ET4169

Microwaves, Radar and Remote Sensing

Practicum 4

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Contents

1 Aim of the experiment

1.1 Objectives:

1. This lab assignment consists of two main parts. In the first part which was carried in the lab, we were supposed to execute and observe real-time data processing.
2. In the second part, we are supposed to implement MATLAB codes to apply and demonstrate the methods for the angle of arrival estimation on different data sets collected by an automotive radar.

1.2 Apparatus Required

1. Texas Instruments IWR1443BOOST mmWave Sensor Evaluation Module (EVM) with the following features.
   1. XDS110-based JTAG with a serial port interface for programming
   2. UART-to-USB interface for control, configuration, and data visualization
   3. Powers from a single 5V supply

1.3 The Set-up

A micro USB cable connects the board to the USB-3 port of the PC. A 5V supply is connected to the board by a 2.1mm barrel plug (center positive).

2 Assignment 1 - Visualization in Lab

While doing the measurements, we selected scatter plot, range profiles and noise profiles to observe different properties inside the room with some targets. If we changed the CFAR, we see some changes where the detection is affected. The less the CFAR, the less the detection capability.

With the same settings, we tried the option of removing static clutter. It improves the profile when we observe doppler measurements like pendulum velocity. It applies a notch filter to the measurements to remove the signals of very low doppler frequencies (0 to a particular threshold).

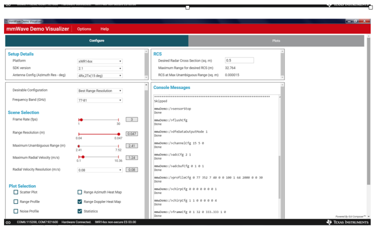
We observed range-doppler and range-angle heatmaps. The low radial velocities are removed from the maps as static clutter is removed. However, the angle resolution can only be improved by the antenna aperture size and the distance between the antenna elements. As it was fixed, there were no significant improvement of angular resolution when clutter is removed. Moreover, the doppler resolution is also not improved as it depends on the measurement time.

The screenshots below in figure 2.0.1 show the configurations that we used for part 1 and part 2. For part 2, we used the cofiguration of figure 2.0.1. The range resolution was set to maximum, the maximum unambiguous range and the radial velocity resolution were set to minimum. The frame rate was set to 3 fps.

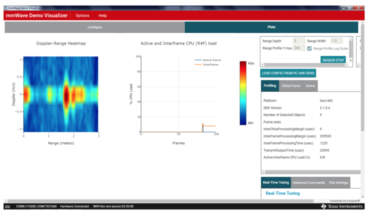
Summary of labs

In lab 2, the radar was not calibrated and we were supposed to find the calibration coefficients to minimize the effects of coupling. In lab 3 and 4 we have radar data properly calibrated. In lab 3 we observe only one target where as in lab 4 we observe and study about the detection of 2 targets.

(a) Doppler/Range heatmap



(b) Configuration



(c) Doppler/Range heatmap

Figure 2.0.1: Configuration

3 Assignment 2 - Data Collection in Lab And Calibration

I used the **yellow** radar in the lab.

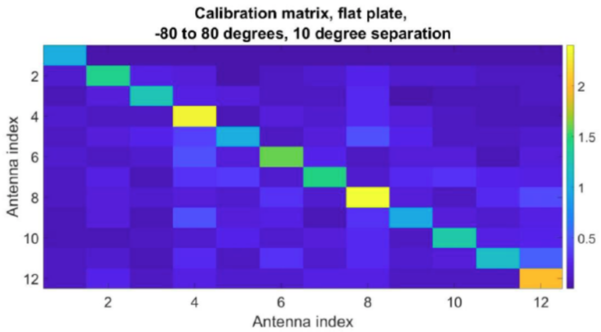


Figure 3.0.1: Calibration map

For calibration, first it can be done by neglecting the coupling effect. However, the coupling effect is there in real scenario and can't be avoided. Therefore, without the coupling, first it is checked for what calibration coefficient the measurements are robust. Four correction coefficients are already given to us.

Calibration of automotive radar is needed because the antenna elements in the array can be different from each other (non-identical) and the radiation from the antenna array may undergo some difference due to the coupling effect. Sometimes it is neglected and only the diagonal elements of the calibration map is taken.

Finding the correction coefficient

The following figures 3.0.2 show the range profile of the radar with different correction coefficients those are given to us. Furthermore, the figure 3.0.3 shows the angle cut at the range where the target is present. It is seen that the calibration coefficient $CorCoef_2$ is suitable for better range profile and angle response. For $CorCoef_2$, the side lobes obtained in the plots are consistent unlike with the other correction coefficients. For a single slow time, all received signals were multiplied by the correction coefficients to cancel erros in amplitude and phase.

Finding my own calibration coefficient

The radar data cube obtained from the lab has 3 dimensions and it was of the form [sensors × fast time × slow time]. We know that the fourier transform along the fast time axis gives us the range, on the sensors axis gives us the angle and along the slow time axis gives us the doppler information. For finding my own calibration coefficient, I used the following steps.

1. The range profiles were found by the following matrix. [sensors × range × slow time] by doing the fft only in the fast time dimension.

2. The sensors data was extracted from the information of the previous data structure.
3. For each sensors, for one particular slow time, the index for maximum range was calculated (For the data we have, it is at 0 degree elevation and azimuth $\theta, \phi = 0$).
4. Then, the calibration coefficient is just calculated as $1/Sensors$ based on the value of the first dimension of sensor data. As there were 8 sensors given, the calibration coefficient has 8 entries with all complex numbers indicating phase shifted corrections for all the antenna elements.
5. Then, the same procedure of previous section was carried out to plot the range profile.

After the calibration, it is seen that the side lobes have better symmetry than in the previous case. Coupling effect was corrected between antenna elements.

The range/angle profile is shown in figure 3.0.4 with the calibration coefficient that I got. The figure 3.0.5 shows the angle cut at the range where the target is present. It shows symmetric response where the antenna broadside is at $\theta, \phi = 0$.

From the measurement of assignment 2, I have the following results regarding the range and angle listed in table 1.

The range resolution in the case is given by:

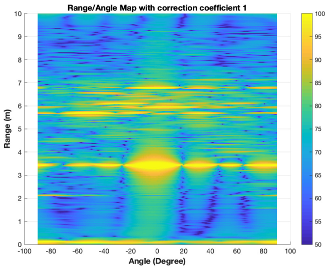
$$\Delta\theta = \frac{0.886\lambda}{Nd\cos\theta} \tag{1}$$

Here, as the boresight is at $\theta = 0$, $d = \frac{\lambda}{2}$, and the number of sensors $N = 8$, the equation 1 becomes:

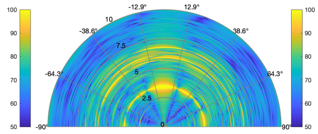
$$\Delta\theta = \frac{0.886}{4} = 0.2215 \quad [rad] = 12.6910^\circ \tag{2}$$

Range	Angle
3.4310 [m]	0°

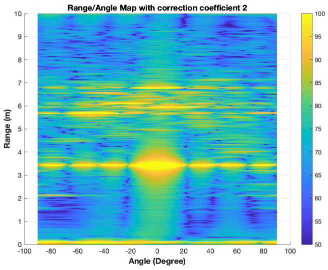
Table 1: Range and Angle of Arrival for assignment 2



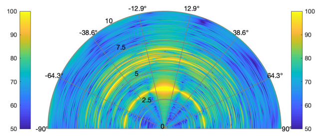
(a) Range/Angle Map for $CorrectionCoeff_1$



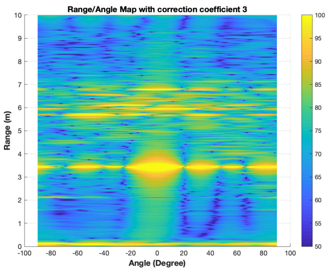
(b) Polar Plot of Range/Angle Map for $CorrectionCoeff_1$



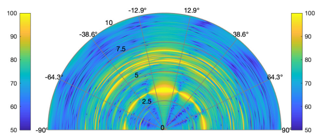
(c) Range/Angle Map for $CorrectionCoeff_2$



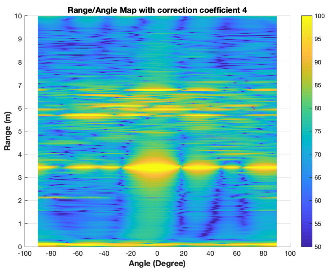
(d) Polar Plot of Range/Angle Map for $CorrectionCoeff_2$



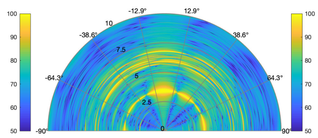
(e) Range/Angle Map for $CorrectionCoeff_3$



(f) Polar Plot of Range/Angle Map for $CorrectionCoeff_3$

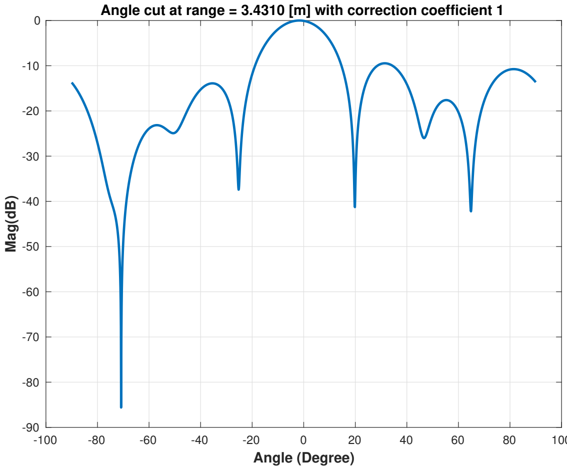


(g) Range/Angle Map for $CorrectionCoeff_4$

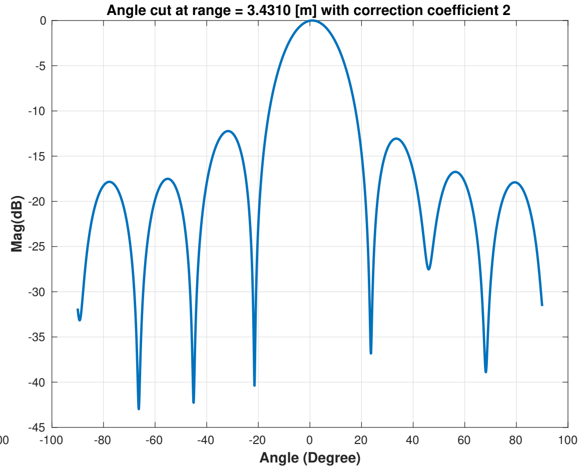


(h) Polar Plot of Range/Angle Map for $CorrectionCoeff_4$

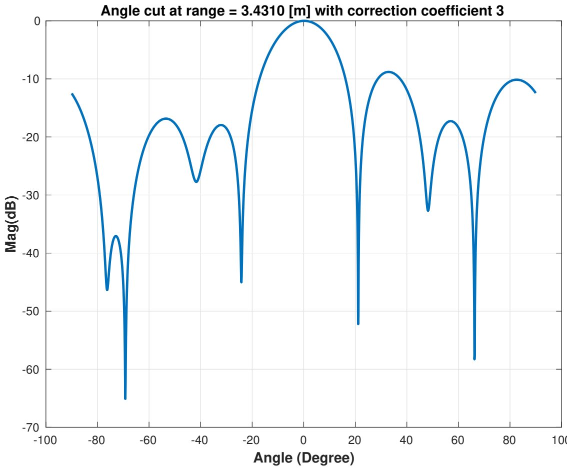
Figure 3.0.2: Range/Angle Maps for different correction coefficients



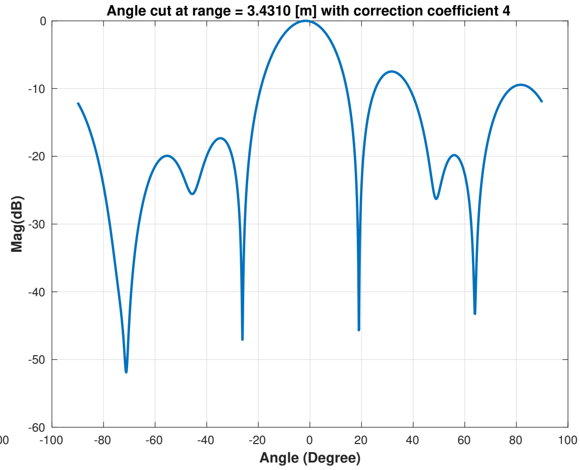
(a) Angle cut for Correction Coefficient 1



(b) Angle cut for Correction Coefficient 2



(c) Angle cut for Correction Coefficient 3



(d) Angle cut for Correction Coefficient 4

Figure 3.0.3: Angle cut for different correction coefficients Normalized

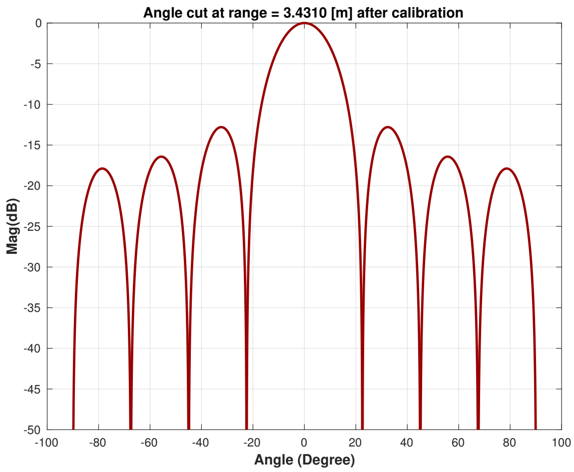
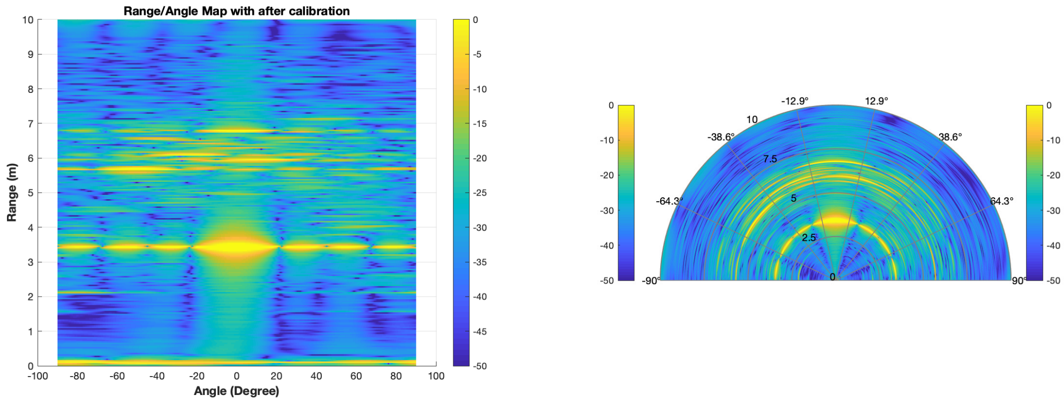


Figure 3.0.5: Angle cut after calibration Normalized



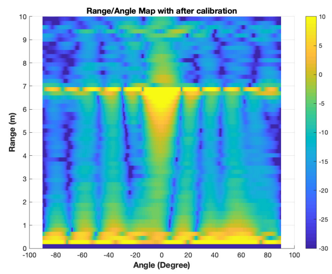
(a) Range/Angle profile after calibration normalized

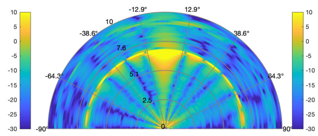
(b) Polar Range/Angle profile cut after calibration

Figure 3.0.4: Range/Angle map after calibration

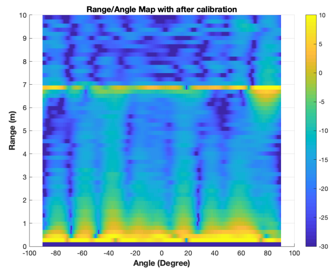
4 Assignment 3

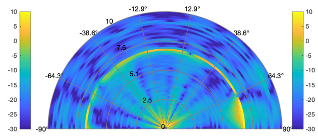
a) We are given with several 2D cuts of the radar cube and it has the information of sensors(antennae) and fast-time. Therefore, a 2D fft of this matrix can give us the information about the angle of arrival and the range. Figure 4.0.1 shows the range/angle response for all the data given. The range is limited from 0 to 10 meters and the angle is shown from $-90°$ to $90°$. The polar plots are shown in the figure 4.0.1. Range resolution of the Radar is given by:



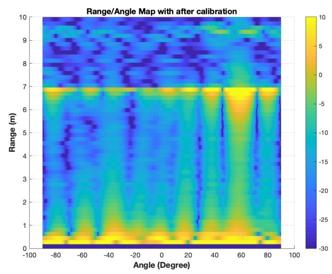


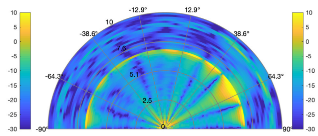
(a) Range/Angle profile for Dataset A **(b)** Polar Range/Angle profile for Dataset A



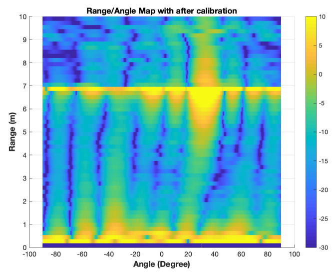


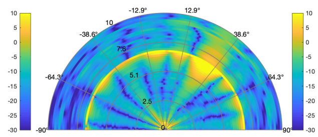
(c) Range/Angle profile for Dataset B **(d)** Polar Range/Angle profile for Dataset B





(e) Range/Angle profile for Dataset C **(f)** Polar Range/Angle profile for Dataset C





(g) Range/Angle profile for Dataset D **(h)** Polar Range/Angle profile for Dataset D

Figure 4.0.1: Range/Angle map for datasets A, B, C and D

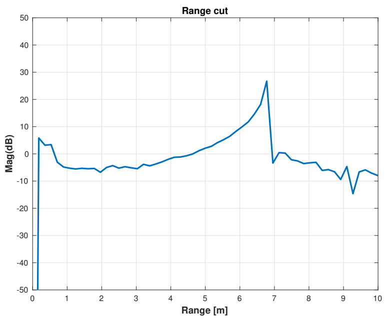
Dataset	ΔR Theoretical [cm]	ΔR Observation [cm]
A	14.92	18
B	14.92	18
C	14.92	18
D	14.92	18

Table 2: Range resolution theoretical and from observation

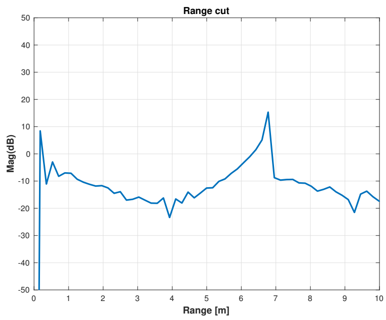
$$\Delta R = \frac{c_0}{2B} = 14.92 \quad [cm] \tag{3}$$

The range resolution is found from the plot is calculated as the difference in range where the target is present and the next range obtained from the plot. The results shown in table 2.

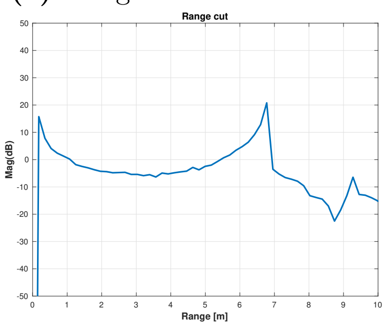
b) The range cut is shown in figure 4.0.2 at the boresight angle for each dataset.



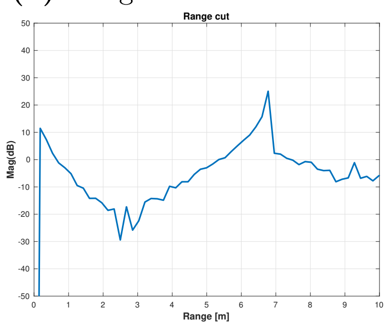
(a) Range cut for Dataset A



(b) Range cut for Dataset B



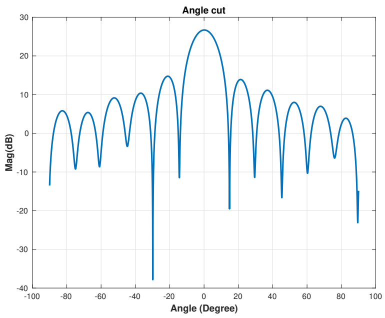
(c) Range cut for Dataset C



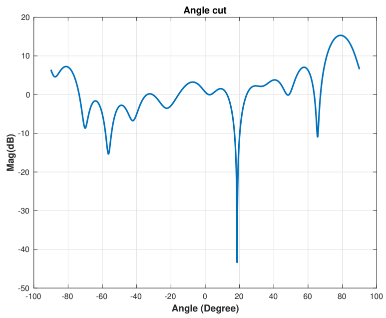
(d) Range cut for Dataset D

Figure 4.0.2: Range cut for datasets A, B, C and D

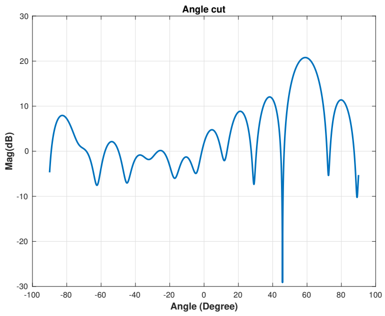
c) The angle cut is shown in figure 4.0.3 at the range where the object is detected. In this case the object was detected at $R = 6.7778[m]$. The theoretical and the observation values are compared in the following table. The angle resolution from the plot is found by the -3dB beamwidth. However, for dataset B, it is not possible to find the angular resolution theoretically because the scan angle is more than 60°. Scan angles for all the datasets are 0°, 79.01°, 58.93° and 39.92° respectively for A, B, C and D. There is indeed some difference of the resolutions from theoretical value because equation 1 is an approximation and only works for scan angles up to 60°.



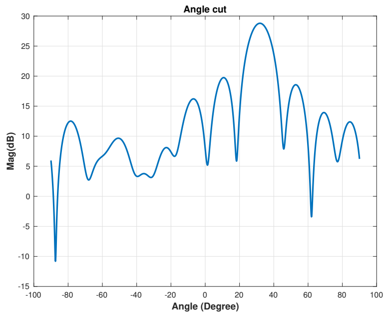
(a) Angle cut for Dataset A



(b) Angle cut for Dataset B



(c) Angle cut for Dataset C



(d) Angle cut for Dataset D

Figure 4.0.3: Angle cut for datasets A, B, C and D

Observations

The range resolution is same in all datasets. However, the angle resolution is different and is dependent on the scan angle and can be computed theoretically based on equation 1.

5 Assignment 4

In this assignment, we are given with 4 datasets where we have a [sensors × fast-time] data worth 12 × 1024 values.

Dataset	$\Delta\theta$ Theoretical	$\Delta\theta$ Observation
A	8.46	13.14°
B	can't be calculated	9.86°
C	16.39	12.43°
D	9.96°	12.78°

Table 3: Angle resolution theoretical and from observation

a) The range vs angle profiles of all the datasets are shown in figure 5.0.1.

b) The angle cuts for the range 6.77 [m] are shown in figure 5.0.2.

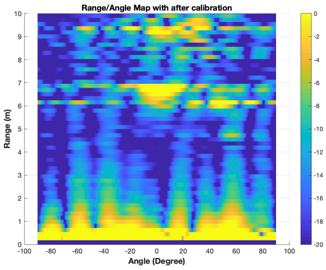
Analysis: For datasets BS_TCR_0_5 the two targets are not at all detected separately. They are detected as one target. However, in the dataset BS_TCR_0_10, though the two targets are detected separately, their main lobes are overlapping. Therefore, that causes ambiguity. For the dataset BS_TCR_0_15 and BS_TCR_0_20, the targets are detected properly.

The table 4 below gives the values for theoretical angle resolutions (From equation 1) for the 2 targets based on their scan angles in all measurements, the difference of main lobe angles for the 2 targets and the addition of the two resolutions.

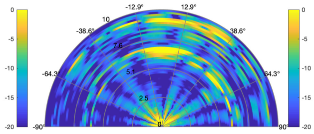
Dataset	$\Delta\theta_1$	$\Delta\theta_2$	$\Delta\theta_1 + \Delta\theta_2$	$\theta_1 - \theta_2$
BS_TCR_0_5	8.4642	NA	NA	$< \Delta\theta_1 + \Delta\theta_2$
BS_TCR_0_10	8.8522	8.4626	17.3148	17.73
BS_TCR_0_15	9.57	8.49	18.06	22.97
BS_TCR_0_20	10.1934	8.4642	18.6576	35.56

Table 4: Comparison of the difference of angles for targets with the sum of their angular resolutions in degrees.

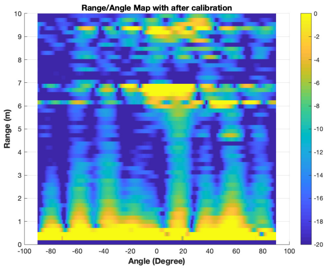
It is verified that when the difference of angles of the boresight of 2 targets are larger than the sum of the angular resolutions of the two targets at their respective scan angles ($(\theta_1 - \theta_2) > (\Delta\theta_1 + \Delta\theta_2)$), the two targets are detected properly. It is depicted in the figures 5.0.1 and 5.0.2 also. For the case of dataset BS_TCR_0_10 as it is seen that the difference of angles of boresight is just larger than the sum of the angular resolutions. Therefore, there is a overlap seen in the figures. For datastes BS_TCR_0_5 and BS_TCR_0_10, there is ambiguity and the targets are not detected as 2 separate targets where as in datasets BS_TCR_0_15 and BS_TCR_0_20, the targets are detected properly and separately.



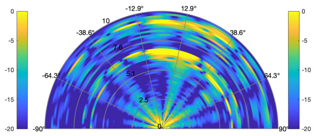
(a) Range/Angle profile for Dataset BS_TCR_0_5



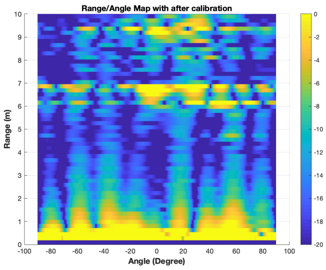
(b) Polar Range/Angle profile for Dataset BS_TCR_0_5



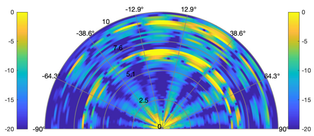
(c) Range/Angle profile for Dataset BS_TCR_0_10



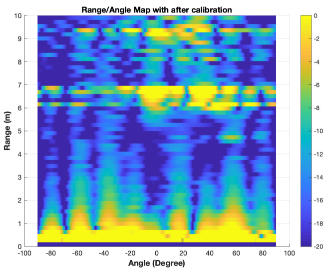
(d) Polar Range/Angle profile for Dataset BS_TCR_0_10



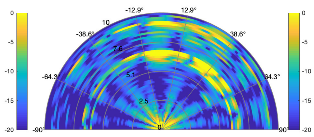
(e) Range/Angle profile for Dataset BS_TCR_0_15



(f) Polar Range/Angle profile for Dataset BS_TCR_0_15

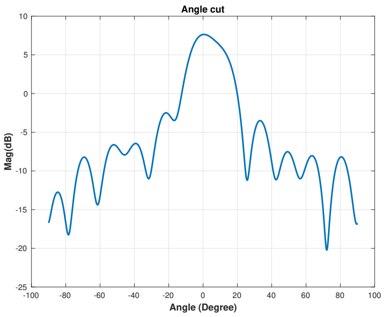


(g) Range/Angle profile for Dataset BS_TCR_0_20

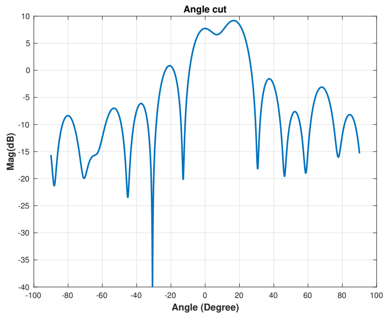


(h) Polar Range/Angle profile for Dataset BS_TCR_0_20

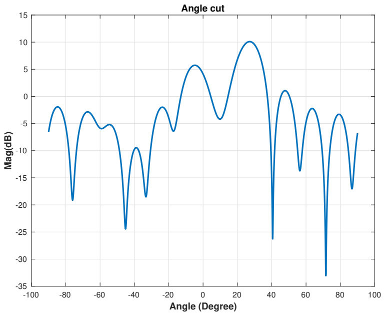
Figure 5.0.1: Range/Angle map for datasets for Assignment 4



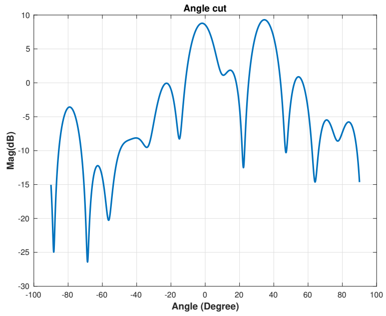
(a) Angle cut for Dataset BS_TCR_0_5



(b) Angle cut for Dataset BS_TCR_0_10



(c) Angle cut for Dataset BS_TCR_0_15



(d) Angle cut for Dataset BS_TCR_0_20

Figure 5.0.2: Angle cut for datasets for Assignment 4

6 Conclusion

In this assignment, I have done several tasks. The first one was to observe a practical use of a mm wave radar with a central frequency of 77 GHz. Furthermore, to compensate the effect of the coupling in the antenna phased array in the mm wave radar, in assignment 2 I verified the correction coefficients that were given to me and I found that for the radar given (radar with **Yellow** sticker) the CorrCoeff_2 was suitable for the correction. Moreover, I found my own calibration coefficient in assignment 2 and I observed symmetric side lobes in both sides of angle 0° with very less coupling effect (ripples on the angle plot). In exercise 3 with different sets of data, I verified the range and angular resolutions for one target. Furthermore, in exercise 4, I verified the angular resolutions of two different targets with the visibility of the targets.

A Matlab code

A.1 Assignment 2

```
load('CorrectionCoefficients.mat');


for j = 1:4

    figure(j);

    [adcRaw2, settings] = ...
       readTIRawData_CCS_capture_demo('script-yellow.raw');

    %Angle = fft(adcRaw2(:, 1, 1))

    a=squeeze(adcRaw2(:,:,1)).* eval(['CorCoef_', num2str(j)]).';

    a = cat(1, a, zeros(2000-size(a, 1), size(a, 2)));

    Range_profile = fftshift(fft2(a),1);
    angle = linspace(-90, 90, size(a, 1));
    range = linspace(0, 10, size(a, 2));
    k = j + 4;
    l = j + 9;

    surf(angle, range, db(abs(Range_profile)).'); view(2); shading ...
       flat;

     xlabel('Angle (Degree)', 'FontSize', 12, 'FontWeight', 'bold');
     ylabel('Range (m)', 'FontSize', 12, 'FontWeight', 'bold');
     title(['Range/Angle Map with correction coefficient ', ...
        num2str(j)], 'FontSize', 12, 'FontWeight', 'bold');
     grid on;

    colorbar;
    caxis([50 100]);

     print(['Range_profile_', num2str(j)], '-depsc')
     figure(k)

    [h, c] = polarPcolor(range, angle, db(abs(Range_profile)).');
    colorbar;
    caxis([50 100]);
```

```
    %title(['Polar plot of Range/Angle map with correction ...
        coefficient ', num2str(j)])
    print(['Range_profile_polar_', num2str(j)], '-depsc')



    figure(1)
    plot(angle, db(abs(Range_profile(:, ...
        83))./max(abs(Range_profile(:, 83))).'), 'LineWidth', 2);

     xlabel('Angle (Degree)', 'FontSize', 12, 'FontWeight', 'bold');
     ylabel('Mag(dB)', 'FontSize', 12, 'FontWeight', 'bold');
     title(['Angle cut at range = 3.4310 [m] with correction ...
         coefficient ', num2str(j)], 'FontSize', 12, 'FontWeight', ...
         'bold');
     grid on;
     print(['Angle_cut_', num2str(j)], '-depsc');



end

% Finding our own calibration coefficient

Range_profile_1 = fft(adcRaw2, [], 2);

C = zeros(1, length(adcRaw2(:, 1, 1)));

for i = 1:8

    [k , l] = max(Range_profile_1(i, :, 1));

    Sensor = Range_profile_1(i, l, 1);

    C(i) = 1/Sensor; % elements of calibration coefficients

end


a = squeeze(adcRaw2(:,:,1)).* C.';

a = cat(1, a, zeros(2000-size(a, 1), size(a, 2))); %zero padding

Range_profile_j = fftshift(fft2(a),1);

figure(16);

angle = linspace(-90, 90, size(a, 1));
range = linspace(0, 10, size(a, 2));
```

```
surf(angle,range,db(abs(Range_profile_j)).'); view(2); shading flat;
xlabel('Angle (Degree)', 'FontSize', 12, 'FontWeight', 'bold');
ylabel('Range (m)', 'FontSize', 12, 'FontWeight', 'bold');
title(['Range/Angle Map with after calibration'], 'FontSize', 12, ...
    'FontWeight', 'bold');
grid on;
colorbar;
caxis([-50 0]);


print(['Range_profile_cal_'], '-depsc')
figure(17);

[h, c] = polarPcolor(range, angle, db(abs(Range_profile_j)).');
%title(['Polar plot of Range/Angle map after calibration ']);
colorbar;
caxis([-50 0]);

print(['Range_profile_cal_polar_'], '-depsc');

figure(20);
plot(angle, db(abs(Range_profile_j(:, 83))).');
ylim([-50 20])
xlabel('Angle (Degree)', 'FontSize', 12, 'FontWeight', 'bold');
ylabel('Mag(dB)', 'FontSize', 12, 'FontWeight', 'bold');
title(['Angle cut at range = 3.4310 [m] after calibration'], ...
    'FontSize', 12, 'FontWeight', 'bold');
grid on;
print(['Angle_cut_cal'], '-depsc');
```

A.2 Assignment 3

```
close all;
clear all;
clc;

load Assignment3.mat


% Collections in the form of [sensor X fast-time]

c=299792458; %speed of light
%data_to_process= eval(['Collection_', num2str(i)]);

data_to_process= CollectionD; %change to CollectionB, CollectionC ...
    and CollectionD
```

```
NSamp = size(data_to_process,2);

NFFTA = 1024; % FFT length angle
NFFTR = 1024; % FFT length range
% Range axis
Ts   = Radar_settings.Chirp_time - Radar_settings.Reset_time - ...
    Radar_settings.DwellTime;     % Duration of the ramp section of ...
    the chirp in s (Sweep Time)
S = Radar_settings.BW/Ts;
Range   = c/(2*S)*linspace(0,Radar_settings.Fs,NFFTR);       % in meters

%% Start writing your code ....

    a = cat(1, data_to_process, zeros(2000-size(data_to_process, ...
        1), size(data_to_process, 2)));

    data_to_sample_fft = fftshift(fft2(a), 1);

    Angle = linspace(-90, 90, 2000);

    %[value_1, index_1] = max(a(40, :));

    figure(1);
    [h,c]=polarPcolor(Range(:, 1:58),Angle, ...
        db(abs(data_to_sample_fft(:, 1:58))).');

    colorbar;
    caxis([-50 10]);

    print(['Range_profile_ex3_polar_D'], '-depsc');

    %colorbar


    figure(2);

    surf(Angle, Range, db(abs(data_to_sample_fft)).'); view(2); ...
        shading flat;
    ylim([0 10]);
    xlabel('Angle (Degree)', 'FontSize', 12, 'FontWeight', 'bold');
    ylabel('Range (m)', 'FontSize', 12, 'FontWeight', 'bold');
    title(['Range/Angle Map with after calibration'], 'FontSize', ...
        12, 'FontWeight', 'bold');
    grid on;
    colorbar;
    caxis([-50 10]);
    print(['Range_profile_ex3_D'], '-depsc')

    %Angle cut
```

```
figure;
plot(Angle, db(abs(data_to_sample_fft(:, 39))).', 'LineWidth', 2);
grid on;

xlabel('Angle (Degree)', 'FontSize', 12, 'FontWeight', 'bold');
ylabel('Mag(dB)', 'FontSize', 12, 'FontWeight', 'bold');
title(['Angle cut'], 'FontSize', 12, 'FontWeight', 'bold');
grid on;
print(['Angle_cut_ex3_D'], '-depsc');

%Range cut

figure;

plot(Range, db(abs(data_to_sample_fft(1433,:))).', 'LineWidth', 2);

grid on;

xlabel('Range [m]', 'FontSize', 12, 'FontWeight', 'bold');
ylabel('Mag(dB)', 'FontSize', 12, 'FontWeight', 'bold');
title(['Range cut'], 'FontSize', 12, 'FontWeight', 'bold');
grid on;
xlim([0 10]);
ylim([-50 50]);
print(['Range_cut_ex3_D'], '-depsc');
```

A.3 Assignment 4

```
close all;
clear all;
clc;

load Assignment4.mat


% Collections in the form of [sensor X fast-time]

c=299792458; %speed of light
%data_to_process= eval(['Collection_', num2str(i)]);

data_to_process= BS_TCR_0_5; %change to CollectionB, CollectionC ...
    and CollectionD
NSamp = size(data_to_process,2);

NFFTA = 1024; % FFT length angle
NFFTR = 1024; % FFT length range
```

```
% Range axis
Ts   = Radar_settings.Chirp_time - Radar_settings.Reset_time - ...
    Radar_settings.DwellTime;     % Duration of the ramp section of ...
    the chirp in s (Sweep Time)
S = Radar_settings.BW/Ts;
Range   = c/(2*S)*linspace(0,Radar_settings.Fs,NFFTR);       % in meters

%% Start writing your code ....

    a = cat(1, data_to_process, zeros(2000-size(data_to_process, ...
        1), size(data_to_process, 2)));

    data_to_sample_fft = fftshift(fft2(a), 1);

    Angle = linspace(-90, 90, 2000);

    %[value_1, index_1] = max(a(40, :));

    figure(1);
    [h,c]=polarPcolor(Range(:, 1:58),Angle, ...
        db(abs(data_to_sample_fft(:, 1:58))).');

    colorbar;
    caxis([-50 10]);

    print(['Range_profile_ex4_polar_5'], '-depsc');

    %colorbar


    figure(2);

    surf(Angle, Range, db(abs(data_to_sample_fft)).'); view(2); ...
        shading flat;
    ylim([0 10]);
    xlabel('Angle (Degree)', 'FontSize', 12, 'FontWeight', 'bold');
    ylabel('Range (m)', 'FontSize', 12, 'FontWeight', 'bold');
    title(['Range/Angle Map with after calibration'], 'FontSize', ...
        12, 'FontWeight', 'bold');
    grid on;
    colorbar;
    caxis([-50 10]);
    print(['Range_profile_ex4_5'], '-depsc')

    %Angle cut

    figure;
    plot(Angle, db(abs(data_to_sample_fft(:, 39))).', 'LineWidth', 2);
    grid on;
```

```
xlabel('Angle (Degree)', 'FontSize', 12, 'FontWeight', 'bold');
ylabel('Mag(dB)', 'FontSize', 12, 'FontWeight', 'bold');
title(['Angle cut'], 'FontSize', 12, 'FontWeight', 'bold');
grid on;
print(['Angle_cut_ex4_5'], '-depsc');
```