Galactic Structure Revealed by HI Observation

- Neutral hydrogen gas in the Galactic disk orbits nearly circularly around the Galactic center.
- Radial velocities Vr from **Doppler shifts of HI 21cm emission lines** provide **distance of HI clouds from the Galactic center.**
- Hydrogen distribution reveals the **large-scale structure of the Galaxy**, obscured by dust in visible wavelengths.

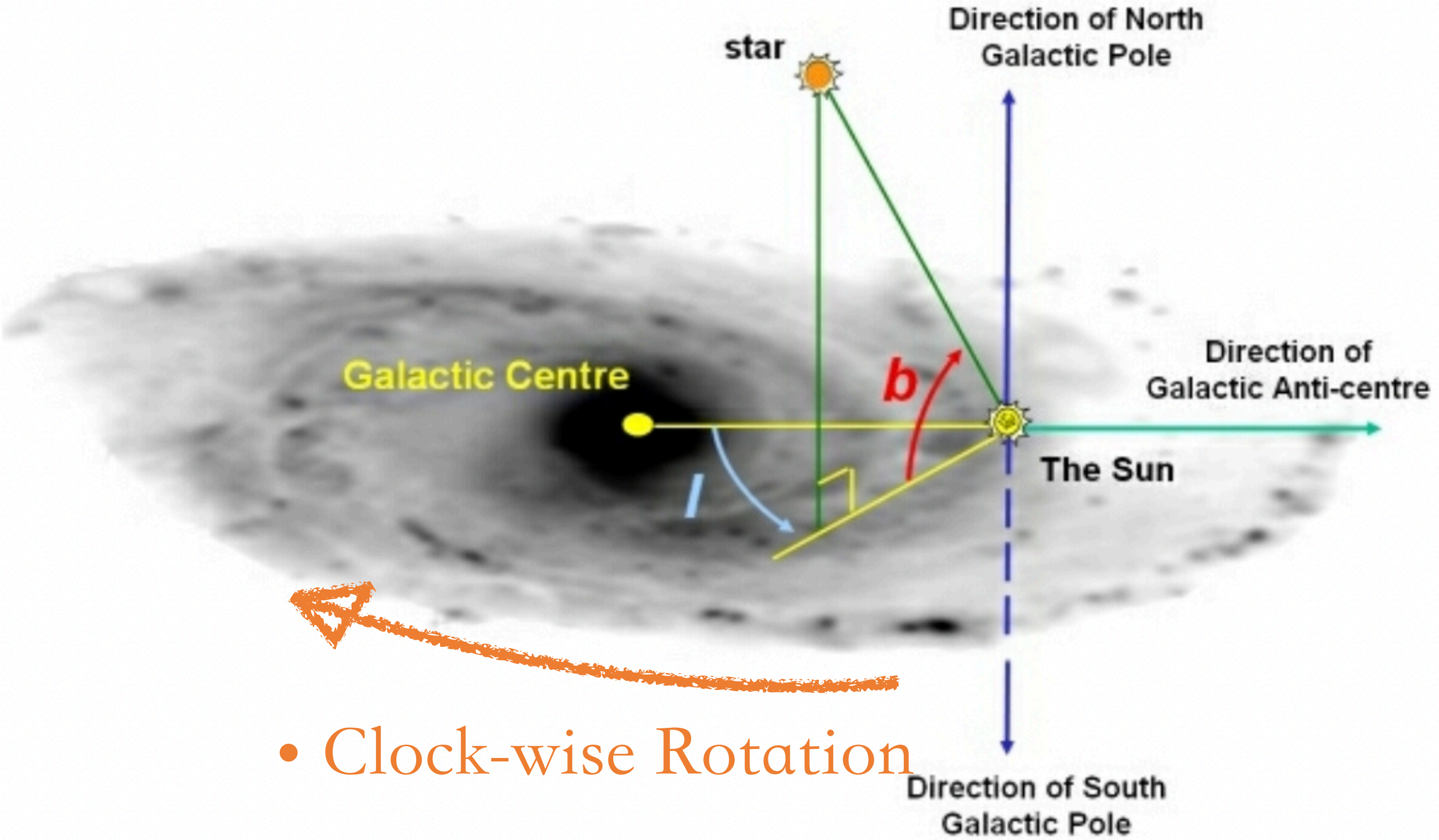
BULLETIN OF THE ASTRONOMICAL INSTITUTES OF THE NETHERLANDS

1954 MAY 14 VOLUME XII NUMBER 452

COMMUNICATION FROM THE NETHERLANDS FOUNDATION FOR RADIO ASTRONOMY AND THE OBSERVATORY AT LEIDEN

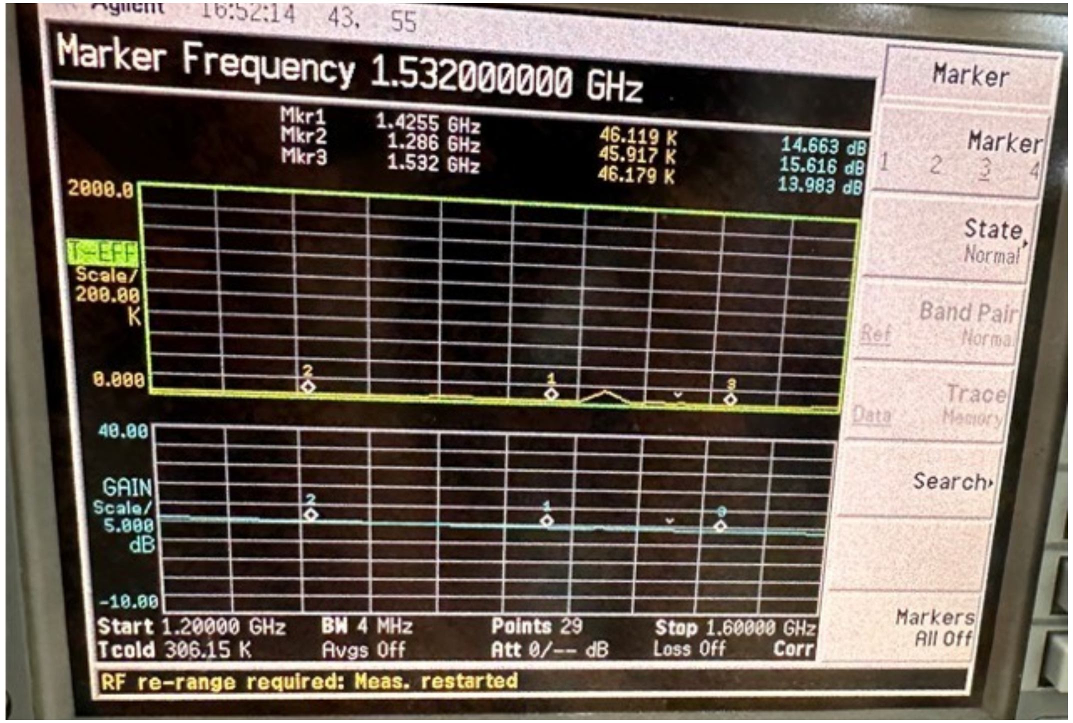
THE SPIRAL STRUCTURE OF THE OUTER PART OF THE GALACTIC SYSTEM DERIVED FROM THE HYDROGEN EMISSION AT 21 cm WAVE LENGTH

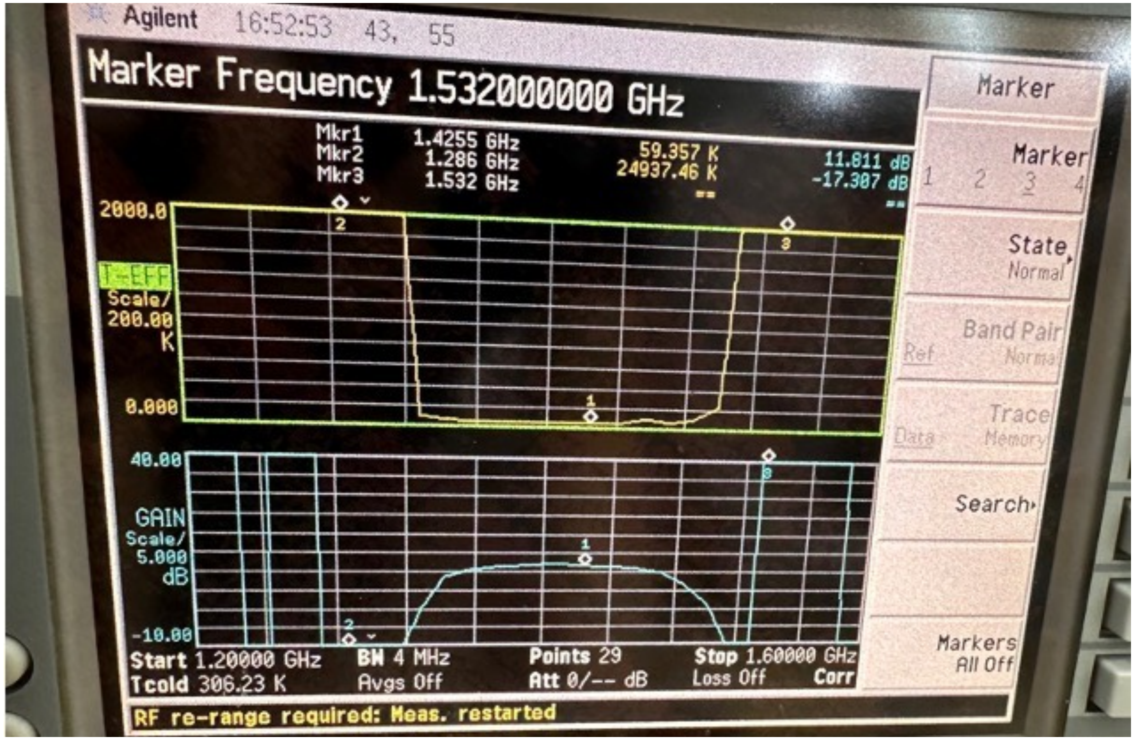
BY H. C. VAN DE HULST, C. A. MULLER AND J. H. OORT



- Clock-wise Rotation

Noise & Gain

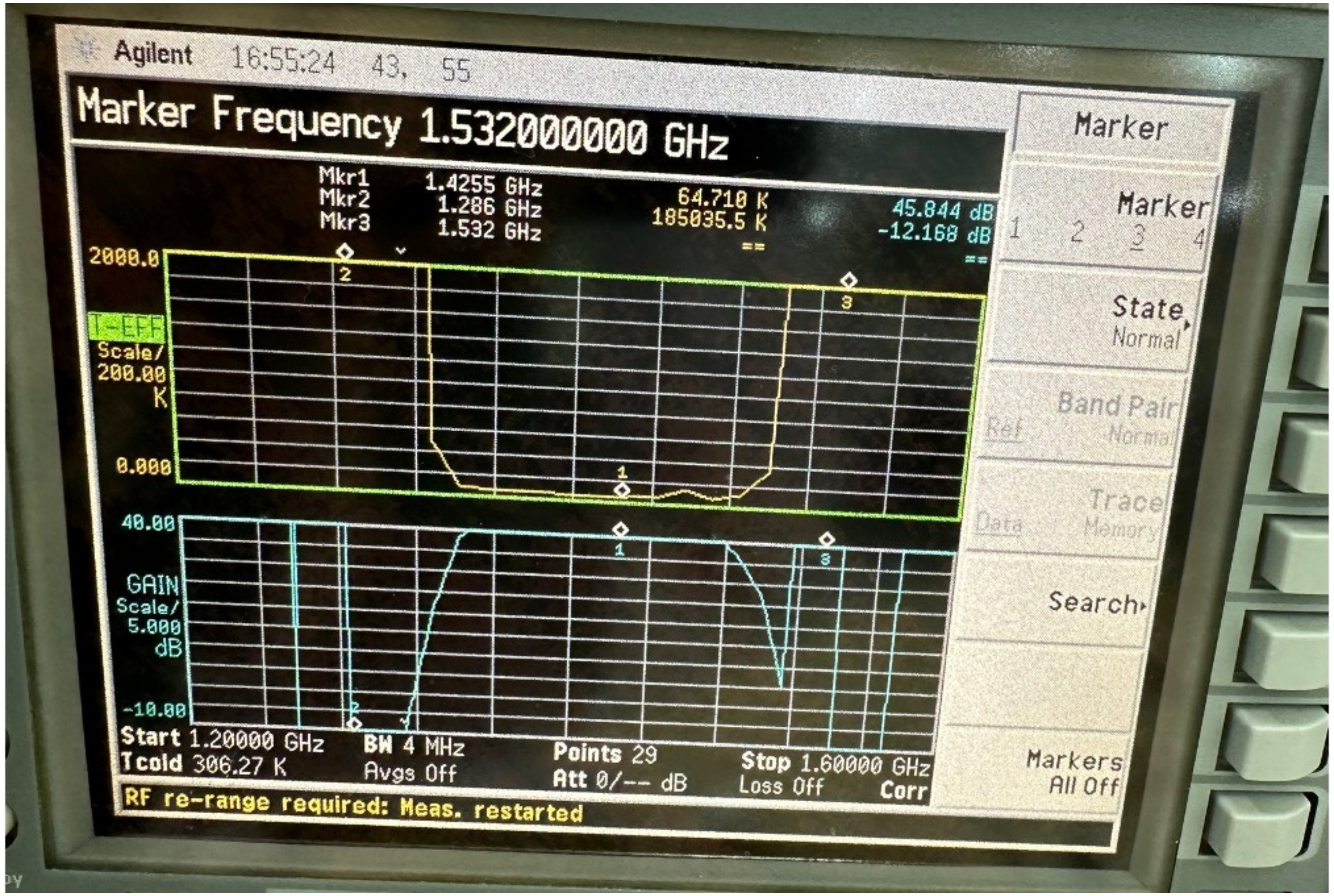




- 1 Amplifier :
  - 5 dB gain
  - Low noise level
  - Wide bandpass

- 1 Amplifier + 1 Filter:
  - Narrow passband centered at ~1.42 GHz
  - prevents signals from producing intermodulation

Noise & Gain



- The Whole Circut :
  - 40dB gain
  - Narrow passband centered at ~1.42 GHz

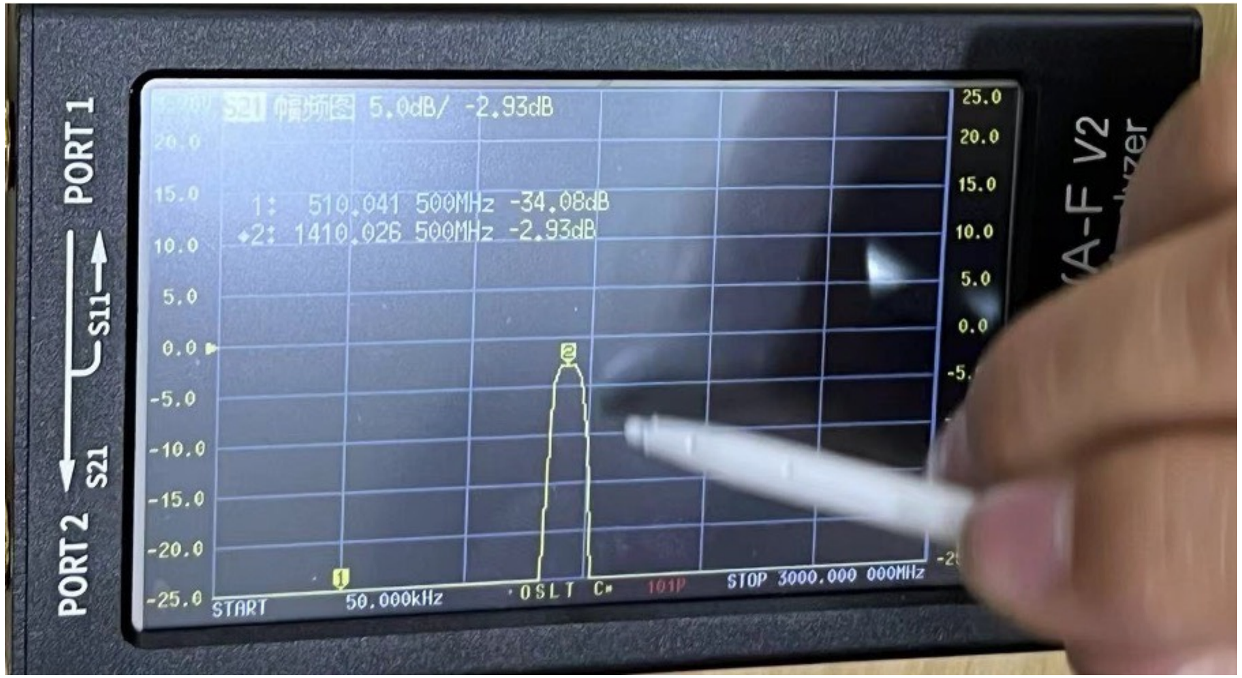
Network Analysis

- NanoVNA-F V2 Portable Vector Network Analyzere.
  - “Network” refers to electric network.
  - Must be calibrated before any measurements are performed.
- The NanoVNA measures the following:
  - Reflection coefficient: S11
  - Transmission coefficient: S21

Network Analysis

- S11

- S12



- Filter
  - Low reflection & high transmission in target frequency range

Network Analysis

- Wave guide
  - Low reflection (thus high transmission) at target frequency
  - Subject to change in the environment

- S11

Network Analysis

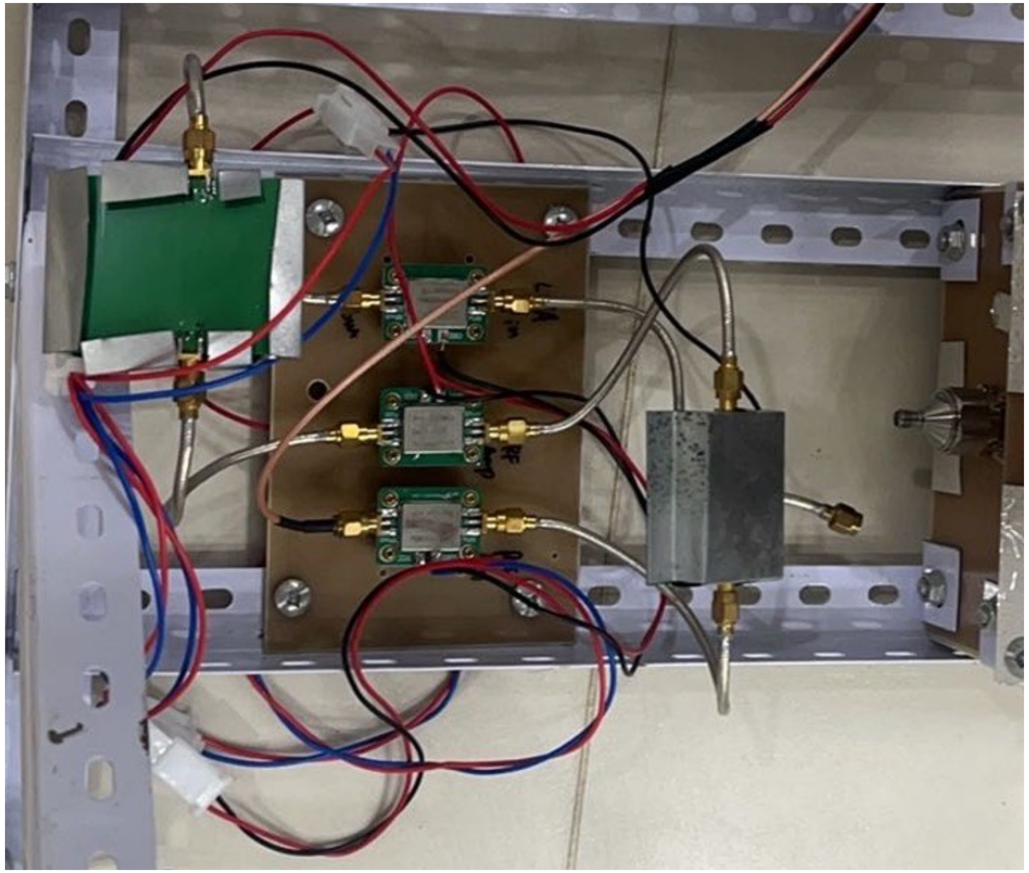
- wave guide + parallel conductor
  - cause malfunction

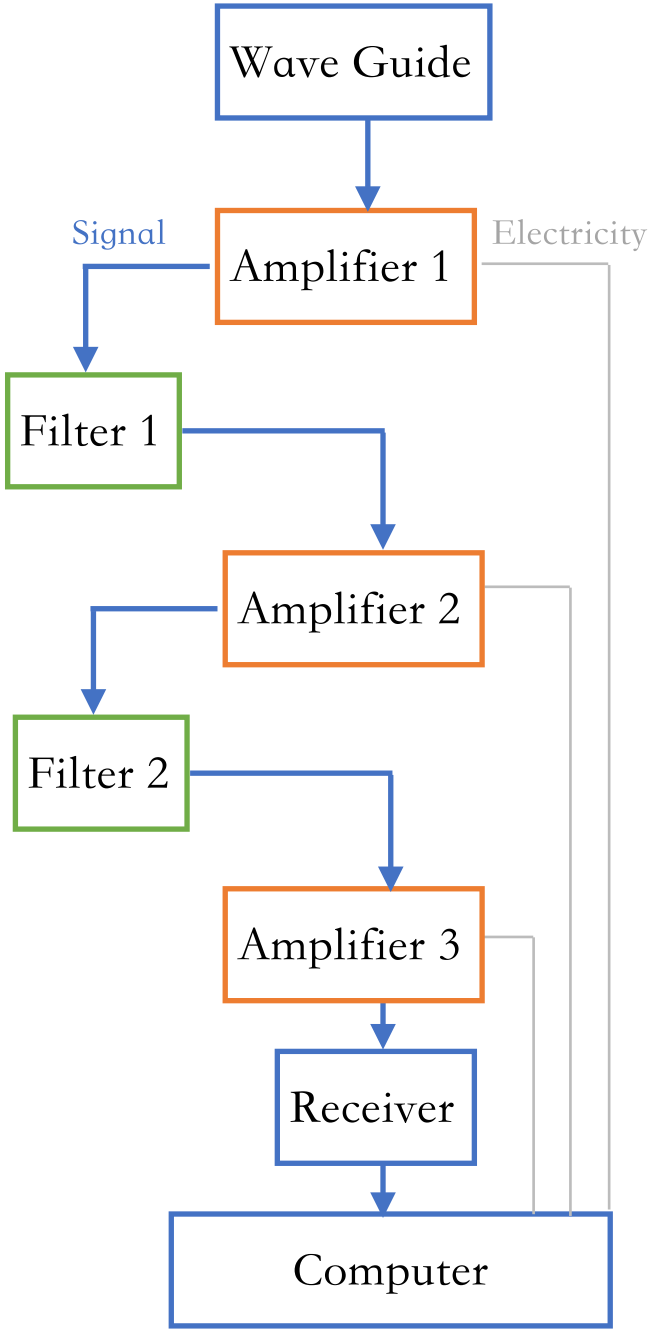
- S11

- wave guide + perpendicular conductor
  - No significant impact

- S11

Connecting the Circut

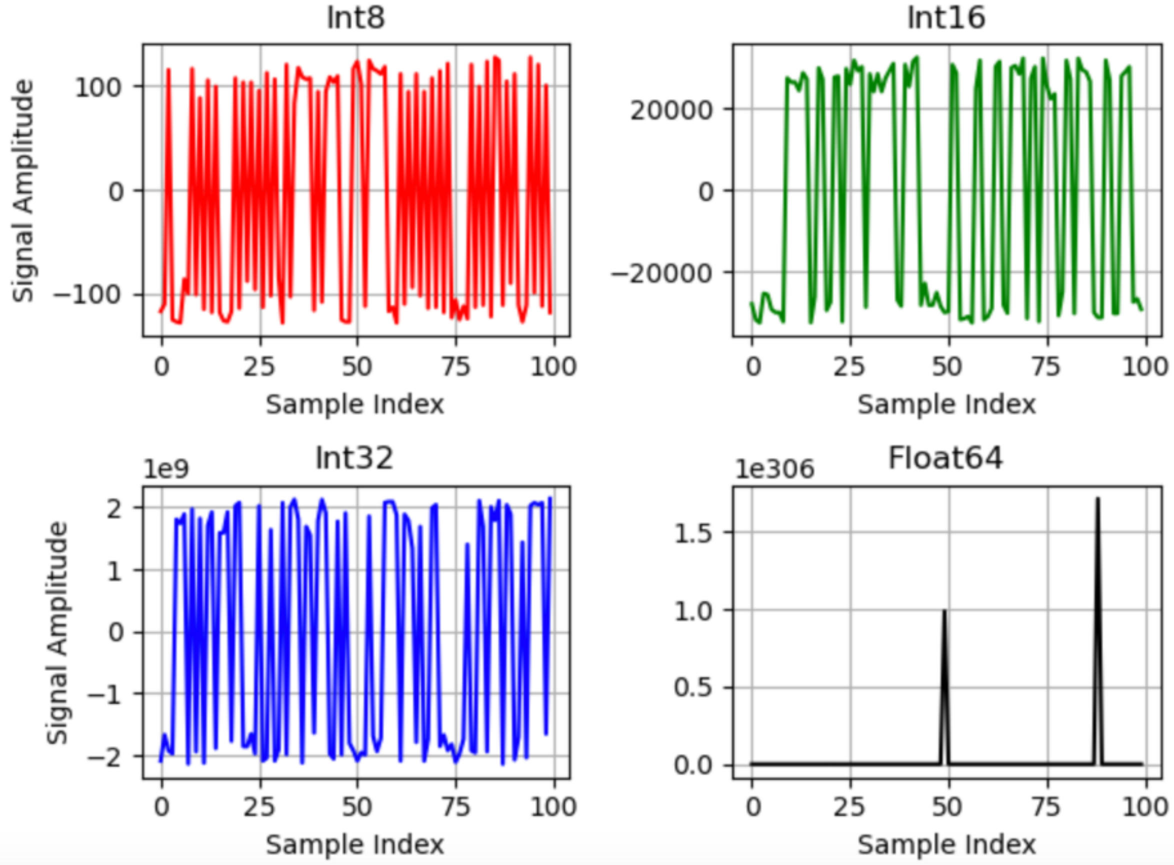


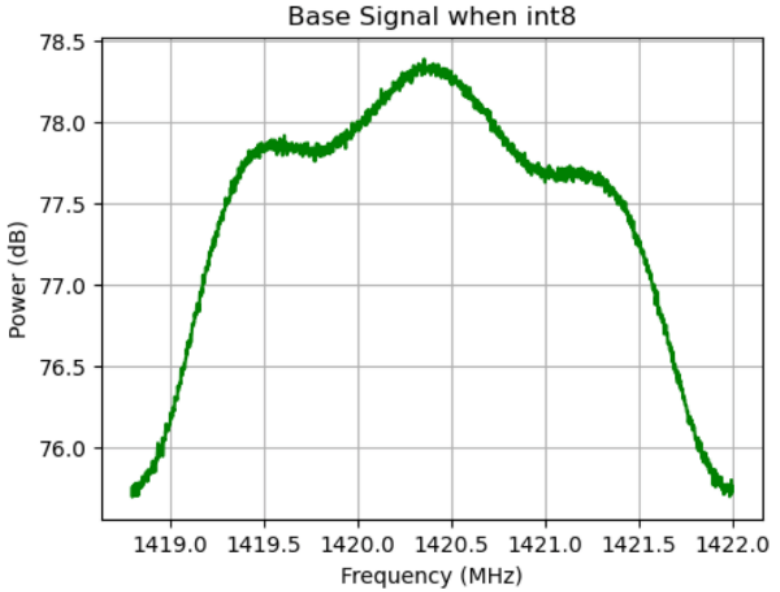


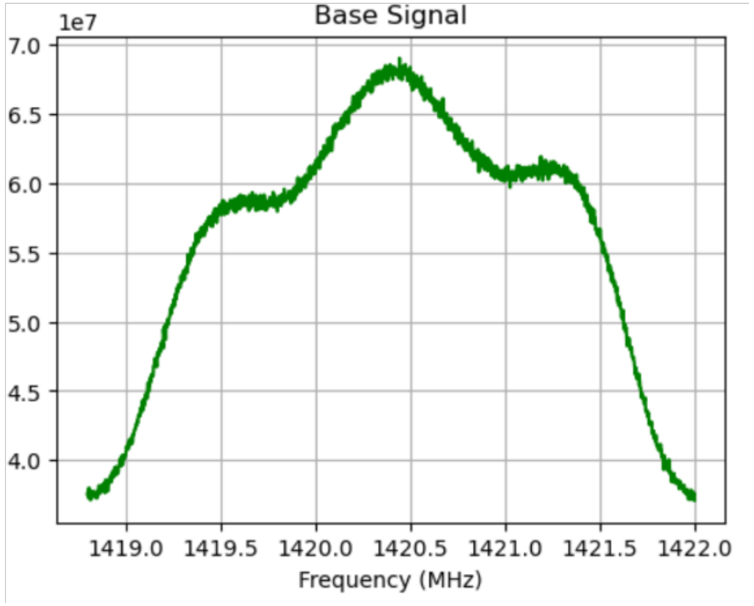
$$L_{dB} = 10 \cdot \log(\frac{P1}{P0})$$

Analysis of original data

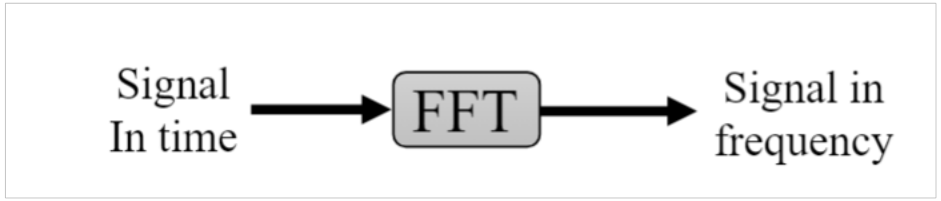
```
int8: 306708480
int16: 153354240
int32: 76677120
float64: 38338560
```

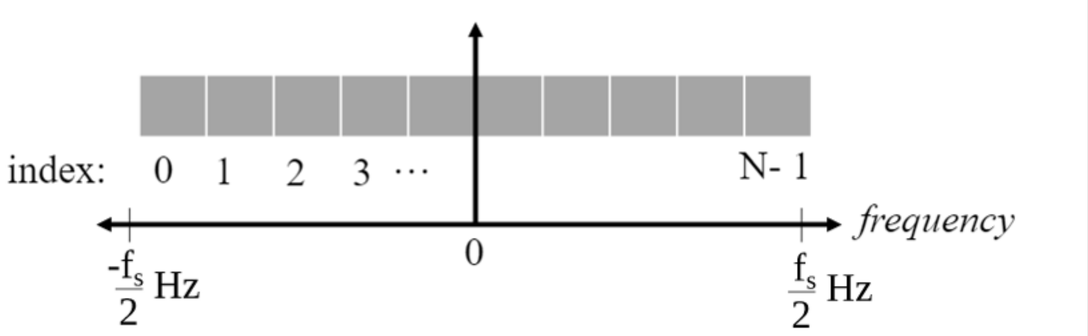






Code for FFT

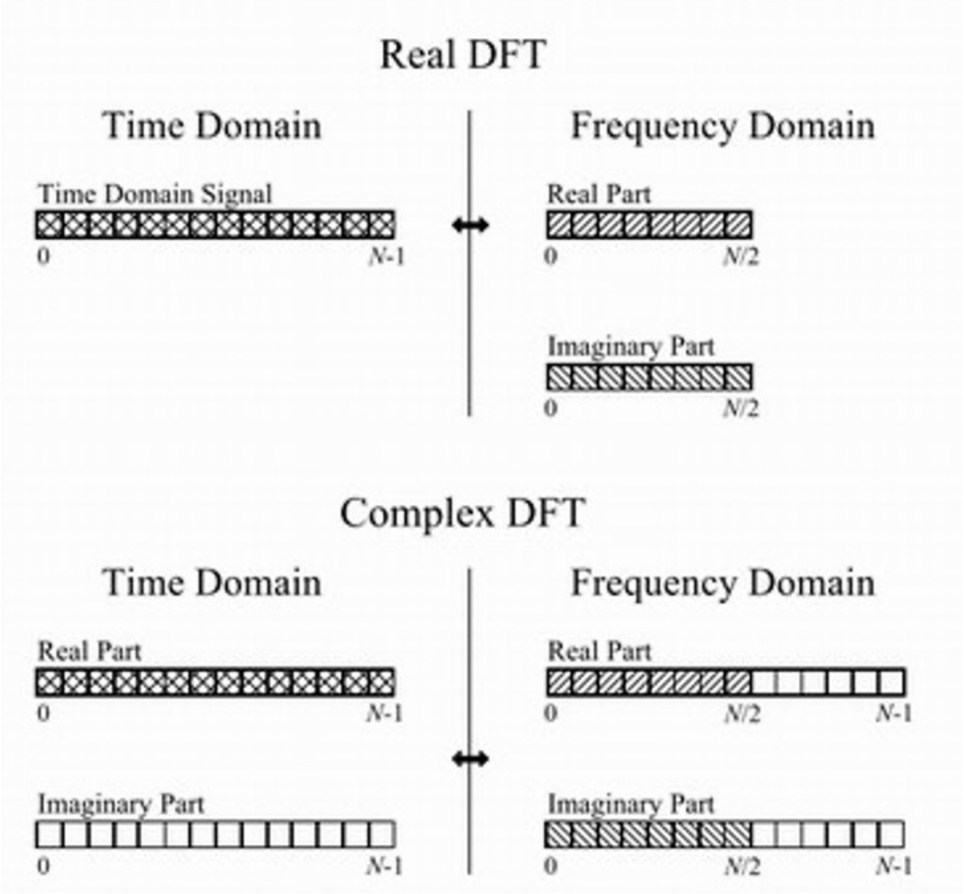


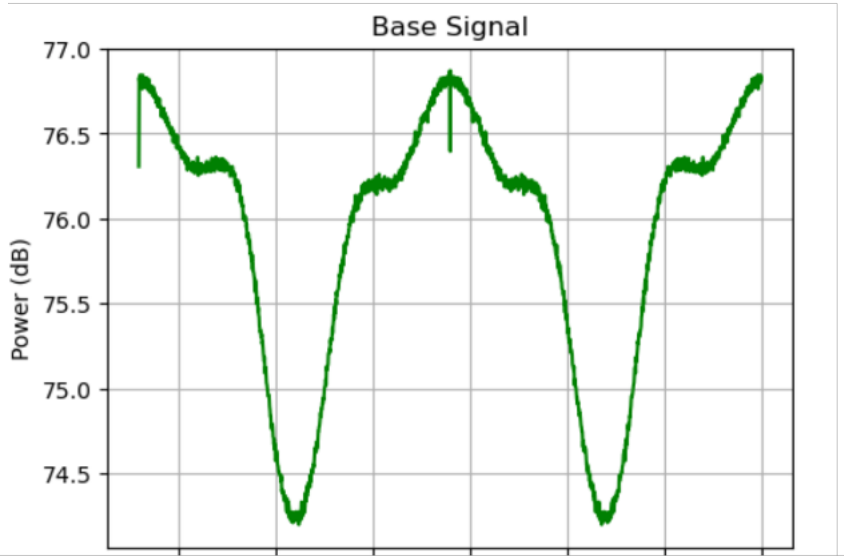


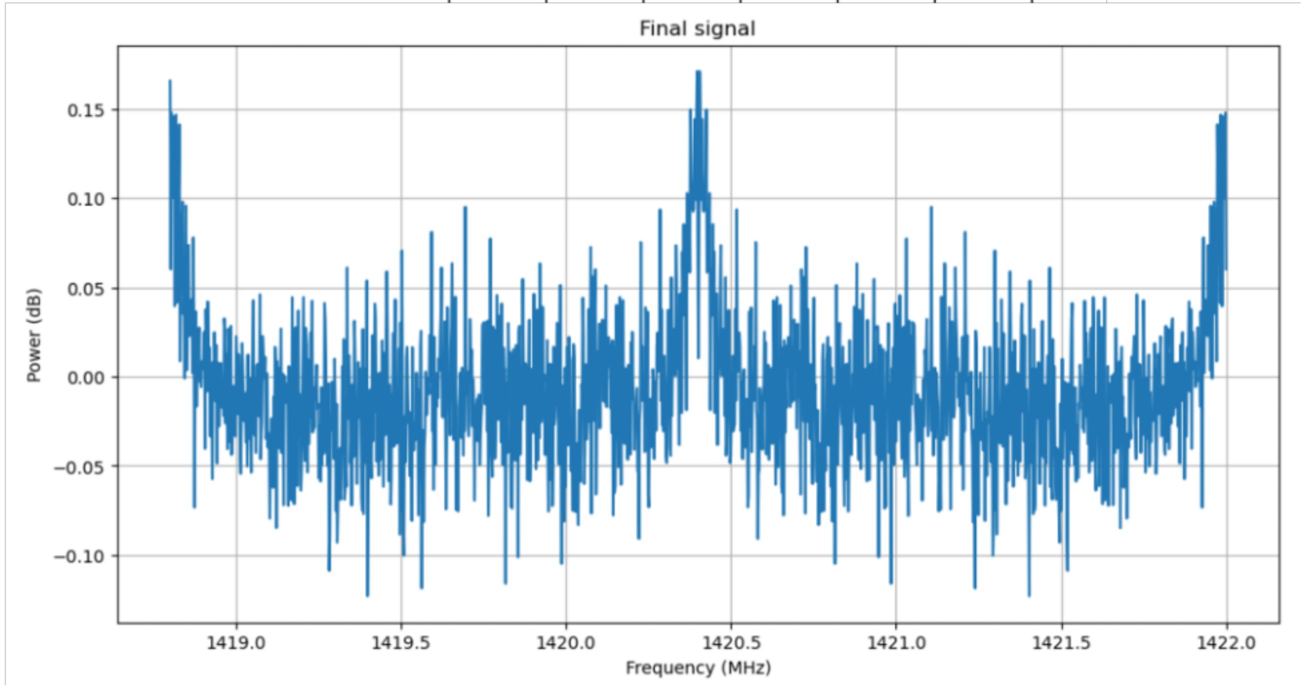

```
    fzz = fzz + abs(np.fft.fft(zz))

for ii in range(0, 800):
    pzz[ii] = fzz[ii+800]
    fre[ii] = f_center - 1.6 + ii*1.6/800

for ii in range(800,1600):
    pzz[ii] = fzz[ii - 800]
    fre[ii] = f_center + (ii - 800)*1.6/800
```

```
    baseline = baseline + abs(np.fft.fftshift(np.fft.fft(zz)))
fre = np.linspace(f_center-1.6, f_center+1.6, sample)
```

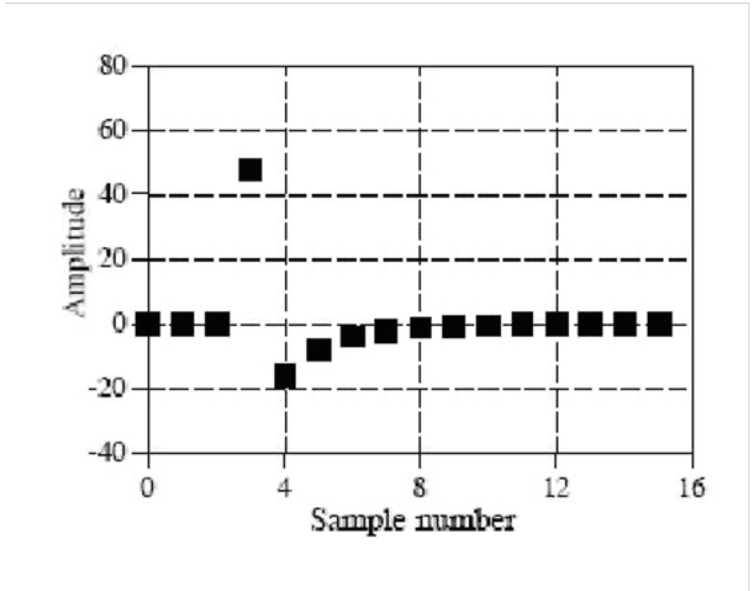
Why is there an imaginary part

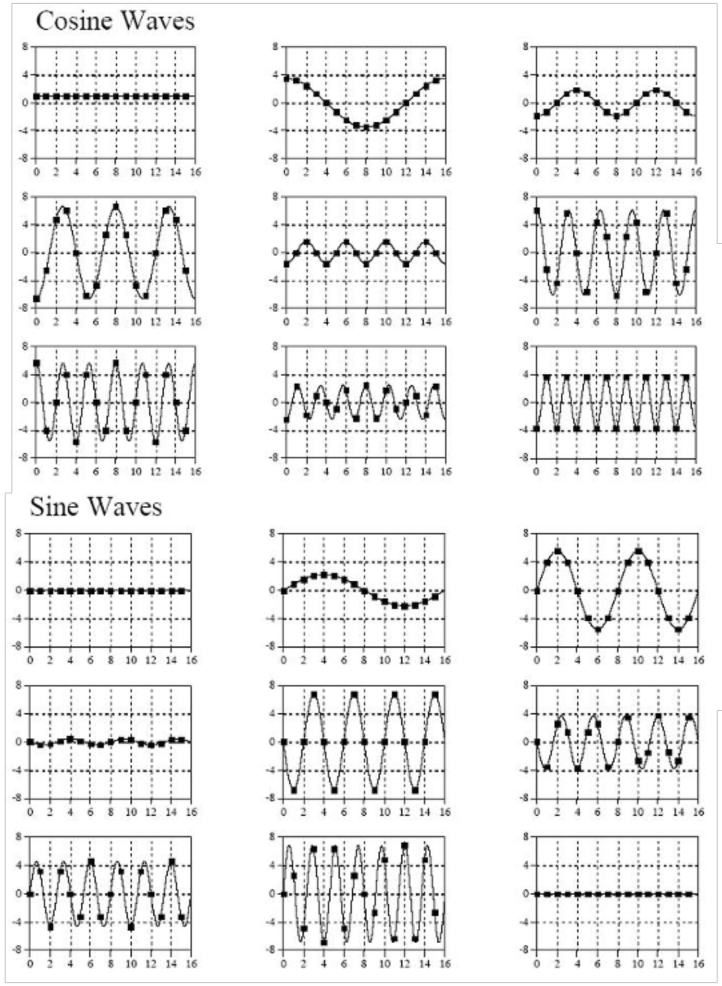


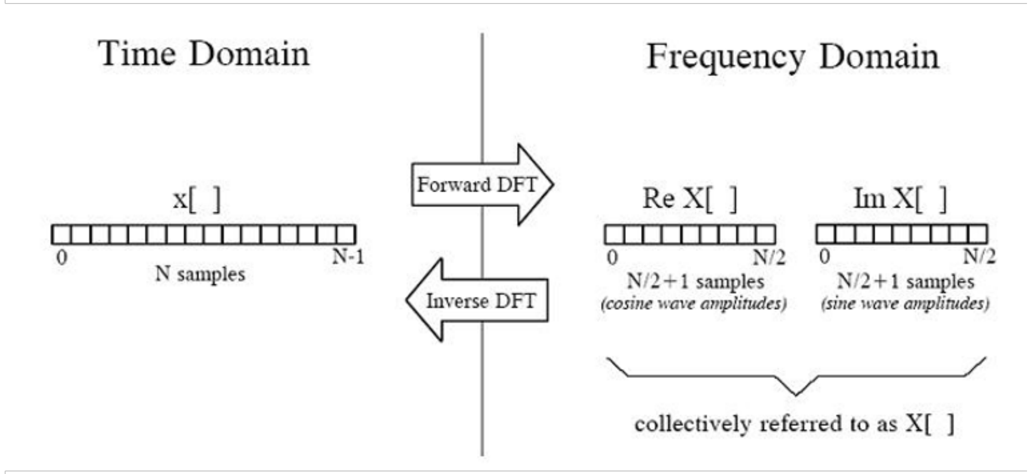




Why is there an imaginary part



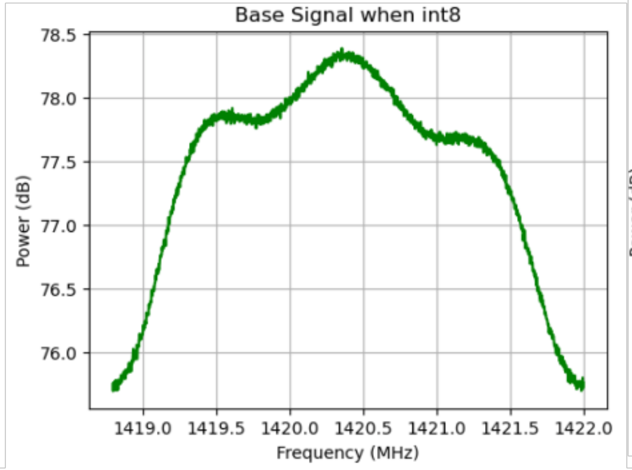


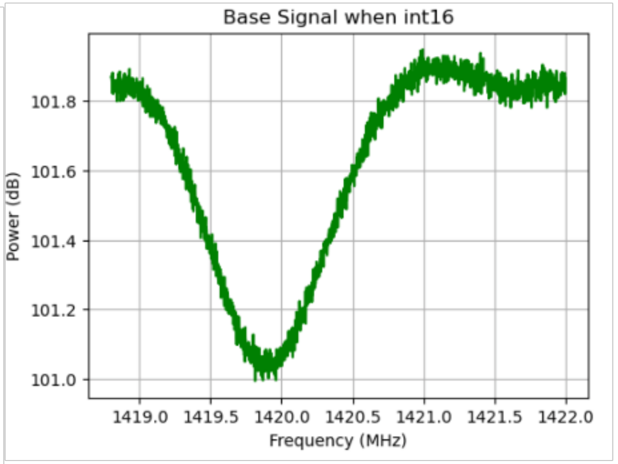


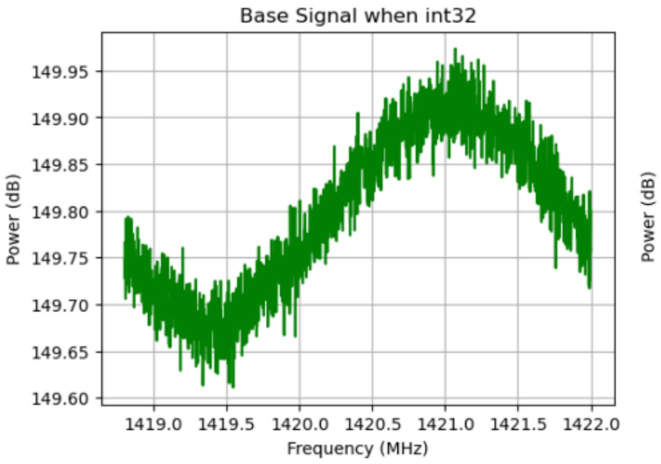
Variables

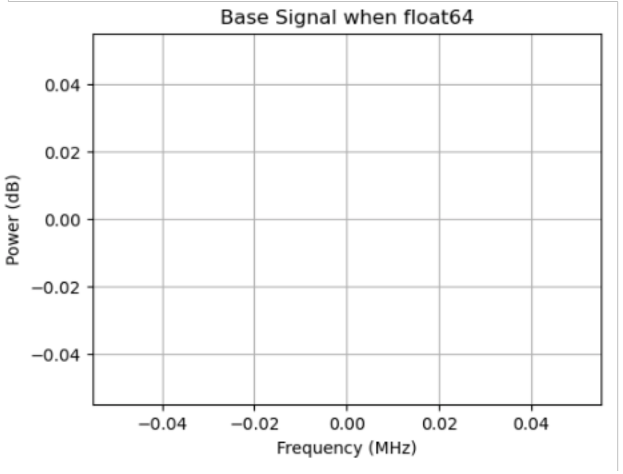
sample & no_of_iteration

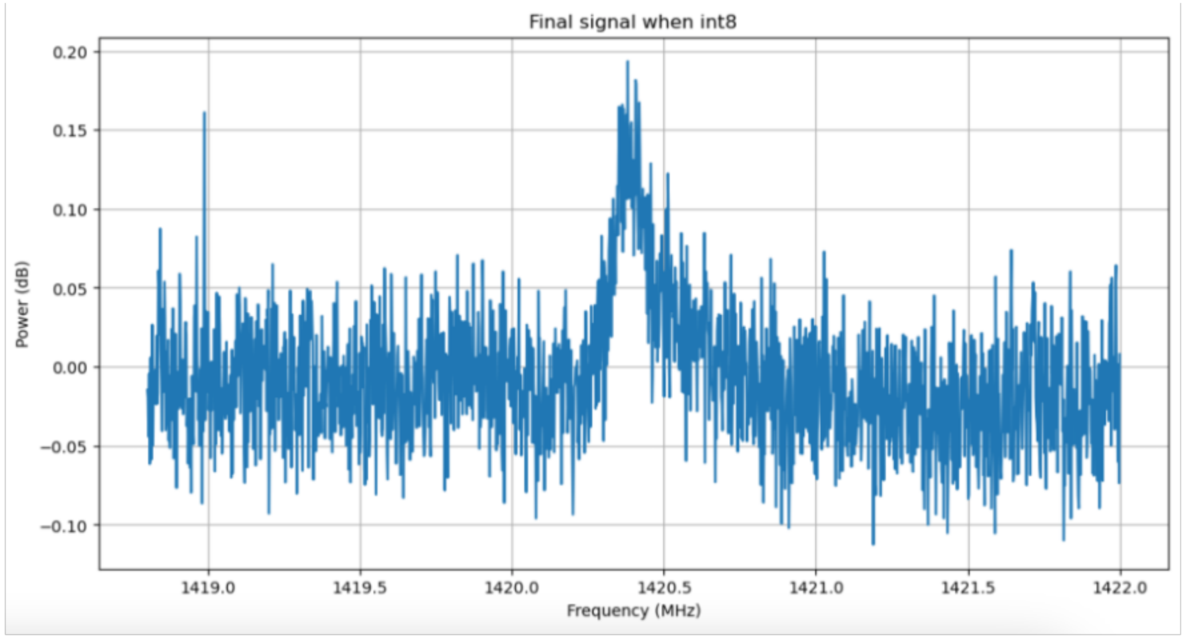
dtype

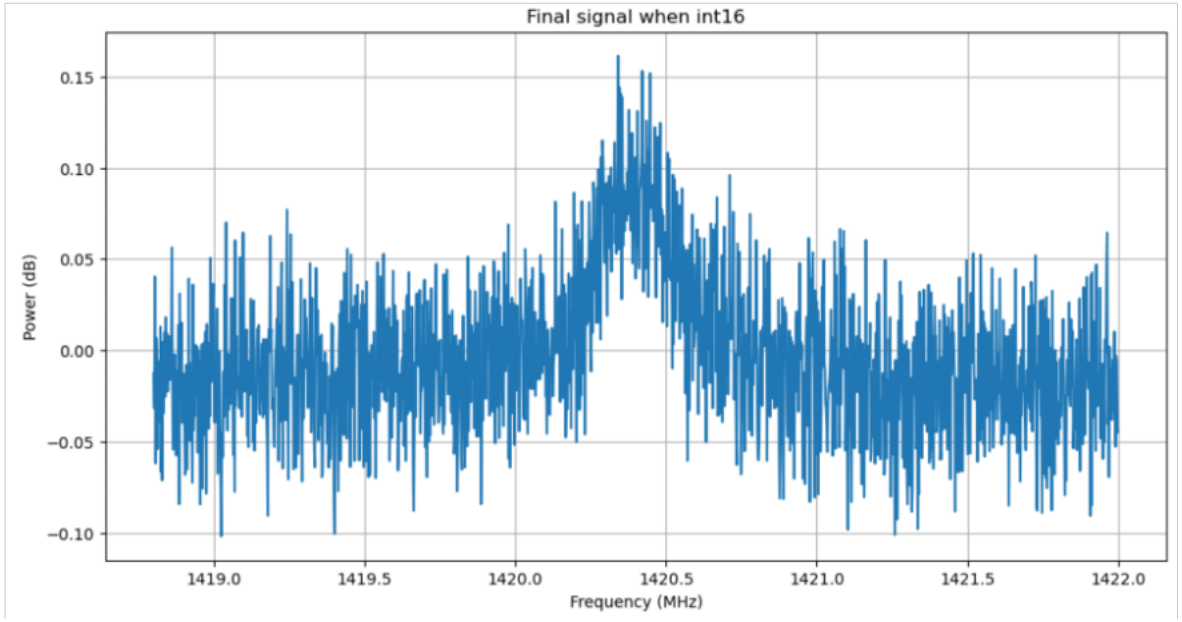






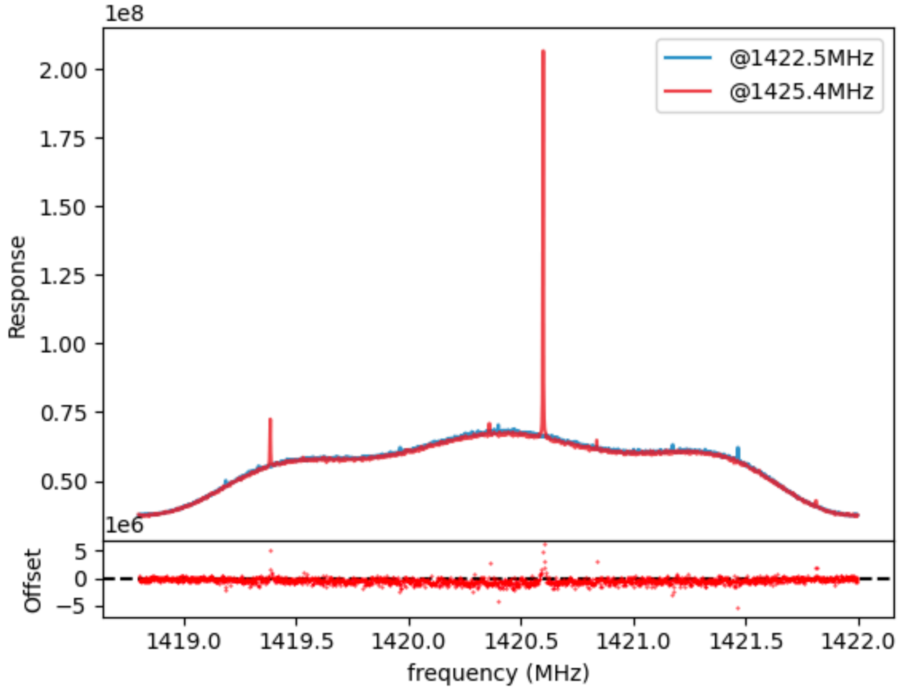






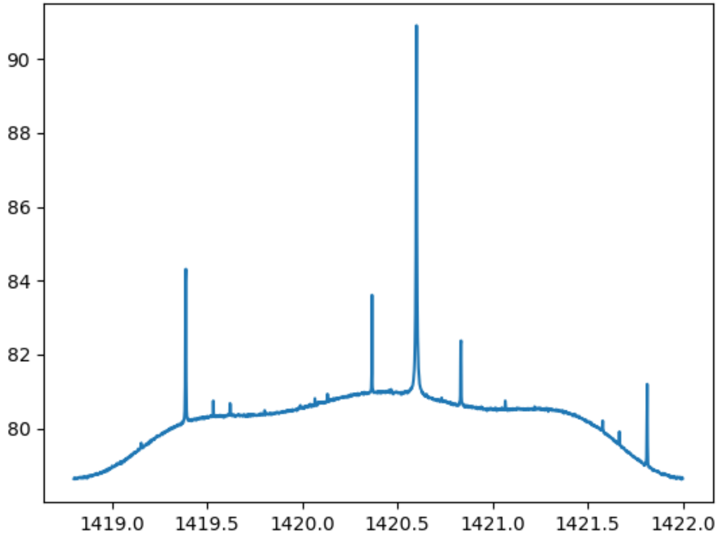
Frequency Switch

- What is the optimal choice of OFF frequency?

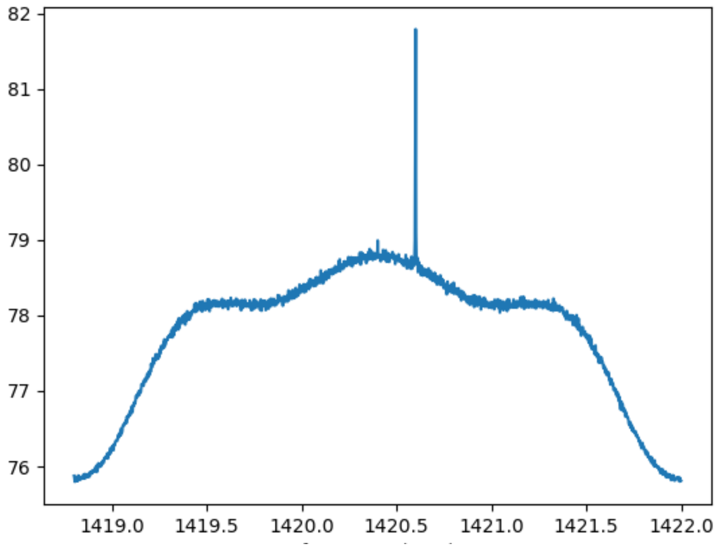


At 1,422.5 MHz, the systematic offset of the response curve and can be lower than 0.369% after 3 sigma-clipping.

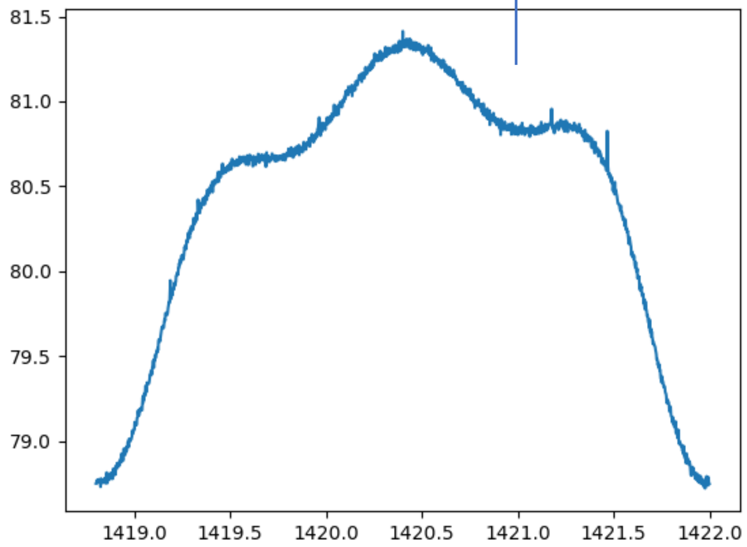
IDEAL OFF POINT



@1,425.4 MHz



@1,423.4 MHz

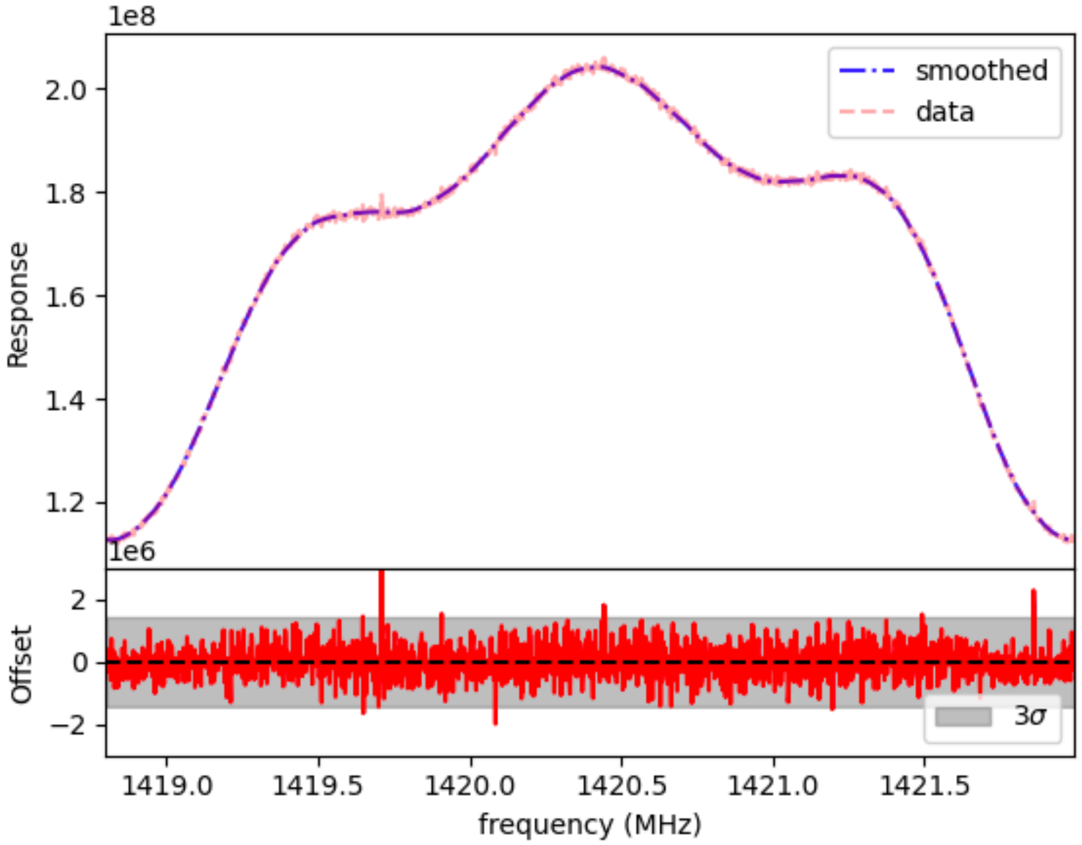


@1,422.4 MHz

Response Curve

- The response curve can be modeled well if:
- RFIs are completely detected and well removed
- Shot noises are mitigated by stacking exposures (with fixed expose time)
- Error is propagated comprehensively

- Stack 8 exposures with 3 sigma criteria to eliminate RFI spikes
- Use mean value and the standard deviation to estimate the response model and its error

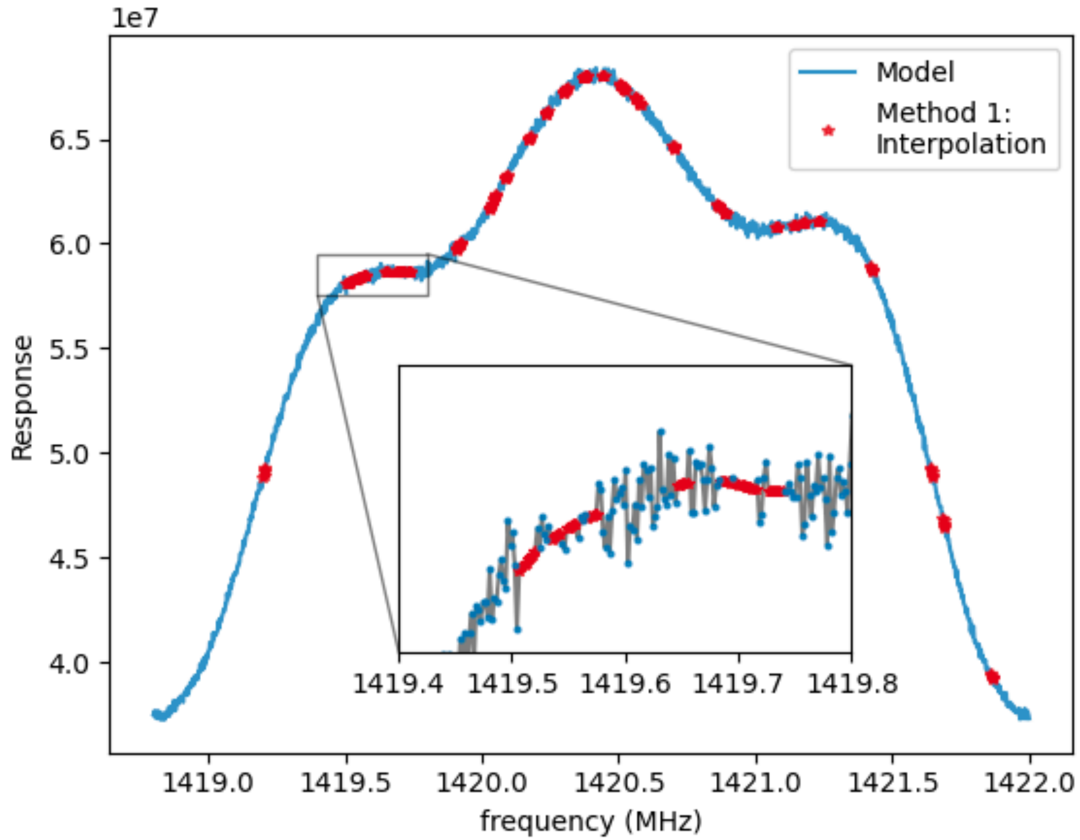


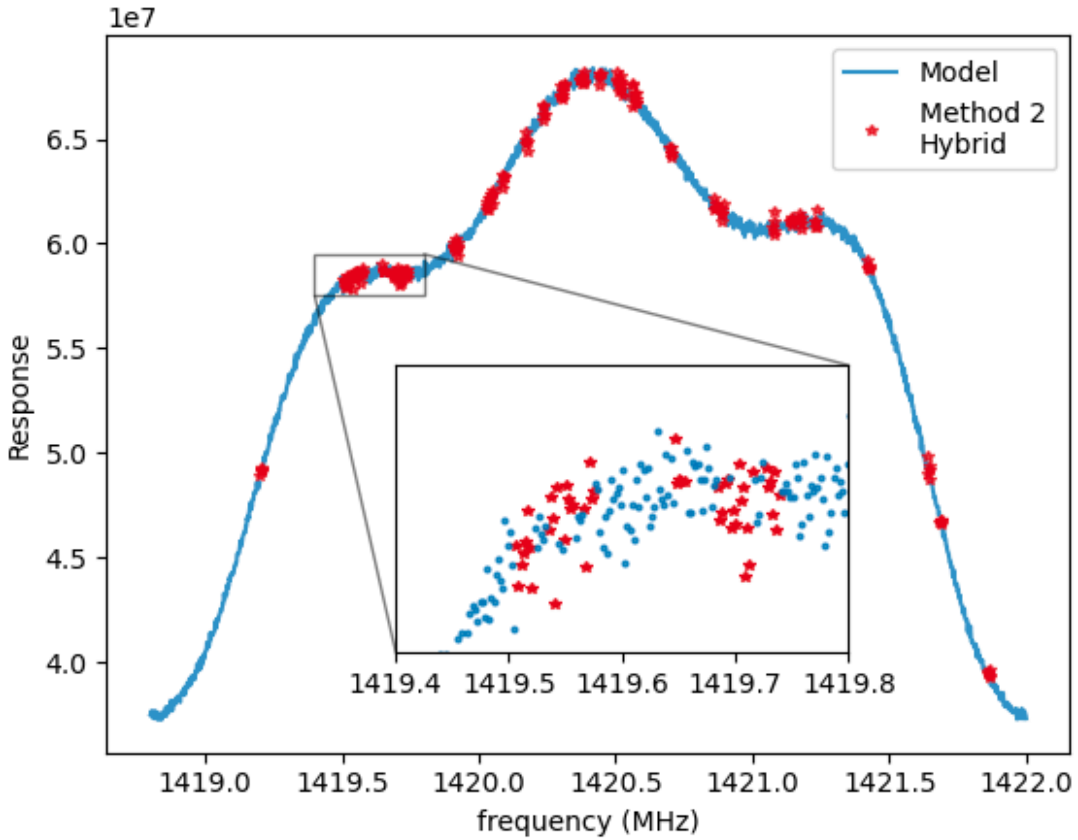
Treatment of RFI Region

- First, grow mask to fully remove RFI spikes

- Method 1: Interpolating RFI gaps
- Intuitive but hard to evaluate error

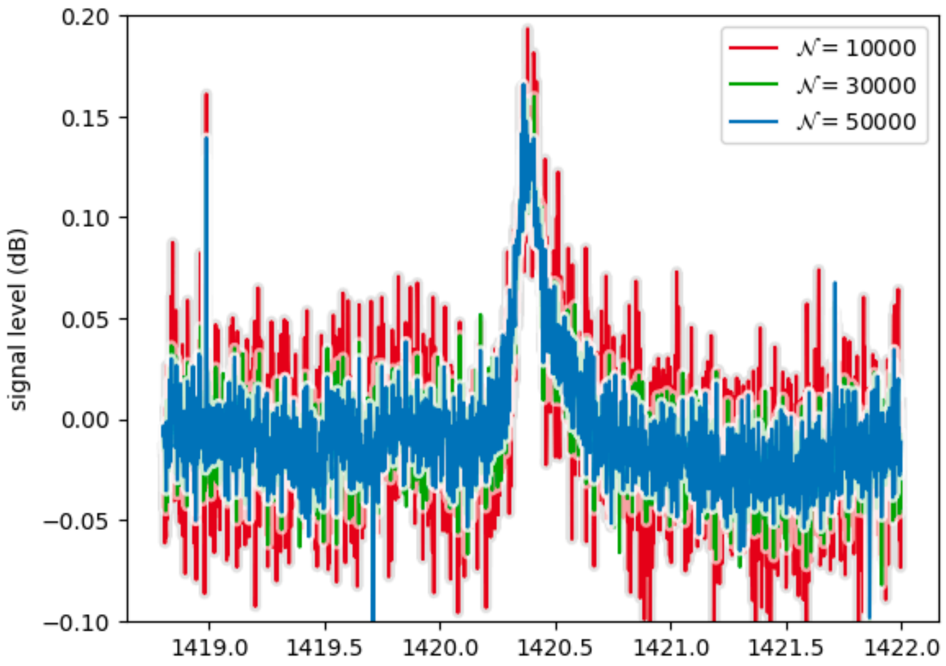
- Method 2: Hybrid Response
- Easy for error propagation but counter-intuitive

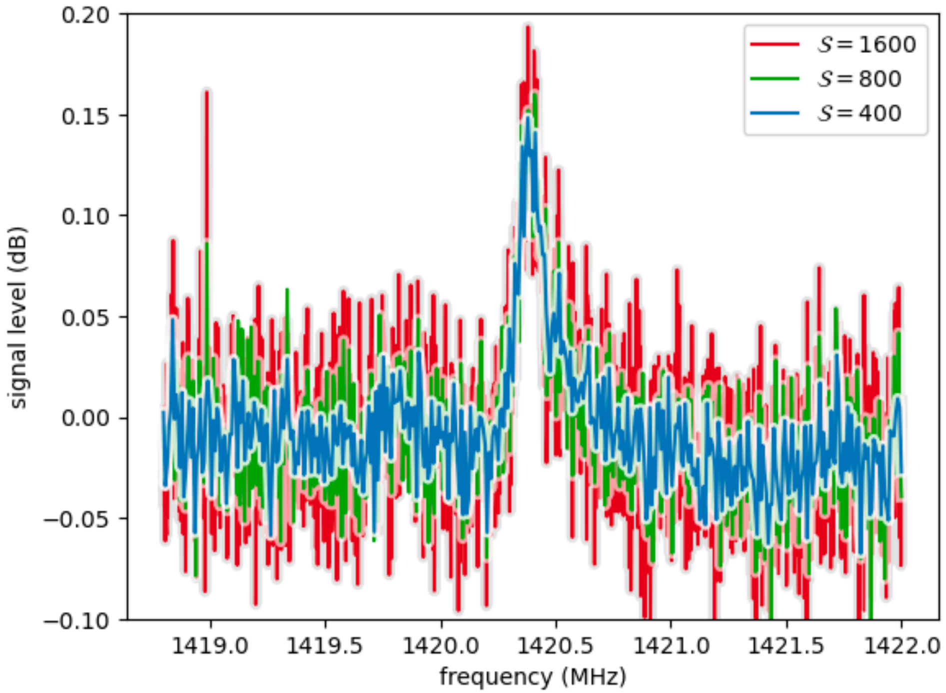




Capturing 21cm Signal: Detection Limit

- Number of Iteration: $\mathcal{N}$
- Sample Number used per iteration: $2\mathcal{S}$
- Sample Rate: 3200000 Hz
- Exposure time $t = \dfrac{2\mathcal{N}\mathcal{S}}{3200000}$ s
- Longer Exposure helps improve Signal-to-Noise ratio.
- At fixed exposure time, we can improve SNR at the expense of Spectral Resolution.





Signal-to-Noise Ratio

$$\mathrm{SNR} = \frac{P_S}{P_N}$$

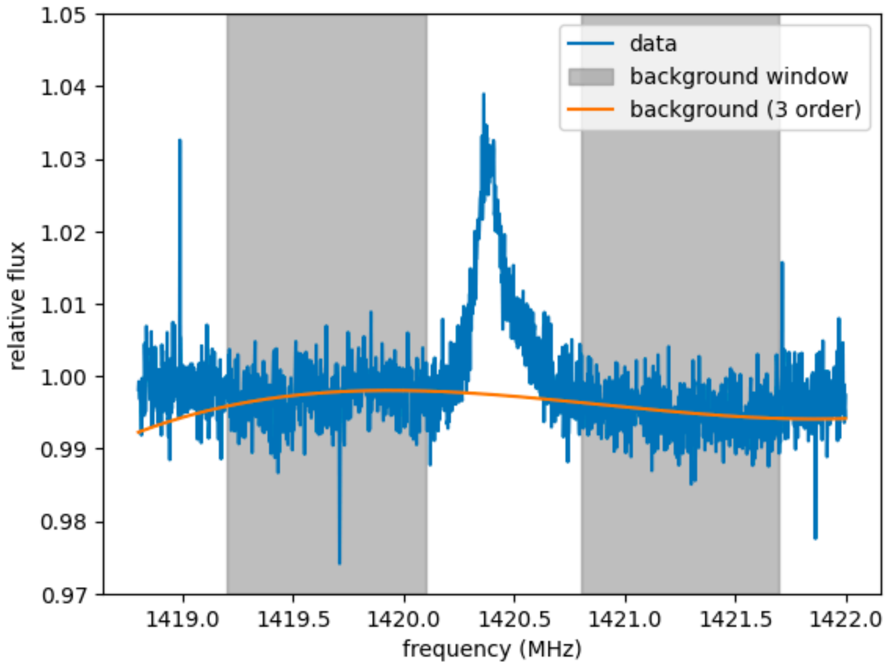
- Define windows for background spectrum (continuum) and apply low order polynomial fit.
- What is Noise? Baseline noise/Propagated uncertainties

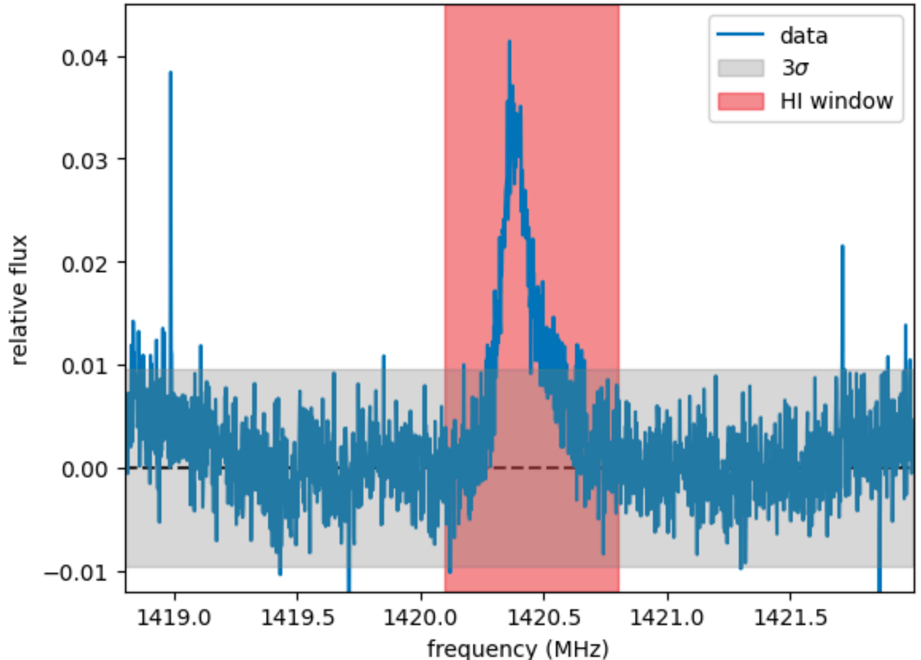
Assuming a constant baseline noise level

- Define 21cm line signal as integral (sum) of the relative flux between 1420.1 MHz and 1420.8 MHz (a tentative aperture/window $\mathscr{D}$).

$$P_{S,\mathrm{rel}} = \int_{\mathscr{D}} F_{\nu,\mathrm{rel}}\, d\nu$$

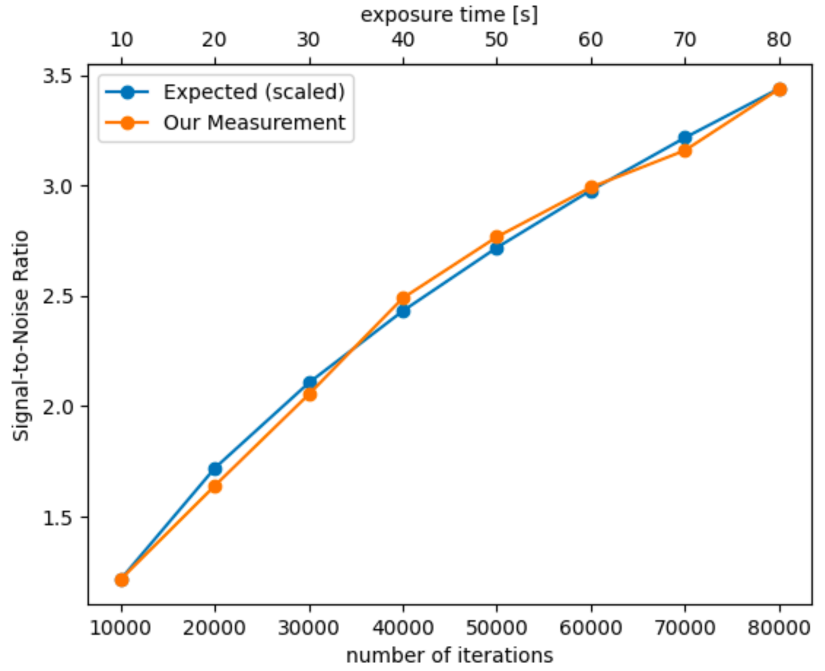
- Similarly, the noise power can be calculated.

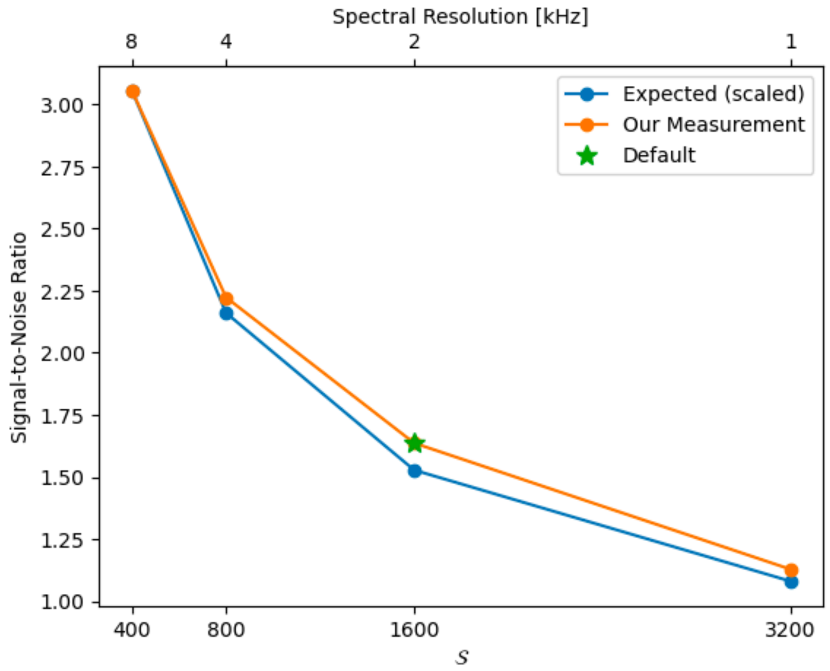




Evaluate Noise Reduction

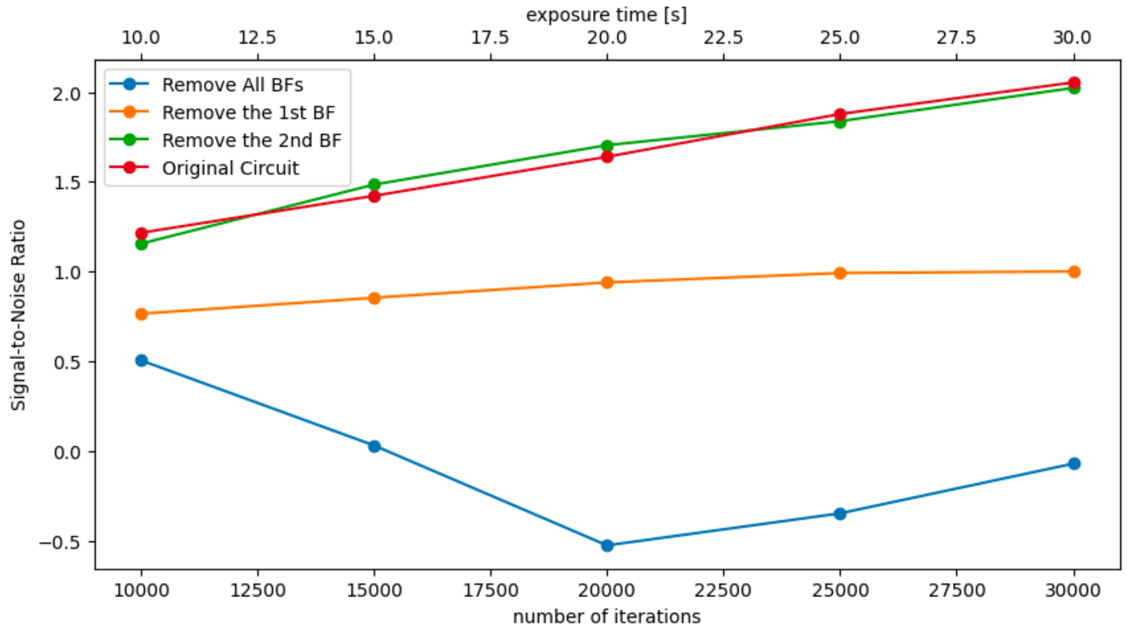
- Longer exposures do improve SNR, as we expected previously.
- For exposure time smaller than 100s, the noise is dominated by Poisson-like noise.
- As expected again, increasing spatial resolution will weaken SNR.
- This method will help us robustly evaluate/test noise reduction.



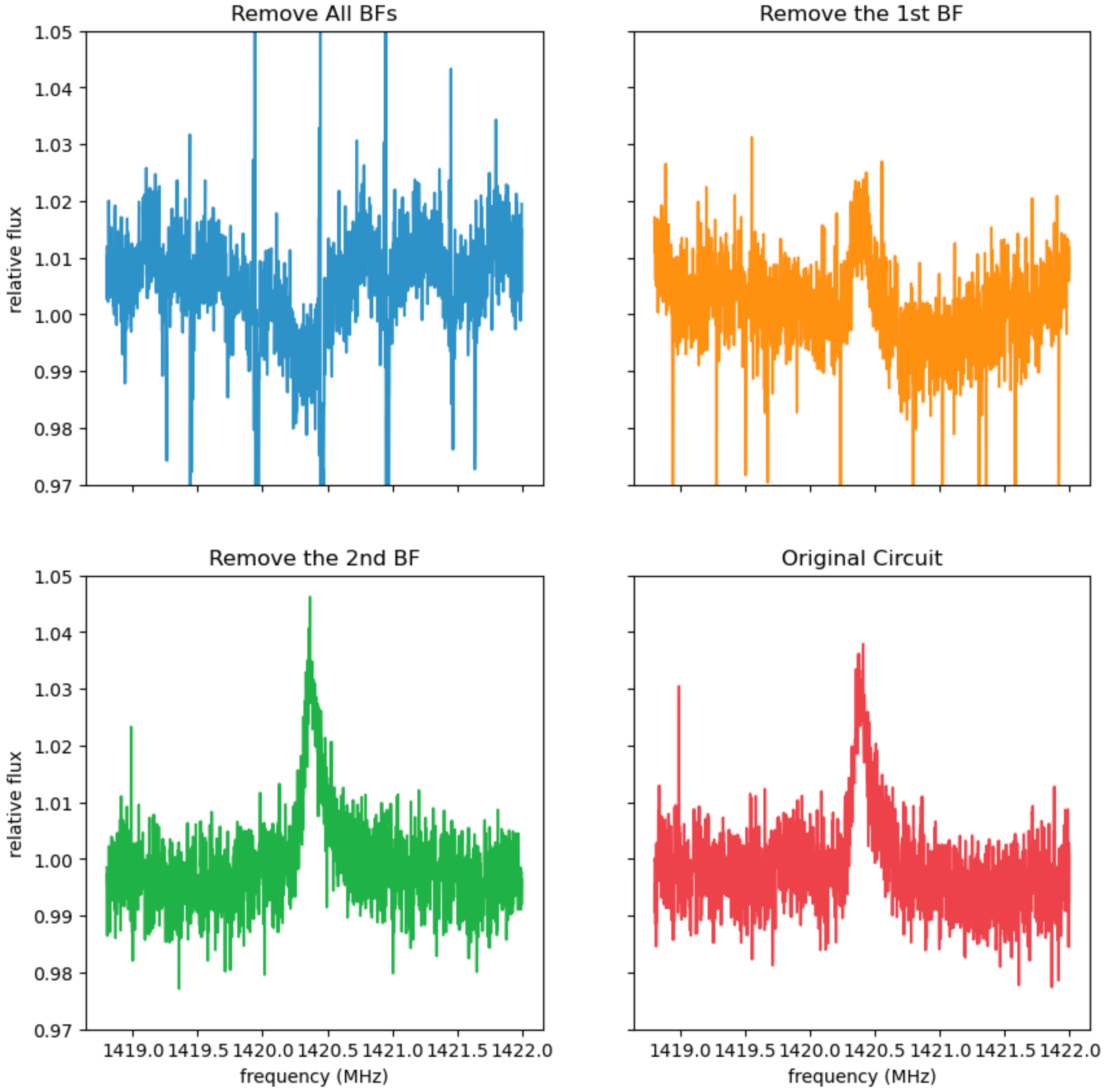


Noise Reduction (cont.)

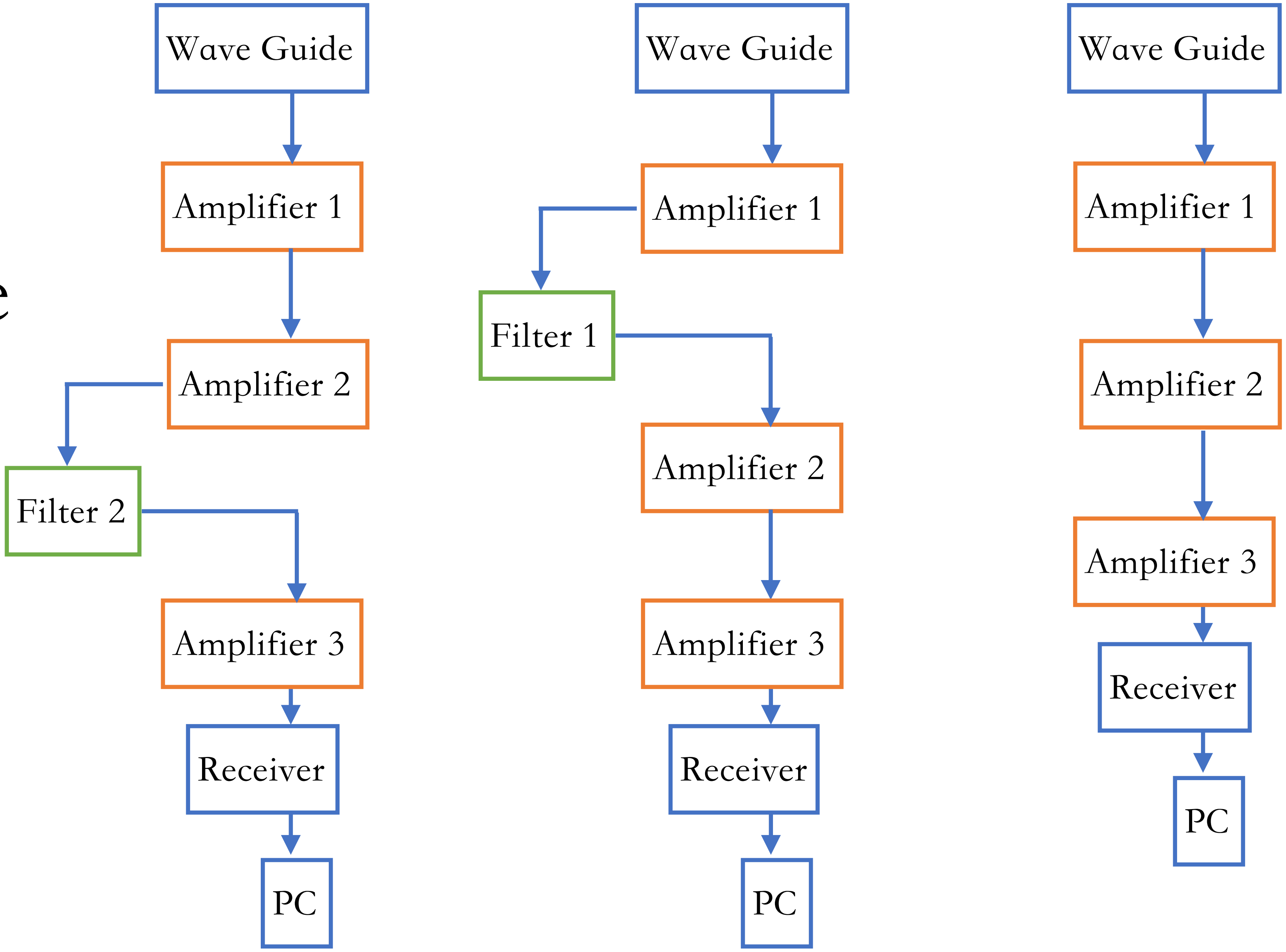
- LNA (Low Noise Amplifier), Band-pass Filters will introduce extra noise to measurement, especially for faint sources or shallow exposure.
- What if we take them off, as long as it still works?



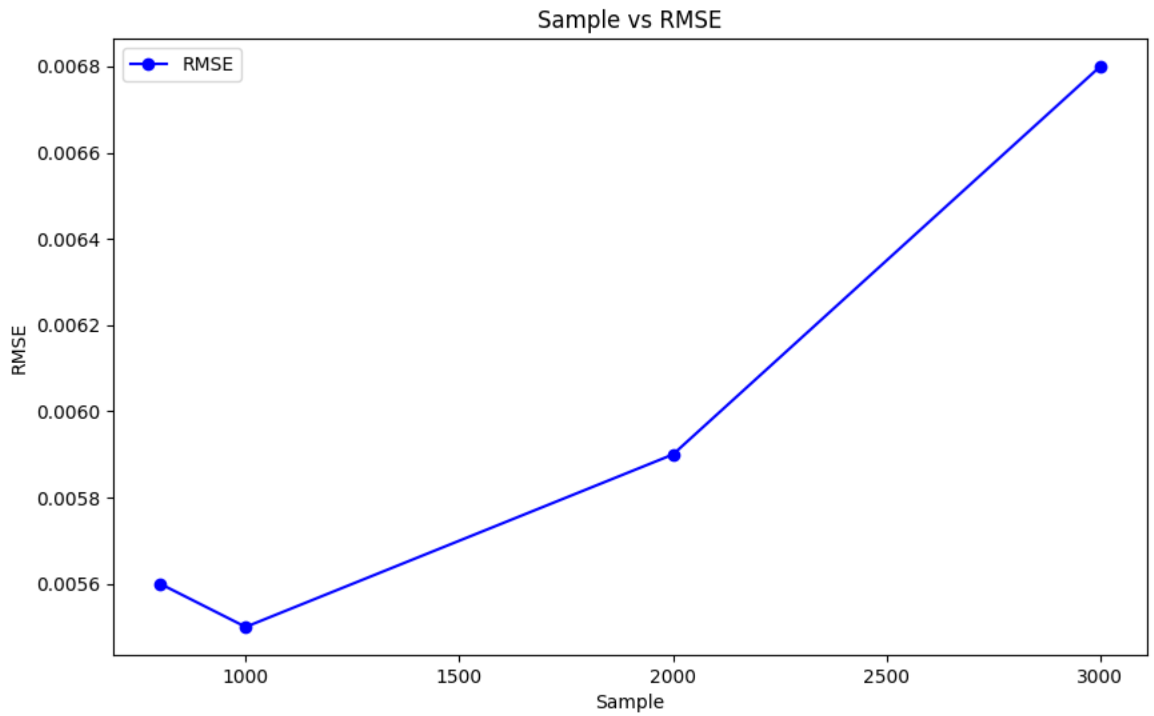
Saturation

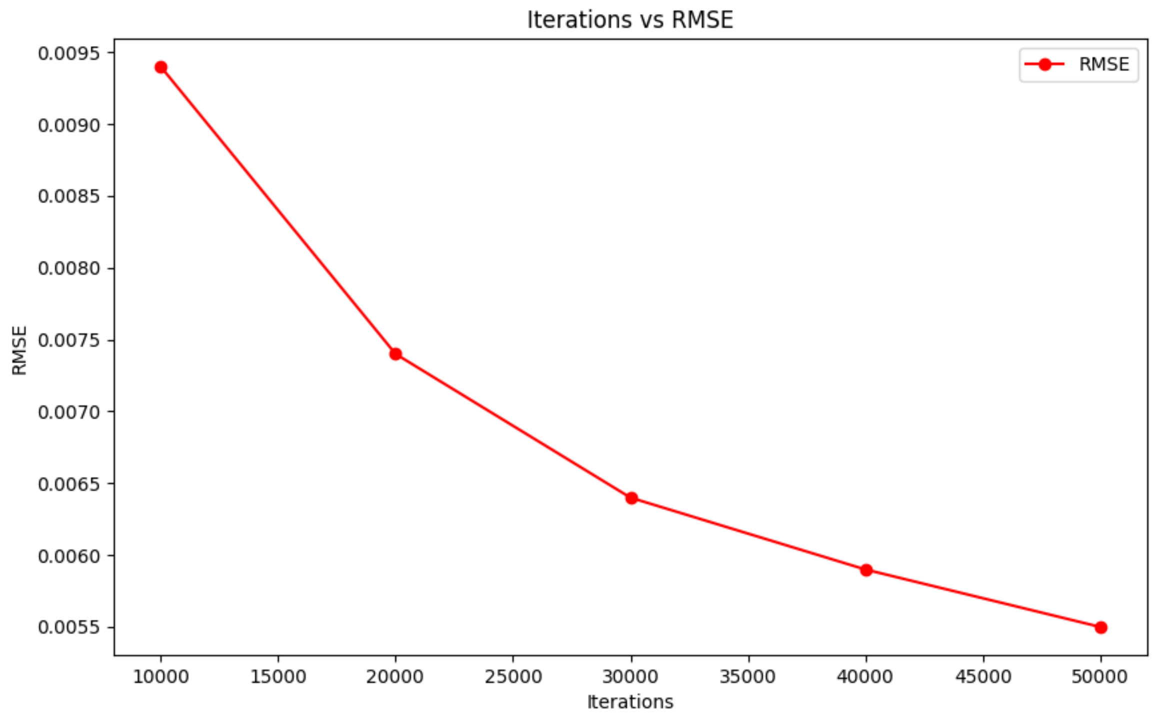


Tests on Filters' Influence



Influence of sample and iterations

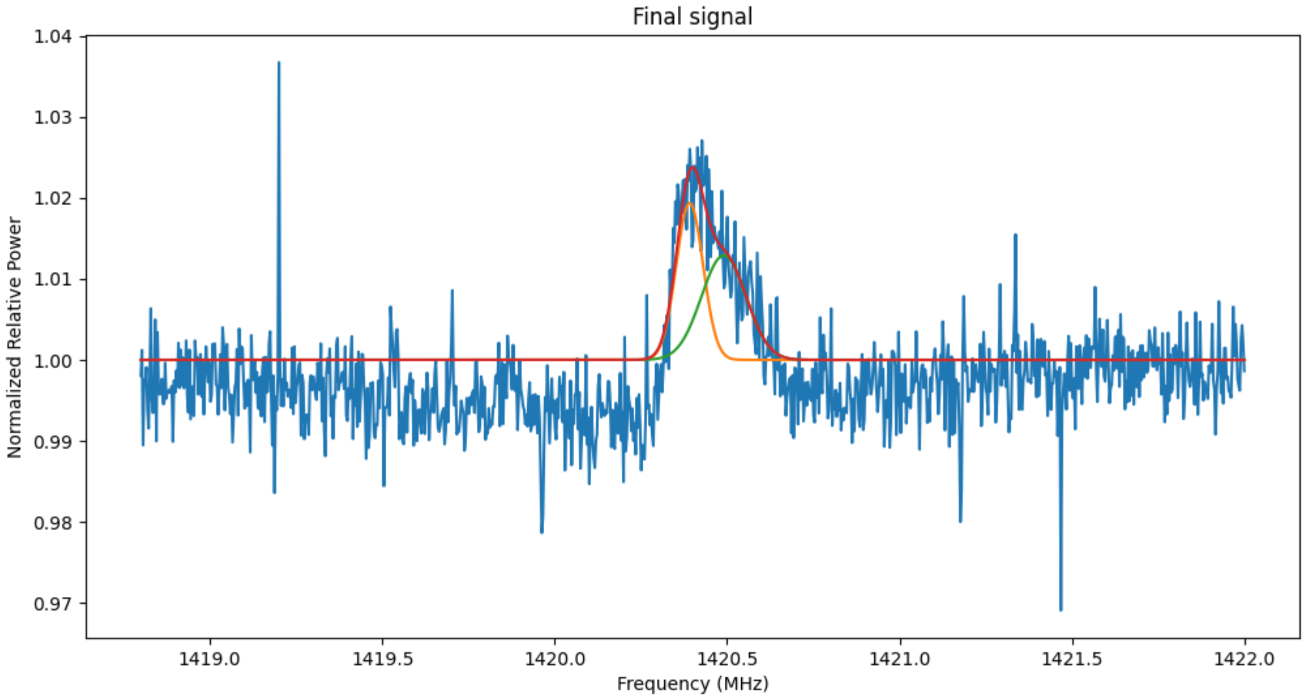




RMSE of Gaussian Fitting:

Increase with Sample, Decrease with Iteration Numbers

Double Gaussian Fit



Parameters:

Central Frequency1: 1420.392MHz

Standard Deviation1: 0.0389 MHz

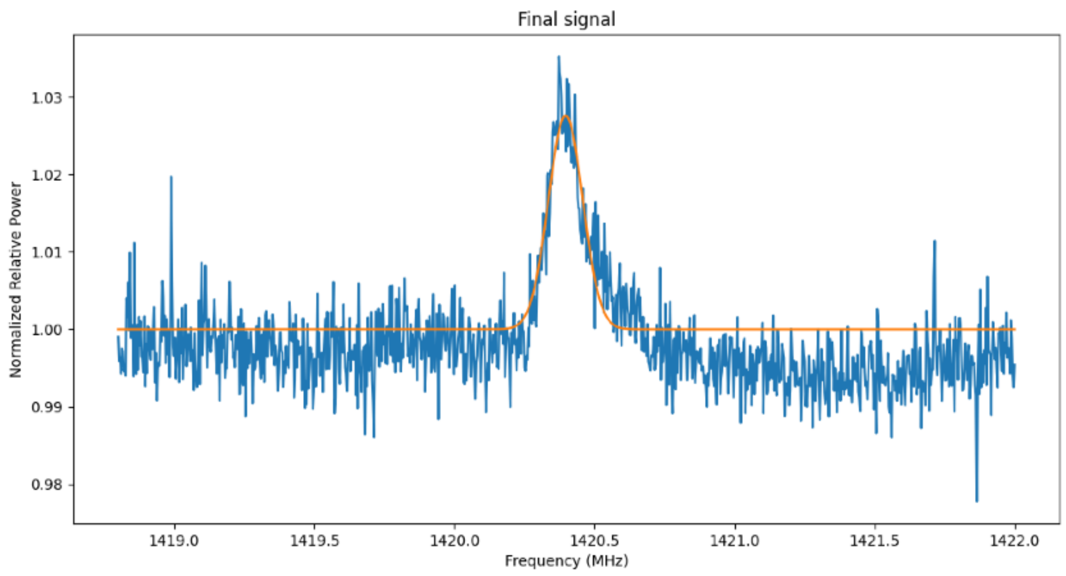
Central Frequency2: 1420.491 MHz

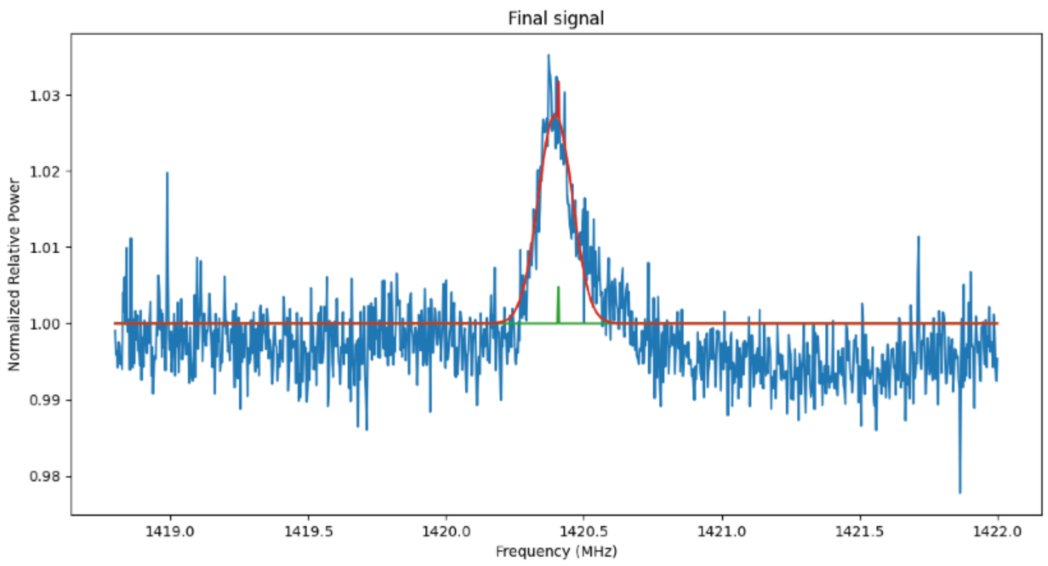
Standard Deviation2: 0.0649 MHz

Corresponding radial velocity:

2.98237208 km/s; -17.9002927 km/s

Single Gaussian Fit





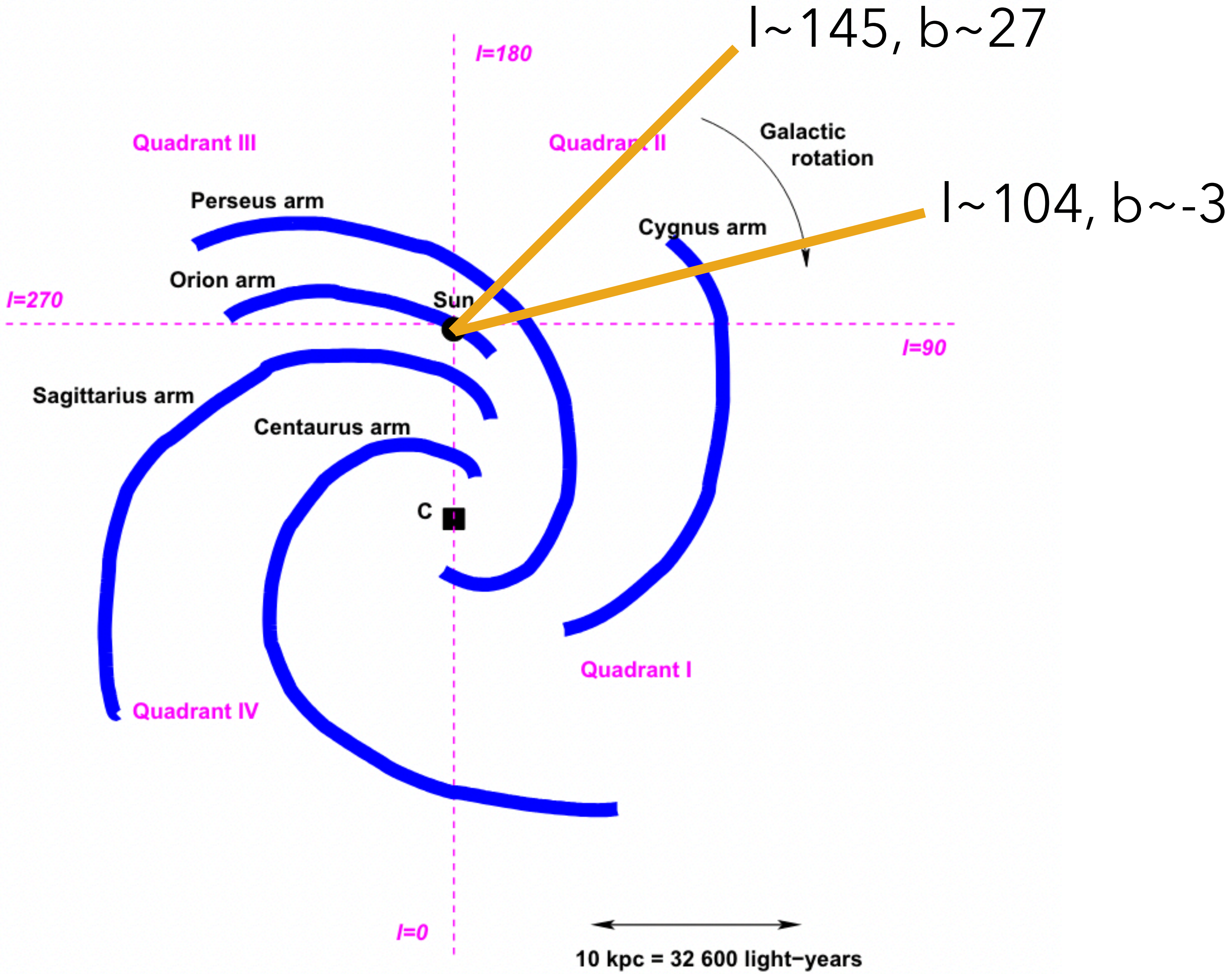
Parameters:

Central Frequency: 1420.397 MHz

Standard Deviation: 0.0614 MHz

Corresponding radial velocity:

1.82953152 km/s



l~145, b~27
l~104, b~-3
l=180
Quadrant III
Quadrant II
Galactic rotation
Perseus arm
Cygnus arm
Orion arm
l=270
Sun
l=90
Sagittarius arm
Centaurus arm
C
Quadrant I
Quadrant IV
l=0
10 kpc = 32 600 light−years