Digital Elevation Model Aided SAR-based GMTI Processing in Urban Environments

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Outline

- Introduction and Motivation
- Methodology
- Experiment and Results
- Conclusions

Introduction

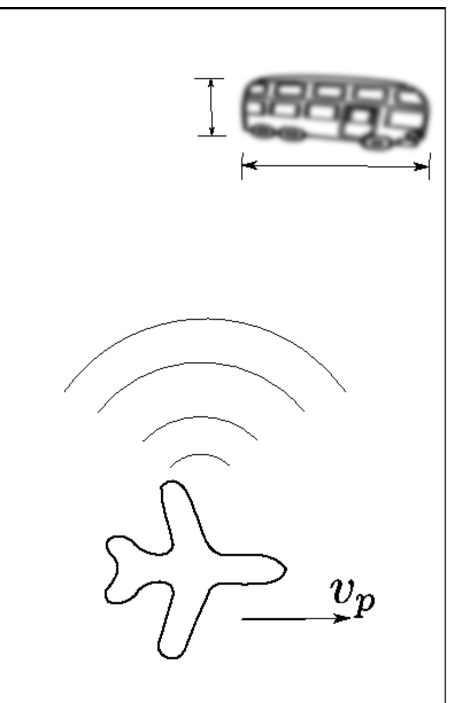
- SAR (Synthetic Aperture Radar)

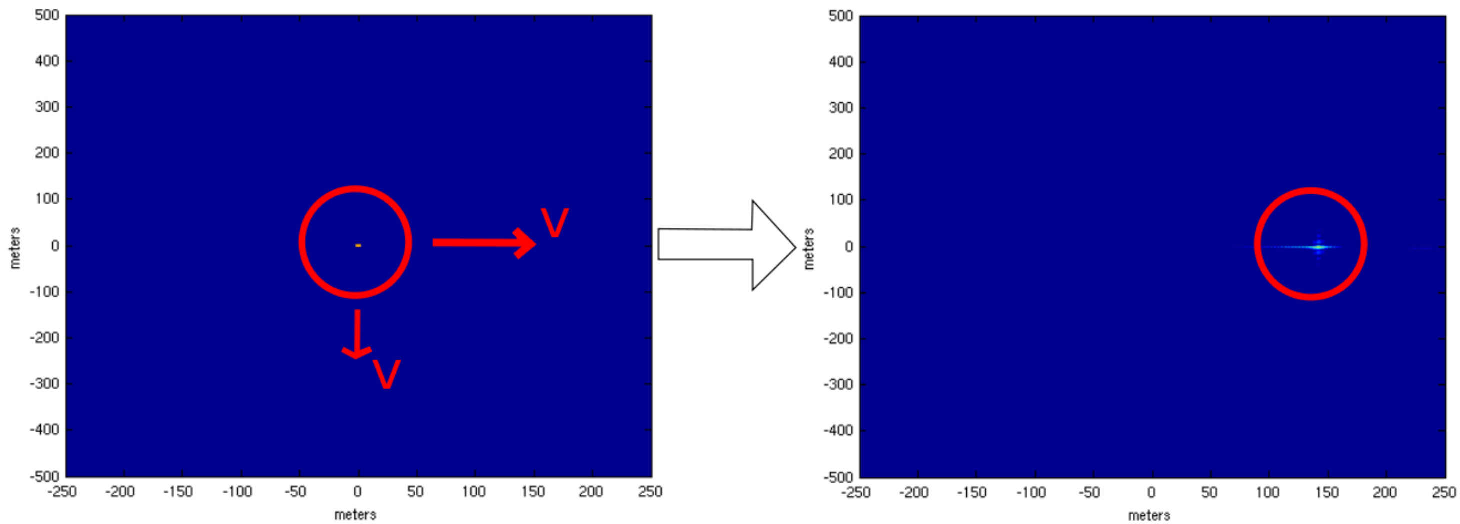
- SAR was developed as a remote surveillance device with all-weather, day-or-night capability which collects the received signals along the flight path of the platform. It synthesises a long virtual aperture to provide the images with high spatial resolution.

- Within the SAR community, GMTI (Ground Moving Target Indication) is an appealing application which aims at revealing the moving targets in SAR images.

Introduction

- It is well known that moving targets will induce displacement and blurring in the image



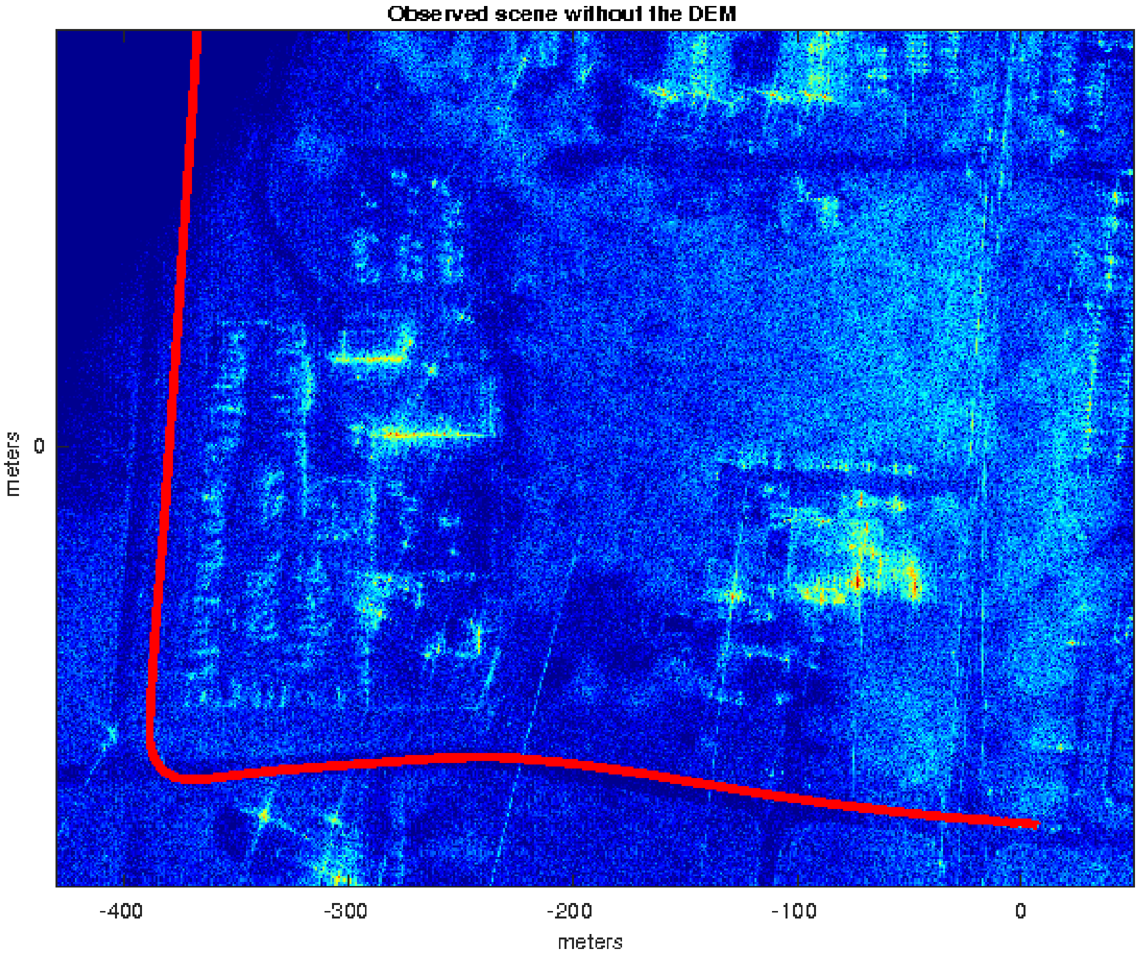


The formed image of one moving target in the simulation. (The target is marked with the red circle.)

Motivation

AFRL Gotcha GMTI Data Set

Motivation



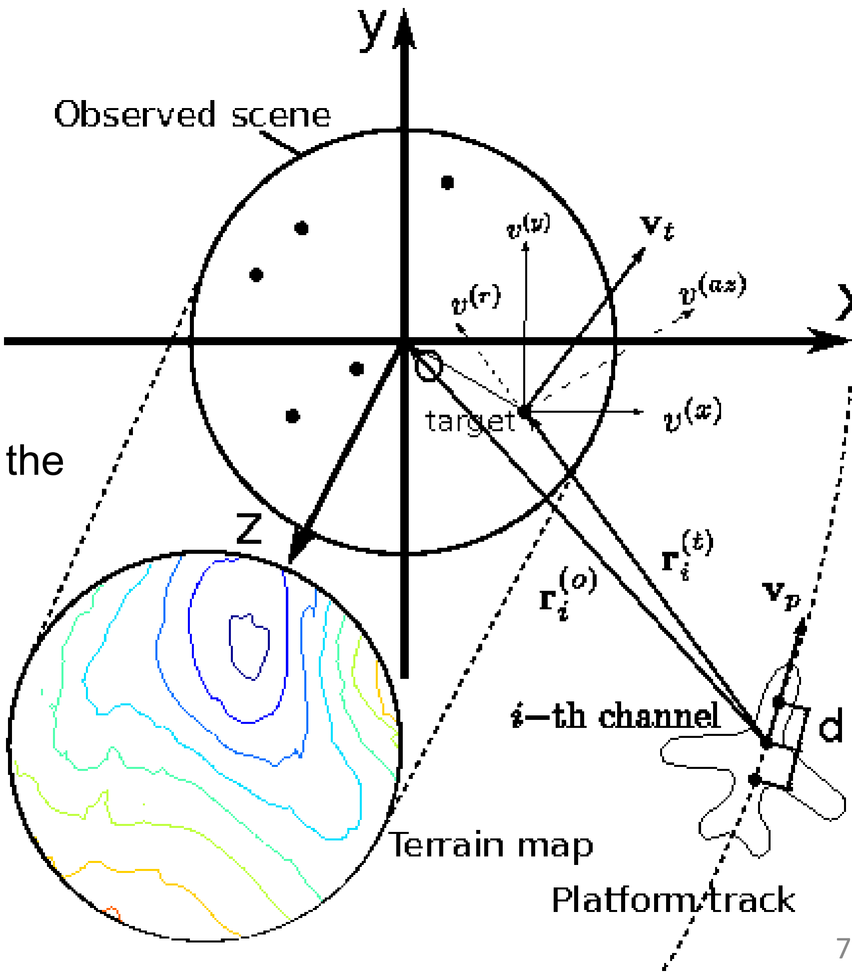
DEM?

The red path indicates the target trajectory.

Methodology

- Geometry

- Approximately far-field model.
- Channels are aligned along the platform track.
- The ‘stop-and-hop’ approximation is applied.
- Sufficiently small sub-apertures imply rapid processing and linear platform trajectory.
- Moving targets have constant velocities during the coherent processing interval (CPI).



Methodology

- Basics

Given only one target, we denote the compensated discrete received signal of the i-th channel as:

$$Y_i(f_k, \tau_n) = A_i \sigma \exp\left(-\frac{j4\pi f_k u_i(\tau_n)}{c}\right)$$

- f_k : range frequencies
- τ_n: azimuth time of the transmitted pulses
- A_i: beam pattern and energy loss
- σ: target reflectivity
- $\mathbf{r}(\tau_n)$: platform position at τ_n
- $u_i(\tau_n)$: differential range $r_i^{(t)}(\tau_n)$- $r_i^{(o)}(\tau_n)$
- c: speed of light

* The received data is recorded with entries k and n.

Methodology

- Conventional SAR Imaging

$$X(m,l)=\sum_{k=1}^{K}\sum_{n=1}^{N}Y_i(f_k,\tau_n)\exp\left(\frac{j4\pi f_k\Delta R_{m\ln}}{c}\right)$$

- $\Delta\mathbf{R}_{mln}$: $\|\mathbf{r}(\tau_n)-\mathbb{G}_{ml}\| - \|\mathbf{r}(\tau_n)\|$
- $\mathbb{G}_{ml}=(x_m,y_l,0)$

In our previous work, we developed a fast image SAR imaging technique to accelerate the imaging operator in this format.

Methodology

- Moving target imaging with DEM (Target Relocation)

$$X_t(m,l) = \sum_{k=1}^{K}\sum_{n=1}^{N} Y_t(f_k,\tau_n)\exp\left(\frac{j4\pi f_k \Delta R'_{mln}}{c}\right)$$

$$\Delta\mathbf{R}'_{mln} = \|\mathbf{r}(\tau_n) - \mathbb{G}'_{ml} - \mathbf{V}_t\tau_n\| - \mathbf{R}_0(\tau_n)$$

- Y_t : target phase history
- V_t: velocity vector
- $R_0(\tau_n) = \|r(\tau_n) - r_{ref}\|$
- $\mathbb{G}'_{ml} = (x_m, y_l, z(m,l))$

Methodology

- Moving target imaging with DEM (Target Relocation)

$$X_t(m,l) = \sum_{k=1}^{K} \sum_{n=1}^{N} Y_t(f_k, \tau_n) \exp\left(\frac{j4\pi f_k \Delta R'_{m\ln}}{c}\right)$$

$$\Delta\mathbf{R}'_{mln} \;=\; \left\|\mathbf{r}'(\tau_n) - \mathbb{G}'_{ml}\right\| \;-\; \mathbf{R}_0(\tau_n)$$

It stays consistent with the fast imaging approach.
Efficient SAR image formation can still be employed using the DEM and target velocities.

Methodology

- Moving target imaging with DEM (Target Relocation)

$$X_t(m,l)=\sum_{k=1}^{K}\sum_{n=1}^{N}Y_t(f_k,\tau_n)\exp\left(\frac{j4\pi f_k \Delta R'_{m\ln}}{c}\right)$$

$$\begin{aligned}\Delta\mathbf{R}'_{mln} &\cong \|\mathbf{r}(\tau_n)-\mathbb{G}'_{ml}\| + v_t^{(rad)}\tau_n - \mathbf{R}_0(\tau_n)\\ &= \|\mathbf{r}(\tau_n)-\mathbb{G}'_{ml}\| - \mathbf{R}'_0(\tau_n)\end{aligned}$$

In a number of scenarios, we only have the estimated radial velocities of the targets instead of the full states.

Methodology

- Target state estimation

The target velocity components follow the geometrical restrictions:

$$v_t^{(rad)} = v_t^{(x)} \left\langle u_x, n^{(rad)} \right\rangle + v_t^{(y)} \left\langle u_y, n^{(rad)} \right\rangle + v_t^{(z)} \left\langle u_z, n^{(rad)} \right\rangle$$

With the DEM, $v_t^{(z)}$ can be estimated by differentiating the elevations. Given the estimated radial velocity, $v_t^{(y)}$ is a function of $v_t^{(x)}$.

One further constraint can fully resolve the problem.

Experiment and Results

- DEM Extraction

We do not have access to the DEM in the AFRL GOTCHA GMTI data set. A rough DEM (approximated 30 by 30 meters resolutioin) is extracted from the United States Geological Survery (USGS) seamless dataset.

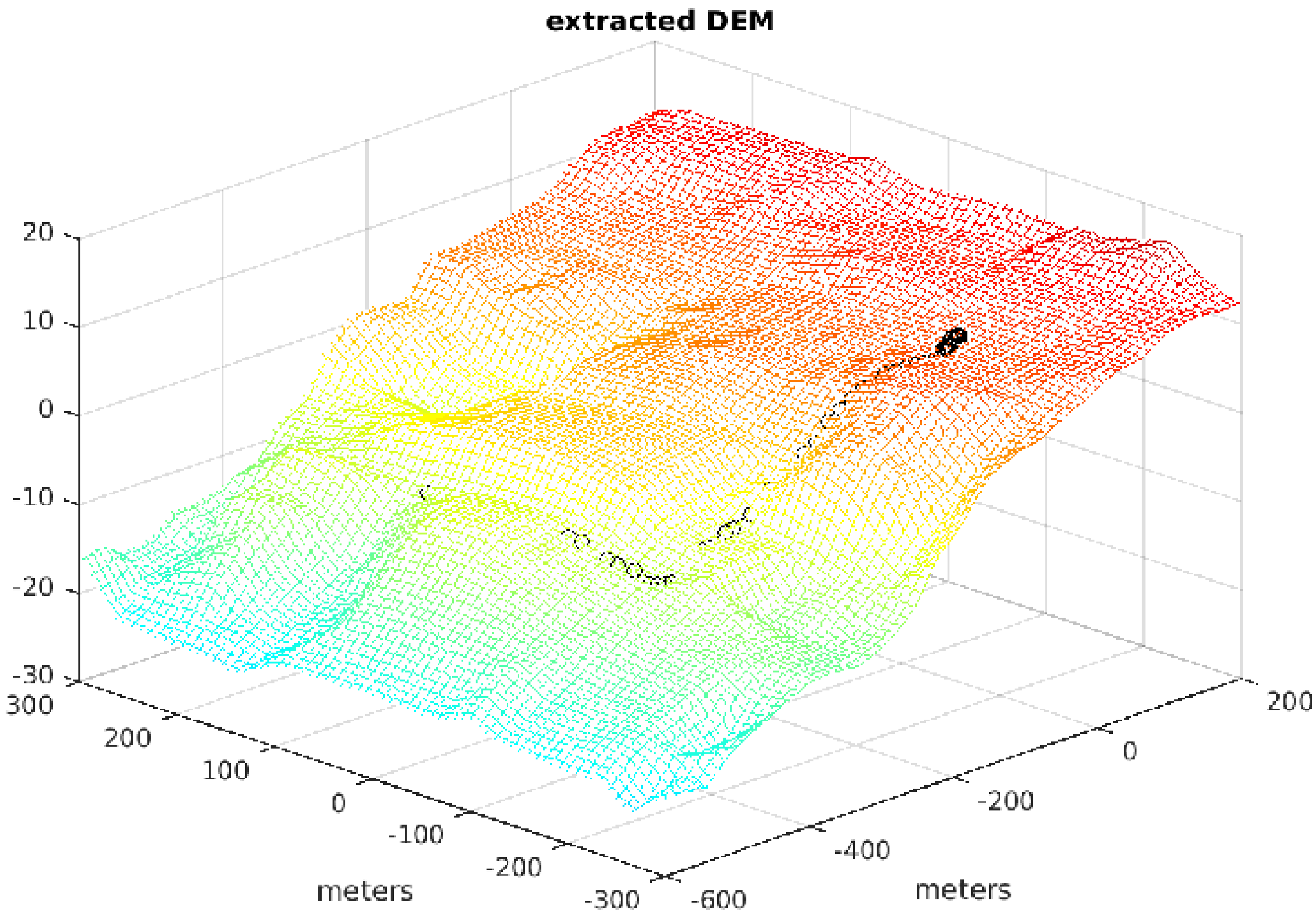
We calibrate the DEM via:

$$\min_{\mathbb{X}_{ref}, E_{ref}} \frac{1}{2} \|\mathbf{E}_t - \Gamma(\mathbb{G}_{coarse} - \mathbb{X}_{ref}, \mathbf{E}_{coarse} - E_{ref}, \mathbb{X}_t)\|_2^2$$

- Raw DEM: $(\mathbb{G}_{coarse}, \mathbf{E}_{coarse})$
- Reference point: $(\mathbb{X}_{ref}, E_{ref})$
- Target GPS: $(\mathbb{X}_t, \mathbf{E}_t)$
- Γ : Interpolation operator.

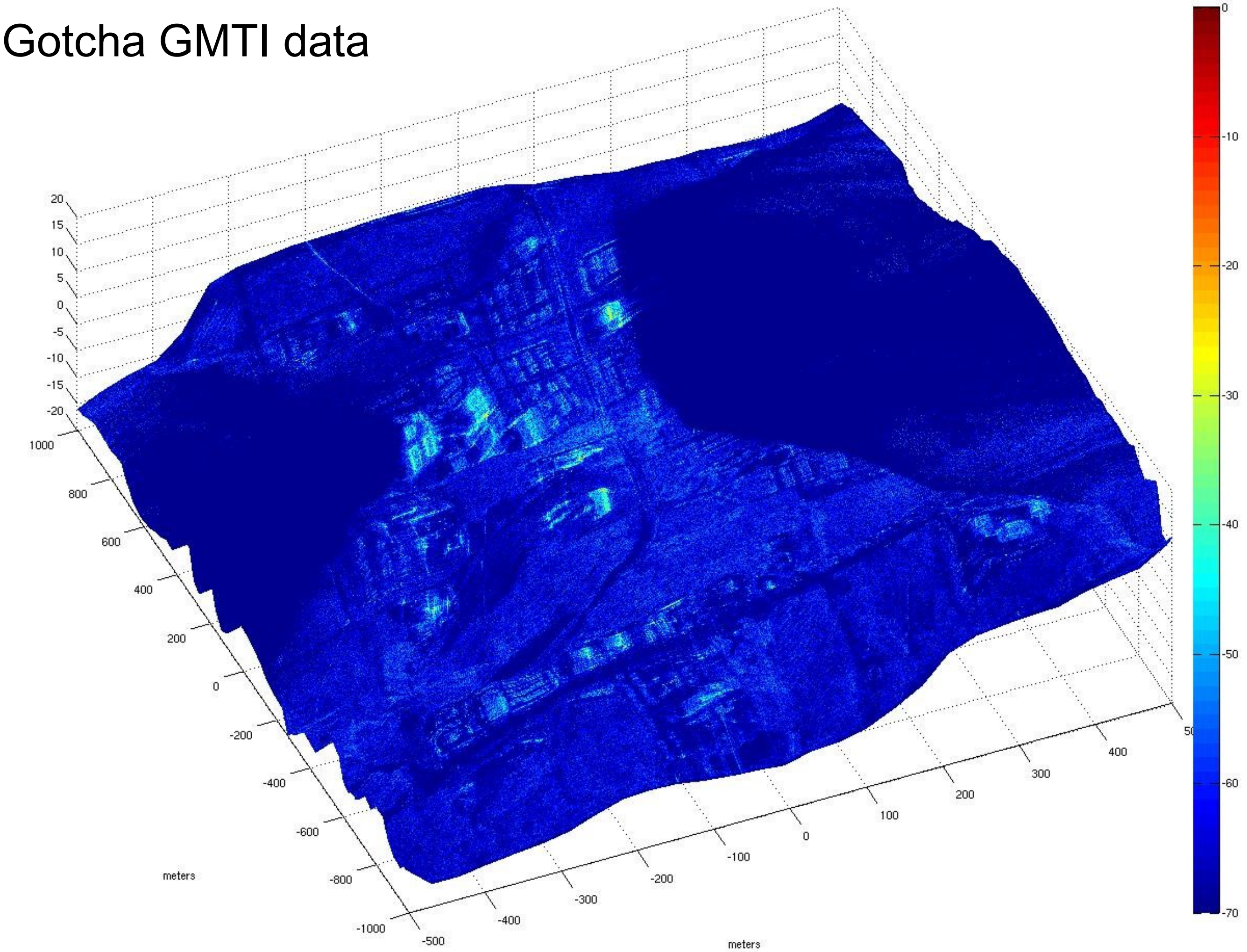
Experiment and Results

- DEM Extraction

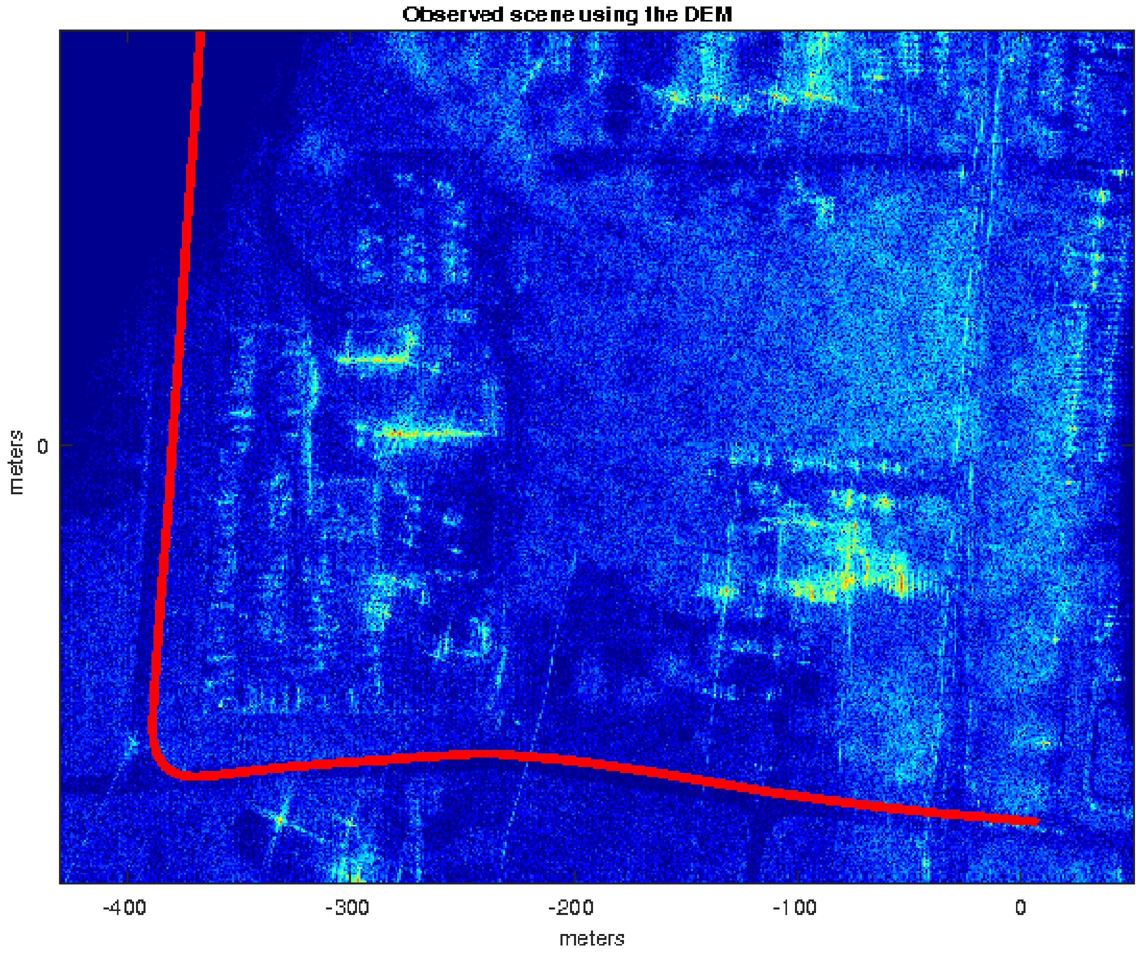


Experiment and Results

AFRL Gotcha GMTI data



Experiment and Results



DEM is applied.

The red path indicates the target trajectory.

Experiment and Results

Preprocessing:

C. Gierull, “Digital channel balancing of along-track interferometric SAR data,” in Technical Memorandum DRDC Ottawa
TM 2003-024. Defence R&D, Ottawa, Canada, March 2003.

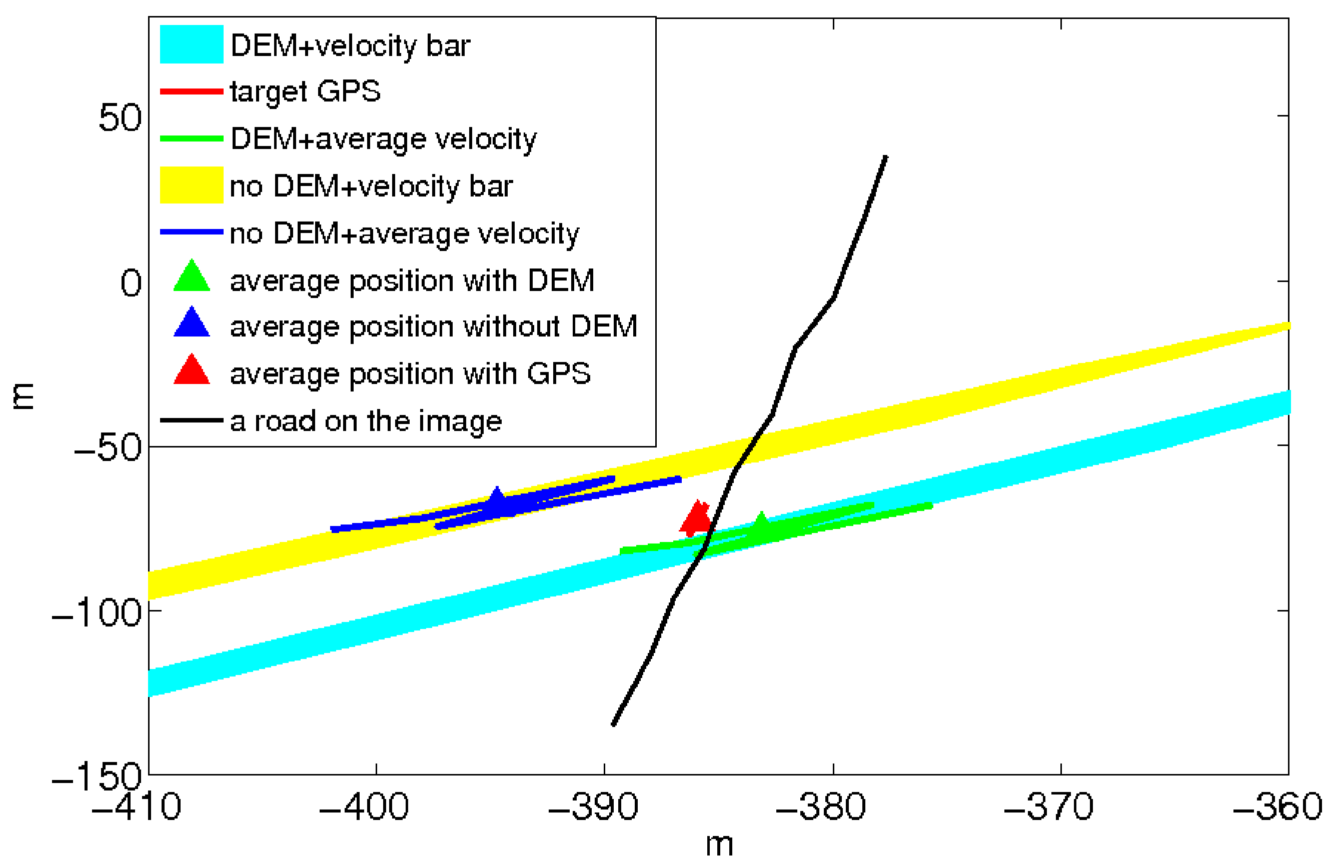
Target Detection and radial velocity estimation:

D. Wu, M. Yaghoobi, and M. Davies, “A new approach to moving targets and background separation in multi-channel
SAR,” in 2016 IEEE Radar Conference, 2016.

Experiment and Results

- Target Relocation

azimuth number 144001 to 146000



Experiment and Results

- Target state estimation

Given the estimated target velocities in the radial and z directions, a number of approaches can be applied in combination with the geometrical restrictions to estimate its velocities in the x an y directions.

To be simple, we assume that the target is on the road. Then we have (based on the road direction):

$$v_t^{(y)} = 14.1 \times v_t^{(x)}$$

Experiment and Results

- Target state estimation

COMPARISONS BETWEEN THE GROUND TRUTH AND ESTIMATIONS

sub-aperture number	1	2	3	4	5
estimated $v_t^{(x)}$ (m/s)	0.88	0.9	0.94	0.95	1.0
ground truth $v_t^{(x)}$ (m/s)	0.99	1.03	1.07	1.1	1.14
estimated $v_t^{(y)}$ (m/s)	12.4	12.72	13.2	13.4	14.1
ground truth $v_t^{(y)}$ (m/s)	12.9	13.1	13.3	13.5	13.7
estimated $v_t^{(z)}$ (m/s)	0.1	0.12	0.2	0.17	0.38
ground truth $v_t^{(z)}$ (m/s)	0.32	0.28	0.25	0.21	0.2

Conclusions

- The DEM can be integrated into our previously proposed SAR imaging and GMTI framework to
  1. enhance the relocations of the moving targets.
  2. improve the estimations on target states.

- We demonstrated the exploitation of the DEM through the AFRL GOTCHA GMTI data set.

Thanks for your attention!

Questions?