EEE5119Z – Intro to Radar

Course Project

Synthetic Aperture Radar

2025

v1.3

Project Requirements – Please READ carefully.

This project consists of 4 Parts and 3 Appendices.

Part 1: SAR Simulator

Build a basic SAR signal model that is then used to simulate a single target within a scene.

Part 2: SAR Processor

Build a SAR processor that takes in the output of the SAR simulator and applies range and azimuth compression to focus the image.

Part 3: Moving Target Simulator

Add moving targets to the simulated scene and investigate the effects of target movement on the SAR focusing algorithm.

Part 4: Focusing Real Data

Run real SAR data through the processor to produce a real SAR image.

Appendix A: System Specifications

Appendix B: Mathematical Signal Representation

Appendix C: Example Outputs

Deliverables:

- Please attempt **ALL** questions.
- You can use any programming language you wish but the real data is in .mat format so matlab is suggested.
- Submit a single PDF, double column (conference style) report (max 6 pages).
- Please submit all your code in a separate .zip folder.

Note:

All .mat files provided contain a data matrix and a class "p" containing all the required variables for processing as outlined in Table 1. As a result, it is highly advised that you maintain the same variable structure as shown in Table 1.

If you cannot complete any of the questions, we have provided sample data which can be used to complete the following questions along with basic code templates to help you get going.

Part 1: SAR Simulator

Important: Keep the name of all the variables the same as indicated in Table 1 as they are defined according to the .mat files containing the raw data.

The parameters of a typical airborne SAR system are listed in Table 1.

1) Determine the sampling frequency to avoid range ambiguities and the PRF to avoid azimuth ambiguities due to sub-sampling. Give the theoretical resolutions in range and azimuth (hint: use IQ sampling).

2) Simulate a baseband chirp with the parameters shown in Table 1.

$$S_{Tx}^{BB}(t) = e^{j\pi\delta t^2} \cdot rect(t)$$

Plot the envelope of the chirp as well as the real and imaginary parts of the signal.

3) Calculate and plot the ambiguity function (AF) of the signal. Also plot the 0 range and 0 Doppler cuts.

4) Assuming a sinc antenna pattern, plot the normalised gain of the antenna.

5) Determine the amplitude response of each scatterer in the scene, *A(T)*. (hint: in this case you can simply assume the target is observed within the 3 dB width of the antenna.)

6) Using the parameters shown in Table 1 and the system geometry shown in Figure 2.

$$S_{Rx}^{BB}(t,T) = A(T) \cdot rect\left(t - \frac{2R(T)}{C}\right) \cdot e^{j\pi\delta\left(t-\frac{2R(T)}{C}\right)^2} \cdot e^{-\frac{j4\pi R(T)}{\lambda}}$$

$$R(T) \approx R_0\left(1 + \frac{(V_{AT} - V)^2 T^2}{2R_0^2} + \frac{V_{CT}T}{R_0}\right)$$

Simulate the raw data of a stationary target (Swerling 0, non fluctuating) and put the output into a [range x azimuth] or [Fast-time x Slow-time] matrix as shown in Figure 2. Target parameters (Swerling 0):

$$(x, y, R_0, [xv, yv]) = \left(0, \sqrt{R_0^2 - h^2}, 3500, [0, 0]\right)$$

Where *xv* and *xy* represents the targets velocity in Along-Track (*AT*) and Across-Track (*CT*) planes respectively.

7) Plot the magnitude and phase of the simulated data.

8) Add Gaussian white noise to the simulated data with an SNR of 10 dB and Plot the magnitude and phase of the resulting data.

Part 2: SAR Processor

Note: If you were unable to complete section 1, you can use the simulated data from ***sim_data_single.mat*** *to complete Part 2. The target appears at R_0 = 8000 m. The sample data can be opened using the* ***SAR_processor.m*** *template file.*

1) Apply range compression and plot the result (hint: matched filtering in fast-time).

2) Estimate the 3 dB range resolution and compare it with the theoretical value.

3) Take a Doppler FFT and plot the range-Doppler plot.

4) Apply azimuth compression and plot the result (hint: match filter each slow time vector with the appropriate azimuth phase correction).

5) Estimate the 3 dB azimuth resolution and compare it with the theoretical value.

6) Investigate the influence of a window function (e.g. Hamming, Blackman) on the 3 dB width and on the side lobe level of the point spread function in first the range and then the azimuth dimension.

Part 3: Moving Target Simulation

Add two additional moving targets to the original simulation.

1) Along-track velocity

   Using the simulated data from Part 1, add a target which is moving with an along-track velocity of 5 m/s using the parameters of Table 1.

   Target parameters:

$$(x, y, R_0, [xv, yv]) = \left(0, \sqrt{R_0^2 - h^2}, 3850, [5, 0]\right)$$

2) Across-track velocity

   Using the simulated data from Part 1, add a target which is moving with an across-track velocity of 0.5 m/s using the parameters of Table 1.

   Target parameters:

$$(x, y, R_0, [xv, yv]) = \left(0, \sqrt{R_0^2 - h^2}, 4000, [0, 0.5]\right)$$

3) Compress the simulated data using the SAR processor developed in Part 2. What influence does the along-track target velocity have on the focusing? What influence does across-track target velocity have on the focusing? Explain why this happens.

   Note: If you were unable to complete section 3.1 or 3.2, you can use the simulated data from ***sim_data_multi.mat*** *(Sim_Data folder) to complete 3.3. The targets appear at: [R_0 = 8000 m, xv = 0, yv = 0], [R_0 = 8200 m, xv = 15, yv = 0] and [R_0 = 8450 m, xv = 0, yv = -5]*

Part 4: Focusing Real Radar Data

Note: The data has been pre-processed and platform motion compensation has already been applied.

1) Focus the real data ***data1.mat*** and ***data2.mat*** (Real_Data folder) which has been acquired using the AER II radar system and plot each step in the same way as was done with the simulated data.

   (hint: This should be as simple as running the processor developed in Part 3 provided all variables are the same.)

2) Identify two moving targets in the real data by highlighting them in red circles.

3) Propose a method to correct for artefacts caused by moving targets and describe on their basic implementation.

Appendix A: System Parameters

Parameter	Notation	Value
Wavelength	p.lambda	0.03 m
Platform height	p.h	2000 m
Platform velocity	p.vplat	100 m/s
Mean depression angle	p.theta	30°
Antenna length	p.L	1 m
Bandwidth	p.B	150 MHz
Chirp length	p.ts	5 µs
Sampling frequency	p.AD	? Hz
PRF	p.PRF	? Hz
Chirp rate	p.chirp_rate	? Hz/s
Range resolution	p.delta_R	? m
Azimuth resolution	p.delta_Az	? m
Reference function in range	p.ref_range	-
Vector range [m]	p.vec_range	-
Vector azimuth [m]	p.vec_azimuth	-
Vector range frequency [Hz]	p.vec_rangefreq	-
Vector Doppler [Hz]	p.vec_Doppler	-
Number of range samples	p.N_range	-
Number of azimuth samples	p.N_azimuth	-
Raw data	data	p.N_range × p.N_azimuth

Table 1: SAR system parameters.

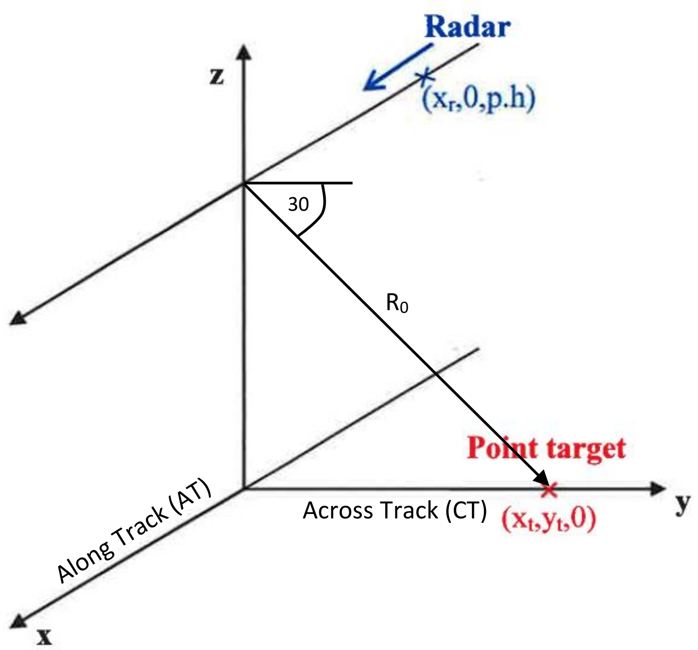


Figure 1: Basic system geometry for simulation.

Appendix B: Basic Signal Construction

$$t = fast\ time$$

$$T = slow\ time$$

$$\delta = \frac{B}{ts}$$

$$\delta = \frac{B\ (chirp\ bandwidth)}{ts\ (chirp\ length)}$$

Baseband transmit signal:

$$S_{Tx}^{BB}(t) = e^{j\pi\delta t^2} \cdot rect(t)$$

Baseband signal mixed to RF:

$$S_{Tx}^{RF}(t) = S_{Tx}^{BB}(t) \times e^{j2\pi f_0 t}$$

Received signal time delayed:

$$S_{Rx}^{RF}(t) = A \cdot S_{Tx}^{RF}\left(t - \frac{2R}{C}\right)$$

Received signal mixed back down to baseband:

$$S_{Rx}^{BB}(t) = S_{Rx}^{RF}(t) \times e^{-j2\pi f_0 t} = A \cdot rect\left(t - \frac{2R}{C}\right) \cdot e^{j\pi\delta\left(t-\frac{2R}{C}\right)^2} \cdot e^{j2\pi f_0\left(-\frac{2R}{C}\right)}$$

If we include platform motion we get:

$$S_{Rx}^{BB}(t,T) = S_{Rx}^{RF}(t,T) \times e^{-j2\pi f_0 t}$$

$$S_{Rx}^{BB}(t,T) = A(T) \cdot rect\left(t - \frac{2R(T)}{C}\right) \cdot e^{j\pi\delta\left(t-\frac{2R(T)}{C}\right)^2} \cdot e^{j2\pi f_0\left(-\frac{2R(T)}{C}\right)}$$

The Doppler shift experienced by the signal is linearly proportional to the azimuth frequency due to the relative platform motion:

$$f_d = -\frac{2v^2}{\lambda r_0}T$$

But the azimuth phase variation is described by:

$$e^{j2\pi f_0\left(-\frac{2R(T)}{C}\right)} = e^{-\frac{j4\pi R(T)}{\lambda}}$$

Where the distance from platform to target, *R(T)*, is defined as:

$$X(T) = X_0 + V_{AT} \cdot T$$

$$Y(T) = Y_0 + V_{CT} \cdot T$$

$$R(T) = \sqrt{(X(t) - VT)^2 + Y^2(T)}$$

Using Taylor series expansion, we can approximate *R(T)* to a parabola:

$$R(T) \approx R_0\left(1 + \frac{(V_{AT} - V)^2T^2}{2R_0^2} + \frac{V_{CT}T}{R_0}\right)$$

Where R_0 is the look distance to the target, V_{CT} is the across track target velocity and V_{AT} is the along Track target velocity.

Therefore the simulated received baseband signal is:

$$S_{Rx}^{BB}(t,T) = A(T) \cdot rect\left(t - \frac{2R(T)}{C}\right) \cdot e^{j\pi\delta\left(t-\frac{2R(T)}{C}\right)^2} \cdot e^{-\frac{j4\pi R(T)}{\lambda}}$$

$$R(T) \approx R_0\left(1 + \frac{(V_{AT} - V)^2T^2}{2R_0^2} + \frac{V_{CT}T}{R_0}\right)$$

Processing the data

1. Perform the matched filter in the range dimension

$$(f * g)(t) = \int_{-\infty}^{\infty} f(\tau)g(t-\tau)\,d\tau$$

Where:

$$f(t) = S_{Rx}^{BB}(t)$$

$$g(t) = S_{Tx}^{BB}(t)$$

2. Perform the matched filter in the azimuth dimension

In order to compress the target response in the azimuth direction, we need to observe the effect of the platform motion in the azimuth. Figure 2 demonstrates that as the platform moves, the distance to the target, R(T), changes depending on where the platform is in relation to the target. This distance, results in a change in Doppler for the target as described above.

In order to do SAR processing, it is important that only the platform is moving and that the targets are stationary otherwise this will change the parabolic approximation that we are relying on – as you will see when you insert moving targets into the simulation. For these simulations, it is a safe assumption.

The azimuth compression is therefore achieved by performing matched filtering in the azimuth direction using the following function:

$$ref_{az} = e^{-\frac{j4\pi R(T)}{\lambda}}$$

Where R(T) is defined as shown in Figure 2 as: $R(T) = \sqrt{x^2 + y^2}$

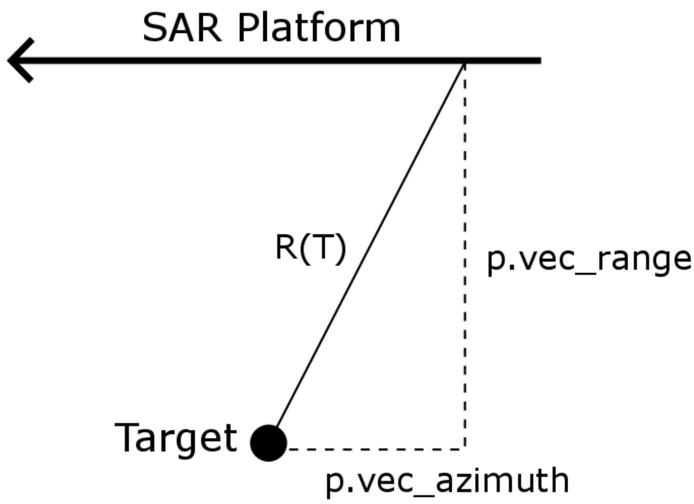


Figure 2: Overhead view of SAR platform geometry

It is important to note that the azimuth vector changes with slow time while the range vector is dependant on where the target is. As a result, an azimuth compression needs to occur for each range line. This is done by applying a matched filter along the azimuth direction.

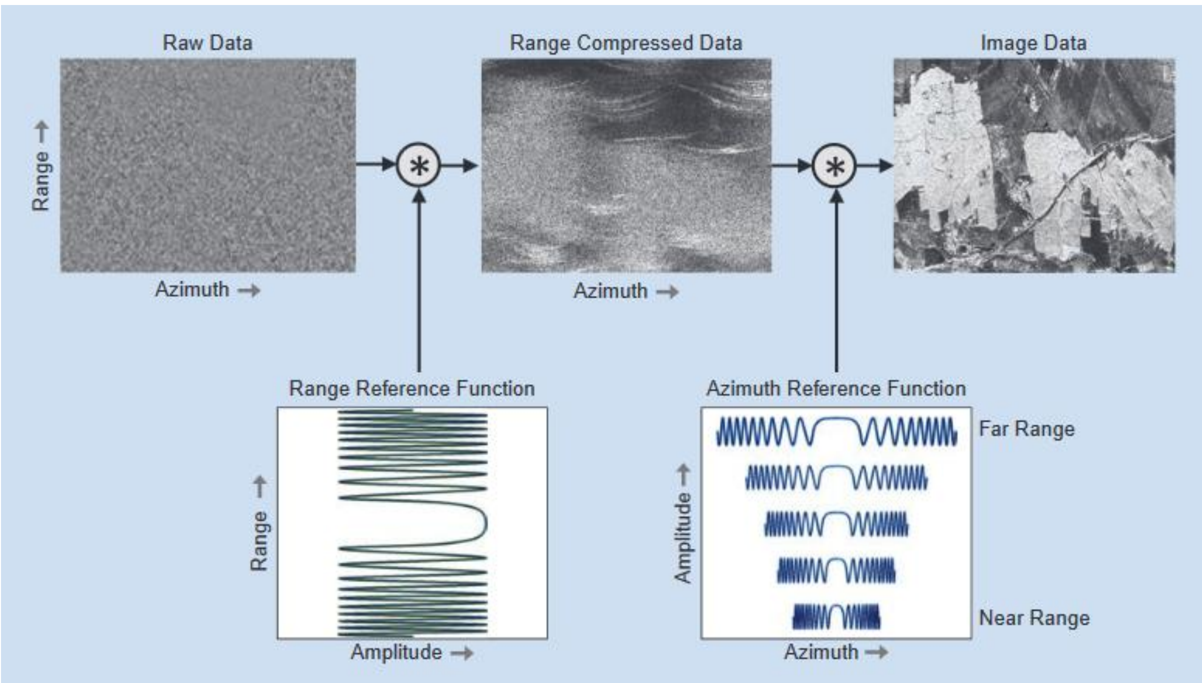
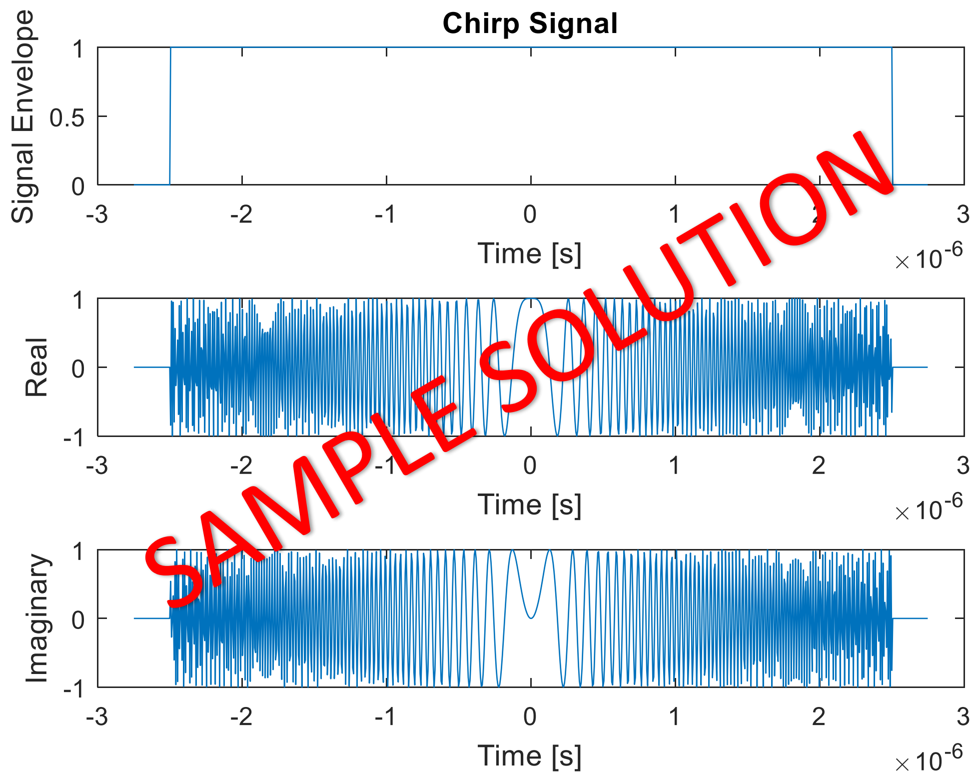
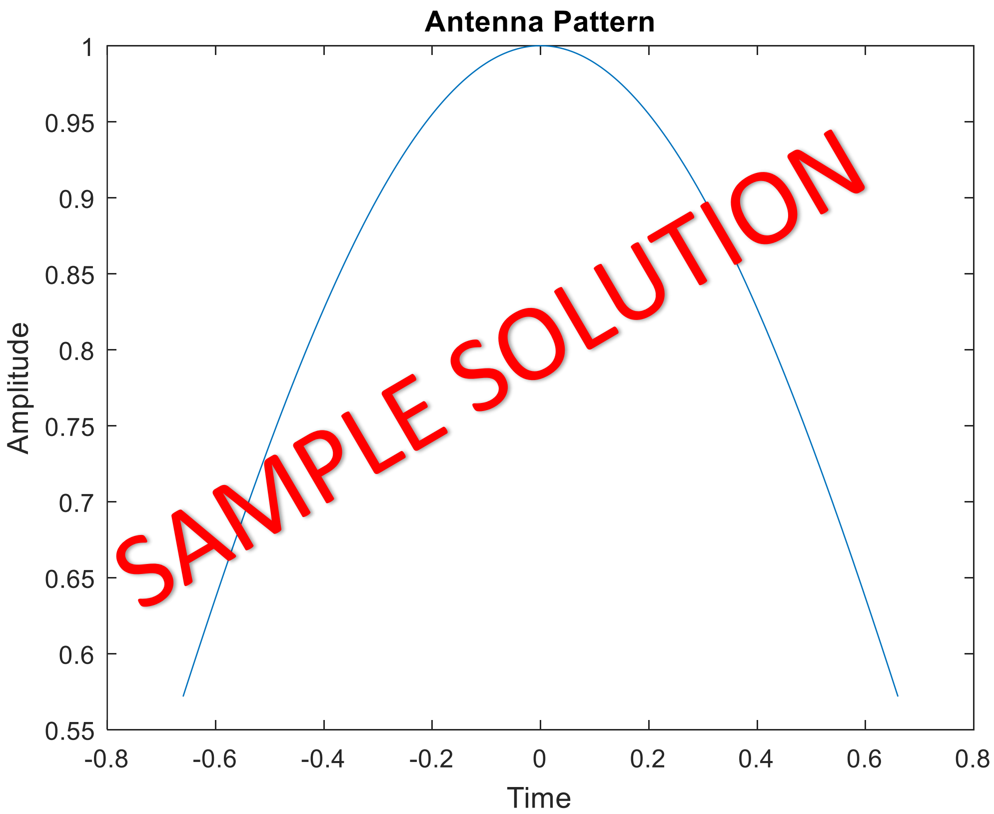


Figure 3: Complete range and azimuth compression for basic SAR processing (http://www2.geog.ucl.ac.uk/~mdisney/teaching/PPRS/PPRS_7/esa_sar_tutorial.pdf)

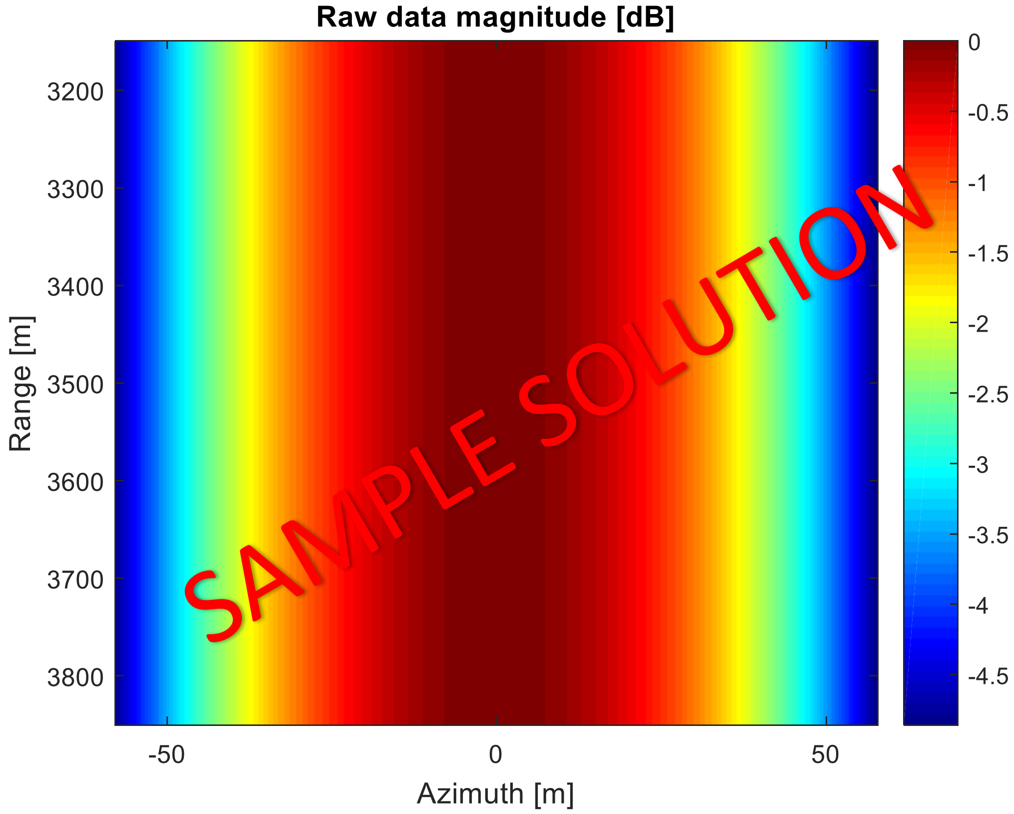
Appendix C: Sample Outputs

Baseband complex chirp and Antenna pattern

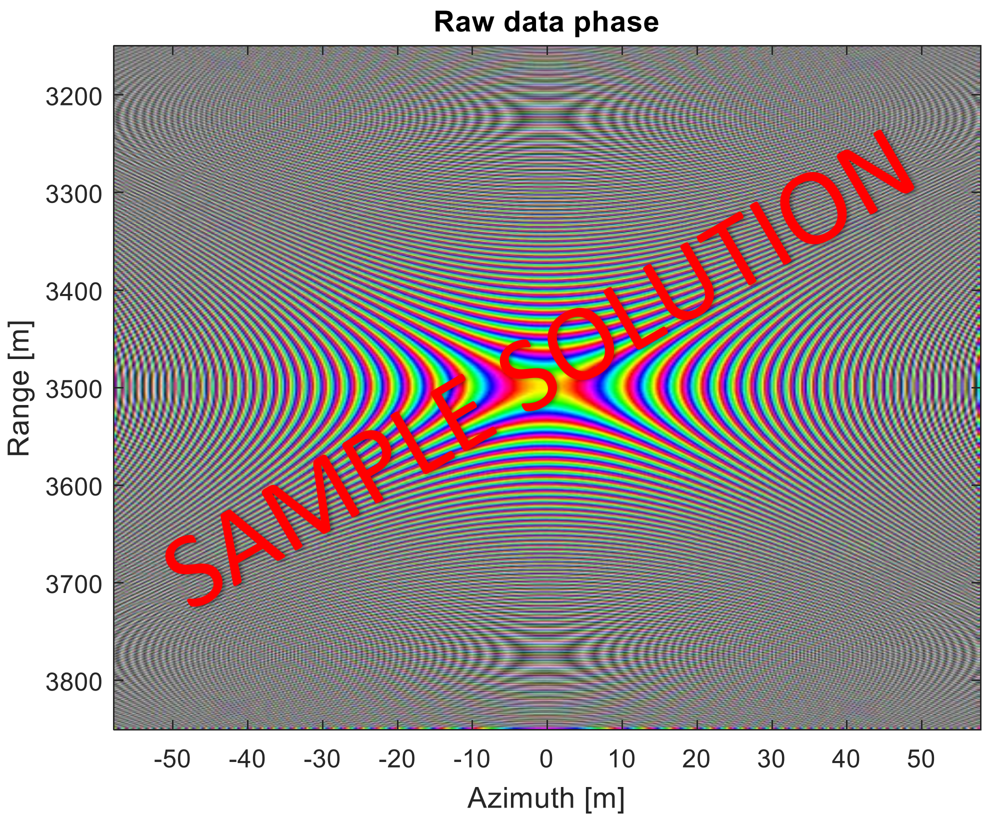




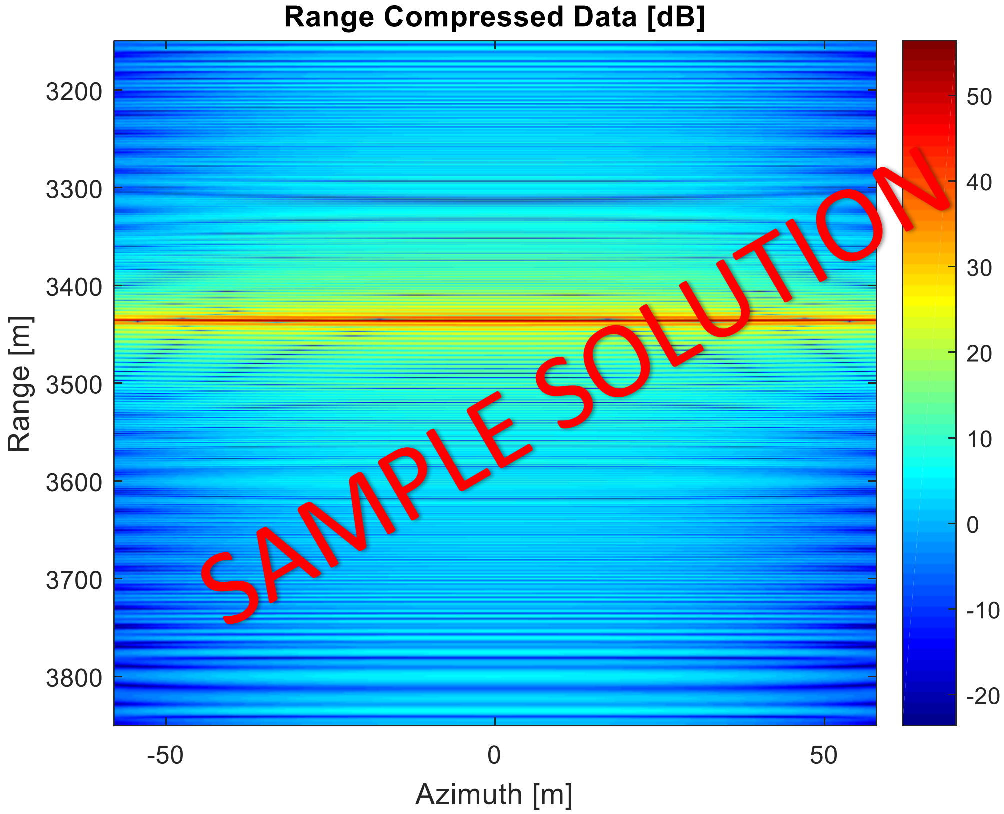
Amplitude plot of range-azimuth matrix (trimmed to desired range and azimuth)



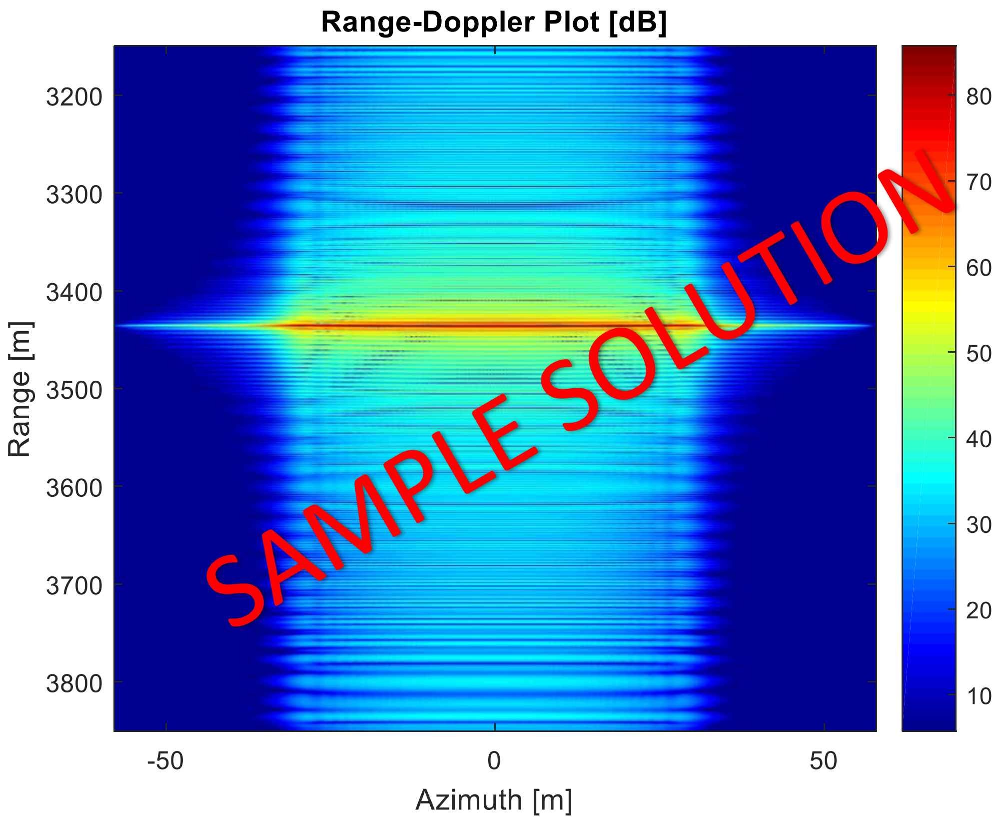
Phase plot of range-azimuth matrix (trimmed to desired range and azimuth)



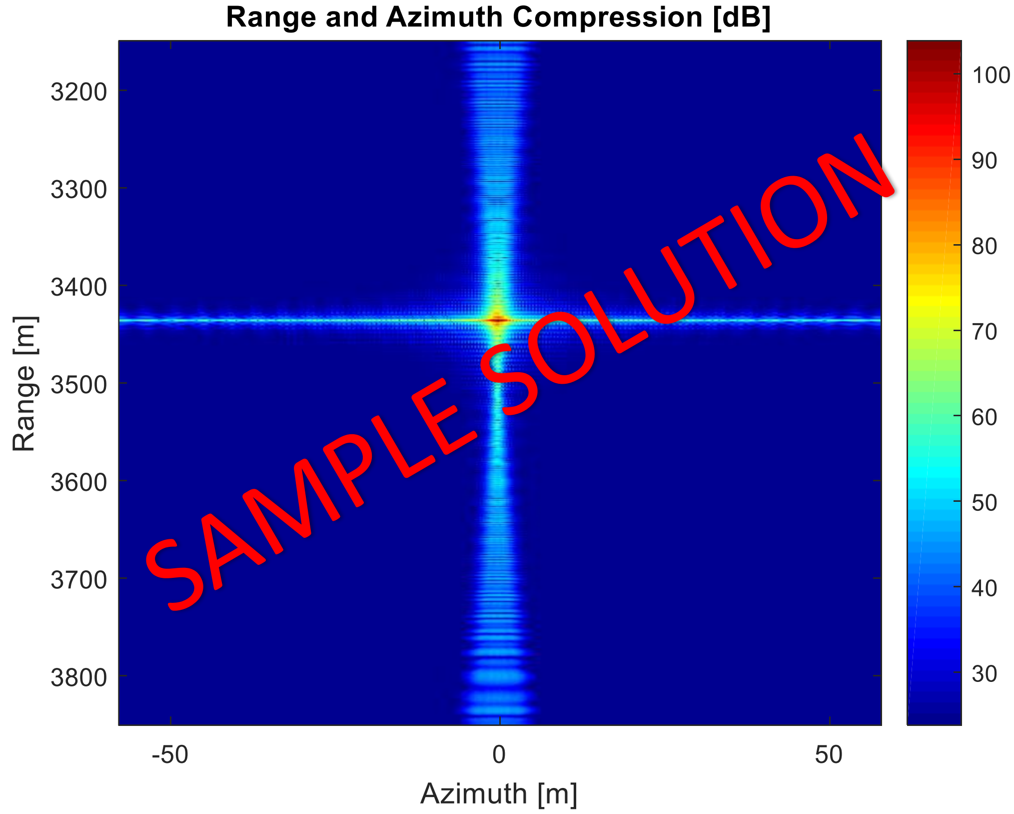
Range compressed range-azimuth plot



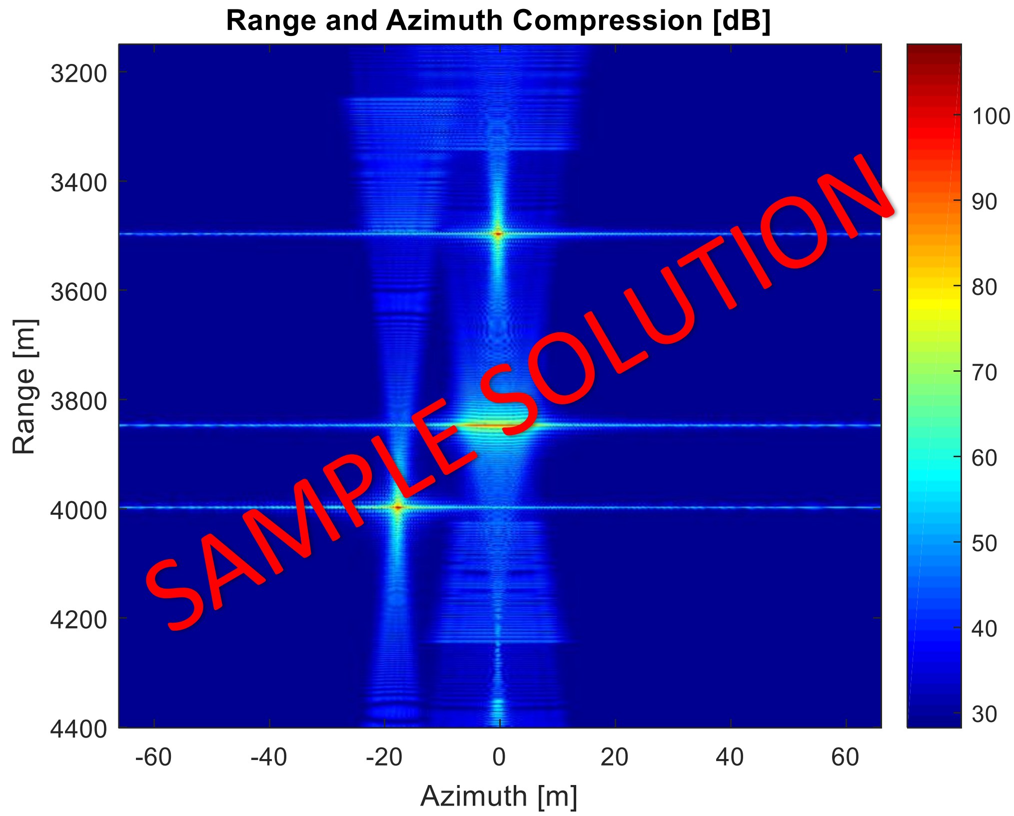
Range-Doppler plot (Doppler FFT of range compressed plot)



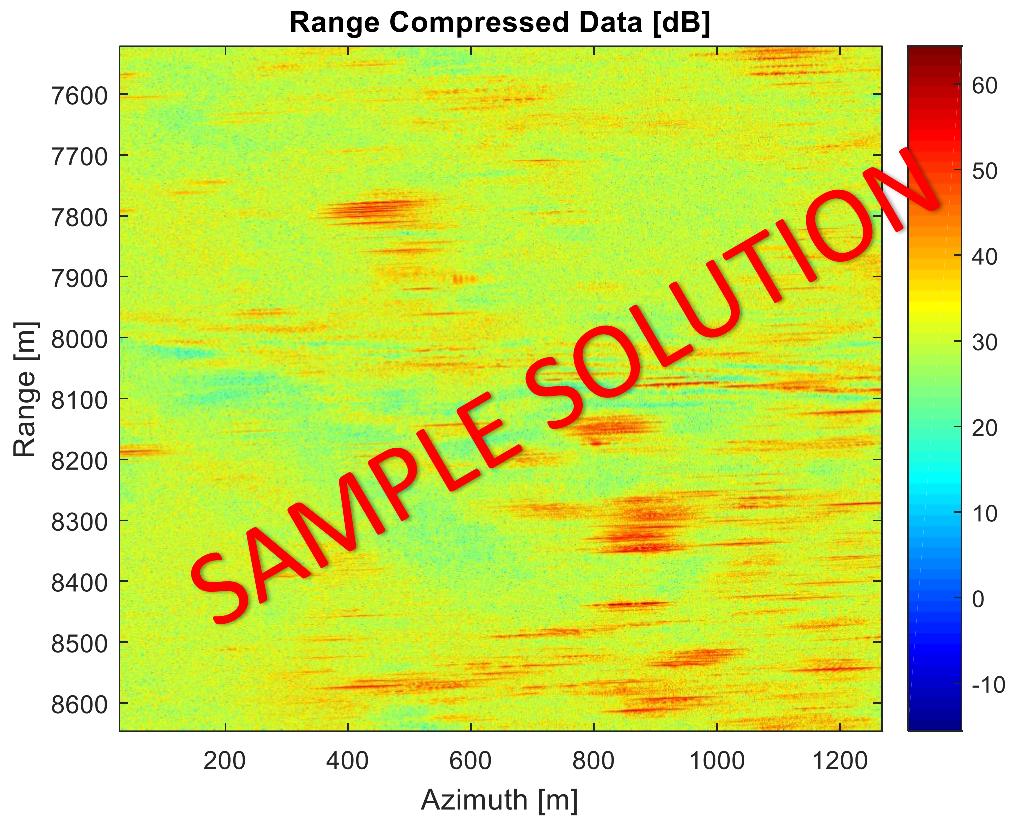
Output after range and azimuth compression

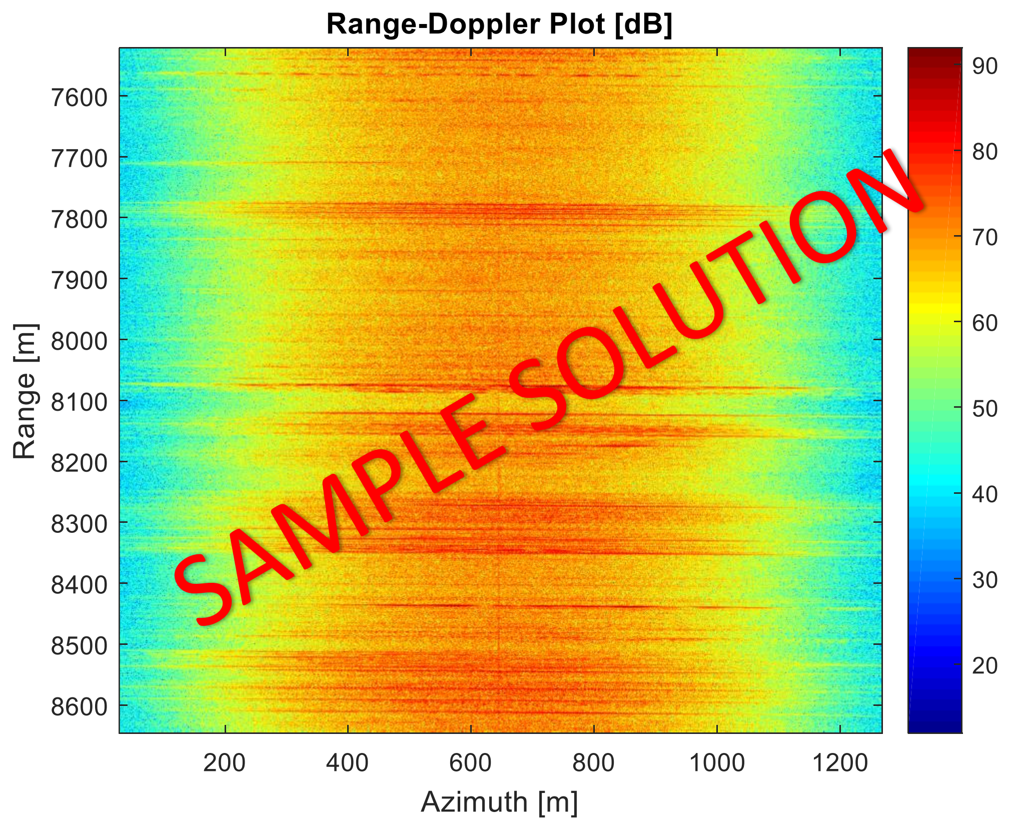


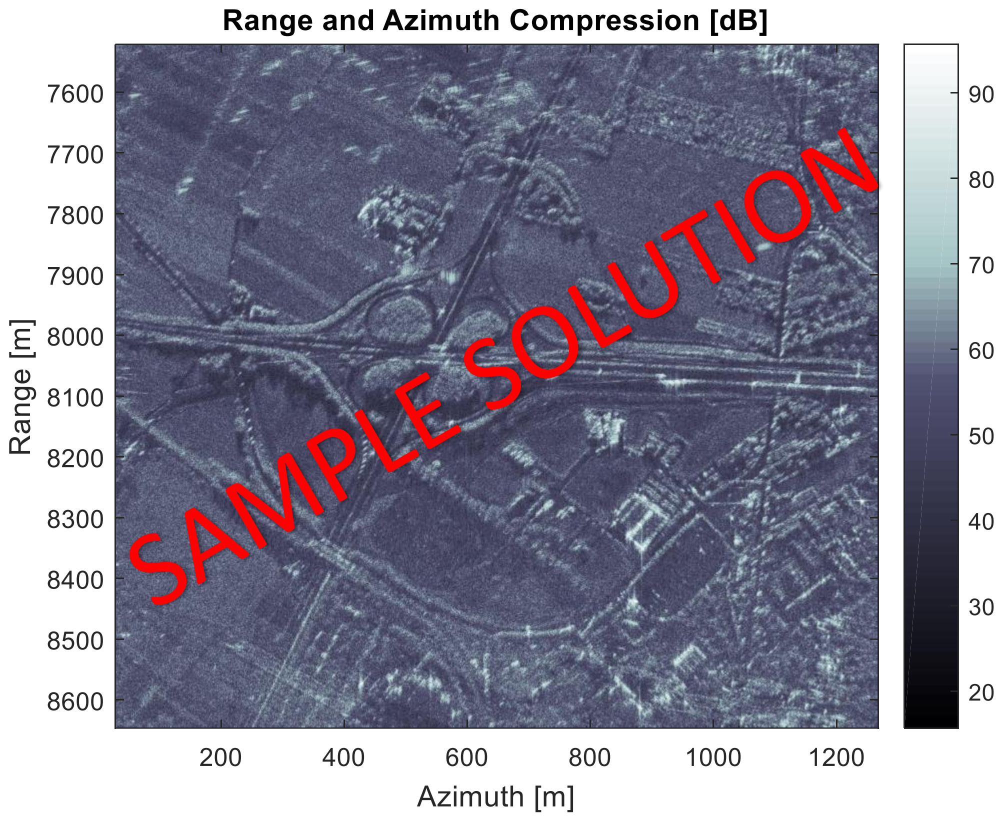
Multiple Targets (Moving)



Sample output from data2.mat file






Range and Azimuth Compression [dB]
Range [m]
7600
7700
7800
7900
8000
8100
8200
8300
8400
8500
8600
Azimuth [m]
200
400
600
800
1000
1200
90
80
70
60
50
40
30
20
SAMPLE SOLUTION