Analysis of Respiratory Patterns Using FMCW Radar: A Study of COPD and Normal Subjects Under Varying Conditions

A INTERNSHIP REPORT

Submitted by

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DECLARATION

I hereby declare that the Internship entitled "**Analysis of Respiratory Patterns Using FMCW Radar: A Study of COPD and Normal Subjects Under Varying Conditions**" to be submitted for the Degree of Bachelor of Technology is my original work and the dissertation has not formed the basis of any degree, diploma, associate-ship or fellowship of similar other titles. It has not been submitted to any other University or institution for the award of any degree or diploma.

Place: Chennai, Tamil Nadu

Date: 06th November, 2024

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1. Introduction

(1.1) Frequency Modulated Continuous Wave (FMCW) Radar

FMCW Radar or Frequency Modulated Continuous Wave (FMCW) Radar is a radar system that transmits a continuous, frequency modulated wave for precise measurement of range and velocity of objects. In such a radar system, the frequency of the transmitted signal varies over time which is usually done in a linear ramp, sawtooth or triangular wave pattern.

Frequency modulation involves changing the frequency of the transmitted signal in each measurement period. This frequency change is called chirp, where the frequency smoothly increases from a starting frequency to a maximum point over a period of time and then either drops back or repeats the cycle. This rate of change in frequency allows the radar to measure how far the object is.

Pulsed radar systems emits short pulses of energy and then waits for the echo to be picked up by the receiver antenna. In FMCW radar, it transmits a continuous wave. This constant transmission is used for continuous tracking of objects without any delay or lag in measurements. It provides a continuous array of information of both range and velocity measurements.

(1.2) Chirp

In a FMCW radar, a chirp is the transmitted signal whose frequency increases linearly over time. It is essentially a frequency-modulated sinusoidal wave. It increases from a start frequency (fc) to a higher frequency and this increase in frequence is called a sweep.

Characteristics of a chirp:

1. Starting Frequency (Fc) – Starting frequency at which the chirp begins
2. Bandwidth (B) – Total range of the frequency swept during the chirp.
3. Duraction (Tc) – Time taken to complete the sweep from start to maximum frequency.

Higher bandwidth allows for precise range resolution, which ultimately helps in distinguishing closely spaced objects. Slope (S) of a chirp is defined as the rate of frequency change over time. Mathematically it is given by:

$$S=B/T_c \qquad \text{(i)}$$

Where:

B = Bandwidth of the chirp

T_c = Time taken for the whole chirp

Chirps are often visualized in frequency-time plots to show the linear sweep of frequency over time. It starts from fc up to the maximum frequency. The amplitude-time plot shows how the frequency increases but the waveform cycles become closer as frequency increases, although the amplitude remains the same.

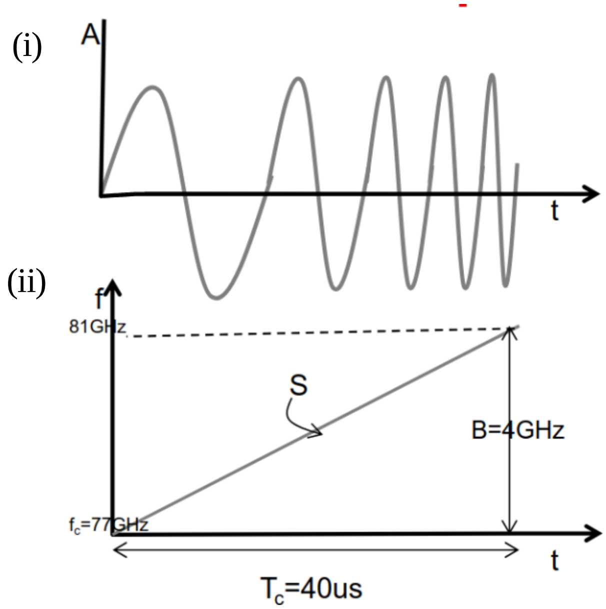

Fig 1: (i) Amplitude v/s Time graph and (ii) Frequency v/s Time graph of a FMCW Radar during transmission of signal [1]

(1.3) 1TX - 1RX FMCW Radar Block Diagram

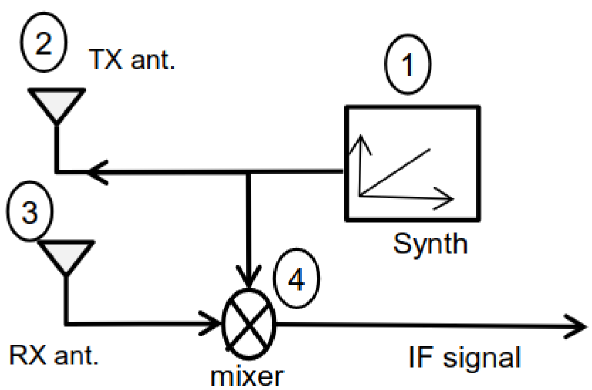

Fig 2: Basic 1TX – 1RX FMCW Radar block diagram showing the connection between various components of the radar [1]

The chirp is generally produced by the synthesizer. It increases frequency over time to the maximum frequency. Once the chirp is generated, it is transmitted by the Transmitting antenna (TX). The antenna converts the electrical signal to an electromagnetic wave which then emits as chirp. When the transmitted signal is obstructed, it is reflected or echoed back to the radar, which is then picked up by the Receiving antenna (RX). Once the reflected signal is received, it is mixed with the transmitted signal with a component called the mixer, and the process is called mixing. It produces a new signal called Intermediate Frequency (IF). It contains the beat frequency, which is difference between the transmitted and the received signal.

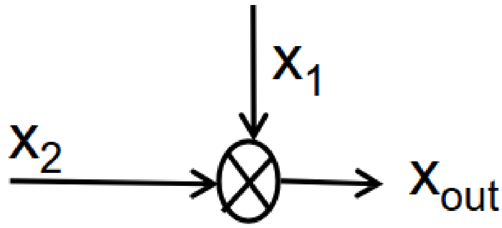

Fig 3: The line diagram of a simple mixer inside a FMCW radar where x_1 is the transmitted signal, x_2 is the received signal and X_{out} is the Intermediate Frequency [1]

The equations of the mixer is given as:

$$x_1 = sin[w_1 t + \phi_1] \tag{ii}$$

$$x_2 = sin[w_2 t + \phi_2] \tag{iii}$$

$$X_{out} = sin[(w_1 - w_2)t - (\phi_1 - \phi_2)]] \tag{iv}$$

where,

x_1 is the transmitted signal

x_2 is the received signal

X_{out} is the Intermediate Frequency (IF) signal

The chirp is increasing at a constant rate over time. The reflected chirp returns after a delay and has a frequency different from the transmitted chirp. This time delay is converted to a frequency offset which corresponds to the distance of the target. The IF signal is analyzed to measure beat frequency that gives the exact range of the object. If the target is moving, the frequency is further shifted due to the Doppler effect, which is used to determining the object's relative velocity.

(1.4) Instantaneous Frequency

As shown in Figure, the frequncy-time plot shows the transmitted signal and the reflected signal. Since the RX signal is a delayed TX signal, the round trip time is denoted by τ. Another key aspect of the chirp is the slope (S) that gives how frequency changes over time. The slope is the rate of frequency increase per unit time in a chirp. Due to the frequency difference of TX and RX, the radar's mixer outputs the Intermediate Frequency (IF), which is mathematically expressed as:

$$f_{IF} = S_\tau = S \, . \, 2d/c \tag{v}$$

where:

S is the chirp slope

τ is the round trip time delay ($\tau = 2d/c$)

This equation shows that the frequency of IF signal is directly proportional to distance d of the object from the radar.

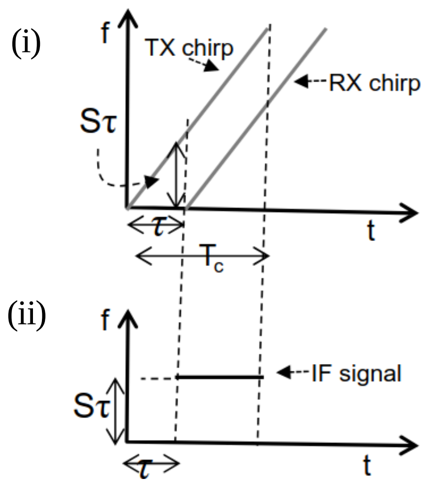

Fig 4: (i) shows the difference of frequency of a transmitted chirp and the reflected chirp, and (ii) shows the Intermediate Frequency which is calculated as the difference between starting of RX chirp and ending of TX chirp [1]

(1.5) Multiple Object Detection

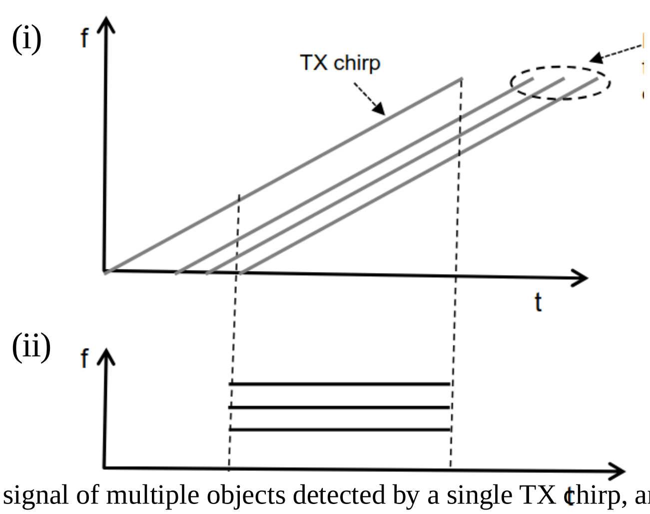

Fig 5: (i) shows the RX signal of multiple objects detected by a single TX chirp, and (ii) shows the Intermediate Frequency of various objects detected shown by horizontal bars where the lowermost bar represent the closest object to the radar and the uppermost bar represent the farthest object from the radar [1]

For multiple object detection, the TX chirp starts from a lower frequency and sweeps linearly over time. The slope represents the rate at which the frequency is increasing. The TX chirp is obstructed by multiple objects at different distances, so each object reflected the RX signal with a different delay. Further the object is, greater is the delay and closer the object, shorter is the delay. It is shown by multiple delayed chirps stacked on top of each other in the graph.

The bottom graph represents the IF signal or beat frequencies that result from the comparison between the TX chirp and the multiple reflected RX chirps. Each horizontal line represents a different constant beat frequency, which corresponds to the distance of an object. For example, a higher beat frequency (upper lines) corresponds to a farther object because the greater time delay causes a larger frequency difference between the TX and RX chirps. A lower beat frequency (lower lines) corresponds to a closer object.

(1.6) Range Resolution

Range resolution is the radar's ability to distinguish between two objects that are placed close to each other. When two objects are in close proximity, their RX signals overlap each other n the radar's frequency spectrum, causing them to appear as one single peak, and therefore as a single object. It is methematically expressed as:

$$d_{res}=c/2B \quad \text{(vi)}$$

where:

c is the speed of light

B is Bandwidth swept by the chirp

This formula demonstrates that range resolution is inversely proportional to bandwidth. As the chirp bandwidth increases, the smallest distance that the radar can resolve between two objects decreases. For example, doubling the bandwidth would halve the minimum distance required to distinguish two objects.

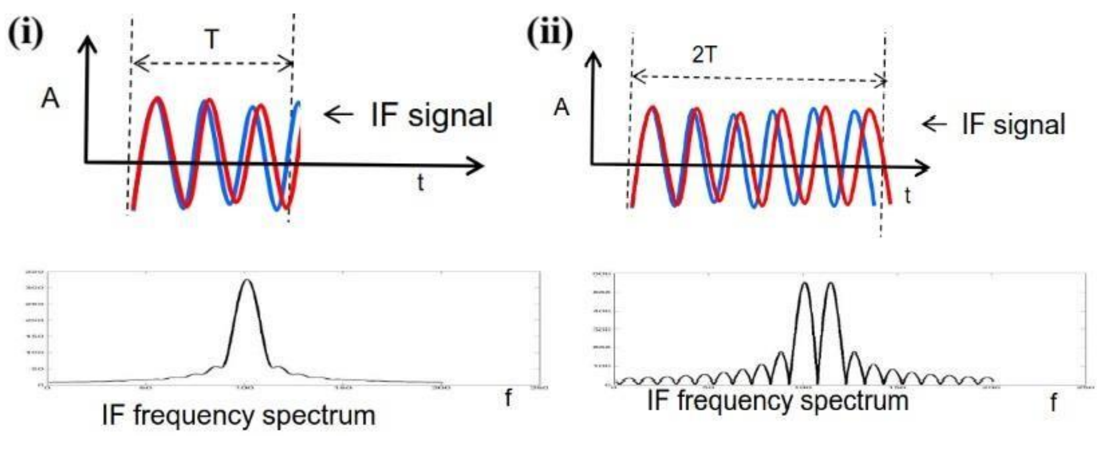

Fig 6: (i) shows when two RX chirps overlap, they show as one object, and (ii) shows increasing the Bandwidth separates the two distinct RX chirps that shows as individual objects [1]

(1.7) Phasor

A phasor is used to represent the sinusoidal signals (both transmitted and received) as complex numbers that carry information about the amplitude and phase of those signals. Both transmitted and received signals can be represented as phasors where their phase (ϕ) indicates the relative position of the wave within its cycle at any given moment. If the transmitted chirp is represented as a phasor:

$$T(t)=Ae^{j(\omega t+\phi)} \tag{vii}$$

and the received chirp is delayed, the received phasor will be:

$$R(t)=Ae^{j(\omega(t-\Delta t)+\phi)\ )} \tag{viii}$$

where Δt is the time delay due to the distance to the target. The phase difference between the transmitted and received phasors gives the distance of the target.

(1.8) Angle of Arrival (AoA)

Angle of Arrival (AoA) is the angle at which a signal arrives at the RX antenna relative to a reference direction. It is used to find the direction from which a reflected signal (from an object) is coming.

For example, if the radar is scanning an area, the AoA tells whether an object is directly in front, slightly to the left or right, or at an angle relative to the radar. The angle can be estimated by measuring the phase difference between signals received by multiple antennas. The phase difference is affected by the position of the object relative to each antenna, thus allowing for calculation of distance.

Each RX antenna detects the object's signal, but because the antennas are spaced apart, there's a small difference in the phase of the signal received by each antenna. This phase difference is called ω. It comes from the slight delay when each antenna picks up the signal. When the object is directly in front of the radar (at an angle of $\theta=0^\circ$), even a small change in the object's angle creates a clear change in the phase difference as the radar is sensitive to slight changes in the surroundings. As the angle θ gets larger (the object moves to the side of the radar, closer to 90°), the radar becomes less sensitive to angle changes. At 90°, the phase difference stops changing and makes it hard for the radar to determine the angle.

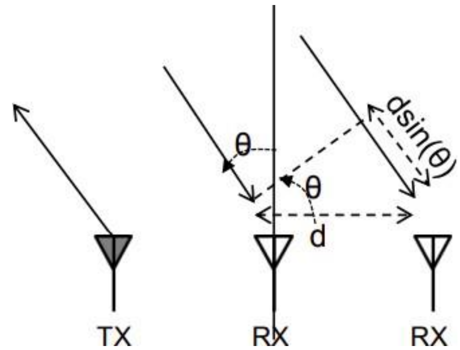

Fig 7: Represents the angle at which the farthest RX antenna is placed relative to the TX antenna and appropriate trigonometric equation to solve for its respective RX signal [1]

To find the θ of the above diagram, we use this mathematical expression:

$$\boldsymbol{\omega} = \mathbf{2\pi d \sin(\theta)/\lambda}$$

$$\Rightarrow \boldsymbol{\theta} = \mathbf{\sin^{-1}}(\boldsymbol{\lambda\omega}\,/\mathbf{2}\boldsymbol{\pi} d) \tag{ix}$$

Here θ is the angle at which the reflected signal is received by the RX antenna. More the angle increases to 90°, less is the phase difference between the TX and the RX signal.

(1.9) Angle Resolution

Angle resolution (θ_{res}) is the smallest angle difference at which a radar system can distinguish two objects as separate. If two objects are close together in an angle, angle resolution defines how far apart they need to be for the radar to see them as distinct. The formula for angle resolution based on antenna separation (d) and angle θ is:

$$\theta_{res} = \lambda/Nd\cos(\theta) \tag{x}$$

where:

λ is the wavelength of the radar signal,

N is the number of RX antennas,

d is the spacing between antennas,

$\cos(\theta)$ is the angle from the radar's center line.

This proves that angle resolution is better with more N number of RX antennas which are closely spaced. Because of the cosine function, the more the angle, less is the angle resolution. The precise values are calculated when θ is less but not close enough such that the RX signals overlap, which in that case, the Bandwidth has to be increased.

(2.0) Instrument Analysis – IWR1843BOOST

(2.1) Introduction

The IWR1843BOOST is an evaluation module developed by Texas Instruments for their IWR1843 radar sensor which is a single-chip FMCW radar device designed mainly for industrial and automotive applications. This module is based on millimeter-wave (mmWave) radar technology, operating in the 77–81 GHz frequency band, and gives high-resolution sensing capabilities for detecting objects. It is also used for measuring range, velocity, and angle of arrival.

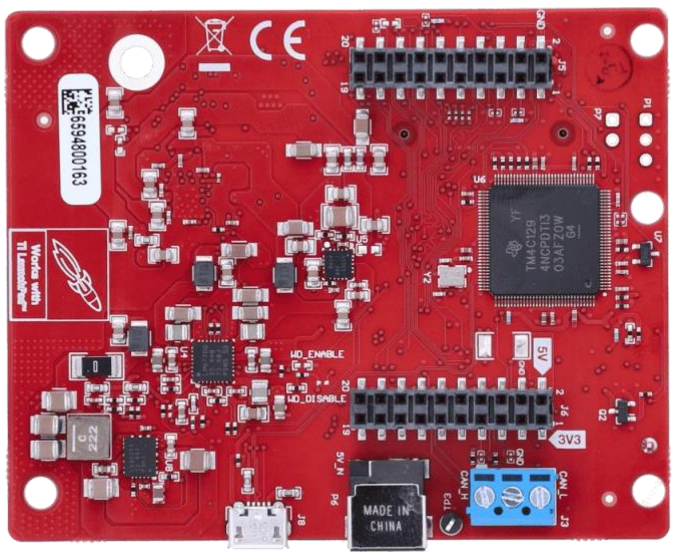

Fig 8: Texas Instruments IWR1843BOOST Evaluation Module (EVM)

(2.2) Features

- Three Transmit (TX) and Four Receive (RX) Antennas: This format lets the radar to determine the distance, velocity and the angle of arrival. Thus, it allows for 3D imaging and mapping of the environment.
- Integrated DSP and Microcontroller: The IWR1843 includes a C674x DSP for radar signal processing and an ARM Cortex-R4F microcontroller for managing control and data communication.
- High Resolution and Range: It operates in the 77–81 GHz band and this module can detect small objects at a significant range which is useful for precise measurements in applications like obstacle detection, level sensing, and people counting.
- mmWave Studio Compatibility: IWR1843BOOST is compatible with mmWave Studio, a Texas Instruments' software for radar signal analysis, configuration, and data capture. It gives a friendly user interface for capturing and visualizing data.
- Low Power Consumption: It uses less power compared to other radars and useful where less power is required to run the setup.

(2.3) Data Format

The captured data is saved as a JSON file with a txt extension. The components of the data is as follows:

- **datenow**: Records the date of data collection (DD/MM/YYYY).
- **timenow**: Records the time of data collection (HH_MM_SS).
- **rp_y (Reflected Power Values)**: Measures the strength of returned radar signals.
- **noiserp_y (Noise Profile Values)**: Measures background noise levels.
- **doppz**: Contains velocity information that shows movement, direction and speed.
- **interFrameProcessingTime**: Measures the time taken between frames.
- **interFrameProcessingMargin**: Represents the available processing time buffer.
- **interChirpProcessingMargin**: Used for determining chirp rate.
- **transmitOutputTime**: Measures the time taken for data transmission.
- **activeFrameCPULoad**: Indicates CPU usage.
- **interFrameCPULoad**: CPU usage for background processing.
- **activity**: Displays output filename with a .txt extension.

(3.0) Experimental Setup

(3.1) Data Acquisition Method

To test the efficiency of the FMCW radar at calculating the respiratory rate of living beings, I have taken an approach towards the medical domain. I have taken raw doppler data from two people- one being a normal person and the other being a Chronic Obstructive Pulmonary Disease (COPD) patient. Data has been taken on these conditions:

- Resting
- Walking
- Running
- Climbing Stairs

Both test subjects were told to make two laps of walking and running and were made to climb two flights of stairs twice. Afterwards, they were made to sit in front of the IWR1843BOOST board at a distance of 75cm away from the board and take deep breaths for 15 seconds for each of the activity.

The evaluation board recorded doppler shift that corresponds to velocity of chest movements and the range, which represents the distance of subject from the radar. Using interpeak distances of inhalation and exhalation, we have calculated the respiratory rate of test subjects under various, previously mentioned activities.

(3.2) Data Processing

I have used Python 3.11.8 inside Google Colaboratory notebook for processing of data. For each condition of various activities, the following plots were generated:

- **Doppler Heatmap**: This shows the Doppler shift over time that detects breathing and motion patterns.
- **Range vs Noise Profile**: The range profile shows the reflected power from the radar at different distances whereas the noise profile helps in identifying and separating signal reflections from noise.

Furthermore, we have calculated the Signal-to-Noise ratio (SNR) by calculating the difference of range profile and noise profile in decibels (dB). We also used the Savitsky-Golay filter to apply on range profile to calculate the respiratory rate of each person in varying activities.

(3.3) Savitsky-Golay Filter

The Savitzky-Golay filter is a digital filter that smoothens out data points by implementing a lower degree polynomial to groups of nearby data points through linear least squares method. Its advantage is that it can soften data without losing the key features of the initial signal like peaks and valleys that could disappear with other methods. The filter operates by moving a fixed-size window across the data and applying a polynomial to the points within this window . The smoothed value is found by evaluating the polynomial at the midpoint of the window. This procedure is done again for every point in the dataset thus producing a smoothed signal.

The practical aspect of determining the correct window size and polynomial degree is based on observations and is as follows:

- **Small** Window Size, **Low** Polynomial Degree – The filter smoothens the data but fails to capture the overall data trend.
- **Small** Window Size, **High** Polynomial Degree – The filter is successful in capturing complex trends but overfits the noise, thus reducing the smoothing capabilities.
- **Large** Window Size, **Low** Polynomial Degree – The filter provides a stable smoothing effect but cancels out important features of the data.
- **Large** Window Size, **High** Polynomial Degree – The filter captures the complex trends but introduces artifacts as the window size is too big.

For this experimentation, I have maintained a polynomial order of 2 and a window size of 51 that provides the appropriate filter parameters to cancel out noise and also not detect artifacts.

(4.0) Results and Discussion

The results have been done by taking a normal person and a COPD patient together at each respective activities to infer the changes a COPD patient shows from a normal person.

(4.1) Resting Phase

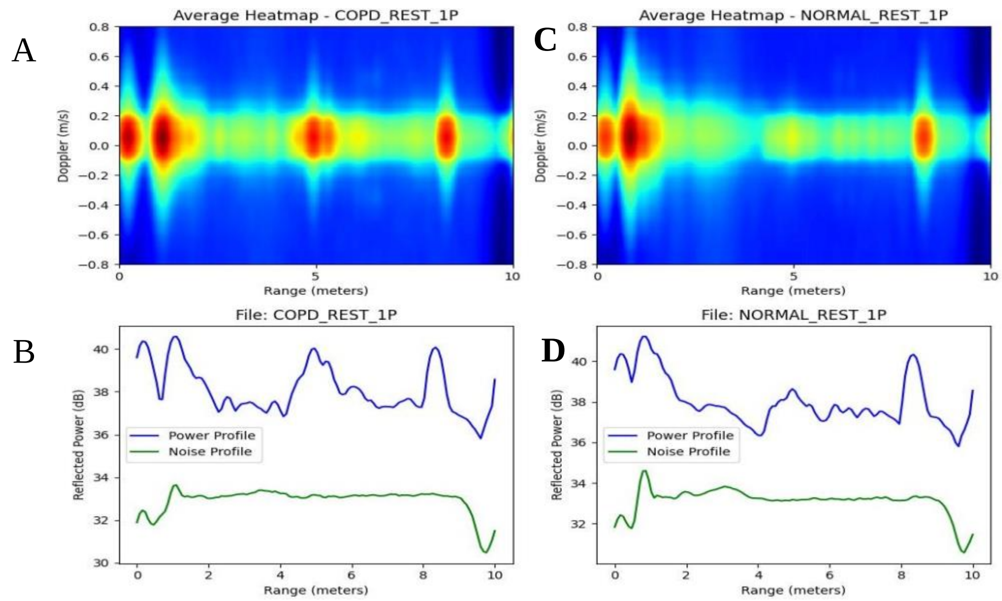

Fig 9: (A) Range-Doppler Heatmap for COPD patient under Resting condition (B) Range Profile v/s Noise Profile for COPD patient under Resting condition and (C) Range-Doppler Heatmap for Normal person under Resting condition (D) Range Profile v/s Noise Profile for Normal person under Resting condition

COPD:

- **Doppler-Range Heatmap** – The COPD heatmap shows high dispersion of the Doppler range with scattered red regions near the 0 m/s mark. This infers shallow chest movements that leads to irregular breathing problems experienced by COPD patients as shown by increased doppler shifts.
- **Range v/s Noise Profile** – The power profile is fluctuating at a very high rate, specially at the 37dB mark at 4.5metre range where the range profile shows that the COPD patient is unable to deeply breathe, indicating towards restricted breathing.
- **SNR** – 5.19 dB.
- **Respiratory Rate** – 13.0 BPM (Breaths Per Minute).

Normal:

- **Doppler-Range Heatmap** – The heatmap for the normal person shows more centralized high-intensity area near the center with a smoother distribution. This infers relatively deep chest movements that results in regular breathing patterns due to less variability in doppler shifts.

- **Range v/s Noise Profile** – The power profile shows a smoother trend with fewer fluctuations. This suggests a less variable breathing pattern at resting phase.
- **SNR** – 4.94 dB.
- **Respiratory Rate** – 12.5 BPM (Breaths Per Minute).

(4.2) Walking Phase

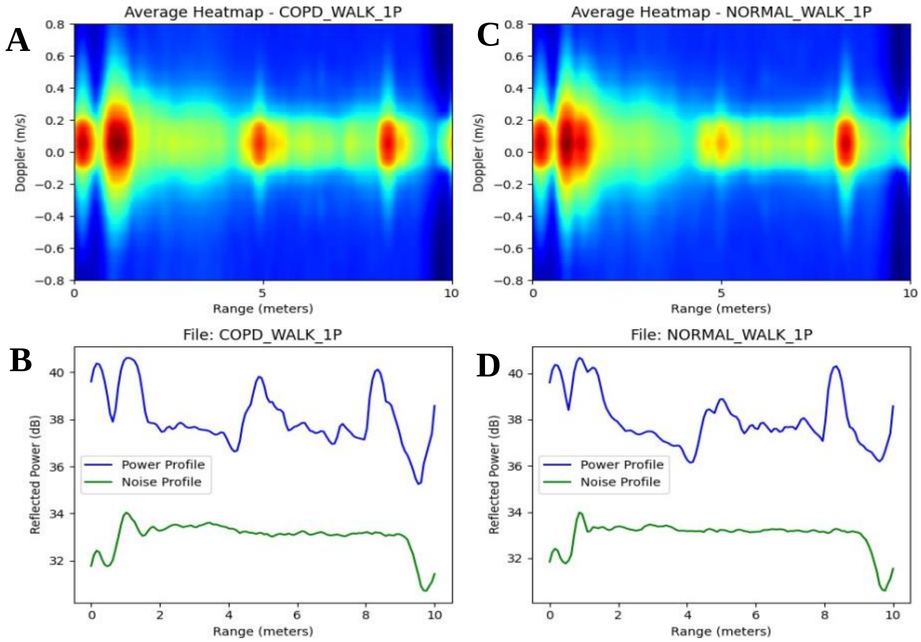

Fig 10: (A) Range-Doppler Heatmap for COPD patient under Walking condition (B) Range Profile v/s Noise Profile for COPD patient under Walking condition and (C) Range-Doppler Heatmap for Normal person under Walking condition (D) Range Profile v/s Noise Profile for Normal person under Walking condition

COPD:

- **Doppler-Range Heatmap** – The doppler values are more spread out. Vertical spread is more. Overall, these suggest labored breathing patterns with shallow chest movements. Horizontal doppler shift is found less, indicating restricted walking rate as compared for the normal person.
- **Range v/s Noise Profile** – The irregular interpeak distances shows moments where the COPD patient had to take more breaths to compensate for body activity.
- **SNR** – 5.02 dB.
- **Respiratory Rate** – 13.8 BPM (Breaths Per Minute).

Normal:

- **Doppler-Range Heatmap** – The heatmap for the normal person shows more centralized high-intensity area near the center with a smoother distribution. Horizontal doppler shift has been noticed. This infers deep chest movements with regular breathing patterns due to less variability in doppler shifts while walking.

- **Range v/s Noise Profile** – The power profile shows high peaks at regular intervals of time. This shows increased breathing at normal time intervals to show no disturbances while breathing.
- **SNR** – 5.03 dB.
- **Respiratory Rate** – 13.1 BPM (Breaths Per Minute).

(4.3) Running Phase

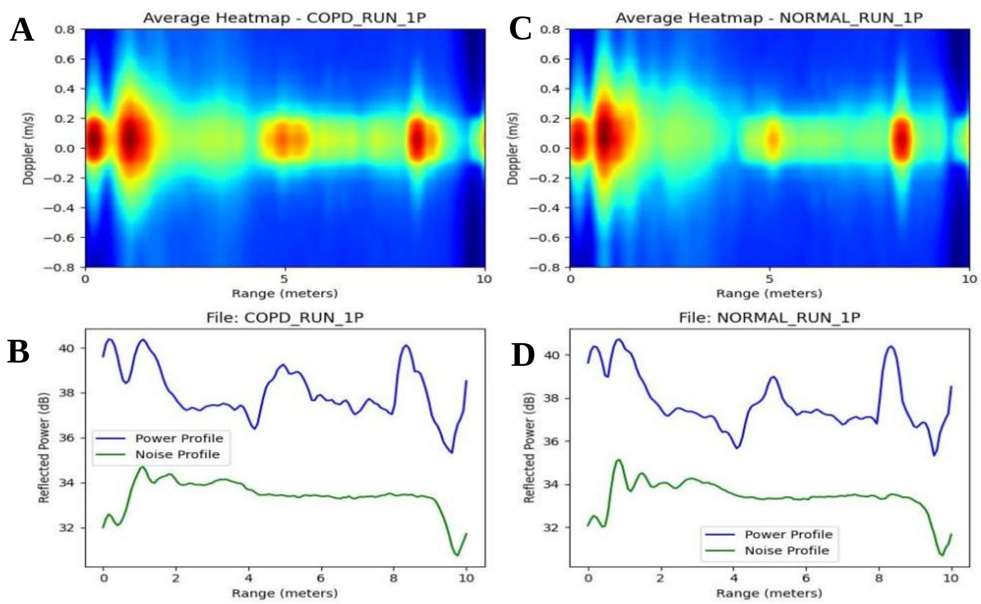

Fig 11: (A) Range-Doppler Heatmap for COPD patient under Running condition (B) Range Profile v/s Noise Profile for COPD patient under Running condition and (C) Range-Doppler Heatmap for Normal person under Running condition (D) Range Profile v/s Noise Profile for Normal person under Running condition

COPD:

- **Doppler-Range Heatmap** – Wider spread of doppler values, indicating running. Spread of doppler values at vertical scale shows increased chest movement, showing trouble in breathing. Scattering of doppler values more aggressive than walking. Shallow chest movements leading to anaerobic respiration.
- **Range v/s Noise Profile** – Higher peaks show increased physical activity. Sharp increase and decrease in power peaks show breathing struggles while running.
- **SNR** – 4.66 dB.
- **Respiratory Rate** – 18.4 BPM (Breaths Per Minute).

Normal:

- **Doppler-Range Heatmap** – Uniform and centralized red area. It has cleaner and more focused highly intensive with less vertical spread in the Doppler signature, showing no trouble while breathing.

- **Range v/s Noise Profile** – Smoother transition in between peaks that show regular rhythmic breathing patterns.
- **SNR** – 4.40 dB.
- **Respiratory Rate** – 17.5 BPM (Breaths Per Minute).

(4.4) Climbing Stairs Phase

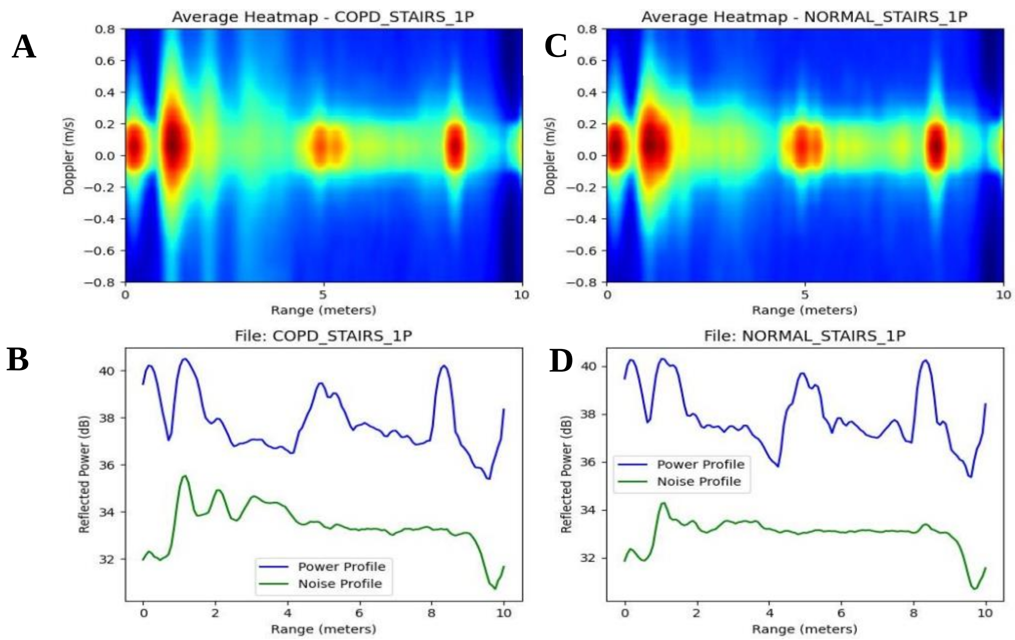

Fig 12: (A) Range-Doppler Heatmap for COPD patient under Climbing Stairs condition (B) Range Profile v/s Noise Profile for COPD patient under Climbing Stairs condition and (C) Range-Doppler Heatmap for Normal person under Climbing Stairs condition (D) Range Profile v/s Noise Profile for Normal person under Climbing Stairs condition

COPD:

- **Doppler-Range Heatmap** – More spread in the vertical Doppler signature, showing increased chest movement for increased breathing. Compared with heatmap of Normal person, it shows three different vertical Doppler signature that shows COPD patient having trouble in breathing. Anaerobic respiration rate increased compared to running condition as climbing stairs recorded more shallow chest movements.
- **Range v/s Noise Profile** – Deeper valley and sharp valleys in between peaks. It also shows more irregular spacing between power spikes, showing increased effort to breathe.
- **SNR** – 4.44 dB.
- **Respiratory Rate** – 19 BPM (Breaths Per Minute).

Normal:

- **Doppler-Range Heatmap** – Uniform Doppler spread with less variations in vertical Doppler Signature. The red zone more focused around the center than the heatmap from the COPD patient, showing a stable rate of increased breathing.

- **Range v/s Noise Profile** – More uniform step pattern with deep valleys compared to COPD graph that shows the normal person's ability to deep breathe after heavy body movement.
- **SNR** – 4.96 dB.
- **Respiratory Rate** – 18.2 BPM (Breaths Per Minute).

(5.0) Conclusion

This report represents the standalone capability of a FMCW radar in detecting the abnormalities present in a COPD patient by Doppler shift. The differences in heatmaps and range-noise plots of a COPD patient compared to a normal person shows how COPD affects in terms of breathing and chest movement where the data from a normal person serves as the baseline for the study.

(6.0) Future Works

Future works involve:

- Calculating Respiratory Rate Variability to understand the breathing patterns of both norma people and COPD patients.
- Collect additional data from normal patients and those with respiratory diseases such as asthma and pneumonia.
- Investigate additional features such as body motion artifact cancellation to improve the analysis.
- Implement a Machine Learning model for detection and classification of COPD patients for Disease classification.

(7.0) References:

[1] *Intro to MMWave Sensing : FMCW Radars - Module 1 : Range Estimation*. (n.d.). [Video]. Video | TI.com. https://www.ti.com/video/5415203482001