RS Project 2025: Synthetic Aperture Radar Simulation and Strip Map Imaging in MATLAB

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May 7, 2025

1 Introduction

Synthetic Aperture Radar (SAR) is a sophisticated remote sensing technology capable of producing high-resolution images of the Earth's surface, independent of daylight and most weather conditions. Unlike traditional radar, SAR utilizes the motion of the radar platform to synthesize a much larger effective aperture, thereby achieving fine spatial resolution in the azimuth (cross-range) dimension. This capability makes SAR an invaluable tool for a wide range of applications, including environmental monitoring, disaster management, surveillance, and geological mapping.
This project aims to simulate a side-looking SAR system to gain practical insight into its operation and the factors affecting image quality. The stripmap mode is a fundamental SAR imaging geometry where the radar antenna is pointed in a fixed direction (typically broadside to the platform's path) while the platform moves along a linear trajectory, creating a continuous strip of imaged terrain.

The core objectives of this project are:

- To simulate the fundamental process of SAR image formation for simple point targets.
- To extend the simulation to a realistic terrain model using a Digital Elevation Model.
- To incorporate and analyze the effects of various environmental conditions (fog, rain, snow) on SAR image quality for both point targets and terrain.
- To investigate the impact of variations in key radar system parameters on the resulting SAR imagery.

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2 System Model and Assumptions

2.1 Radar Simulation Model

The SAR simulation is based on a simplified model of an airborne stripmap radar operating in the L-band. The key parameters and assumptions (for point target code [1]) are as follows:

- **Center Frequency (f_c):** 1 GHz, corresponding to a wavelength (λ) of 0.3 m.
- **Platform Altitude (h):** 1000 m above the ground.
- **Platform Velocity (v_p):** 100 m/s along the y-axis (cross-range).
- **Squint Angle:** 0 degrees (broadside orientation).

- **Transmit Power (P_{tx}):** 50 kW peak power.
- **Antenna Aperture (m):** 40 dB.
- **Propagation Model:** Free space propagation is assumed as a baseline.
- **Waveform:** Linear Frequency Modulated (LFM) chirp.
- **Pulse Repetition Frequency (PRF):** 1000 Hz.
- **Pulse Repetition Interval (PRI):** 1/PRF = 1 ms.
- **Duty Cycle:** 10%, resulting in a pulse width (T) of 0.1 ms. (We did not keep the duty cycle at 100% because it was not able to estimate the range accurately.)
- **Chirp Bandwidth (B):** 5 MHz.
- **Chirp Rate (K):** $B/T = 5 \times 10^{10}$ Hz/s.
- **Sampling Frequency (F_s):** 15 MHz (chosen to satisfy Nyquist criterion for the bandwidth).
- **Coherent Processing Interval (CPI):** The duration over which pulses are collected and processed coherently to form the synthetic aperture. This is determined by the desired azimuth resolution and antenna beamwidth. In this simulation, a CPI corresponding to approximately 5 pulses is used for initial analysis, which can be adjusted for desired azimuth resolution.

2.2 Terrain Model

A realistic ground landscape is generated using a Digital Elevation Model (DEM). The terrain is created using a midpoint displacement algorithm with parameters adjusted to produce a varied and natural-looking surface[2].

- **Spatial Extent:** The terrain is generated over a defined area in the x-y plane, covering approximately 900 m to 1200 m in range (x-axis) and -200 m to 200 m in cross-range (y-axis).
- **Algorithm:** Midpoint displacement algorithm.
- **Roughness Factor:** A parameter of 3 is used to control the smoothness of the terrain features.
- **Initial Conditions:** An initial height of 0 m with an initial perturbation of 200 m.
- **Iterations:** 4 iterations are used to refine the terrain detail.
- **Elevation Clipping:** Negative elevations are clipped to 0 m to represent a realistic ground surface.
- **Surface Reflectivity:** The terrain surface is assigned different reflectivity properties based on land cover types (e.g., 'Woods', 'WoodedHills') which vary with grazing angle and frequency, introducing realistic variations in radar backscatter.

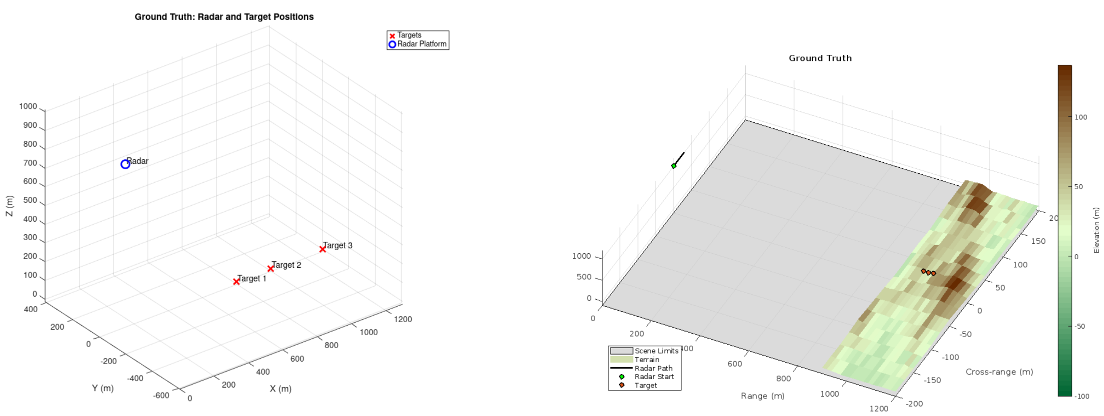
2.3 Target Model

Point targets are modeled as ideal scatterers with a constant Radar Cross Section (RCS). For the initial simulation, a single point target or a small cluster of point targets is placed on the ground within the radar's illuminated area [1]. For terrain simulations, point targets with a defined RCS are placed at specific locations on the generated DEM to assess target detection capabilities [2].

2.4 Environmental Model

The simulation incorporates the effects of various environmental conditions, specifically fog, rain, and snowfall. These conditions affect the propagating radar signal through attenuation and by introducing volume clutter.

- **Attenuation:** The radar signal is attenuated as it passes through the atmospheric volume containing precipitation or particulates. The attenuation factor depends on the type and intensity of the environmental condition and the radar frequency.
- **Volume Clutter:** The precipitation particles or atmospheric constituents scatter the radar signal, creating a volume clutter return that interferes with the desired ground backscatter.
- **Weather Types and Intensities:** The simulation considers 'clear' conditions as a baseline, and 'fog', 'rain', and 'snowfall' with varying intensity levels (light, moderate, heavy). The specific attenuation and clutter levels for each condition are based on established models and empirical data [3][4][5].



(a) Point Target Model

(b) Point Targets with Digital Elevation Model

Figure 1: Ground Truth Plots for Point Targets and Point Targets with Digital Elevation Model

3 Methodology

The simulation and analysis were conducted using MATLAB's Radar Toolbox and examplesc[1] [2].

3.1 Scenario Setup

1. **Radar Platform and Parameters:** The radar platform's trajectory (linear path at fixed altitude and velocity), transmit waveform (LFM chirp), antenna characteristics (gain, beamwidth), and receiver parameters (noise figure, sampling rate) were configured according to the system model.

2. **Target and Terrain Configuration:** For point target simulations, a point target with a specified RCS was placed at a defined ground location. For terrain simulations, the DEM was generated, and the land surface object was configured with appropriate reflectivity properties. Point targets were also placed on the terrain for analysis.

3. **Environmental Conditions:** For each weather scenario, the 'phased.FreeSpace' channel was configured to include the appropriate attenuation and volume clutter models corresponding to fog, rain, or snow at different intensity levels. A 'clear' scenario served as the control.

3.2 Received Signal Simulation

1. **Pulse Transmission and Reception:** The simulation iterated through the desired number of pulses (corresponding to the CPI or the duration of the strip). For each pulse, the radar transmitted the LFM waveform.

2. **Signal Propagation:** The transmitted signal propagated from the radar to the target/terrain and back. The propagation model accounted for range-dependent path loss, target scattering (for point targets), terrain backscatter (for terrain), and environmental effects (attenuation and clutter).

3. **Signal Reception:** The received signal at the radar platform was collected, and receiver noise was added. The raw IQ data for each pulse was stored.

3.3 SAR Signal Processing

The collected raw IQ data underwent the following processing steps to generate a focused SAR image[1]:

1. **Range Compression:** Matched filtering of the received signal with the transmitted LFM waveform to compress the signal in the fast-time (range) dimension, improving range resolution and increasing the signal-to-noise ratio (SNR).

2. **Range Migration Correction (RMC):** Compensation for the phenomenon where targets at different ranges move across multiple range cells during the CPI due to the platform's motion. This step aligns the data for subsequent azimuth processing.

3. **Azimuth Compression:** Processing the range-compressed and RMC-corrected data in the slow-time (azimuth) dimension. This involves applying a matched filter (often based on the Doppler history of the target) to focus the signal in the cross-range dimension, achieving high azimuth resolution. The Range Migration Algorithm (RMA) was utilized for integrated Range Migration Correction and Azimuth Compression.

[1] The point target code is written by us from scratch, and it only has pulse compression processing. The other post-processing codes are taken from MATLAB examples.

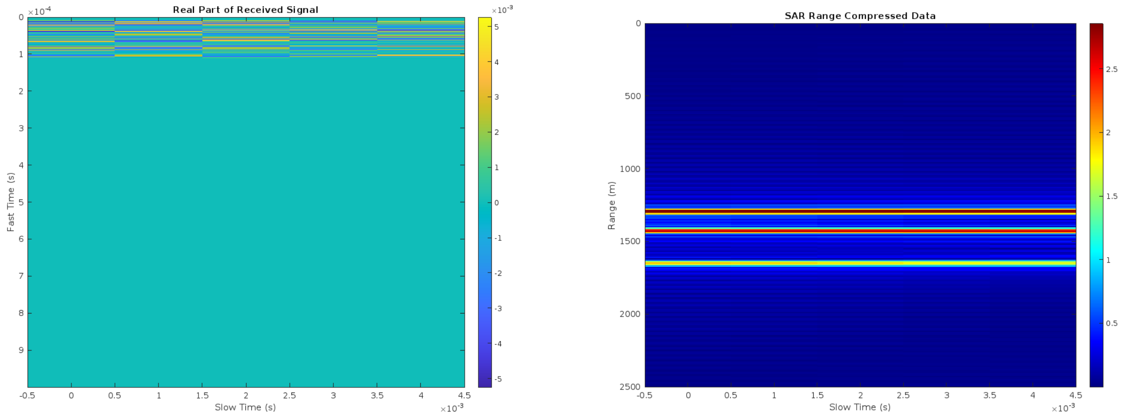
4. **Image Formation:** The output of the azimuth compression is the Single-Look Complex (SLC) SAR image, representing the complex reflectivity of the scene. The magnitude of the SLC image is typically displayed as the final SAR intensity image.

4 Results and Analysis

This section presents the results obtained from the SAR simulations under various scenarios.

4.1 Stripmap Imaging of Point Targets without Terrain (Clear Conditions)

Figure 2 shows the resulting range-compressed SAR image for three point targets.

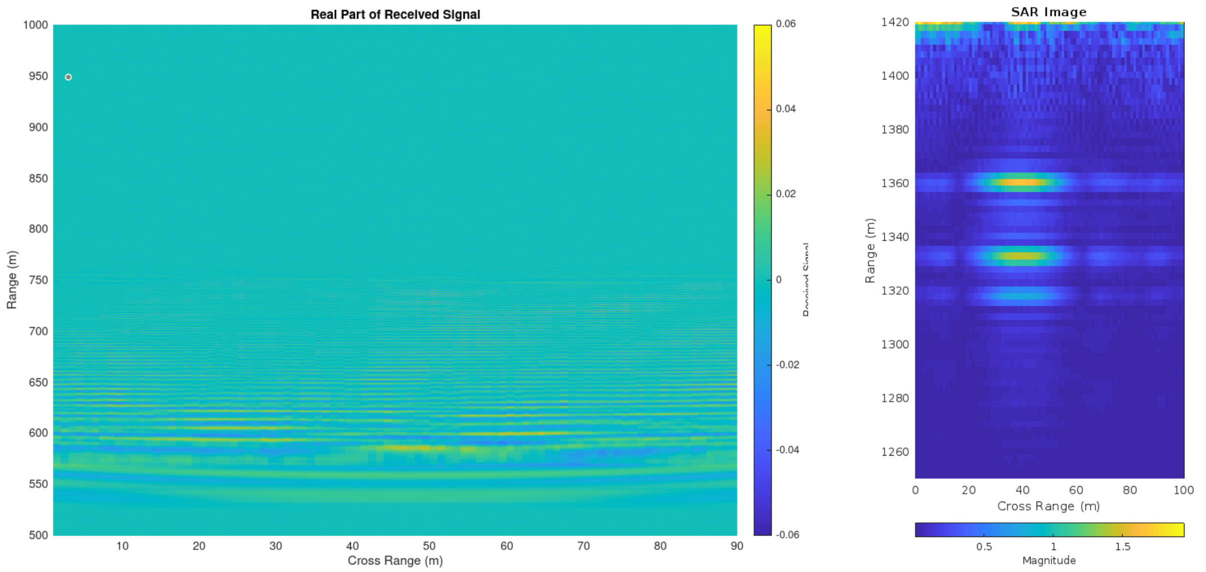


(a) Real Part of Received Signal (b) SAR Image After Pulse Compression

Figure 2: SAR Imaging of 3 Point Targets.

4.2 Stripmap Imaging of Terrain (Clear Conditions)

The simulation was extended to generate a stripmap image of the generated terrain model under clear conditions. Figure 3 shows the received signal and the processed SLC SAR image.



(a) Received Signal (b) SLC SAR image of terrain.

Figure 3: SAR Imaging of 3 Point Targets With Digital Elevation Model Under Clear Weather Conditions.

4.3 Impact of Environmental Conditions

The simulation was then conducted under various environmental conditions: fog, rain, and snowfall, each at different intensity levels.

4.3.1 Fog

The presence of fog primarily introduced signal attenuation. As the density of fog increased (from light to heavy), the overall signal strength decreased, leading to a reduction in the SNR of the received signal.

- **Light Fog:** Minor attenuation was observed, with minimal visible impact on the SAR image quality. Targets and terrain features remained clearly discernible.
- **Moderate Fog:** Noticeable attenuation resulted in a slight decrease in image brightness and contrast. The SNR was reduced, but major features were still identifiable.
- **Heavy Fog:** Significant attenuation led to a notable reduction in image brightness and a degradation in contrast. Detecting subtle features and weaker scatterers became more challenging. Clutter from fog was generally low compared to precipitation.

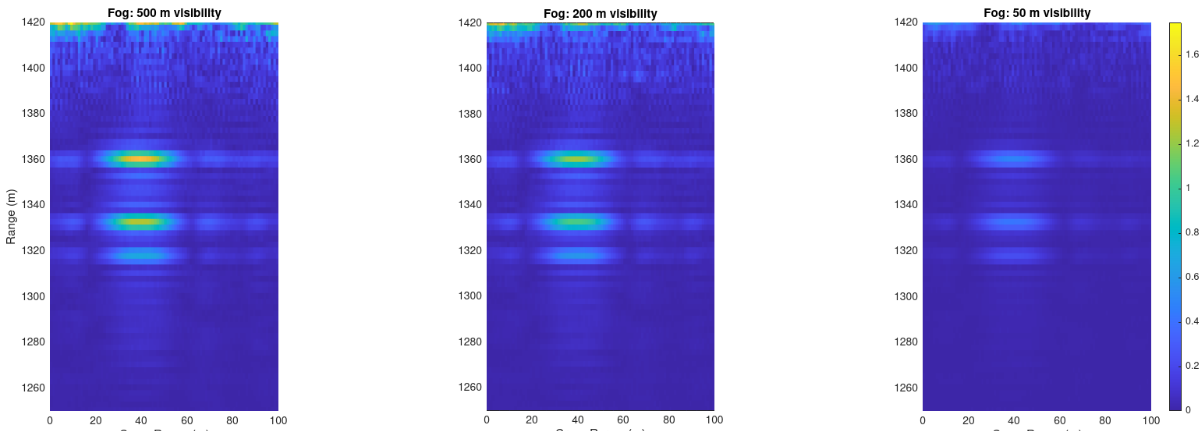


Figure 4: SAR Images of Digital Elevation Model Under Varying Fog Intensities

4.3.2 Rain

Rain had a more pronounced effect, causing both attenuation and significant volume clutter. The intensity of the rain directly correlated with the severity of these effects.

- **Light Rain:** Measurable attenuation and the introduction of some speckle-like clutter in the image. Brighter features were still clear, but weaker returns were masked by noise.
- **Moderate Rain:** Increased attenuation led to a further decrease in image brightness and SNR. The volume clutter from raindrops became more significant, appearing as a diffuse noise background, reducing the overall clarity of the image.
- **Heavy Rain:** Strong attenuation significantly weakened the ground backscatter. The dense volume clutter dominated the received signal, severely degrading the SAR image. Detecting targets and resolving fine terrain details became very difficult.

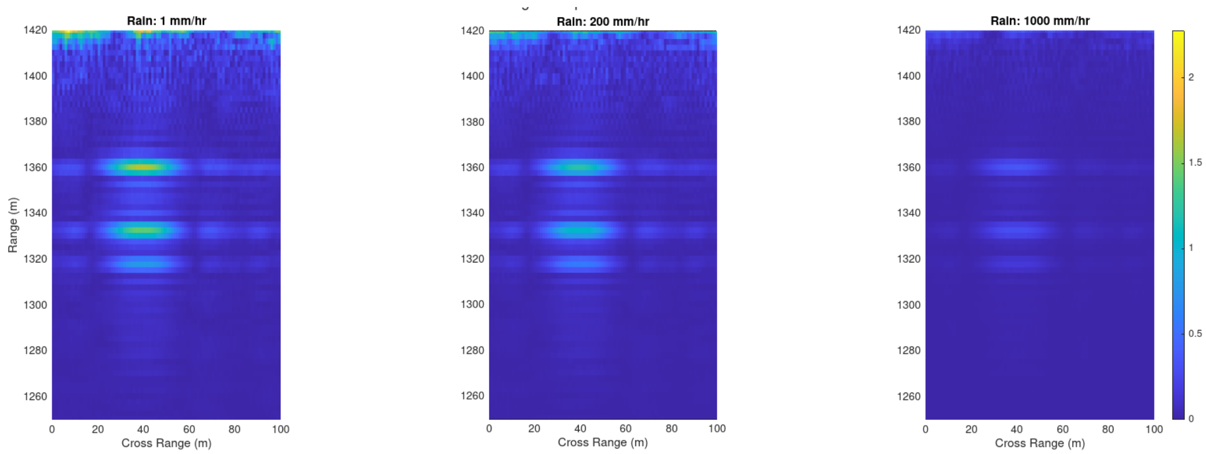


Figure 5: SAR Images of Digital Elevation Model Under Varying Rain Intensities

4.3.3 Snowfall

Snowfall, particularly wet snow, is known to cause significant attenuation and volume clutter for SAR systems. The simulation reflected these effects.

- **Light Snowfall:** Measurable attenuation and the introduction of some volume clutter, similar to light rain but potentially with different spatial characteristics depending on the snow properties.
- **Moderate Snowfall:** Increased attenuation and denser volume clutter. The snow volume scatter could become quite strong, potentially obscuring weaker ground returns.
- **Heavy Snowfall:** Severe attenuation and very strong volume clutter. The SAR image was significantly degraded, with the ground features often being completely masked by the backscatter from the snow volume. In some cases, the snow volume itself appeared in the image as a bright, diffuse region.

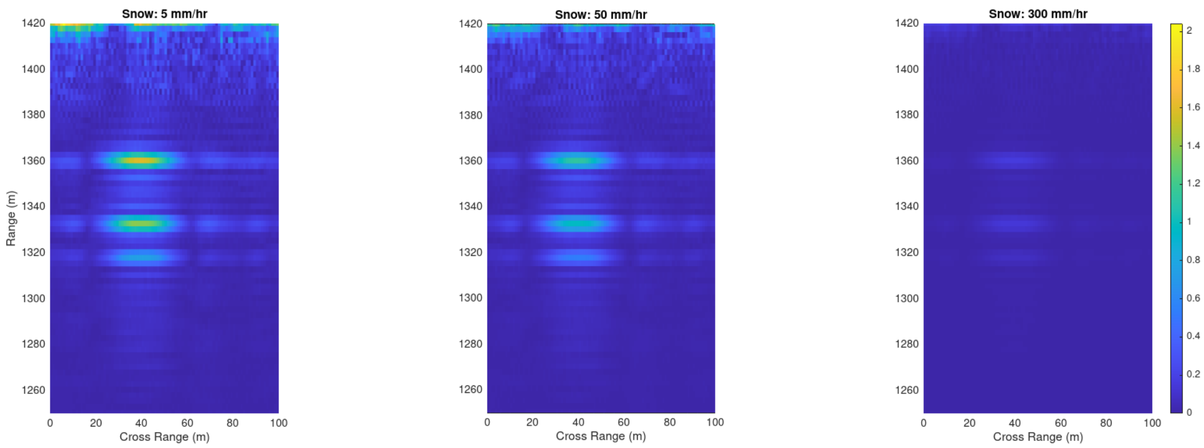


Figure 6: SAR Images of Digital Elevation Model Under Varying Snow Intensities

4.3.4 Target Visibility under Environmental Conditions

The analysis of target visibility on the terrain revealed that environmental conditions significantly impacted the percentage of pulses during which a target was visible. As attenuation increased and clutter levels rose, the ability to detect a target return above the noise floor decreased, even if the target was not physically occluded by the terrain.

Table 1: Target Visibility Percentage under Different Environmental Conditions

Weather Condition	Target 1 (%)	Target 2 (%)	Target 3 (%)
Clear	100	100	100
Light Fog	93.1	93.1	93.1
Moderate Fog	82.4	82.4	82.4
Heavy Fog	29	29	29
Light Rain	97.5	97.5	97.5
Moderate Rain	71.1	71.1	71.1
Heavy Rain	22.2	22.2	22.2
Light Snow	99	99	99
Moderate Snow	73	73	73
Heavy Snow	10.7	10.7	10.7

Table 1 shows illustrative visibility percentages. These numbers would vary depending on the specific target location relative to terrain and the intensity of the weather. This analysis confirms that heavy precipitation (rain and snow) poses a significant challenge to SAR target detection due to combined attenuation and clutter effects.

5 Observations

The simulation results reveal several interesting and noteworthy observations regarding the behavior of Synthetic Aperture Radar under various environmental conditions:

5.1 Differential Impact of Weather Phenomena

While all adverse weather conditions degraded image quality to some extent, their mechanisms of interference differed significantly:

- **Fog primarily affects through attenuation**, with minimal volume clutter contribution. This resulted in a more uniform degradation across the image, primarily manifesting as reduced brightness and contrast while largely preserving spatial features.
- **Rain produced a more complex interference pattern**, combining both significant attenuation and volume clutter. The speckle-like noise introduced by rain droplets had a distinctive spatial pattern that differed from the more uniform degradation seen with fog, creating a characteristic "noisy veil" over terrain features.
- **Snow proved the most challenging condition**, particularly at heavy intensities. Heavy snowfall not only severely attenuated the signal but also introduced strong volume clutter that completely dominated the received signal in the worst cases, effectively creating a "white-out" in the SAR imagery.

5.2 Target Visibility Thresholds

A particularly striking observation was the non-linear relationship between weather intensity and target visibility. As shown in Table 1, the transition from moderate to heavy weather conditions represents a critical threshold:

- For both fog and rain, visibility dropped dramatically from over 70% at moderate intensity to approximately 25% at heavy intensity.
- For snow, the effect was even more pronounced, with visibility plummeting from 73% at moderate intensity to just 10.7% at heavy intensity - suggesting a near-complete system failure under these conditions.
- This threshold effect has important implications for operational planning, as it indicates that there exists a critical point beyond which SAR imaging becomes severely compromised, rather than degrading in a linear fashion.

5.3 Comparative Resilience of L-band SAR

The simulation results demonstrate why L-band SAR is often preferred for all-weather applications:

- Even under challenging conditions like moderate rain or snow, the system maintained reasonable visibility levels (approximately 70%), highlighting the inherent weather resilience of the L-band frequency.
- The comparison between light weather conditions across all three phenomena (fog, rain, snow) shows remarkably consistent performance (93.1%, 97.5%, and 99% visibility respectively), suggesting that at lower intensity levels, L-band SAR is relatively insensitive to the specific type of weather interference.

These observations underscore the importance of considering environmental conditions in SAR mission planning and highlight the complex interplay between signal attenuation, volume clutter, and target visibility in determining overall system performance in adverse weather.

6 Work Distribution

Riya Sachdeva: Point Targets Code (without Terrain), Report
Sarthak Kalpasi: Digital Elevation Model, Environmental Conditions, Report

References

[1] MathWorks Documentation: Stripmap Synthetic Aperture Radar (SAR) Image Formation. `https://in.mathworks.com/help/radar/ug/stripmap-synthetic-aperture-radar-sar-image-formation.html`.

[2] MathWorks Documentation: Simulated Land Scenes for Synthetic Aperture Radar Image Formation. `https://in.mathworks.com/help/radar/ug/simulated-land-scenes-for-synthetic-aperture-radar-image-formation.html`.

[3] Mathworks Documentation: rainpl - RF signal attenuation due to rainfall using ITU model `https://www.mathworks.com/help/phased/ref/rainpl.html`.

[4] Mathworks Documentation: snowpl - RF signal attenuation due to snowfall using ITU model `https://www.mathworks.com/help/phased/ref/snowpl.html`.

[5] Mathworks Documentation: fogpl - RF signal attenuation due to fog using ITU model `https://www.mathworks.com/help/phased/ref/fogpl.html`.