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Project 2 MATLAB Programming

Introduction

1. Master time-domain processing methods:

(1) Digital down conversion;

DDC is the process where you take a signal centered around a high frequency (such as those usually transmitted by a radio station) and pull it down so that it is centered around baseband (0 Hz) instead. This usually happens in three steps:

- Mixing

  Mixing (or in this case complex mixing) is the process of multiplying the input signal with a carrier frequency fc by a complex exponential $e^{-j2\pi * fc * t}$ to shift its frequency spectrum down to 0 Hz. Real-valued signals have Hermitian symmetry, so in the case that it has a carrier frequency of fc, it will have equal magnitude but complex conjugate components centered around +fc and -fc in the frequency domain.

  So for example, if the input signal is x(t), then the mixed signal would be $x(t)e^{-j2\pi * fc * t}$ and the components in the frequency domain would be centered around -2fc and 0 due to the shift.

- Low pass filtering

  The LPF will filter out and get rid of the components that are not the ones currently centered around 0 Hz, keeping only the desired baseband component.

- Decimation

Decimation is the combination of low pass filtering and downsampling. After reducing the signal's bandwidth to center around baseband, we no longer need the original high sampling rate fs, so we can safely downsample the signal to reduce data rate, making it smaller and easier to store, process, or transmit, while still retaining the information contained in the signal.

To decimate without losing information, the new sampling rate $f's$ needs to be larger than twice the current bandwidth of the filtered signal that is centered at the baseband. This would result in us having a decimation factor D = fs /$f's$. Then we have to filter out all frequencies above $f's$ / 2 to prevent aliasing. Finally, to downsample, we just have to keep every D-th sample, and the output will be the final result of the DDC process.

(2) Digital filter design and usage;

A filter is a wall of sorts that blocks certain frequencies while letting others through. There are four types of filters commonly used in signal processing:

- low-pass filters: lets frequencies lower than the cutoff frequency pass
- high-pass filters: lets frequencies higher than the cutoff frequency pass
- band-pass filters: lets frequencies within the frequency band pass
- band-stop filters: blocks frequencies within the frequency band

To design a filter, first choose the type of filter, then decide the cutoff frequency or frequency band. Then, choose the filter order: the higher the order the sharper - the more abrupt - the cutoff will be. Lastly, use filter design methods (e.g. butterworth, chebyshev, etc) to get the filter coefficients, which for digital filters come in two types, the feedforward coefficients (b) and the feedback coefficients (a). These coefficients will then define the filter's difference equation.

To apply the filter on a signal, the filter's difference equation is computed onto the input signal, which in FIR filters would be identical to a convolution since it only has feedforward coefficients.

(3) Calculation of ambiguity function (cross-correlation).

The ambiguity function, in the case of cross-correlation, measures the similarity between the surveillance signal and a time delayed and frequency shifted version of a reference signal, revealing the time delay and Doppler shift of potential targets.

It is defined as:

$$\mathrm{Cor}(\tau, f, t_0) = \int_{t_0}^{t_0+T} y_{\mathrm{sur}}(t) \cdot y^*_{\mathrm{ref}}(t-\tau) \cdot e^{-j2\pi f t}\, dt$$

Where $y_{sur}(t)$ is the received signal from the surveillance channel, in which the signal transmitted by the transmitter has been reflected by the target towards the receiver, and $y_{ref}(t)$ is the received signal from the reference channel, which is the direct signal from the transmitter. Integrating over $[to, to\ +\ T]$ lets us observe the signals in a long enough time frame to capture the full reflection of it. In this function, $y^*_{ref}(t - \tau)\ .\ e^{-j2\pi * f * t}$ is the conjugate of the reference signal $y_{ref}(t)$ delayed by τ and doppler shifted by frequency f.

We aim to sweep over every possible delay and doppler shift to see if any version of it matches the surveillance signal $y_{sur}(t)$. A match will produce a strong correlation, which appears as a peak in the ambiguity function, indicating the presence of a target with a specific time delay and Doppler shift.

$$\left(\hat{\tau}, \hat{f}_D\right) = \underset{\tau, f}{\operatorname{argmax}}\, Cor(\tau, f, t_0)$$

The maximum of these correlations will be our best estimate on the time delay and doppler shift of the surveillance signal. From there, we can estimate the range and velocity of the target with these formulas:

$$\text{Range} = \frac{c \cdot \tau}{2} \qquad v = \frac{f_d \cdot c}{2 f_0}$$

Where c is the constant speed of light and fo the frequency of the reference signal.

2. Master frequency-domain processing methods:

(1) Analyze signal spectrum;

The spectrum of a signal describes how much energy the signal has at different frequencies. This lets us identify the frequency components that make up a signal, design and verify filters for the signal, as well as see how much bandwidth the signal occupies.

Spectrum analysis is done by applying the fourier transform on a time-domain signal, which results in a complex valued function in the frequency domain. This complex output can be expressed in terms of magnitude and phase for each frequency component.

Magnitude Spectrum:

- The magnitude at each frequency shows how strong (how much energy) that particular frequency component is in the signal. The magnitude spectrum tells us the energy distribution over frequency, which helps us identify dominant frequencies, harmonics, noise levels, and overall bandwidth.

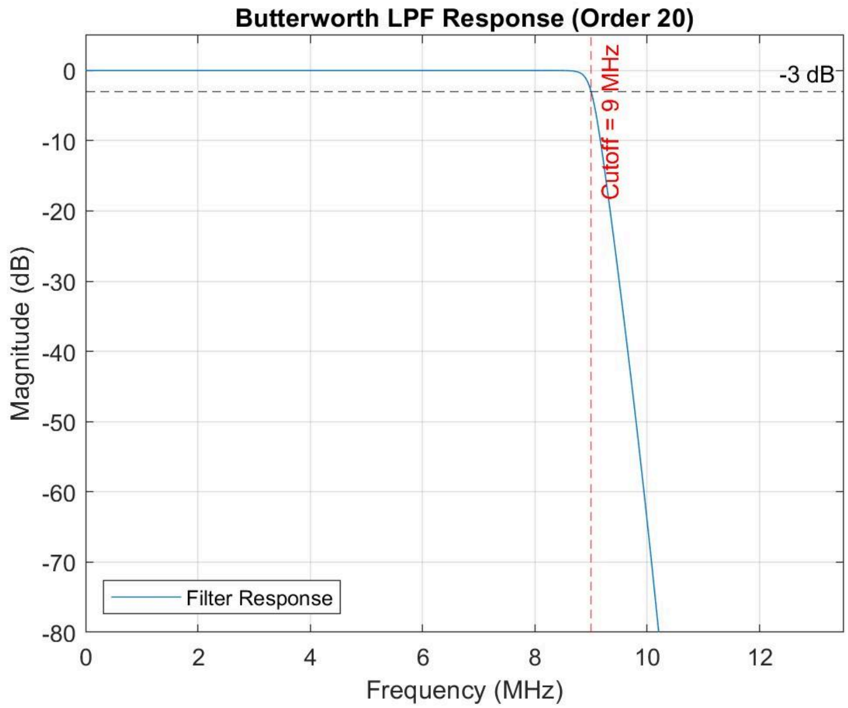
Phase Spectrum:

- The phase tells us how much each frequency component is shifted in time, relative to a cosine wave of the same frequency that starts at time zero. Phase is important because it affects how different frequency components add up in the time domain and changing the phase can also change the shape of the reconstructed signal even if magnitude remains the same. The phase spectrum shows how each frequency component is shifted in time, which is crucial for accurate signal reconstruction, modulation, and understanding signal delays.

So in conclusion, the magnitude spectrum reveals what frequencies are present and how strong they are while the phase spectrum tells us how those frequencies are aligned in time. Both of these allow us to fully reconstruct the original time-domain signal by applying the inverse Fourier Transform.

(2) Design and verification of low-pass filters.

A low pass filter blocks frequencies higher than the cutoff frequency while letting those lower through. To design a low pass filter, first decide the cutoff frequency. Then, choose the filter order: the higher the order the sharper - the more abrupt - the cutoff will be. Lastly, use filter design methods (e.g. butterworth, chebyshev, etc) to get the filter coefficients, which for digital filters come in two types, the feedforward coefficients (b) and the feedback coefficients (a). To verify if the filter works, check the frequency response graph of the resulting signal. If it only passes the frequencies below the cutoff frequency, then it is working. Here’s the frequency response of LPF response:



It can be seen from the plot that the cutoff frequency of the LPF is 9 MHz, therefore the LPF is correct.

3. Real-world application of motion detection technology that leverages communication signals:

- Home Security
  When someone moves within the coverage area, their body scatters Wi-Fi packets, causing tiny fluctuations in the channel-state information (CSI). By analyzing these fluctuations, the system can distinguish normal background noise from human motion and send an alert if an unauthorized person is detected. This technology removes the need for additional cameras making the installation more simple and reduces the cost.

- Elderly & Health Monitoring
  In most homecare, motion detection Wi-Fi based can detect falls by identifying sudden high energy Doppler created when someone hits the floor. In addition, the analysis of CSI can track slow, rhythmic chess movements that refer to breathing or small changes in a patient's condition. Residents don’t need to wear any devices since it is entirely contactless and the technology works as long the Wi-Fi is present. Therefore, alerts can be sent to caregivers if there’s abnormal patterns detected such as pauses in breathing.

- Smart-Home Automation

Motion detection using communication signals can replace occupancy sensors in a smart home. As people enter or leave the room, it causes measurable changes in CSI, so lights, thermostats, or blinds, can automatically adjust without pressing switches. It is also possible to detect hand gestures using micro-Doppler analysis which lets you control devices with a simple wave. All of this technology works without cameras which makes it more comfortable.

- Retail & Public Spaces
  Retailers can use motion detection Wi-Fi based to count how many customers walk through a store in a specific aisle by monitoring how the customers disturb the signal. Analyzing the CSI fluctuations can estimate the foot-traffic patterns helping optimize the store layout and staffing. Then, at checkout lines, Doppler shift can reveal when people join or leave the queue, triggering an alert to open a new register if the line grows too long. Instead of cameras, this technology can preserve the privacy of the customers because no faces or identities are captured.

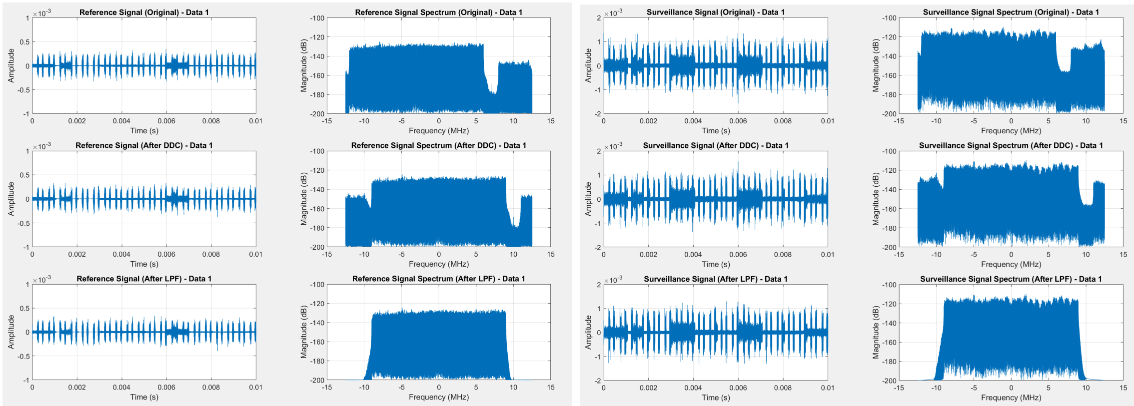
- Smart Factory
  Factories can use motion detection Wi-Fi based to monitor machine health and safety. Rotating equipment such as motors or conveyor belts create unique Doppler patterns that change if abnormal vibration occurs, enabling predictive maintenance without sensors on every machine. In smart buildings, Wi-Fi signals detect human traffic to optimize lighting and space utilization. For instance, if no one is in a conference room for a while, the system can automatically lower heating or lighting to save energy.

Results and Analysis

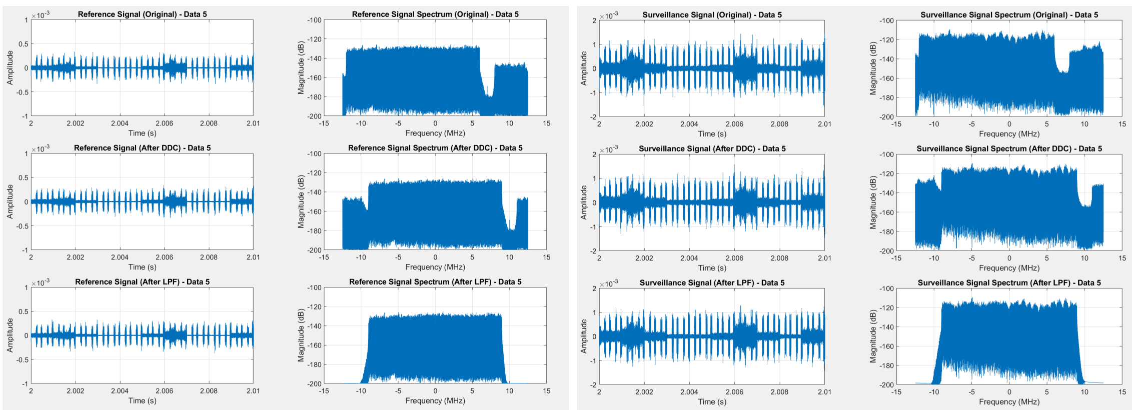
- ### Task 1:
  The objective of this task is to plot the time-domain and frequency domain waveform of the reference signal and surveillance signal going through pre-processing step-by-step. We're going to this only for the data files that are being processed in Task 2 which are Data 1, 5, 11, and 15.

  This pre-processing section plotting includes the original waveform, the waveform after doing a Digital Down Convert, and then after that passing it through a Low Pass Filter. So each Data file will consist of 6 subplots as seen below.

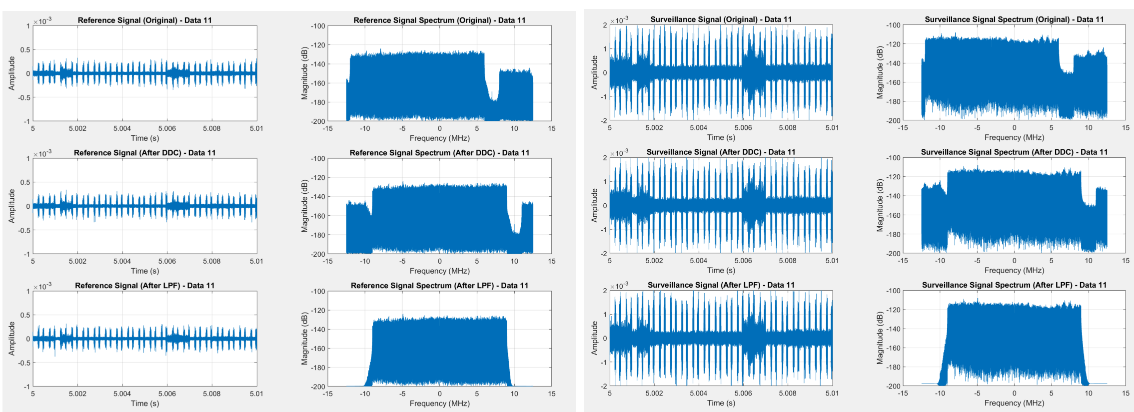
  Data 1:



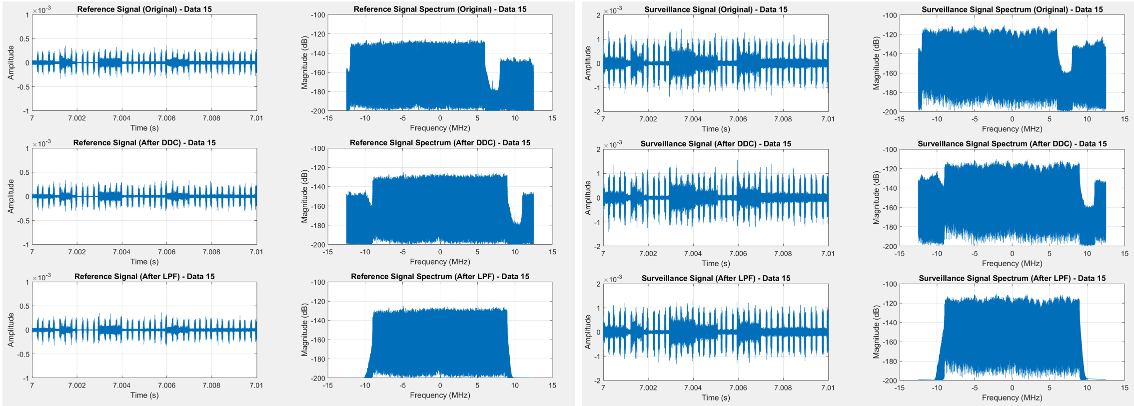
Data 5:



Data 11:



Data 15:



Analysis & Interpretation of Results:

Time-Domain signals

From the time-domain plot for both the reference signal and the surveillance signal, we can clearly see that there is absolutely no difference that can be seen from the original, after DDC, and after LPF signals, so we can conclude that the time-domain signal is largely unchanged or unaffected by DDC and LPF at least at this level of clarity.

Frequency-Domain signals

Now in the frequency domain we can see that there are significant changes between each process being done on the original signal.

DDC

What the DDC is supposed to do is its supposed shift the frequency by the amount that we want in the frequency domain. The DDC shift that we used in this task is -3MHz and we can see accurately that in all the frequency-domain graphs of both the reference and surveillance signals the graph was shifted to the right by 3MHz equivalent to multiplying by $e^{-j2\pi(-3 * 10^{6} * t)}$ in the time domain. This essentially aligns the useful signal to be a certain range of frequency for easier analysis later on, making the doppler shifts appear as low-frequency offsets around 0Hz.

LPF

What the LPF is supposed to do is to remove or attenuate high frequency components and preserve the low frequency components of the signal to reduce the noise, aliasing, or unwanted signals while preserving the wanted signal. The LPF value that we used in this task is 9MHz, and again we can see in all the frequency-domain graphs that above 9MHz and below -9MHz, the signal is quickly attenuated due to the high filter order of 20 which makes the transition band narrow and so the cutoff is sharp. This should in theory enhance the signal quality or SNR by removing the clutter and noise making the signal cleaner which aids in signal detection.

Task 2:

This task requires us to generate the Range-Doppler spectrum for the four segments (0–0.5 s, 2–2.5 s, 5–5.5 s, and 7–7.5 s). To do this, we first apply the preprocessing from Task 1, then we compute its ambiguity function based on the window range, which follows that:

1. The window [0–0.5 s) is spanned by **Data 1** (current time = 0.0 s)
2. The window [2.0–2.5 s) is spanned by **Data 5** (current time = 2.0 s)
3. The window [5.0–5.5 s) is spanned by **Data 11** (current time = 5.0 s)
4. The window [7.0–7.5 s) is spanned by **Data 15** (current time = 7.0 s)

For each window, we calculate its ambiguity function, which is a 2D correlation map in (k, Doppler) space. The range we use is [0, 12, 24, 36, 48, 60, 72] and the doppler shift ranges from –40 Hz to 40 Hz in 2 Hz steps. From that range vector, we also can obtain the τ where it's necessary variable to calculate the ambiguity function (can refer to the introduction section). τ can be obtain by this equation,

$$\tau = \frac{range}{c}$$

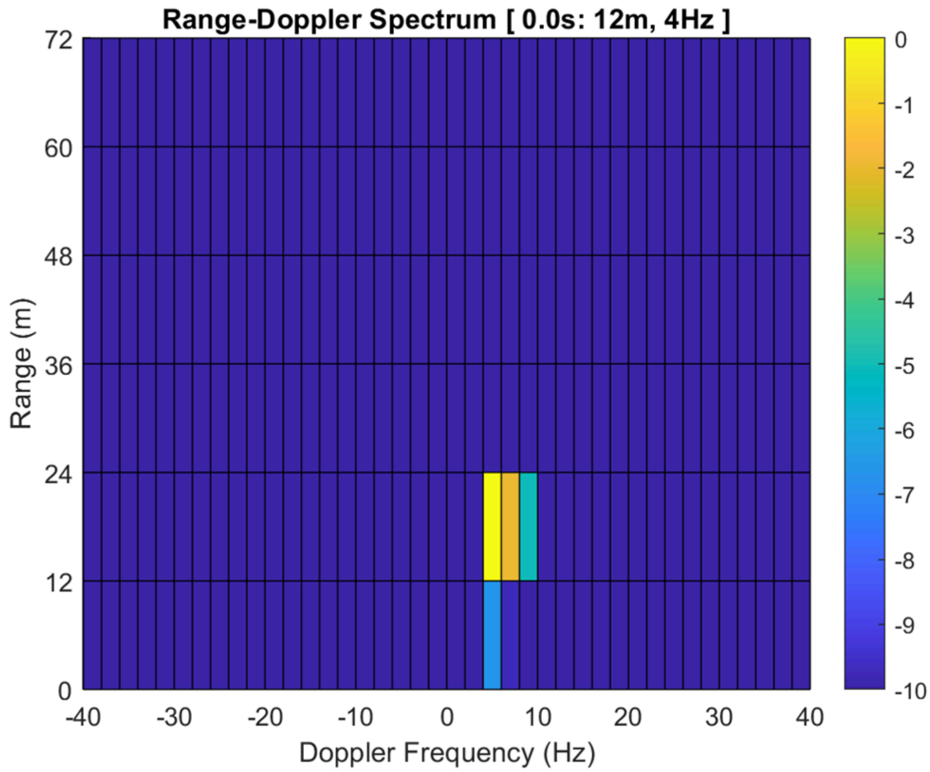
Where:

- c is the speed of light

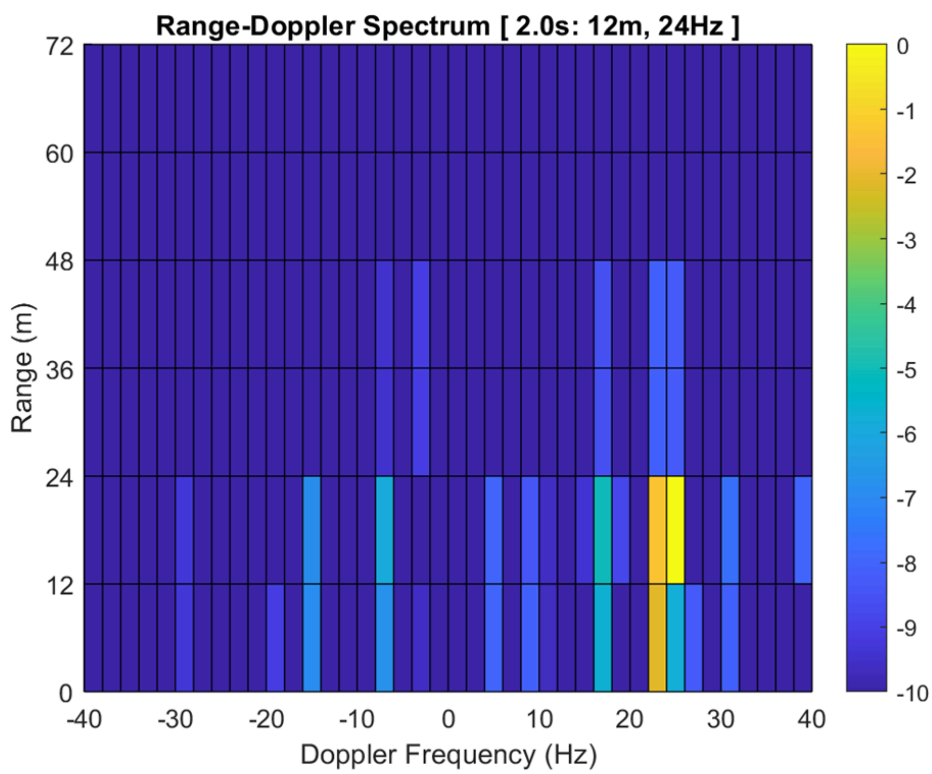
Finally we convert the map to decibel scale and plot the Range-Doppler spectrum based on that map as a function of range vs doppler shift. Here's the result:

Note: To avoid having -inf when scaling the ambiguity function to decibel, we set a small value ε = 0.001, and make the values smaller ε to ε. Therefore, when we do the decibel scaling to the ambiguity function, the minimum value would be -30d dB.

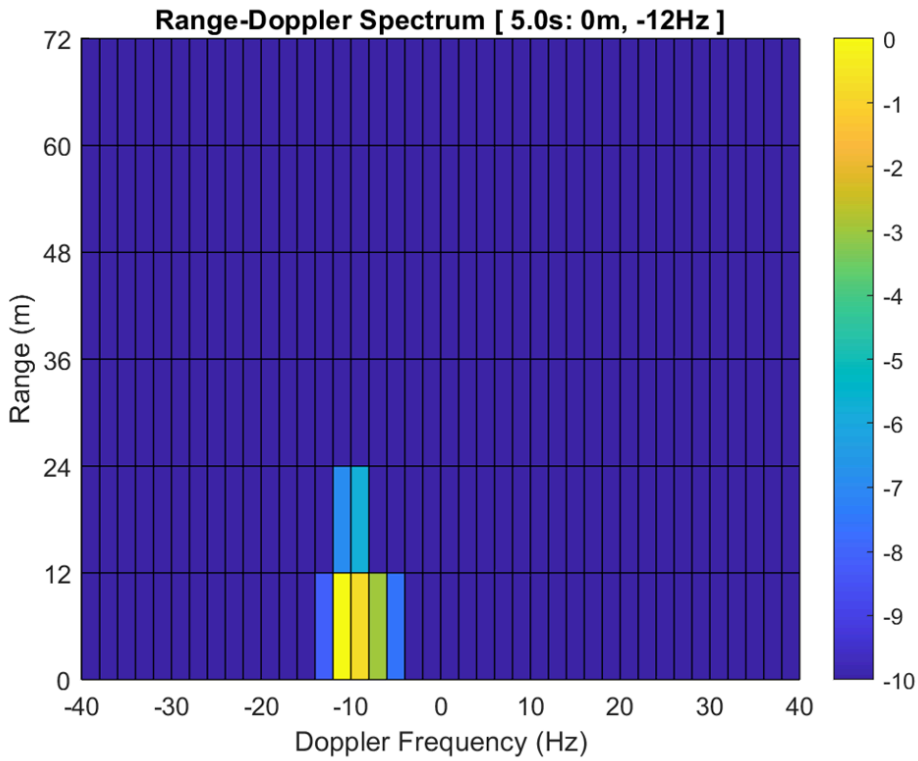
- 0 - 0.5s


Range-Doppler Spectrum [0.0s: 12m, 4Hz]
Range (m)
Doppler Frequency (Hz)
72
60
48
36
24
12
0
-40
-30
-20
-10
0
10
20
30
40
0
-1
-2
-3
-4
-5
-6
-7
-8
-9
-10

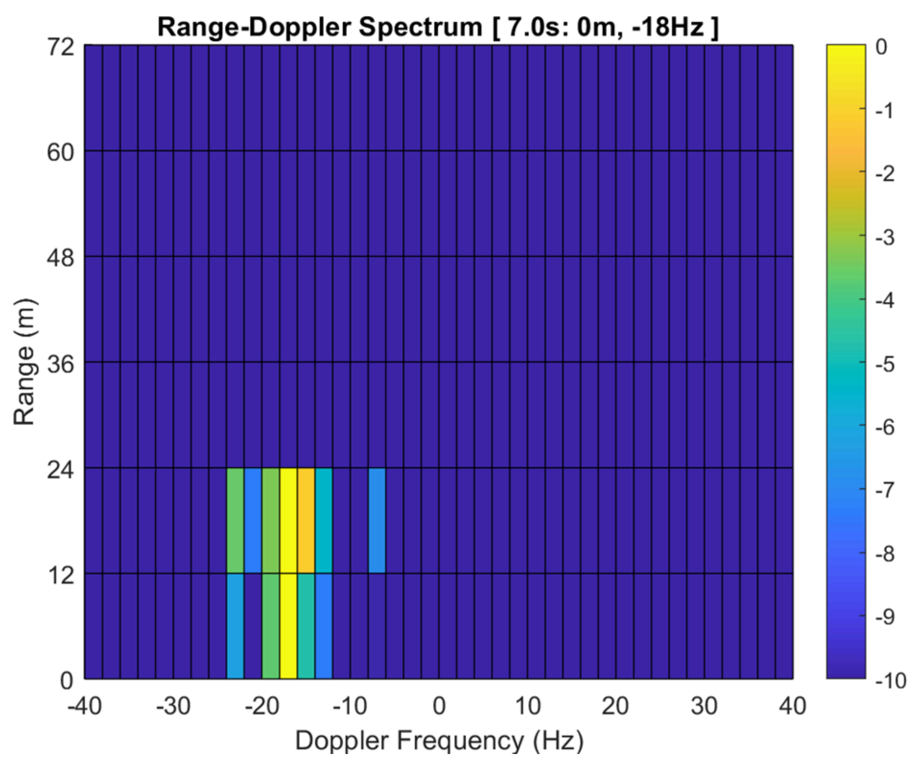
- 2 - 2.5s


Range-Doppler Spectrum [2.0s: 12m, 24Hz]
Range (m)
Doppler Frequency (Hz)
72
60
48
36
24
12
0
-40
-30
-20
-10
0
10
20
30
40
0
-1
-2
-3
-4
-5
-6
-7
-8
-9
-10

- 5 - 5.5s



- 7 - 7.5s



Range-Doppler Analysis:

To interpret the meaning of the spectrum, we need to know what the bright colored bands mean in a certain range and Doppler frequency. If the bright band appears at a certain range, it means that the object is away at that range from the radar. The Doppler frequency can estimate the object's velocity, by using this equation:

$$v = \lambda_s f_D$$

Where:

- v is the velocity
- λ_s is the source wavelength
- f_D is the Doppler frequency

Therefore, if the Doppler frequency is positive, the object is approaching the radar, whereas if it is negative, the object is moving away from the radar. The magnitude of the Doppler frequency (high or low) indicates how fast or slow the object is moving.

- Range-Doppler Spectrum [0s: 12m, 4Hz]
  There are several bright vertical bands around 12m and 0 to 10 Hz Doppler frequency. However, the brightest yellow vertical band a appears at 12m with a Doppler frequency at 4Hz indicates that an object is detected at approximately 12 meters from the radar where it's moving slowly towards the radar.
- Range-Doppler Spectrum [2.0s: 12m, 24Hz]
  There are also several bright vertical bands around 0-12m with Doppler frequency around -20 to 30 Hz. The brightest yellow band appears at 12m with a Doppler frequency 24Hz. This suggests that the object is 12m away from the radar and the object's primary motion is approaching the radar at high speed compared to the previous plot. In addition, the light blue vertical band most likely represents parts of the object moving at different speeds.
- Range-Doppler Spectrum [5.0s: 0m, -12Hz]
  There are a few bright bands located around the range 0-12m with -12 to -8 Hz and the brightest yellow band appears at -12m with Doppler frequency of -12Hz. Since the green/light blue seems to surround the bright yellow band, this most likely suggests that the whole part of the object is moving away from the radar at moderate speed.

- Range-Doppler Spectrum [7.0s: 0m, -18Hz]
  There are several bright bands around 12-24m with a Doppler frequency around -24 Hz -14Hz. The plot also seems to have 2 similar bright yellow bands at the same Doppler frequencies which is -18Hz, one at 12m and the other at 24m. However, the peak seems to be the band at 24m with several green/light blue bands surrounding it. This most likely suggests that there are 2 objects moving away from the radar at the same velocity.

- ## Task 3:

The objective of this task is to compute and plot the Time-Doppler spectrum (with a 0.5 s coherent integration time). For each data, apply digital down-conversion and low-pass filtering, compute the FFT-based ambiguity surface over range delays and Doppler bins, and then build a time-Doppler map showing how the target's Doppler signature evolves from 0 s to 9.5 s.

My Approach:

1. **Sliding-Window Setup**
   - Define a 0.5 s coherent integration time (CIT) and a 0.1 s step.
   - Precompute the number of samples per CIT (num_samples_cit) and the Doppler bin vector (±40 Hz in 2 Hz steps).

2. **Memory-Efficient Data Loading**
   - At each time step t_0, determine which 0.5 s data file contains t_0.
   - Maintain a 1 s sliding buffer by loading only two files—file N and N+1—into memory.
   - The window slides forward within the buffer until more data is needed; then, load the next file while keeping the current one, avoiding reloading any file that has already been fully processed.
   - Each time a file is loaded, apply DDC (−3 MHz shift) and a 9 MHz LPF to both the reference and surveillance sequences.
   - This keeps memory usage low and ensures smooth, continuous data access.

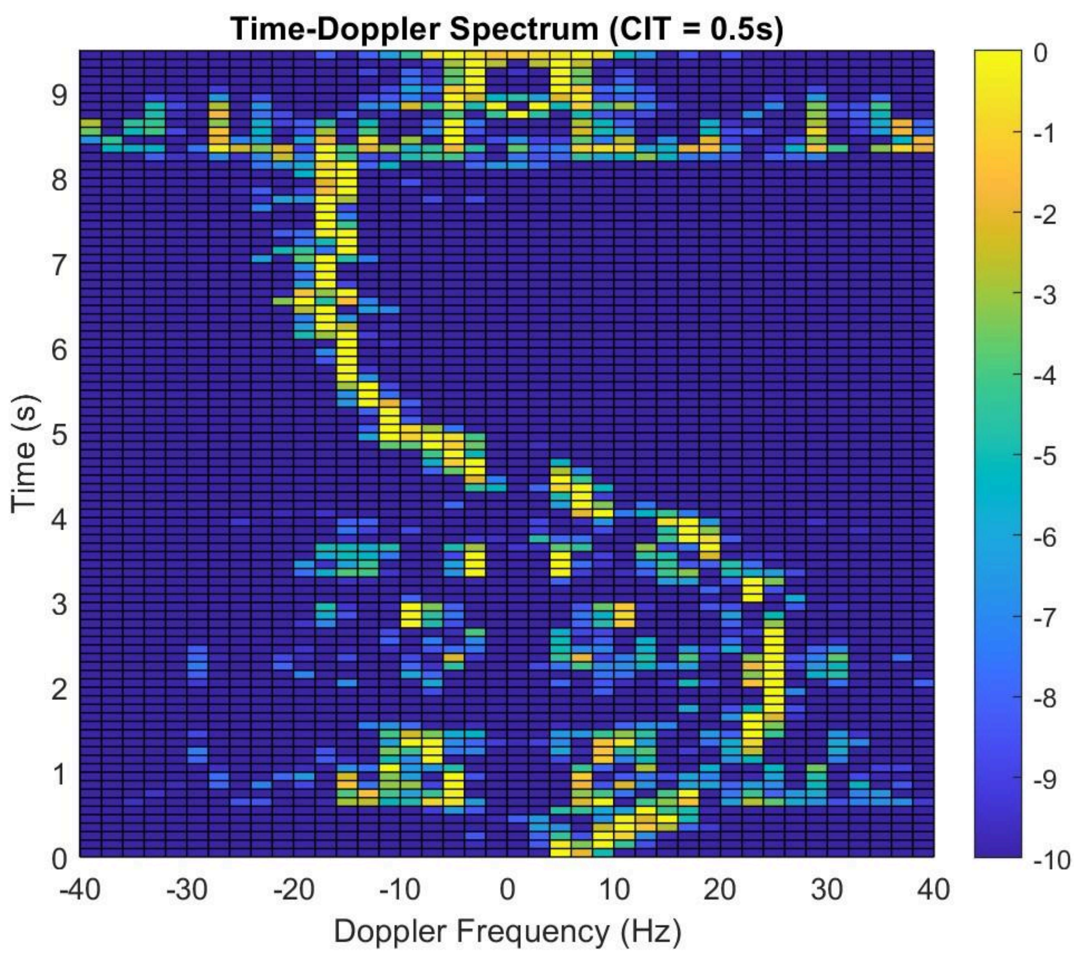
3. **Ambiguity Surface Computation**
   - For each range lag (0 to the maximum delay corresponding to 72 m), delay the reference signal and multiply it with the conjugated surveillance signal.

- Take an FFT of length num_samples_cit to get Doppler content, then select bins from −40 to +40 Hz.

4. **Extracting the Primary Doppler Signature**
    - Instead of taking the max value across range for each Doppler bin (as suggested in the slide), I locate the global peak over the full ambiguity surface and extract the Doppler slice at that specific range lag to get a cleaner, more stable target track through time.

5. **Normalization and Mapping**
    - Normalize each time slice so its peak is 0 dB.
    - Convert to dB ($20 \cdot \log_{10}$) with a small ε to avoid –∞.
    - Stack all slices into time_doppler_map and plot with a top-down surf view, clamped between –10 and 0 dB.

Here's the result:



Time-Doppler spectrum analysis:

The plot shows a yellow strand pattern that represents the main motion detected—corresponding to the person's movement during the experiment.

- From **time = 0s to 4s**, the yellow strand appears on the **positive Doppler side**, indicating that the person is moving **towards the radar**. The increasing Doppler frequency up to around **+25 Hz** suggests that the person is **speeding up** until about **t = 2s**, then **slows down** from **t = 2s to t = 4s** as the Doppler frequency decreases.
- Starting from **t = 4s**, the yellow strand shifts to the **negative Doppler side**, showing that the person begins to **move away from the radar**. The maximum Doppler frequency during this phase is slightly above **-20 Hz**, which is **lower than the maximum frequency when approaching**, suggesting that the person is **moving away at a slower speed** than when they were approaching.

Experience

Workload:
Introduction: Dhana & Charissa
Task 1: Dhana & Charissa
Task 2: Vincent
Task 3: Kevin

Problems met:

- Have no clear idea on how to calculate the ambiguity function since it involves integration which we haven't learned before.
- Finding the specific parameters to match the plot/spectrum in the PPT.
- Need to have an understanding on how the given code works in the PPT.
- The resulting Time-Doppler spectrum looked noticeably different from the one in the PPT, especially between t = 8 s and t = 9.5 s. I spent a lot of time trying to figure out why and adjusting my approach to get a result closer to the reference.
- Handling a large number of files became a challenge. To make the Time-Doppler spectrum processing more memory-efficient, I ended up using a 1 s buffer strategy to load and process data.

- The Time-Doppler spectrum was heavily affected by noise, and I spent a considerable amount of time experimenting with methods to reduce the noise and clean up the final output.

Experience Gained:

- Have a deeper and clearer understanding of the inner workings of the digital signal process of a passive radar.
- Gained experience in interpreting and implementing project tasks, breaking them into manageable steps
- Acquired experience in computing **Range-Doppler spectra**, using cross-correlation for time delays (range) and FFTs for Doppler shifts (velocity)
- Developed skills in coherent integration

Self Assesment:

- Kevin: 70
- Dhana: 70
- Charissa: 70
- Vincent: 70

We quite understand how motion detection technology works using communication signals. However we are not confident on how to apply it to real-world problems.