Synthetic Aperture Radar (SAR) Simulation and Analysis Using MATLAB

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1. Introduction

Synthetic Aperture Radar (SAR) is a powerful remote sensing technology used to generate high-resolution images of the Earth's surface. Unlike optical imaging systems, SAR operates in the microwave spectrum and can penetrate clouds, fog, and even vegetation to a certain degree. It functions by emitting microwave pulses towards the Earth and measuring the returned echoes. By exploiting the motion of the radar platform (typically mounted on an aircraft or satellite), SAR synthesises a large virtual aperture, enabling high-resolution imaging in the azimuth direction.

This project aims to set up a complete SAR simulation using MATLAB's Radar Toolbox. The simulation begins with a point-target-based scenario and then extends to a terrain-based simulation using a Digital Elevation Model (DEM). Environmental effects (such as rain, fog, and snow) are considered, and a parametric study is conducted to analyse how various radar system parameters influence SAR imaging performance. The report provides a detailed technical overview of the implementation, analysis, and insights derived from the experiments.

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2. Team Members and Contributions

Group Members:

- Param Gupta
- Kumar Rishav
- Naman Garg

Contributions:

- Param Gupta: Implementation of point-target SAR system, parameter variation analysis, environmental modelling
- Kumar Rishav: DEM integration and terrain-based SAR imaging, data visualisation, final presentation
- Param Gupta, Kumar Rishav and Naman Garg: MATLAB code documentation, analysis of radar parameter effects, compilation of report

As mentioned, we collaborated on discussing the design of experiments, debugging code, and interpreting the results.

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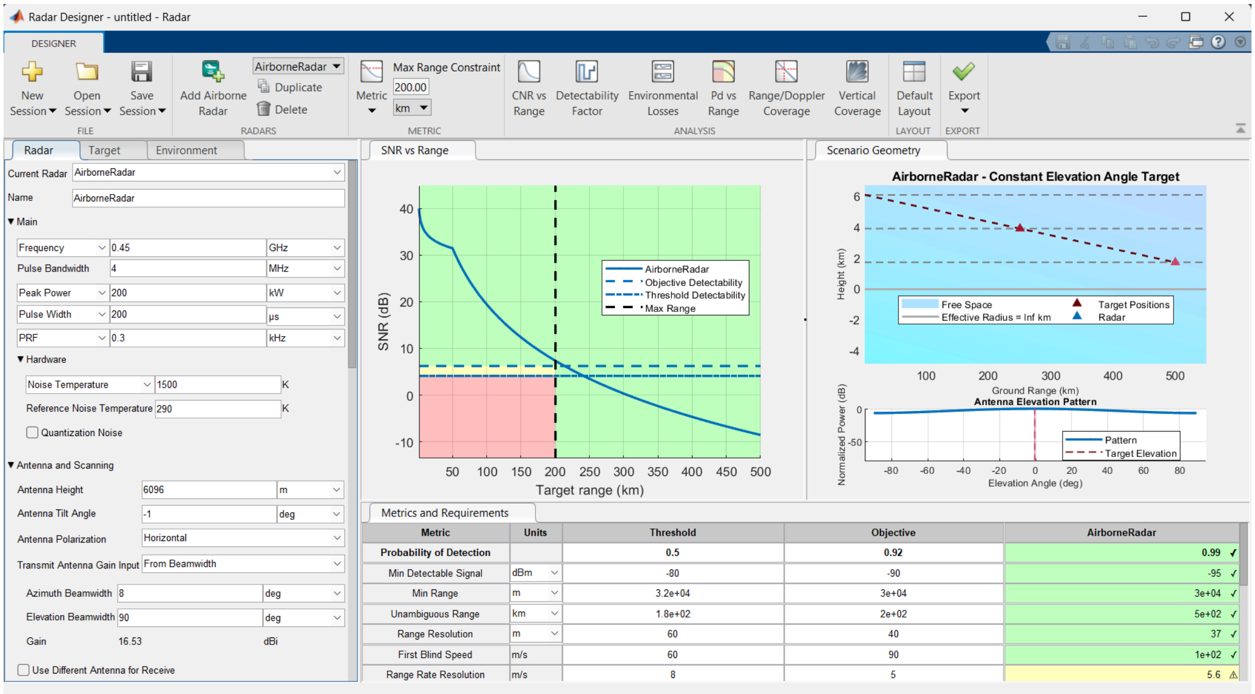
3. SAR System Design in MATLAB Radar Toolbox



SAR Setup Code (Airborne Radar speed and location setup)

```
% Aircraft Speed is 100 m/s with a flight duration of 4 seconds.
speed = 100;
flightDuration = 4;
radarPlatform  = phased.Platform('InitialPosition', [0;-200;1000], 'Velocity', [0; speed; 0]);
slowTime = 1/prf;
numpulses = flightDuration/slowTime +1;
```

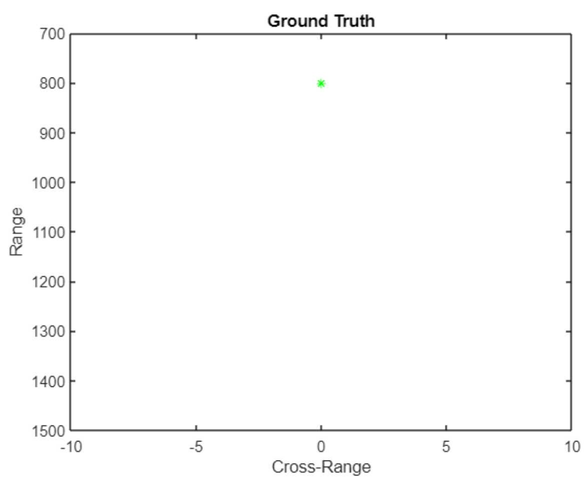
3.1 Point Target Scene

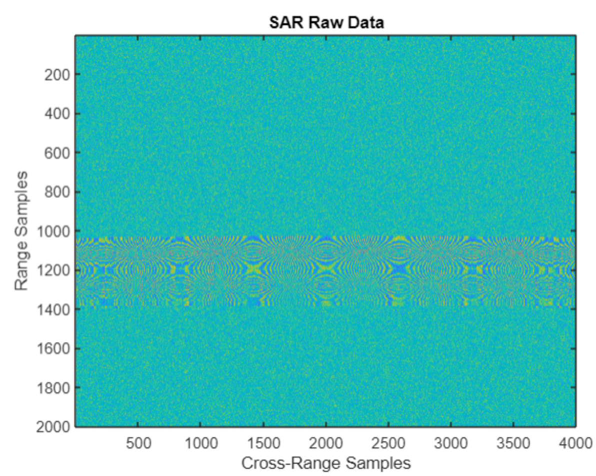
A synthetic ground target is modelled as a point reflector placed at a known range and azimuth. The radar transmits chirp pulses, and the echoes from the target are collected and processed to form an image.

```
%Scene Configuration
targetpos= [800,0,0]';
targetvel = [0,0,0]';
target = phased.RadarTarget('OperatingFrequency', fc, 'MeanRCS', 1);
pointTargets = phased.Platform('InitialPosition', targetpos,'Velocity',targetvel);
% The figure below describes the ground truth based on the target
figure(1);h = axes;plot(targetpos(2,1),targetpos(1,1),'*g');
set(h,'Ydir','reverse');xlim([-10 10]);ylim([700 1500]);
title('Ground Truth');ylabel('Range');xlabel('Cross-Range');
```

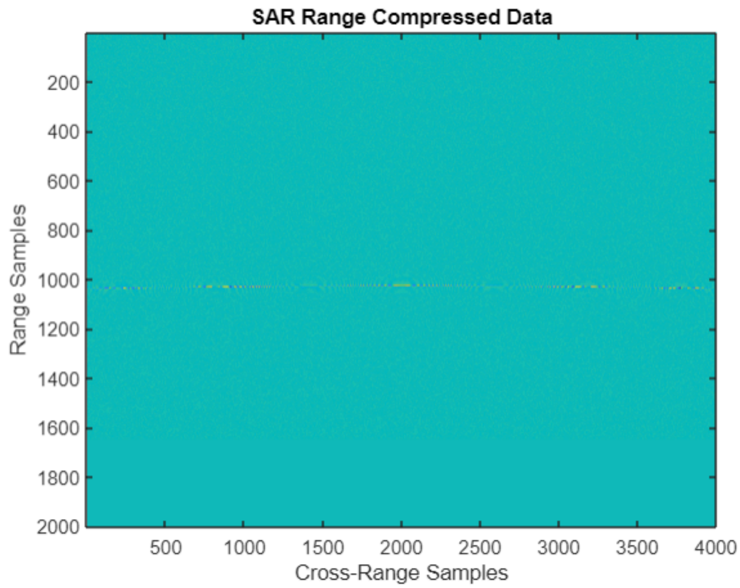
Ground Truth for target position setup for the position of a Single target. (Shown is the figure below (Left).) RAW SAR Data collected for the position of a Single target. (Shown is the figure below (Right.)

OUTPUT

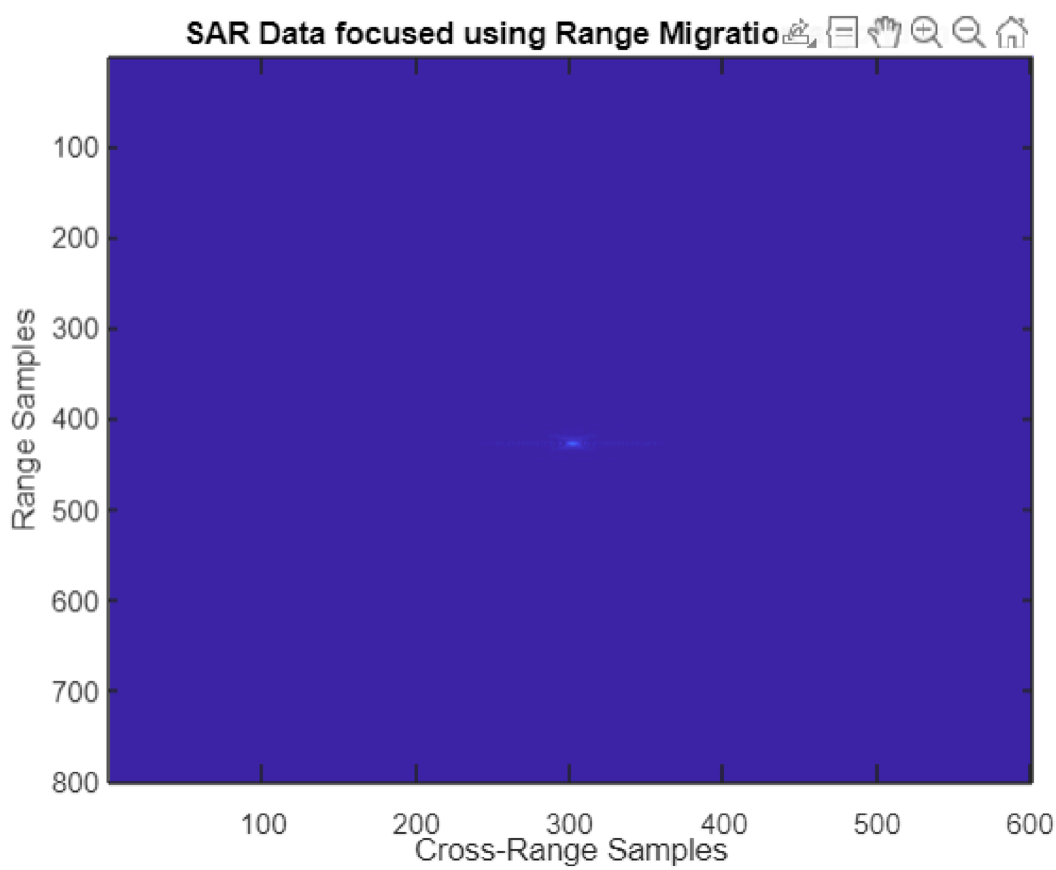




SAR Range compressed data



SAR DATA focused using Range Migration Algorithm

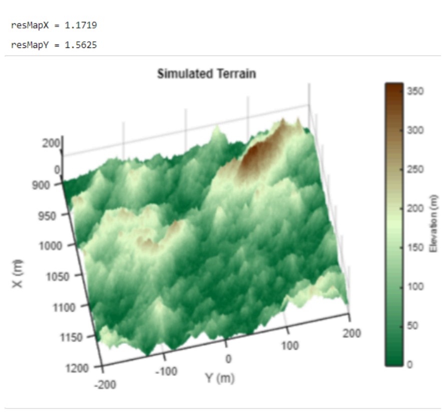


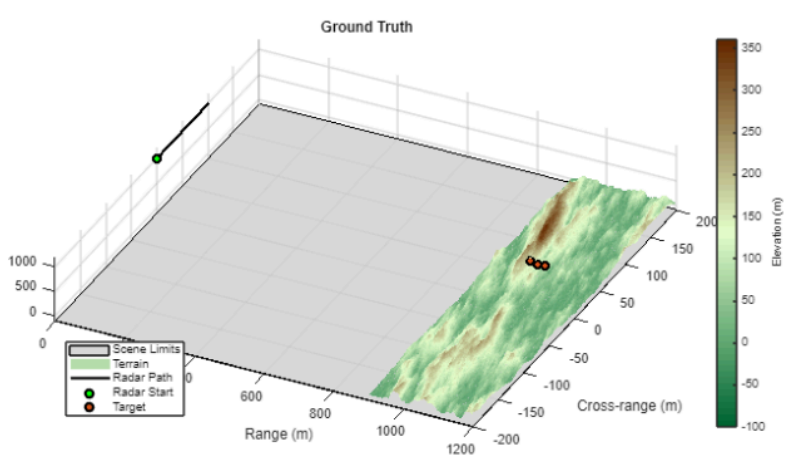
Terrain-Based Scene

Using a Digital Elevation Model (DEM), simulated terrain is constructed in MATLAB. The same radar parameters are used to generate strip-map SAR images of the terrain. The DEM helps to understand terrain-induced variations in SAR imaging.

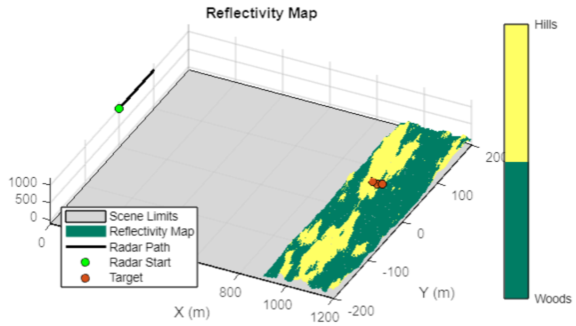
```
% Initialize random number generator
rng(2025)

% Create terrain
xLimits         = [900 1200]; % x-axis limits of terrain (m)
yLimits         = [-200 200]; % y-axis limits of terrain (m)
roughnessFactor = 1.75;       % Roughness factor
initialHgt      = 0;          % Initial height (m)
initialPerturb  = 200;        % Overall height of map (m)
numIter         = 8;          % Number of iterations
[x,y,A] = helperRandomTerrainGenerator(roughnessFactor,initialHgt, ....
    initialPerturb,xLimits(1),xLimits(2), ...
    yLimits(1),yLimits(2),numIter);
A(A < 0) = 0; % Fill-in areas below 0
xvec = x(1,:);
yvec = y(:,1);
resMapX = mean(diff(xvec))

resMapY = mean(diff(yvec))
% Plot simulated terrain
helperPlotSimulatedTerrain(xvec,yvec,A)
```

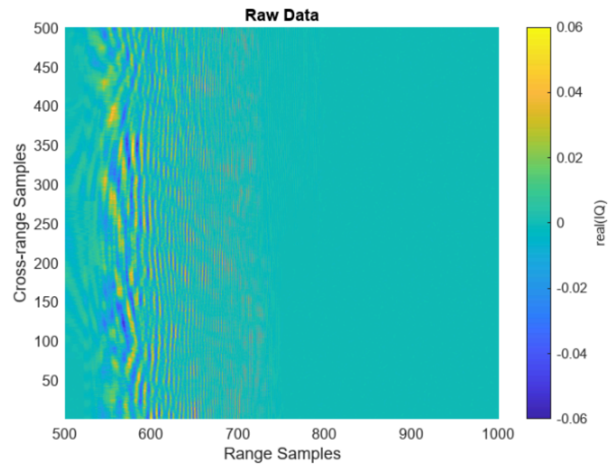
Ground Truth for target position setup for the position of a Digital Elevation Model, using a Simulated terrain.



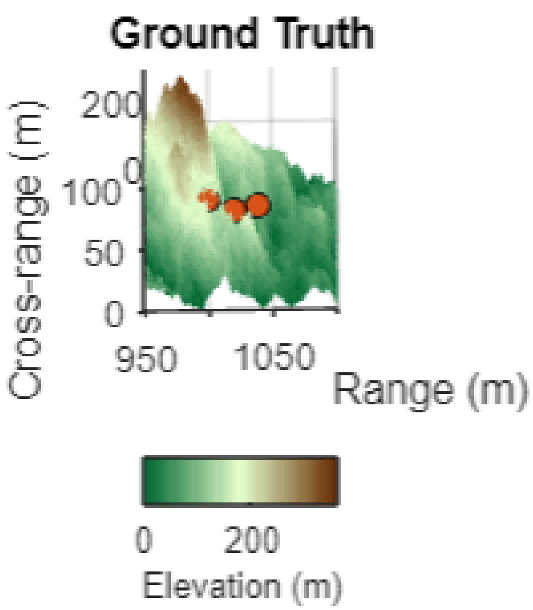


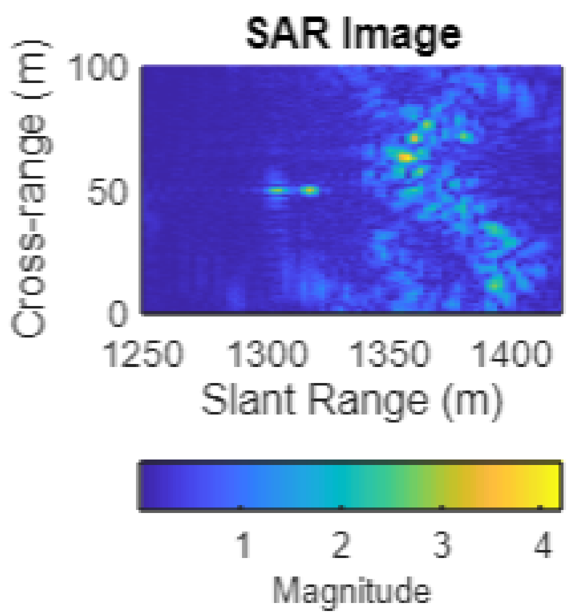
Reflectivity Map for the terrain (left) and Raw SAR Data (Right)





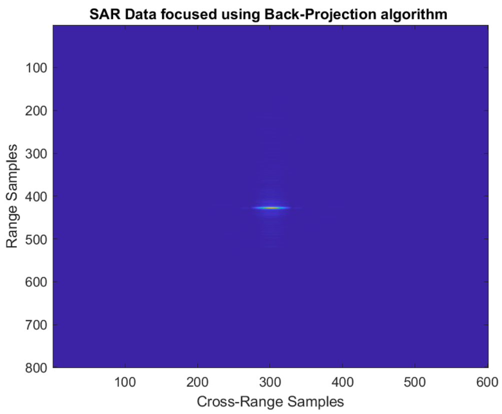
SAR DATA focused using Range Migration Algorithm

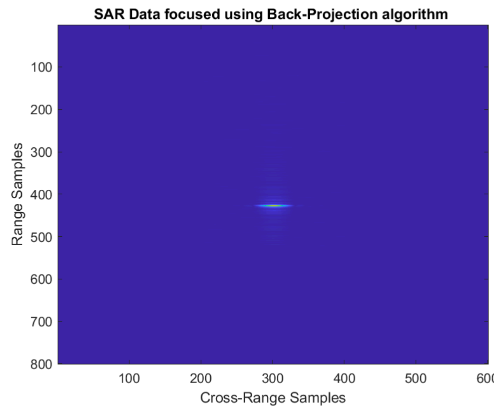


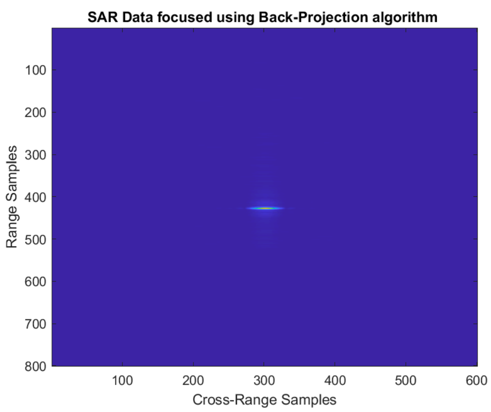


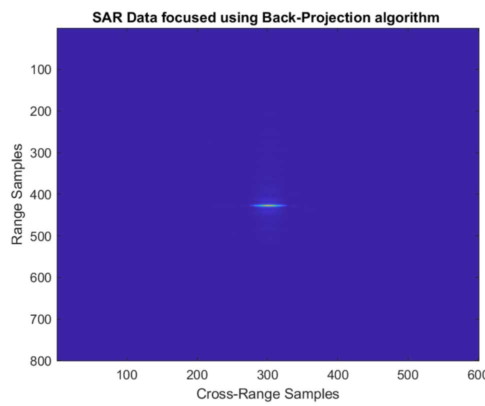
3.4 Incorporated Environmental Conditions

- Light Rain
- Heavy Rain
- Fog
- Snow









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4. Simulation Results for Point Target

4.1 Baseline Result

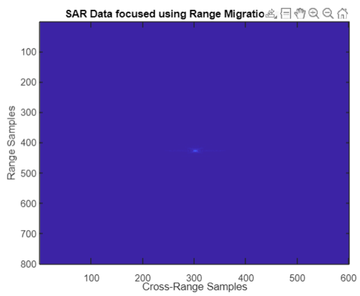
Under the baseline configuration, the SAR image of the point target displays a clear, localised response with low sidelobes. The range and azimuth resolutions are consistent with theoretical predictions.

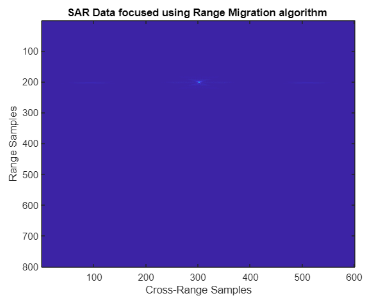
4.2 Varying Radar Parameters

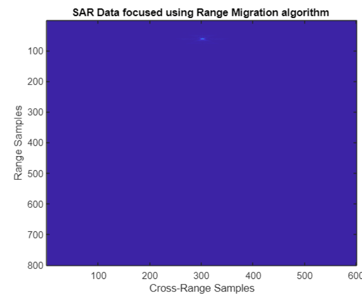
To understand the sensitivity of SAR performance to radar parameters, the following were varied one at a time:

4.2.1 Altitude (h)

- **0 m:** Improved SNR, sharper image with good resolution (left)
- **400 m:** Broader footprint (raw SAR data), reduced range resolution, and cross-range degrades (center)
- **800 m:** Noticeable SNR degradation and in visibility and azimuth smearing (right)

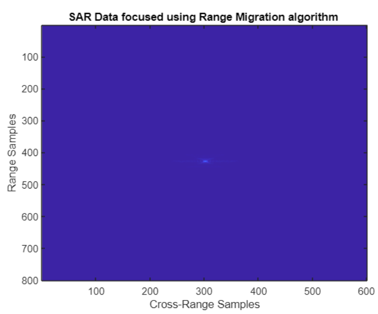


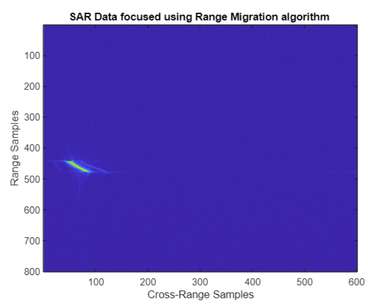


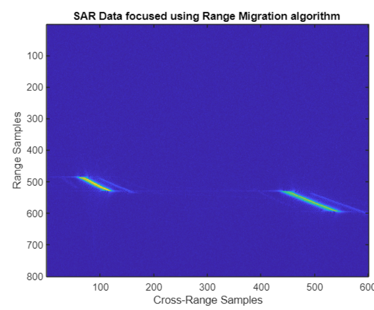


4.2.2 Platform Velocity (v)

- **100 m/s:** Lower Doppler resolution, blurred azimuth profile (left)
- **300 m/s:** Improved azimuth resolution (center)
- **400 m/s:** High resolution but more Doppler aliasing (right)

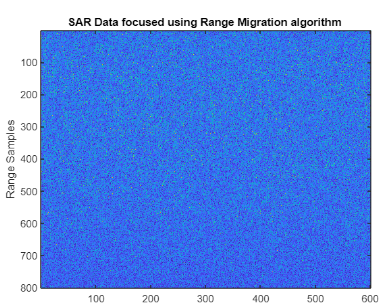


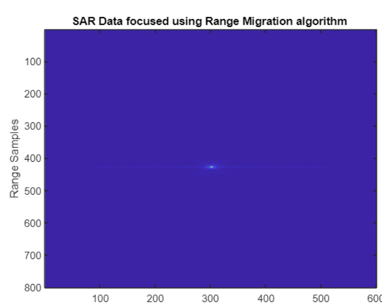


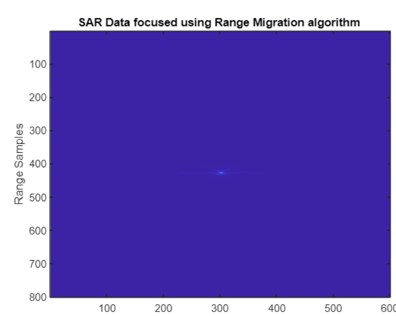


4.2.3 Wavelength (lambda)(changes can be done on center frequency of radar)

- **0.01 m:** High resolution but heavy distortion (left)
- **0.06 m:** Reduced resolution but more robust (center)
- **0.1 m:** Further resolution loss (right)

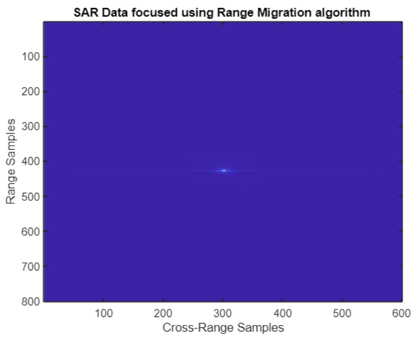


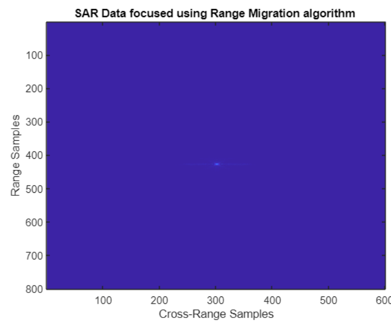




4.2.4 Chirp Rate (mu)

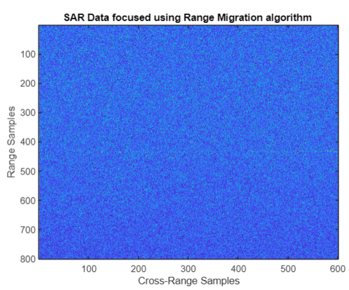
- **Lower mu:** Poor range resolution, broader mainlobe (left)
- **Higher mu:** Enhanced resolution, but processing complexity increases (right)

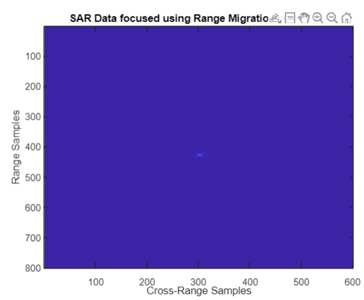


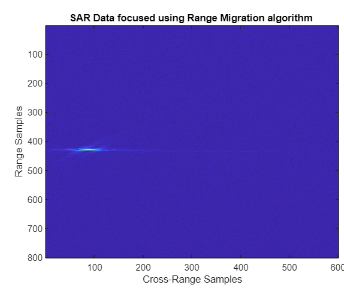


4.2.5 PRI

- **25 us:** Better Doppler resolution, potential range ambiguity
- **100 us:** Worse azimuth resolution, no ambiguity
- **200 us:** Severe resolution loss

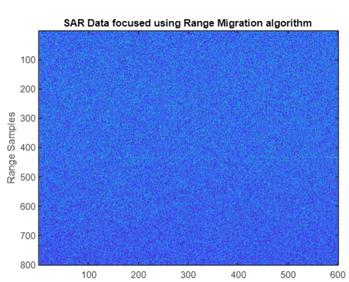


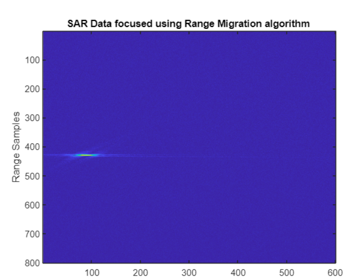


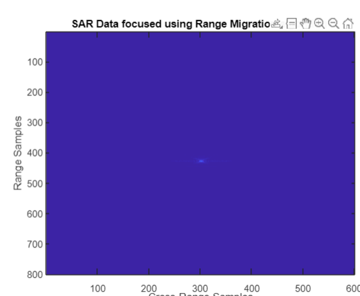


4.2.6 Transmit Power (Pt)

- **100 W:** Very noisy image
- **500 W:** Acceptable SNR
- **2000 W:** Excellent SNR, high dynamic range

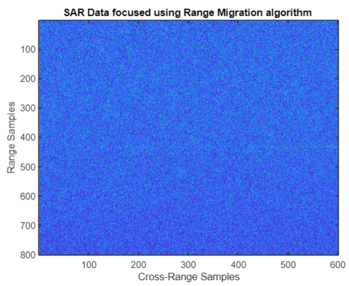


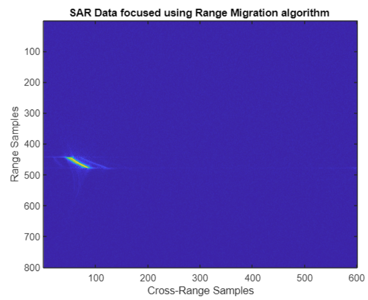


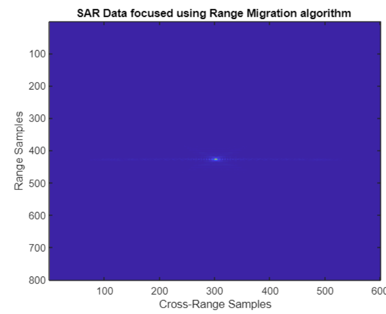


4.2.7 Antenna Gain (G)

- **20 dBi:** Low SNR
- **35 dBi:** Improved resolution
- **40 dBi:** Highly focused beam, better target discrimination







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5. DEM-Based Strip Map Imaging

A real-world digital elevation model (DEM) of a terrain patch is synthetically generated in MATLAB. The radar transmits chirp waveforms over the terrain, and strip-map SAR imaging is carried out using matched filtering and back projection algorithms.

The image shows height-induced foreshortening and layover effects, typical in SAR imaging over complex terrains. Despite longer processing time and higher memory usage, the DEM-based SAR images provide more realistic insights into operational SAR systems.

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6. Environmental Condition Modelling

To understand the robustness of SAR in different weather conditions, we model rain, fog, and snow using standard attenuation coefficients from the ITU-R recommendation.

6.1 Rain

- Attenuation: ~0.1 dB/km/mm/hr
- Result: Moderate reduction in SNR, slight blurring in image

6.2 Fog

- Attenuation: ~0.01 dB/km
- Result: Negligible effect

6.3 Snow

- Attenuation: ~0.05 dB/km
- Result: Slight increase in image noise

Images generated in these conditions show that SAR maintains imaging capability under all three weather types, though SNR is noticeably impacted in rain.

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7. Analysis and Observations

7.1 Radar Parameter Trade-Offs

- Higher altitudes increase coverage but reduce resolution
- Higher velocities improve azimuth resolution but introduce Doppler aliasing
- Shorter wavelengths improve resolution but suffer from atmospheric attenuation
- Power and gain directly impact image SNR
- Chirp rate controls range resolution
- PRI must be optimized to avoid range-Doppler ambiguity

7.2 Environmental Robustness

SAR is robust against most weather conditions. Rain has the most pronounced effect, especially at shorter wavelengths. Fog and snow have minor impact.

7.3 Processing Considerations

Point-target imaging is computationally efficient and suitable for parametric analysis.
DEM-based imaging is more realistic but computationally intensive.

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9. Conclusion

This project demonstrates the successful setup and execution of a Synthetic Aperture Radar simulation using MATLAB. Through both point-target and DEM-based scenarios, key insights were gained regarding radar parameter selection, image formation techniques, and environmental robustness. Parameter sweeps revealed important trade-offs in system design. Overall, SAR proves to be a versatile and resilient imaging technology, with performance highly dependent on the thoughtful configuration of its many parameters. Future work could include:

- Implementing spotlight SAR mode
- Including multipath and clutter modelling
- Using real aircraft trajectory data
