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GPU based Time Domain SAR Simulation and Focusing for Arbitrary Trajectories

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Introduction

The SAR raw data simulation is recognized as an important tool for:

- ✓ Designing system parameters.
- ✓ Testing focusing algorithms.
- ✓ Analyzing scattering effects.
- ✓ Planning flight missions.
- ✓ Costing much less.

SAR data focusing uses the information in SAR raw data to reconstruct a SAR imagery with 2D resolution.

Introduction

SAR raw data simulation and focusing are mainly implemented in time domain and frequency domain.

Frequency domain based methods efficiently apply to ideal trajectories under certain approximations.

Time domain based methods precisely handle arbitrary trajectories without approximations.

The drawback of the time domain based methods is their huge computation burdens.

Seek helps from High Performance Computing (HPC)

Distributed Computing: SAR raw data simulation.(Fan zhang, et al., Journal of System Simulation, 2008).
Features: large scale cluster, high scalability
Disadvantage: high costs, privileged availabilities.

FPGA: JAXA spaceborne focusing system (Y. Sugimoto, et al., IGARSS, 2018).
Features: Specialized for certain applications.
Disadvantage: Special applications, hardware knowledge requirements.

GPU : Single- and double-bounce SAR simulation (Timo Balz, et al., TGARS, 2009)
Features: Cost-efficient, extensive availabilities.
Disadvantage: Parallel algorithms requirements.

About this work

We here try to address the computational inefficiencies by using the inherent parallelism in the time domain based methods.

The parallelism is fully utilized by massive cores of Graphic Processing Units (GPUs).

Goals:

- Present an optimized time domain SAR simulation method with both efficiency and certain accuracy.
- Demonstrate the validations of Time Domain Back-projections (TDBP) focusing on highly deviated, circular trajectories.
- Assess the efficiency performance improvements by GPU based implementations.

SAR simulation in Time Domain

Time Domain Integral Method

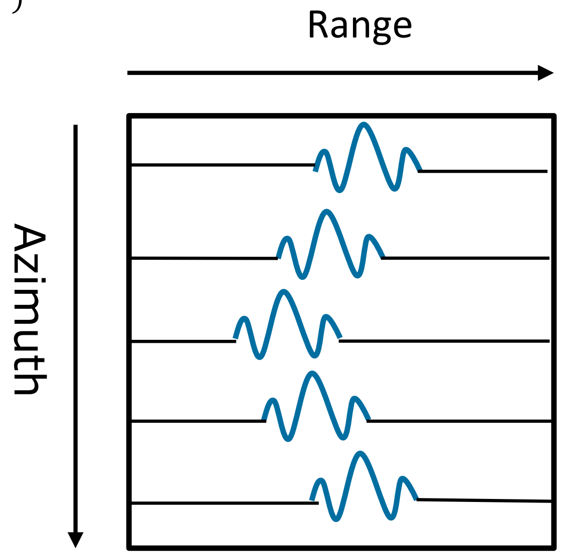
For the *i-th target,* the received signal in baseband:

$$S_i(\tau,t) = A \cdot W_a(\tau) \cdot p(t - \frac{2R_i(\tau)}{c})exp^{(-j\frac{4\pi R_i(\tau)}{\lambda})}$$

Accumulate all targets to get Raw SAR data:

$$S_{raw}(\tau,t) = \sum_i^n S_i(\tau,t)$$

- (t,τ): fast time and slow time;
- T: pulse duration;
- t_i: the fast time delay of the *ith* target.
- $p(\cdot)$: Chirp signal.
- $W_a(\tau)$: Antenna pattern.
- A: Reflectivity



Really time consuming for $O(n^4)$ complexity.

Optimized Time Domain Method

For the *i-th target:*

$$S_i(\tau,t) = A \cdot W_a(\tau) \cdot exp^{\left(-j\frac{4\pi}{\lambda}R_i(\tau)\right)}$$

Sum over all targets with rounding the time delay $\frac{2R_i(\tau)}{c}$ into the nearest fast time sampling:

$$S_a(\tau,t) = \sum_i^n S_i(\tau,t) \cdot \delta(t - t_s) \qquad t_s = round\left(\frac{2R_i(\tau)}{c}\right)$$

Convolve $S_a(\tau,t)$ with the chirp signal $p(t)$ within pulse duration *T*

$$S_{raw}(\tau,t) = \int S_a(\tau,z) \cdot p(t-z) \cdot dz$$

In O(n^3) complexity.

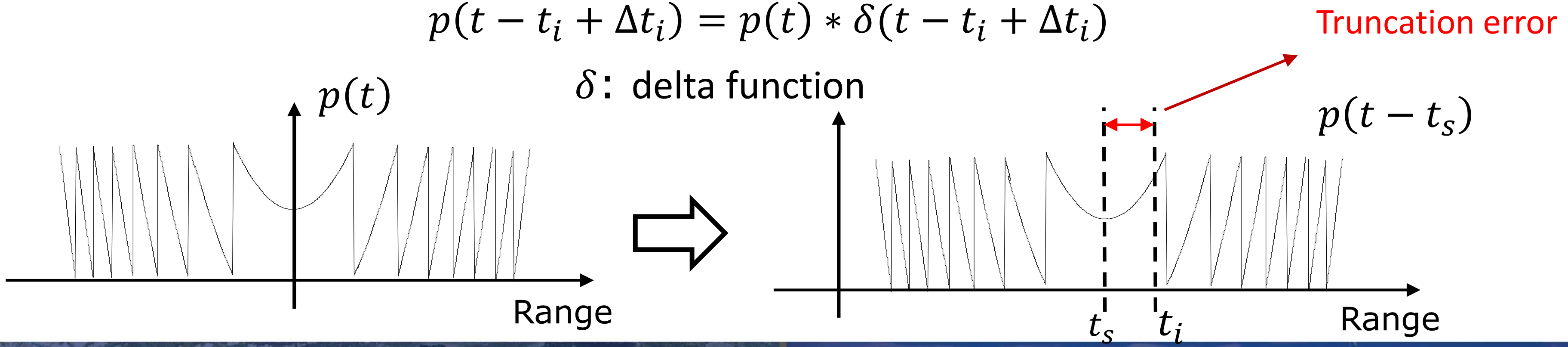
Drawback:

For the *i-th target:*

Estimated time delay part $t_i = \frac{2R_i(\tau)}{c}$ is rounded to the nearest fast time sampling point $t_s = round\left(\frac{2R_i(\tau)}{c}\right)$, leading to a truncation error $\Delta t_i = t_i - t_s$. After convolution, this method produces less accurate SAR raw data:

$$p(t - t_i + \Delta t_i) = p(t) * \delta(t - t_i + \Delta t_i)$$

δ: delta function



Solution:

Oversampling on fast time sampling to mitigate truncation errors.

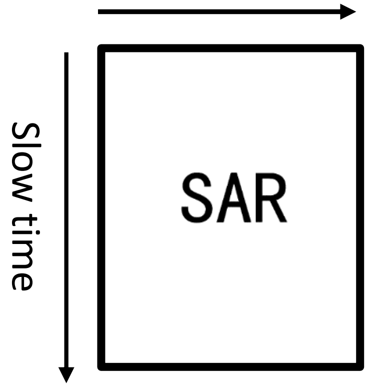
Trade-off:

- ☐ Theoretically, errors can be minimized using an infinite oversampling factor.
- ☐ The efficiency and memory problem arise when using large oversampling factors.
- ☐ Three factors are tested: 8, 16, and 32.

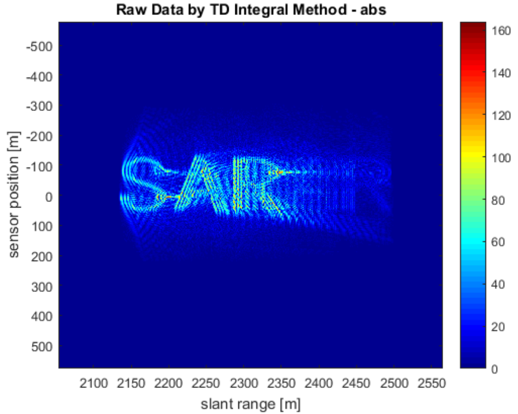
- ☐ *Ideal rectilinear trajectory.*
- ☐ *Highly deviated trajectory.*
- ☐ *Circular trajectory.*

- Ideal rectilinear trajectory

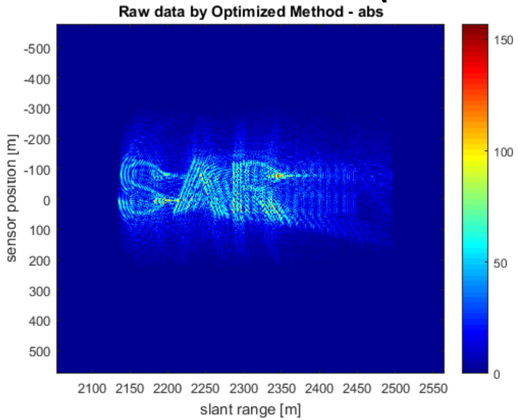
  - Carrier frequency: 1 GHz
  - Slow time samples: 1270
  - Fast time samples: 1024
  - Fast time sampling frequency: 3.33e-9 [s]
  - Pulse Bandwidth: 150 [MHz]
  - Number of targets: 36966



TD integral SAR Simulation

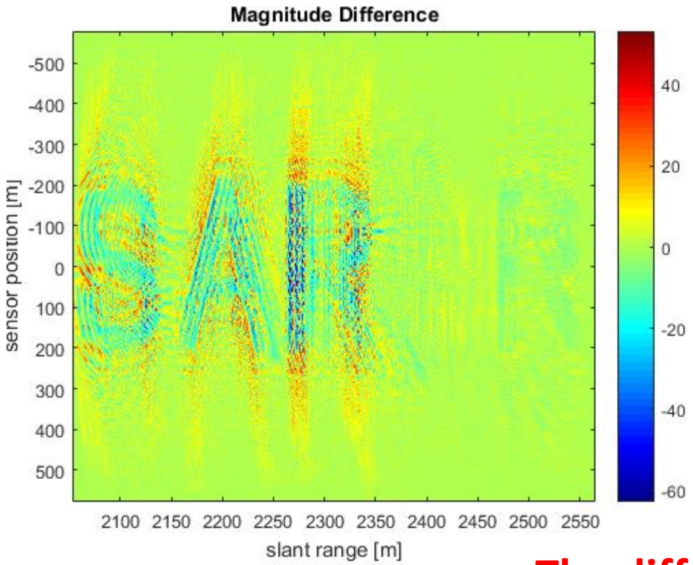


TD optimized SAR Simulation (without up-sampling)

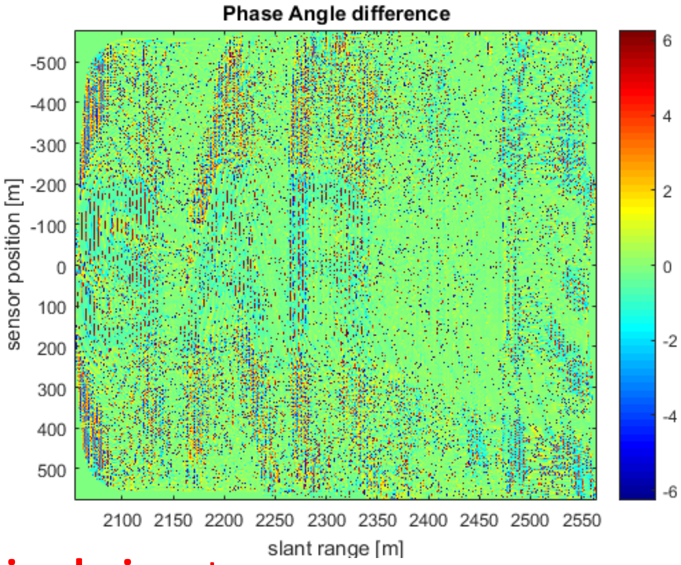


Ideal rectilinear trajectory

Magnitude Difference Map



Phase Difference Map



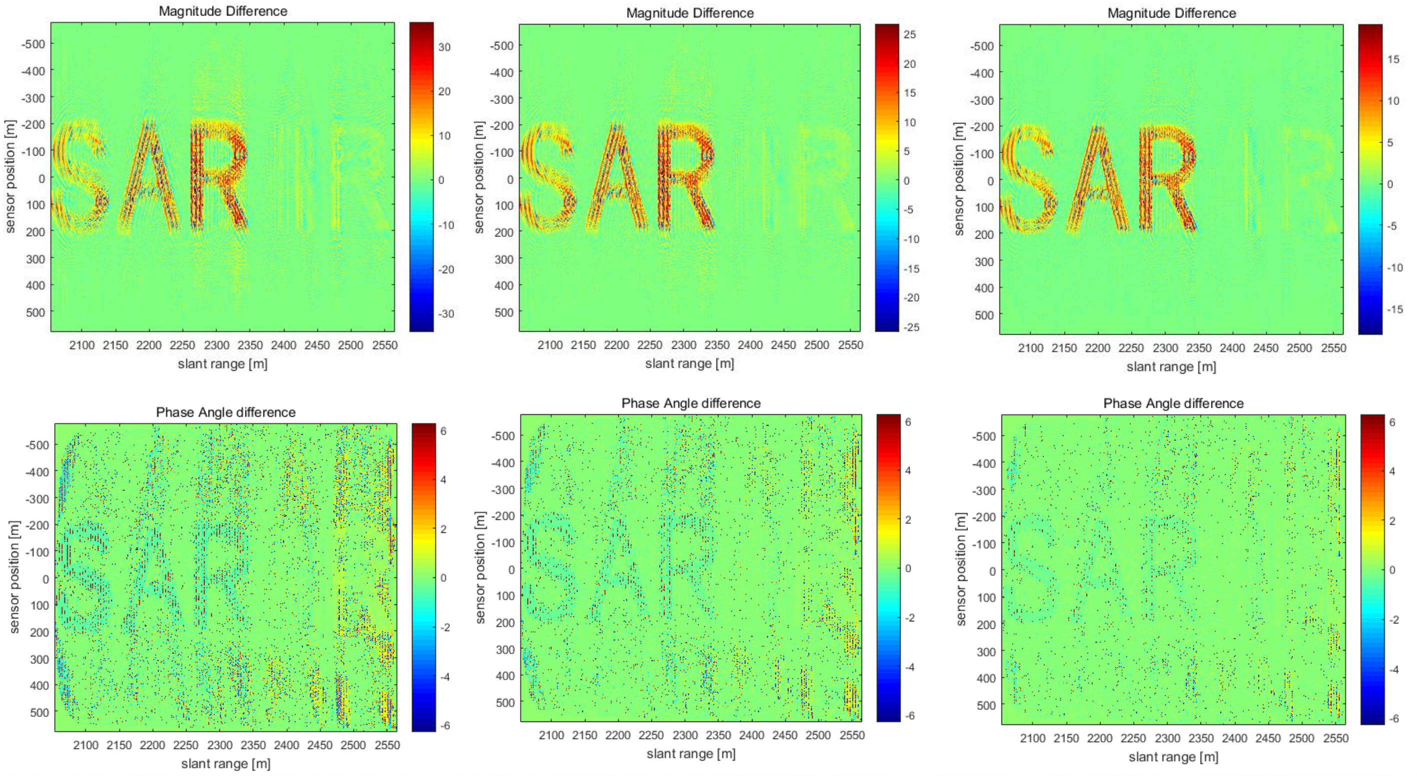
The difference is obvious!

Ideal rectilinear trajectory

OVS factor 8 | **OVS factor 16** | **OVS factor 32**

Magnitude difference

Phase difference



Ideal rectilinear trajectory

- Evaluate the precision by the Mean Square Error (MSE).

$$MSE = \frac{\sqrt{\Sigma(x_{ob} - x_{ref})^2}}{n}$$

Table 1. Precision Evaluation

	Without OVS	with OVS factor 8	With OVS factor 16	With OVS factor 32
Maximum mag. error	62.80	35.44	26.72	19.18
Mag. MSE error	4.28	2.27	1.54	0.99
Phase MSE error (rad)	0.65	0.33	0.19	0.11

Ideal rectilinear trajectory

- **Time cost comparison between the original method and the optimized methods (Op).**

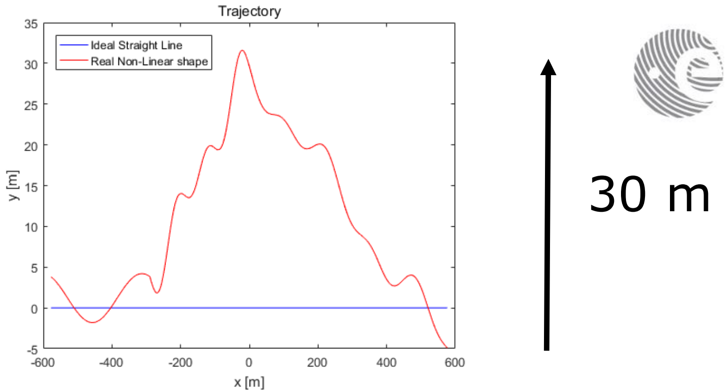
Table 2. Runtime comparisons

	Original Method	Op without OVS	Op with OVS factor 8	Op with OVS factor 16	Op with OVS factor 32
CPU	919.01 [s]	2.77 [s]	3.81 [s]	4.84 [s]	5.75 [s]
GPU		17.76 [ms]	17.82 [ms]	26.92 [ms]	44.99 [ms]

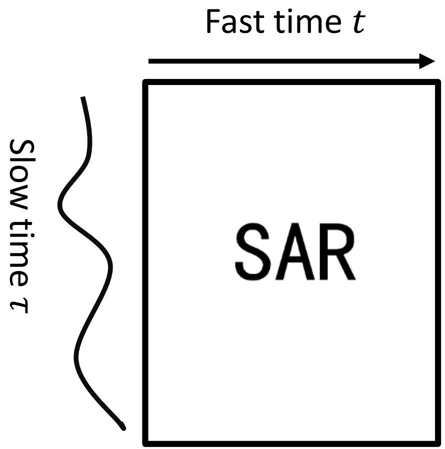
Notes: FFT based convolution is used here.

Highly Deviated Trajectory

- Carrier frequency: 1e9 Hz
- Slow time samples: 1270
- Fast time samples: 1024
- Fast time sampling frequency: 3.33e-9 [s]
- Bandwidth: 150 [Mhz]
- Number of targets: 36966



The trajectory profile in X-Y plane



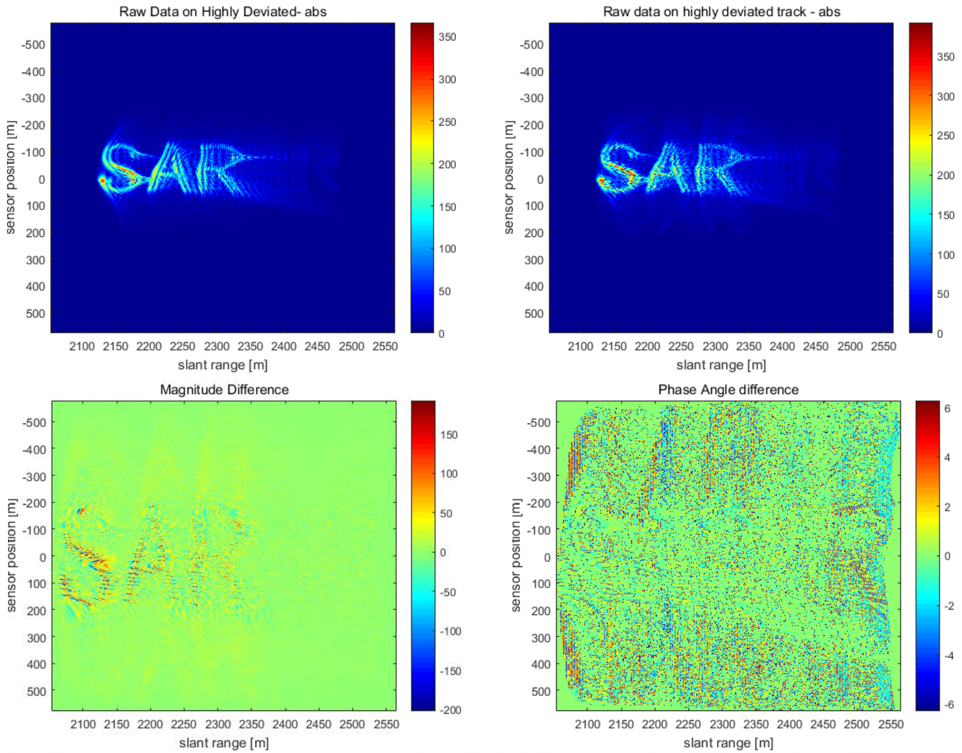
Template File

Highly Deviated Trajectory

TD integral SAR Simulation

TD optimized SAR Simulation (without up-sampling)

Magnitude difference



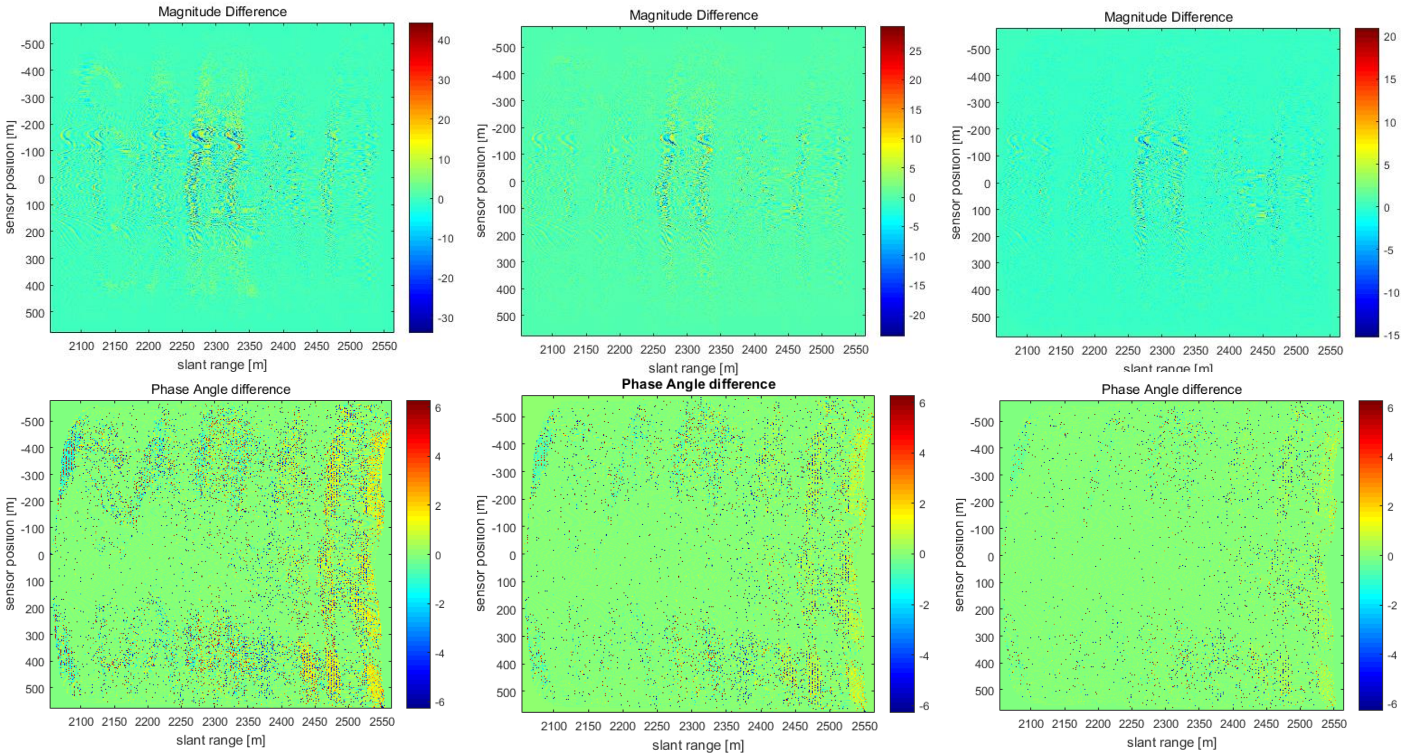
Phase difference

Highly Deviated Trajectory

OVS factor 8 | **OVS factor 16** | **OVS factor 32**

Magnitude difference

Phase difference



Highly Deviated Trajectory

Table 3. Precision Evaluation

	Without OVS	with OVS factor 8	With OVS factor 16	With OVS factor 32
Maximum mag. error	92.45	44.41	29.17	21.01
Mag. MSE error	7.41	2.08	1.08	0.62
Phase MSE error (rad)	0.74	0.33	0.18	0.10

Highly Deviated Trajectory

- Time cost comparison between the original method and optimized method of different oversampling factors.

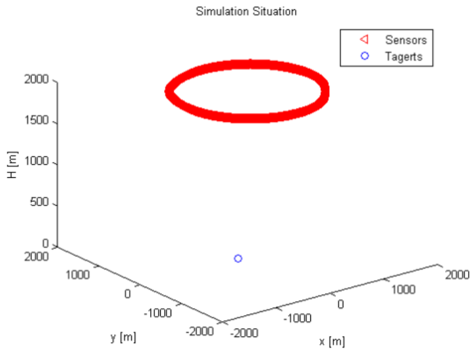
Table 4. Runtime comparisons

	Original Method	Op without OVS	Op with OVS factor 8	Op with OVS factor 16	Op with OVS factor 32
CPU	911.66 [s]	2.77 [s]	3.87 [s]	4.54 [s]	5.91 [s]
GPU		17.87 [ms]	18.28 [ms]	27.50 [ms]	45.43 [ms]

Notes: FFT based convolution is used here.

Circular Trajectory

- Wavelength: 0.24 [m]
- Slow time Angular samples: 7201
- Fast time samples: 1807
- Bandwidth: 100 [MHz]
- Platform Height: 3500 [m]
- Number of targets: 9684

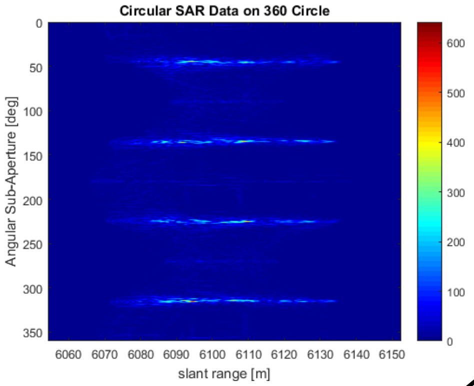


360° Circle

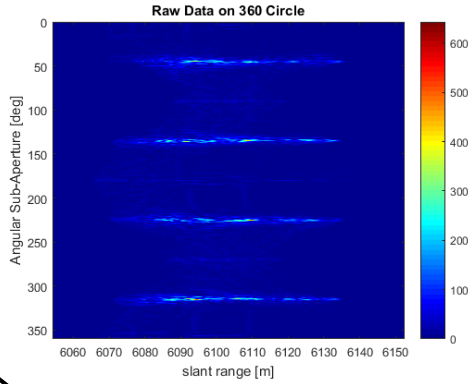
Imaging Template File

Circular Trajectory

TD integral SAR Simulation



TD optimized SAR Simulation (without up-sampling)



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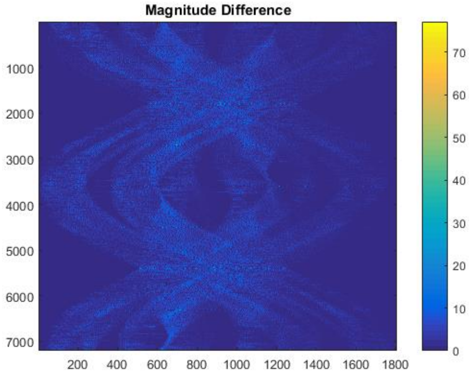
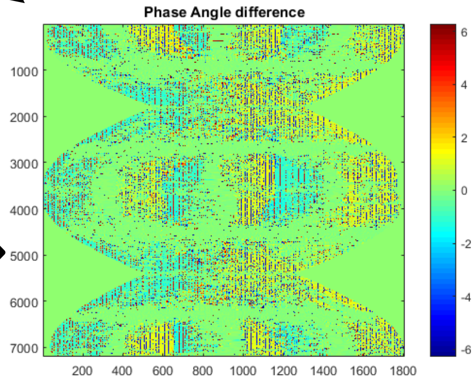


Magnitude Difference

Phase Difference

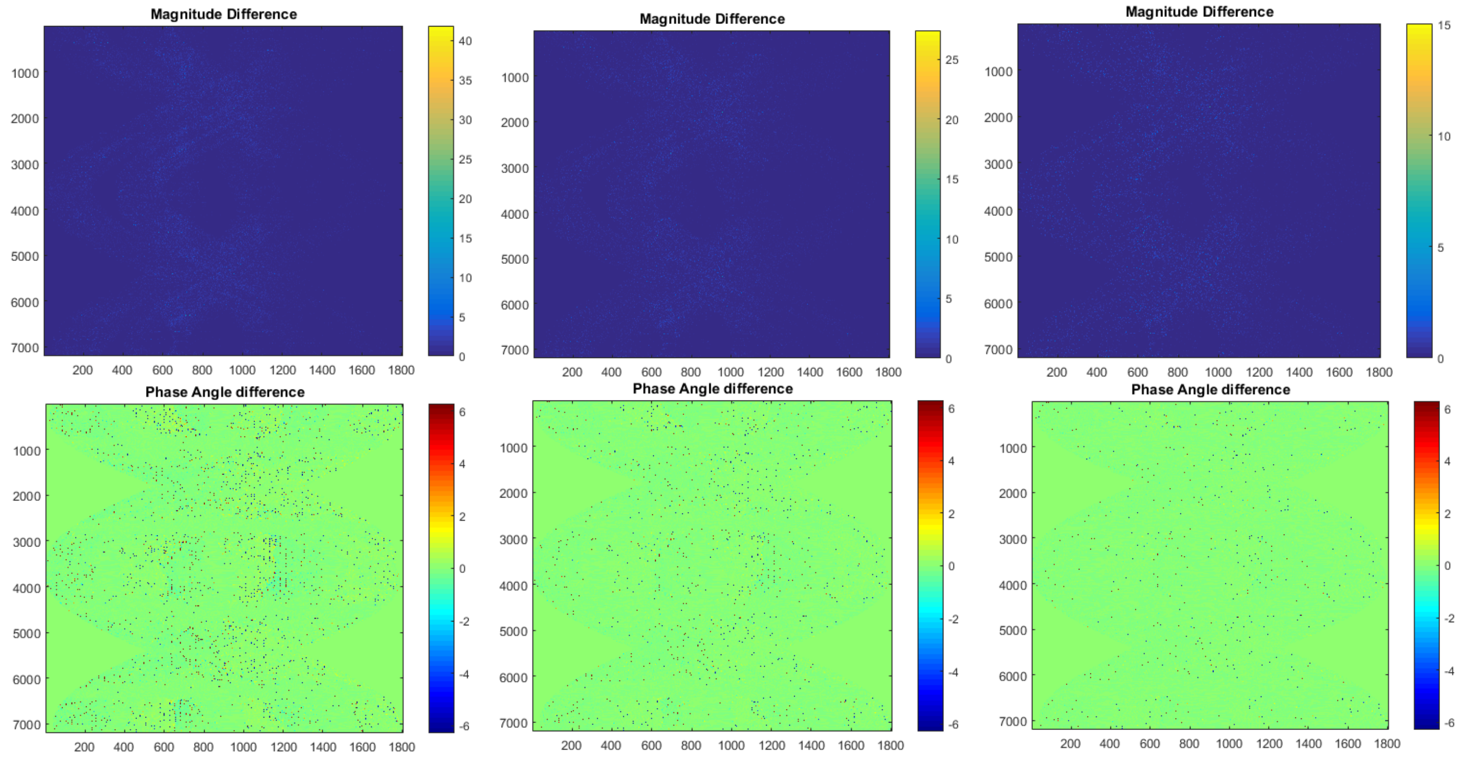


Circular Trajectory

OVS factor 8 | OVS factor 16 | OVS factor 32

Magnitude difference

Phase difference



Circular Trajectory

Table 3. Precision Evaluation

	Without OVS	with OVS factor 8	With OVS factor 16	With OVS factor 32
Maximum mag. error	77.16	41.85	27.41	15.03
Mag. MSE error	1.86	0.27	0.14	0.07
Phase MSE error (rad)	0.52	0.07	0.04	0.02

Circular trajectory

- **Time cost comparison on different implementations with optimized method of different oversampling factors.**

Table 4. Runtime comparisons

	Original Method	Op Without OVS	Op with OVS factor 8	Op with OVS factor 16	Op with OVS factor 32
CPU	3142.22 [s]	4.58 [s]	8.43 [s]	13.52 [s]	43.38 [s]
GPU		45.75 [ms]	114.96 [ms]	219.94 [ms]	442.11 [ms]

Time Domain Back-projection Focusing

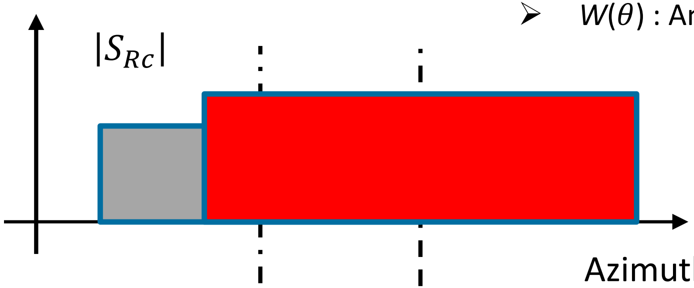
Time Domain Back-projection

TDBP is a powerful focusing algorithm for arbitrary trajectories.

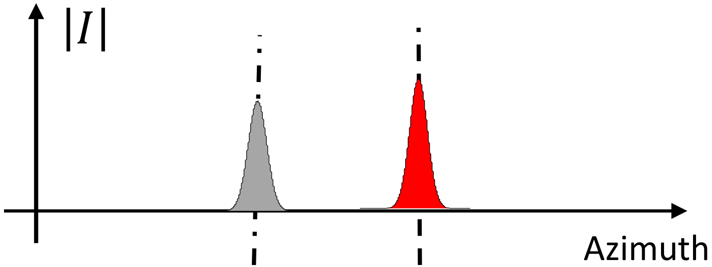
TDBP can be derived as the concept of matched filtering:

$$I(x,y) = \int S_{Rc}\left(t = \frac{2R(\tau;x,y)}{c}, \tau\right) e^{+j\frac{4\pi}{\lambda}R(\tau;x,y)} W(\theta) d\tau$$

- S_{Rc}: Range Compressed SAR Data.
- *x:* azimuth coordinate.
- *y:* ground range coordinate.
- *I*(*x, y*)*:* 2D focused image.
- $W(\theta)$: Antenna pattern.



TDBP



- *Ideal rectilinear trajectory*.
- *Highly deviated trajectory.*
- *Circular trajectory.*

Ideal rectilinear trajectory

Ideal Rectilinear Trajectory

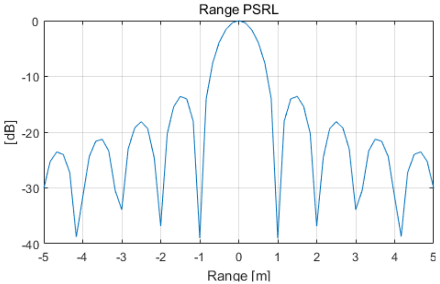
- Single Simulated target

Quantitative measurements:

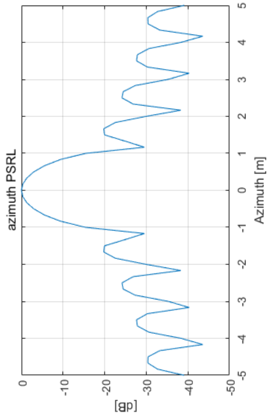
- Spatial Resolution (Res.).
- Peak Side-Lobe Ratio (PSRL)
- Integrated Side-Lobe Ratio (ISRL)

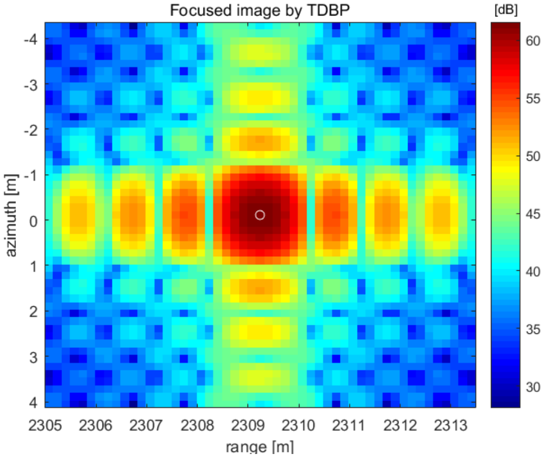
Range Res. :	0.9 m
Azimuth Res.:	1 m
Azimuth PSRL:	-19.95dB
Range PSRL:	-13.98dB
ISRL:	-9dB

Range PSRL



Azimuth PSRL

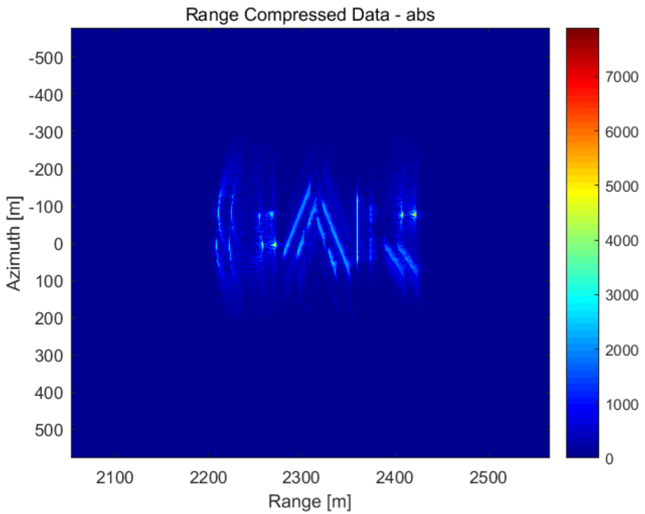




Ideal Rectilinear Trajectory

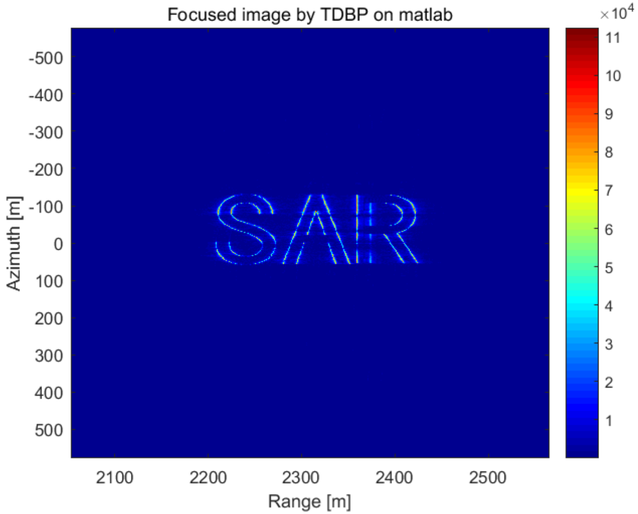
- Multi Simulated target

Range Compressed Data



TDBP

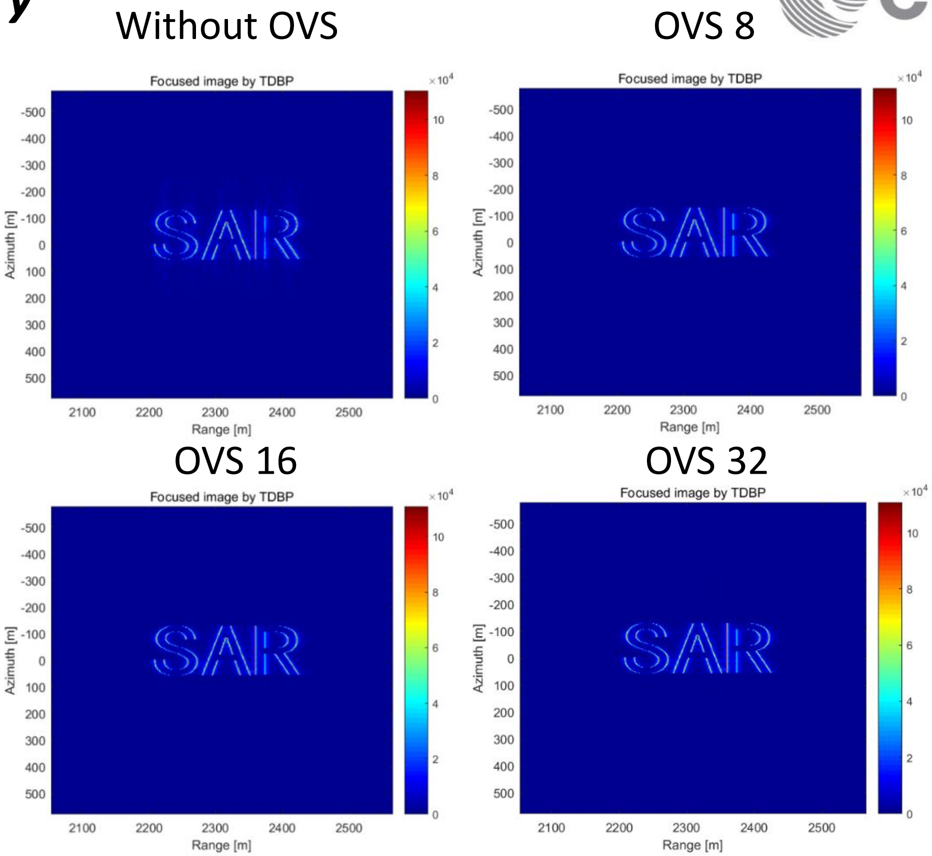
Focused Data



Ideal Rectilinear Trajectory

☐ Multi Simulated target

Focusing the SAR Raw Data generated by Optimized methods with different oversampling (OVS) factors.

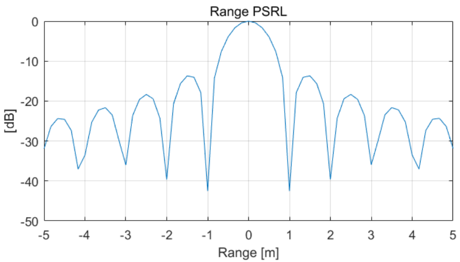


Highly deviated trajectory

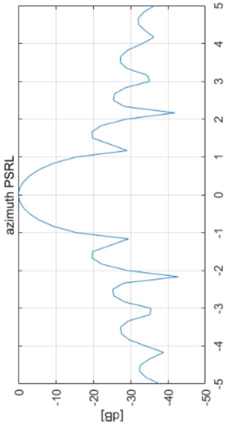
Highly Deviated trajectory

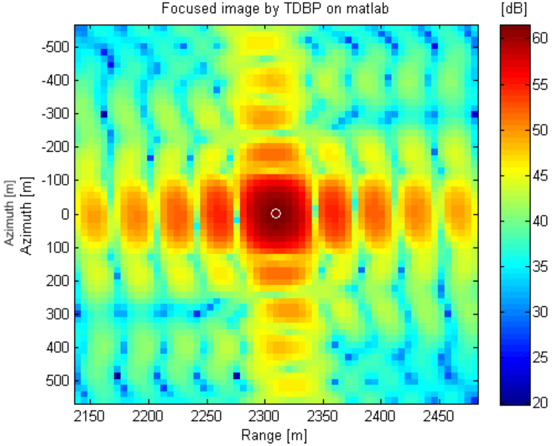
Range Res. : 0.9 m
Azimuth Res.: 1 m
Azimuth PSRL: -19.06dB
Range PSRL: -13.68dB
ISRL: -8.9dB

Range PSRL



Azimuth PSRL



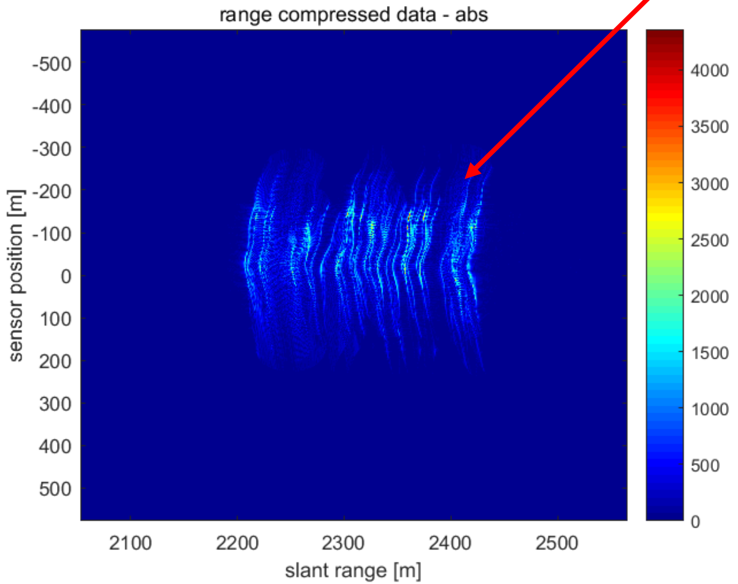


Highly Deviated Trajectory

- Multi Simulated target

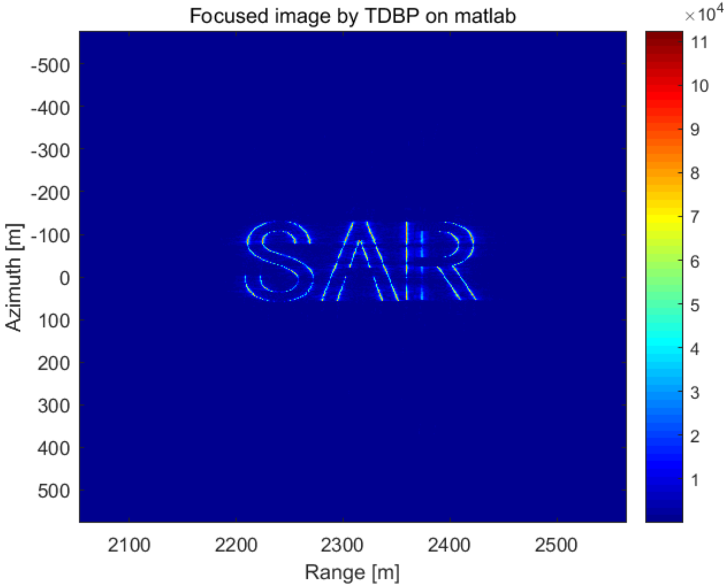
Irregular range history caused by highly deviated track

Range Compressed Data



TDBP

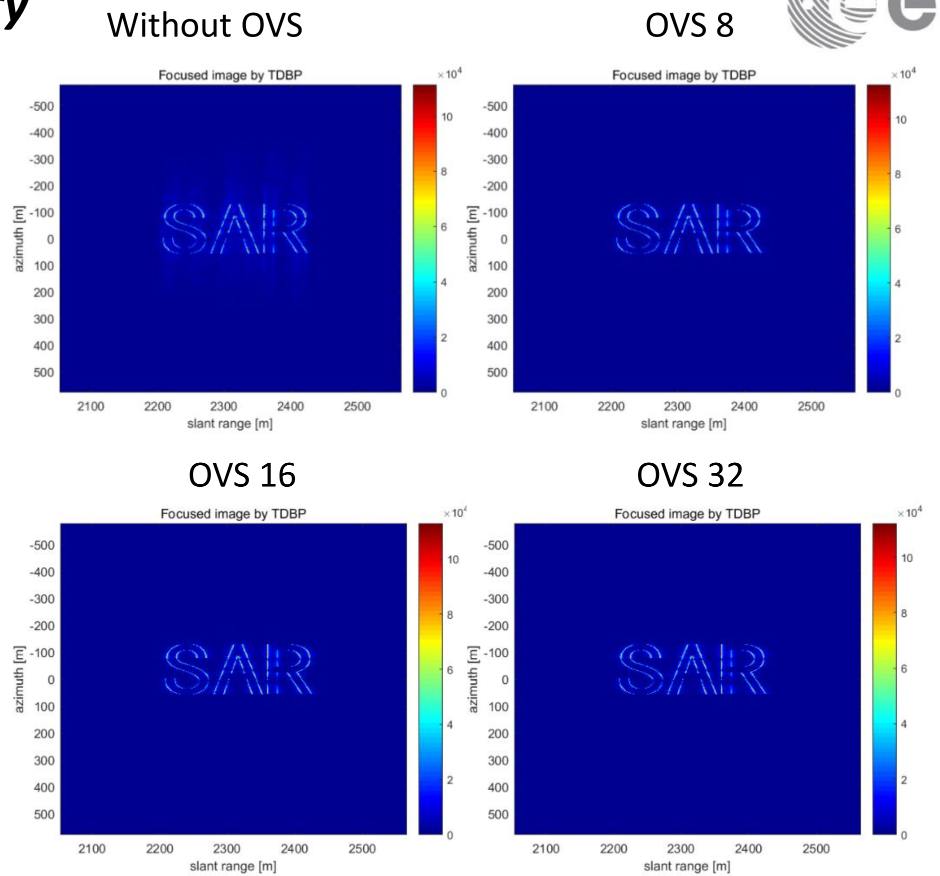
Focused Data



Highly Deviated Trajectory

- Multi Simulated target

Focusing the SAR Raw Data generated by Optimized methods with different oversampling (OVS) factors.



Circular trajectory

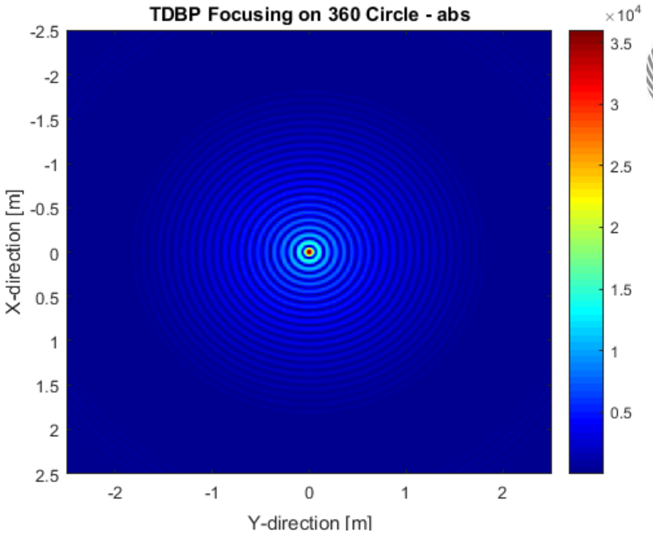
Circular Trajectory

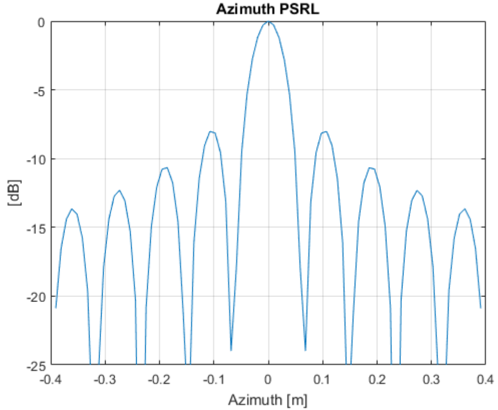
- Single Simulated target

Focusing on the X-Y (Azimuth / Ground range) plane.

Single isotropic target at $(x, y, z) = (0, 0, 0)$ is seen in a full 360 degree Circle.

Super high resolution : $\sim \frac{\lambda}{4}$

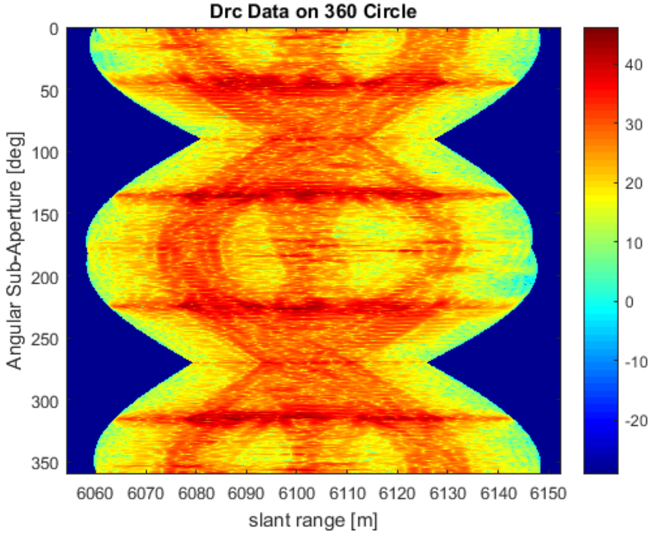


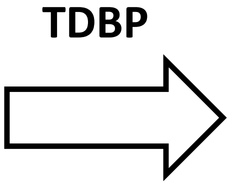


Circular Trajectory

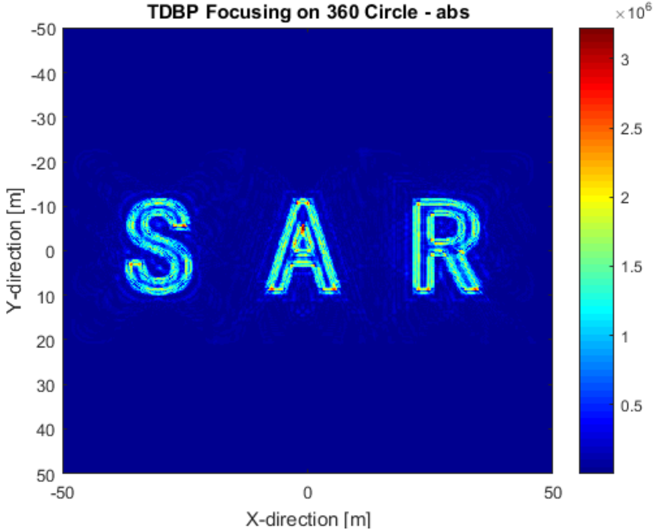
- Multi Targets

Range Compressed Data





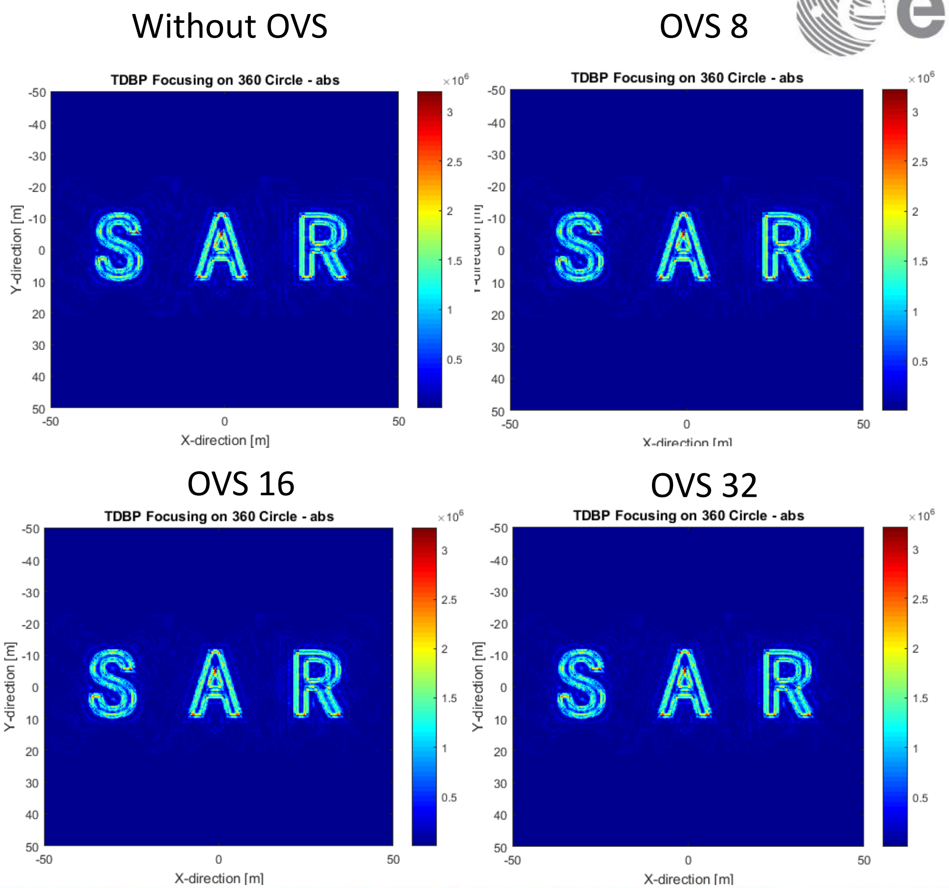
Focused Data



Circular Trajectory

☐ Multi Targets

Focusing the SAR Raw Data generated by Optimized methods with oversampling (OVS) factors 8, 16, and 32.



Efficiency analysis

- **Time cost comparisons of TDBP on three trajectories.**

Table 4. Runtime comparisons

	Ideal Rectilinear Trajectory	*Highly Deviated Trajectory*	Circular Trajectory
CPU (C++)	17.56 [s]	18.03 [s]	130.09 [s]
GPU	54.28 [ms]	63.18 [ms]	197.56 [ms]
Speed-Up	323x	285x	658x

Conclusions

- The GPU-based optimized SAR raw data simulation method can apply to any tracks in certain accuracy. Moreover, the processing efficiency have been improved above thousands times.
- The Time Domain Back-projection exactly reconstructs the SAR raw data in arbitrary trajectories. Its high computational burden is solved by GPU parallel computing.
- The GPUs make time domain Simulation and Focusing available solutions.

Thank You!