WWV/WWVH
Experimental Signal Timing

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***Abstract*—The United States National Institute of Standards and Technology have been using the transmission of of unique radio signals to create a worldwide standard of reference time and frequency [1]. These signals are transmitted from the WWV and WWVH radio stations, where they become refracted by the ionosphere. This allows them to be received around the globe however the received signal becomes distorted in the process of propagating through the ionosphere [1]. To mitigate this, HamSCI has been researching ionospheric effects and creating new signals that allow for ionospheric measurements with increased precision [1]. By applying various signal processing techniques such as filtering, correlating signals, and computing a signal to noise ratio, a proper timing analysis and corresponding confidence interval can be calculated. This will allow for the observation of ionospheric effects on said signal leading to measurement values that explain the broken symmetry between the transmitted and received signal.**

I. Introduction

WWV and WWVH are two shortwave radio time signal stations, operated by the United States National Institute of Standards and Technology, that aim to globally promulgate standards of reference time and frequency [1]. They operate by each transmitting a unique signal across specific frequencies within the 2-20 MHz range, many of which are mutual [1]. These scheduled signals contain various features such as a carrier, audio tones, time ticks, a time code, and voice announcements. The ability of these signals to travel internationally stems from the tendency of Earth's ionosphere to refract signals below frequencies 40 MHz [2]. The ionospheric effects include frequency, amplitude, and/or phase alterations. HamSCI's Personal Space Weather Station Project, takes advantage of this phenomenon using the WWV and WWVH signals to compute ionospheric measurements [1]. Proper analyzation of such signals requires the identification of time measurements indicative of the reception of each specific signal component. To further understand the ionosphere and increase measurement accuracy, WWV and WWVH will be transmitting new signals created by HamSCI.

II. Task

This project aims to compute a timing analysis of these newly derived signals. We are striving to accurately pinpoint the timing of each feature embedded within the provided signal. We will be studying two signals, a manufactured/transmitted signal and its corresponding collected/received signal. The collected signal differs from the manufactured signal due to interference, including the ionospheric delay. We want to observe this effect, and compute values representing the disconnect between the two. If done so correctly, the result is a highly accurate timing description of the events, where timing is described as the amount of elapsed time between the first pulse of pseudo-random Gaussian white noise and each of the proceeding features. Upon the completion of said task, insight on ionospheric reflection effects will be revealed providing an explanation on how a signal is modulated through the ionosphere.

III. Methodology and Algorithm

From a broad perspective this seems like a daunting task as a lot is required to achieve our end goal. To combat this, we split the task into various subsections. Of course each comes with their own complications but in the end each of the sub tasks provide a road map towards a complete timing analysis of our signal.

A. *Preparation for the Manufactured Signal*

First and foremost signal preparation is required before anything else can be done. This entails the initial acquisition and loading of the manufactured test signal acquired from WWV into our Jupyter Notebook. Once loaded in, its sampling frequency is detected so that we can play and listen to the signal before we normalizing it. Normalization scales the signals to fit between 0 and 1, for the purpose of comparing signals more effectively. We then display the time domain and spectragram plots of our normalized signal allowing for the observation of the its features and their timing (See Fig. 1).

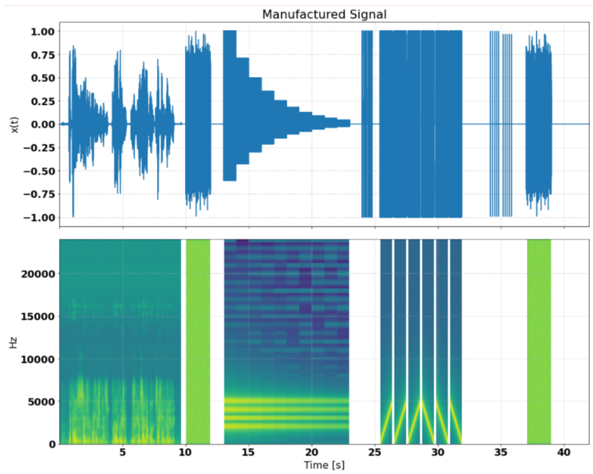

Fig. 1: Manufactured Signal

B. Extraction

Using our time domain and spectragram plots of the normalized signal we are able to roughly discern the start and end times of each component. With these times, indices of each feature are acquired by multiplying each timestamp by the sampling frequency of the signal. This essentially allows us to extract each individual component from the original signal. What you'll observe is a graph containing solely a specific feature while no other feature are present. Honing in on each component individually is a key step towards acquiring its precise timing measurement. Figures 2 and 3 display the plots of the extracted components we are focusing on, the white noise and the chirps. To verify that our extraction behaves as expected, we perform auto-correlation between the extracted features and the original manufactured signal. The resulting timing matches the signal's descriptions perfectly, which is an indication that our method works.

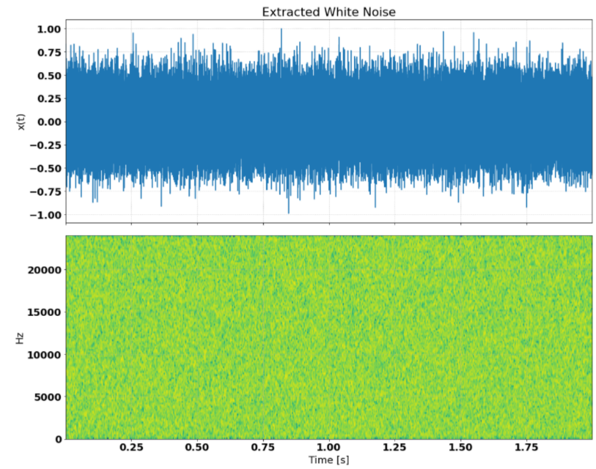

Fig. 2: Extracted White Noise

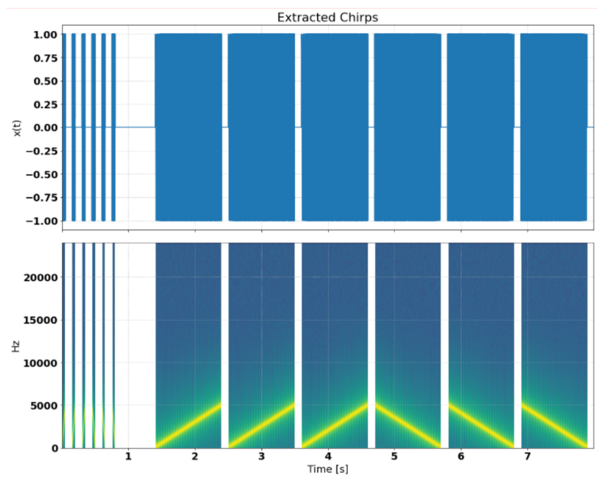

Fig. 3: Extracted Chirps

C. Preparation for the Collected Signal

Now that we have each feature separated, we can load in the the collected signal. We received this signal as an IQ signal, which must be demodulated back to its original form.What demodulation does is that it helps extract the original sound of the signal away from the modulated carrier [3]. Once demodulated, we are able to see that this signal is essentially the same signal as the original manufactured signal. However, we know that there will be slight variations caused by the interference during transmission including ionospheric effects. Next, to center the signal around zero, we perform DC offset removal. Similarly to the previous signal, once prepped we can plot it in the time domain and as well as plot its spectragram (Fig. 4).

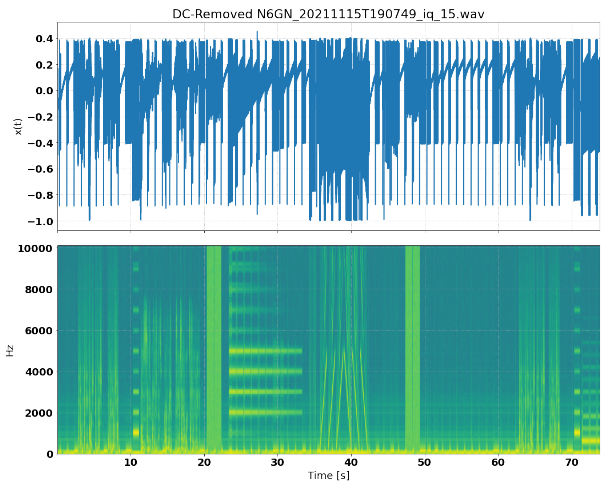

Fig. 4: Demodulated collected signal with DC Offset removed

D. Filtering

With each feature extracted, we are looking to cross-correlate it with the collected signal to locate the feature within the signal. Removing noise and filtering of the signal, however, is necessary to achieve a proper correlation. The application of a high-pass Butterworth filter allows us to clean up the signal by removing unwanted frequencies and hone in on the white noise. We chose a filter with a cutoff frequency as high as possible without exceeding the Nyquist frequency, leaving us with a 10kHz cutoff frequency. The filter and its corresponding signal plots can be seen in figures 5 and 6. Similarly, we applied a band-pass filter with a frequency range of 1-5kHz, trimming the signal enough for us to locate the chirps effectively, as seen in figures 6 and 7.

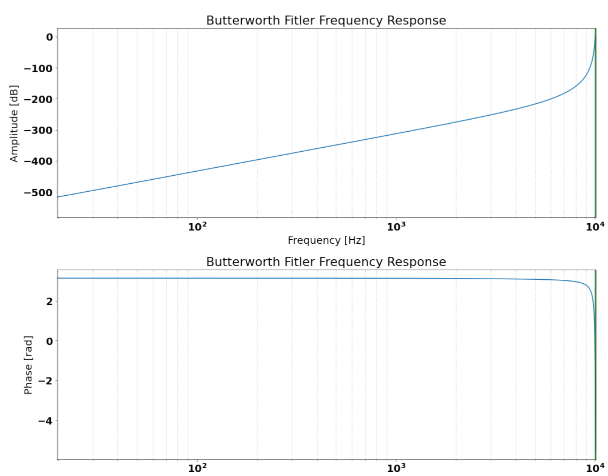

Fig. 5: High-pass Butterworth filter (10kHz cutoff frequency)

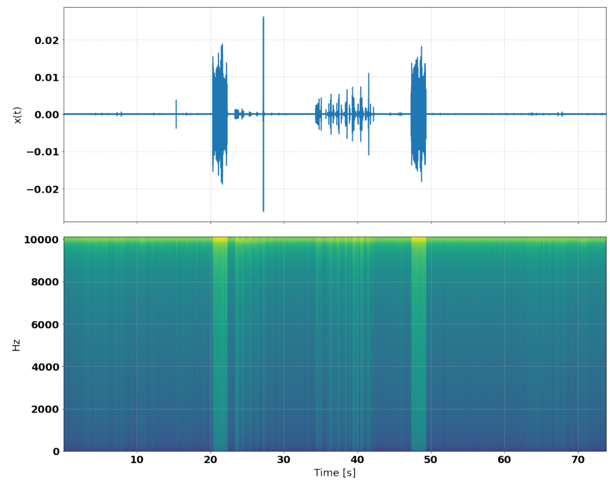

Fig. 6: Collected Signal filtered with high-pass Butterworth

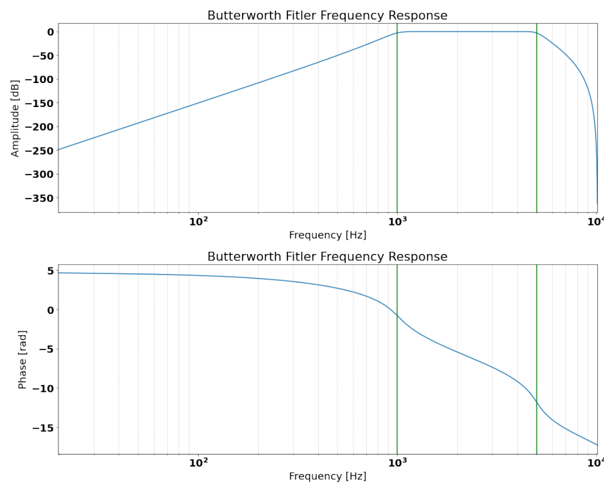

Fig. 7: Bandpass Butterworth filter (1kHz & 5kHz)

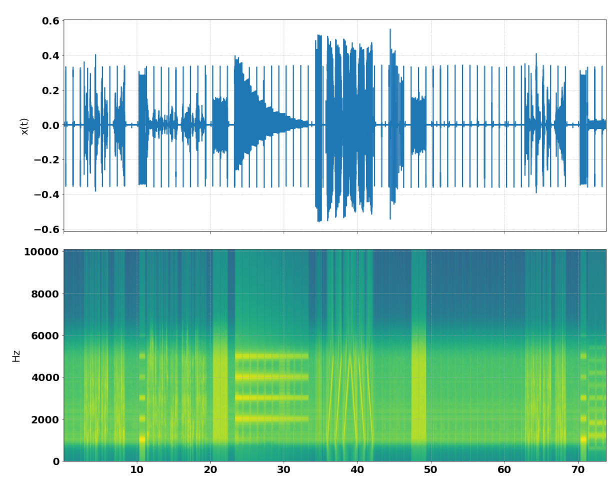

Fig. 8: Collected signal filtered with bandpass Butterworth

E. Timing Analysis

When comparing time domain plots of the signals, despite containing the same features, we see a big difference between them. This could be due to the effects of the ionosphere. For a more in depth comparison between the two, we can cross-correlate them together. This will allow us to objectively analyze the different time series and assess how well they match each other, more specifically, when the best match occurs [4].

The output of the correlation comes as an array. Within the array, find the maximum correlation value and the index where that value occurs. Taking the index and dividing by the sampling rate we are able to compute the time (T_a) at which the first white noise occurs in the collected signal. To check that this indeed corresponds to the first white noise, we can perform the same process but this time for the signal segment before $T_a - 4$. Now, if the new correlation value is approximately the same as the previous, we can assume that the new time is the actual start time of the first white noise (T_1).

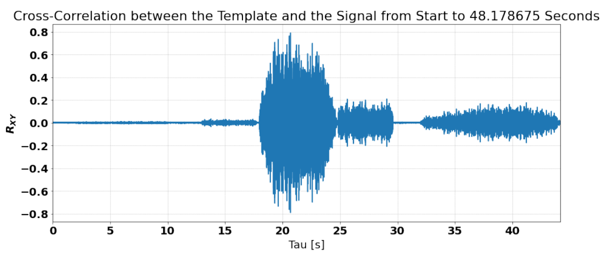

Fig. 9: Cross-Correlation between the White Noise and the Manufactured Signal

Now, we can cross-correlate the white noise again, but with the signal segment from the start of the manufactured signal to the approximate end time of the chirps. Using the max correlation value from this, we can calculate the timing of the second white noise (T_b), relative to the end of the chirps. Approximately 22 seconds elapse between T_1 and the end of the chirps. So, $T_b + 22$ gives us the time of the second white noise, (T_2), relative to T_1.

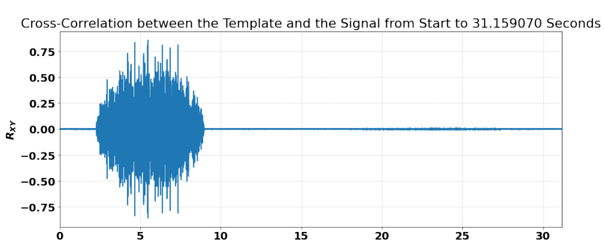

Fig. 10: Cross-Correlation between the White Noise and the Manufactured Signal between ($T_1 + 22$) and the signal's end

Now for the chirps, we perform the cross-correlation between the manufactured chirps with the collected signal between the first white noise and the second white noise, or from T_1 to $T_1 + T_2$. Taking the index of the maximum correlation value and dividing again by the sampling rate we get the time of chirps (T_{chirps}) relative to T_1. We now have a complete timing analysis of our signal outlining the times of the specific features we wanted relative to T_1. Using these timestamps, we can observe the distortions due to the ionospheric effects.

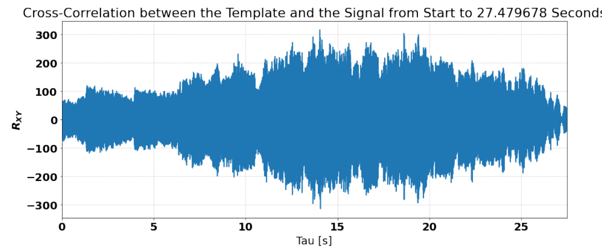

Fig. 11: Cross-Correlation between the Chirps and the Manufactured Signal ($T_1, \ T_1 + T_2$)

F. Signal To Noise Ratio

It is important to determine the effectiveness of any algorithm or system. To estimate how well our method performs with different signals, we calculate the Signal to Noise Ratio, (SNR). SNR is the ratio between the desired signal and the unwanted background noise. In order to calculate the SNR you must take the signal, subtract it by the noise, and divide that difference by noise. Calculating SNR allows the signal to be deciphered more easily. SNR is the ratio between the desired signal and the unwanted background noise. "It affects the performance between the transmitter and receiver" [5]. This means that within this project SNR helps us check the performance of the signal. The higher the SNR, the stronger that signal is.

Using the "N6GN" wav file, we attempted to construct and test a code that could calculate the SNR of any wavfile. Initial tests were performed on the "AMOD-N6GN" wav file, and after much trail and error the result was a dead end. The hours spent testing with the N6GN wav file, resulted in a Power Density vs Frequency graph graph of a straight vertical line. However, altering the x-y limits of the plot to zoom in revealed that there was in fact a signal present. Attempting again from another angle, the technique was to extract the sound and noise separately. Beginning with the calculation of the discrete Fourier transform (DFT), we were able to calculate a frequency response value. The signal was then sampled with a 50Hz bandwidth beginning at 500 Hz and plotted in the frequency domain, allowing for the calculation of signal power. The process was repeated, this time for the noise in the signal resulting in a noise power calculation. With both the signal power and the noise power, SNR could be conducting but our results proved to be inaccurate. The output values ended up being negative values or values that simply didn't add up. Despite working on this restlessly for days, we were not able to overcome this barrier and compute a correct SNR, unfortunately we were unsuccessful in this portion of the project.

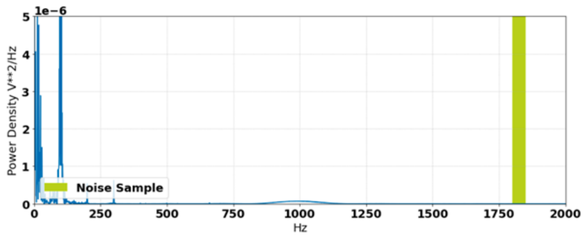

Fig. 12: Power Density vs. Frequency

IV. Results

- Timing of the first white noise: T_1 = 20.70 seconds
- Timing of the chirps: T_{chirps} = 14.04 seconds
- Timing of the second white noise: T_2 = 27.48 seconds

Theoretically, performing timing analysis before or after AM demodulation should yield similar results. However, our algorithm was not designed to compute complex values in the calculations with IQ data. Convolution involving complex numbers in software is a time-consuming task. So, it is more suitable to perform the analysis using the collected signal after AM demodulation. On the other hand, hardware implementation of a correlation system tends to be much more capable of handling modulated signals.

The accuracy of the algorithm depends on the SNR. The evidence is that our algorithm performs poorly against signals with high level of noise, and unrelated activities.

V. Acknowledgment

As a unit, we would like to express a great appreciation for Dr. Frissell, for not only providing us with the opportunity to complete this project and further our knowledge, but for also providing us with all the necessary skills and tools needed to do so. We also want to express our thankfulness to The United States National Institute of Standards and Technology for the operation of the WWV and WWVH radio stations which provide us with the signals researched within the project. Another special thanks goes out to the HamSCI foundation for providng insight on ionospheric research as well as techniques used to complete this project. For the group, we want to give a thanks to Vaibhavi Patel for her extensive work regarding the cross correlation of the various signals as well as offering valuable group assistance. A thanks to Joseph Tholley for his work regarding AM Demodulation of IQ data, and especially his restless efforts working on the Signal to Noise Ratio. A thanks to Cuong Nguyen for managing group operations as a whole, while building on functions from the group to create valuable functions that aid in ease of use. Also, for his work on extraction, filtering, and calculation of timestamps. He also contributed greatly to the group by providing valuable assistance and insight. And a final thanks to Tyler Jordan for his assistance in DC Offset removal, signal normalization, group assistance, and preparation/completion of a final report. These collective efforts contributed to a final product of a complete timing analysis.

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