UT Austin ECE 313 Linear Systems and Signals

Mini Project #2: Filtering Out Satellite Signals

Ms. Alice Liu

November 10, 2026, *Version 1.0*

1.0 Introduction

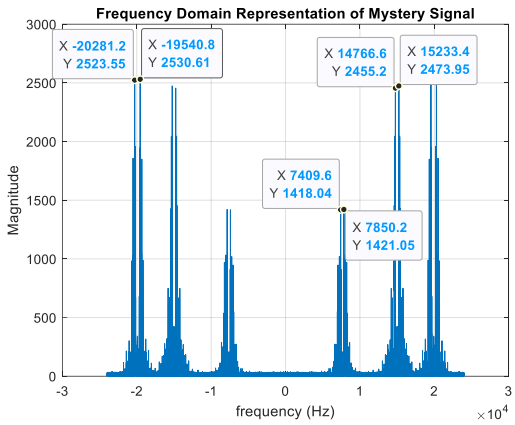
For this mini-project, we implement the reception of a simple wireless communications example. In our simple example, we are a hand-held cellular phone user that is in the Field-of-View of three satellite communication systems, and each satellite is transmitting a signal down to the user in direct-to-cellular (D2C) communications. The goal of this mini-project is to filter out each satellite signal from the combined signal received by the hand-held user and bring the higher-frequency component down to baseband (centered at 0 Hz) to recover the audio clips sent from each satellite through the process of cascaded nulling filters and demodulation. We utilize techniques learned in the course such as Finite Impulse Response (FIR) filter design to filter out each satellite signal, modulate the filtered higher-frequency spectrum down to baseband via multiplication with a tailored cosine signal, and filter the resulting signal once again to remove higher-frequency copies duplicated by modulation. Once each satellite signal is recovered at baseband, we are able to recover the audio clips sent from each satellite: The Entertainer from AST, Nocturnes from AmazonLeo, and Swan Lake from Starlink.

2.0 Filtering Out Unwanted Signals and Noise

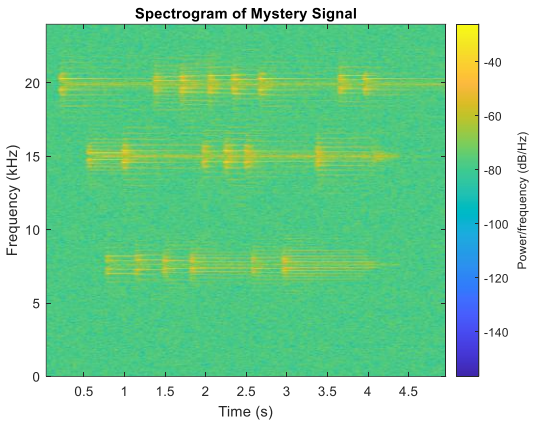
Before we can filter out undesired signals and unwanted noise, we must first identify which signals to keep. Thus, given a received mystery satellite signal, our first order of business is to analyze the frequency domain representations of the signals to identify what frequencies are present. After identifying each signal, we can then remove undesired signals and unwanted noise via a cascade of Nulling Filters.

Signal Identification

At a glance, we can visually identify from Figure 1 in the frequency domain and spectrogram plots that there are 3 distinct signals, each corresponding to a signal from the 3 satellites (AST, AmazonLeo, Starlink). We identify each signal's center frequency, f_c, and frequency ranges in Table 1.



(a) Frequency Domain Plot



(b) Spectrogram Plot

Figure 1. Frequency Representation of Received Mystery Satellite Signal

Table 1. Signal Identification			
#	Satellite System	Center Frequency (f_c)	Positive Frequency Ranges
(1)	AST	$7.63\ kHz$	$5.76 - 9.5\ kHz$
(2)	AmazonLeo	$15\ kHz$	$13 - 17\ kHz$
(3)	Starlink	$19.911\ kHz$	$18.42 - 21.40\ kHz$

Since we are given the downlink carrier frequencies of each satellite D2C system in the assignment [1], we use those same center frequencies to identify each signal present in `mystery_satelliteSignal`. We can also verify the center frequencies by using the Data Tip tool in MATLAB to identify the peaks of each signal unique in Figure 1a and average their values to obtain the same center frequencies.

To determine the frequency ranges of each signal, we set a threshold on the magnitude of the frequency domain representation. This threshold is a value we choose to separate the signal from the noise floor. By zooming into Figure 1a at the base of the plot, we see that the noise floor never rises above a magnitude of 50. Thus, we eyeball Figure 1a and choose frequencies that first break the magnitude of 50 around the center frequencies of each identified signal to determine their frequency ranges. Another factor that influences our choice of frequency ranges is the symmetry surrounding the center frequency of each signal that is present in Figure 1b. Thus, we choose our frequency ranges such that they will be centered around each identified signal's center frequency component. As a final sanity check, we compare against the spectrogram in Figure 1b to ensure the range of values we select encompass only the spectrum surrounding each signal that is higher than a value of 40 dB/Hz.

In Table 1, we list only the positive-valued center frequencies and frequency ranges because the symmetry in Figure 1a implies that the negative center frequencies and corresponding frequency ranges would simply be mirrored.

Filtering the Mystery Signal

Having identified the present and desired signals received, we now move on to separating each of the 3 signals out of the combined mystery signal. To do so, we will need to design Nulling Filters to remove undesirable components such as additional frequency components and noise.

The general form of the Nulling Filter can be derived from the zero-plot, where the locations of the zeros placed on the unit circle determine the resulting frequency to null-out (or remove, filter out).

Given the desired frequency to remove, f_0, the discrete time frequency to null out should be $\widehat{w_0} = 2\pi \frac{f_0}{f_s}$, where f_s is the sampling frequency of the system.

Then, the zeros of the transfer function are computed from w_0 as complex conjugates of one another:

$$z_0 = e^{j\widehat{w_0}}, {z_0}^* = e^{-j\widehat{w_0}}$$

Which we use to compute the numerator of the transfer function as follows:

$$numer = [1 \quad -(z_0 + {z_0}^*) \quad z_0{z_0}^*]$$

Thus, we have the generalized form of the transfer function for the Nulling Filter, which is designed to remove frequencies present around f_0 for a system sampled at f_s.

$$H(z) = C\left(1 - z^{-1}(z_0 + {z_0}^*) + z^{-2}(z_0{z_0}^*)\right)$$

Where C is a normalization constant to ensure the filter does not change the amplitude of the input signal and is computed from the 1-norm of the numerator vector.

$$C = \frac{1}{\|numer\|_1}$$

Since each Nulling Filter can only remove one frequency component, we will need to implement a cascade of these filters. For each identified satellite signal, we will need to remove the other 2 undesired satellite signals (and noise, if desired). This means we will design a total of at least 3 unique Nulling Filters – one filter for each uniquely identified signal.

For each identified satellite signal, we process each signal from the beginning – a clean copy of the `mystery_satelliteSignal`. Now, let us examine each signal one at a time.

Signal (1) – AST

Our AST-like signal is centered around $f_c = 7.63\ kHz$, so to isolate this signal out of the received mystery signal, we will need to filter out the signals centered around $f_c = 15\ kHz$ and $f_c = 19.911\ kHz$.

We first design a Nulling Filter to remove the components from the AmazonLeo signal centered around $f_c = 15\ kHz$. From Figure 2, we see that this Nulling Filter zeros out frequencies centered around a discrete frequency of $\widehat{w_0} = 0.625\pi\ radians$. From the magnitude response in Figure 2, we see that this filter design is very sharp, only affecting a narrow band of frequencies around the frequency to remove.

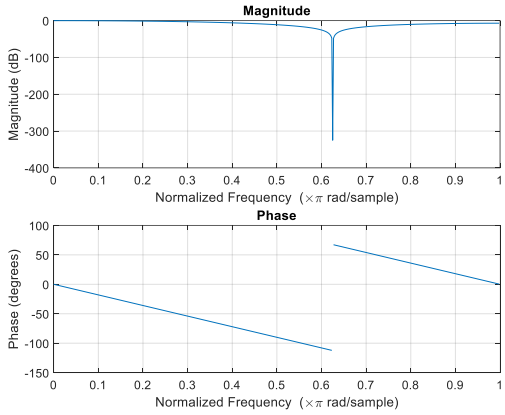
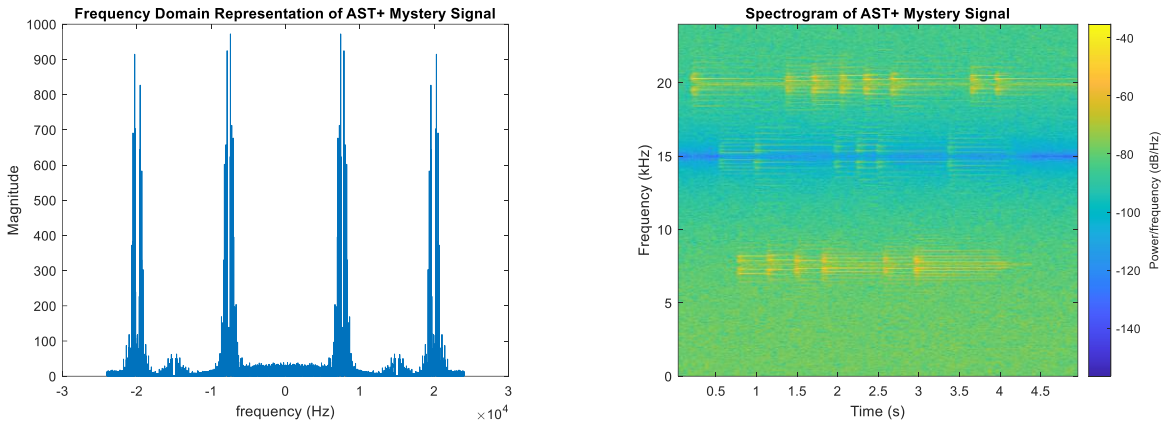


Figure 2. Frequency Response of AmazonLeo Nulling Filter

After passing `mystery_satelliteSignal` through the AmazonLeo Nulling Filter, we find that the spectrum components from the AmazonLeo component are removed, which can be seen in Figure 3. However, we still have components present from the Starlink signal, which can be seen in the peaks of Figure 3a and the high magnitude in the higher frequency area of Figure 3b. So, we still need to filter at least one more time.



(a) Frequency Domain Plot (b) Spectrogram Plot

Figure 3. Frequency Representation of Filtered Mystery Signal (AST+Starlink)

To remove the components from the Starlink signal centered around $f_c = 19.911\ kHz$, we now design a Nulling Filter to filter out frequencies centered around a discrete frequency of $\widehat{w_0} = 0.830\pi\ radians$ as shown in Figure 4. In contrast to Figure 2, we see that this Nulling Filter greatly affects surrounding frequency components and begins suppressing frequencies starting as early from $\widehat{w} \cong 0.2\pi\ radians$. This will be good for isolating the AST signal, as this filter will suppress further the components from the higher frequency AmazonLeo and Starlink signals.

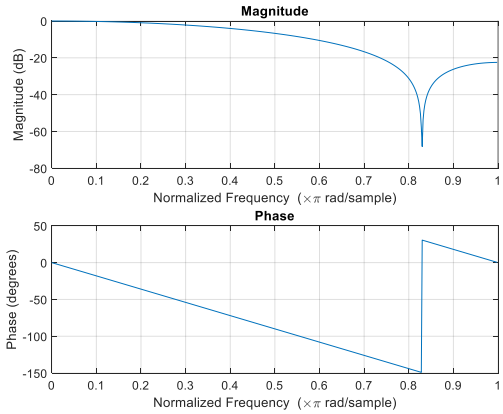
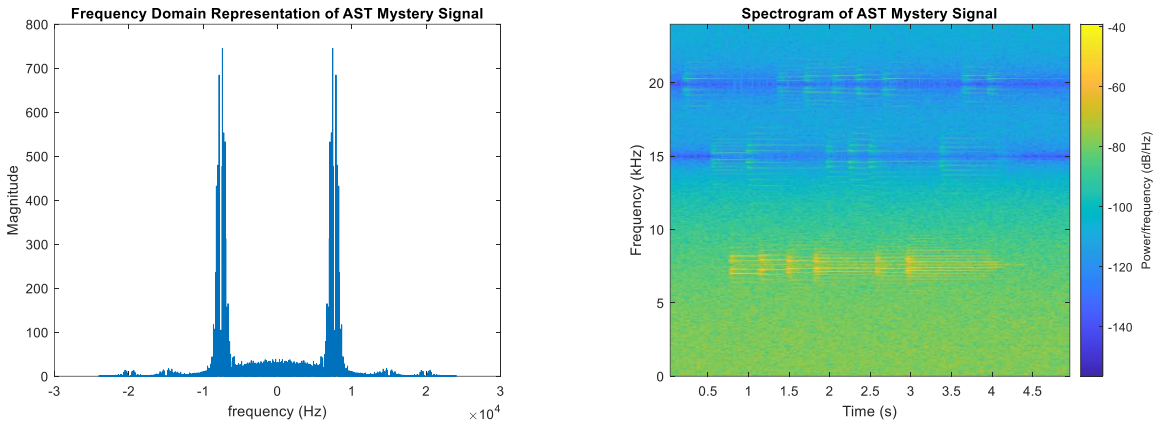


Figure 4. Frequency Response of Starlink Nulling Filter

Now, having passed `mystery_satelliteSignal` through a cascade of 2 Nulling Filters, we see that all the frequency components from the other 2 undesired satellites are removed from the frequency domain plot in Figure 5a and significantly suppressed from the spectrogram in Figure 5d.



(a) Frequency Domain Plot (b) Spectrogram Plot

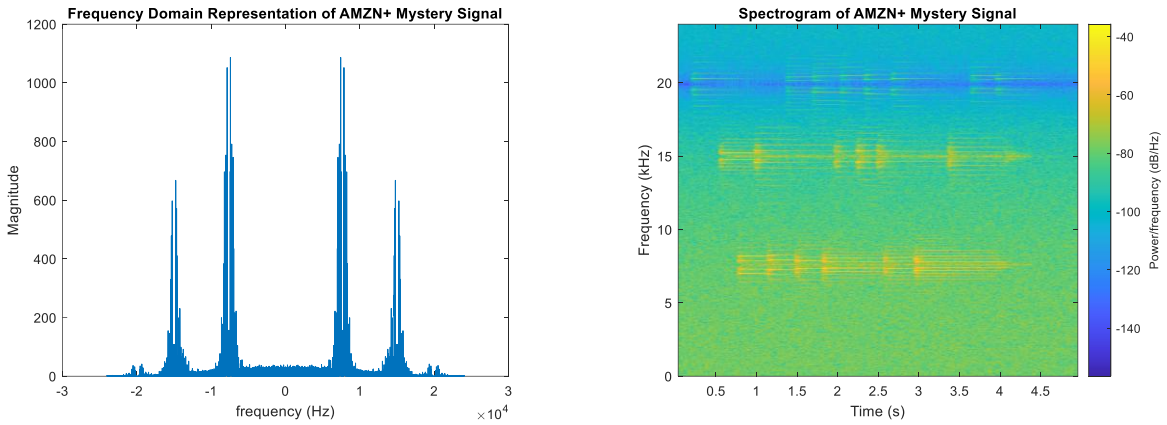
Figure 5. Frequency Representation of AST Satellite Signal

Although these nulling filters have greatly reduced the signals from the AmazonLeo and Starlink satellites, we see that there are still some components remaining in Figure 5a. Thankfully, these remaining components fall below the noise floor which we can see is still largely present at baseband (centered around 0 Hz). We could continue to apply a cascade of nulling filters to remove additional noise at baseband and the residual components from the AmazonLeo and Starlink signals, but for now we consider to have obtained the AST signal and move on to obtaining the other signals.

Signal (2) – AmazonLeo

Our AmazonLeo-like signal is centered around $f_c = 15\ kHz$, so to isolate this signal out of the received mystery signal, we will need to filter out the signals centered around $f_c = 19.911\ kHz$ and $f_c = 7.63\ kHz$.

As we have already designed a Nulling Filter to remove the Starlink signal, we will directly apply the filter to the mystery signal. We find that the Starlink Nulling Filter removes the components at the high end of the spectrum as seen in Figure 6a but still leaves components in the lower frequencies. In fact, we see that the Starlink Nulling Filter also suppresses the desired signal due to its to the undesired Starlink signal. In this scenario, the behavior of the filter from Figure 2 is less desirable as it also affects the amplitude of our desired AmazonLeo signal.



(a) Frequency Domain Plot (b) Spectrogram Plot

Figure 6. Frequency Representation of Filtered Mystery Signal (AmazonLeo+AST)

To remove the undesired AST signal component, we need to design a new filter. We design a Nulling Filter to filter out frequencies centered around a discrete frequency of $\widehat{w_0} = 0.318\pi\ radians$ as shown in Figure 7. Similar to the Nulling Filter for the Starlink components, this AST Nulling Filter also affects a wide range of frequencies.

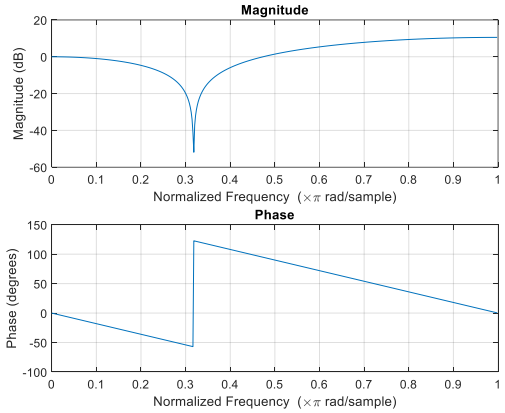
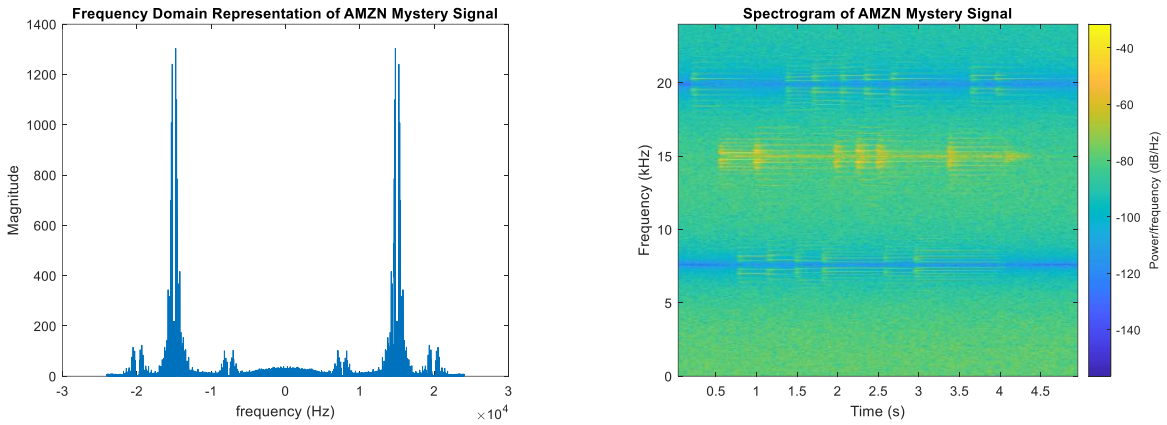


Figure 7. Frequency Response of AST Nulling Filter



(a) Frequency Domain Plot (b) Spectrogram Plot

Figure 8. Frequency Representation of AmazonLeo Satellite Signal

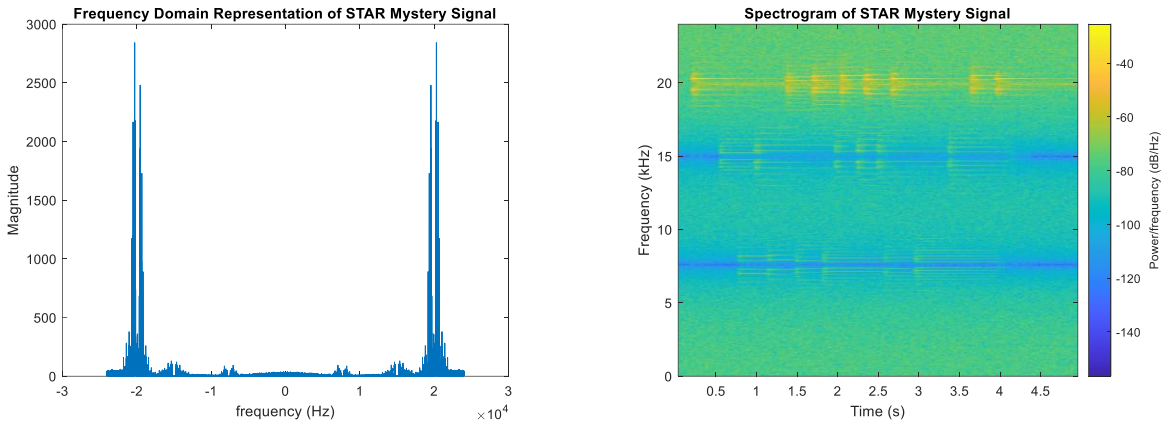
In the case of our desired AmazonLeo signal, the performance of the AST Nulling Filter actually improves the magnitude of our frequency response, as seen when comparing Figure 8a to Figure 6a. This is a direct result of the increasing magnitude response as $\widehat{w}$ increases to higher frequencies in the AST Nulling Filter seen in Figure 7.

Similar to our discussion for the AST signal, we can continue to pass the signal through Nulling Filters to further reduce undesirable components. However, as we saw for the Starlink and AST Nulling Filters, at times the filters may suppress our desired signal which may degrade our signal quality later for demodulation. Thus, we conclude our cascade of Nulling Filters to obtain the AmazonLeo satellite signal.

<u>Signal (3) – Starlink</u>

Our Starlink-like signal is centered around $f_c = 19.911\ kHz$ and so to isolate this signal out of the received mystery signal, we will need to filter out the signals centered around $f_c = 15\ kHz$ and $f_c = 7.63\ kHz$.

At this point, we have already discussed all the unique FIR Nulling Filters and their corresponding magnitude and phase response and filter responses onto signals. Thus, for the Starlink signal we sill directly examine the filtered response after cascading through both filters to remove the undesired AST and AmazonLeo signals.



(a) Frequency Domain Plot (b) Spectrogram Plot

Figure 9. Frequency Representation of Starlink Satellite Signal

We see in Figure 9a that only the frequency components centered around $f_c = 19.911\ kHz$ remain, and in Figure 9b the components corresponding to the signals sent from AST- and AmazonLeo-like satellites have been suppressed. We have isolated and filtered out the Starlink-like signal from the received mystery signal.

Now that we have successfully obtained all three identified signals, we can move on to the next step: demodulation.

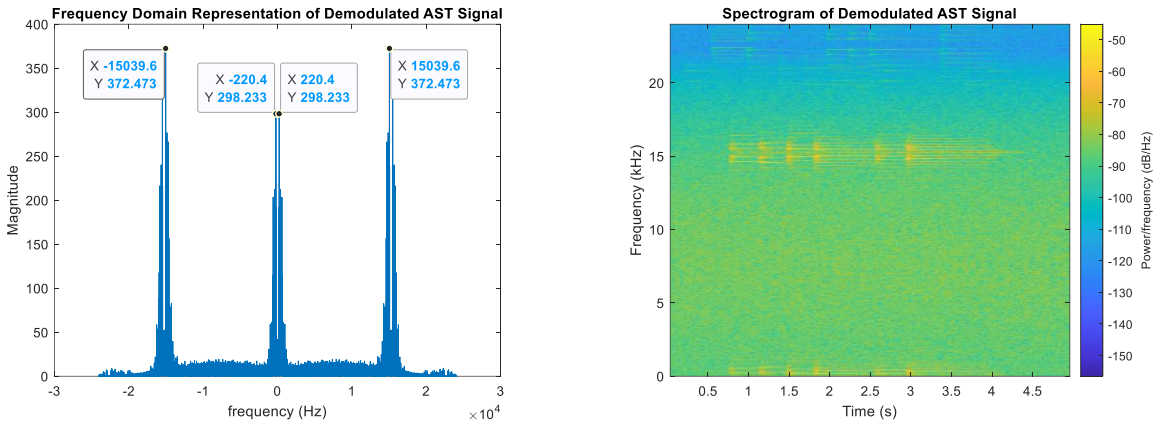
3.0 Demodulation

Demodulation consists of two steps: 1) modulation from higher frequencies down to baseband frequencies centered at 0 Hz, and 2) additional Lowpass Filtering (LPF) to remove duplicated copies that resulted from modulation.

3.1 Modulation

The modulation step in demodulation brings signals at higher frequencies down to baseband. This process is done by multiplying the signal with a sinusoid that operates at its corresponding carrier frequency. Earlier in signal identification, we identified each signal's center frequency, which we can now use to generate sinusoidal signals to modulate each filtered satellite signal down to baseband. We will now modulate each signal one by one.

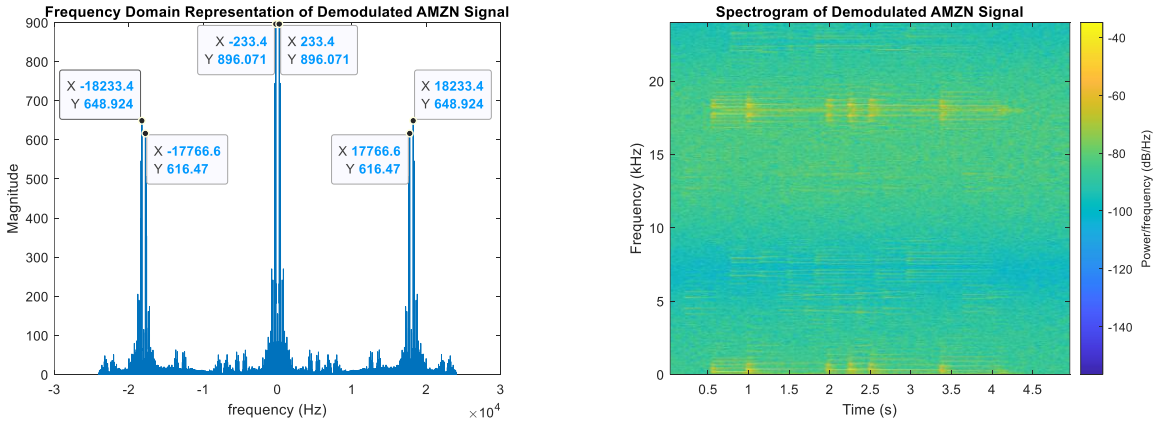
For the AST satellite signal, we modulate it by multiplying the signal with a sinusoid at a carrier frequency of $7.63\ kHz$. In Figure 10 we see that this introduces a total of 2 copies, one centered at baseband around $0\ kHz$ and another copy at $\pm 15.26\ kHz$. From Mini-Project #1 [2] and previous Tune-up assignments, we know that the resulting center frequency of the duplicated copy is the sum of the original signal's center frequency and the sinusoid's frequency.



(a) Frequency Domain Plot (b) Spectrogram Plot

Figure 10. Frequency Representation of Modulated AST Satellite Signal

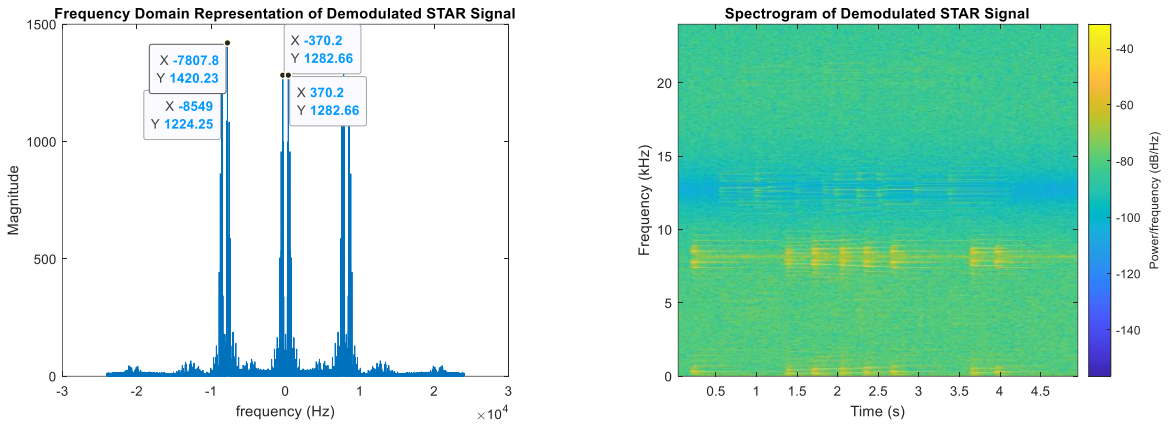
For the AmazonLeo satellite signal, we modulate it by multiplying the signal with a sinusoid at a carrier frequency of $15\ kHz$. In Figure 11 below we see that this introduces a total of 2 copies, one centered at baseband around $0\ kHz$ and another copy at $\pm 18\ kHz$. The duplicated AmazonLeo copy is located at a different frequency than expected. We expect to see the duplicated copy at $\pm 30\ kHz$; however, we must recall that our sampling frequency is only at $48\ kHz$, and so we are only able to examine frequencies up to $\pm 24\ kHz$. Thus, we will not be able to see the desired duplicate at $30\ kHz$ because it is aliasing down to $\pm 18\ kHz$. For the AmazonLeo signal, the lowpass filtering in the next step is crucial, in order to remove effects due to aliasing.



(a) Frequency Domain Plot (b) Spectrogram Plot

Figure 11. Frequency Representation of Modulated AmazonLeo Satellite Signal

For the Starlink satellite signal, we modulate it by multiplying the signal with a sinusoid at a carrier frequency of $19.911\ kHz$. In Figure 12 we see that this introduces a total of 2 copies, one centered at baseband around $0\ kHz$ and another, also aliased, copy at $\pm 8178\ kHz$.



(a) Frequency Domain Plot (b) Spectrogram Plot

Figure 12. Frequency Representation of Modulated Starlink Satellite Signal

After modulation, we can roughly hear the melody in the received signals. At this time, we playback each baseband signal and compare the audio against online recordings to determine the piece transmitted from each satellite. We map each satellite signal to their corresponding pieces in Table 2 below:

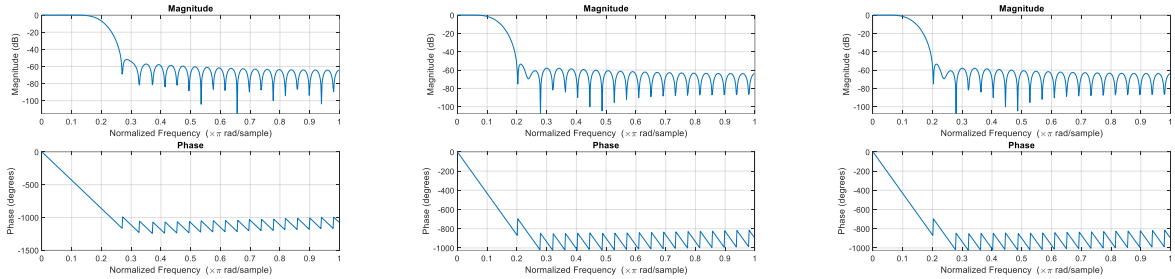
Table 2. Mapping Satellite Signals to their Transmit Audio Signal Pieces			
(1)	AST	from in $f_c = 7.63\ kHz$ spectrum in `mystery_satelliteSignal`	The Entertainer (1902), by Scott Joplin
(2)	AmazonLeo	from in $f_c = 15\ kHz$ spectrum in `mystery_satelliteSignal`	Nocturnes, Op. 9 No. 2 (1832), by Frederich Chopin
(3)	Starlink	from in $f_c = 19.911\ kHz$ spectrum in `mystery_satelliteSignal`	Swan Lake Op. 20 Act 2 No. 10 (1876), by Pytor Tchaikovsky

3.2 Filtering, Once Again

As we saw in 3.1 Modulation, the duplicated copies of the modulated signals can at times result in aliasing. Thus, the lowpass filtering step is crucial to ensure we can receive back our desired signal. Additionally, even if the duplicated signals were not aliased, as is the case for the AST signal, the extra copies result in undesired artifacts in the signal that distort the audio we hear.

In this following section, rather than generating our simple Nulling Filters, we instead opt to use built in MATLAB functions to perform the lowpass filtering. For this solution, we will discuss the MATLAB "`fir1`" filter command and compare its performance and implementation against our Nulling Filters we designed in 2.0 Filtering out Unwanted Signals and Noise.

Unlike our Nulling Filter which can only null out one frequency at a time, the `fir1` command may be used to design Lowpass, Highpass, Bandpass, and Bandstop filters. One key difference is that our Nulling Filters only have one pair of zeros, where as in `fir1`, it can design with as many zeros up to half the filter order, '`n`'. The user can input a desired filter order, say `n=48`, then `fir1` can design a filter to meet the desired specifications on filter type and cutoff frequencies. In the following Figure 13, we see the difference in frequency response that the `fir1` filters can achieve with a filter order of `n=48`. In all the LPF, the desired cut-off frequency varies from $1000\ Hz$ to $1500\ Hz$, and unlike the Nulling Filters, we see that all the frequencies after the cutoff are suppressed. In our Nulling Filters, at worst we were only able to remove one frequency as is the case with the AmazonLeo Nulling Filter in Figure 2, and at best, we were able to suppress nearby frequencies around the desired center frequency.



(a) AST (b) AmazonLeo (c) Starlink

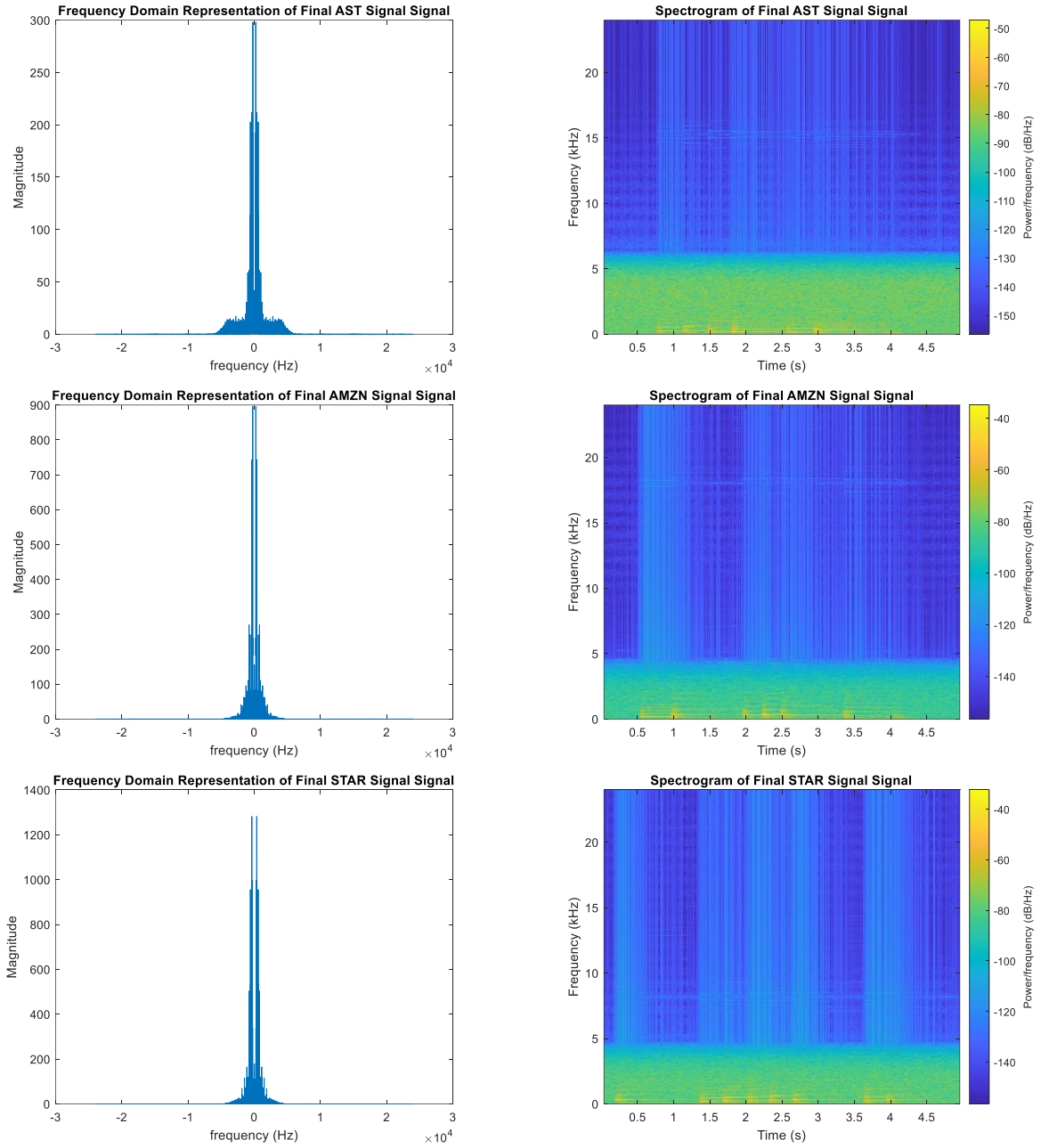
Figure 13. `fir1` Lowpass Filter Magnitude and Phase Response Comparison

Because the additional zeros are able to assist in suppressing frequencies outside of the cutoff frequency, we see significant improvements after passing the signals through the LPF as seen in Figure 14. We see that for all the signals, the noise is significantly reduced for frequencies higher than $5\ kHz$, and we see that for all of the systems, the duplicated frequency components have been removed in Figure 14a. However, we still see traces of the duplicated copies in the spectrogram in Figure 14b, that may still be audible to some listeners.

While we have improved filtering performance, we do have an implementation cost incurred by using the MATLAB `fir1` command: memory usage increases with the filter order due to increasing number of coefficients, run-time performance is longer due to computation for a higher filter order, and implementation complexity increases in order to find all the coefficients required to generate such a filter.

For each Nulling Filter, we only needed enough memory for 3 coefficients, but for the 48-order filter designed by `fir1`, we require memory for 49 coefficients. In terms of run-time performance, we see in Table 3 that our simple double cascaded Nulling Filter computes

the coefficients much faster compared to MATLAB's `fir1` implementation. There is a trade-off of cost and benefit between simpler and more complex systems.



(a) Frequency Domain Plot (b) Spectrogram Plot

Figure 14. Frequency Representation of Final AST, AmazonLeo, and Starlink Signals

Table 3. FIR Filter Run-Time Performance Comparison		
	Cascaded Nulling Filter	`fir1` Lowpass Filter (order N=48)
AST	0.012546 seconds	0.061459 seconds
AmazonLeo	0.011169 seconds	0.014698 seconds
Starlink	0.009311 seconds	0.017205 seconds

We now compare the audio quality before and after this last filtering step in 3.2, and we note that the noise in the signal remains present even with the additional LPF. However, we highlight that because of the LPF, the higher frequency components duplicated as a result of the modulation step in 3.1 have either been removed, as is the case in the AST signal, or significantly suppressed, as is the case in the AmazonLeo and Starlink signals. Instead, we can hear the original, but still noisy, audio signal received from each satellite. Through this audio playback of the received signal, we understand the importance of the final filtering step in demodulation to remove as much as possible the duplicated copies that naturally result from modulation.

4.0 Conclusion

In this mini-project 2, we identified in the received `mystery_satelliteSignal` a total of 3 satellite signals identified from AST-, AmazonLeo-, and Starlink-like satellite signals. Through design and implementation of multiple FIR Nulling Filters, we isolated each satellite signal out of the received signal that contained a combination of all three signals by cascading the filtered signals through additional Nulling Filters. Further processing to implement demodulation through a two-step operation of modulation and additional filtering enabled us to successfully receive back the original audio signal sent from each satellite.

References

1. Alice Liu, “Mini-Project #2: Filtering Out Satellite Signals – Assignment.” https://users.ece.utexas.edu/~bevans/courses/signals, October 30, 2026.
2. Alice Liu, “Mini Project #1: Digital Audio Effects – Solution.” https://users.ece.utexas.edu/~bevans/courses/signals, September 29, 2026.
3. The MathWorks, Inc., “MATLAB Help Center – fir1.” https://www.mathworks.com/help/signal/ref/ fir1.html.