Draft version August 2, 2022
Typeset using LaTeX **twocolumn** style in AASTeX63

Analyzing the Parameters of the Frequency Hough Pipeline for an All Sky Search for Continuous Gravitational Waves in Neutron Star Binary Systems

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ABSTRACT

In this paper we present a parameter analysis of a pipeline using the Frequency Hough method developed by the Rome Virgo Group for the LIGO/Virgo Collaboration. This pipeline has been used to search for isolated neutron star systems emitting continuous gravitational waves, and is constantly being changed and upgraded in anticipation for LIGO/Virgo O4 data. Now, in the most preliminary sense, we attempt to introduce binary neutron star signal injections in order to observe how to pipeline performs by changing binary parameters. We report an expected increase in the signals critical ratio as the orbital period of the NS binary injection is increased past an epoch of one year. We also report a more significant separation in maximum critical ratio values in the Hough map when increasing the orbital ellipticity parameter without surpassing the pipelines limit of 0.1.

1. INTRODUCTION

Gravitational waves (GW) were first predicted by Albert Einstein after his publication in 1916, which introduced his General Theory of Relativity. They are described as ripples in space time caused by changing gravitational fields that can carry information about the source origin. Preliminary detection methods failed to capture any wave signal coming from distant sources due to their extremely small amplitudes of 1 part in $\mathcal{O}(10^{-20})$. However, modern operations such as LIGO and Virgo have been able to detect a particular type of gravitational waves using extremely sensitive interferometric techniques. On the advent of these detections, gravitational wave astronomers continue their search for signatures of events on an even smaller scale. Improving noise reduction and computational efficiency in data analysis is a crucial step for the detection of gravitational wave types that have yet to be observed.

On September 14, 2015, the LIGO interferometer in the United States first detected the GW150914 source which is now known to have been a black hole-black hole (BH-BH) merger event [5]. This specific event is more generally labeled as *compact binary coalescence* (CBC) as it can also include the collision between a black hole and a neutron star (NS), or a NS binary. CBCs emit strong GWs for a short period of time as the frequency of the wave increases during the inspiral and the final merger. Prior to merging, this frequency falls into a sensitivity range - between $\mathcal{O}(10^1)$ and $\mathcal{O}(10^3)$ Hz of optimal sensitivity that can be detected by LIGO/Virgo interferometers. There are 90 confirmed CBC detections to date. Yet, not every type of GW can be detected with current technology. For instance, the *stochastic gravitational wave background* is a theoretically predicted signal that is produced by many, individually undetected events occurring all throughout the universe at random points in space-time. This signal would likely contain events that occurred in the early universe giving us a new perspective to study the Big Bang, however, the signal is expected to peak at considerably lower frequencies that are not currently feasible to detect with modern facilities.

Furthermore, *continuous gravitational waves* (CW) are another class of signals that current interferometers are entirely expected to be able to detect. As opposed to CBCs, CWs are quasi-monochromatic in that they have a well-established frequency that only changes very slowly over periods of thousands of years at minimum. The prototypical sources of CWs are fast rotating, asymmetric NS. There are several ways in which small asymmetries in the NS shape can be produced. Strong magnetic fields contribute, as well as elastic strains slowly building up within the NS *crust*. Not only that, but external factors such as the accretion of matter, piling up to form a μm-tall, mountain-like structure on the NS surface may also cause asymmetry. These deformations would cause the star to have a rotating mass-quadrupole moment, and therefore produce a gravitational wave signal with a frequency equal to twice the NS spin frequency, and slowly varying with time (as stated above) as the spin decreases. The frequency at which the neutron star rotates decreases due to the rotational kinetic energy being lost to two different mechanisms: one is the emission of GW itself and the other, typically much stronger, is the magnetic dipole radiation produced by the rotation of their magnetic (dipole) fields. This is known as the *spin-down*, $\dot{\nu}$, which is usually a small parameter on the order of less than 10^{-9} Hz/s, reflecting the extremely low rate of change of the NS spin [3].

One major setback that astrophysicists encounter when looking for candidate CW sources is that most of these NS are not visible from Earth. In fact, astronomers have located about 2,500 pulsars to date, yet there are a predicted one billion neutron stars in our galaxy. This suggests that an all-sky search would be the most promising way to detect CWs, as this type of search does not rely on any initial parameter input. In other words, all reasonable combinations of source frequency, spin down, and location in the sky must be tried in the parameter space in order to maximize the chances of finding candidate signals. While this may be the only reasonable way to target sources that have yet to be found in the electromagnetic window, searching for every parameter at once quickly becomes computationally expensive beyond our current or even foreseeable capabilities. Directed, narrow-band and targeted searches are alternative routes that require, in increasing order, some prior knowledge about a particular source. While these impose reduced computational costs, which implies an increased the sensitivity for a particular search, they proportionally reduce the sky coverage. Luckily, various analysis methods have been developed which can significantly reduce the computing cost of each type of search, and in turn enhance their sensitivities at fixed computing resources.

The Rome Virgo Group has created a pipeline which shows promising results for the characterization of noise and the identification of parameters when looking for *isolated* neutron star systems. The group is now in the very beginning stages of applying a similar pipeline to neutron star binaries which calls for further analysis. It begins with a hierarchical procedure centered around the Hough Transform which is a method able to sum weighted counts as long as the equalized power of the Fourier Transform bin is greater than a set threshold. While there are different techniques using this Hough Transform, the Frequency Hough is one that takes interesting data points and maps them in a parameterized frequency/spin-down plane in order to be considered candidates for detection. At the present stage, in order to test and characterize the procedure, the data points being analyzed are actually fake data, or injections, which get incorporated into the real LIGO/Virgo data for the purpose of simulating how a NS binary may appear on the Hough maps. These injections are not blind, meaning we are given all of the relevant parameters about them, including the frequency and the spin-down, in advance. Indeed, these can be defined as input for the injection software, or they can be chosen randomly by the latter ad then recorded in the data file, as described in later sections.

Provided this algorithm succeeds in the identification of these injected signals, future plans to implement it using updated detector data increases our chances of making the first continuous wave detection to date. It should be noted that the overall intent for this newer pipeline for binaries is simply to investigate its *current* efficiency with the knowledge that it may not be the optimal approach, but that it could still be useful for the discovery of particularly strong binary signals.

2. THEORY

When a NS rotates rapidly, with frequency, ν, around an axis with respect to which it has a non-negligible mass-quadrupole moment, its rotation is expected to lead to the emission of a GW signal, with frequency $f = 2\nu$ and a characteristic amplitude (or strain) of the order

$$h_0 = \frac{4\pi^2 G}{c^4}\frac{I_{zz}\epsilon f_0^2}{d} \tag{1}$$

.

This amplitude (at the detector, not at the source) depends on the stars moment of inertia, I_{zz}, with respect to the principal axis that is aligned with the axis of rotation. This also influences the equatorial ellipticity $\epsilon = \frac{I_{xx}-I_{yy}}{I_{zz}}$ which describes how much the star is deformed from a shape that is symmetric about the rotation axis. Interestingly, estimations for the maximum breaking strain of neutron stars have not been successfully done, causing the actual equatorial ellipticity to remain an unknown quantity. The distance, d of the source is the final important parameter for h_0.

This rotational movement is predicted to emit a continuous gravitational wave signal on the order of 10^{-25}. More precisely, the strain amplitude of the source as a function of time is expressed as [1]

$$h(t) = H_0(H_+A^+ + H_\times A^\times)e^{j(\omega(t)t+\Phi_0)} \tag{2}$$

In this expression, the signal frequency at time t_0 is $f_0 = (\omega(t_0))/\pi$, and the phase is Φ_0. The two complex amplitudes can further be represented by [2]

$$H_+ = \frac{\cos 2\psi - j\eta \sin 2\psi}{\sqrt{1+\eta^2}} \tag{3}$$

$$H_\times = \frac{\sin 2\psi + j\eta \cos 2\psi}{\sqrt{1+\eta^2}} \tag{4}$$

where η is the ratio of the semi-minor axis to the semi-major axis of the polarization ellipse (ranging from [-1,1] where η=0 is a linearly polarized wave and η=1 is the CCW direction), and ψ is the polarization angle that defines the direction of the major axis with respect to the sources celestial parallel. Moreover, the relationship between the amplitude detected (H_0) and the amplitude at the source (h_0) is

$$H_0 = h_0\sqrt{\frac{1 + 6\cos^2\iota + \cos^4\iota}{4}} \tag{5}$$

Even though continuous gravitational waves are essentially one set wavelength, there are several effects that modulate the observed frequency of the neutron star source. For instance, the source spin-down is associated with the loss of rotational energy due to the production of either electromagnetic radiation or gravitational waves. This causes the intrinsic frequency to decrease, which can be represent with a series expansion [2]

$$f = f_0 + \dot{f}(t - t_0) + \frac{\ddot{f}}{2}(t - t_0)^2 + ... \tag{6}$$

In this expansion, t_0 is the time the source frequency is emitted, t is the time which we observed a Doppler corrected frequency (f) on Earth, f_0 is the frequency emitted from the source, $\dot{f}$ is the sources first spin down parameter (Hz/s), and $\ddot{f}$ is the second derivative (Hz/s/s). This second spin down parameter, along with the smaller terms that follow, can generally be neglected.

Doppler correction and propagation effects are other factors which must be considered before data analysis, especially in the case of a CW signal within a binary system. In isolated systems, these effects are generalized into two main categories including the relativistic modulations caused by the Earth's orbital and rotational motion, and the effect of massive bodies in our solar system that lie close to the line-of-sight of the source. It can be represented by the equation

$$f(t) = f_0(t)(1 + \frac{\vec{v}\cdot\hat{n}}{c}) \tag{7}$$

Where $\vec{v}$ is the velocity of the Earth-based detector relative to the solar systems center of mass, $\hat{n}$ is the unit vector describing the source's position in the sky, and the represented frequency terms are both functions of time. In binary systems, the orbital and rotational movement of the neutron star itself must also be accounted for, which poses difficulty in the case of a blind, all-sky search.

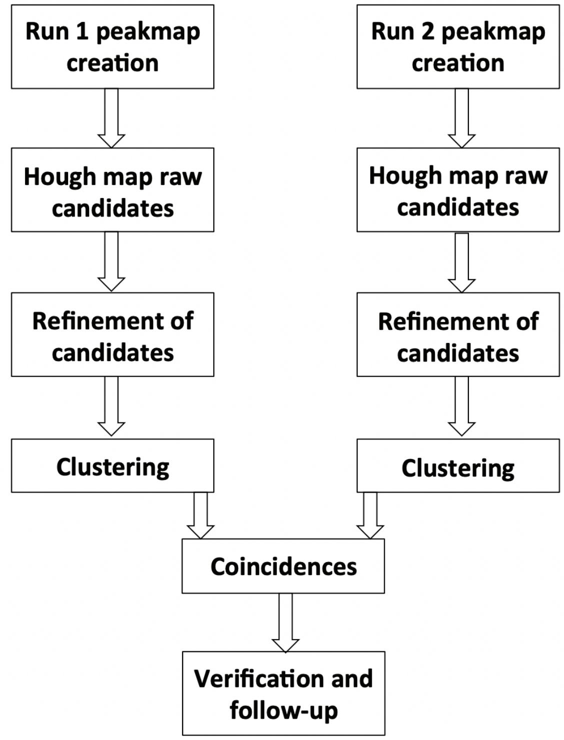


Figure 1. Scheme of the Hierarchical Procedure.

3. THE HIERARCHICAL PROCEDURE

As previously mentioned, all-sky searches would require extreme amounts of computational time and power if they were to be analyzed coherently. So instead, the LIGO/Virgo collaboration utilizes a hierarchical approach in order to select data points that are most interesting. This method reduces the computational time immensely in exchange for a small loss in detection sensitivity.

The scheme [2] begins with detector calibrated data from the LIGO/Virgo O3 run. A *short Fast Fourier Transform database* (SFDB) is constructed to store information about all of the FFTs done on segments of the data. This database stores information about each of the FFTs for the entire frequency range of the LIGO/Virgo detectors (10-2048 Hz) in chunks of different duration *coherence times* so as to reduce computational power. These chunks are small enough so that a signal can be detected, Doppler-corrected and adjusted for its spin down parameter(s) and still remain within a frequency bin.

The width of one frequency bin is determined by

$$\delta f = \frac{1}{T_{FFT}} \tag{8}$$

T_{FFT} represents the length of one FFT performed on a given segment of data. For any given frequency band, there is a natural T_{FFT} that provides an optimal length depending on the specific parameters. Yet, the search has used four different T_{FFT} for certain frequency bands in order to reduce computational power.

B (Hz)	T_{FFT} (sec)	δt (sec)	δf (Hz)
1024-2048	1024	2.44×10^{-4}	9.77×10^{-4}
512-1024	2048	4.88×10^{-4}	4.88×10^{-4}
128-512	4096	9.77×10^{-4}	2.44×10^{-4}
10-128	8192	1.95×10^{-3}	1.22×10^{-4}

Table 1. A breakdown of the four frequency bands used in the all-sky search across the entire LIGO/Virgo sensitivity band. T_{FFT} is the time duration of each FFT, δt is the sampling time, δf is the frequency resolution of the FFT.

It can be shown that the maximum FFT duration is a function of the maximum frequency given by $\sim \frac{1.1\times10^5}{\sqrt{f_{max}}}$. With this relationship, the SFDB can be divided into frequency blocks as visualized in Table 1, where the FFT length is dependent on the maximum block frequency. It is also important to note that as the maximum block frequency increases, the measured frequency at the detector changes more from the original source frequency. Therefore, shorter FFTs are used for larger maximum frequencies.

This method to separate the data into four frequency bands is what has been used so far in the search for CW using the frequency Hough pipeline. However, the group has more recently developed a new version of the pipeline based on *Band Sampled Data* (BSD), which enables the user to define a personalized FFT and create peak maps and Hough maps upon the execution of the code. So, while the past pipeline only offered 4 different FFT lengths for the data chosen, it can now be easily changed depending on the frequency band. This ability will be further described in the next section of this paper.

The average noise is also estimated across every frequency in each of the FFTs performed for each incoherent segment of detector data. This is a lower resolution, auto-regressive spectrum called a *very short FFT* which is then stored in the SFDB for reference during the peakmap making process. That is, for each of the N FFTs in the SFDB, we compute the power spectral density $S_{P;i}(f), i = 1, ...N$ as a ratio with the auto-regressive spectrum S_i^{AR} [2]

$$R_i(j) = \frac{S_{P;i}}{S_i^{AR}} \tag{9}$$

This value is calculated to be approximately 1 for all j frequency bins for the ith FFT unless there exists a peak at that frequency. A threshold value is then defined based on the number of candidates that the code is set to collect, and selects only local maxima in order to reduce computational and reduce noise.

The next step in the hierarchical procedure uses the Frequency Hough Transform in order to better identify possible CW sources. The Hough transform is a feature extraction technique used in image analysis that linearly maps Doppler-corrected data taken in the time-frequency plane of the detector to the source frequency/spin-down plane. Referring back to Equation 6, we can assume that the frequency has already been Doppler-corrected for a given sky position, and we can also neglect all higher order terms after the spin-down parameter, such that

$$\dot{f}_0 = -\frac{f_0}{(t-t_0)} + \frac{f}{(t-t_0)} \tag{10}$$

Each point in the input plane $(t-t_0, f)$ is transformed linearly into $(f, \dot{f})$ with a slope of $-\frac{1}{(t-t_0)}$.

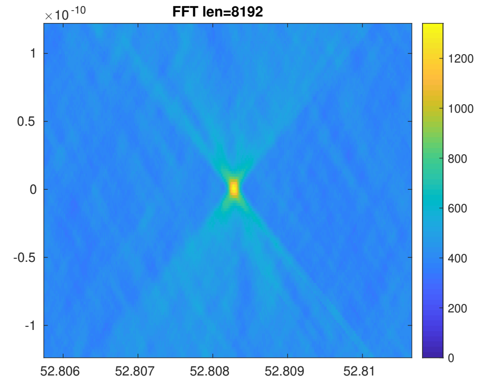
Figure 2 shows a Hough Map of the same hardware injection at two different T_{FFT} lengths. This injection has a spin down of 0, and a frequency of 52.8083 Hz which can be deduced from the visualizations. It is important to note that the reason the all sky search will use binned T_{FFT} values instead of the natural T_{FFT} for each incoherent set of data is to decrease computational power without losing sensitivity. The candidate can still be discovered with reasonable resolution by the program when the T_{FFT} length is set to a value that depends on the frequency band as described in Table 1. As the T_{FFT} value strays away from this local range, the critical ratio becomes much weaker.

3.1. *Critical Ratio Comparisons*

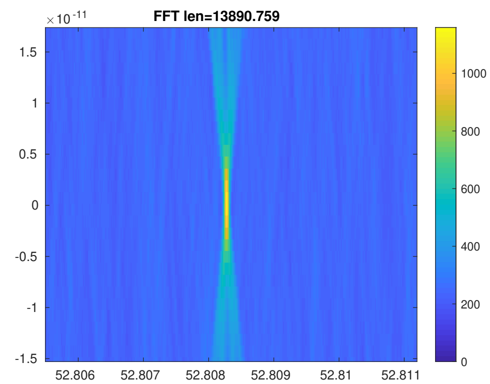
The critical ratio is defined as a random variable measuring the statistical significance of the number count n found in a given pixel of a Hough map, with respect to the expected value in presence of noise alone. It can be represented by

$$CR = \frac{x-\mu}{\sigma} \tag{11}$$

where x is the number of peaks at a particular frequency, and μ and σ are the median and standard deviation of the number of peaks across a particular frequency band. The CR gives us an estimate of significance for each candidate when comparing it to the signal to noise ratio (SNR), and is influenced by the length of the FFT that is being performed.



[a]



[b]

Figure 2. Hough Maps of the hardware injection *pulsar 5* at a) the binned FFT length of 8192 seconds, as used in the Rome Group's all sky search and b) at the natural FFT length of 13890.759 seconds for the given BSD file.

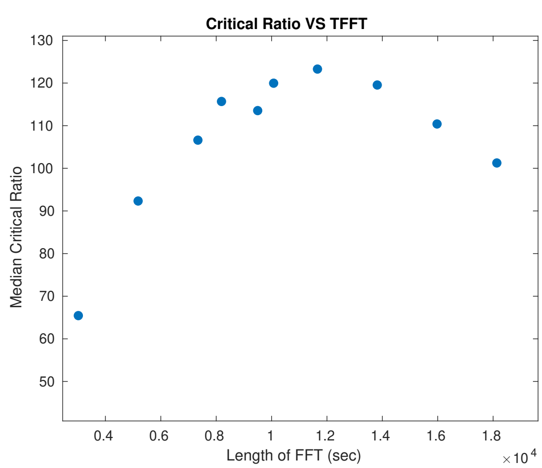


Figure 3. A graph of the median critical ratio versus different lengths of FFTs. These were all run over the same frequency band of 109-110 Hz, taking the median CR of 4 injections for every FFT. The FFT used in the all sky search for this band is 8192 seconds.

Investigating how the critical ratio changes according to FFT length gives a better idea of how the Frequency Hough Transform could best be implemented in both isolated and binary systems. In Figure 3, there appears to be a range of values that offer relatively high CR values close to the optimal value. Yet, if the code used the natural T_{FFT} length for every incoherent stretch of data, it would require huge amounts of storage and computation.

Let it also be known that the amplitudes used in this analysis were above the normal amplitude used, and therefore the corresponding critical ratios were also very high. Not only that, but for this visualization, only 4 signal injections were used. Since this was just a preliminary test to begin understanding the features of the code, this task was only completed to support an already well-known relationship between the FFT length and optimal resolution.

4. METHODS

4.1. *Binary Neutron Star Pipeline*

As previously mentioned, the Rome group has already obtained promising results for their Frequency Hough pipeline that detects candidates for CWs from isolated neutron stars. The next step in the search is to apply the same technique to binary neutron star systems in order to understand if some of the candidates selected in the search for isolated neutron stars could possibly be due to binary sources instead. Of the 2,500 neutron stars that we have observed electromagnetically, roughly 1,300 of these observed radio pulsars are in binary systems, and allegedly can emit CWs in the advanced LIGO-Virgo sensitivity band. These binary system could potentially have parameters that lie in the parameter space of the isolated NS pipeline, which would surely contribute to the CW search. For instance, even a weak signature from a particularly strong binary system may be revealed from this sensitive pipeline and encourage a source to be followed up by other means more apt for binaries.

The pipeline used for binary systems must implement new equations in order to account for the additional frequency modulation effects that are being introduced. To relate the CW phase in the source frame to that of the detector frame when the neutron star source is in orbit in its own system (without accounting for relativistic effects), the following equation can be implemented [4]

$$\tau(t_{arr}) = t_{arr} + \frac{\vec{r}(t_{arr}) \cdot \vec{n}}{c} - \frac{D}{c} - \frac{R(\tau)}{c} \tag{12}$$

This mathematical relationship recognizes the source emission time τ in terms of the wavefront arrival detection time t_{arr} where $\vec{r}$ is the vector describing our solar systems barycenter to the detector on Earth, D is the distance between the solar systems barycenter and the neutron star binary barycenter, and $R(\tau)$ represents the radial distance of the neutron star source from its own barycenter along our line of sight. Furthermore, the light travel time across the orbit, referred to as the Rømer Delay, is [4]

$$\frac{R}{c} = a_p[\sin\omega(\cos E - e) + \cos\omega(\sin E\sqrt{1-e^2})] \quad (13)$$

In this equation, the projected semi-major axis $a_p \equiv \frac{a \sin I}{c}$ of the neutron star orbit, I is the inclination angle between the orbital plane and the sky, a the semi-major axis, ω is the argument of periapse, e the orbital eccentricity, and E is the eccentric anomaly.

Using the pipeline for isolated NS, one can search for binaries instead by setting the `BINARY` parameter equal to one which will implement the equations described above. Another important aspect of the preliminary binary search is to set the signal injections internal spin down (`MIN_SD` and `MAX_SD`) equal to zero due to the pipelines tendency to manipulate the spin down parameter amid detection. Since `BASE=O3LL`, the results come from calibrated data taken by the Livingston LIGO detector during their most recent data run (O3).

4.2. *Random Injections*

In order to ensure proper running of the code and to observe certain affects of the resulting Hough maps and candidate maps, three injections were randomly injected into the LIGO data with randomly chosen orbital periods between 100 and 1,200 days at an ellipticity value of zero. It should also be mentioned that the critical ratio values for each of these injections have been amplified in order to best observe the changes that occur when certain parameters vary. Usually, the CR lies around one order of magnitude above the noise, yet in this study the CR lies approximately two orders of magnitude above the noise.

It is important to identify the randomly chosen orbital period of each injection in order to conclude why some of the injections are more visible than the others before beginning more formal trials to test the pipelines efficiency. The injection located at 109.24 Hz (INJ1) was selected to have a orbital period of 482.1135 days which was the lowest period of the three total injections. It also appears to have the highest spin down value approximately 2 even though each injection was set to have an internal spin down of 0. Since this run was chosen to use a full year of data, this means that the neutron star represented in INJ1 had already completed one full orbit around the other object in the binary system. The pipeline, however, prefers orbits that are much larger than the acquisition period (or epoch), because it does not have to use data from multiple orbits and average

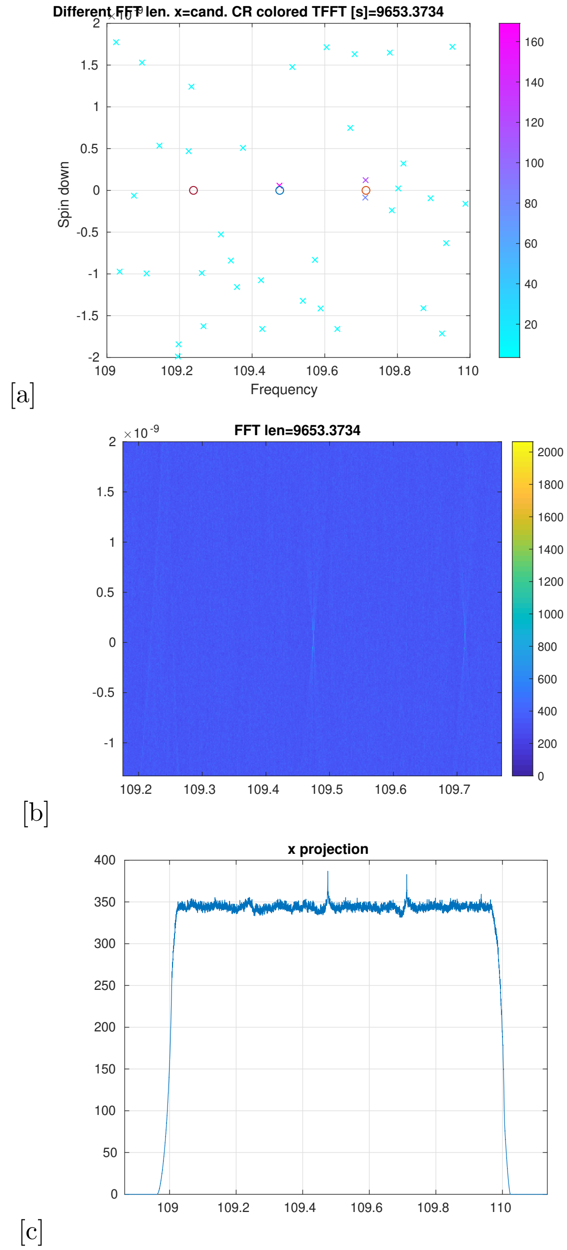


Figure 4. Three software injections placed randomly at 109.24 Hz, 109.48 Hz, and 109.71 Hz respectively in the 109-110Hz frequency band represented via a) a candidate map where the injections are represented as circles and the best potential candidates are crosses b) a Hough map and c) an x-axis projection.

the spin down values at every moment. The average will naturally be more noisy if the NS binary system has completed multiple orbits within the epoch, and easier to read if the orbital period is greater than it. In other words, at much larger orbits, the NS acts as an isolated source rather than a binary source. Therefore the injections at 109.48 Hz (INJ2) and 109.71 Hz (INJ3) should inherently produce a larger critical ratio and be more obvious in the Hough map due to their orbital periods of 1005.3 days and 688.9259 days respectively.

5. RESULTS

5.1. *Varying Orbital Period*

Instead of injecting multiple signals into the same Hough map, one signal was tested at different NS binary system orbital periods with all the other parameters remaining static. This signal injection has a frequency of 109.47 Hz with a static ellipticity of 0.0 and a randomly chosen position of [359.8283, 69.5830] in the sky. The maps have been incremented from a period of 100 days up to 1,200 days, where each map represents an epoch of one year.

Looking at Figure 6, there is a clear trend in the trials that exhibit variable orbital period, as expected from the random injection trails performed previously. The Hough maps show that as the period length increases past the data acquisition time, the more vivid the source becomes, and the higher the [unnormalized] critical ratio appears (according to the color bar). This is due to orbits longer than the epoch acting essentially as isolated sources, since their effects do not influence the results sufficiently.

Another pattern noticed in the maps was the movement of the spin-down value of the source injection. Theoretically, we expect to see the spin-down move from a positive value to a negative value when changing the period of the NS system, since the sinusoidal frequency vs time graph will naturally contain points with negative slopes (i.e. when approaching a local minimum value). However, in the data, only positive spin-down values are observed, which tend to zero as the orbital period increases. The reason why this occurs is because the phase shift of the injections frequency with respect to time (Φ) is fixed within these trials, which means the phase always begins from zero and proceeds to travel up to its local maximum. Each of the spin down values along this graph are positive because the frequency vs time graph is increasing a these points. In future, it will be important to vary the phase shift as it will not always be fixed in nature.

The critical ratio is a more quantitative component that can be informative of the efficiency of the pipeline in this new search. Normally, a higher critical ratio indicates that the pipeline is more effective at locating and reporting candidate and coincidence sources.

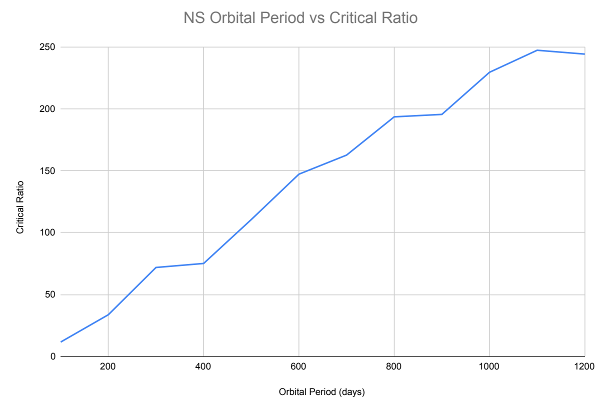


Figure 5. A line graph of the [maximum] critical ratios of the injection at each orbital period length.

It appears in Figure 5 that as the orbital period increases linearly, the critical ratio follows. The equation of the trend line can thus be easily represented by a simple linear equation

$$y = 0.225x - 3.03 \tag{14}$$

5.2. *Varying Orbital Ellipticity*

Similar to the section prior, the orbital ellipticity parameter within the pipeline was also changed incrementally in order to observe its impact on the pipelines performance. This signal injection used for each run has a frequency of 109.47 Hz with a randomly chosen position of [359.8283, 69.5830] in the sky. It has a static orbital period of 500 days, and each trial is incremented from an ellipticity value of 0 to without surpassing 0.1 (which is the limit of the binary pipeline).

From the sequence of Hough maps in Figure 7, the changes in ellipticity appear to change the location of the maximum critical ratio as indicated by the color bar, but not necessarily its magnitude. As the ellipticity increases, the critical ratio tends to spread out in completely separate regions - at a spin down of approximately 2 and -2, and even at two different frequencies. Yet, the signal strength remains at a relatively constant CR between 100 and 117, as shown in Figure 7. Unlike the trials with change the orbital period, this graph does not appear to have a clear pattern or trend, which makes it difficult to fit a line to try to describe how the ellipticity parameter changes the CR.

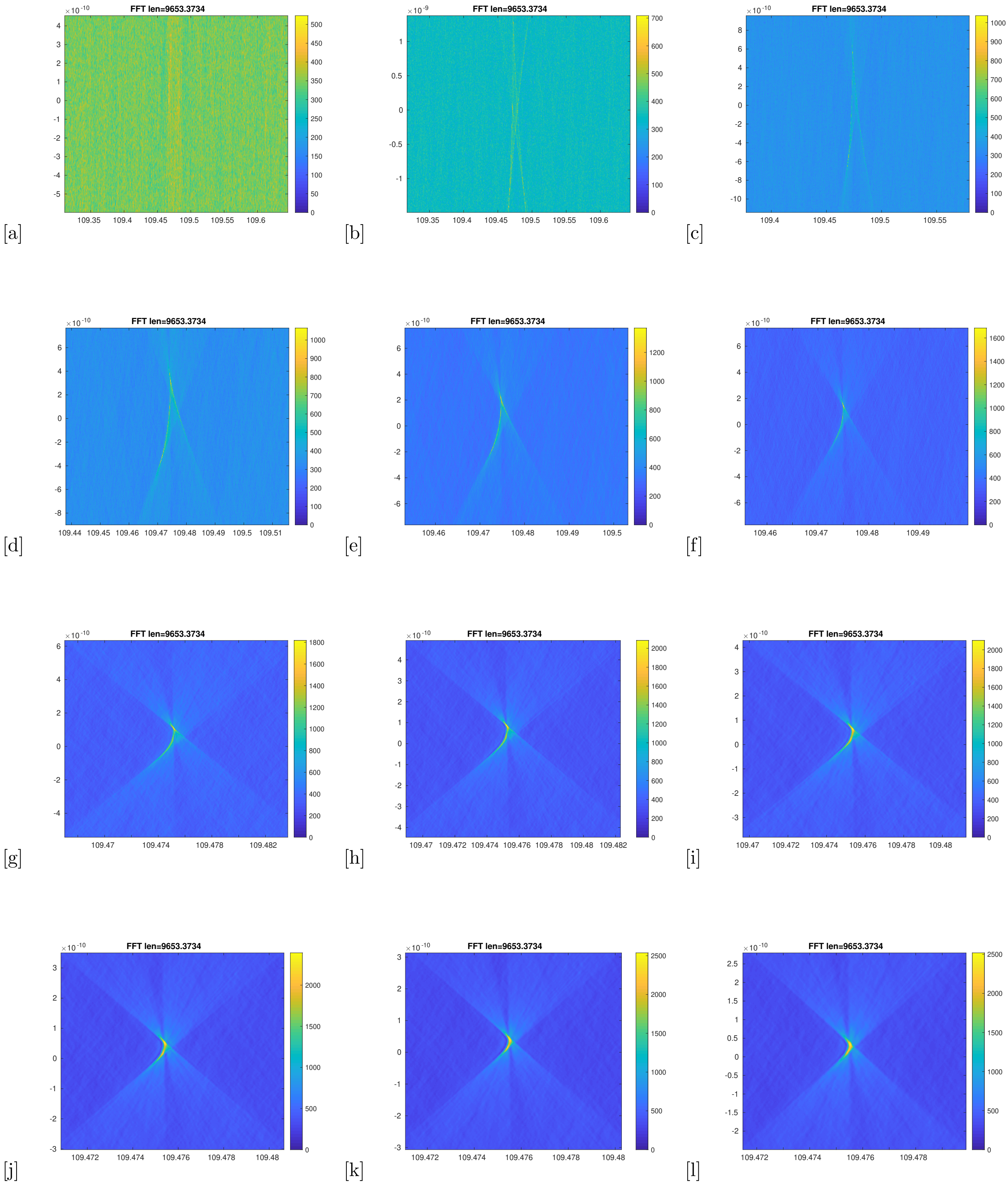


Figure 6. A series of Hough maps of a single software injection at an orbital period beginning from a) 100 days all the way up to l) 1200 days by increments of 100 days. This map plots the frequency (Hz) vs the spin-down (Hz).

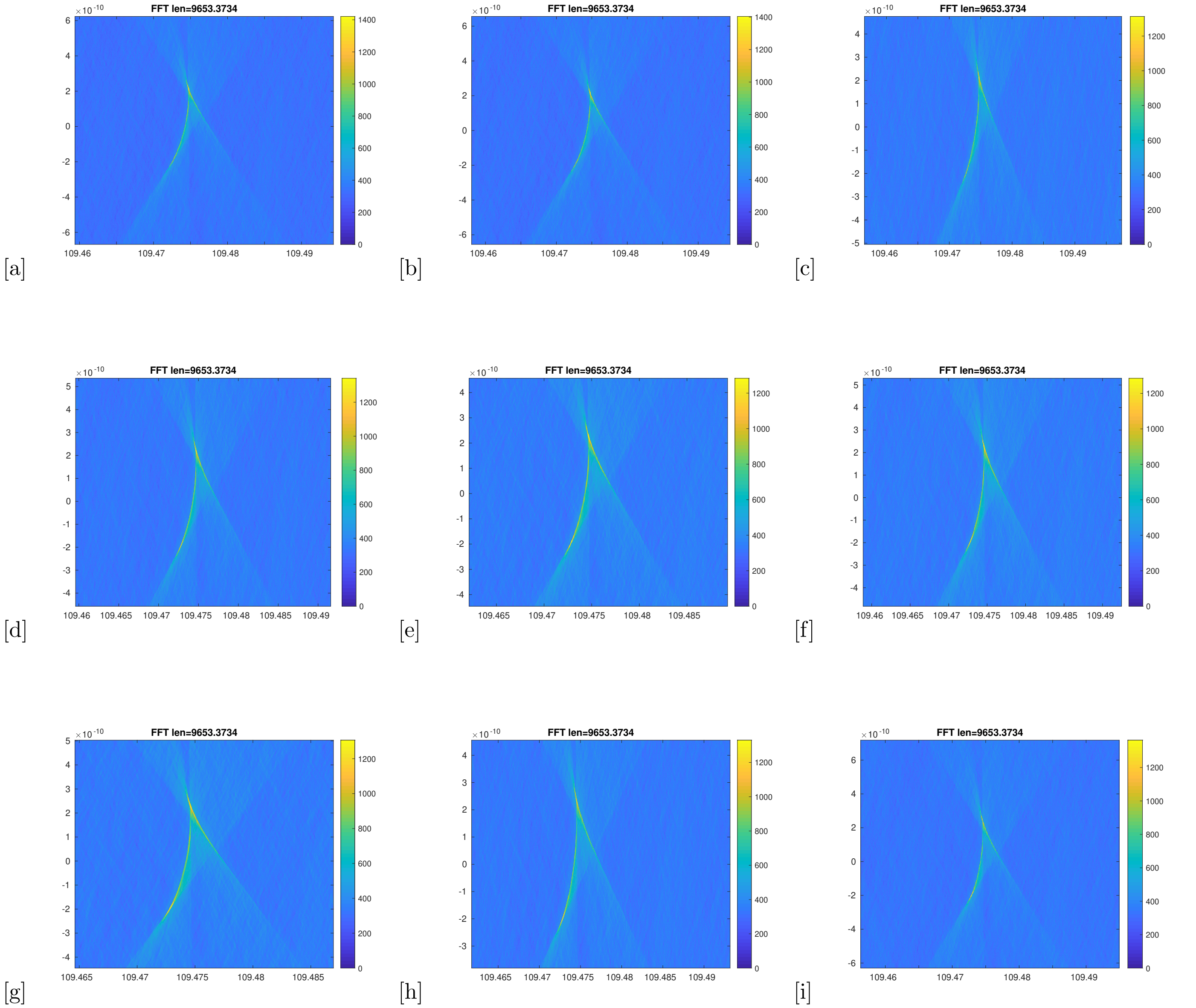


Figure 7. A series of Hough maps of a single software injection at 109.47 Hz with a static orbital period of 500 days and a position of [359.8283, 69.5830] with a varying ellipticity from 0.0 to 0.09 by graduations of 0.01.

While we do expect a spread of the signal after the FH transform due to the fact that we ignore some orbital parameters, we can study the spread versus the injected parameters in order to model it. One theory behind the result is that these distributions are actually the same signal that have been warped into seemingly different sources during the Hough Transform. However, due to the lack of symmetry between the two maxima, it is difficult to tell how these ratios are spread, and even more unclear how to retrieve the correct information from them. In general, testing different ellipticities for neutron star binary orbital paths is difficult at this point due to the pipeline's novelty.

In an attempt to better study how the signal differs by changing the ellipticity parameter, it might be reasonable to lower the length of the FFT being performed on the data so that the bins are larger and the separation in the critical ratio is more visible due to a lower image resolution. Looking at Figure 9, it is evident that the spread of the signal is much more visible due to lower resolution. This is a great example of how we can still retrieve extremely useful information at the cost of much lower sensitivity.

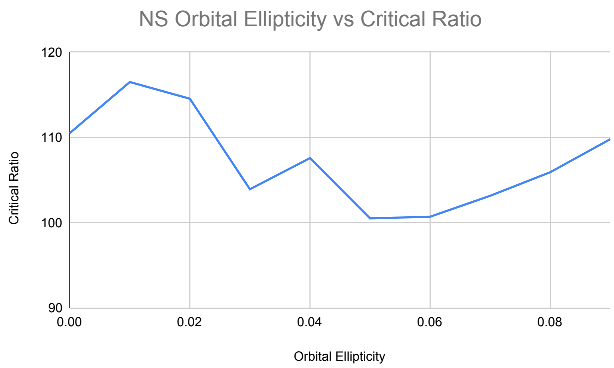


Figure 8. A line graph of the [maximum] critical ratios of the injection at each orbital ellipticity.

6. CONCLUSION

The frequency Hough pipeline is a robust technique, designed for isolated neutron star searches and used for many recent analyses. The idea behind this work is to check whether it could be used to identify candidate binary systems, even if in a restricted region of the entire parameter space. We have thus, through injections, set the basis for additional work to be completed. It is clear that, in the future, indications from this work could lead to the addition of novel features to the pipeline, aimed at improving the sensitivity for these [highly computationally bounded] searches. Since this pipeline was built specifically for isolated neutron stars, additions to include binary systems will inherently be less efficient. However, it may still be able to identify candidates that can be studied using more appropriate means instead.

The conclusions reached from this preliminary study include the pipeline exhibiting a larger degree of success when dealing with binary systems of large orbits. Using a years worth of data, the Hough maps that contain signal injections of binaries with orbital periods of about 500 days or greater show particularly centralized points in the source frequency/spin-down plane.

Alternatively, changing the orbital ellipticity does produce an effect on the shape of the Hough map, however any particular trend is unclear due to the fluctuations in the maximum CR. In both cases, decreasing the maps resolution by shortening the FFT length may actually lead to better results as the power spread across bins will obviously be reduced. This tendency to increase the noise contribution to the power in each bin requires a compromise that must be found in order to proceed with this genre of research. Given that searches for isolated neutron stars through this pipeline are currently the highest priority for the collaboration, understanding if the results might possibly contain indication of the presence of signals from binary systems is an important additional point. On identifying and locating these possible candidates, more sensitive searches can be performed.

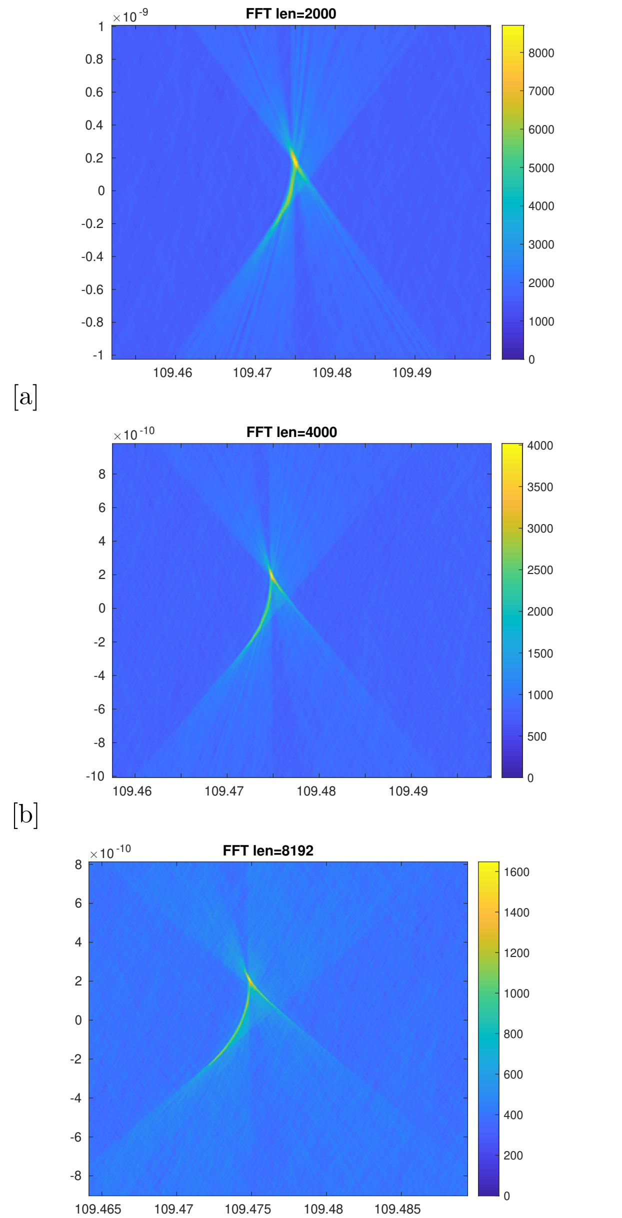


Figure 9. A single software injection placed at 109.48 Hz represented at different T_{FFT} lengths. a) T_{FFT}=2000 s b) T_{FFT}=4000 s c) T_{FFT}=8192 s. In the case of non-adaptive FH, the z-axis would indicate how many times the signal was present in the bin. For this reason, we cannot easily compare the numbers in the plot, rather we must evaluate the SNR itself.

7. REFERENCES

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8. ACKNOWLEDGEMENTS

I would like to thank Dr. Pia Astone and Dr. Simone Dall'Osso for their generosity and leadership in this project at Universtià di Roma "Sapienza". This project was completed through the University of Florida, funded by the National Science Foundation Grant 1460803 and Grant 1950830. I would also like to thank Dr. Paul Fulda and Dr. Peter Wass for organizing the entire program and giving me to opportunity to work on such an informative project.