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GINGER

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THE EUROPEAN PHYSICAL JOURNAL PLUS

Regular Article

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Comparative analysis of local angular rotation between the ring laser gyroscope GINGERINO and GNSS stations

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Abstract The study of local deformations is a hot topic in geodesy. Local rotations of the crust around the vertical axis can be caused by deformations. In the Gran Sasso area, the ring laser gyroscope GINGERINO and the GNSS array are operative. One year of data of GINGERINO is compared with the ones from the GNSS stations, homogeneously selected around the position of GINGERINO, aiming at looking for rotational signals with period of days common to both systems. At that purpose the rotational component of the area circumscribed by the GNSS stations has been evaluated and compared with the GINGERINO data. The coherences between the signals show structures that even exceed 60% coherence over the 6–60 days period; this unprecedented analysis is validated by two different methods that evaluate the local rotation using the GNSS stations. The analysis reveals that the shared rotational signal's amplitude in both instruments is approximately 10^{-13} rad/s, an order of magnitude lower than the amplitudes of the signals examined. The comparison of the ring laser data with GNSS antennas provides evidence of the validity of the ring laser data for very low frequency investigation, essential for fundamental physics test.

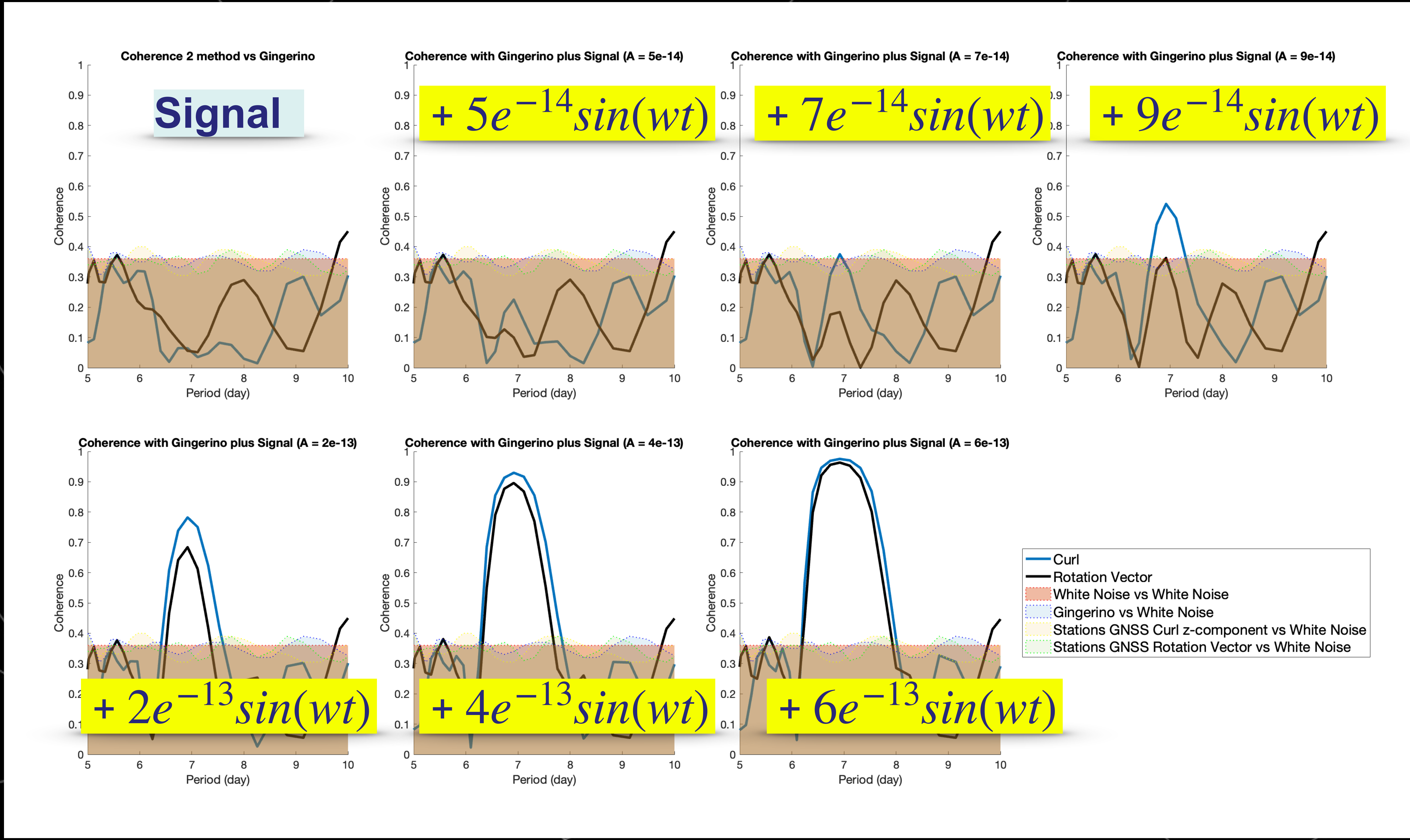
The presentation is based on an article we published

Please refer to this link for more details:

https://link.springer.com/article/10.1140/epjp/s13360-024-04960-3

Detection of a synthetic signal at a known frequency

We enhanced the angular speeds obtained through the already mentioned methods by introducing a simulated signal that exhibited spikes over a duration of 7 days. This simulated signal had a variable amplitude, reaching up to two orders of magnitude lower than the actual signal.



The constellation of GNSS stations

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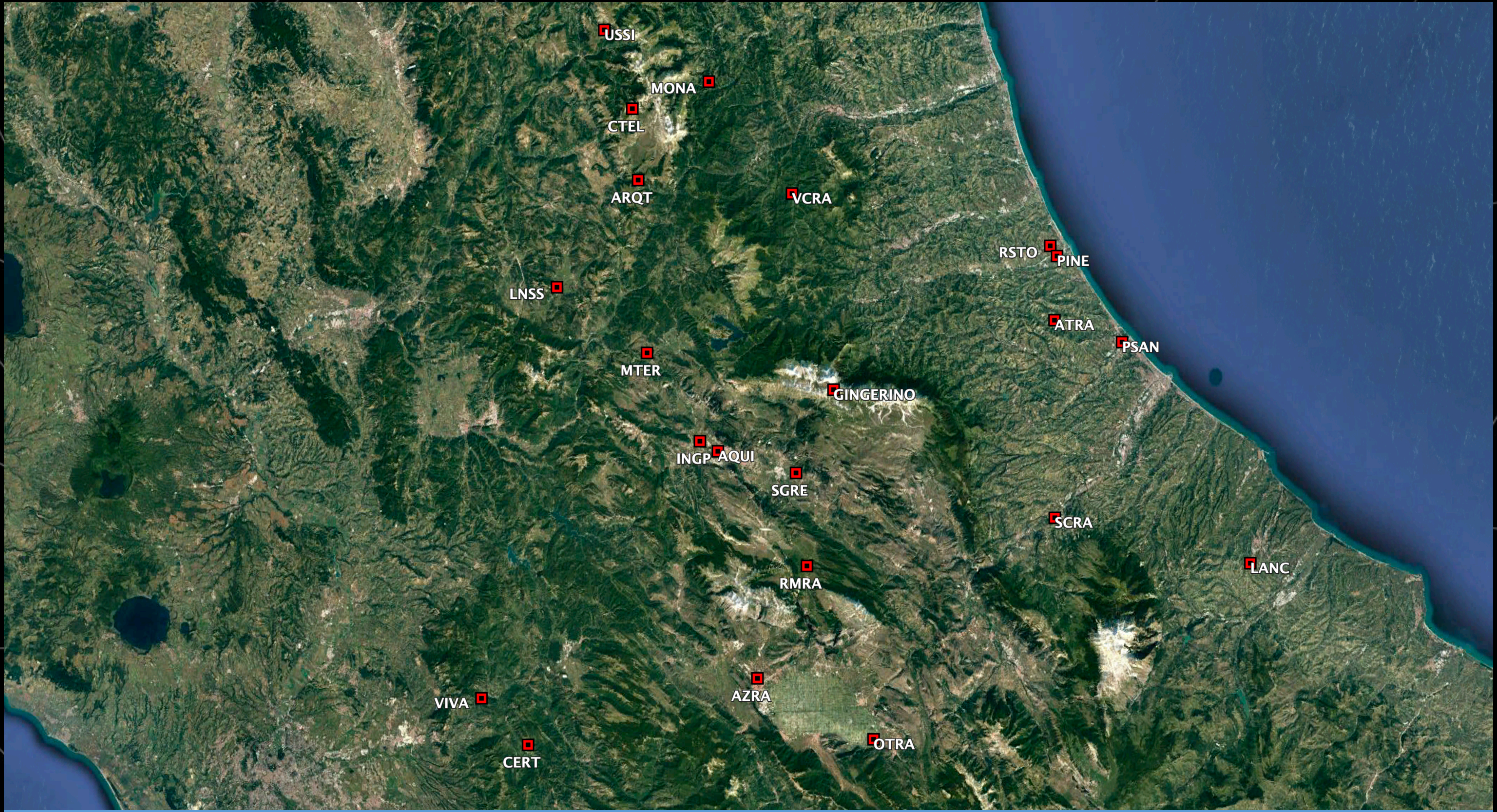
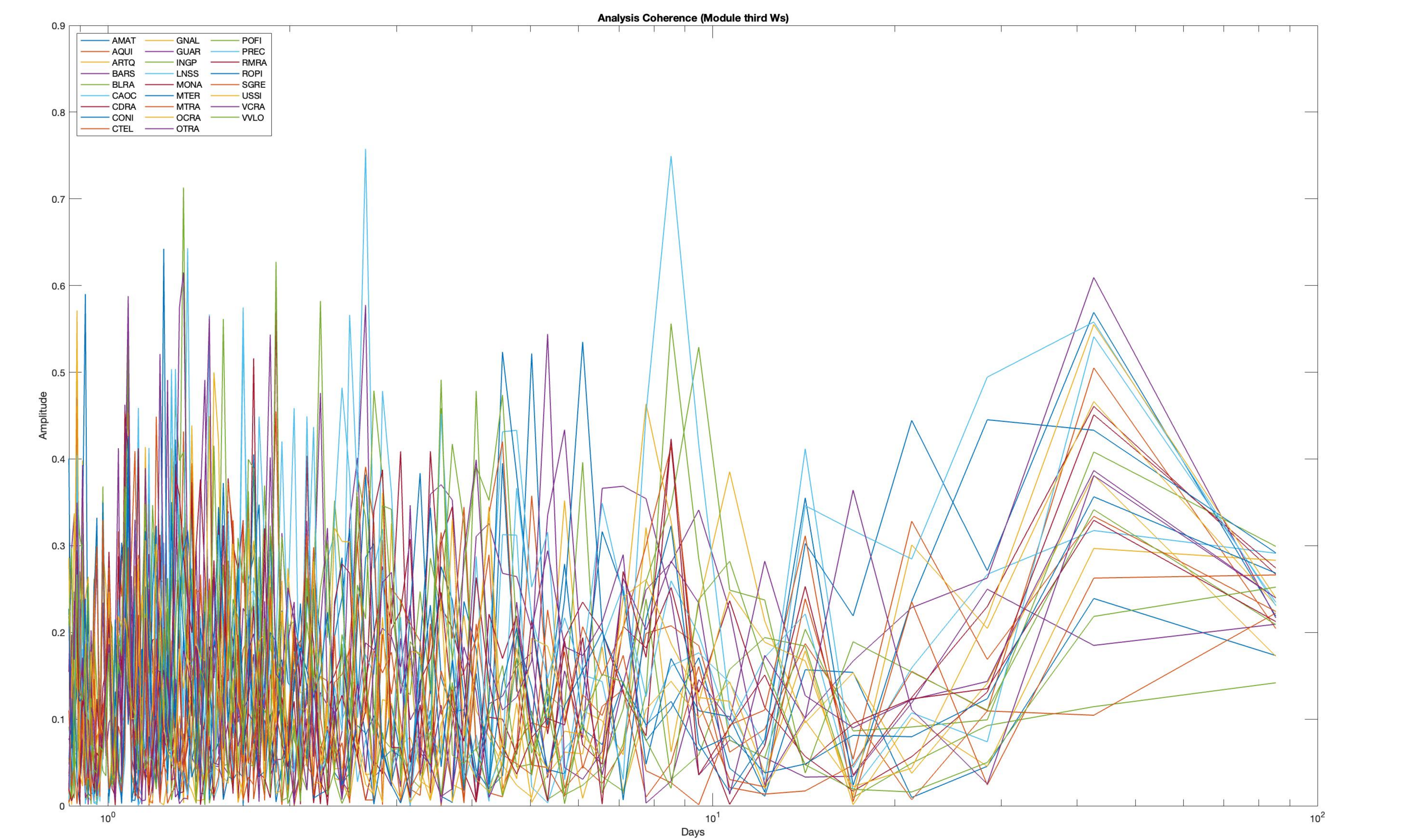


The detection of local deformations is a hot topic in geodesy. In our analysis for the first time a comparison between these instruments has been performed, we compare the signal from Gingerino with the ones from the GNSS stations, homogeneously selected around the position of Gingerino.

Coherence across all time periods



Since we are solely considering the stations and their positions relative to Gingerino, a direct comparison becomes challenging.

Topographical Trend

our focus is on identifying a shared peak among all periods, but no clear topographical pattern emerges.

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Rotational component from GNSS stations

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$$\omega_1 = \frac{|v_1|}{|r_1|}\sin(\alpha_1 - \theta_1)$$

$$v_1 = \sqrt{v_E^2 + v_N^2}$$

$$\alpha_1 = \arctan\left(\frac{v_N}{v_E}\right)$$

$$\sigma_{\omega_1} = \sqrt{\left(\frac{\partial\omega_1}{\partial v_1}\right)^2 \sigma_{v_1}^2 + \left(\frac{\partial\omega_1}{\partial r_1}\right)^2 \sigma_{r_1}^2 + \left(\frac{\partial\omega_1}{\partial \alpha_1}\right)^2 \sigma_{\alpha_1}^2 + \left(\frac{\partial\omega_1}{\partial \theta_1}\right)^2 \sigma_{\theta_1}^2}$$

$\sigma_{r_1}, \sigma_{\theta_1}$ THEY ARE EVALUATED WITH A MONTECARLO METHOD, BECAUSE THEY ARE OBTAINED WITH THE "DISTANCE" FUNCTION OF MATLAB

Using Gingerino position as the pole, the rotational component of each individual station is derived and then the rotation vector associated to the area circumscribed by the stations is obtained by performing a weighted average.

Curl z-component seen from GNSS stations

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$$\omega_z = \left(\frac{\partial v_x}{\partial y} - \frac{\partial v_y}{\partial x} \right)$$

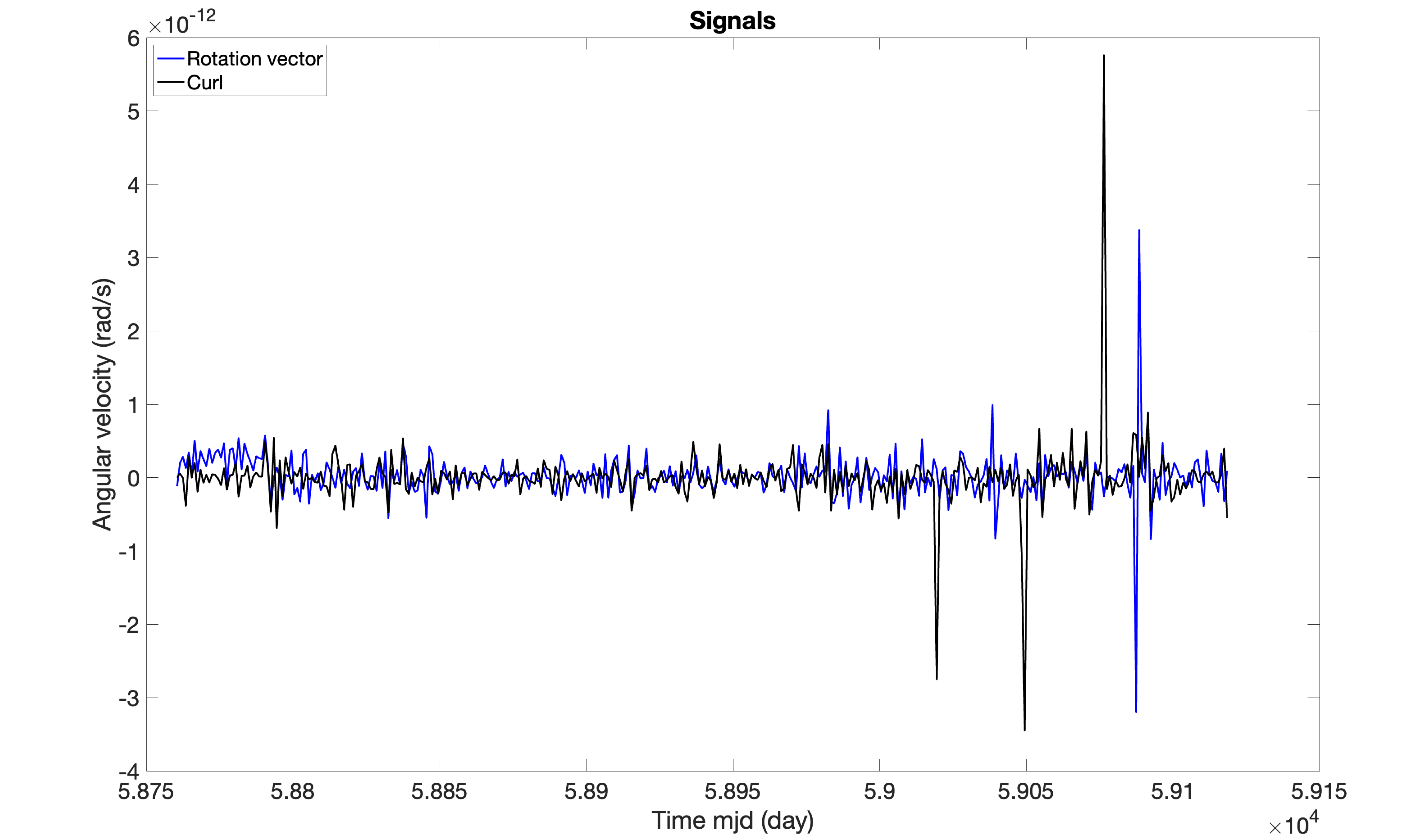
$$v_i = t_i + \frac{\partial v_i}{\partial x_j} x_j = t_i + e_{ij} x_j$$

$$e_{ij} = \epsilon_{ij} + \omega_{ij} = \frac{(e_{ij} + e_{ji})}{2} + \frac{(e_{ij} - e_{ji})}{2}$$

The z-component of the curl of the area circumscribed by the constellation of stations at Gingerino position.

Allmendinger, Richard & Reilinger, Robert & Loveless, John. (2007). Strain and Rotation Rates from GPS in Tibet, Anatolia, and the Altiplano. Tectonics.

Comparison between the different methods



It is noteworthy that the signals obtained, with two different methods, share a common feature: they exhibit identical amplitudes, with some points even reaching peak values, and display coinciding trends.

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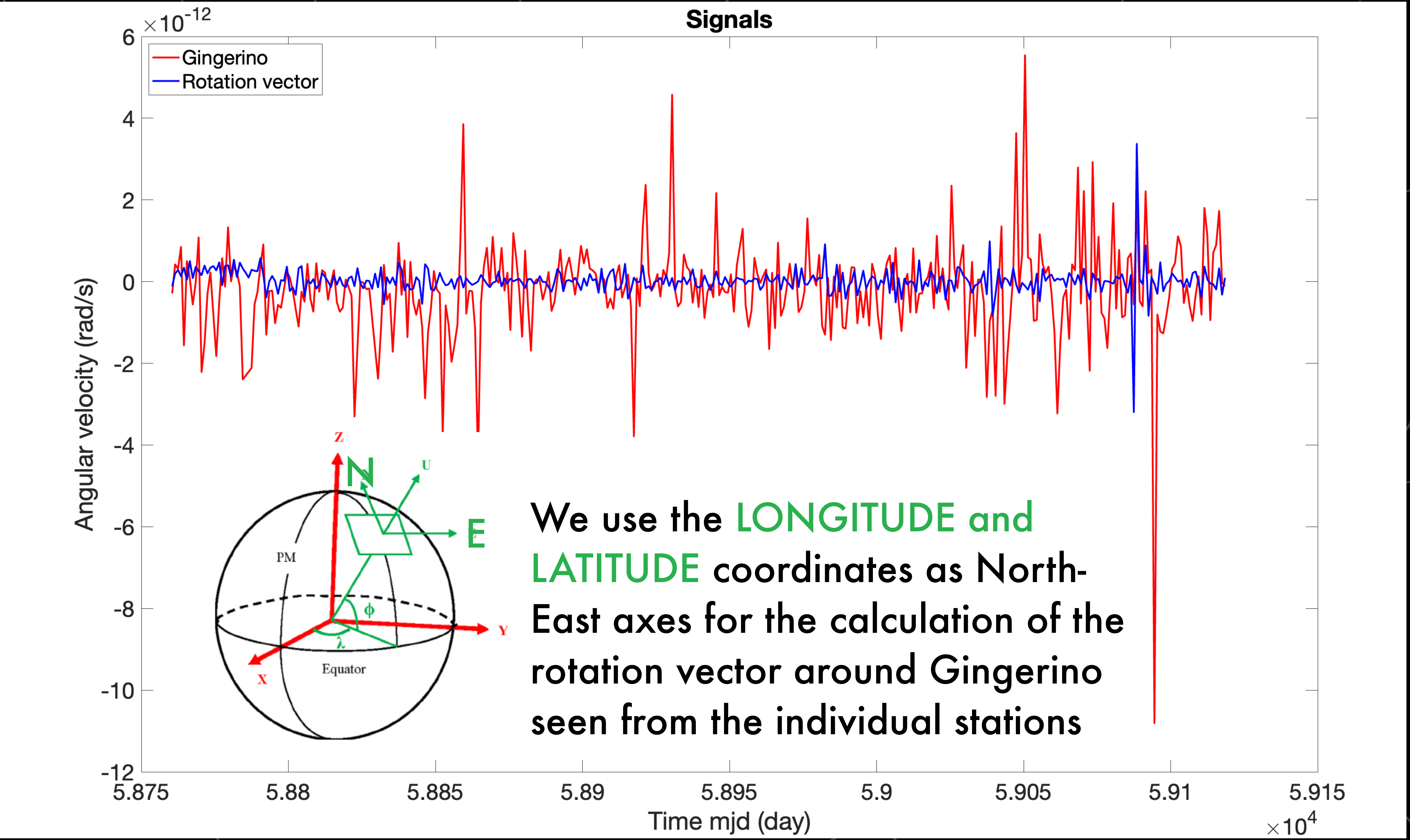
Rotational component from GNSS stations



We use the LONGITUDE and LATITUDE coordinates as North-East axes for the calculation of the rotation vector around Gingerino seen from the individual stations

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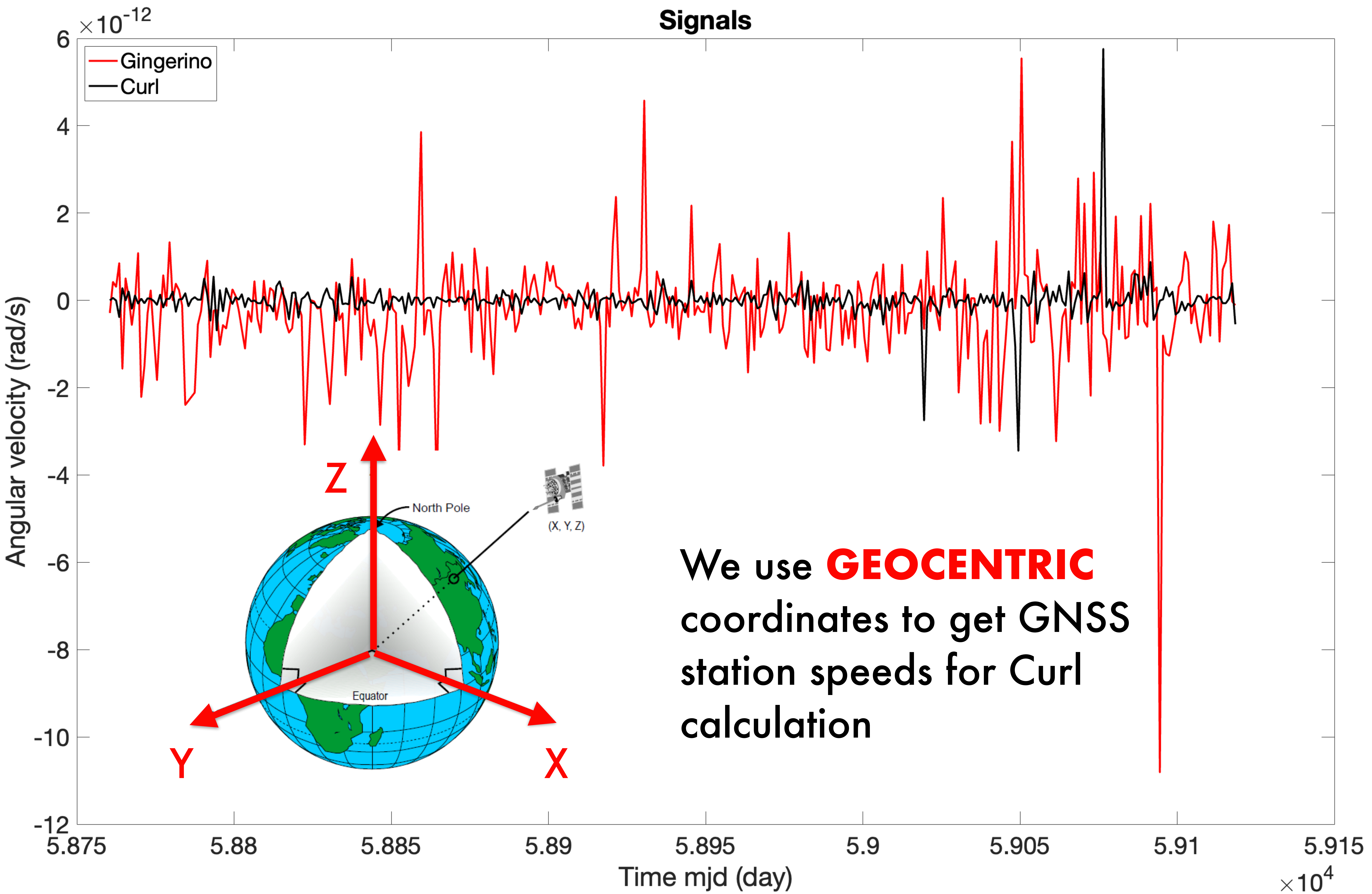
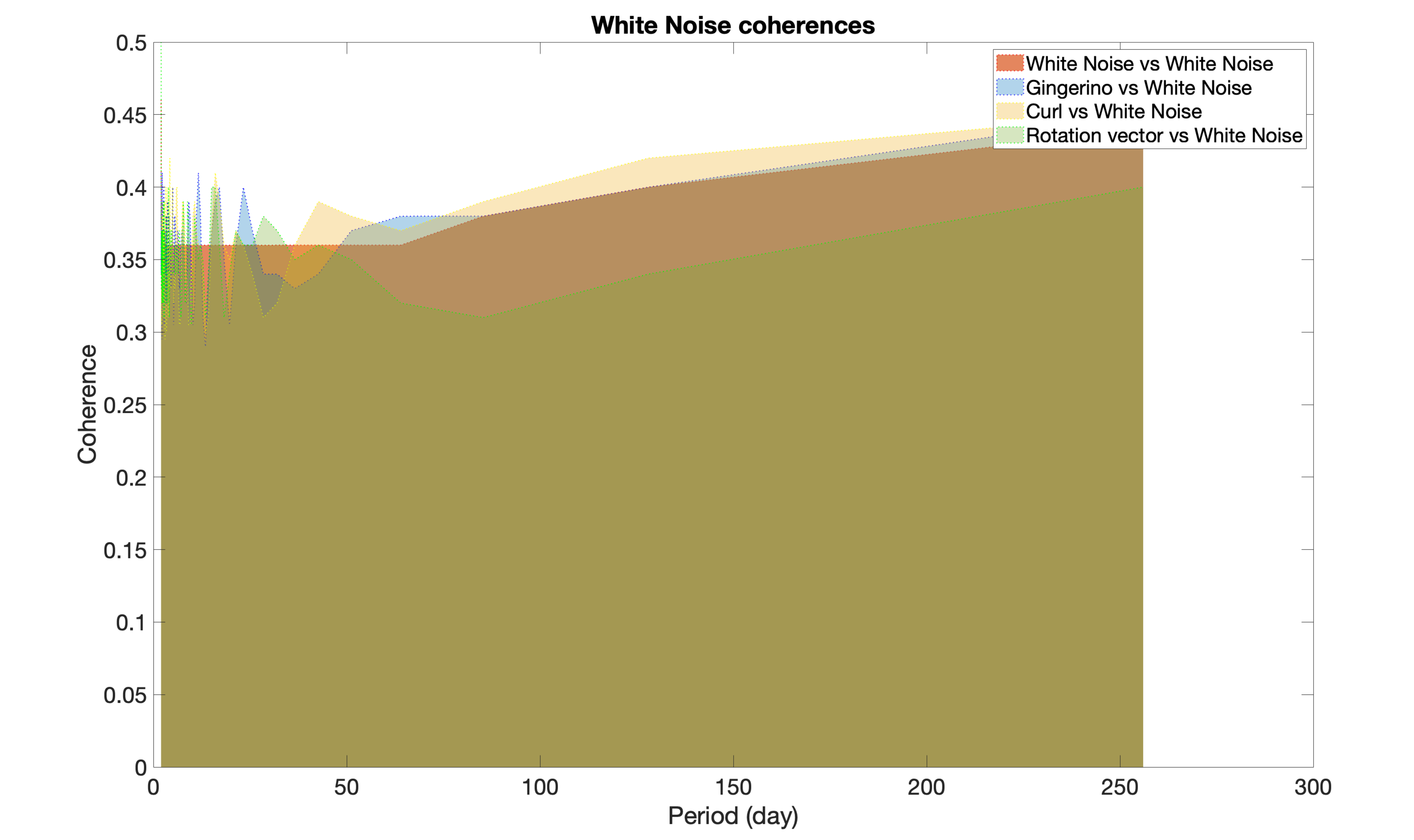
Curl z-component seen from GNSS stations



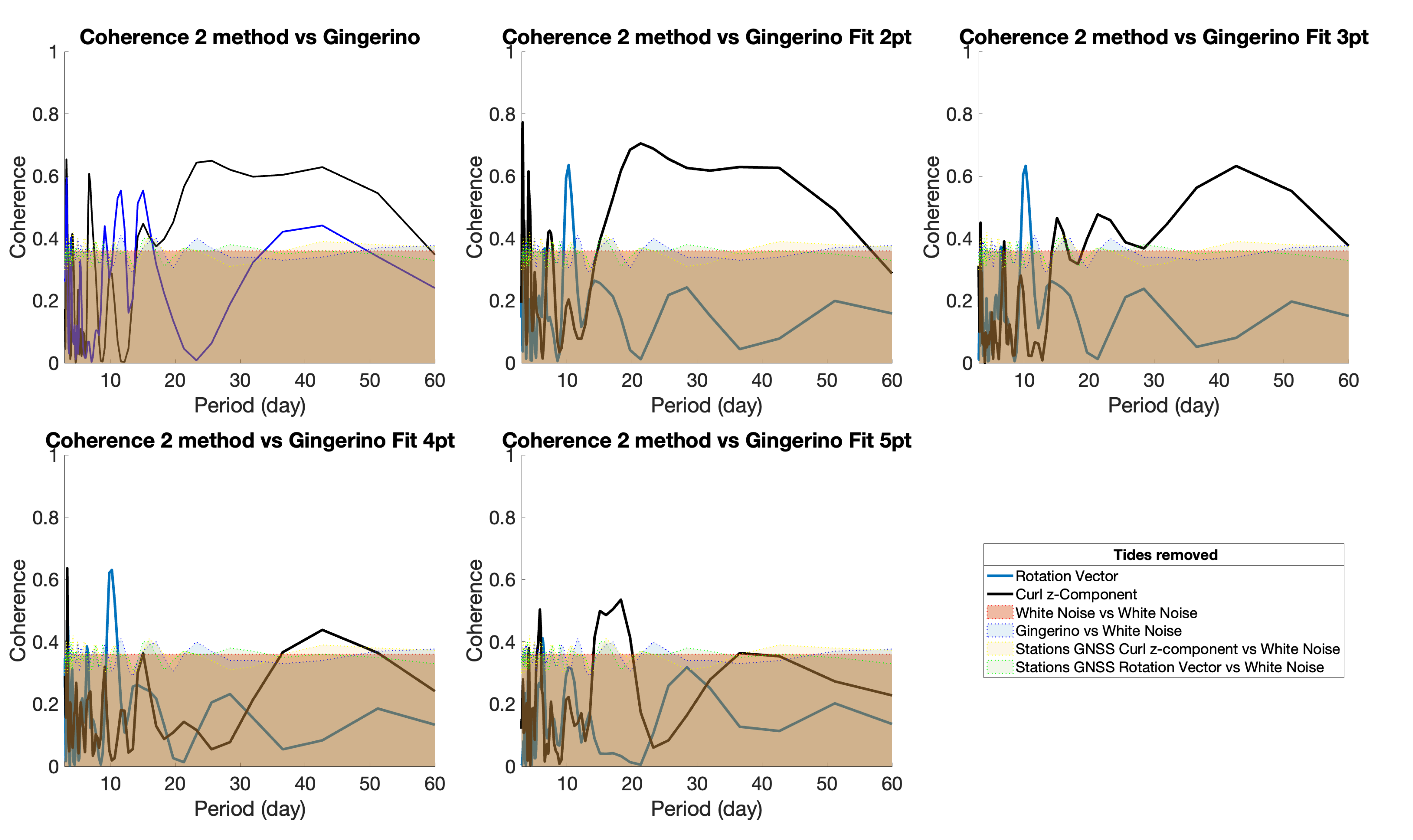
We use **GEOCENTRIC** coordinates to get GNSS station speeds for Curl calculation

Baseline for zero coherence: "mscohere"



To determine the actual degree of coherence between the two signals, we conducted tests using the **mscohere** function along with simulated white noises. Employing a Monte Carlo simulation approach.

Results



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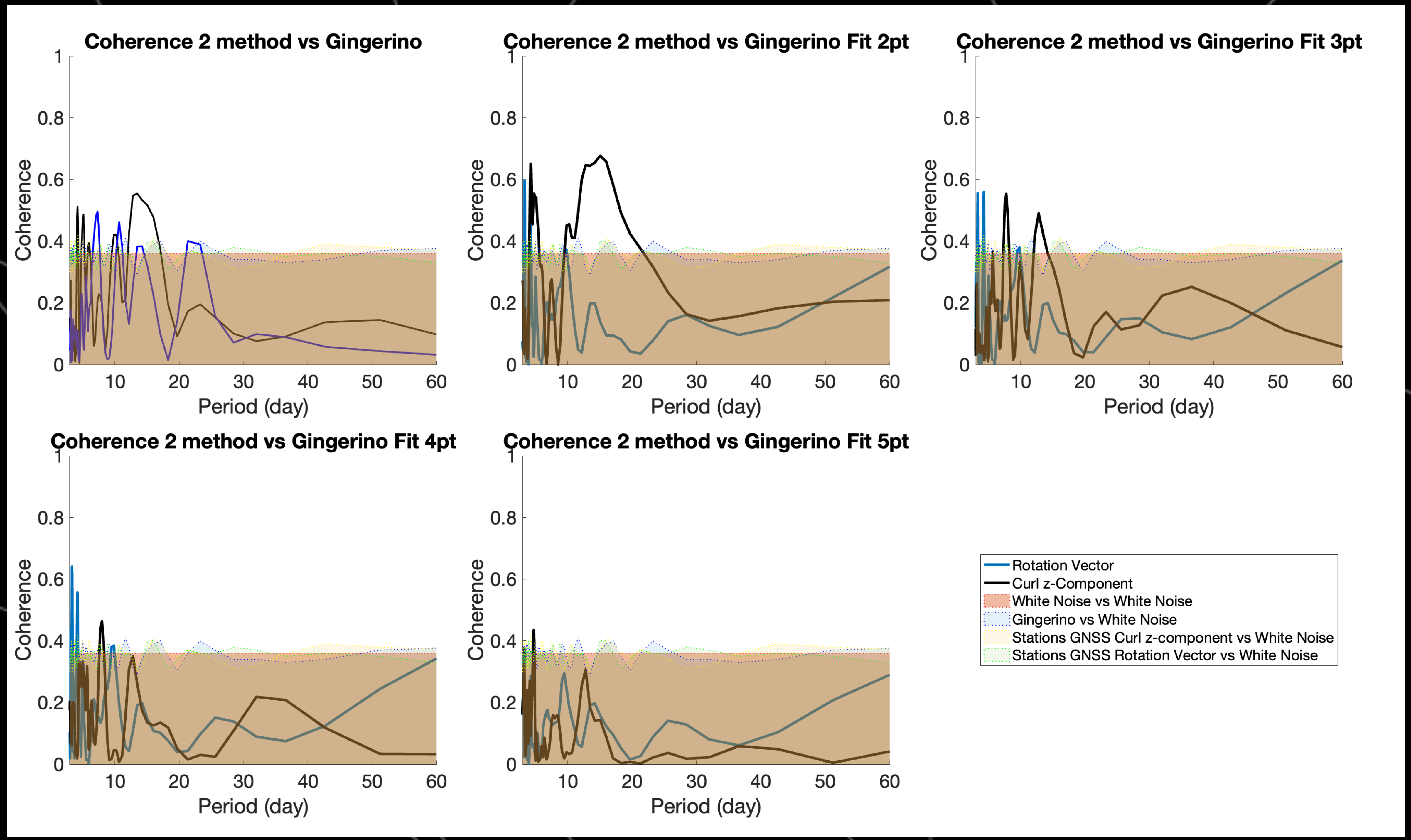
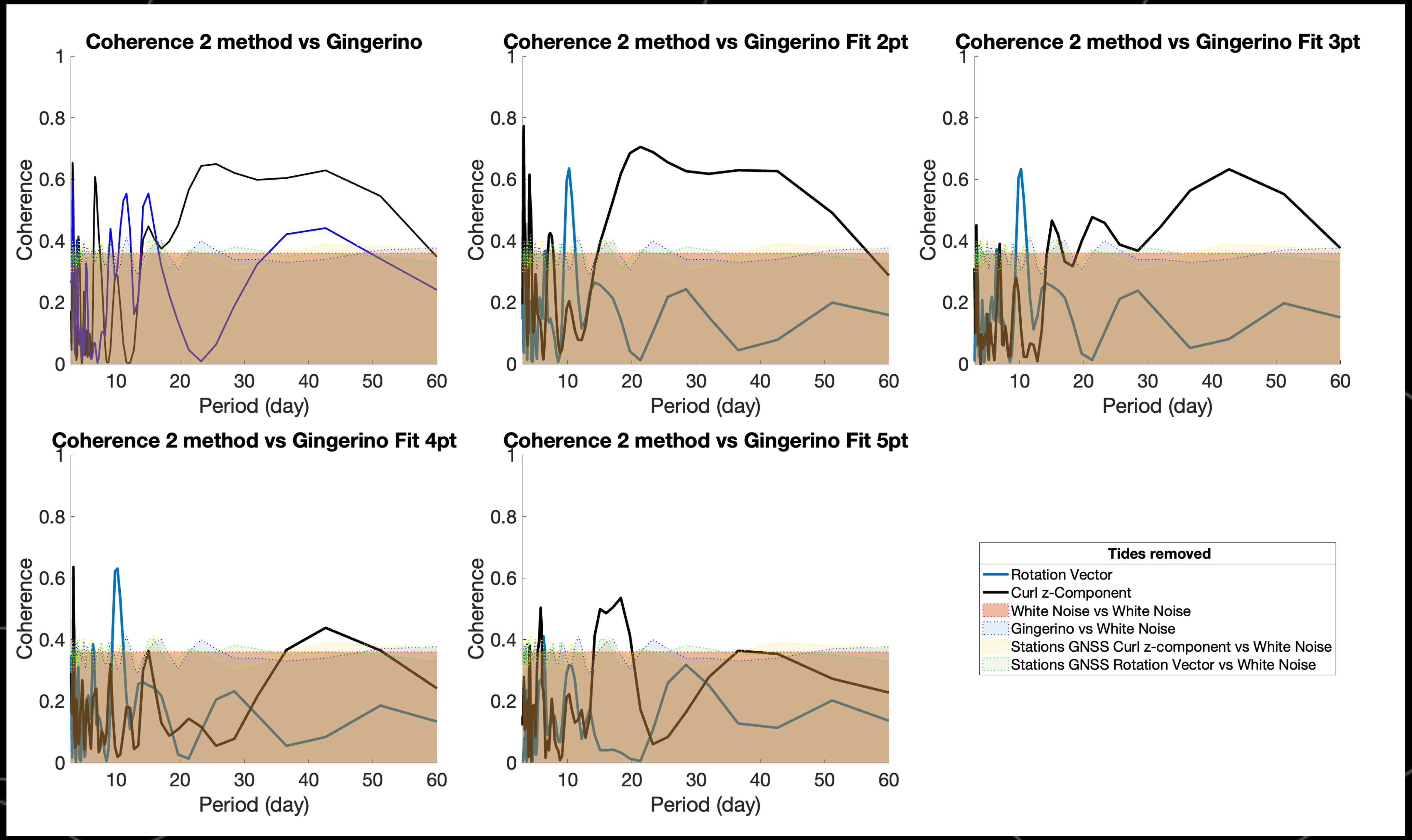
Fit of linear velocities



Coherence obtained without subtracting the contribution of the tides, clear structures emerge with the 2-point fit, these are decreasing for multi-point fit because the statistics decrease and the signals obtained go under the noise of the Gingerino signal.



Coherence achieved through the resolution of tides in Gingerino. In this case, the usual tidal peaks are reduced, revealing previously hidden structures with periods exceeding 20 days.

TCN and correlations

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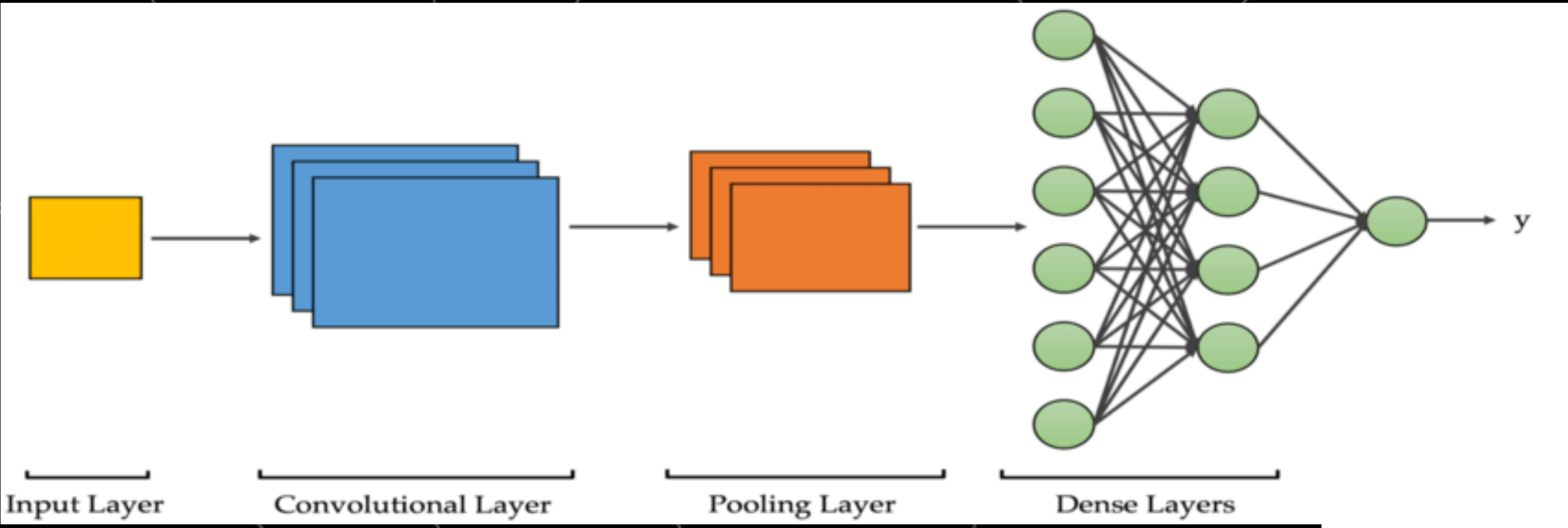

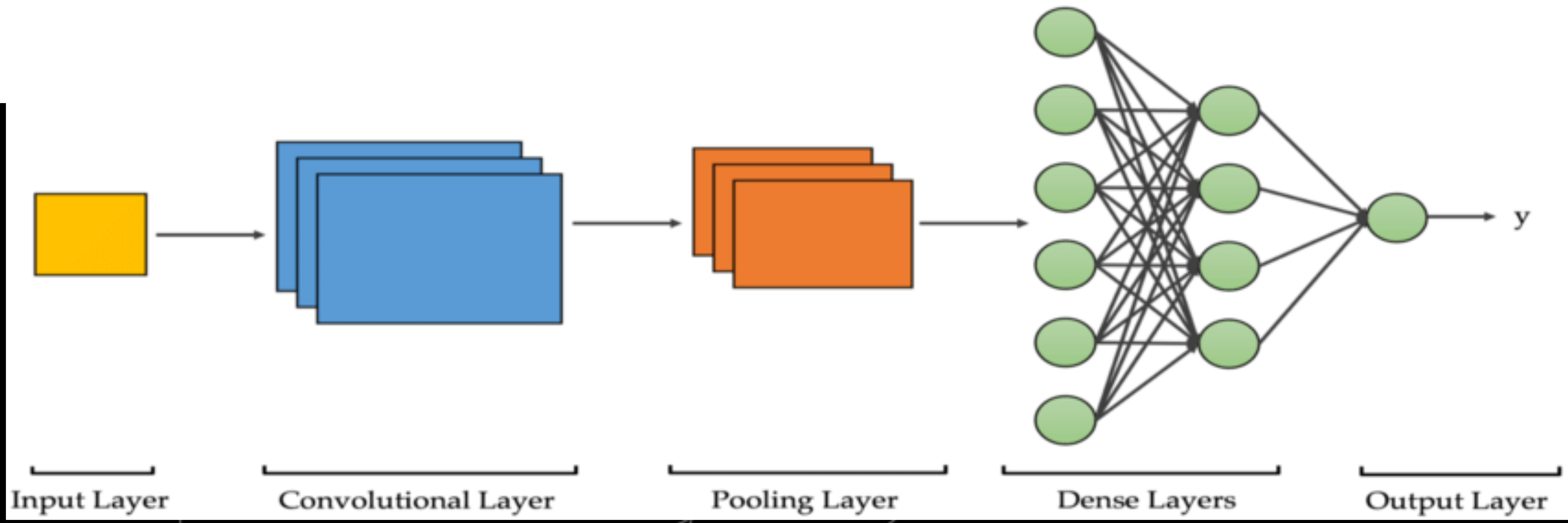

We used synthetic sinusoids with different frequencies and starting phases; we also varied their amplitude and mean value, or adding Gaussian noise to avoid overfitting; since the real signal always has the same average frequency, the network memorizes without generalizing and loses its robustness. Additionally, the network that achieved the best results was the one that output both the frequency and the cleaned sinusoid. This strategy ensures that by reconstructing both the clean sinusoid and the frequency, the network learns to better correlate the two pieces of information.

Testing on signals at different frequencies

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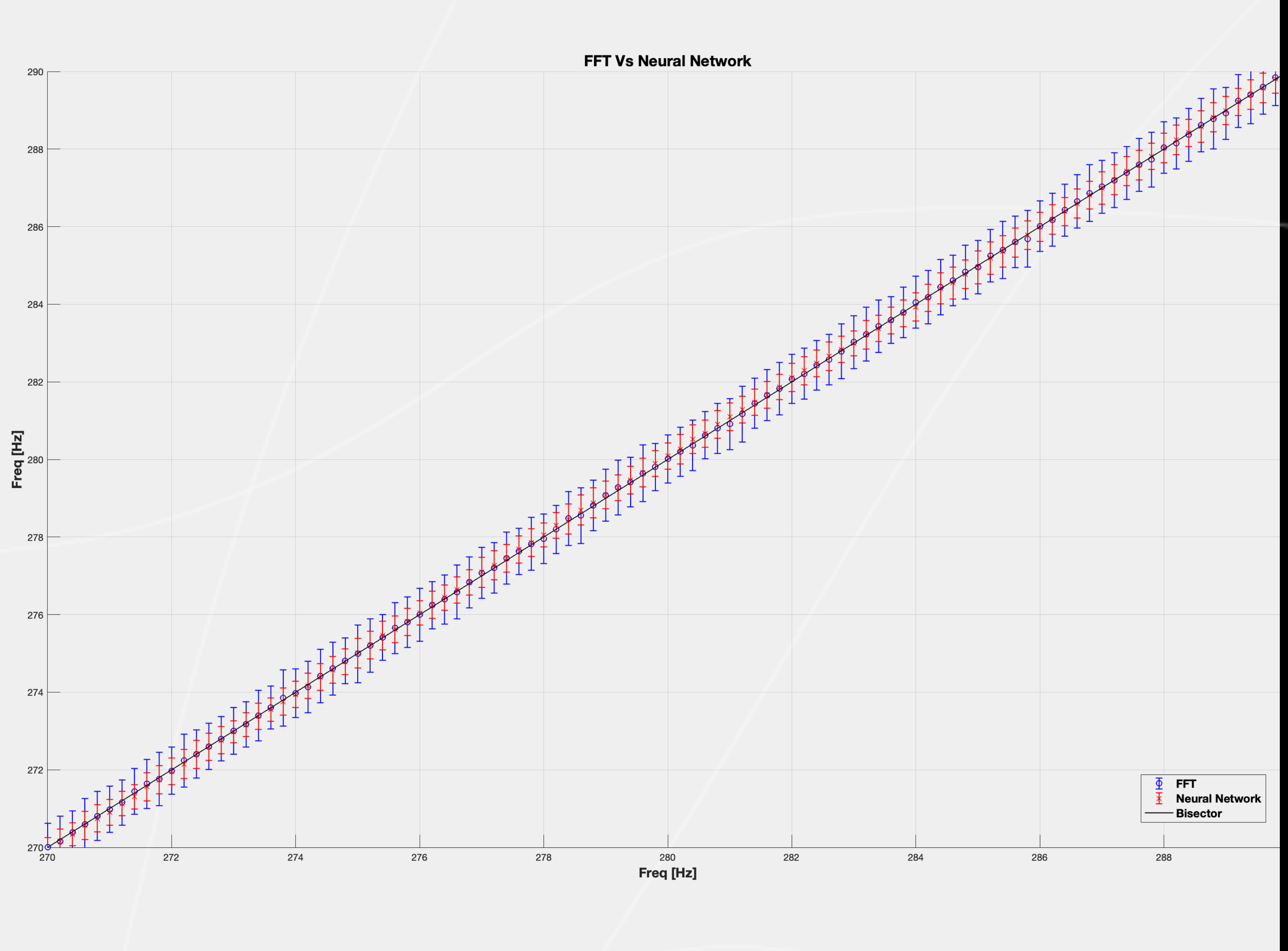
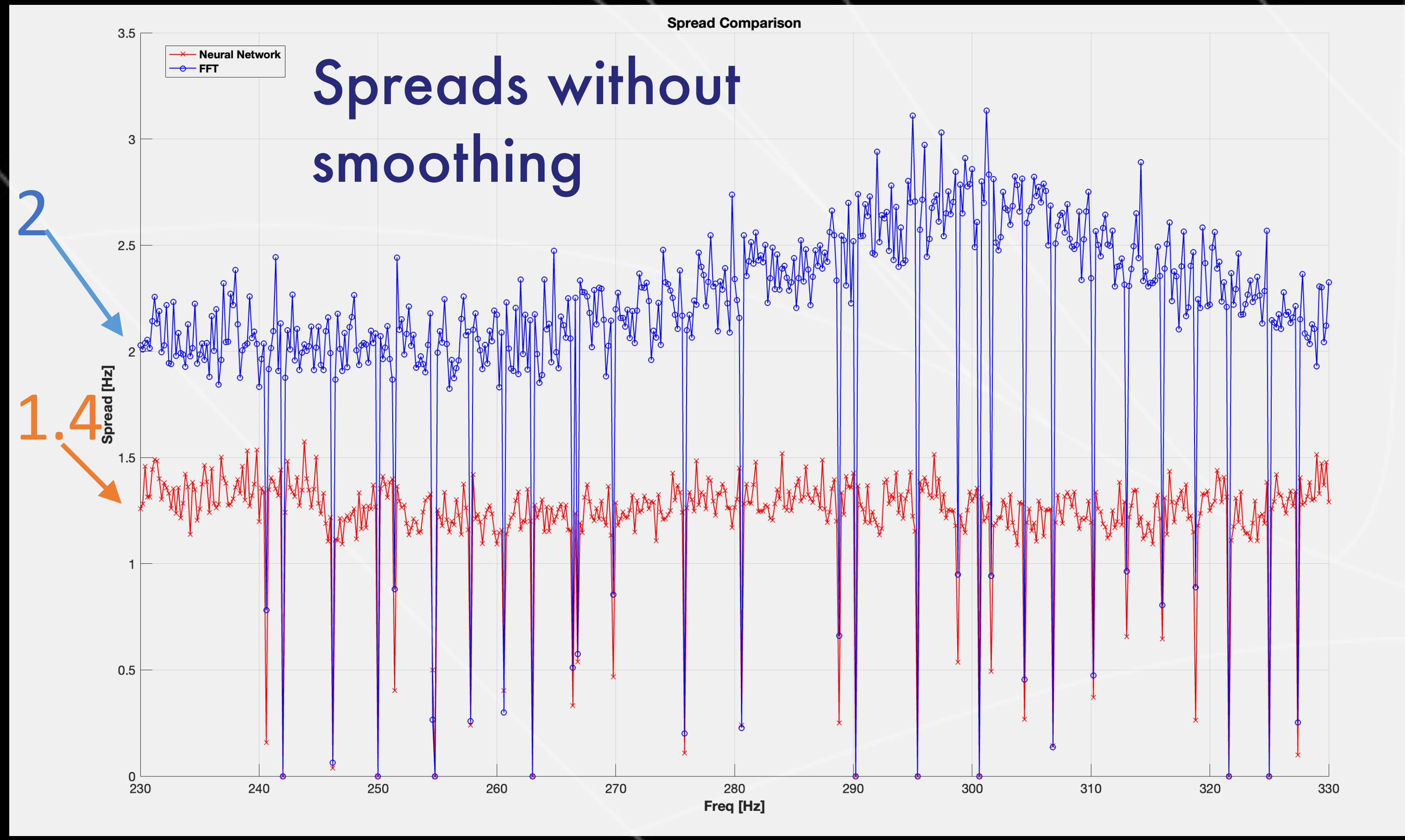
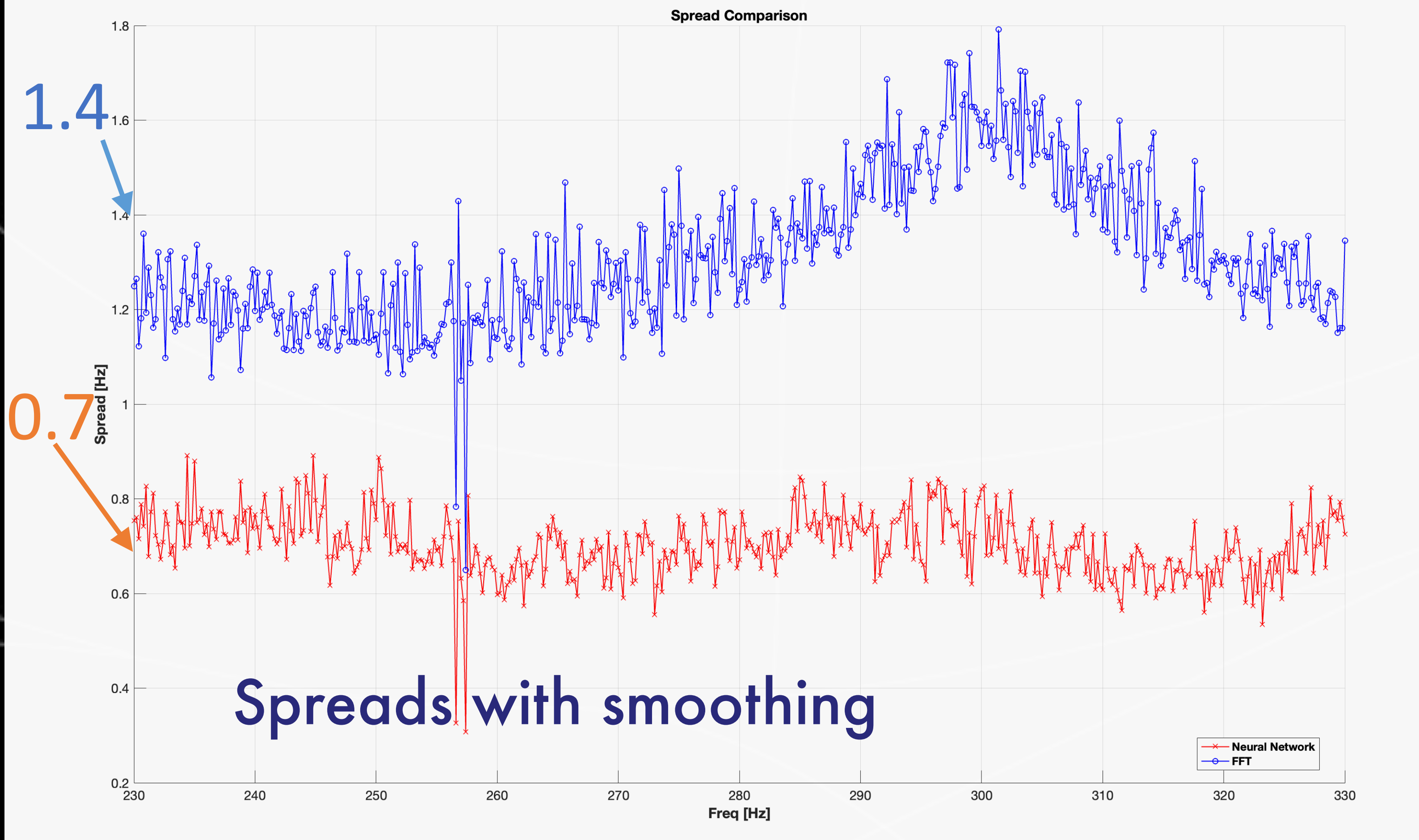
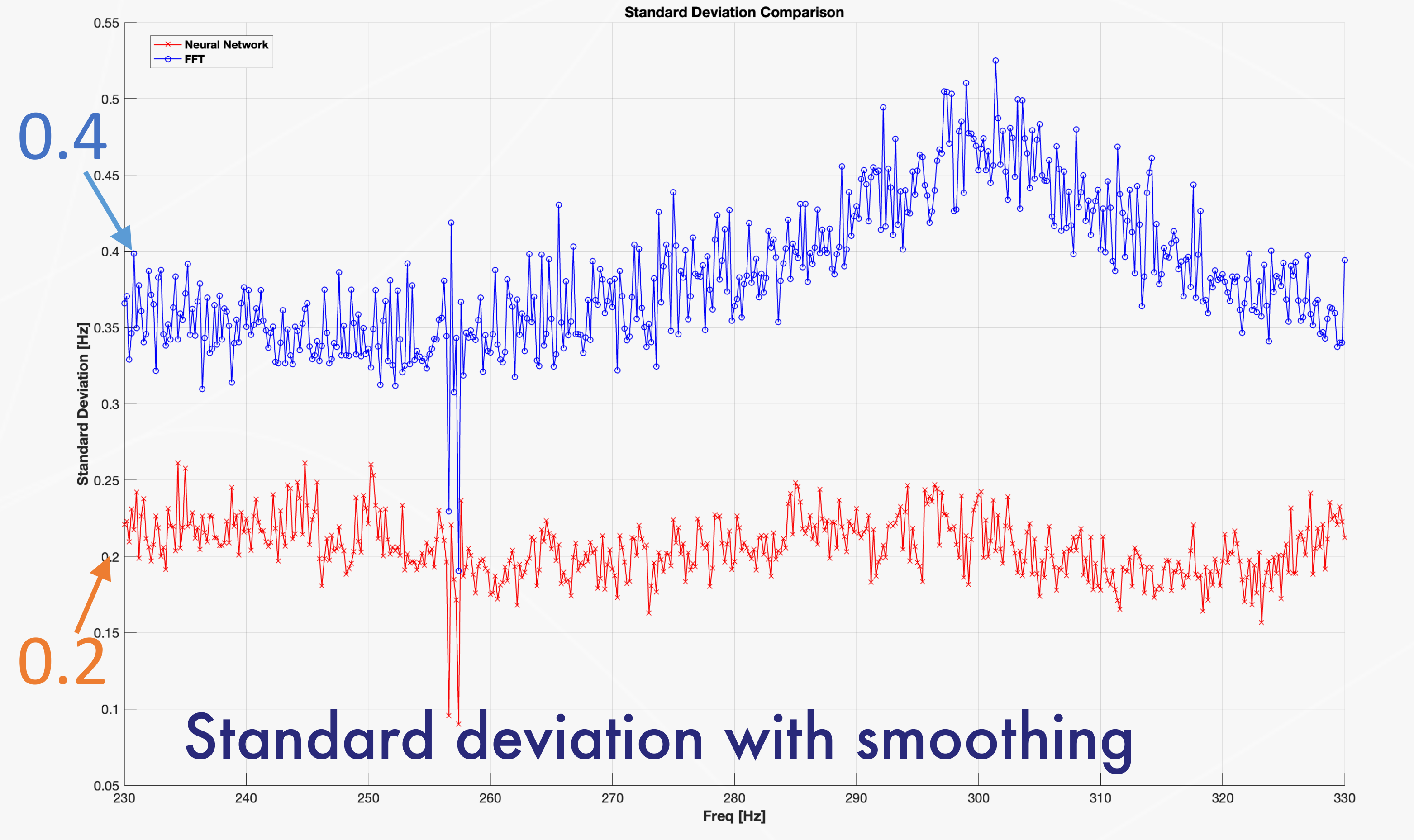
We compared this NN with a tool implemented in Labview based on FFT. We applied these two methods to recover frequency from simulated signal with Gaussian noise and a frequency range between 150 Hz and 350 Hz. Across the entire range, the NN is twice as accurate as the FFT in terms of both the standard deviation of the reconstructed frequency signal and the spread.

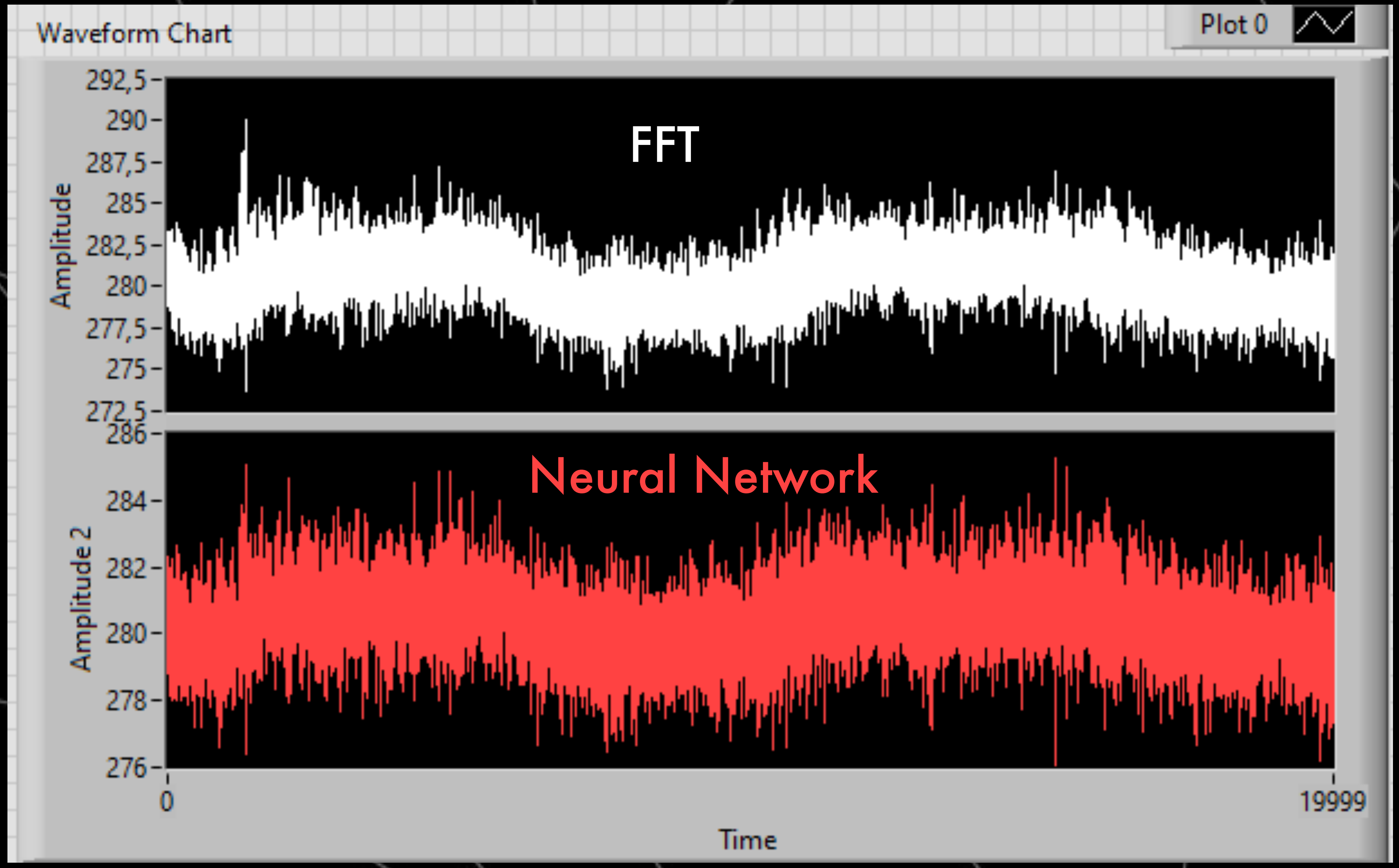








Testing on real-signal



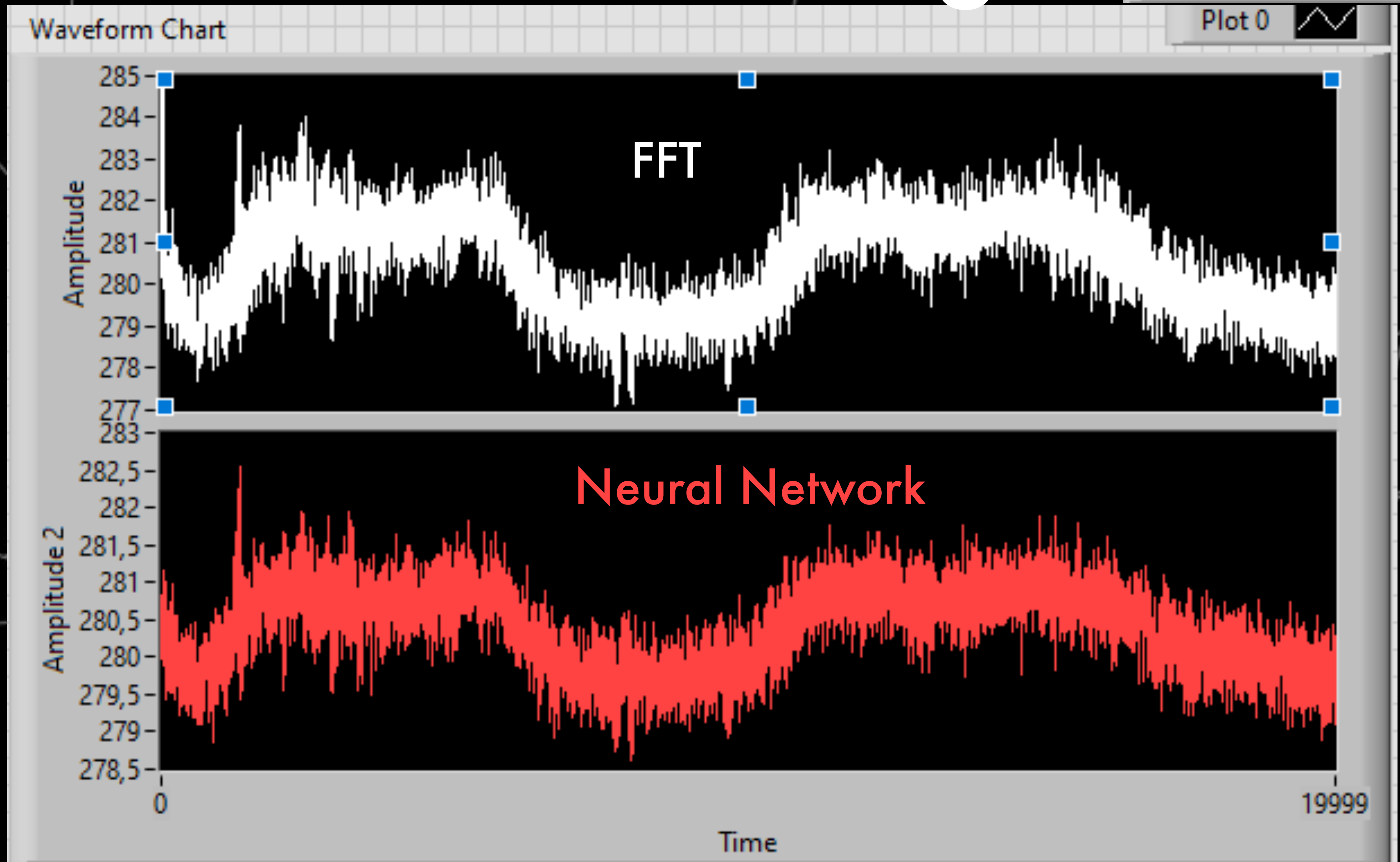
Spread: 16.2 Hz
σ: 4.7 Hz

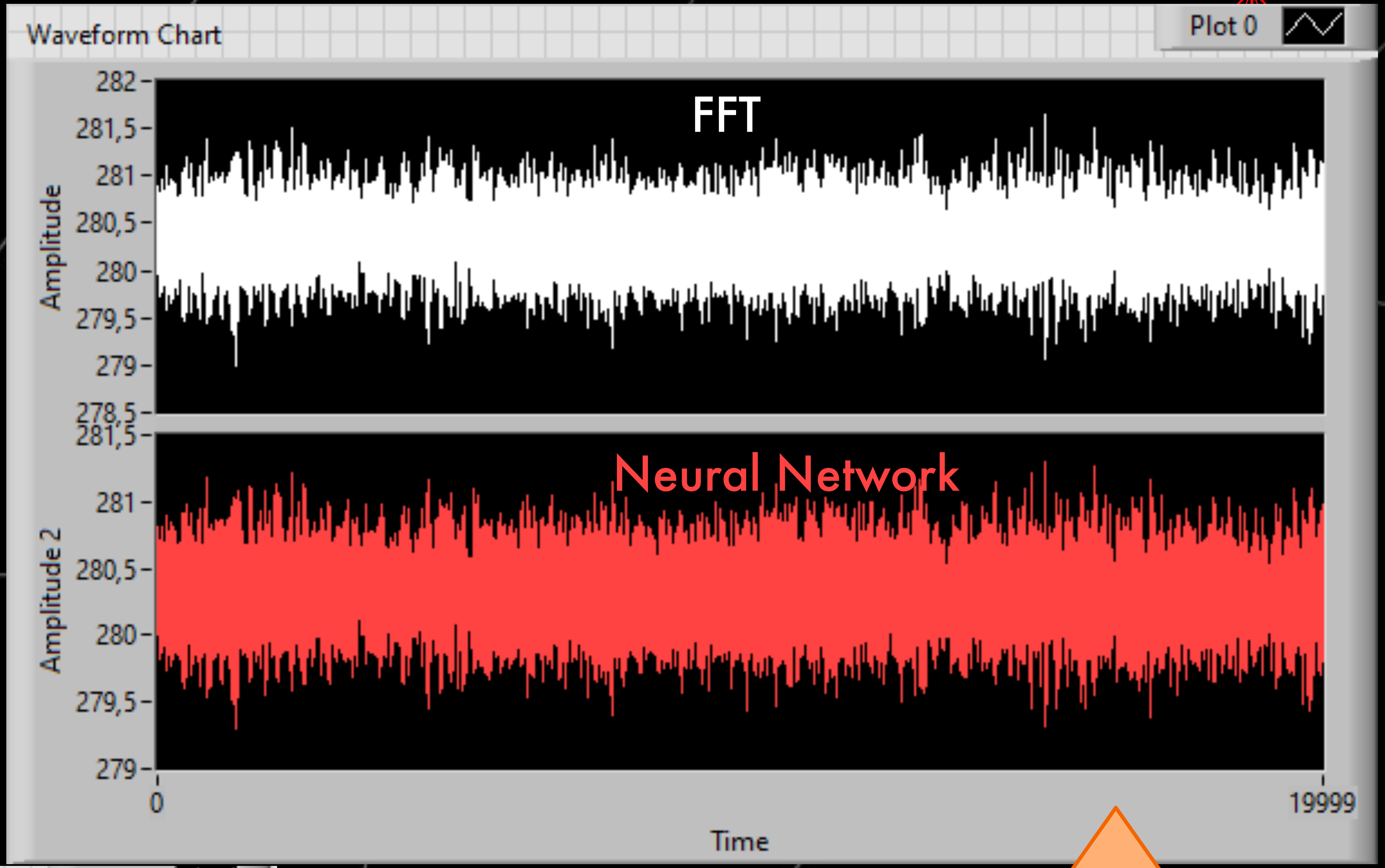
Spread: 9.1 Hz
σ: 2.7 Hz

Spread: 6.8 Hz
σ: 2.0 Hz

Spread: 3.5 Hz
σ: 1.0 Hz

Smoothing





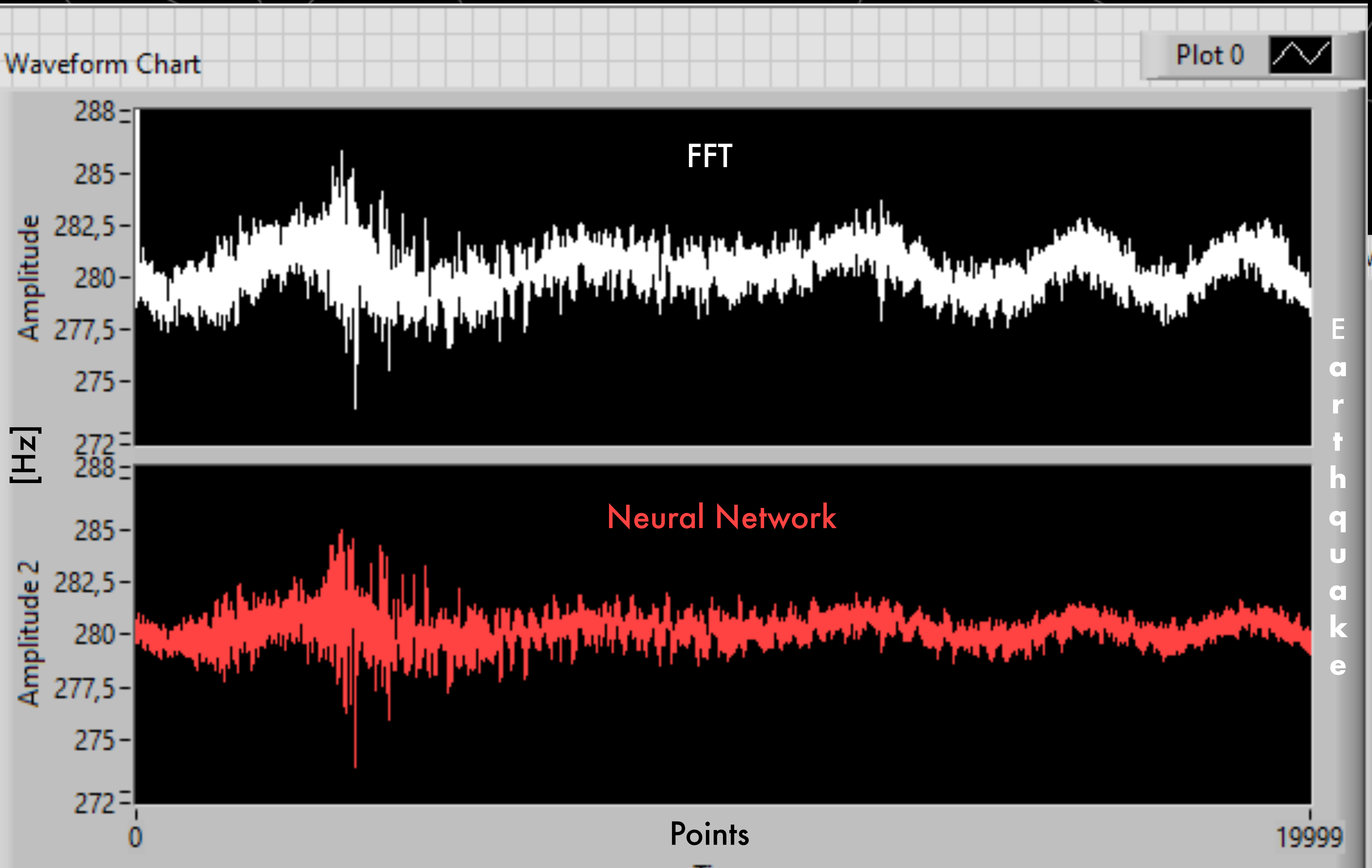
Filter

Spread: 2.6 Hz
σ: 0.8 Hz

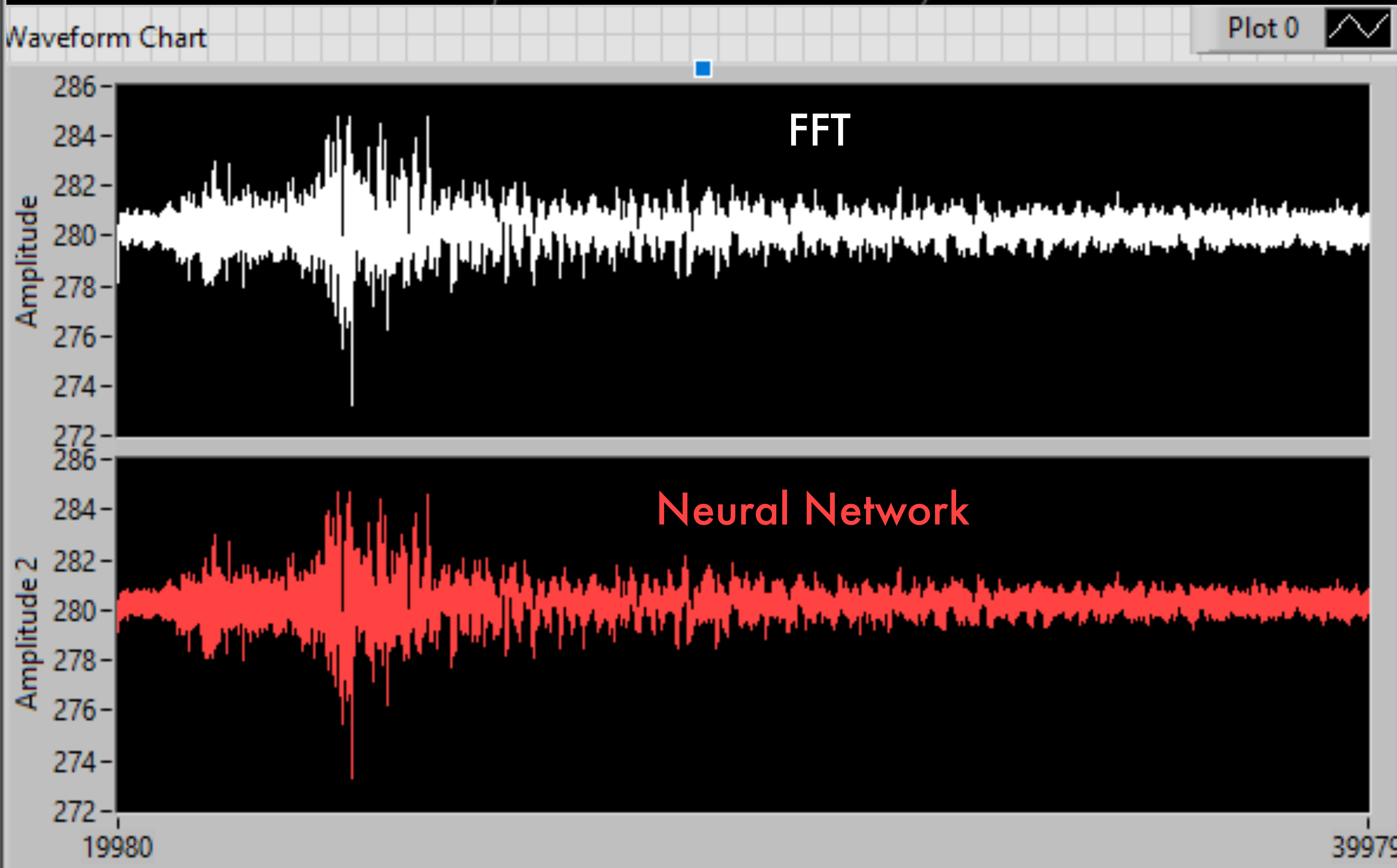
Spread: 2.0 Hz
σ: 0.6 Hz

Test on an earthquake signal

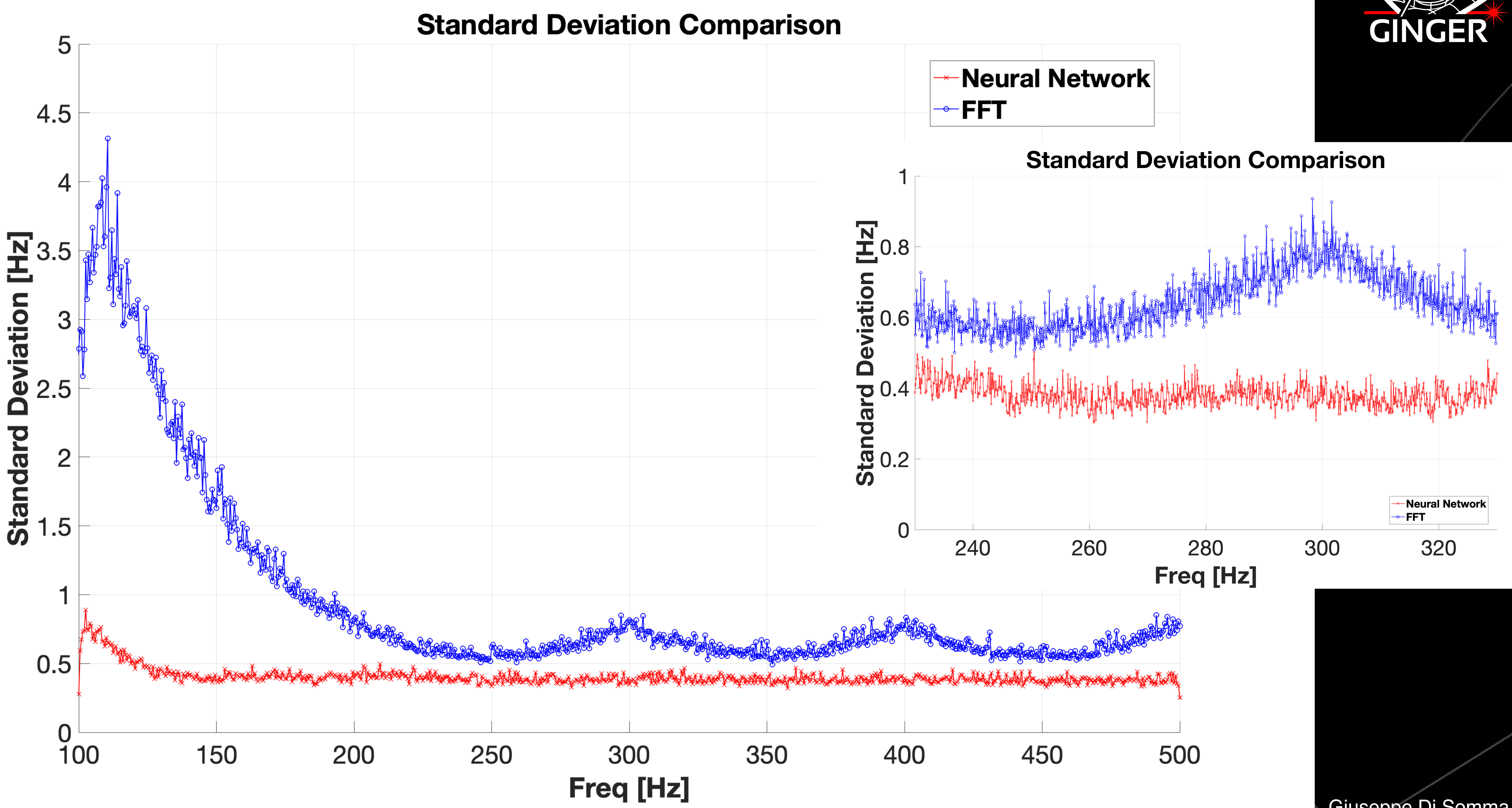
By comparison of the NN with the FFT on a real signal we can see that it does not eliminate or depress part of the signal but reduces the effects of low-frequency spuris signals (Completely deleted using a Filter), thus improving the noise signal ratio.



Filter



Standard Deviation Comparison



Spread Comparison

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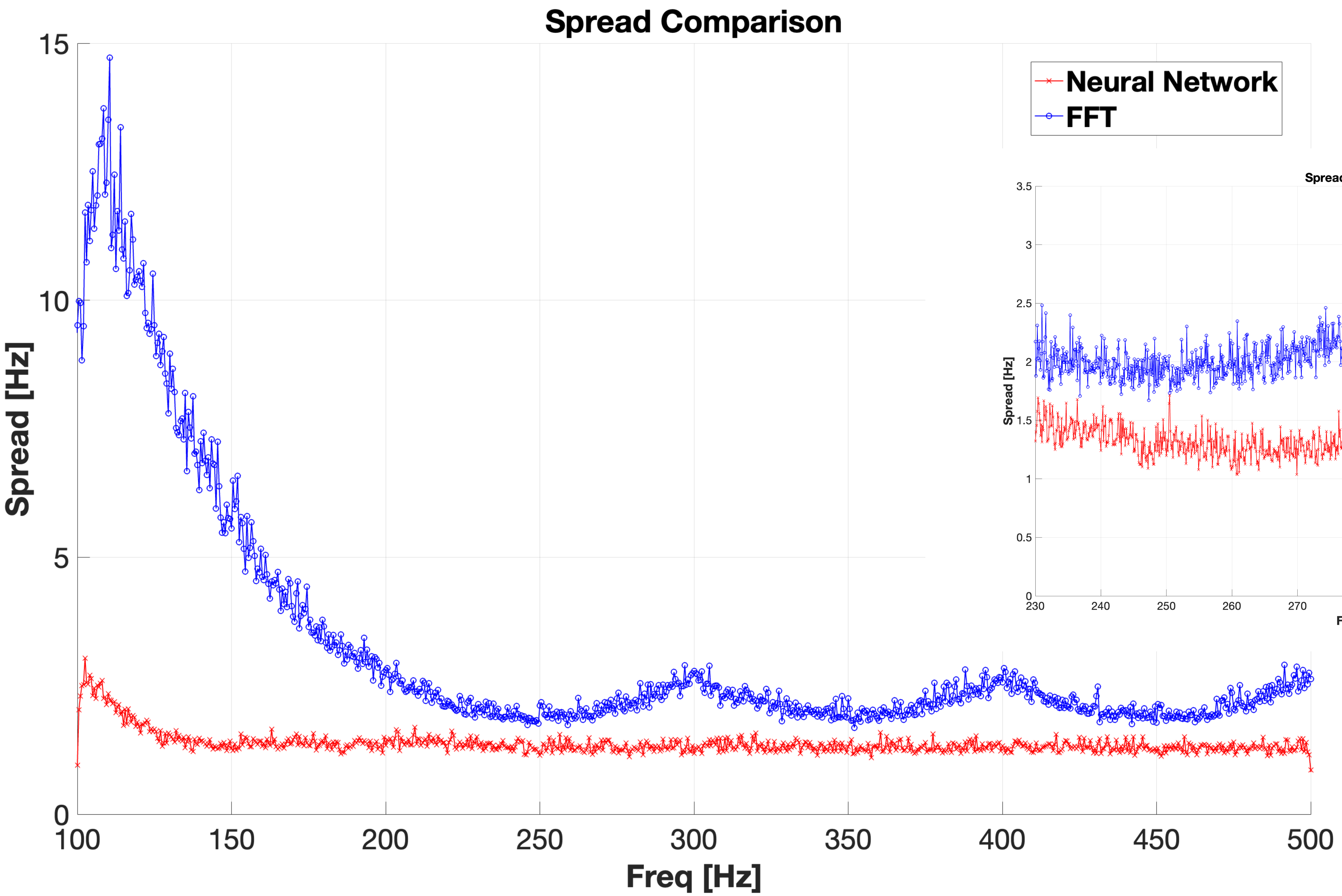
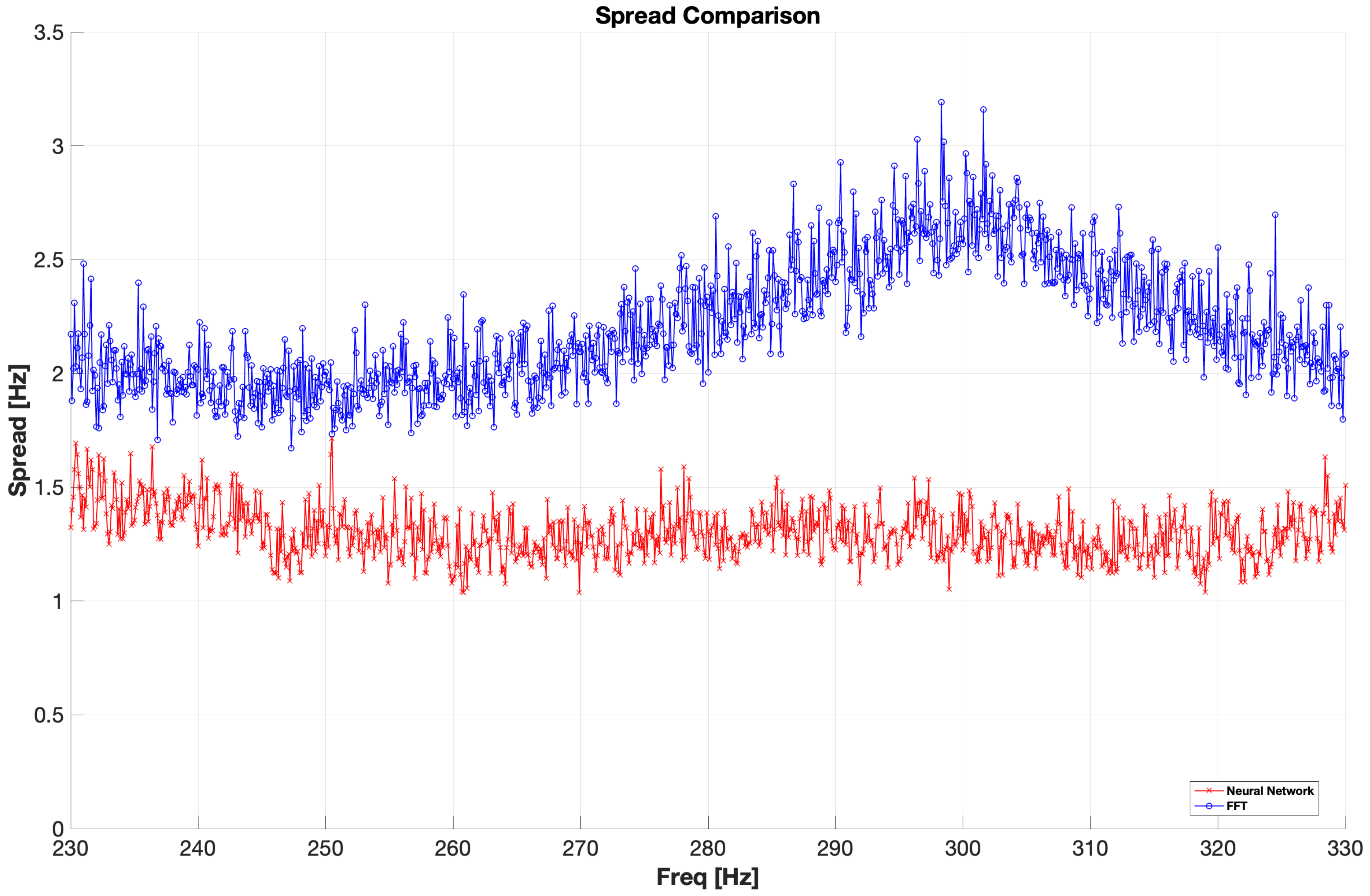
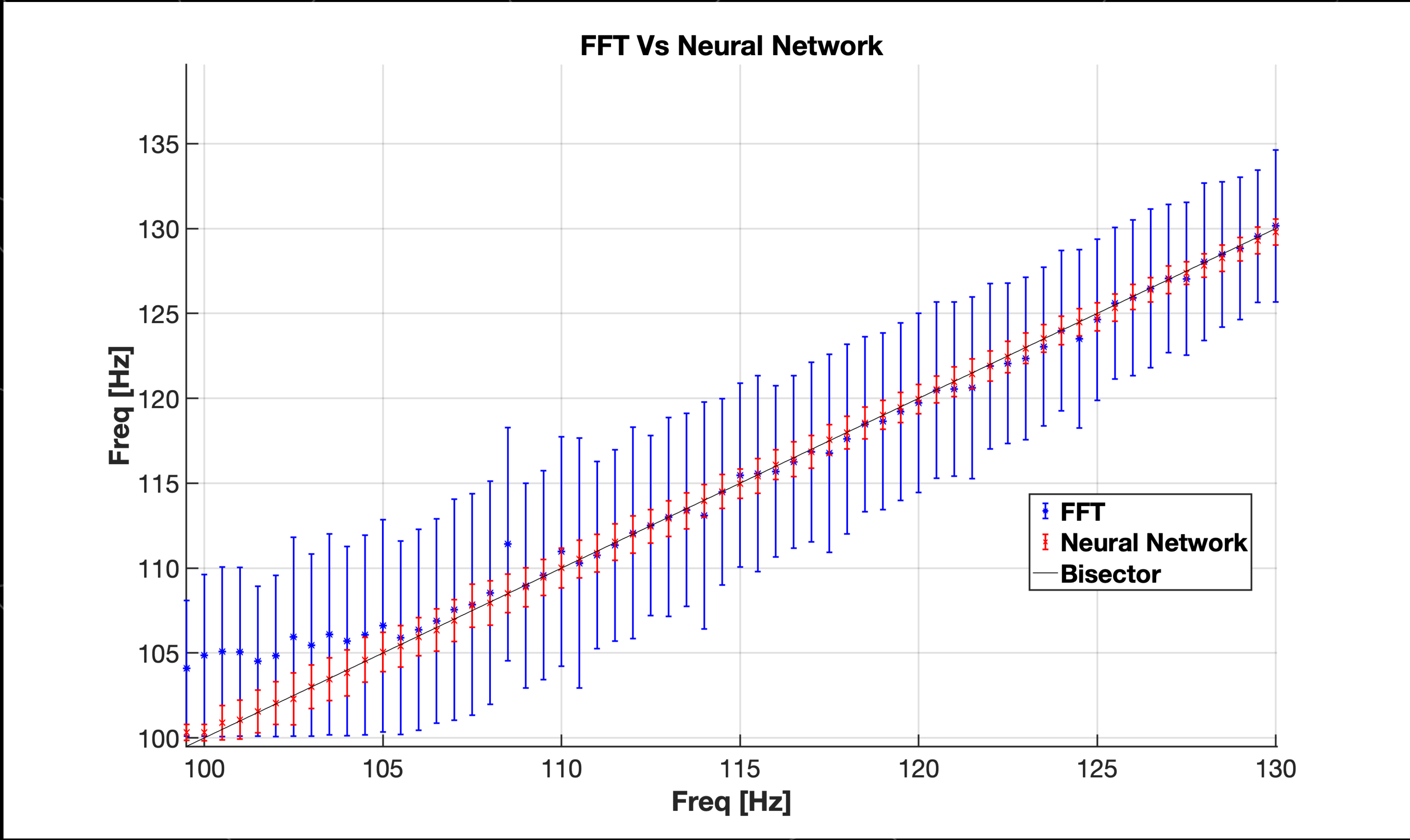




Accuracy Comparison



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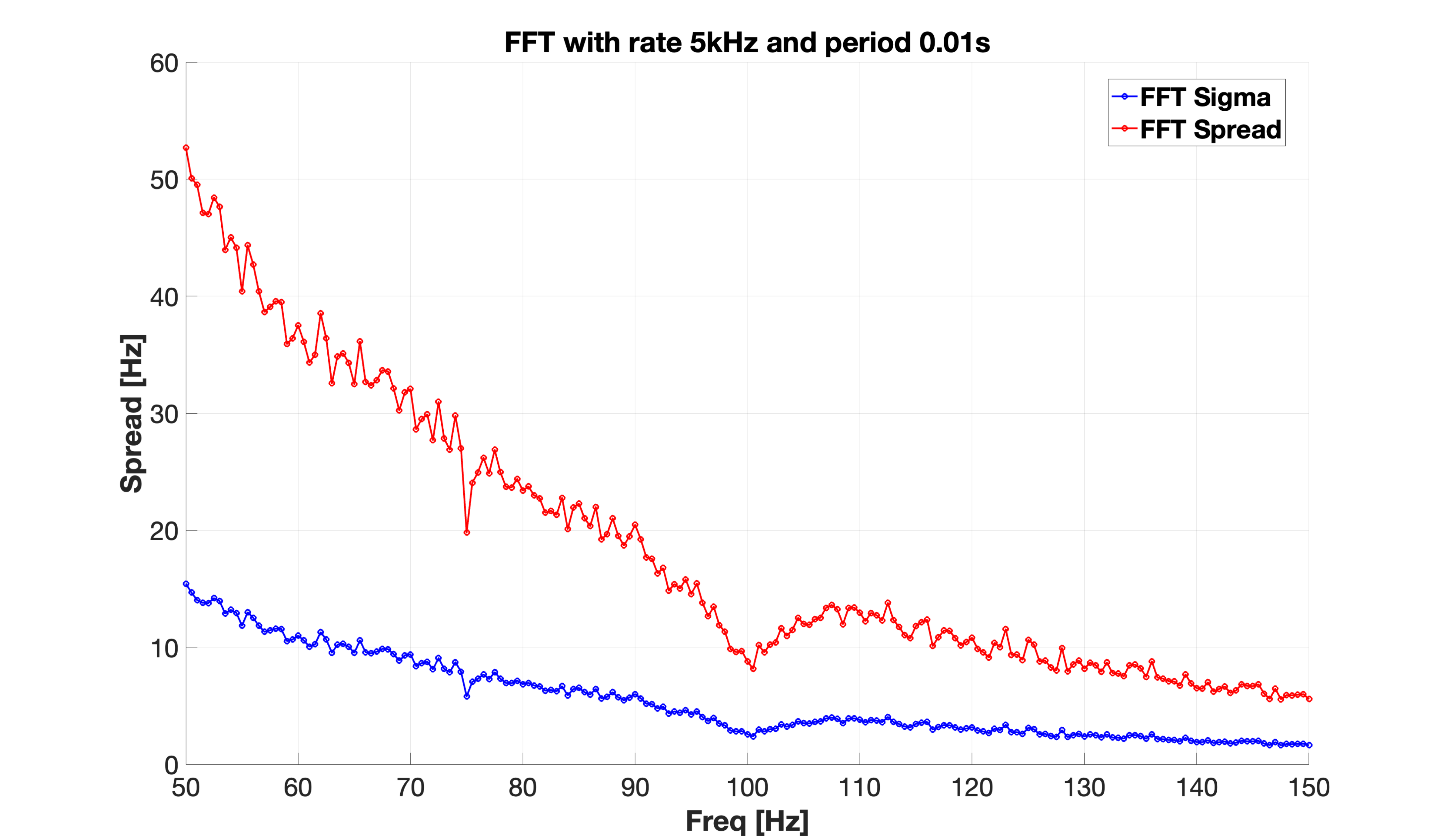
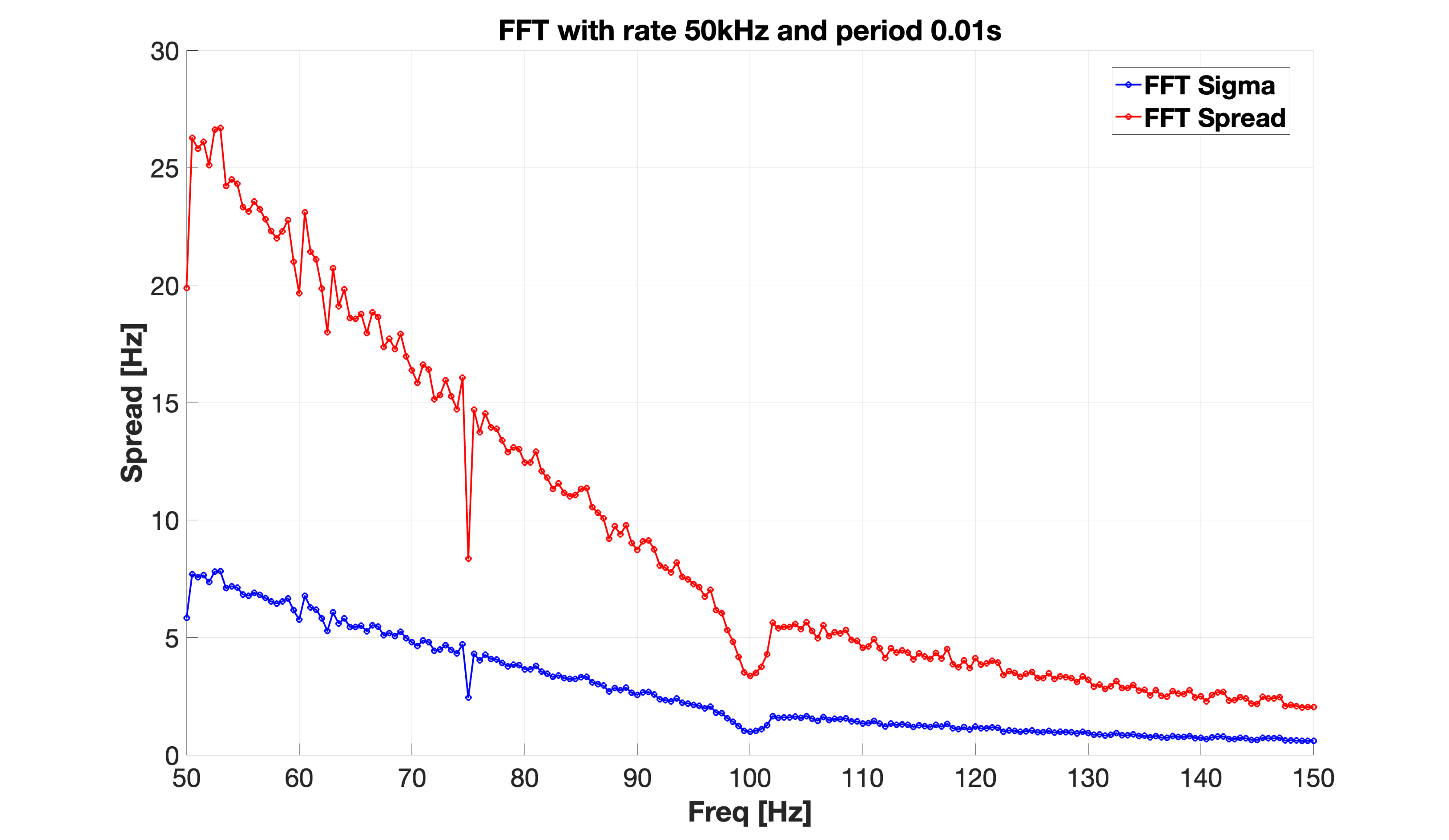
Low frequency FFT test

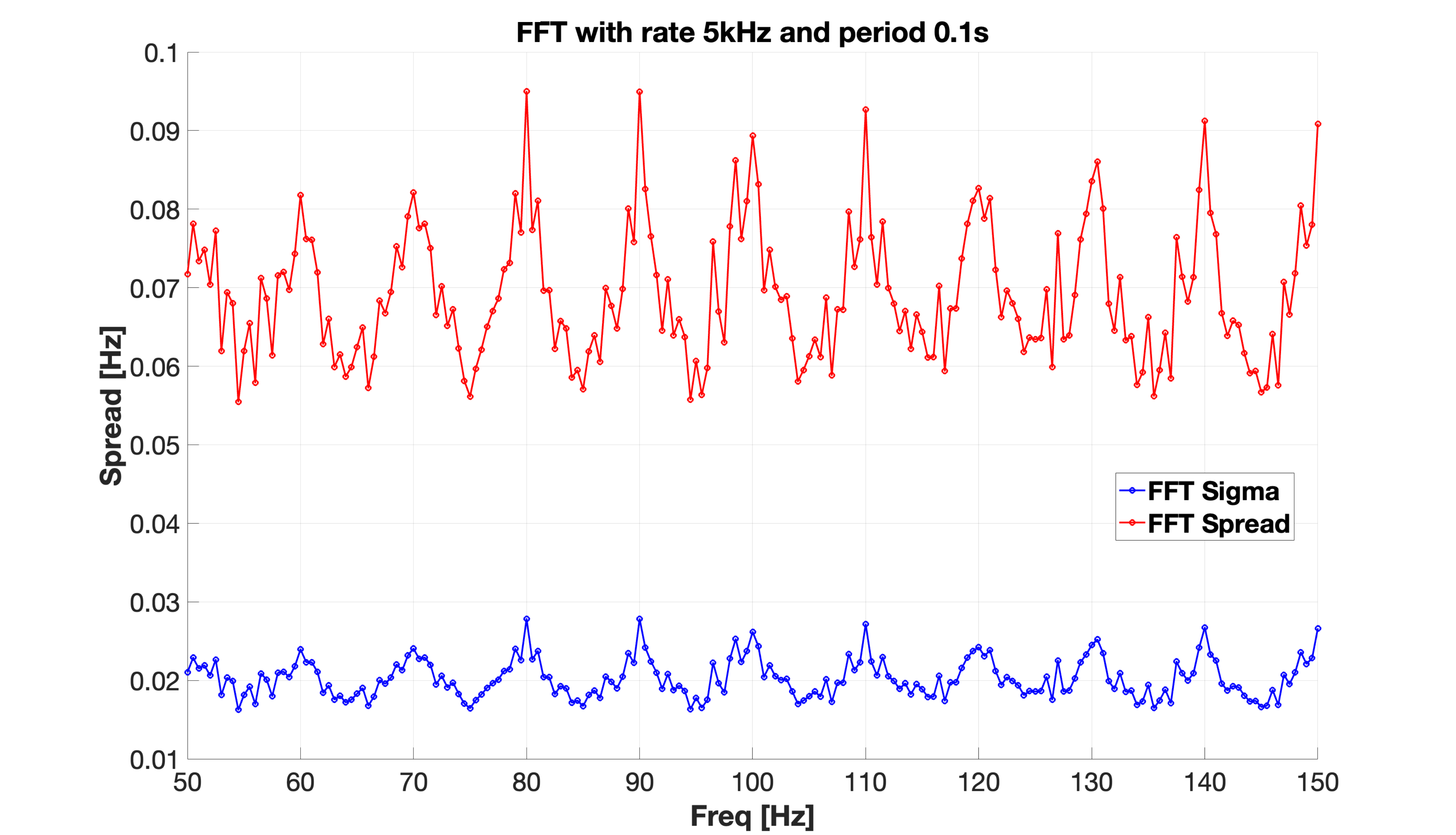
Rate = 5kHz
Delay = 0.01 sec



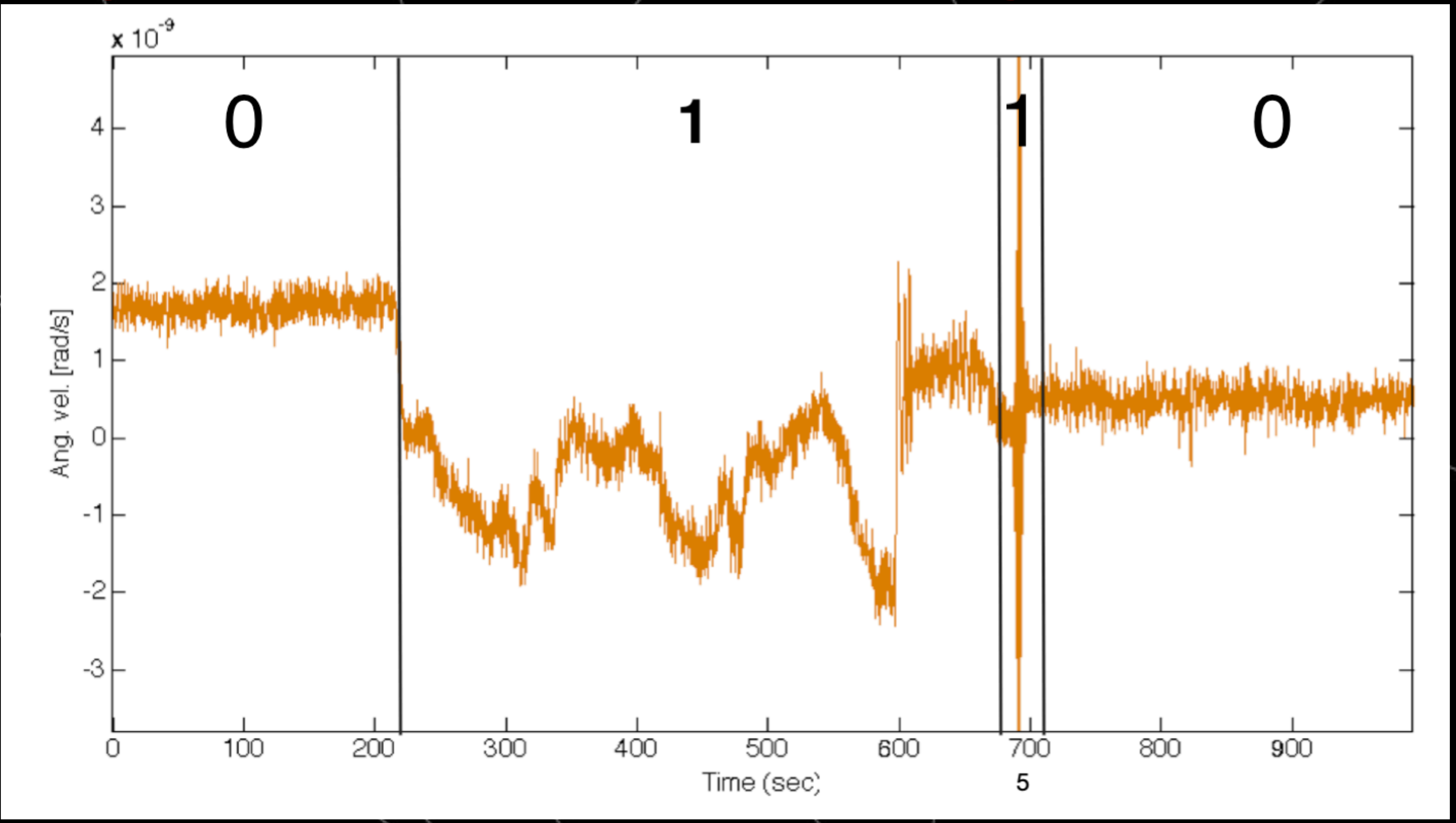
Rate = 50kHz
Delay = 0.01 sec



Rate = 5kHz
Delay = 0.1 sec

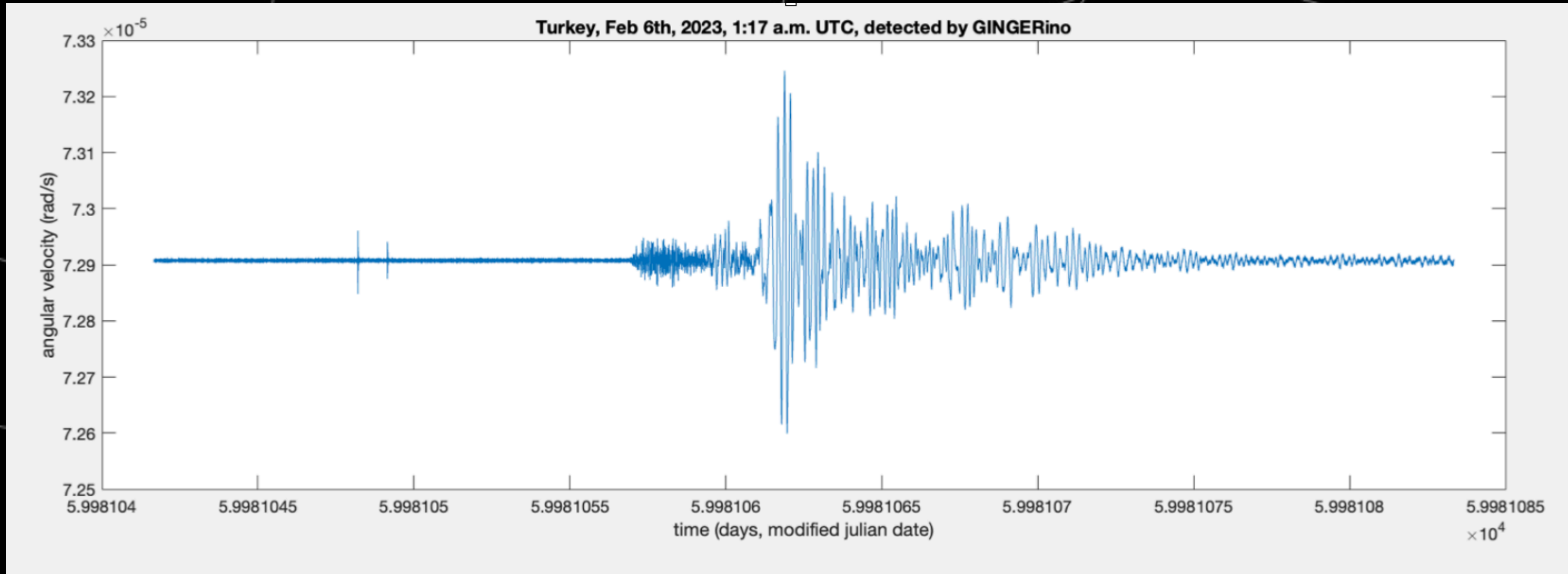


The typical disturbances of the reconstructed signal

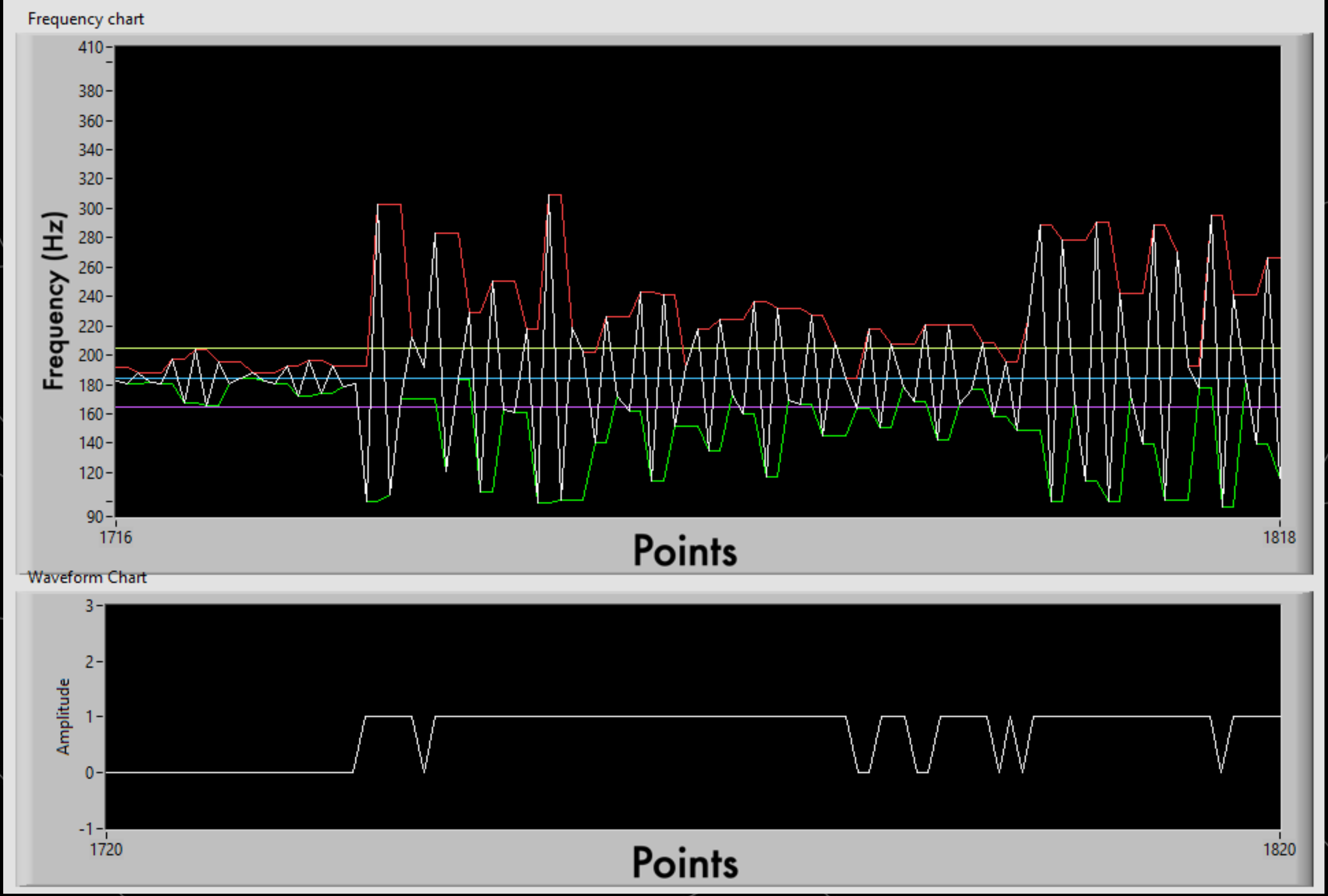


Contribution of the earthquake of Turkey of February 6th

Typical disturbance due to laser dynamics during the mode jump

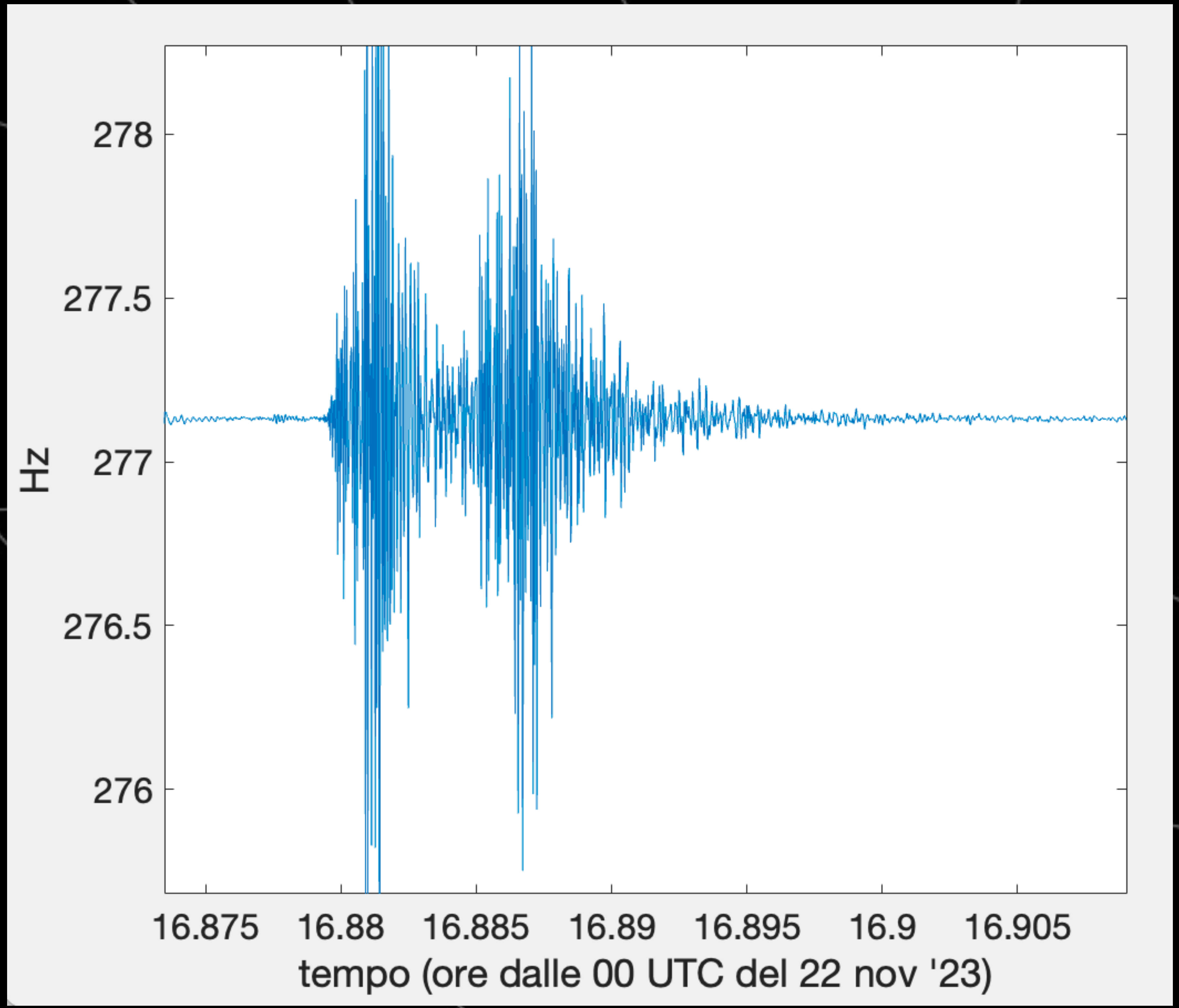


Implementation on GP2

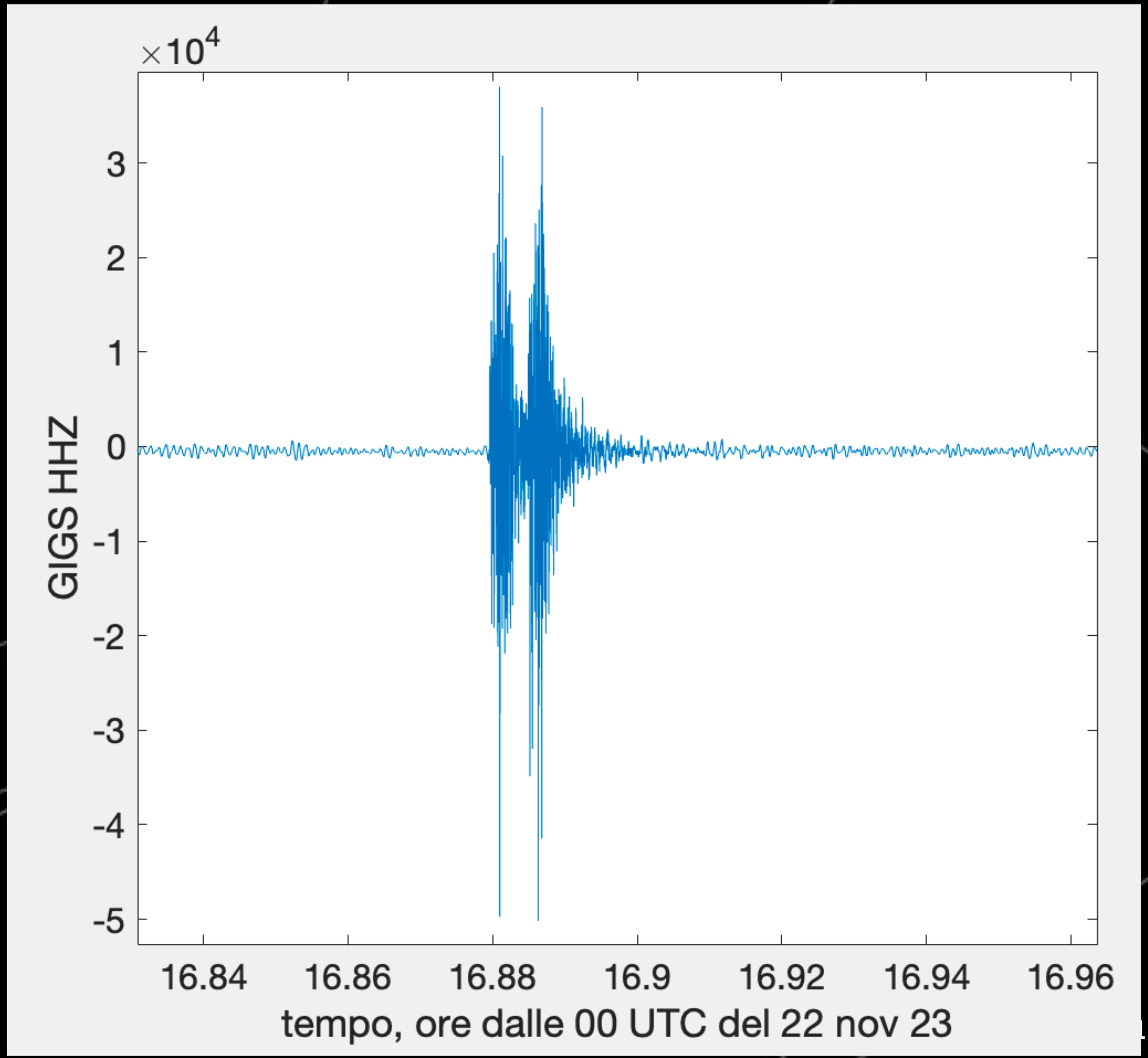


Map from GIGS to GINGERINO

To have enough examples of earthquakes to train a network to recognize them, we create a network that generates the earthquakes seen by a Ring Laser Gyroscope (RLG), starting from the earthquakes revealed by GIGS. This is possible because we have a GIGS station co-located with GINGERINO. This NN is later applied to other stations similar to GIGS to obtain new examples of earthquakes seen by an RLG



Map from GIGS to GINGERINO



Map of earthquake origins

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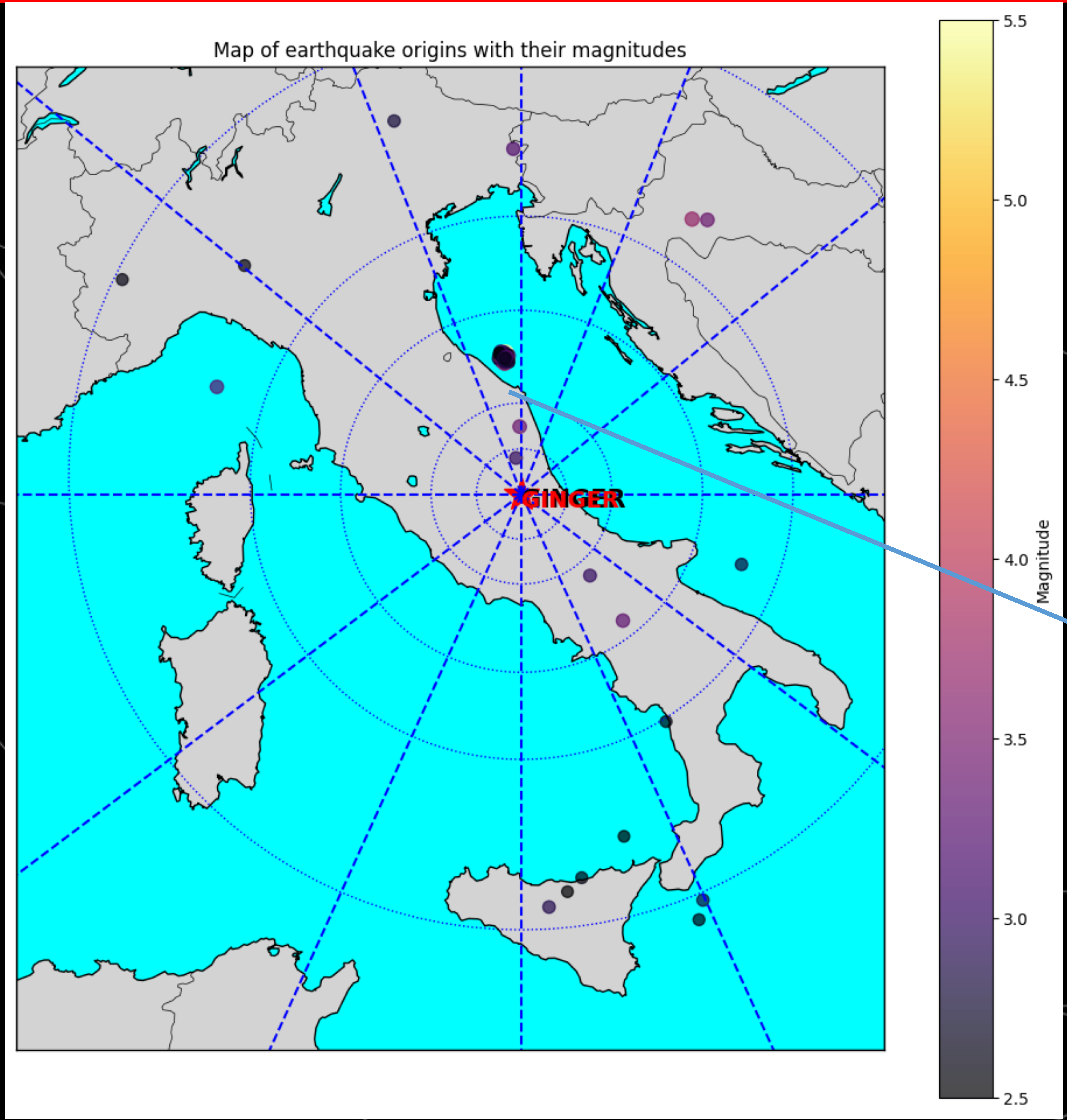


For the NN training we have selected 94 earthquakes starting from magnitude 2.5 to 5.5

Occurred between 1-11-22 and 17-11-22 (UTC)

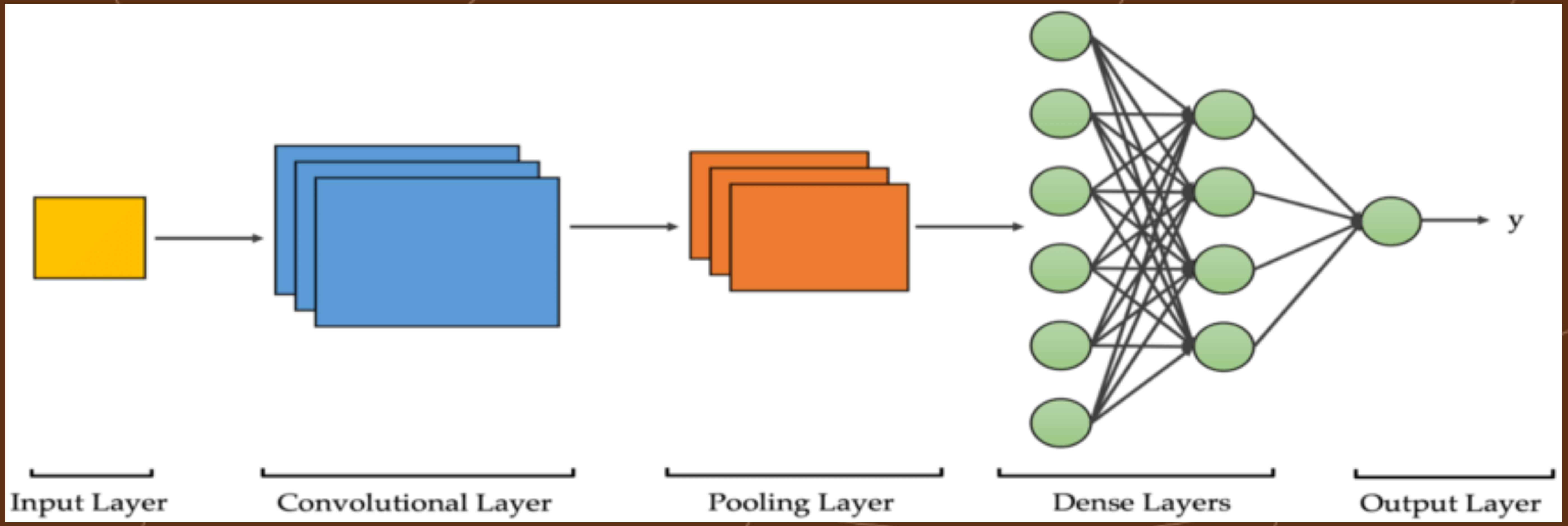
In this small portion are concentrated 75 events that are part of a seismic swarm


Test Example (Positive Label)
Amplitude
Points
Origi
Filter
Test Example (Positive Label)
Original Signal
Filtered Signal
Amplitude
Points
Test Example (Positive Label)
Original Sign
Filtered Sign
Amplitude
Points
Test Example (Positive Label)
Original Signal
Filtered Signal
Amplitude
Points

Test Example (Positive Label)
Original Signal
Filtered Signal
Amplitude
Points
Test Example (Positive Label)
Original Signal
Filtered Signal
Amplitude
Points
Test Example (Positive Label)
Original Signal
Filtered Signal
Amplitude
Points
Test Example (Positive Label)
Original Signal
Filtered Signal
Amplitude
Points

Fundamental points for training

- Structure



- Folding

1064 examples divided into 4 folds and repeated the training using each fold as validation data

- Metrics

$$\text{Accuracy} = \frac{\text{True Positives (TP)} + \text{True Negatives (TN)}}{\text{Total Samples}} = \frac{TP + TN}{TP + TN + FP + FN}$$

$$\text{Precision} = \frac{TP}{TP + FP}$$

$$\text{TPR (True Positive Rate)} = \frac{TP}{TP + FN}$$

$$\text{Recall} = \frac{TP}{TP + FN}$$

$$\text{FPR (False Positive Rate)} = \frac{FP}{FP + TN}$$

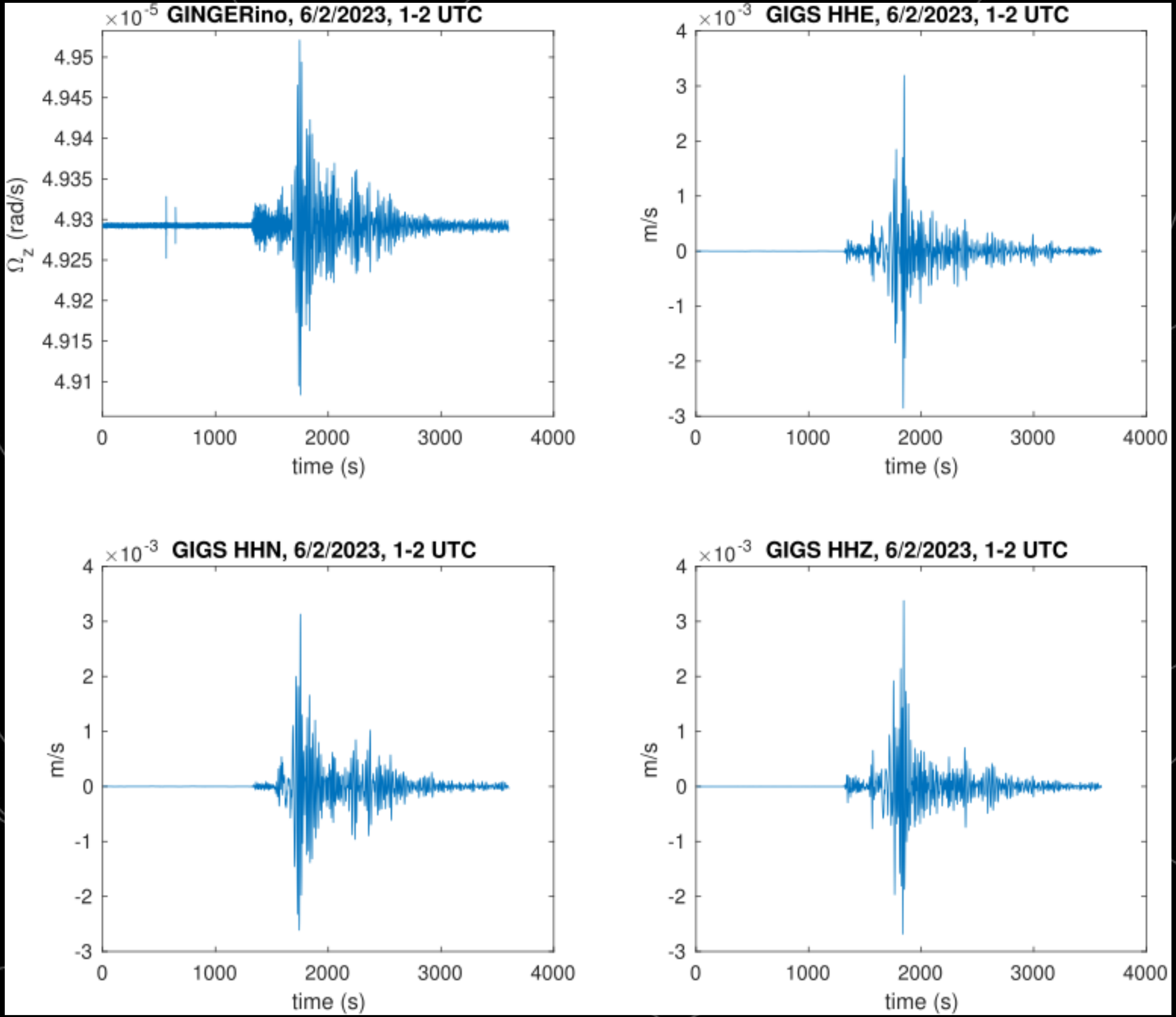
$$\text{AUC} = \int_0^1 \text{TPR}\, d(\text{FPR}),$$

Confusion Matrix and Results

We obtained 100% accuracy on data never seen by NN


False Negative 761
Prob = 2.861955e-06
Original Signal
Filtered Signal
Amplitude
Points
False Negative 62
Prob = 0.4224405
Prob = 0.4224405
Original Sign
Filtered Sign
Amplitude
Points
False Negative 519
Prob = 2.9153218e-12
Original Signal
Filtered Signal
Amplitude
Points
False Negative 744
Prob = 0.17842172
Original Signal
Filtered Signal
Points

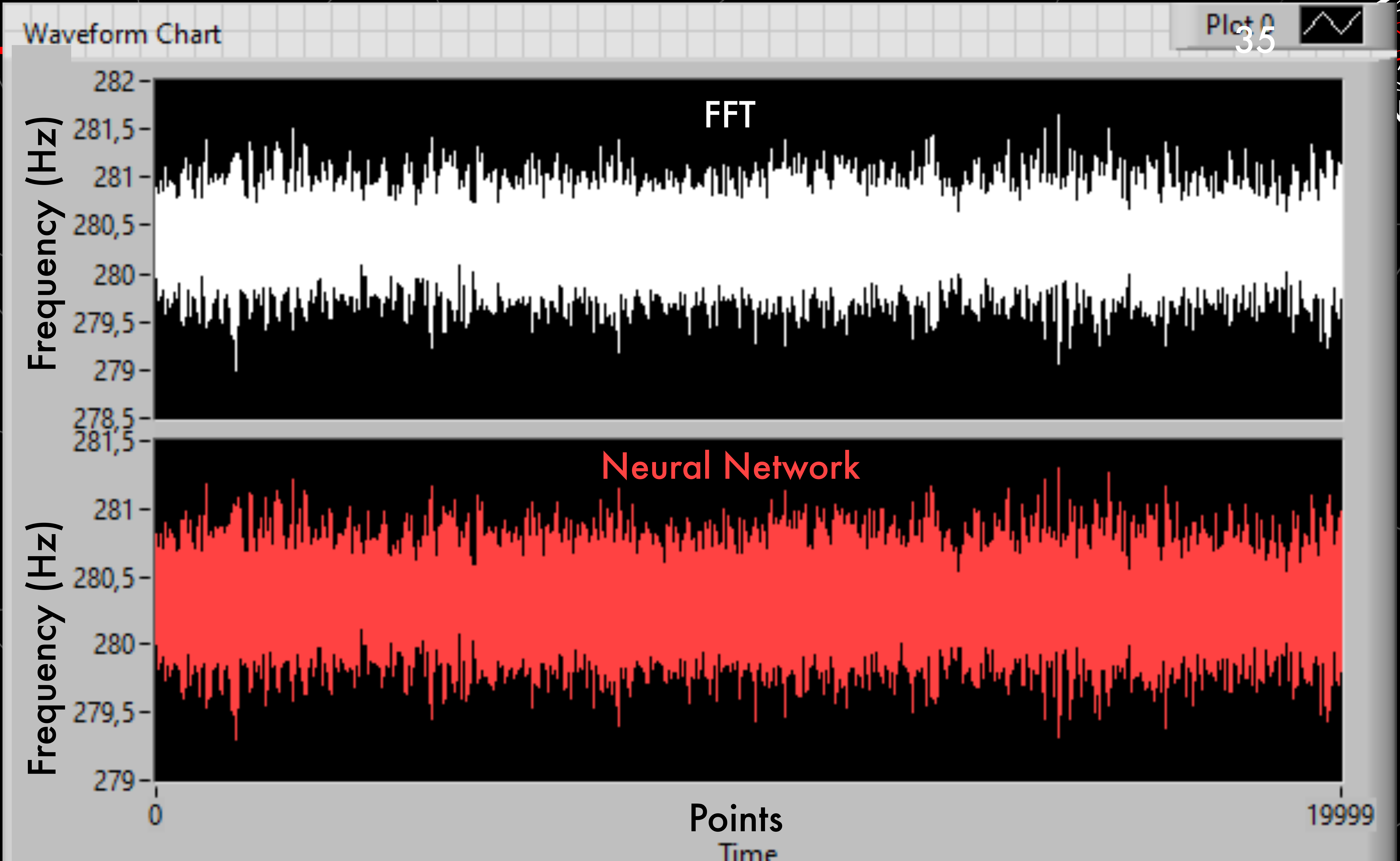
Map from GIGS to GINGERINO



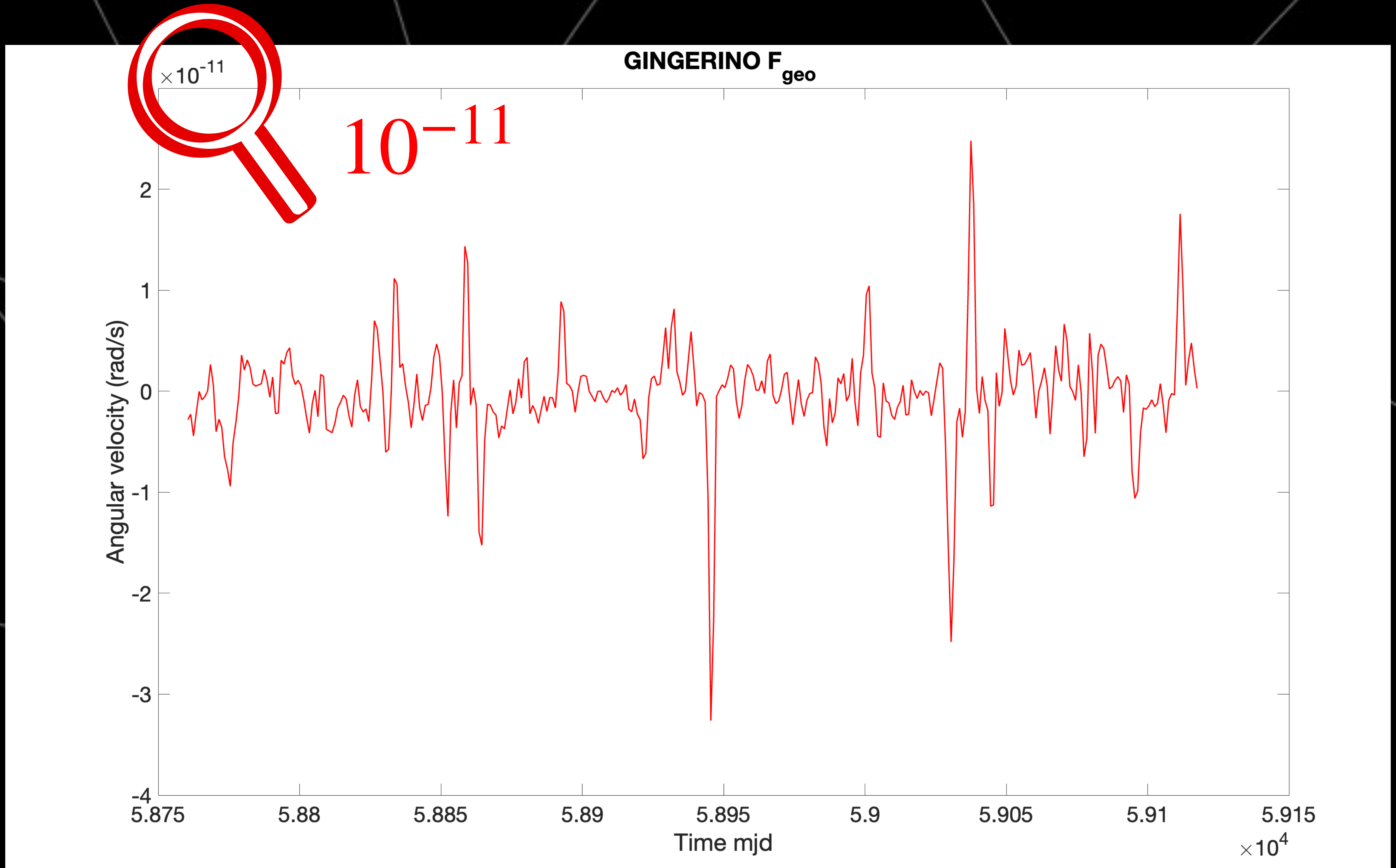
GINGER

THANKS FOR YOUR ATTENTION

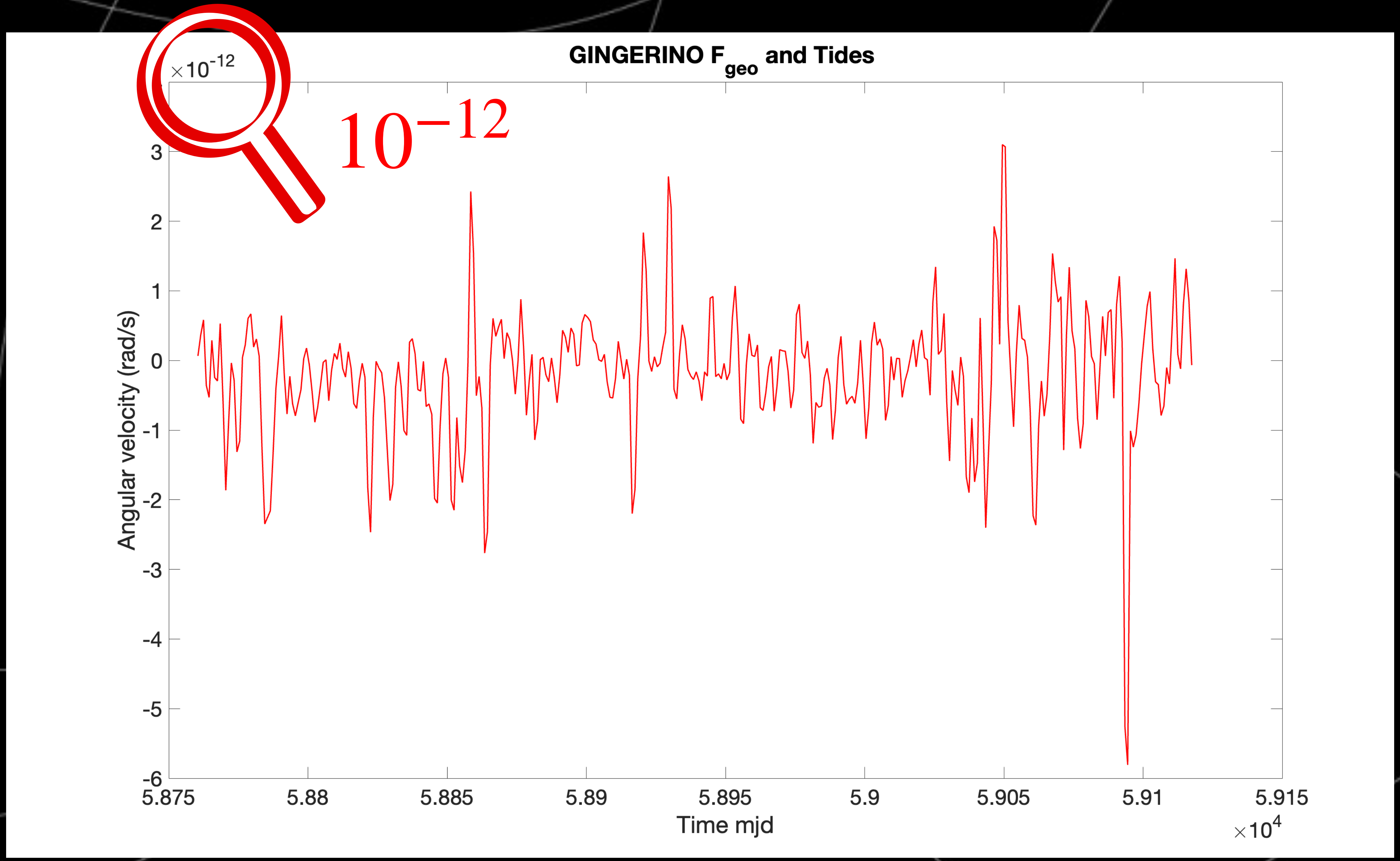
GINGER


Waveform Chart
Plot 0
FFT
Neural Network
Frequency (Hz)
282
281,5
281
280,5
280
279,5
279
278,5
Frequency (Hz)
281,5
281
280,5
280
279,5
279
0
19999
Points
Time

Gingerino Signals



We have on the left the Gingerino signal in which systematic laser corrections and terrestrial rotational componete, including polar motion and Chandler wobble (obtained from IERS measurements) were removed.



On the right we have the Gingerino signal, obtained starting from the previous one, in which we solved and subtracted the tides through the use of the GOTIC2_mod program [2].

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$$\theta = \frac{\pi}{2} - \alpha \qquad \gamma = \theta + \frac{\pi}{2}$$

$$f_{TOT} = S\Omega_{\oplus}[cos(\beta) - (a-b)sen(\theta)sen(\beta-\theta) + 2bcos(\theta)cos(\beta-\theta)]$$

S is the scale factor of our Sagnac ring

LET'S PUT Z-AXIS LONG $\hat{u}_r$. SO β, THE ANGLE BETWEEN THE AXIS OF OUR SAGNAC RING AND THE EARTH'S AXIS OF ROTATION, MUST BE PUT EQUAL TO θ :

$$a = 2\frac{m}{r} = 1.3918082245(20) \times 10^{-9}$$

$$f_{zTot} = S\Omega_{\oplus}[cos(\theta) + 2bcos(\theta)]$$

$$b = \frac{GI}{c^2r^3} = 2.301326(700) \times 10^{-10}$$

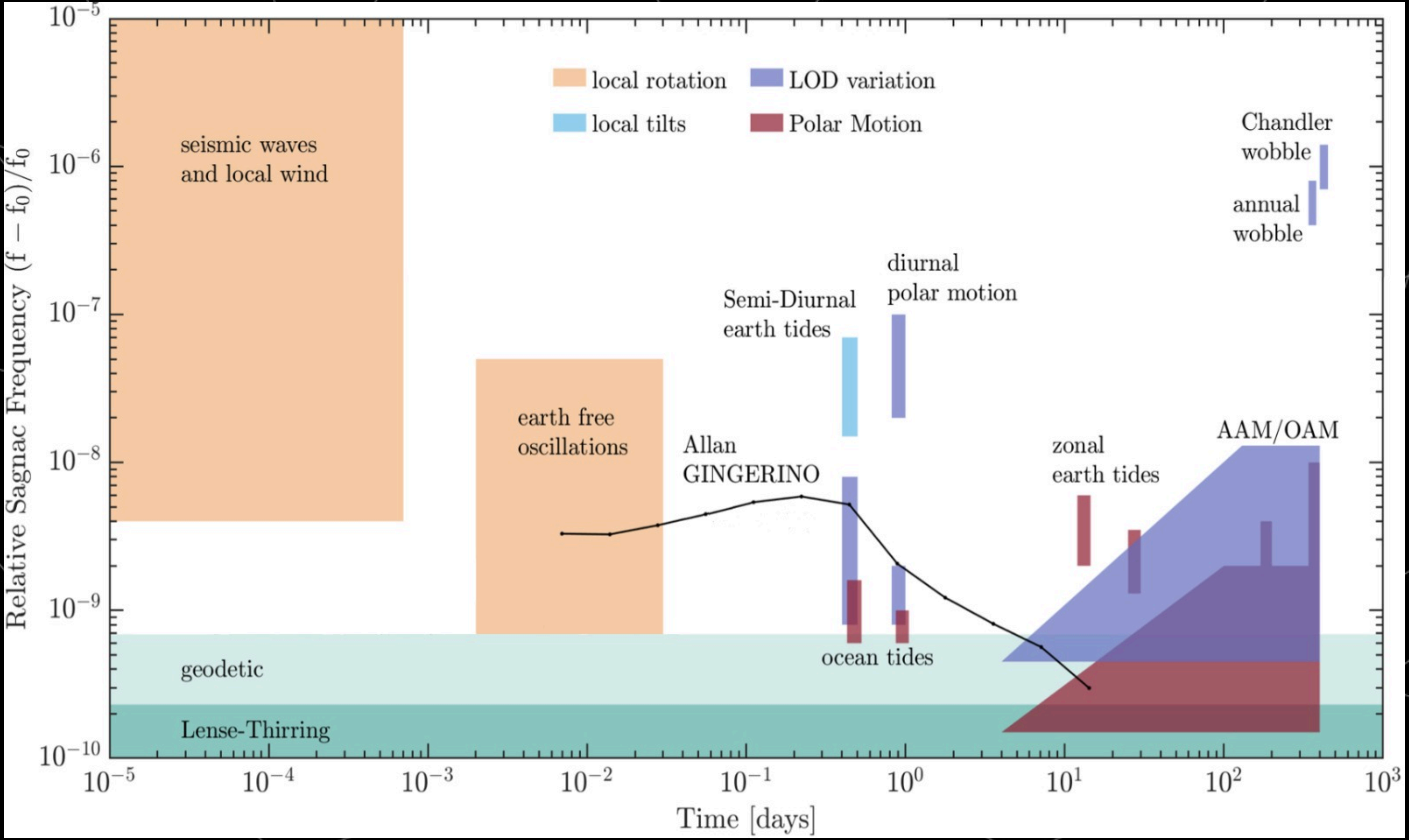
Earth's rotation — Lense-Thirring effect

PUTTING Z-AXIS LONG $\hat{u}_\theta$ WE HAVE THAT $\beta = \gamma = \theta + \frac{\pi}{2}$ (ATTENTION IS DOWNWARDS) :

$$f_{xTot} = S\Omega_{\oplus}[-sen(\theta) - asen(\theta) + bsen(\theta)]$$

Earth's rotation — deSitter effect — Lense-Thirring effect

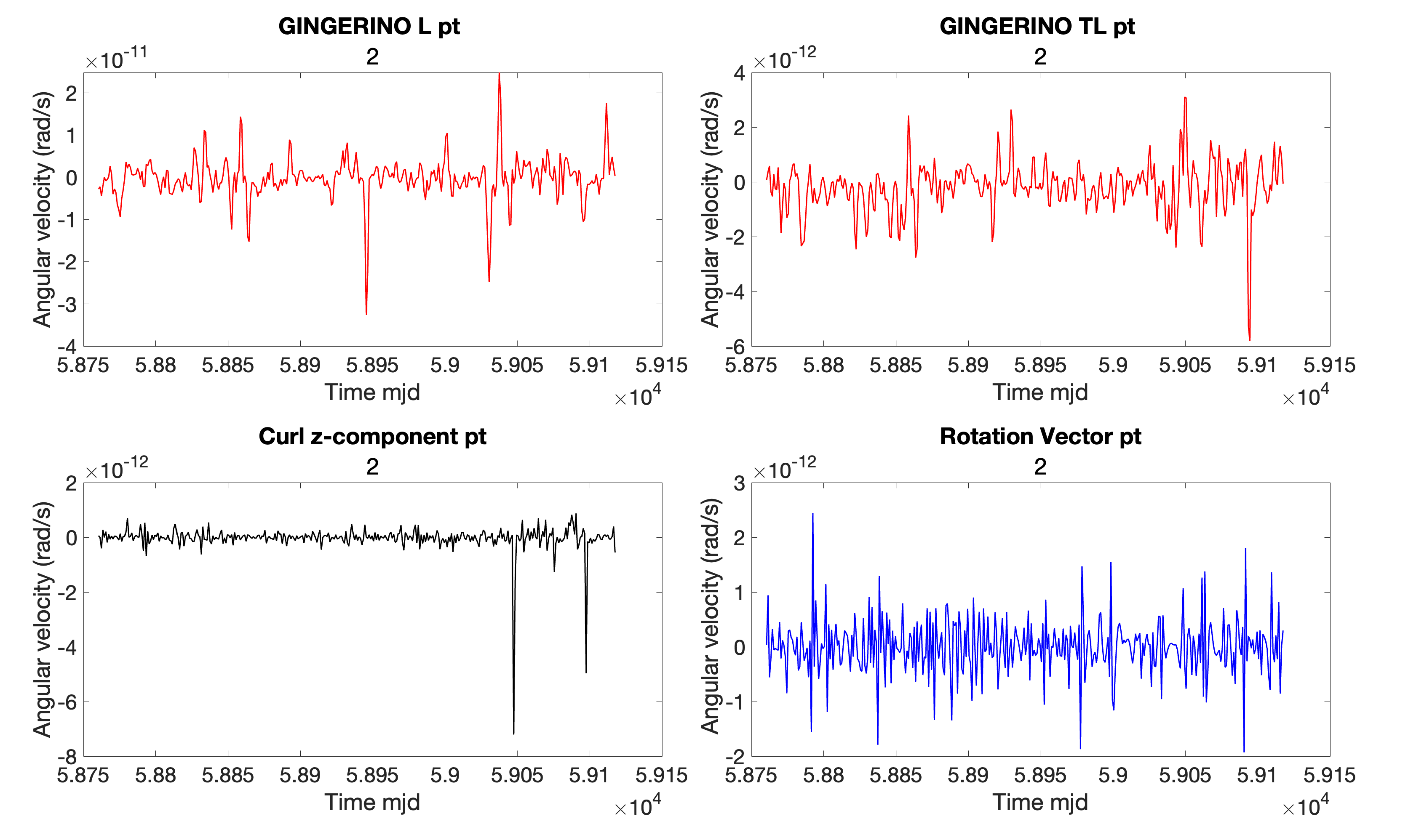
Allan deviation



GINGER sensitivity targets: 1 part out of 10^9 ***-*** 10^{11} ***of the Earth's rotation***

1 part out of 10^9 ***is the fundamental physics watershed***

GINGER



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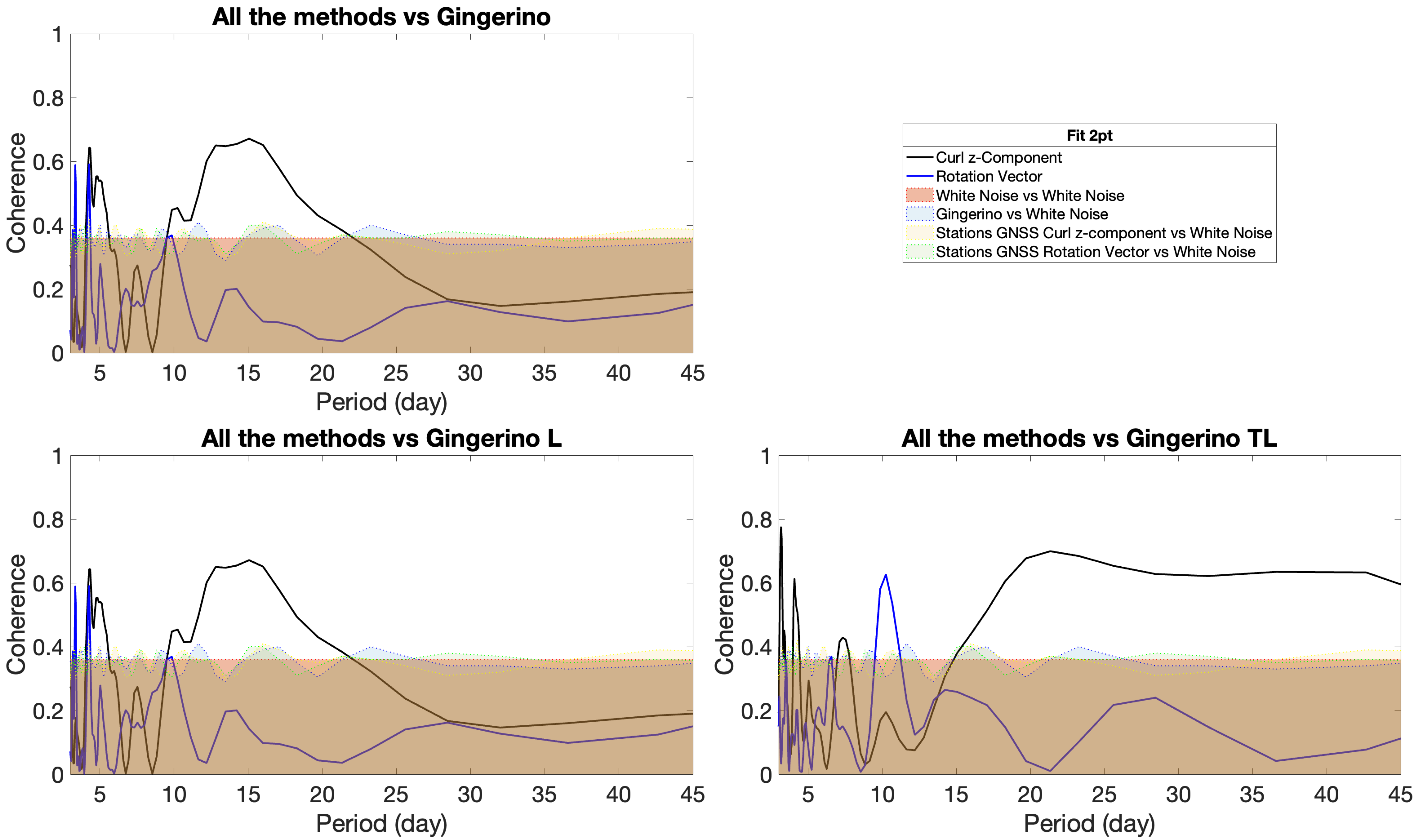
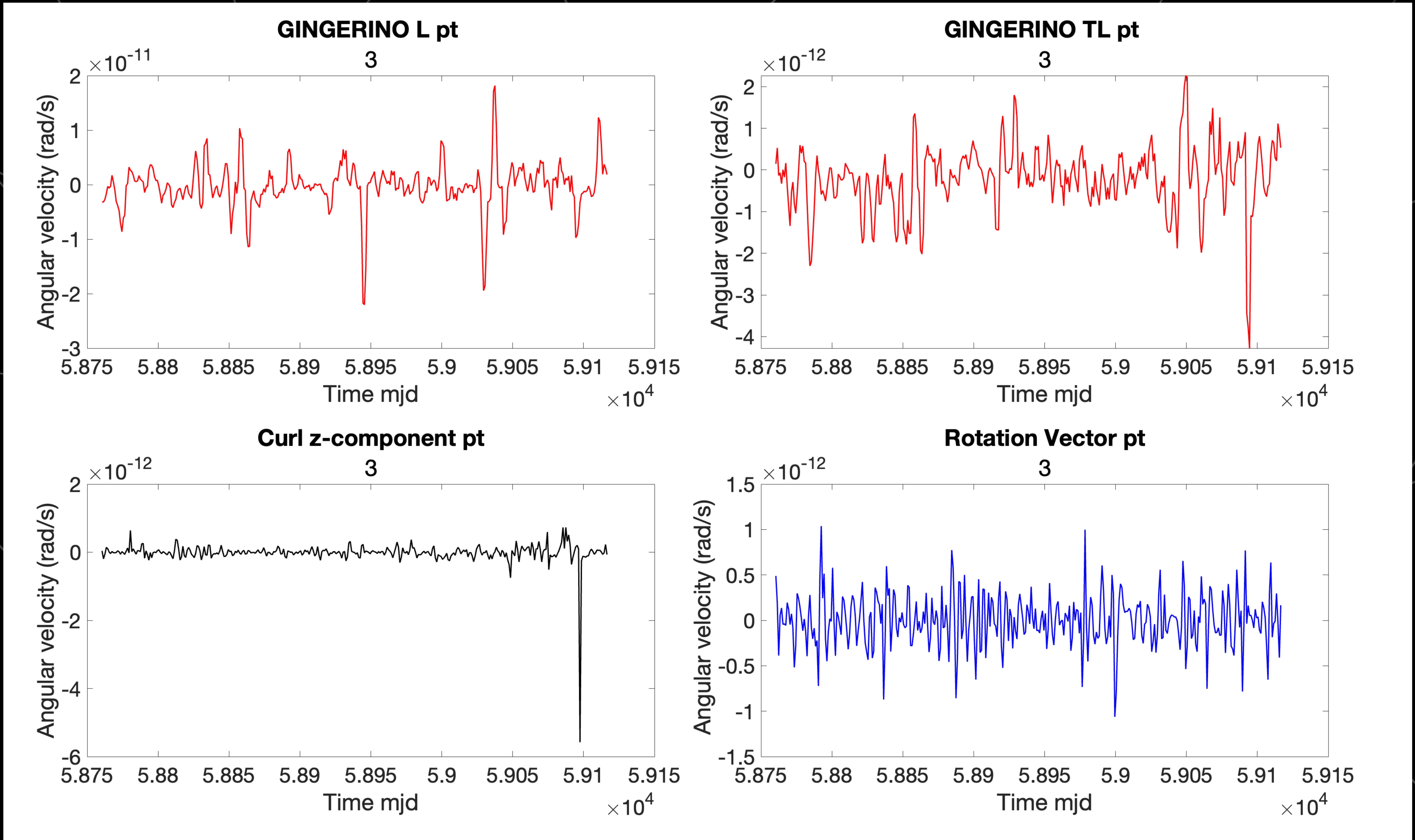
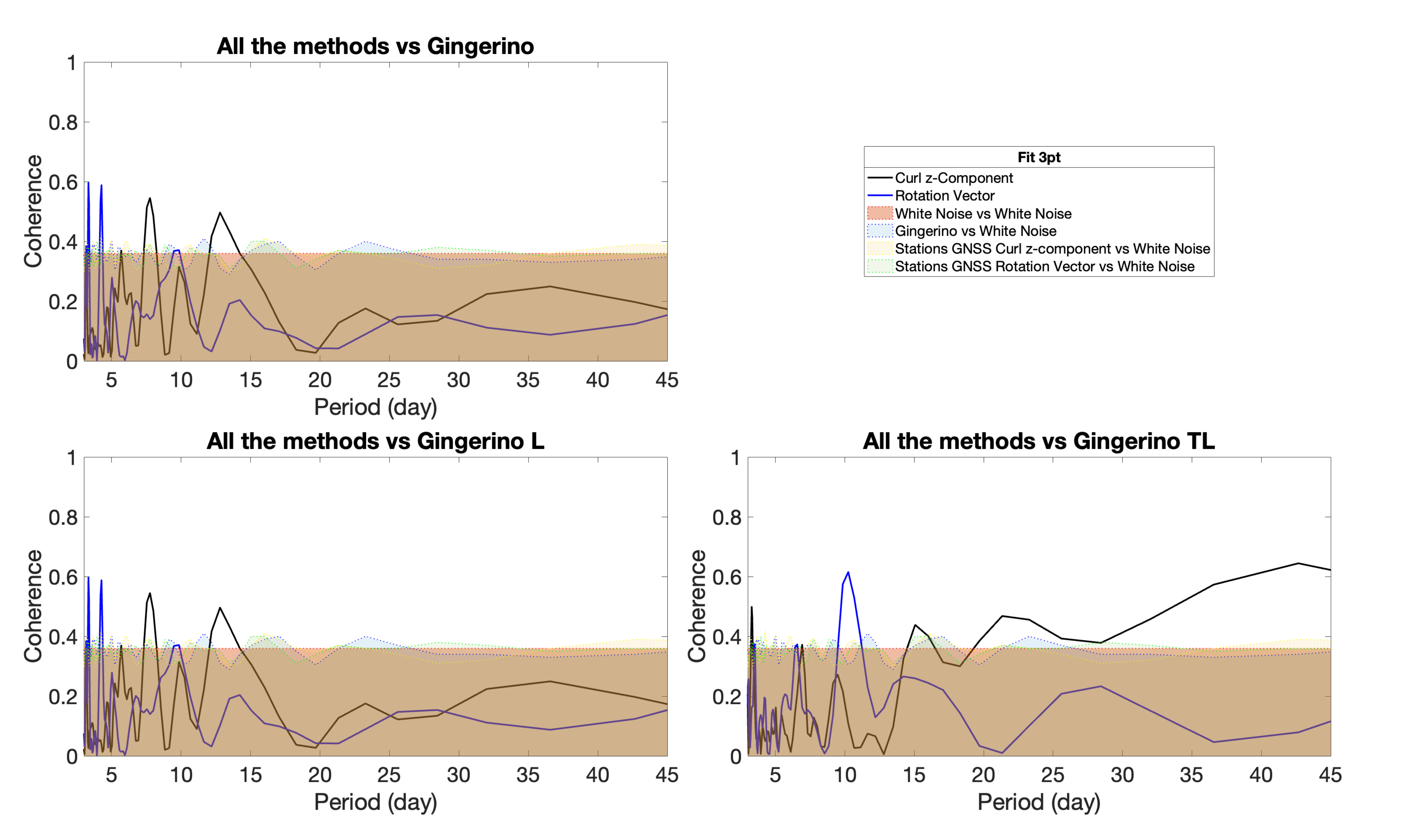
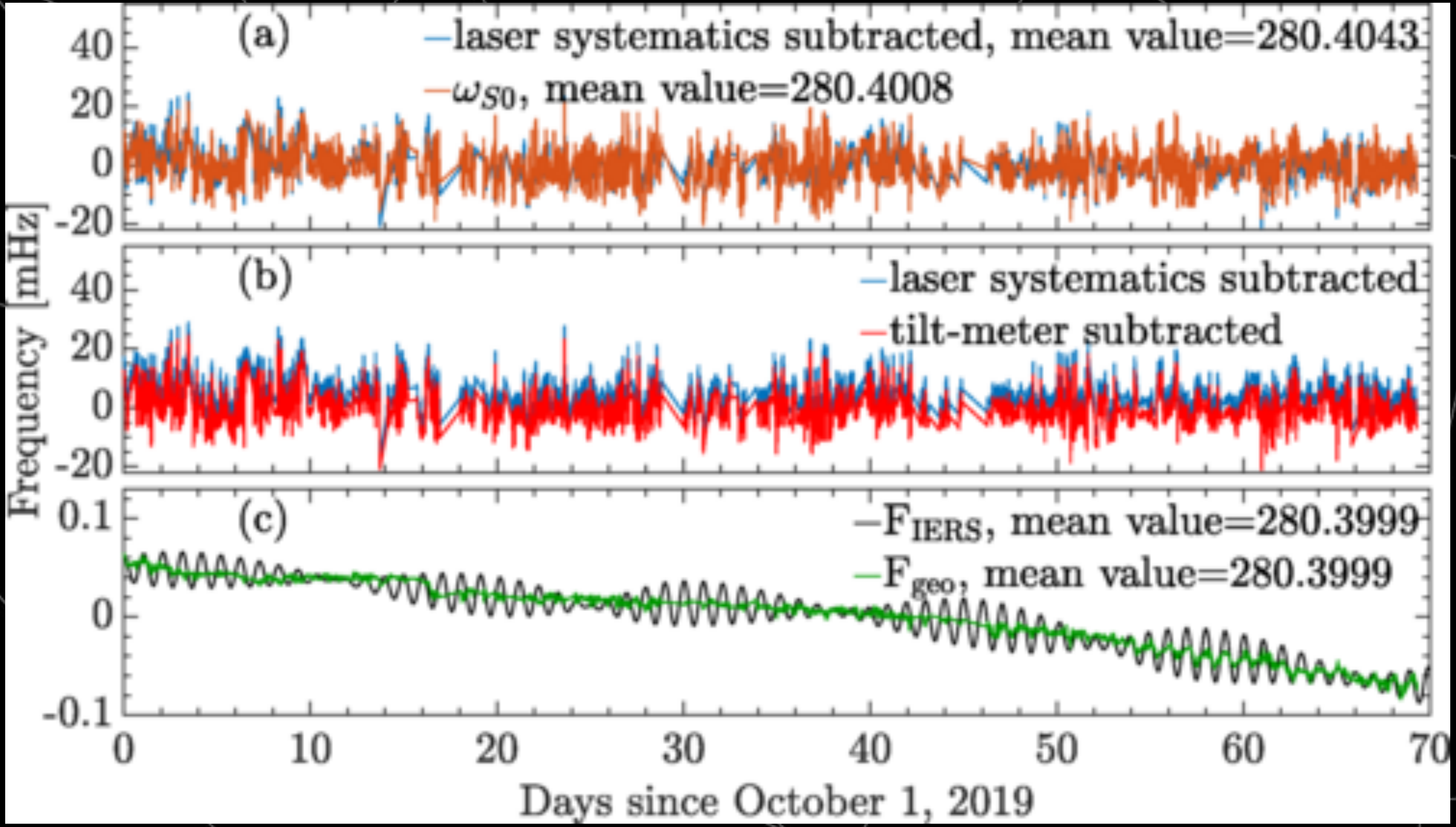
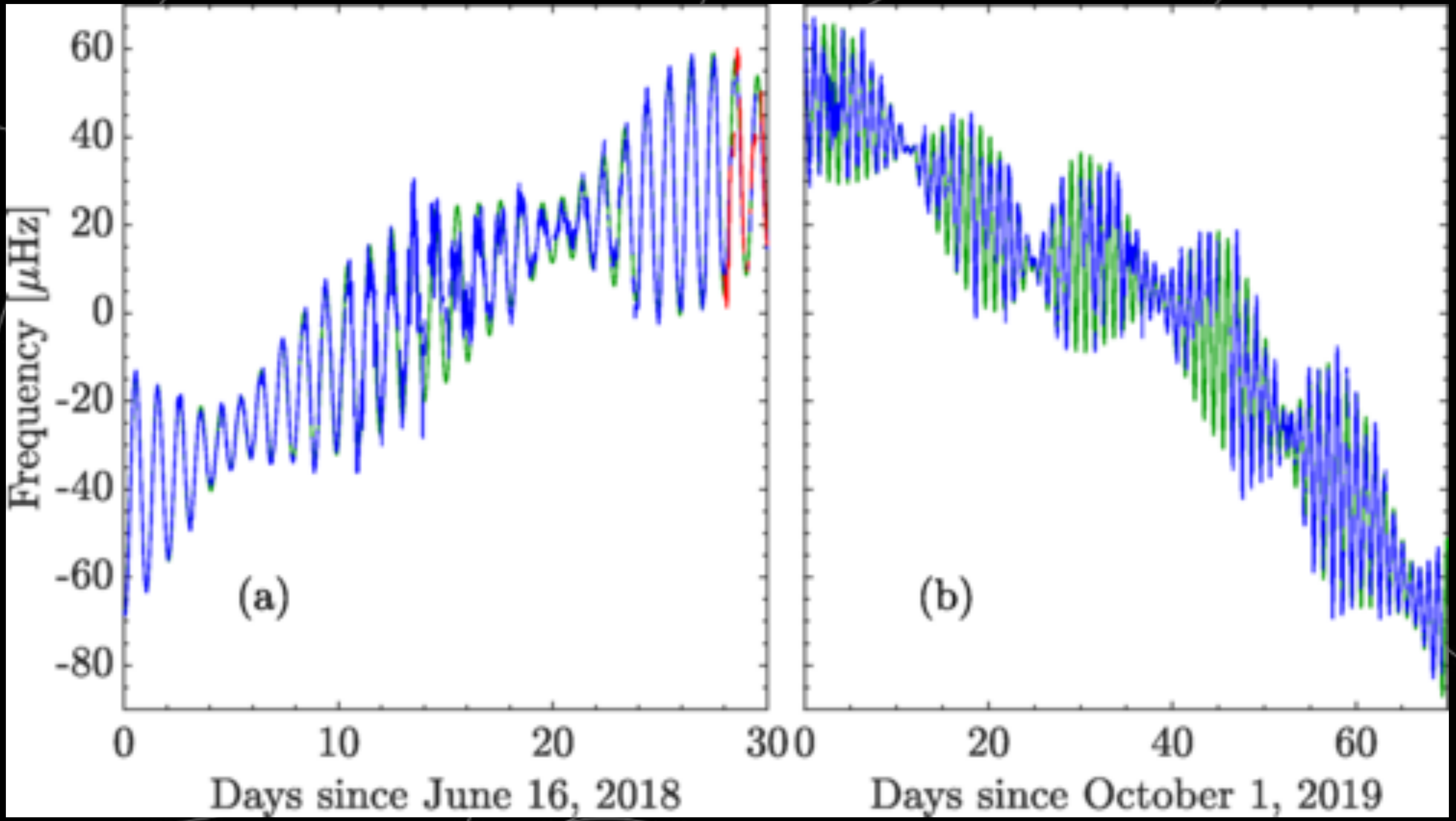
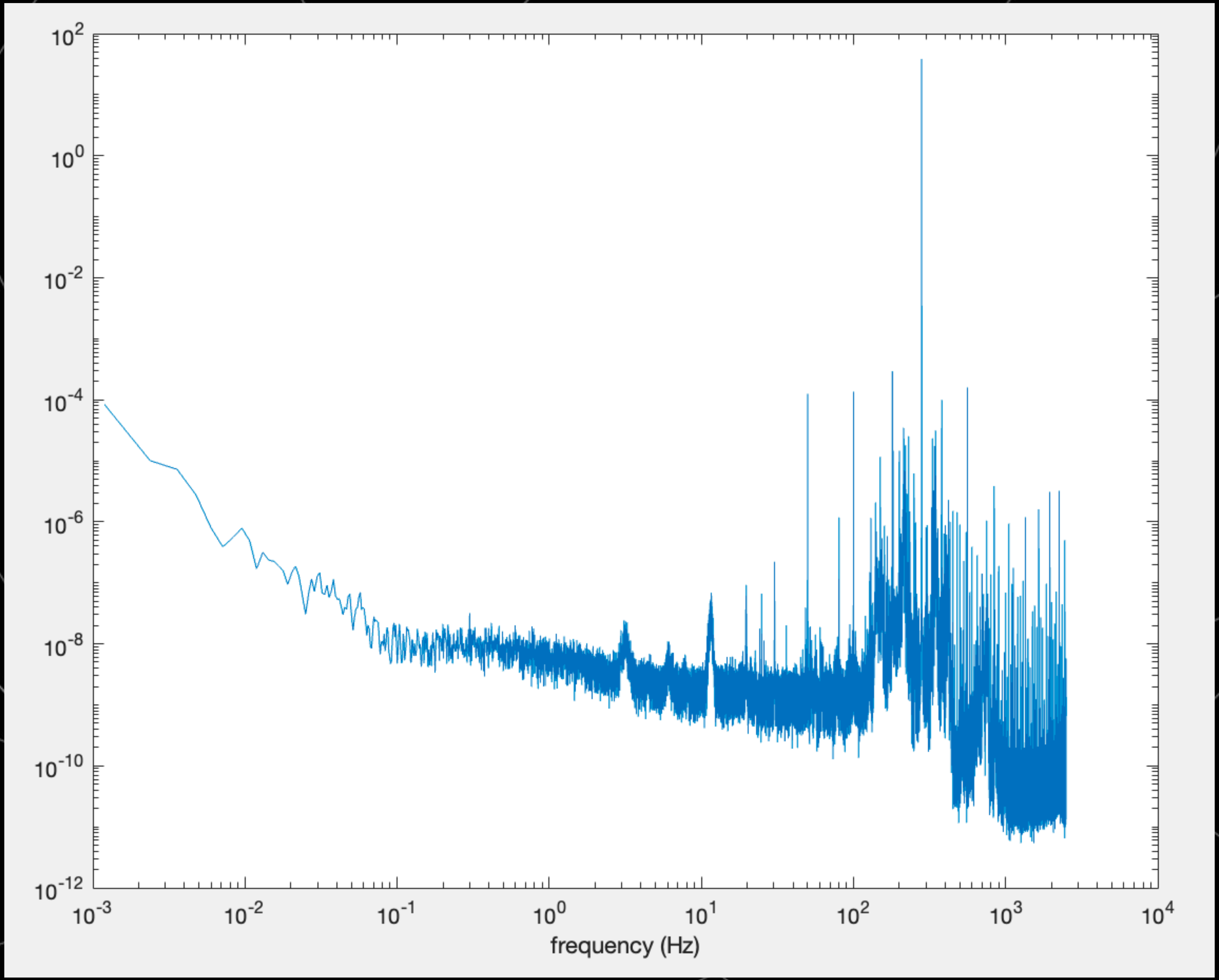

All the methods vs Gingerino
Coherence
Period (day)
Fit 2pt
Curl z-Component
Rotation Vector
White Noise vs White Noise
Gingerino vs White Noise
Stations GNSS Curl z-component vs White Noise
Stations GNSS Rotation Vector vs White Noise
All the methods vs Gingerino L
Coherence
Period (day)
All the methods vs Gingerino TL
Coherence
Period (day)


GINGERINO L pt
3
×10^-11
Angular velocity (rad/s)
2
1
0
-1
-2
-3
5.875 5.88 5.885 5.89 5.895 5.9 5.905 5.91 5.915
Time mjd
×10^4
GINGERINO TL pt
3
×10^-12
Angular velocity (rad/s)
2
1
0
-1
-2
-3
-4
5.875 5.88 5.885 5.89 5.895 5.9 5.905 5.91 5.915
Time mjd
×10^4
Curl z-component pt
3
×10^-12
Angular velocity (rad/s)
2
0
-2
-4
-6
5.875 5.88 5.885 5.89 5.895 5.9 5.905 5.91 5.915
Time mjd
×10^4
Rotation Vector pt
3
×10^-12
Angular velocity (rad/s)
1.5
1
0.5
0
-0.5
-1
-1.5
5.875 5.88 5.885 5.89 5.895 5.9 5.905 5.91 5.915
Time mjd
×10^4


All the methods vs Gingerino
Coherence
Period (day)
Fit 3pt
Curl z-Component
Rotation Vector
White Noise vs White Noise
Gingerino vs White Noise
Stations GNSS Curl z-component vs White Noise
Stations GNSS Rotation Vector vs White Noise
All the methods vs Gingerino L
Coherence
Period (day)
All the methods vs Gingerino TL
Coherence
Period (day)


(a)
laser systematics subtracted, mean value=280.4043
ω_{S0}, mean value=280.4008
(b)
laser systematics subtracted
tilt-meter subtracted
(c)
F_{IERS}, mean value=280.3999
F_{geo}, mean value=280.3999
Frequency [mHz]
Days since October 1, 2019


(a)
(b)
Frequency [μHz]
Days since June 16, 2018
Days since October 1, 2019



10^2
10^0
10^-2
10^-4
10^-6
10^-8
10^-10
10^-12
10^-3
10^-2
10^-1
10^0
10^1
10^2
10^3
10^4
frequency (Hz)