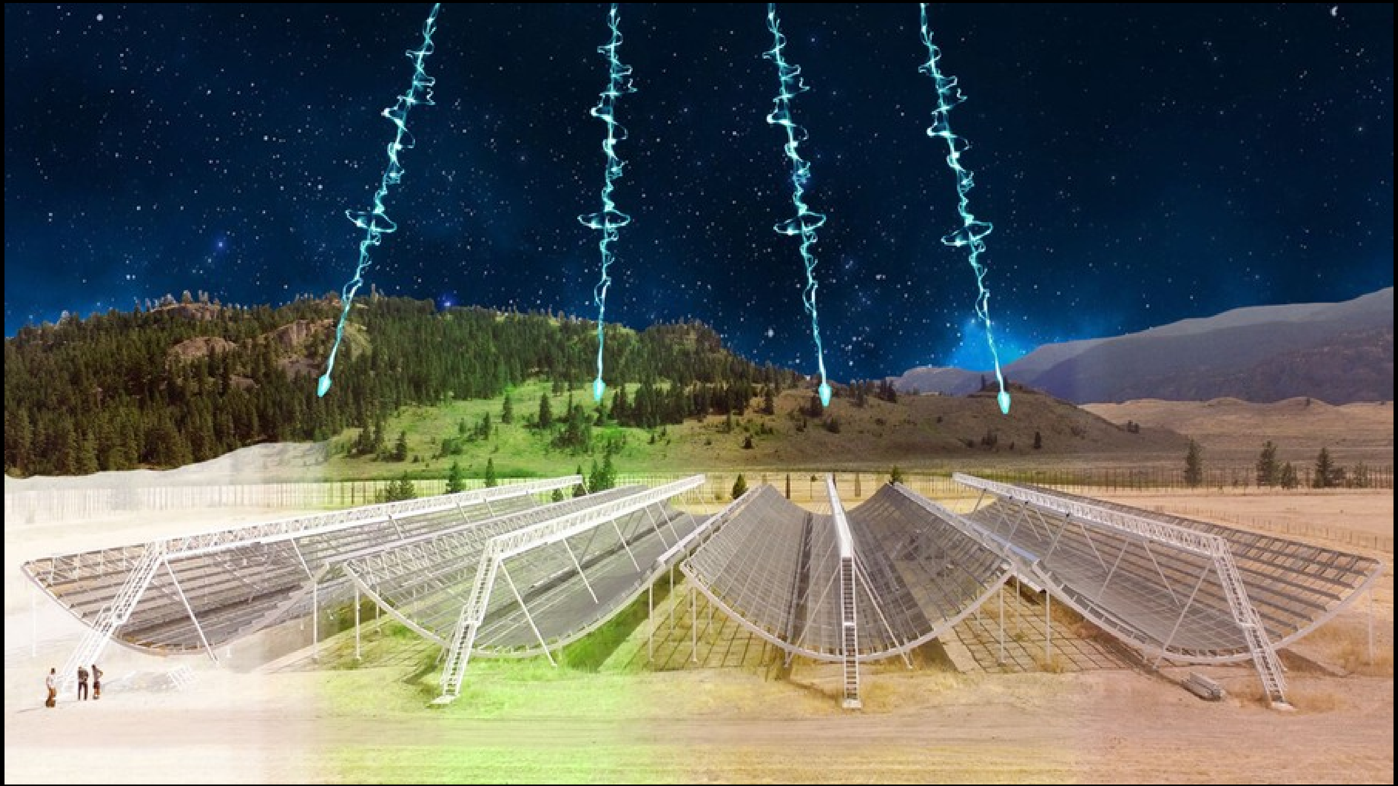
Map hydrogen in the past just by tuning



Credit: National Astronomical Observatory of Japan

CHIME **C**anadian **H**ydrogen **I**ntensity **M**apping **E**xperiment

400–800 MHz; 1024 dual-pol; 1024 frequency channels



MIT News May 25, 2023 about Fast Radio Bursts
Credit: CHIME/FRB Collaboration, with artistic additions by Luka Vlajić.

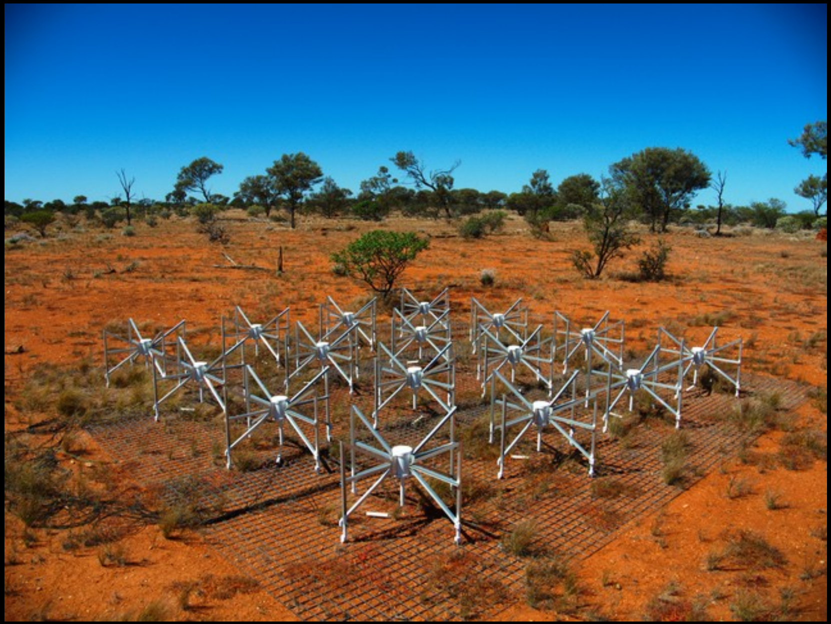
CHORD **C**anadian **H**ydrogen **O**bservatory and **R**adio-transient **D**etector

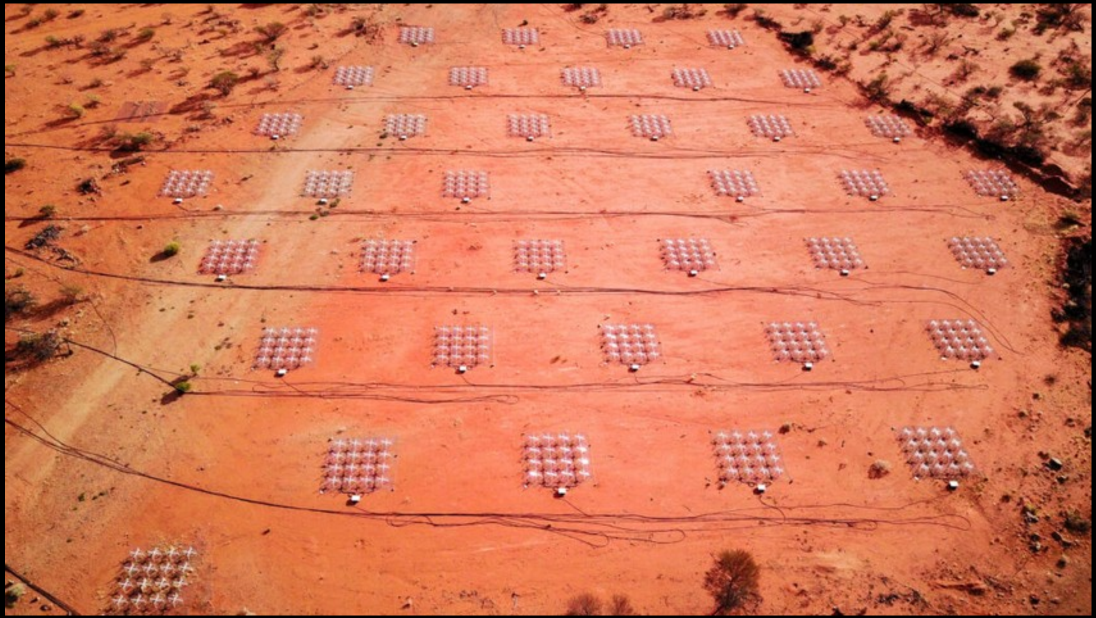
300–1500 MHz (future 512 6 m dishes; basically CHIME++)

artist's rendering https://www.chord-observatory.ca/

MWA

Murchison **W**idefield **A**rray in Western Australia
70–300 MHz for Epoch of Reionization; 30° fov





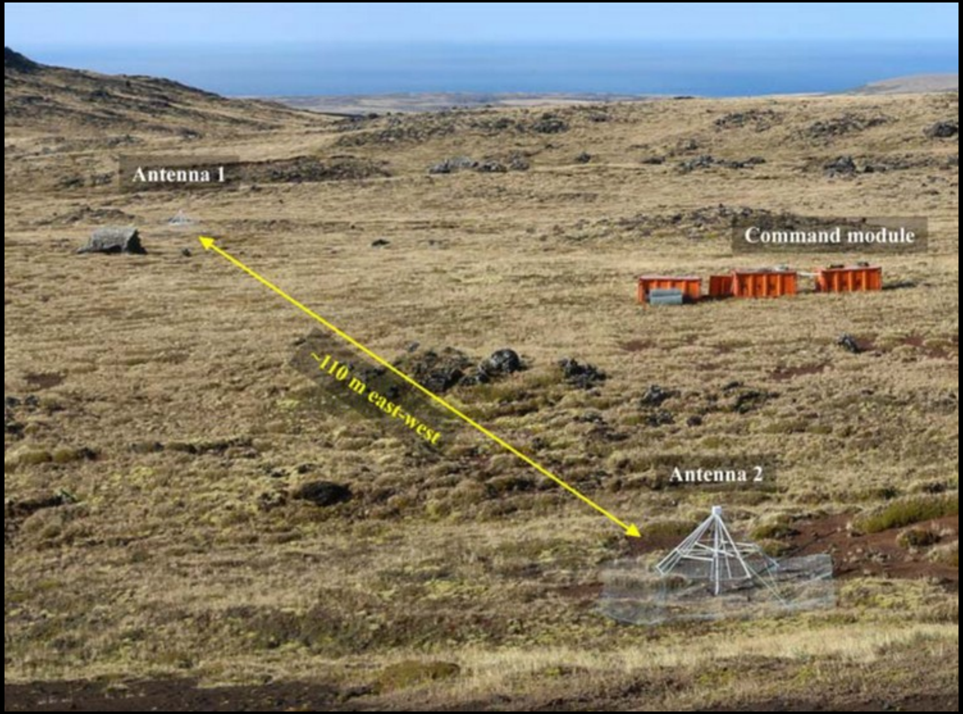
https://www.mwatelescope.org/

ALBATROS

Array of **L**ong **B**aseline **A**ntennas for **T**aking **R**adio **O**bservations from the **S**ub-antarctic/**S**eventy-ninth parallel

1.2–125 MHz in Marion Island / Canadian Arctic

Long Wavelength Array (LWA) antennas;

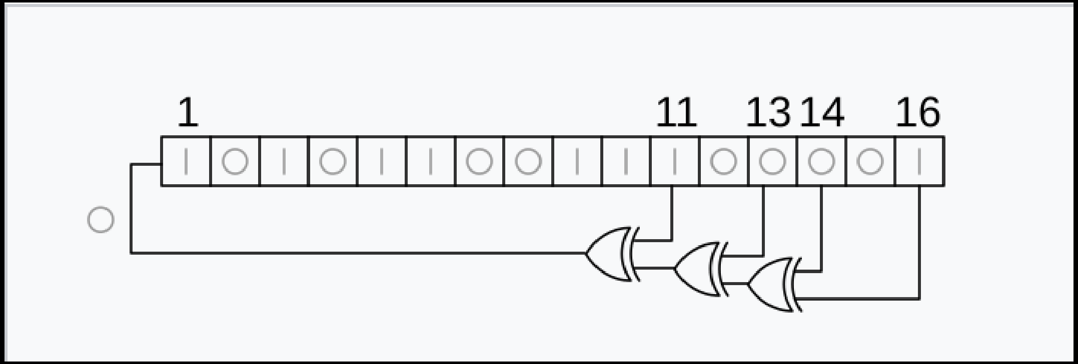


Credit: H. Cynthia Chiang; Anthony Zerafa

What to transmit?

- Single tone on/off
- Wide-band analog noise source on/off
- Random digital noise to correlate against
- LFSR (repeat at exactly the data-taking window)
- Analog Chirp (also repeat)

LFSR idea that I pushed in 2014



- Small FPGA running a fast LFSR; digital output pin
- Maybe “up-converted” via XORing fast clock to center of band

LFSR and its FFT

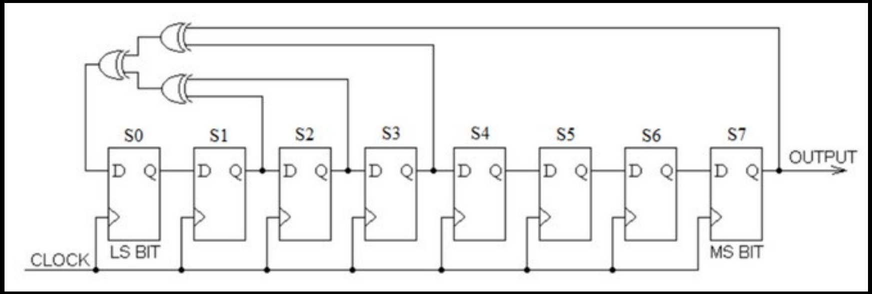
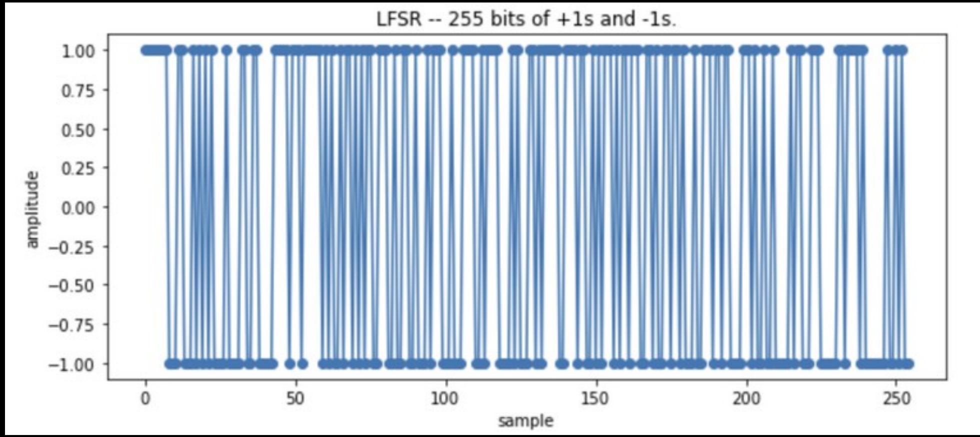
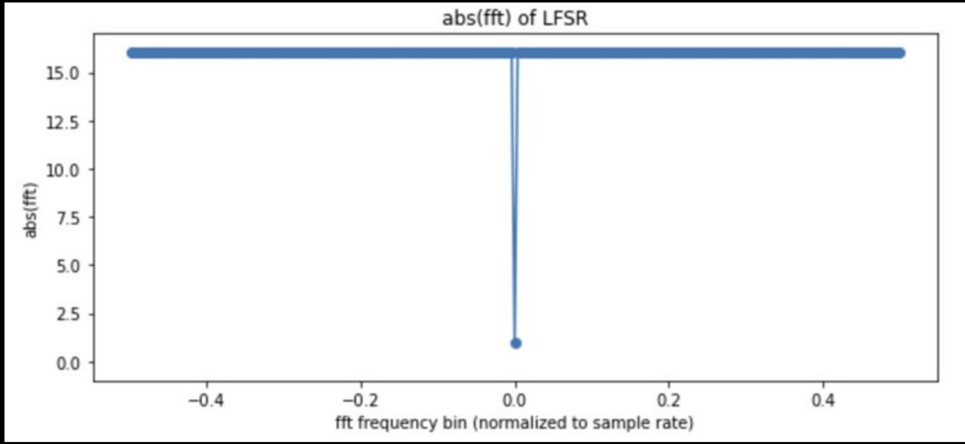


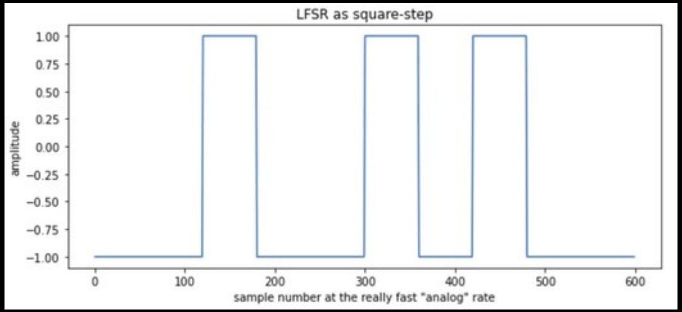
image credit: Siswanto and Rudiyanto 2017

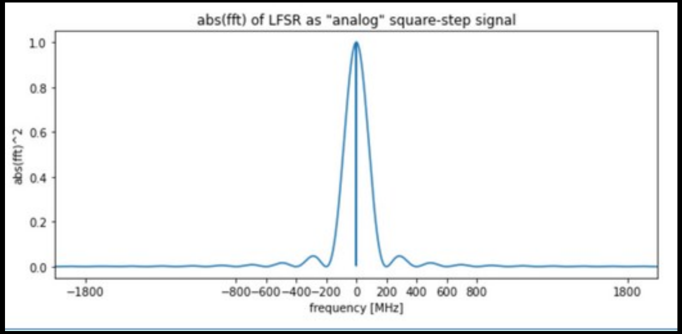




“Analog” LFSR square-steps & spectrum

A few bits
of LFSR





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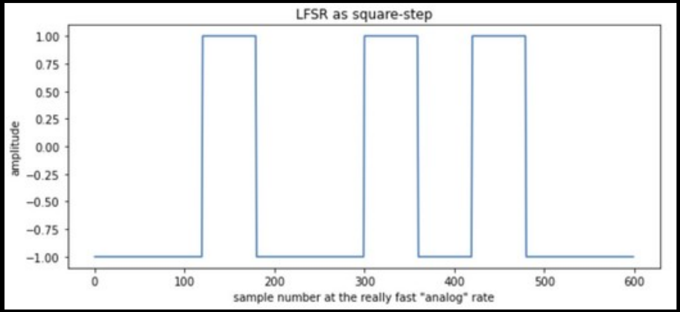
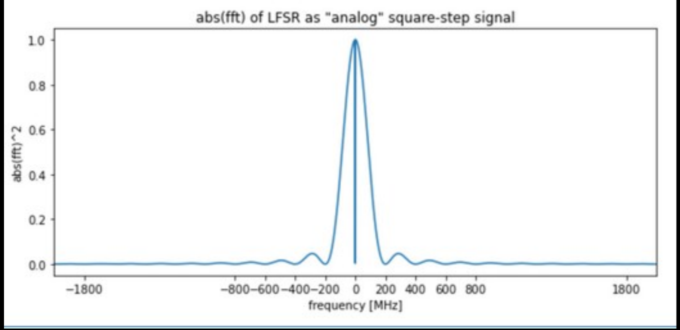
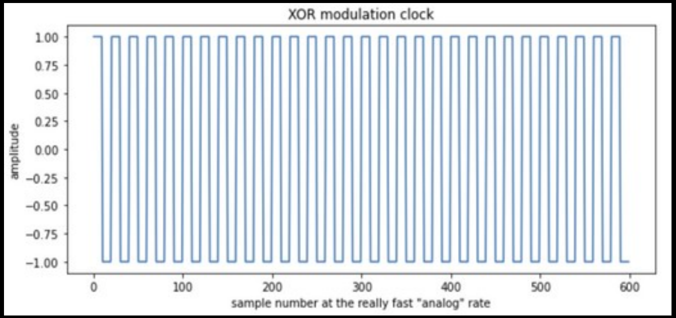
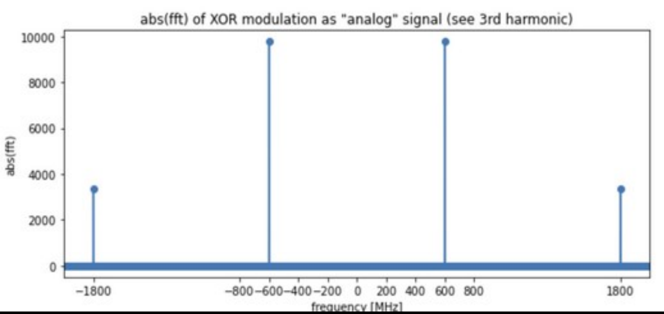




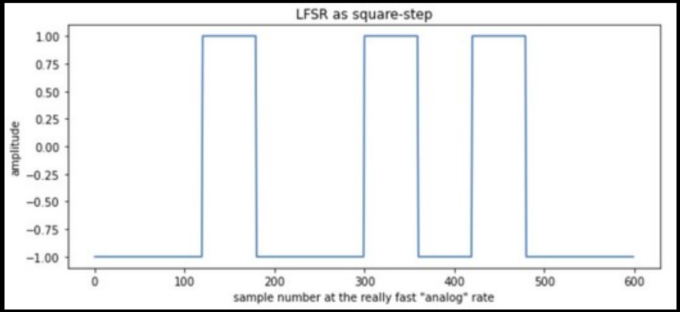
600 MHz Fast clock

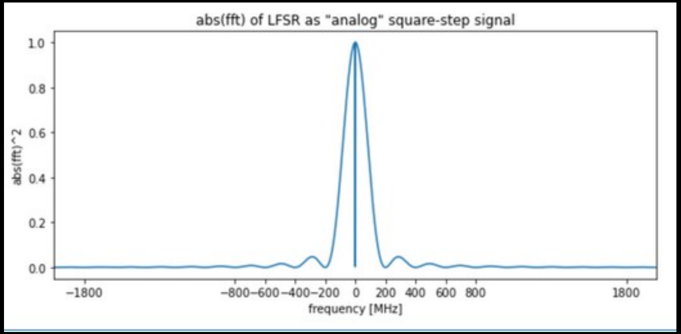




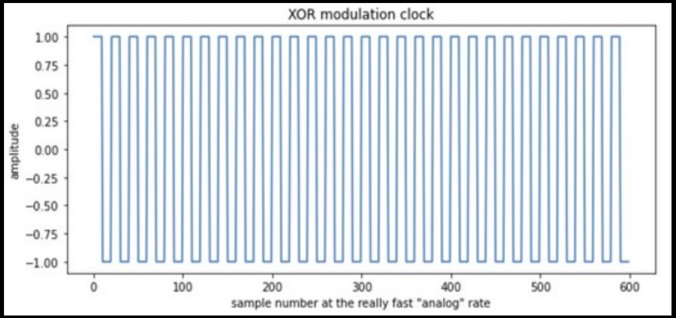
“Analog” LFSR square-steps & spectrum

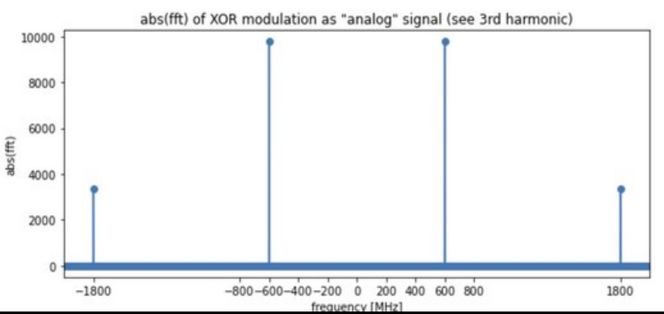
A few bits of LFSR



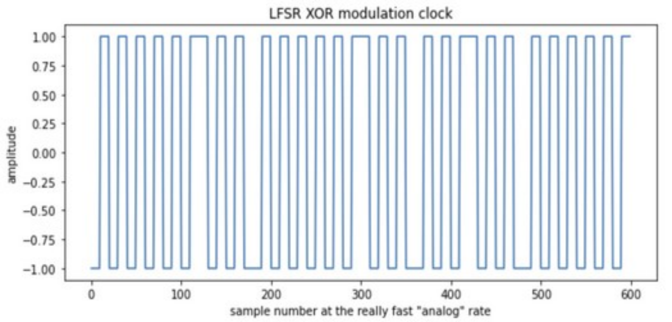


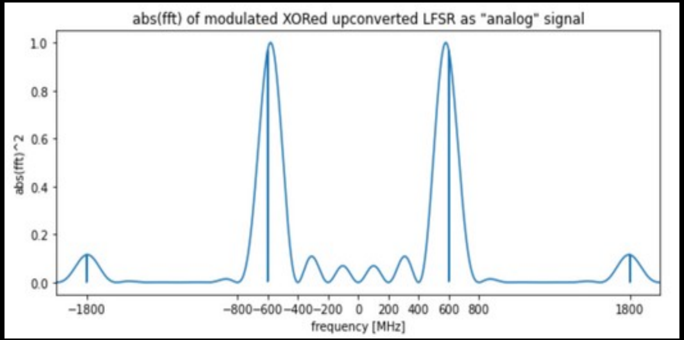
600 MHz Fast clock





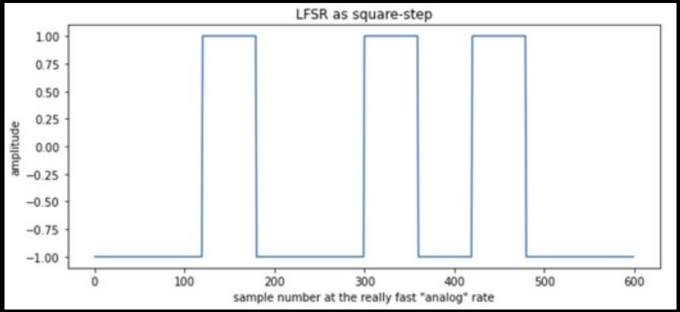
XOR

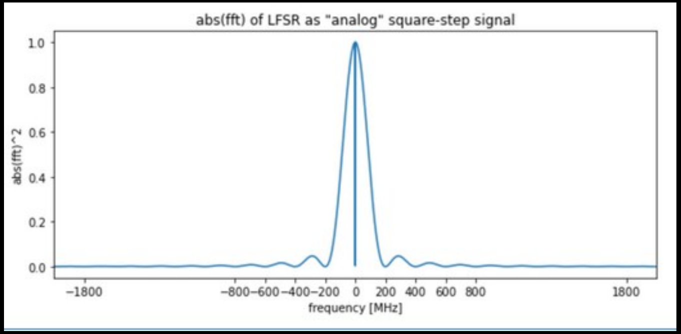




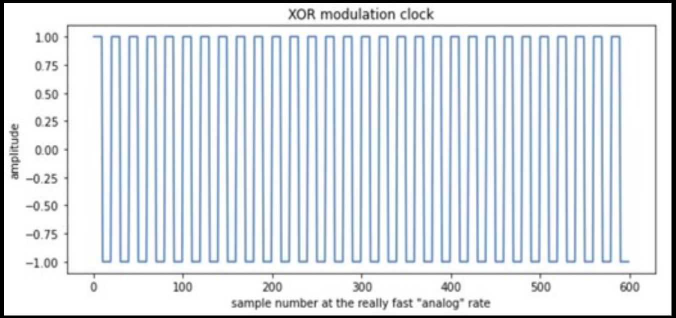
“Analog” LFSR square-steps & spectrum

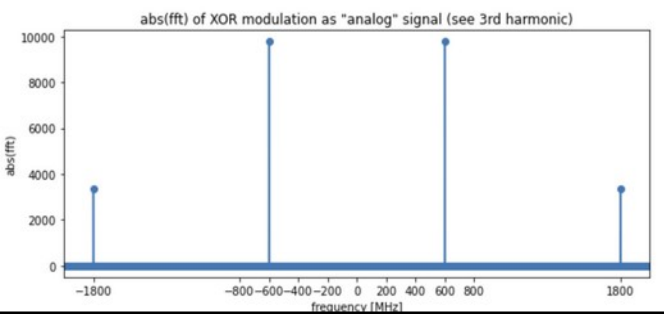
A few bits of LFSR



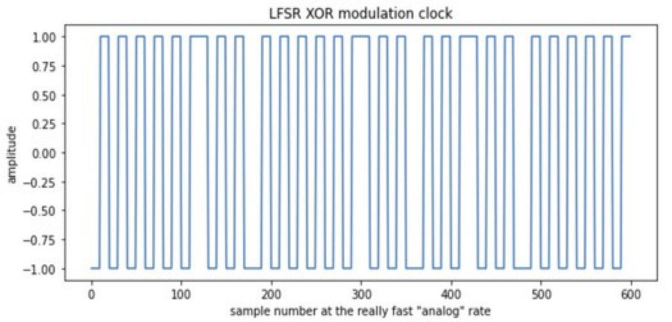


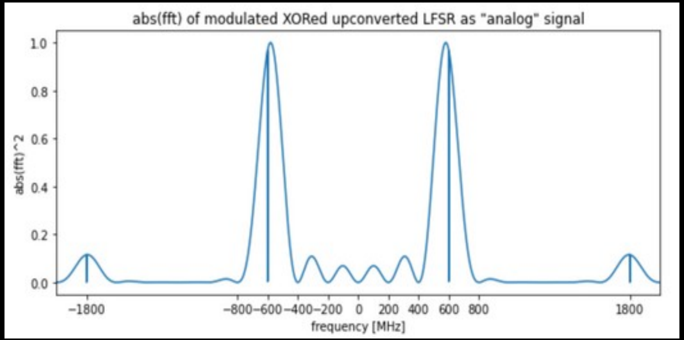
600 MHz Fast clock





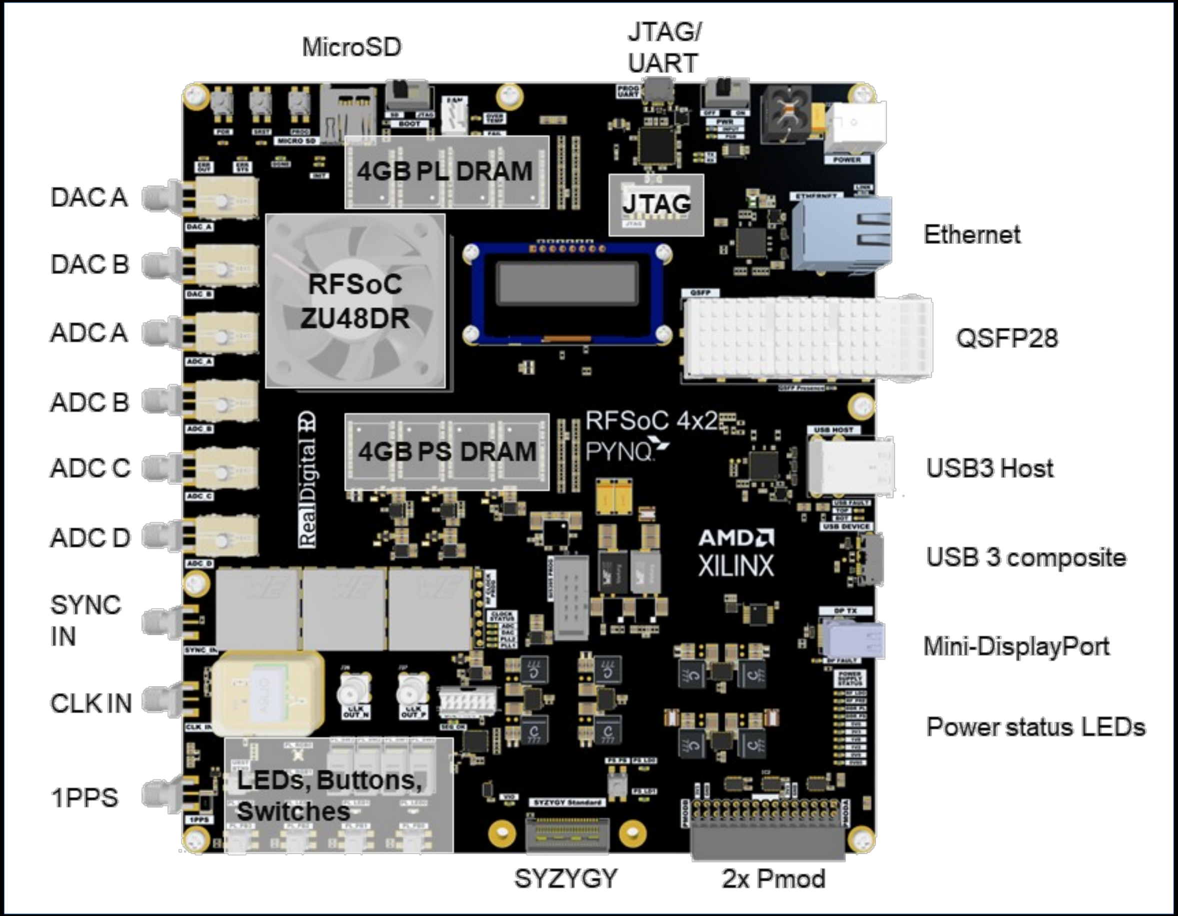
XOR





Digital outputs don’t go fast enough on “small” FPGAs

Bite the Analog Bullet with RFSoC 4x2



- 4x 14-bit RF ADCs up to 5.0GSPS
- 2x 14-bit RF DACs up to 9.85GSPS
- 10 MHz & 1pps for timing
- 50Ω SMA in/out
- ARM boots Linux (ssh from ground)
- PYNQ python environment

Zadoff-Chu as Ideally-Sampled Chirps

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Zadoff–Chu sequence

2 languages

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From Wikipedia, the free encyclopedia

A **Zadoff–Chu (ZC) sequence**, also referred to as **Chu sequence** or **Frank–Zadoff–Chu (FZC) sequence**,[1]:152 is a complex-valued mathematical sequence which, when applied to a signal, gives rise to a new signal of constant amplitude. When cyclically shifted versions of a Zadoff–Chu sequence are imposed upon a signal the resulting set of signals detected at the receiver are uncorrelated with one another.

They are named after Solomon A. Zadoff, David C. Chu and Robert L. Frank.

Description [edit]

Zadoff–Chu sequences exhibit the useful property that cyclically shifted versions of themselves are orthogonal to one another.

A generated Zadoff–Chu sequence that has not been shifted is known as a *root sequence*.

The complex value at each position *n* of each root Zadoff–Chu sequence parametrised by *u* is given by

$$x_u(n) = \exp\left(-j\frac{\pi u n(n + c_\mathrm{f} + 2q)}{N_\mathrm{ZC}}\right),$$

where

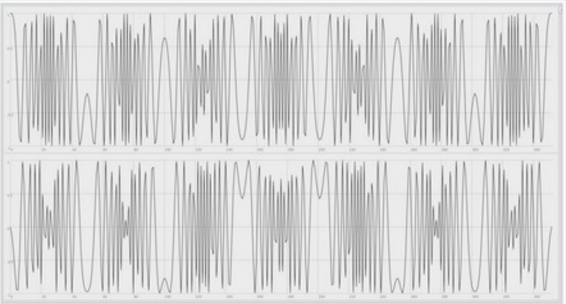
$0 \le n < N_\mathrm{ZC}$,

$0 < u < N_\mathrm{ZC}$ and $\gcd(N_\mathrm{ZC}, u) = 1$,

$c_\mathrm{f} = N_\mathrm{ZC} \mod 2$,

$q \in \mathbb{Z}$,

N_ZC = length of sequence.



Plot of a Zadoff-Chu sequence for u=7, N=353

Zadoff–Chu sequences are CAZAC sequences (constant amplitude zero autocorrelation waveform).

Note that the special case $q = 0$ results in a Chu sequence,[1]:151. Setting $q \neq 0$ produces a sequence that is equal to the cyclically shifted

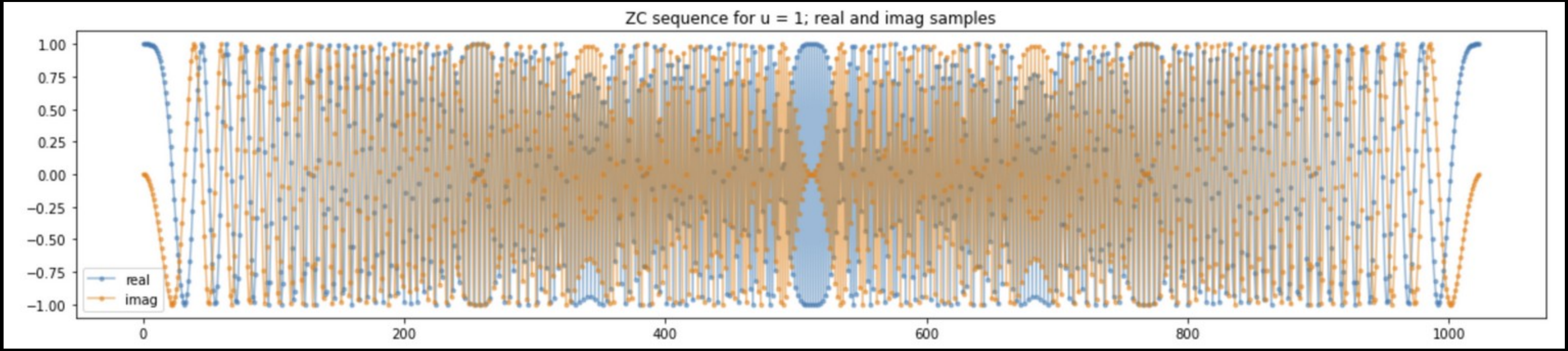
- Just a chirp for $\mathrm{u}=1$
- Double chirp for $\mathrm{u}=2$, etc (but exactly orthogonal)
- Looks like noise for high u
- Delta-function autocorrelation
- Always magnitude 1 (good for DACs and amps)
- *exactly* flat FFT spectrum
- Used in LTE, 5G, radar

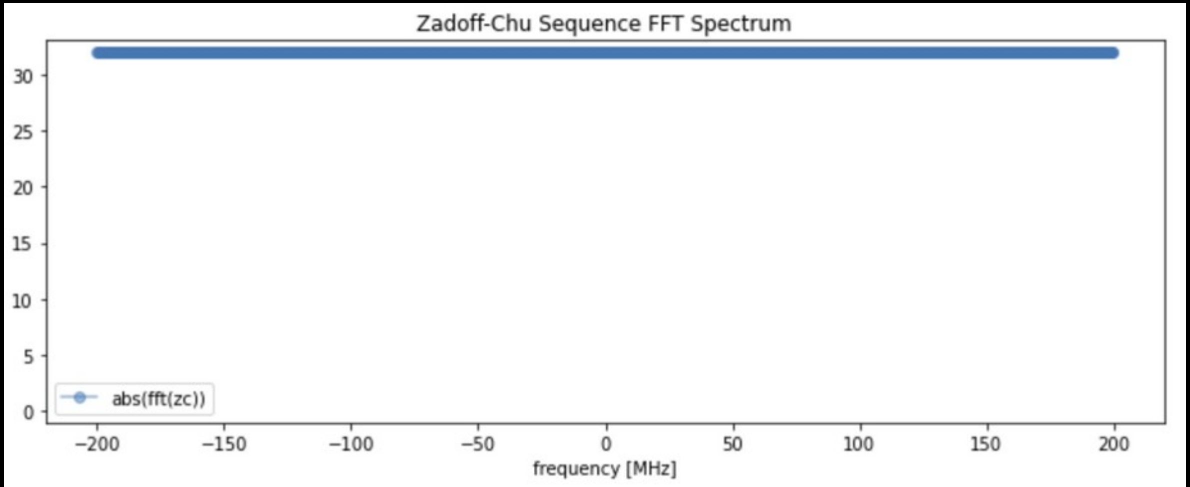
Example: Mapping CHIME’s Beam

- Transmit one copy from *drone*
- Plug another copy into *correlator* (or digitally re-generate)
- Parameters:
  - 400–800 MHz
  - 1024 freq bins
  - 2.56 μs repeating data-taking time window
  - 2^{14} windows get cross correlated and averaged
  - ~42 ms ~24 Hz write to storage

CHIME collaboration

Procedure for CHIME Step 1: choose N_{ZC}

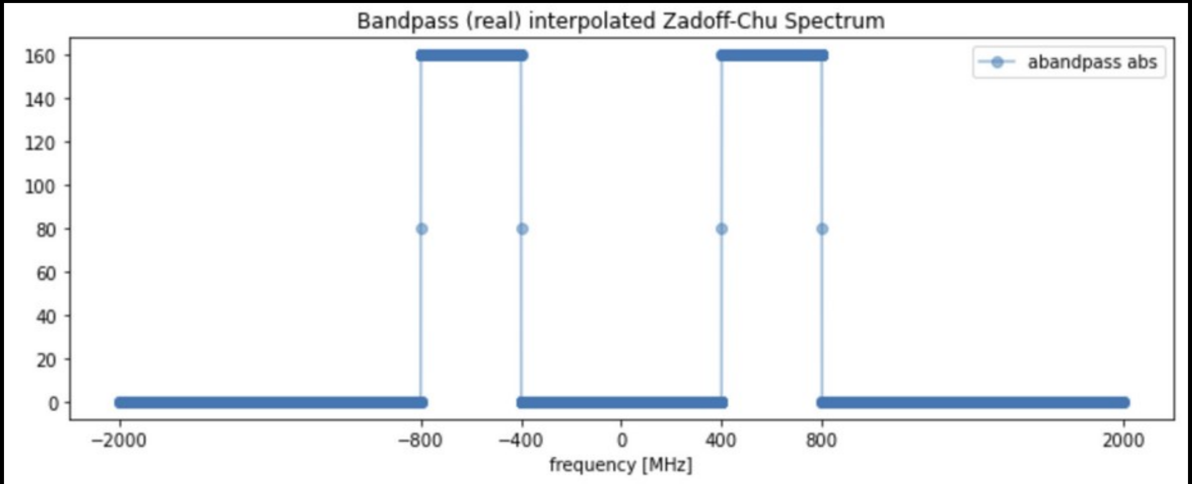




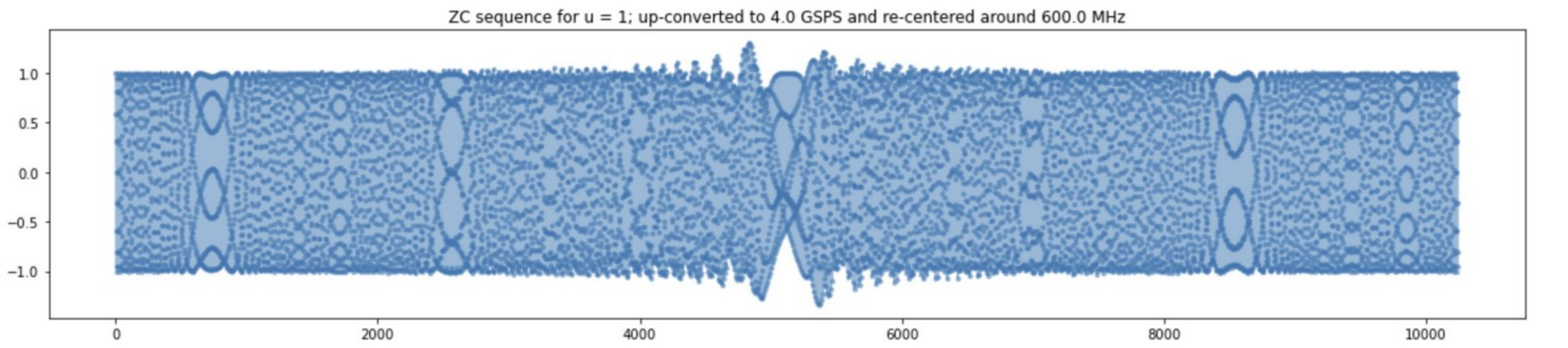
N_{ZC}=1024

1024 bins;
400 MHz wide;
phase not plotted

Procedure for CHIME Step 2: paste FFT

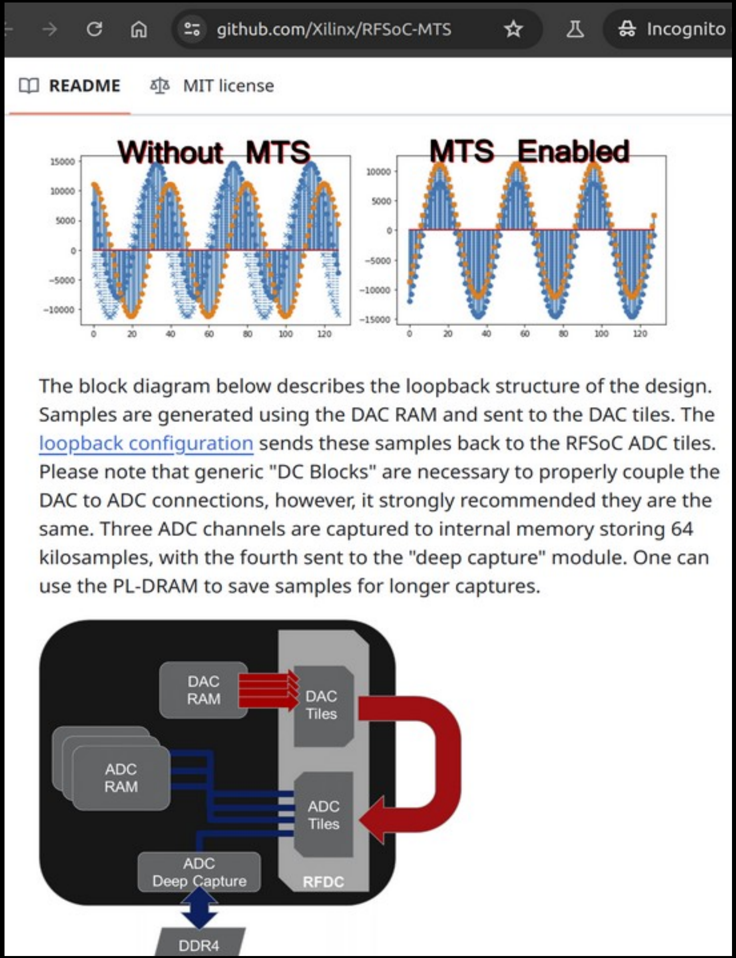


2.56 μs @ 4 GSPS
=10,240 samples



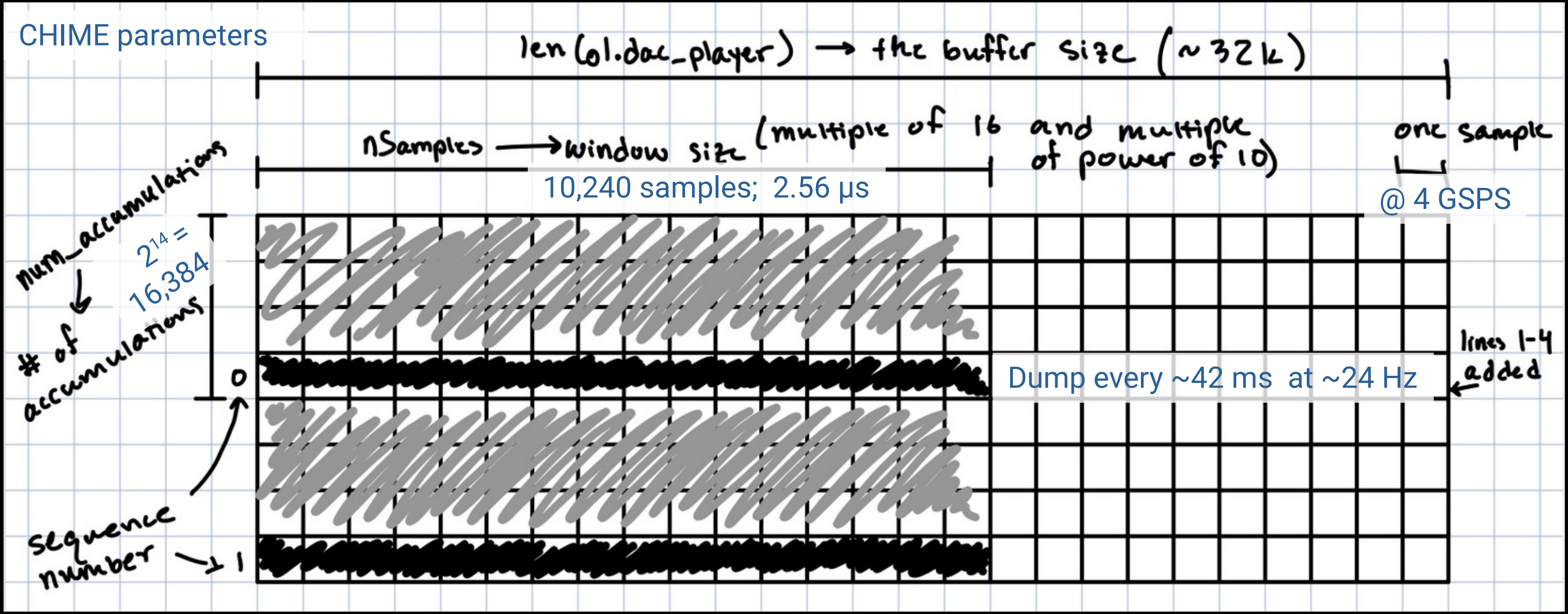
Procedure for CHIME Step 3: FPGA

- Inspired by Xilinx PYNQ
  Multi-Tile Sync (MTS) example
- Block diagram with a few Verilog blocks
- Python for parameters & memory access
- Transmitter:
  - little modification; load int16 array and go.
- Receiver:
  - "Accumulate and Dump" int32 array
  - with no gaps (the only custom Verilog block)



Receiver's "Accumulate and Dump"

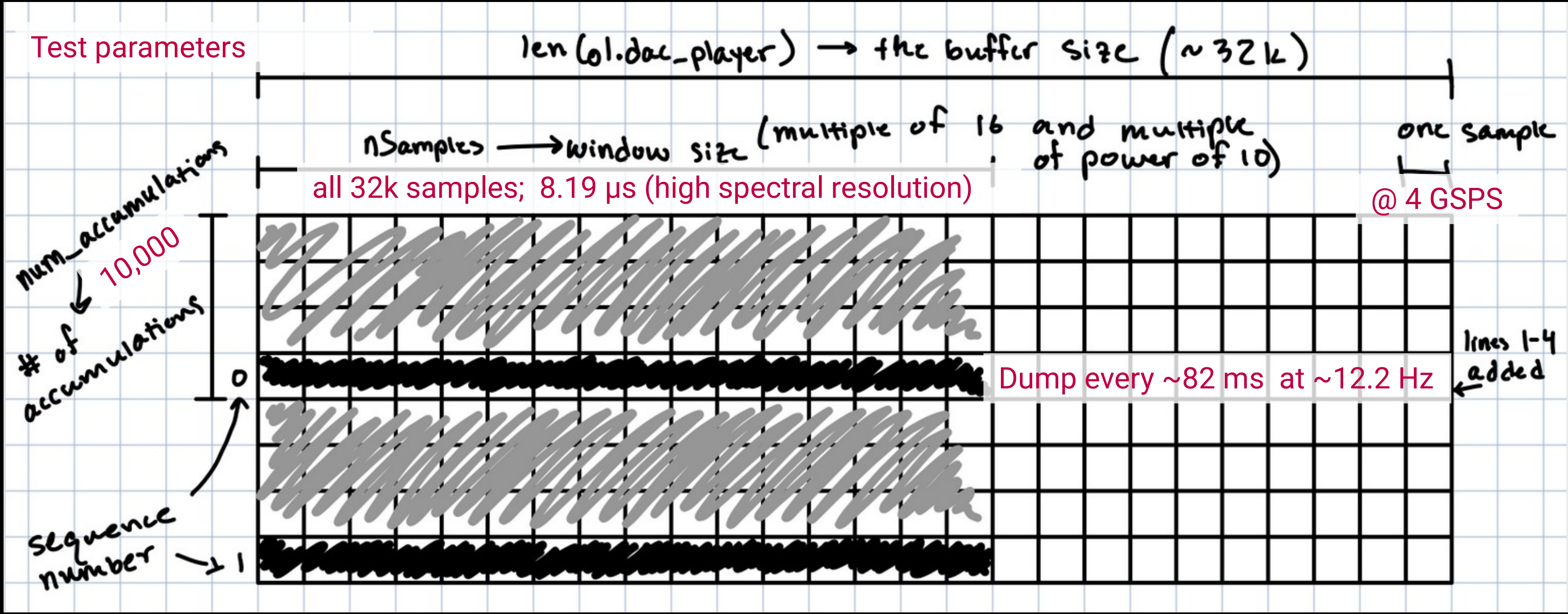
400−800 MHz chirp



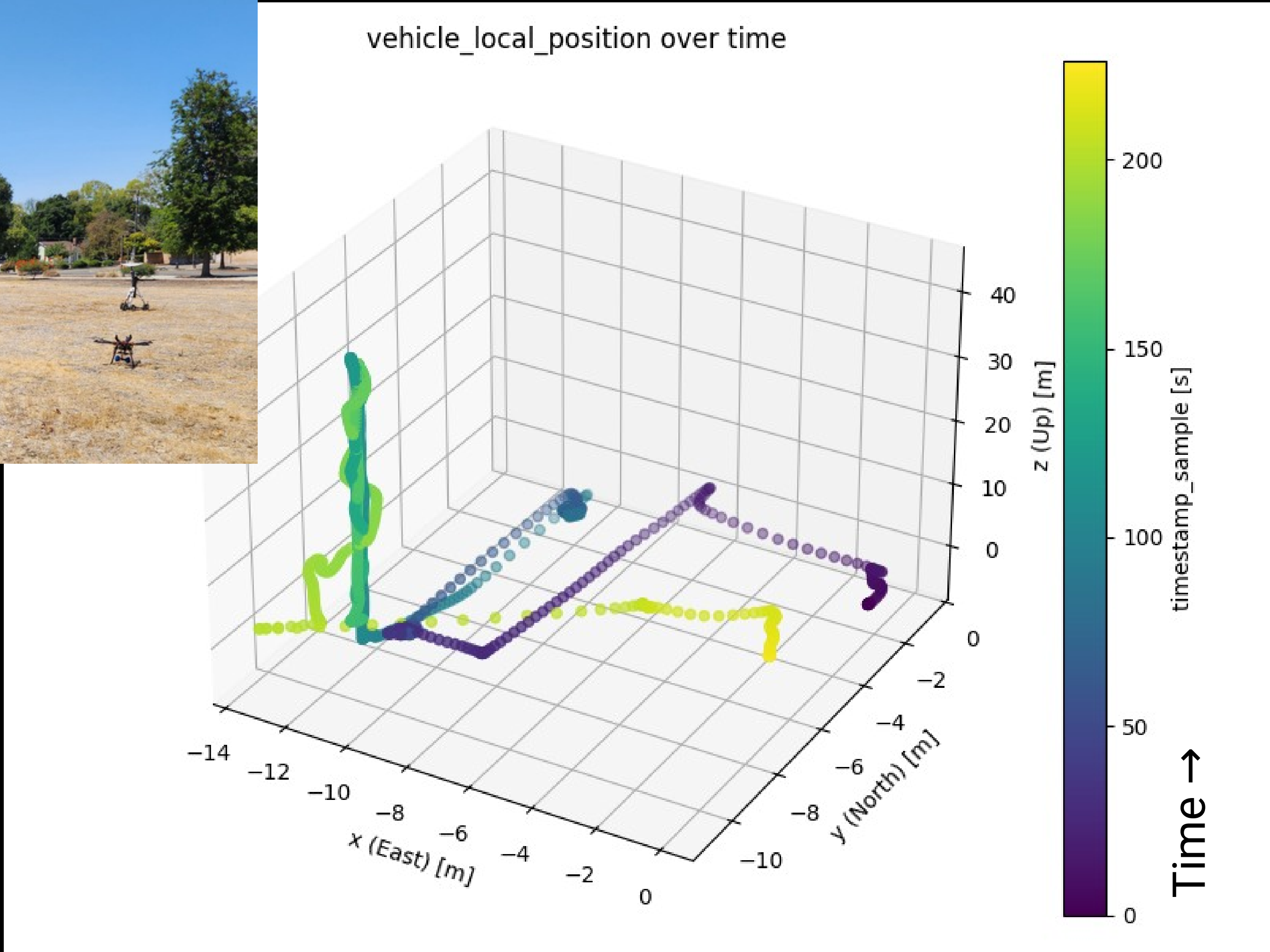
Average 2^{14} copies of same chirp, different noise. Do FFTs later in python

Accumulate and Dump for Drone Flight

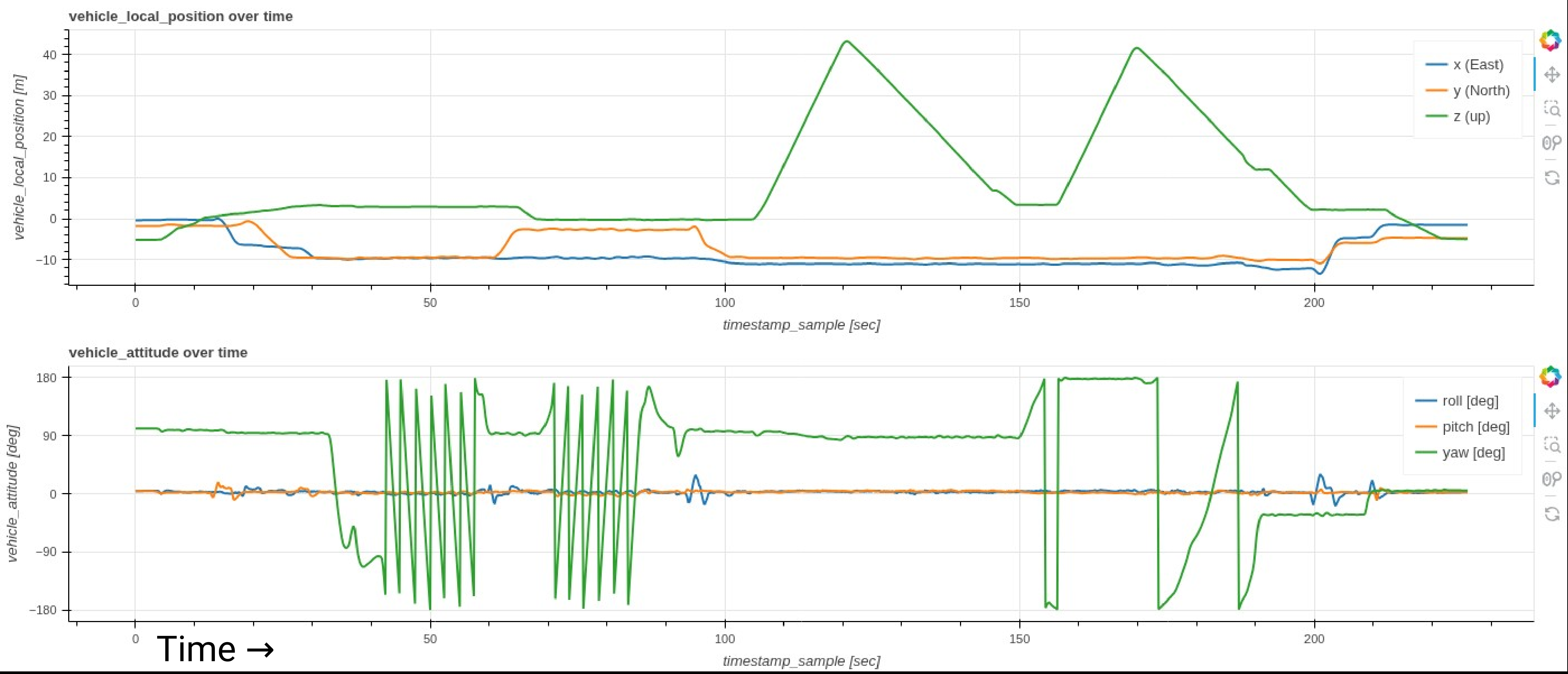
600–1200 MHz chirp



Our First Test Flight: spins, up&down



Our Test Flight in Time: spins, up&down



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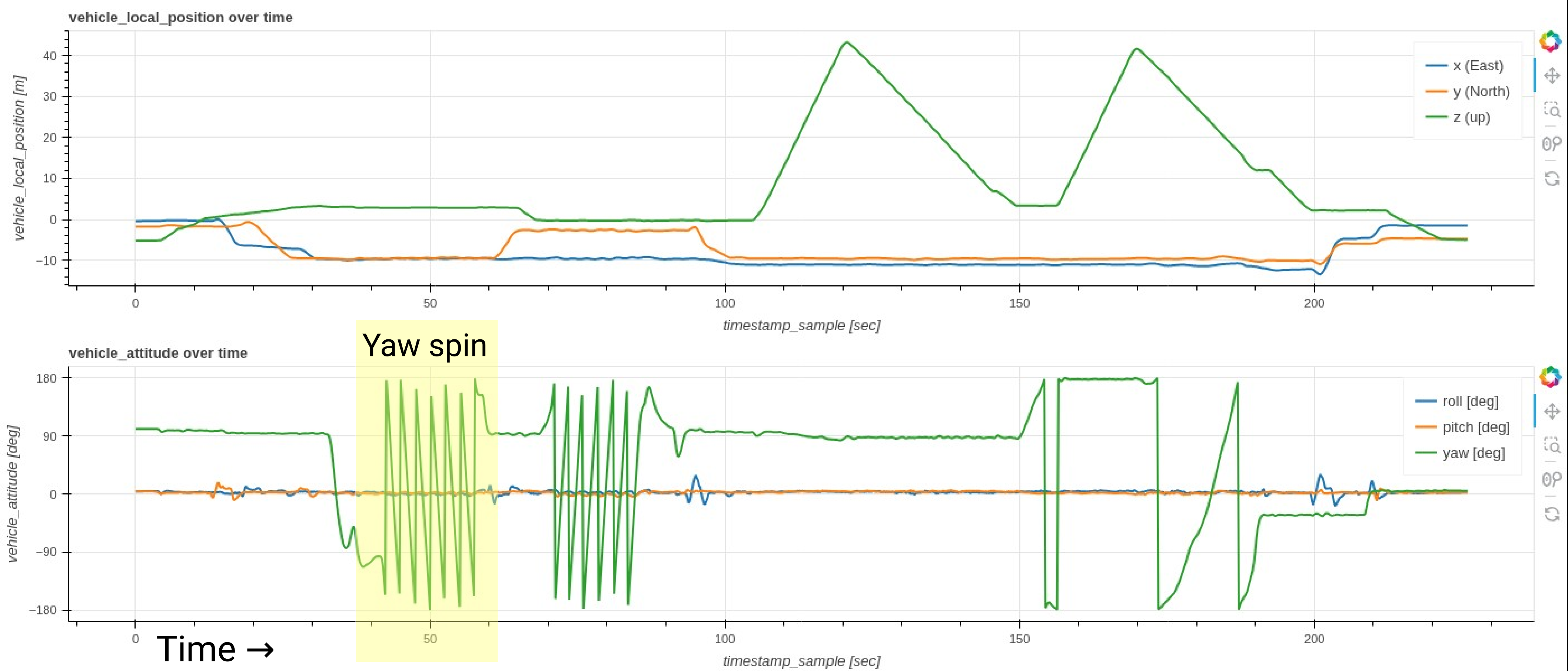

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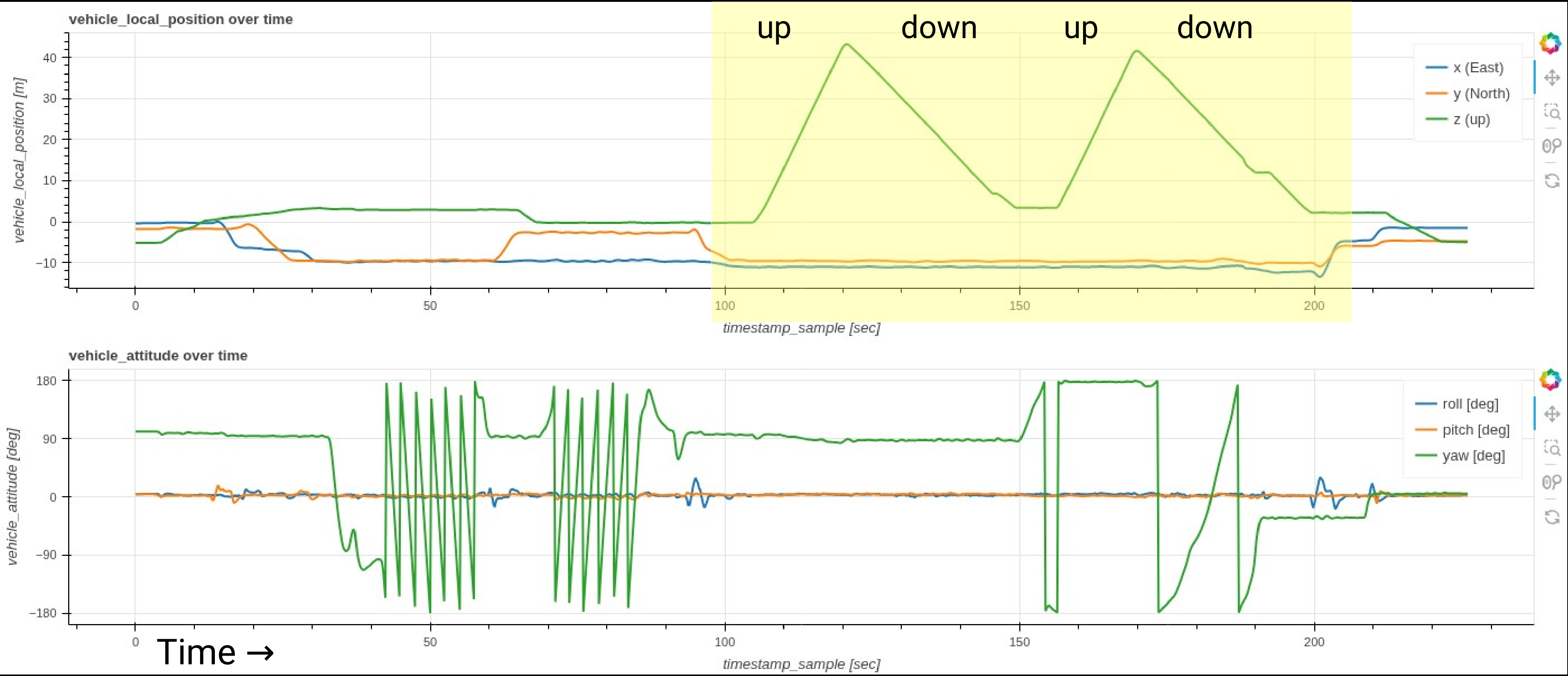
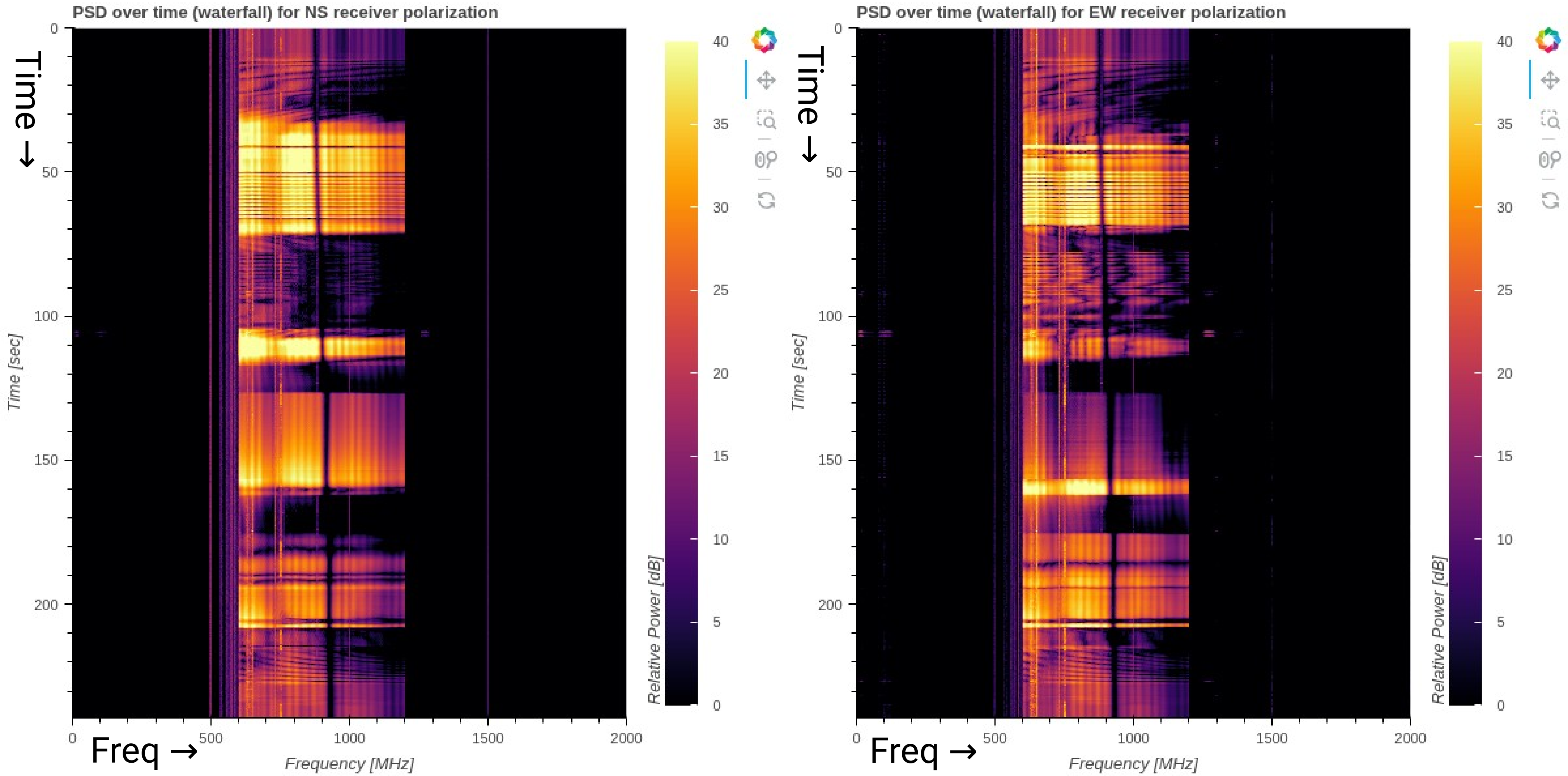
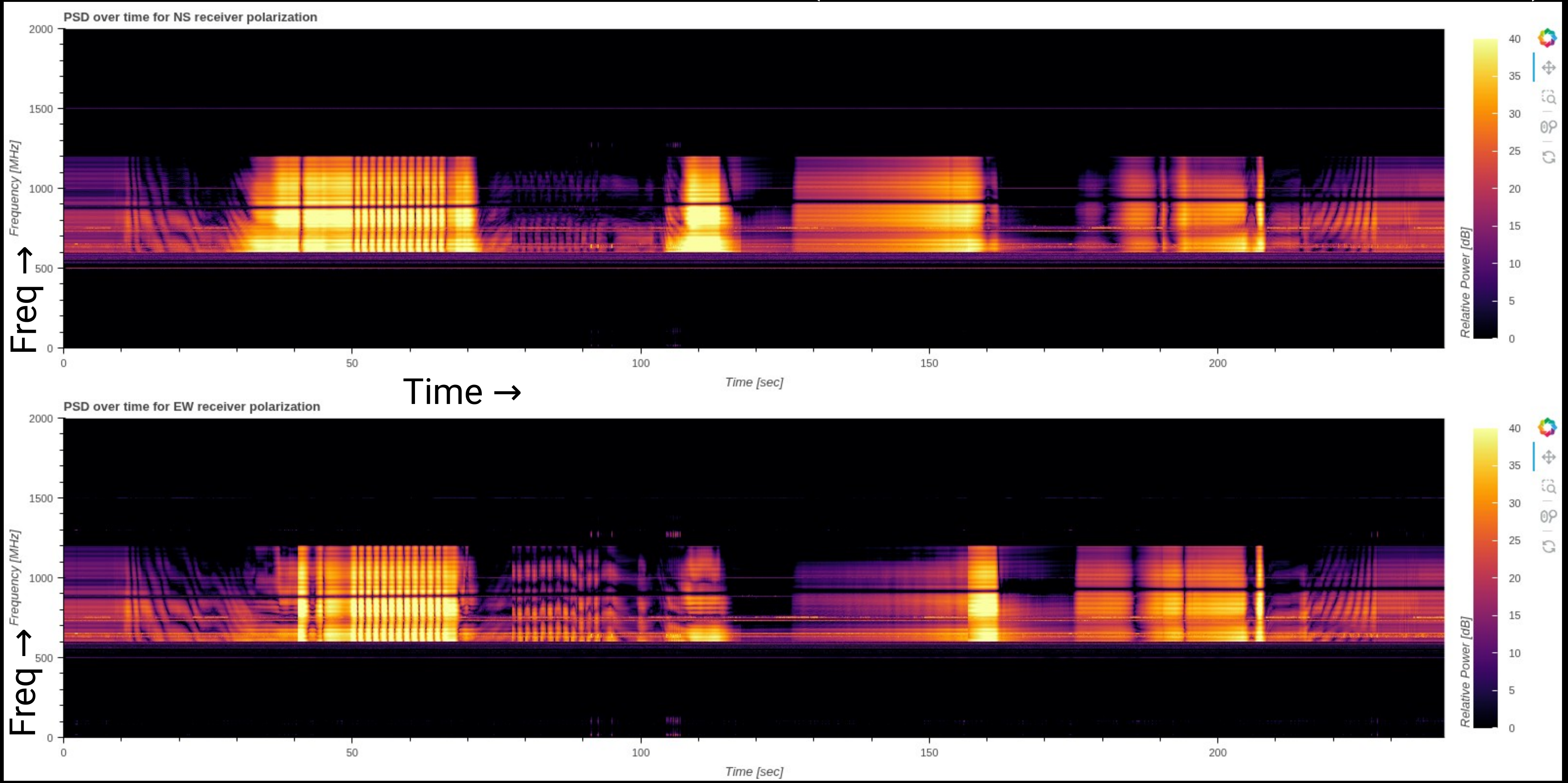


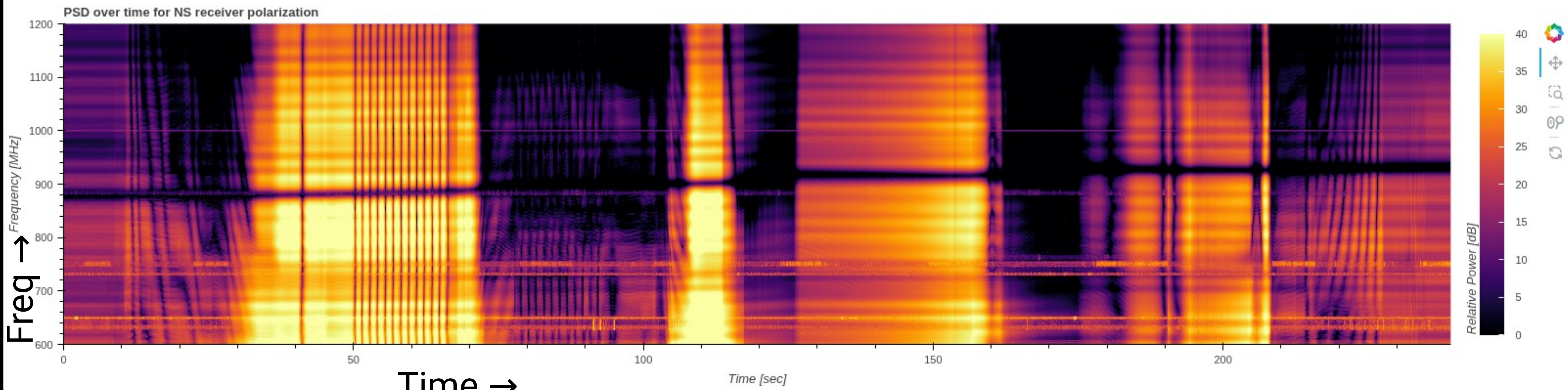
First Waterfall (PSD of each dump)

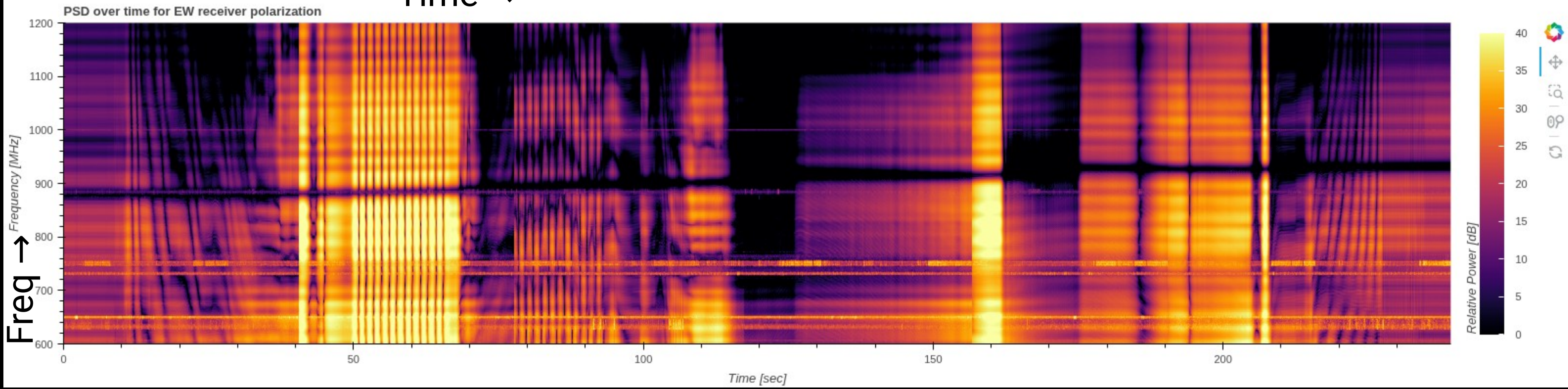


Sideways Waterfall (full 0–2GHz range)

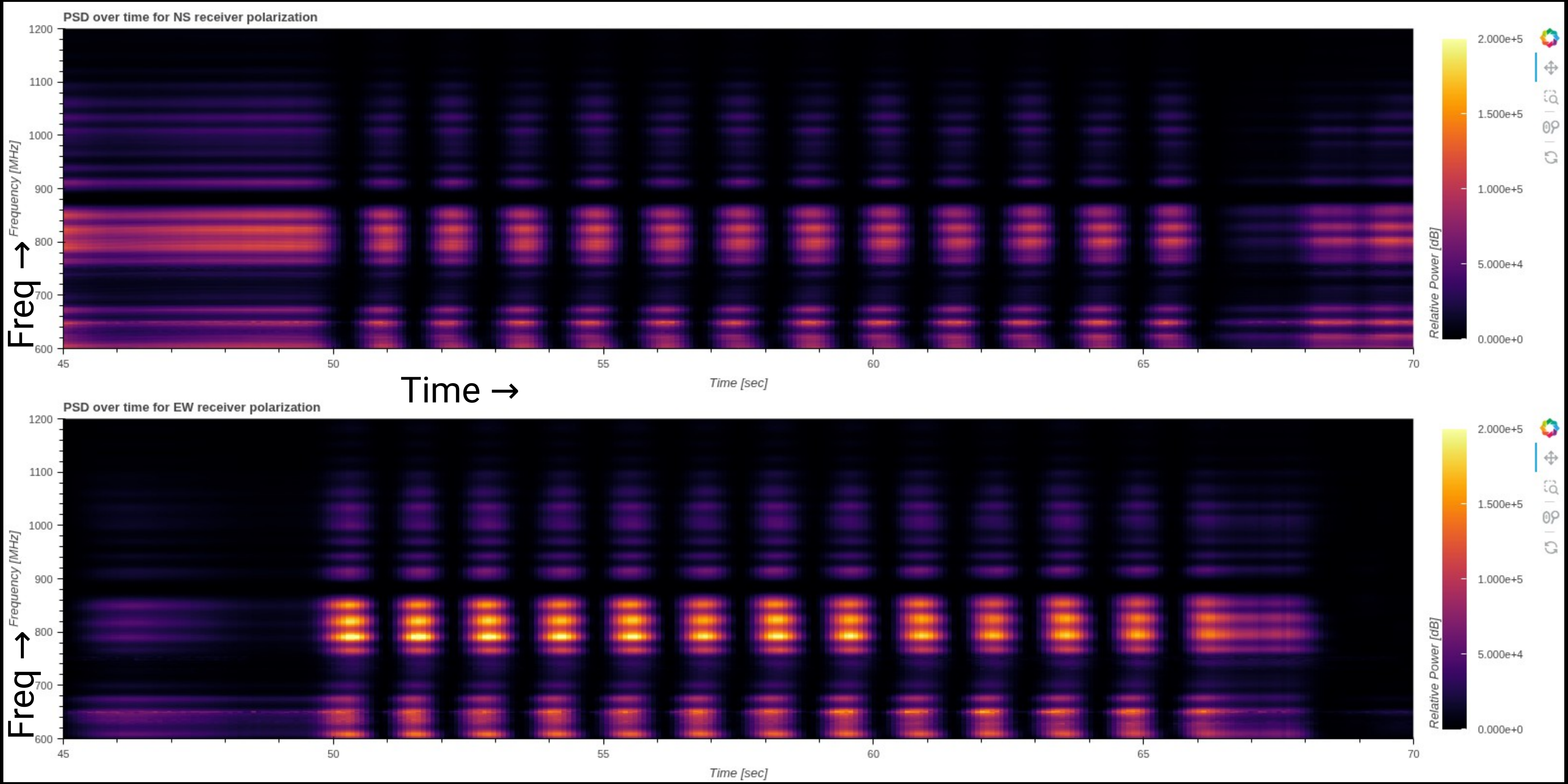


Sideways Waterfall zoom 600–1200 MHz

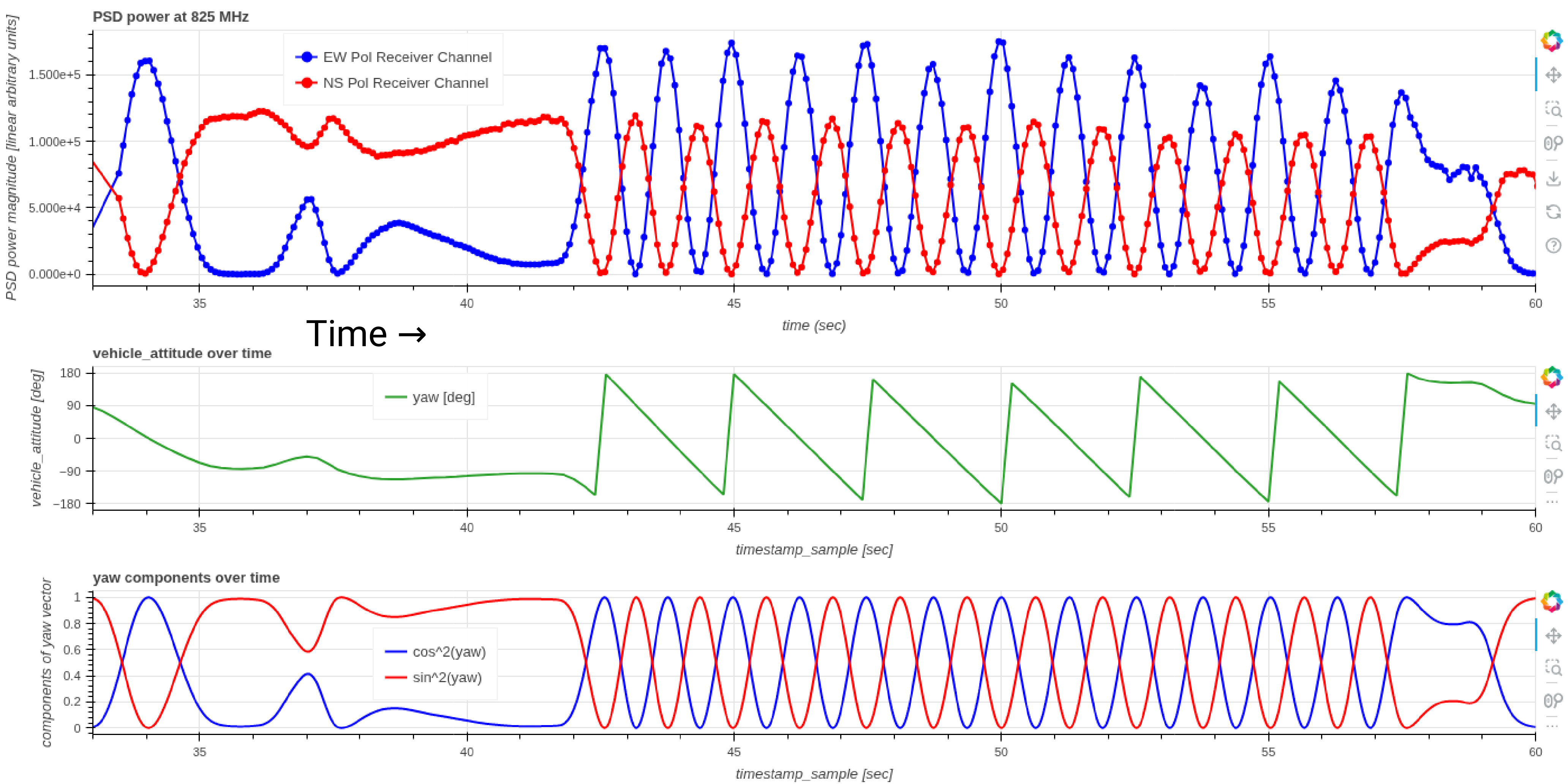




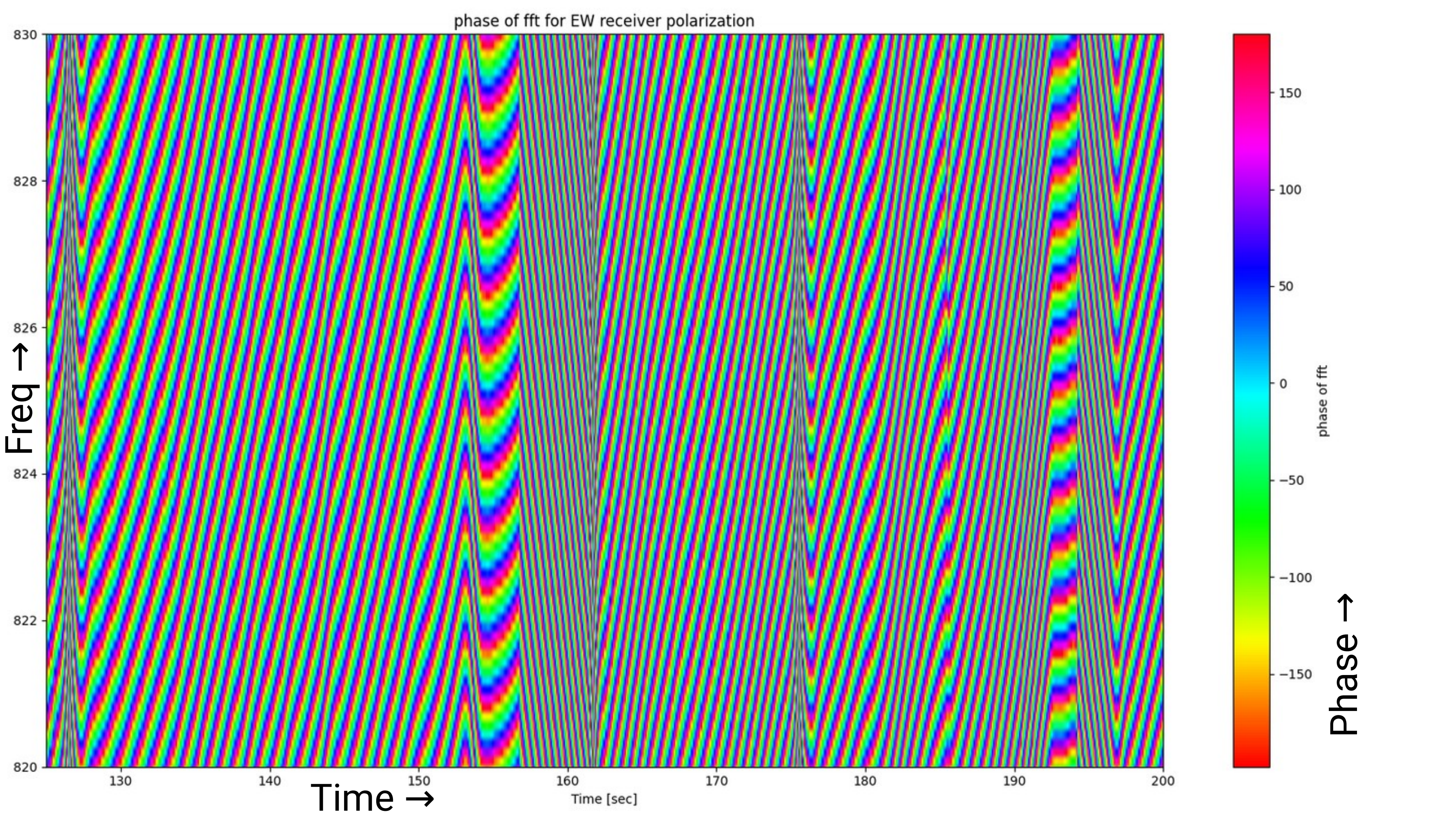
Sideways Waterfall zoom into Yaw Spin



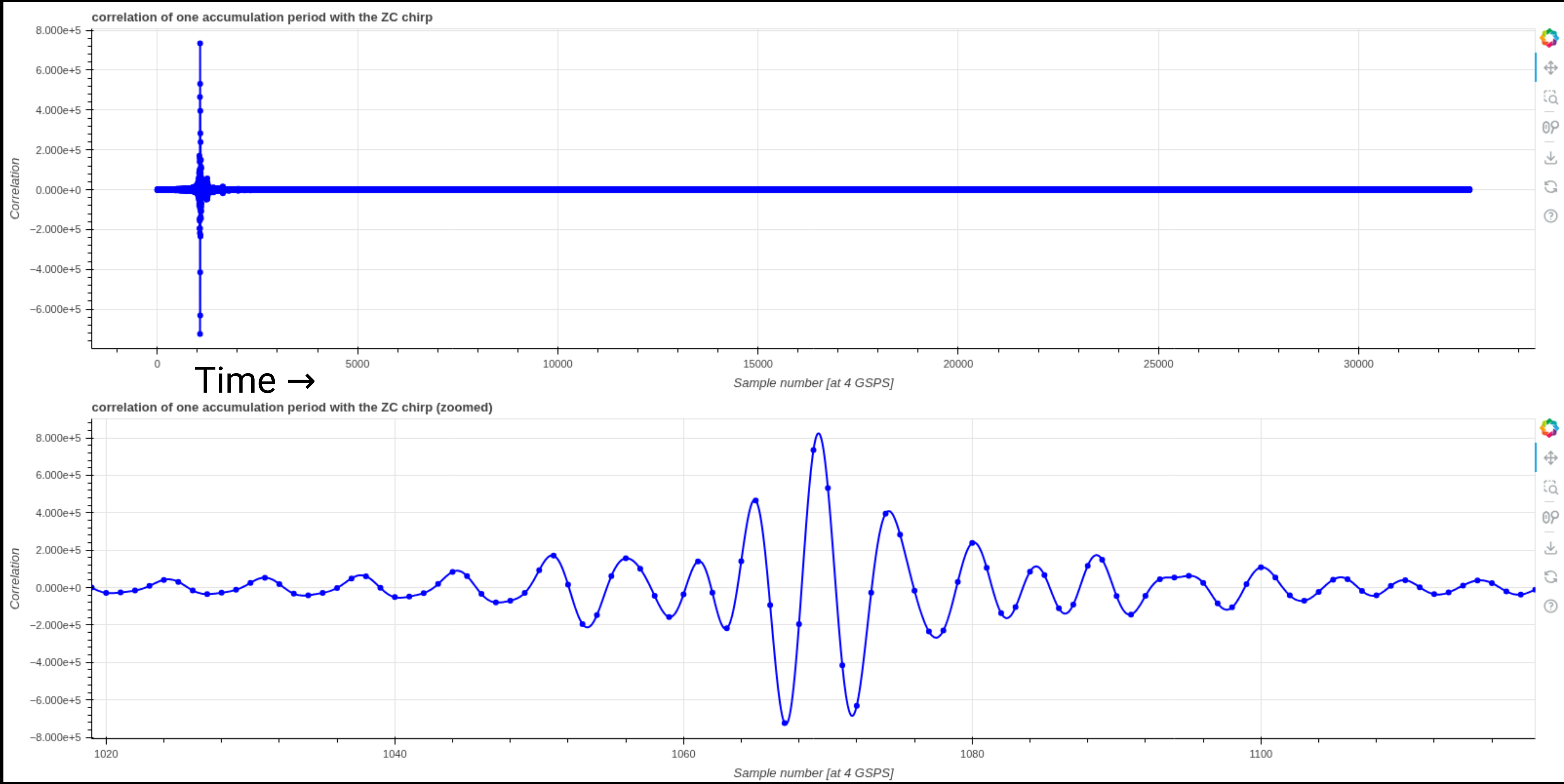
Polarization & Power during Yaw Spin



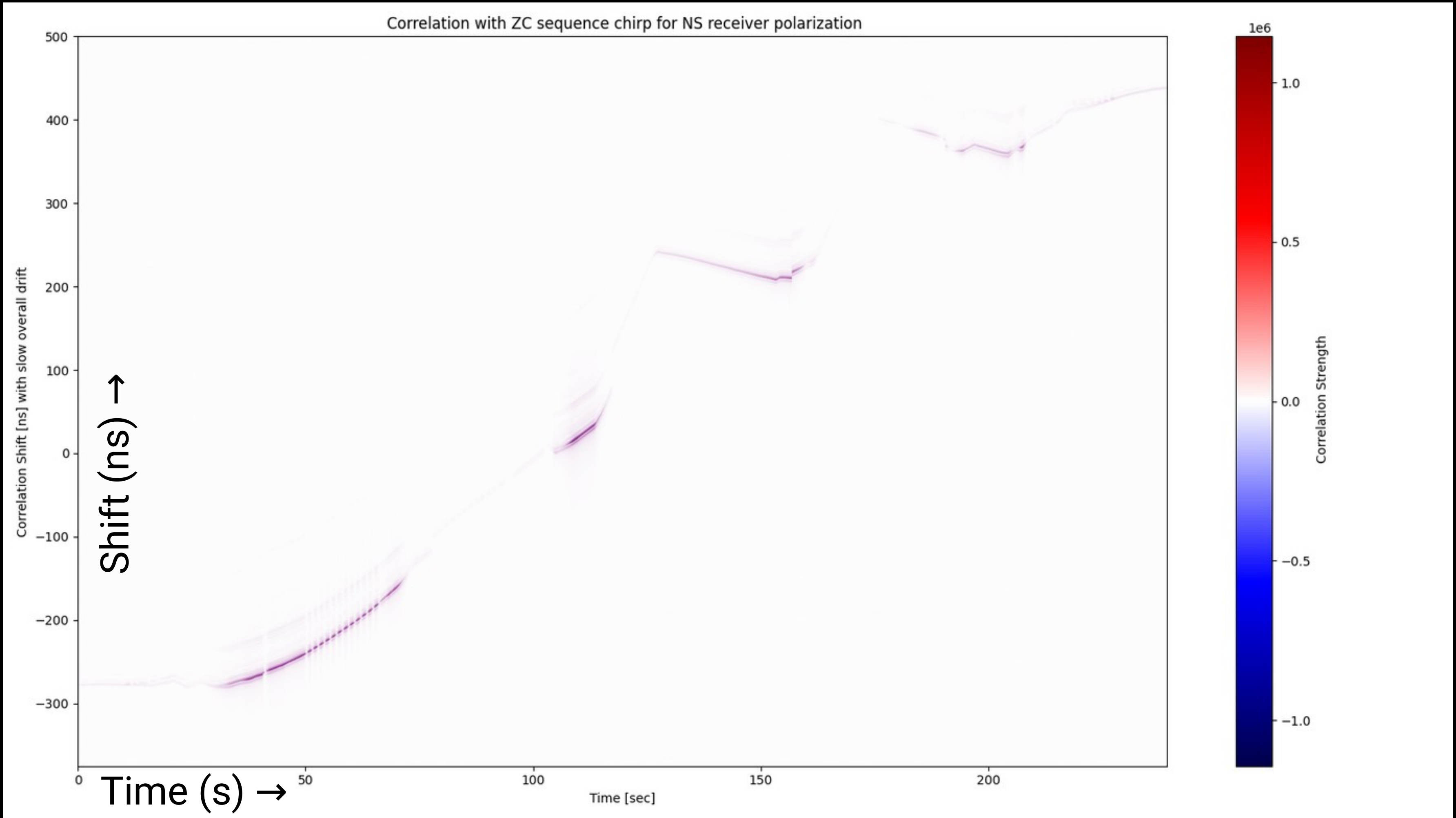
Phase information during up&down



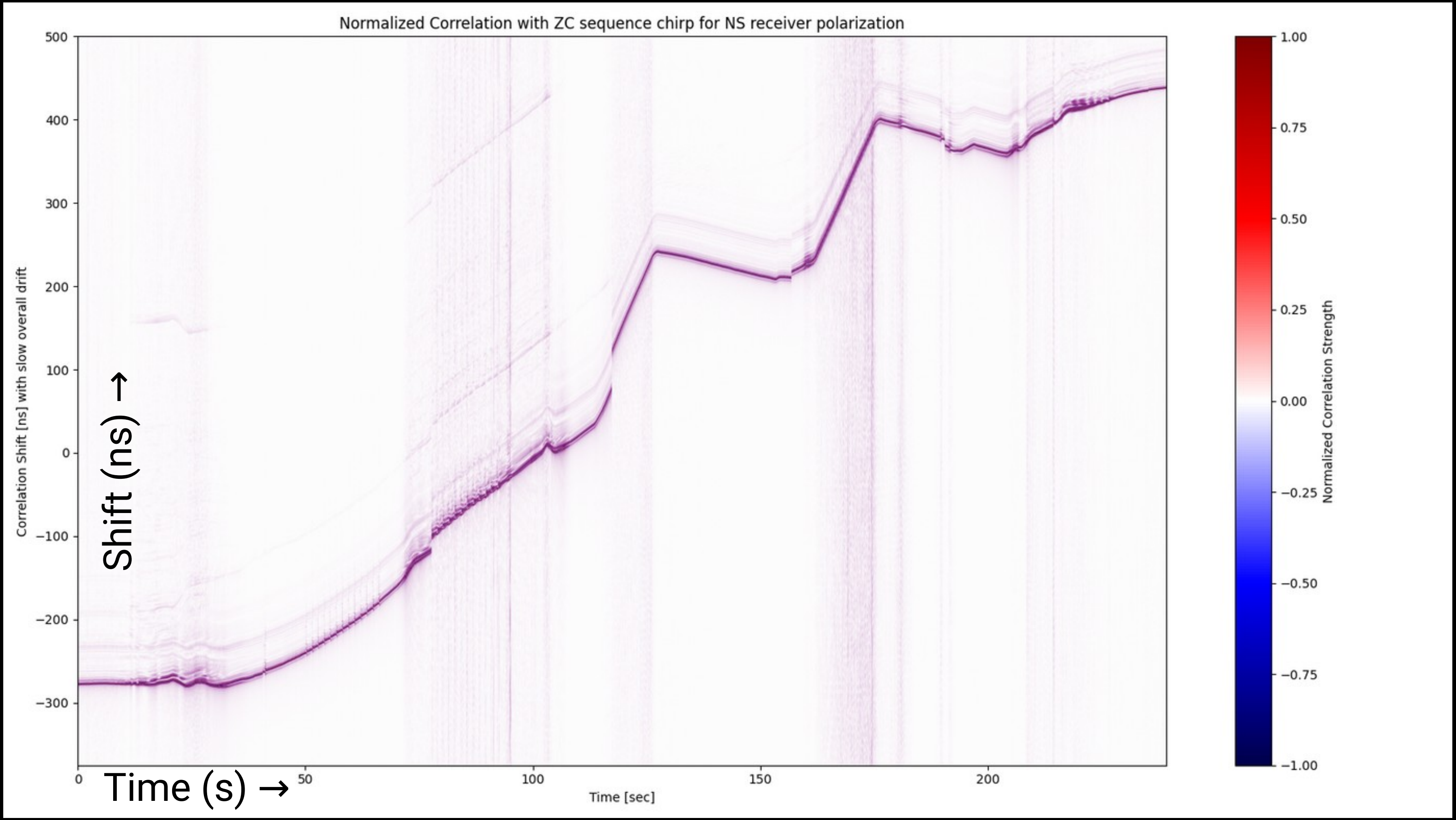
Correlation of one dump against chirp



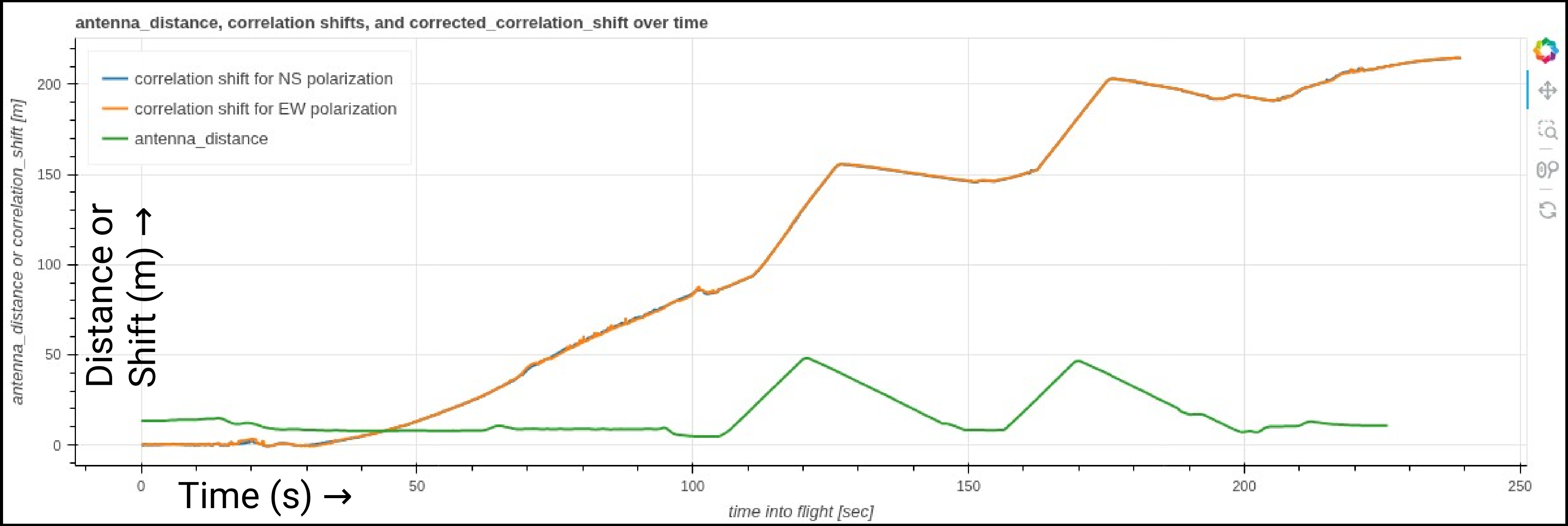
Correlation of each dump against chirp



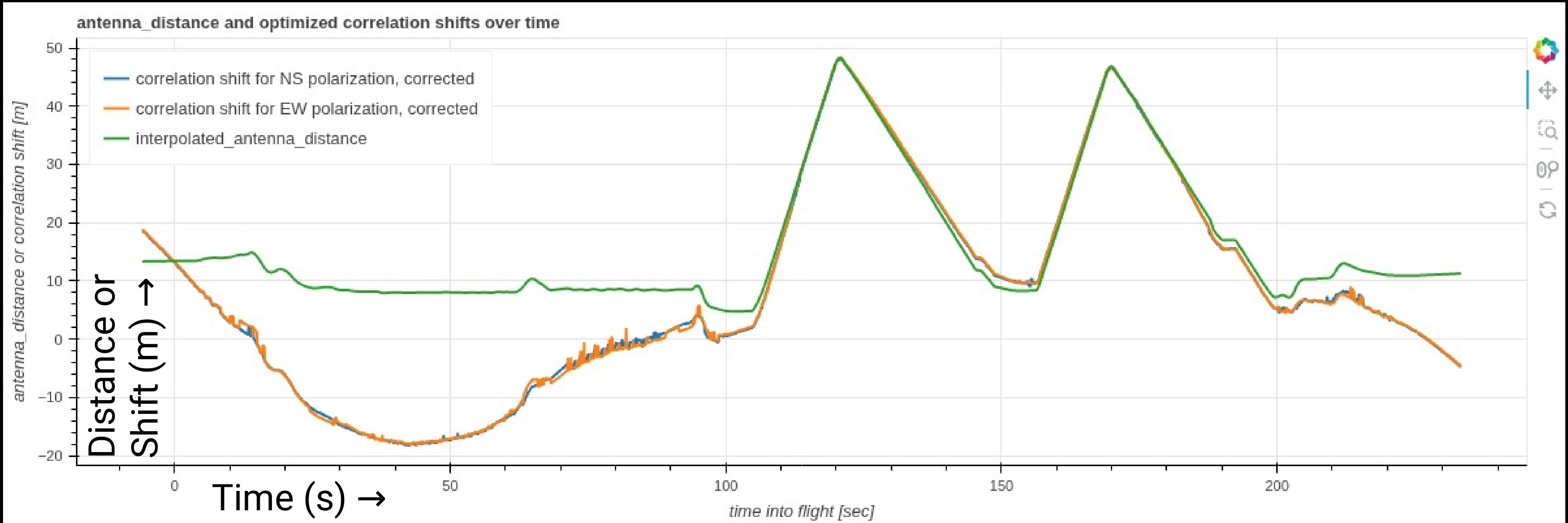
Normalized correlations against chirp



Correlation maximum: shift over time

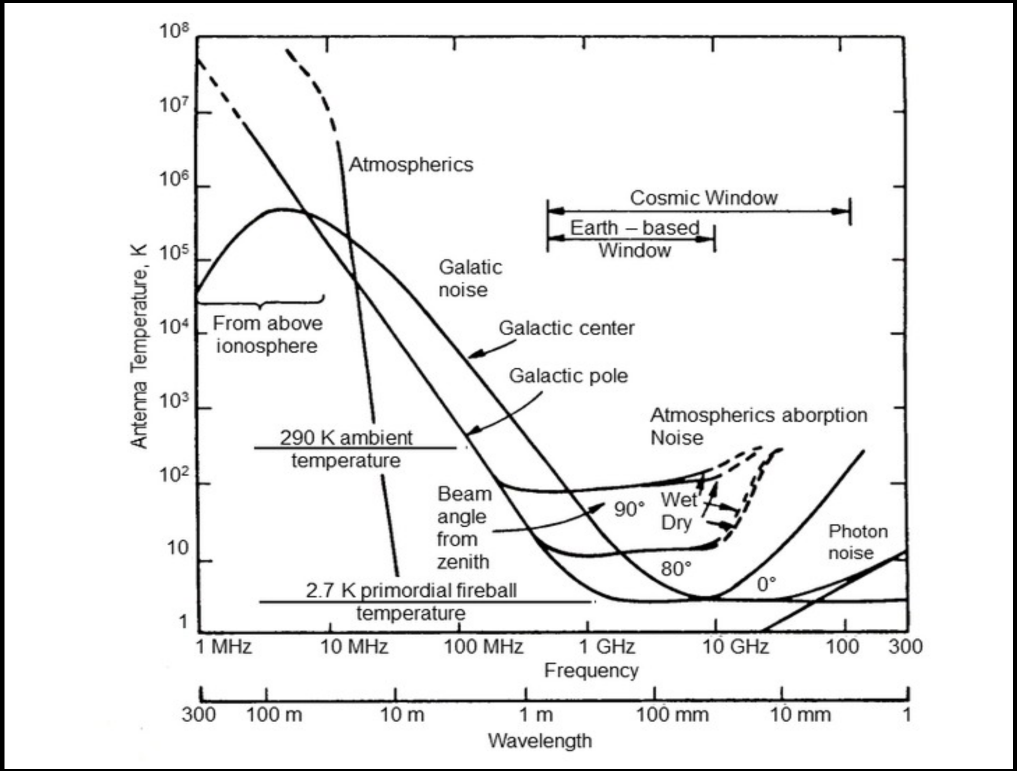


Correlation shift with drift correction



drift rate *linear* fit in the up-down-up-down region:
~ 1 m/s or ~ 3 ns/s

Signal to Noise Ratio *too* high?

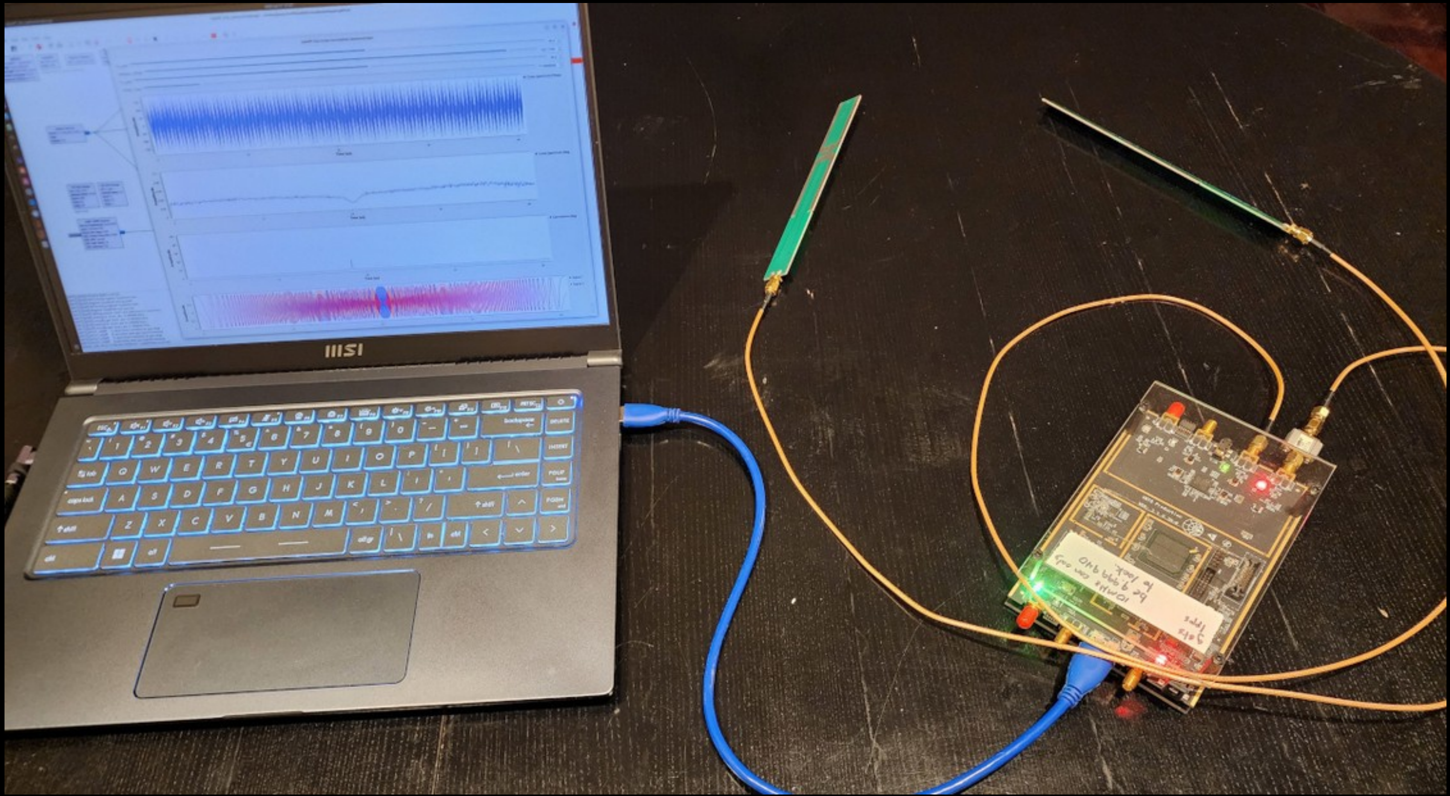


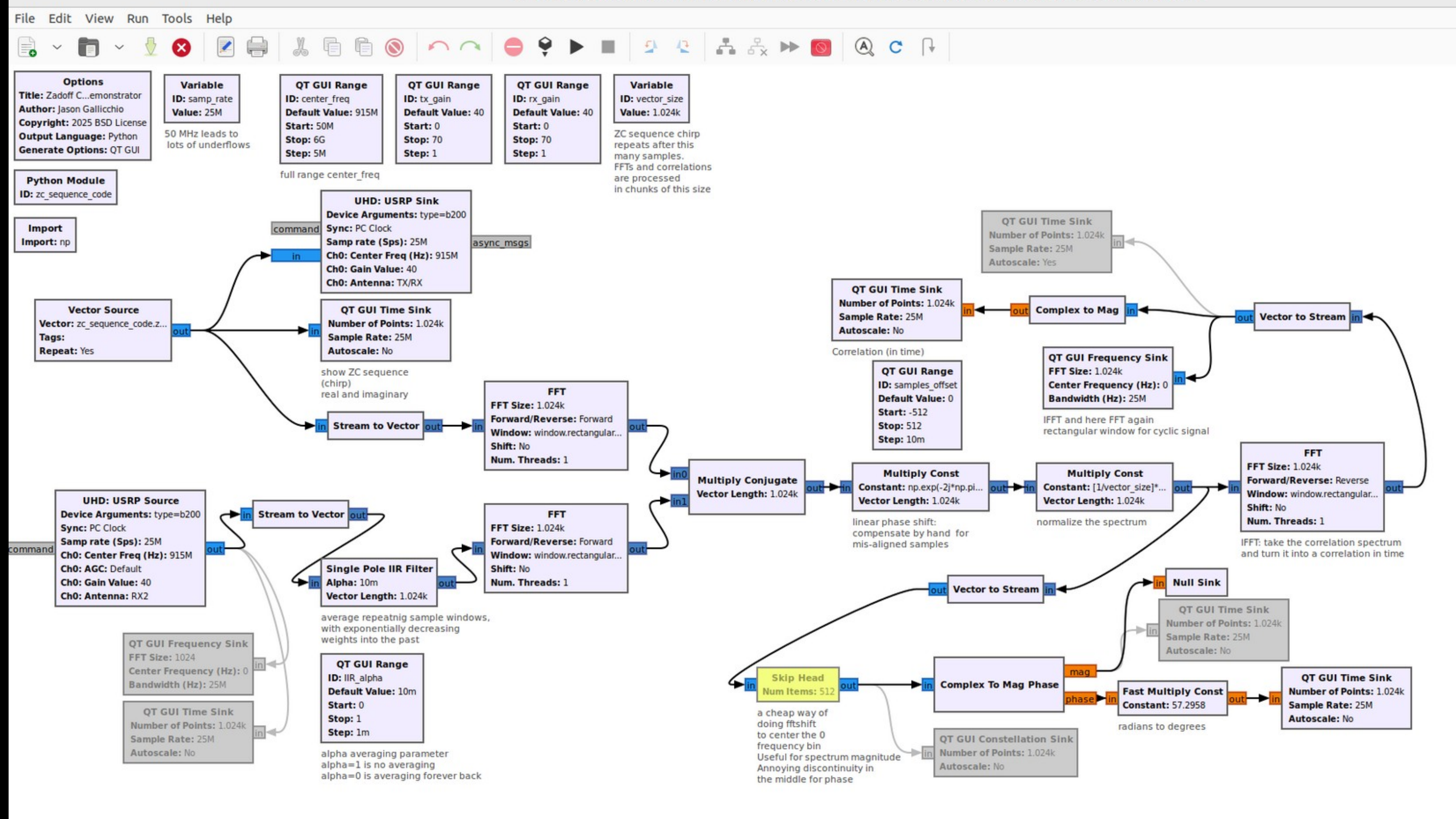
Rochat et al. reworked from Kraus, 1986

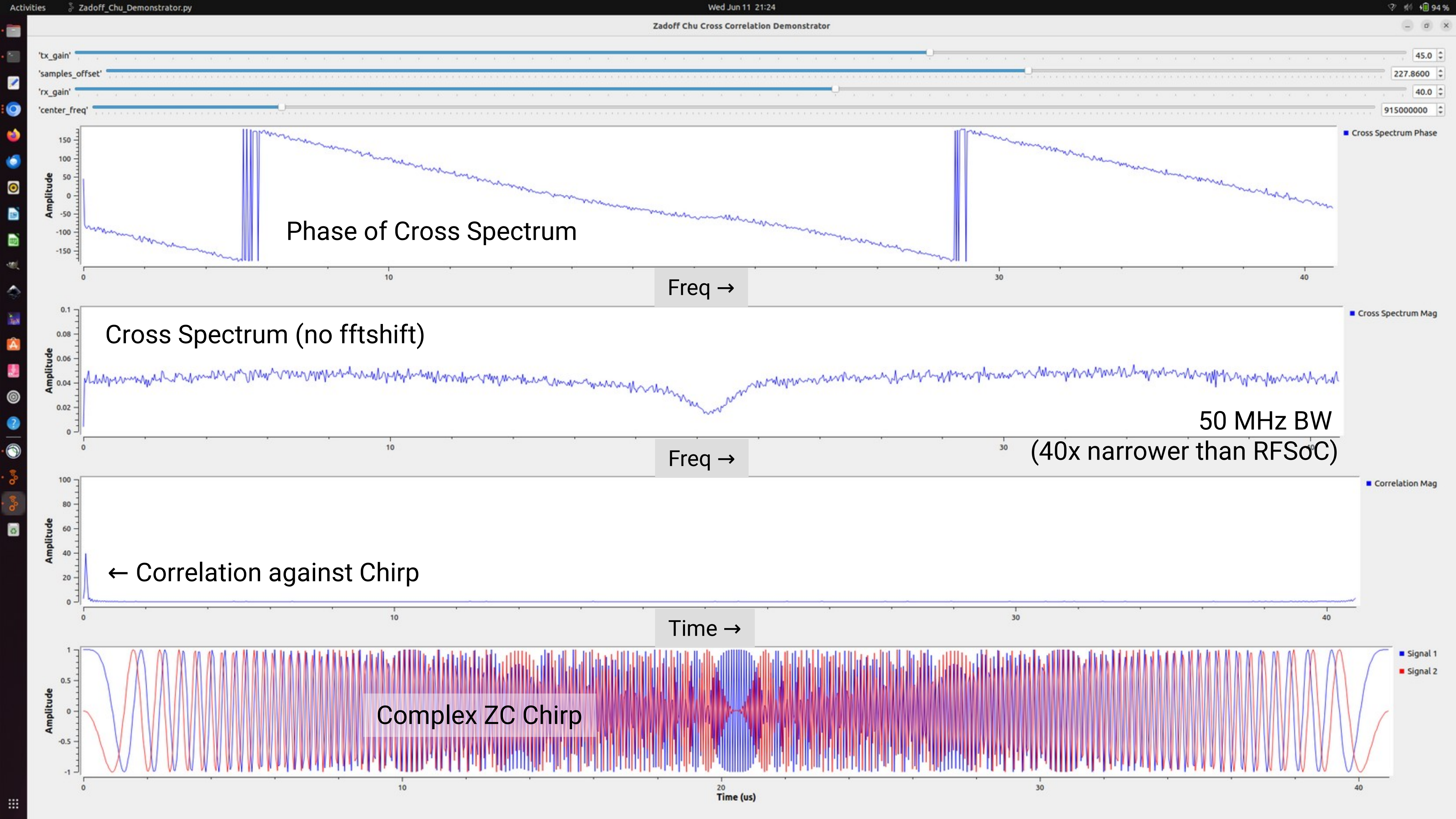
- <1mW spread across 600–1200 MHz
- looks like 300K a few hundred meters away

GNU Radio Prototype

https://github.com/QuantumQuasars/DroneBeamMappingRFSoC



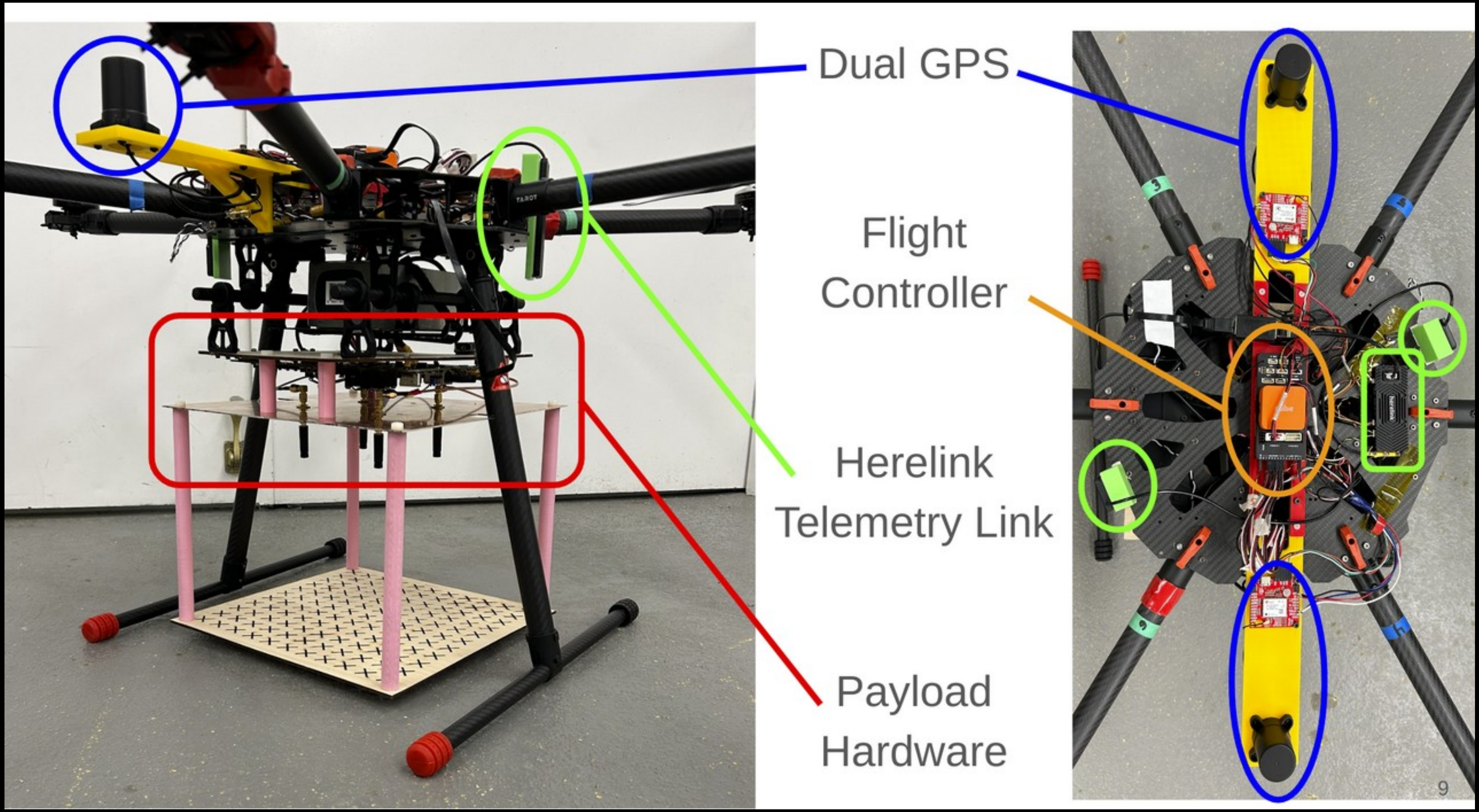

File Edit View Run Tools Help
Options
Title: Zadoff C...emonstrator
Author: Jason Gallicchio
Copyright: 2025 BSD License
Output Language: Python
Generate Options: QT GUI
Variable
ID: samp_rate
Value: 25M
50 MHz leads to lots of underflows
QT GUI Range
ID: center_freq
Default Value: 915M
Start: 50M
Stop: 6G
Step: 5M
full range center_freq
QT GUI Range
ID: tx_gain
Default Value: 40
Start: 0
Stop: 70
Step: 1
QT GUI Range
ID: rx_gain
Default Value: 40
Start: 0
Stop: 70
Step: 1
Variable
ID: vector_size
Value: 1.024k
ZC sequence chirp repeats after this many samples. FFTs and correlations are processed in chunks of this size
Python Module
ID: zc_sequence_code
Import
Import: np
UHD: USRP Sink
Device Arguments: type=b200
Sync: PC Clock
Samp rate (Sps): 25M
Ch0: Center Freq (Hz): 915M
Ch0: Gain Value: 40
Ch0: Antenna: TX/RX
command
in
async_msgs
Vector Source
Vector: zc_sequence_code.z...
Tags:
Repeat: Yes
out
QT GUI Time Sink
Number of Points: 1.024k
Sample Rate: 25M
Autoscale: No
show ZC sequence (chirp) real and imaginary
Stream to Vector
FFT
FFT Size: 1.024k
Forward/Reverse: Forward
Window: window.rectangular...
Shift: No
Num. Threads: 1
UHD: USRP Source
Device Arguments: type=b200
Sync: PC Clock
Samp rate (Sps): 25M
Ch0: Center Freq (Hz): 915M
Ch0: AGC: Default
Ch0: Gain Value: 40
Ch0: Antenna: RX2
Stream to Vector
Single Pole IIR Filter
Alpha: 10m
Vector Length: 1.024k
average repeatnig sample windows, with exponentially decreasing weights into the past
FFT
FFT Size: 1.024k
Forward/Reverse: Forward
Window: window.rectangular...
Shift: No
Num. Threads: 1
QT GUI Frequency Sink
FFT Size: 1024
Center Frequency (Hz): 0
Bandwidth (Hz): 25M
QT GUI Time Sink
Number of Points: 1.024k
Sample Rate: 25M
Autoscale: No
QT GUI Range
ID: IIR_alpha
Default Value: 10m
Start: 0
Stop: 1
Step: 1m
alpha averaging parameter
alpha=1 is no averaging
alpha=0 is averaging forever back
Multiply Conjugate
Vector Length: 1.024k
in0
in1
Multiply Const
Constant: np.exp(-2j*np.pi...
Vector Length: 1.024k
linear phase shift: compensate by hand for mis-aligned samples
Multiply Const
Constant: [1/vector_size]*...
Vector Length: 1.024k
normalize the spectrum
FFT
FFT Size: 1.024k
Forward/Reverse: Reverse
Window: window.rectangular...
Shift: No
Num. Threads: 1
IFFT: take the correlation spectrum and turn it into a correlation in time
QT GUI Time Sink
Number of Points: 1.024k
Sample Rate: 25M
Autoscale: Yes
QT GUI Time Sink
Number of Points: 1.024k
Sample Rate: 25M
Autoscale: No
Correlation (in time)
Complex to Mag
Vector to Stream
QT GUI Range
ID: samples_offset
Default Value: 0
Start: -512
Stop: 512
Step: 10m
QT GUI Frequency Sink
FFT Size: 1.024k
Center Frequency (Hz): 0
Bandwidth (Hz): 25M
IFFT and here FFT again rectangular window for cyclic signal
Vector to Stream
Null Sink
QT GUI Time Sink
Number of Points: 1.024k
Sample Rate: 25M
Autoscale: No
Skip Head
Num Items: 512
a cheap way of doing fftshift to center the 0 frequency bin
Useful for spectrum magnitude
Annoying discontinuity in the middle for phase
Complex To Mag Phase
mag
phase
Fast Multiply Const
Constant: 57.2958
radians to degrees
QT GUI Time Sink
Number of Points: 1.024k
Sample Rate: 25M
Autoscale: No
QT GUI Constellation Sink
Number of Points: 1.024k
Autoscale: No


Zadoff Chu Cross Correlation Demonstrator
'tx_gain' 45.0
'samples_offset' 227.8600
'rx_gain' 40.0
'center_freq' 915000000
Cross Spectrum Phase
Phase of Cross Spectrum
Freq →
Cross Spectrum Mag
Cross Spectrum (no fftshift)
50 MHz BW
(40x narrower than RFSoC)
Freq →
Correlation Mag
← Correlation against Chirp
Time →
Signal 1
Signal 2
Complex ZC Chirp
Amplitude
Time (us)

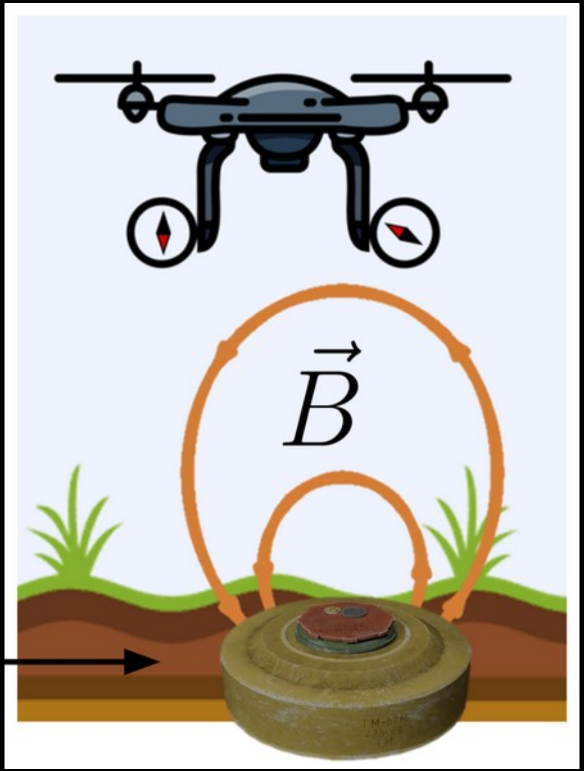
Next Steps

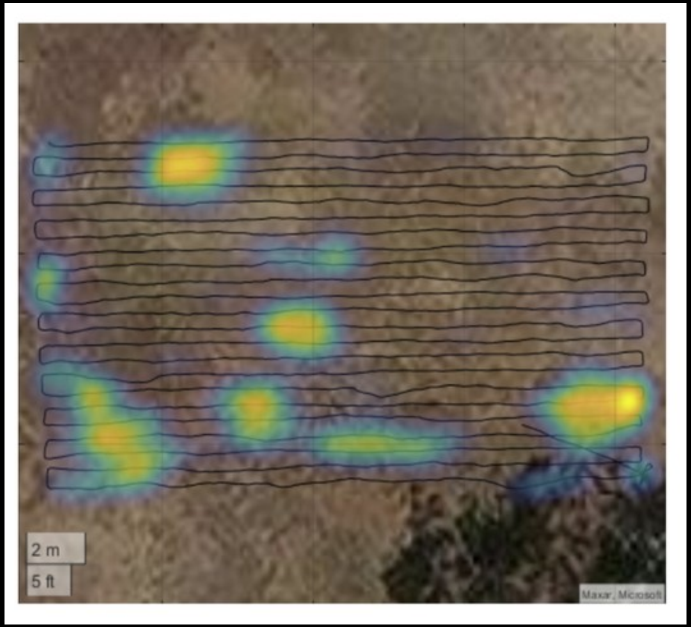
- Fix GPS “spoofing” and “jamming” issues (even with no payload)
- Fix drone flight controller freakouts
- Fix clock drifts (10 MHz ref)
- 1pps to start TX and RX
- Doppler compensation?
- Mixers? Higher Nyquist zones?
- Actually measure an antenna pattern!
- Flights to compare to tone, noise, on/off and LFSR
- Simulate/measure antenna pattern and spectrum of drone itself
- Go to a real radio telescope!
- Publish where? Talk where else? Get $ from where?

Drone Direction Finding Project



Drone Humanitarian Demining Magnetometer





http://sokil.io

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  - Joaquin Gonzalez-Salgado
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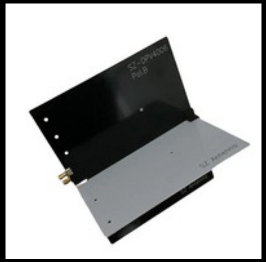
  - Laura Newburgh’s Group (Yale)
  - Danny Jacobs’s Group (Arizona State University)
  - Emily Kuhn (NASA JPL)
- Funding

Advantages compared to methods in use

- Theoretically 16x better/faster than noise on/off
  - No on/off subtraction
  - No gaps
  - Phase information
- Repeat at exactly the FFT window rate of the correlator:
  - No issues synchronizing long random noise (FFT is cyclic)
  - No FFT window (signal is cyclic)

- VNA “through” amplitude & phase
  - *near field* measurements with modeling to far field
  - Fixed TX on ground to measure *drifts* of RX chain
- Simultaneous dual-pol TX with orthogonal signals

Aaronia PowerLOG® PRO
300 MHz - 3 GHz; 8.8 kg; €€€€€



eBay 400 MHz – 6 GHz $249