Raw Data Compression for Synthetic Aperture Radar using Deep Learning

Research as part of the ESA Internal Research Fellow Scheme

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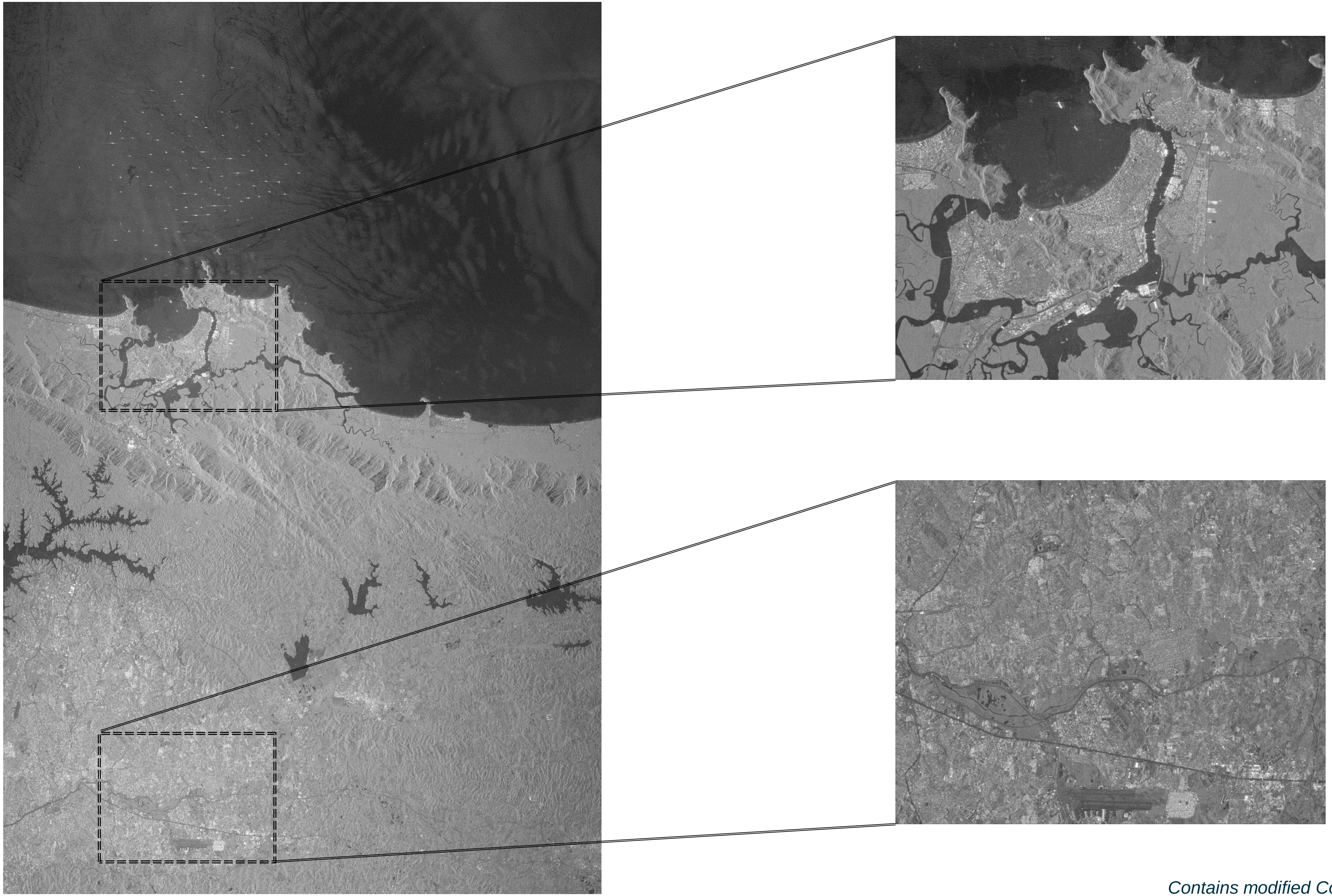

Contains modified Copernicus Sentinel data [2022]

Overview

- Synthetic Aperture Radar (SAR)
- Lossy data compression
- Proposed methodology
- Experiments
- Conclusions

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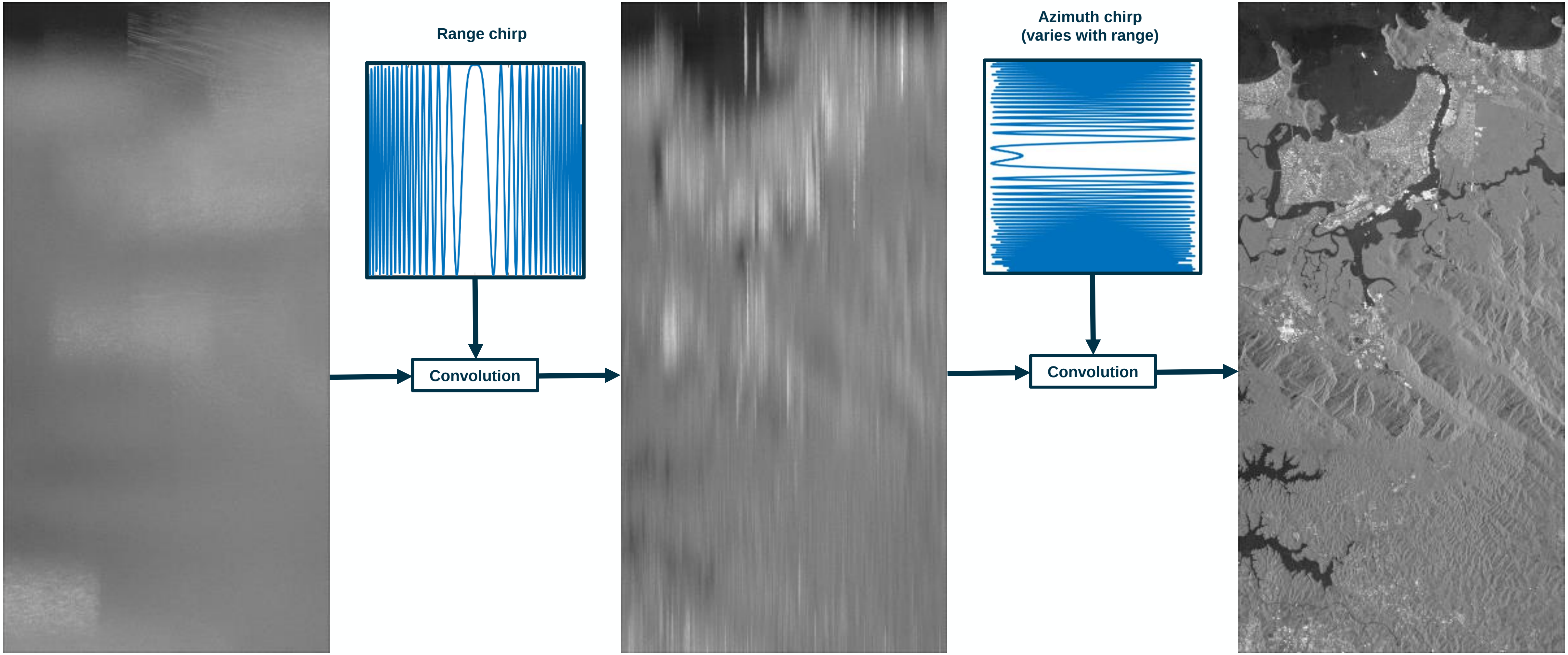
Synthetic Aperture Radar (SAR)

- Transmitter/receiver **emits pulses** (chirps) and **records echoes**.
- Each received pulse is digitised to an **azimuth line**, consisting of **range samples**.
- **Travel-times** taken by **electromagnetic waves** to propagate are utilized in **focusing the raw data.**
- **Range-Doppler Algorithm (RDA)** is widely used.

Synthetic Aperture Radar (SAR) – Image focusing

Unfocused data | Range compressed and migrated data | Focused image



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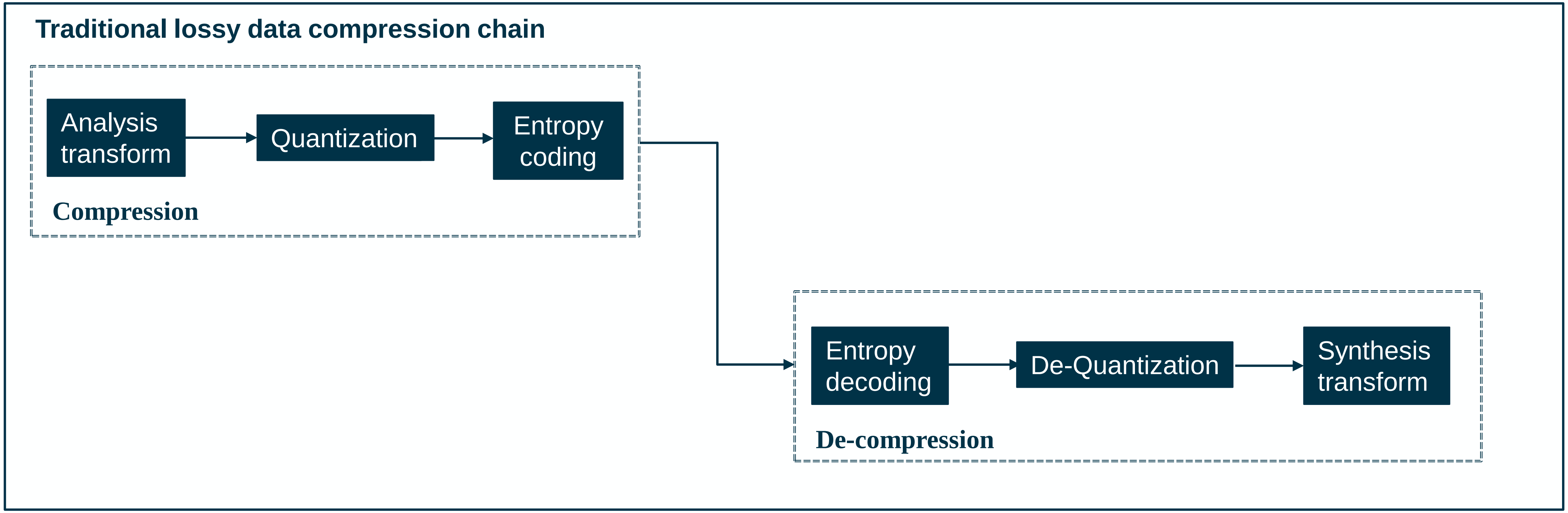
Lossy data compression



Lossy data compression

- Usually, components are **optimized independently**.
- If one component is **upgraded**, potentially, **re-optimization** needed.
- Quality of **higher level products** not always considered.

Lossy data compression - SAR

- Block Adaptive Quantization **(BAQ)-based algorithms** perform **quantization** on **blocks of samples**.
- Quantizers and consequently **bit-rate varies** depending on **block statistics**.
- **Entropy coding** following quantization.
- **No data transformation** is performed.

Lossy data compression - SAR

- SAR data compression should attain:
  - **High compression ratio** on **raw data**,
  - Retain **high quality** in the **SLC image**.

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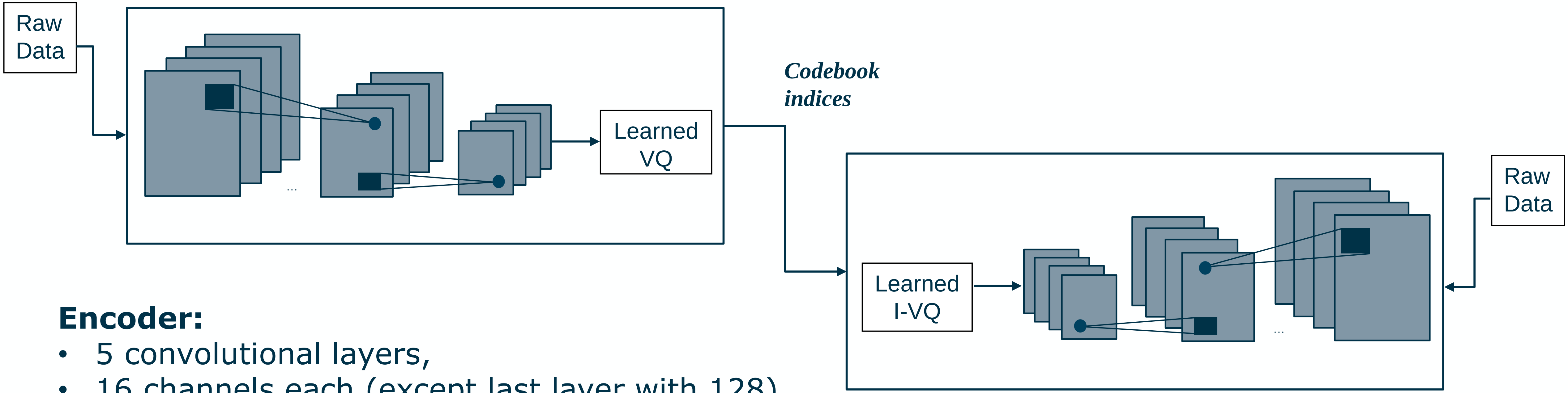
Proposed methodology

- Lossy SAR raw data compression using **deep learning**.
- Vector-Quantized Variational Auto-Encoder (**VQVAE**) [1].
- **Learned** analysis/synthesis **transforms**, **vector quantization**.
- **Two** strategies followed: one compresses **raw data** to **raw data** directly. Second compresses **raw data** to **Single Look Complex (SLC) images**.

[1] A. Oord, K. Kavukcuoglu, and O. Vinyals. Neural discrete representation learning, *Advances on Neural Information Processing Systems (NIPS)*, 2017.

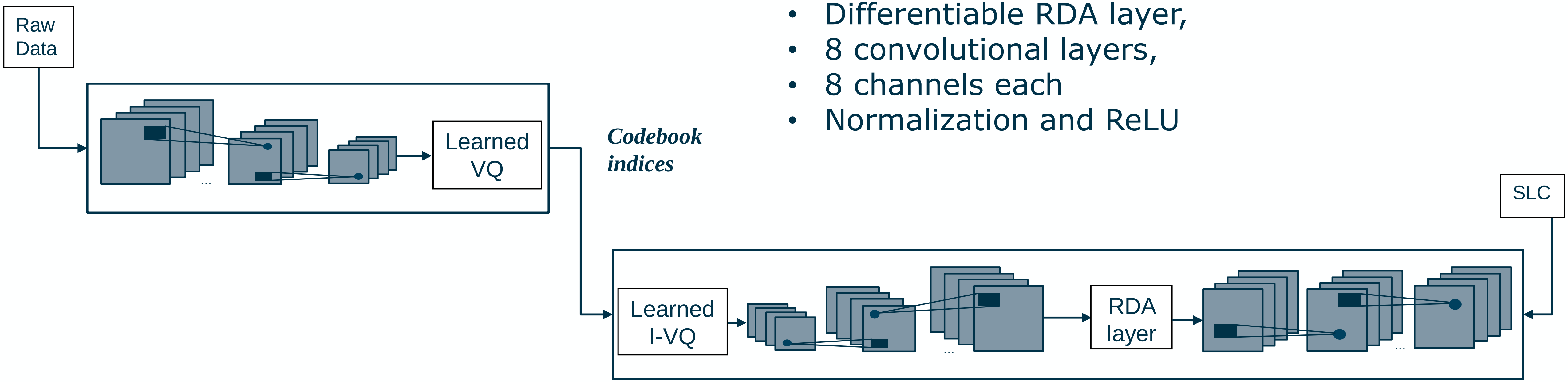
VQVAE (raw data to raw data)

Decoder:
- Same as encoder in reverse order



Encoder:
- 5 convolutional layers,
- 16 channels each (except last layer with 128)
- Codebook size of 512 codewords.
- Normalization and ReLU

VQVAE-RDA (raw data to SLC image)



Decoder:

- Same as encoder but in reversed order.
- Differentiable RDA layer,
- 8 convolutional layers,
- 8 channels each
- Normalization and ReLU

Encoder:

- 5 convolutional layers,
- 8 channels each (except last layer with 128)
- Codebook size of 512 codewords.
- Normalization and ReLU

VQVAE-RDA (raw data to SLC image)

- **Mean squared error** between original **SLC images** and estimated SLC images.
- **Intermediate data** before RDA layer **might not be directly usable**.
- **Differentiable RDA layer** implemented to enable gradients to pass through during backwards pass.

Architecture choices

- Number of layers,
- Number of channels,
- Number of striding,
- Codebook size,
- Normalization and activation functions.

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- Proposed framework
- **Experiments**
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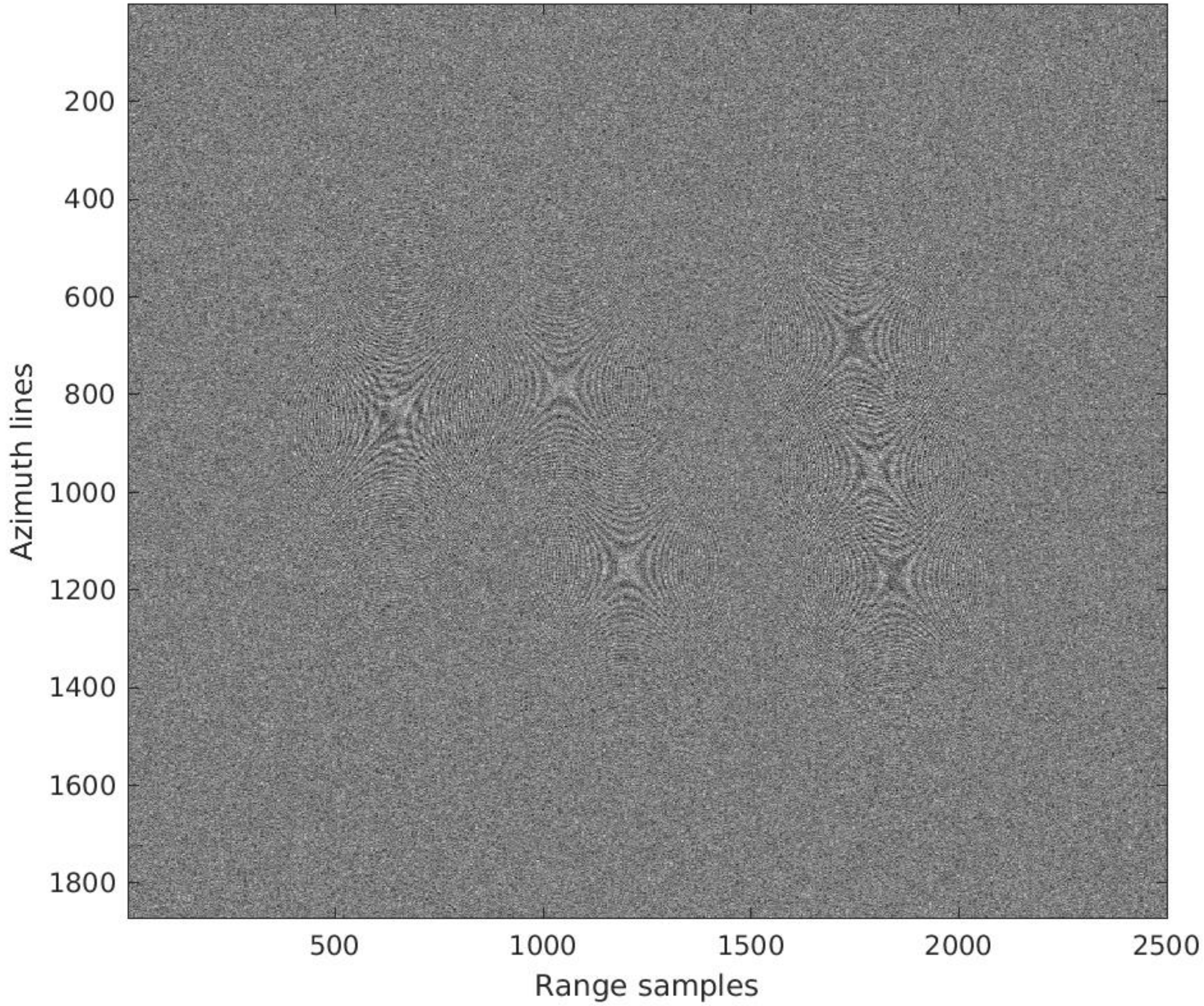
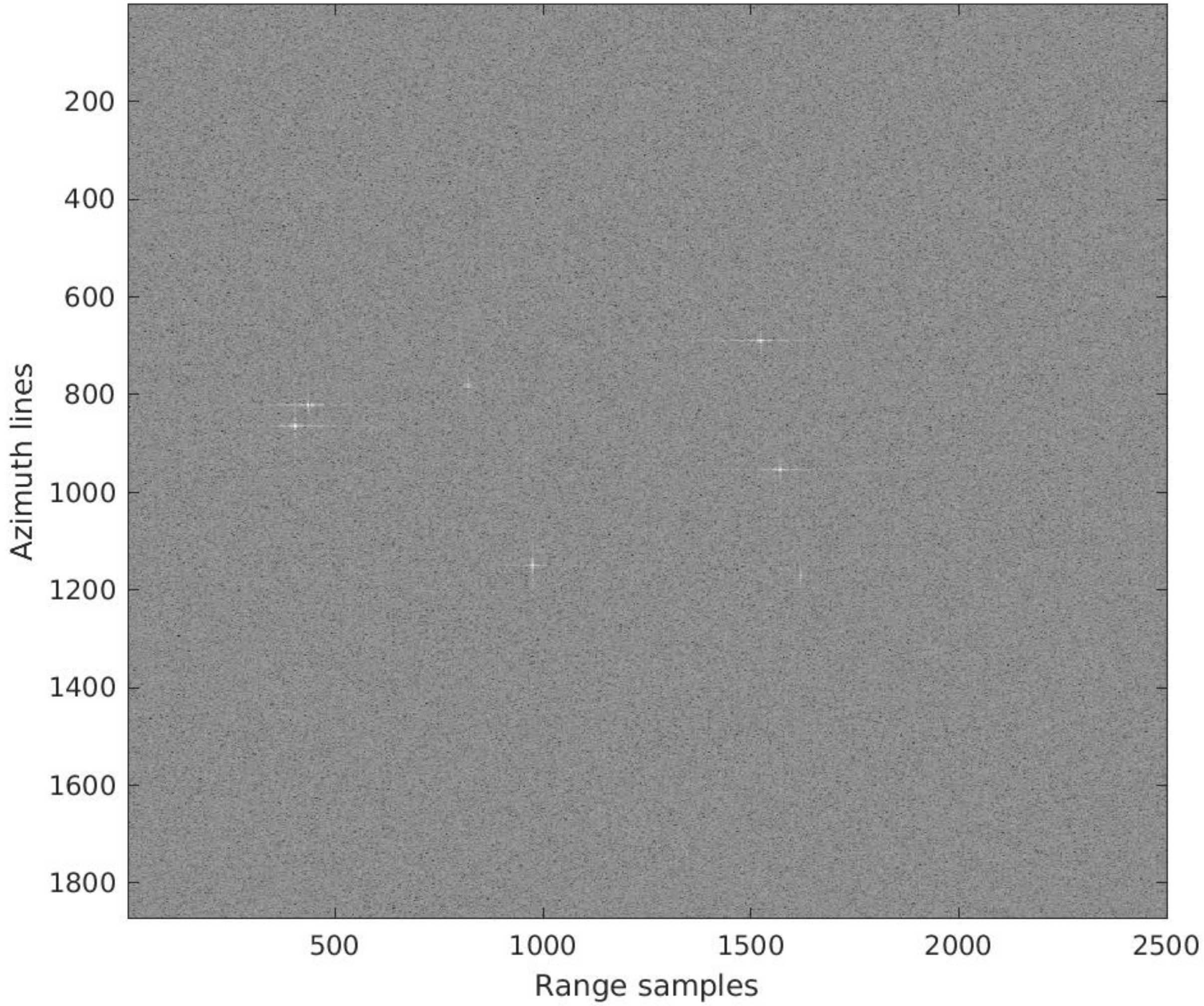
Custom point target SAR raw data simulator



1. **Two-way travel time** between platform and targets.
2. **Phase shift** on the **chirp** depending on distance travelled.
3. **Antenna gain** depending on measurement angle
4. **Circular** complex **Gaussian** noise**.**

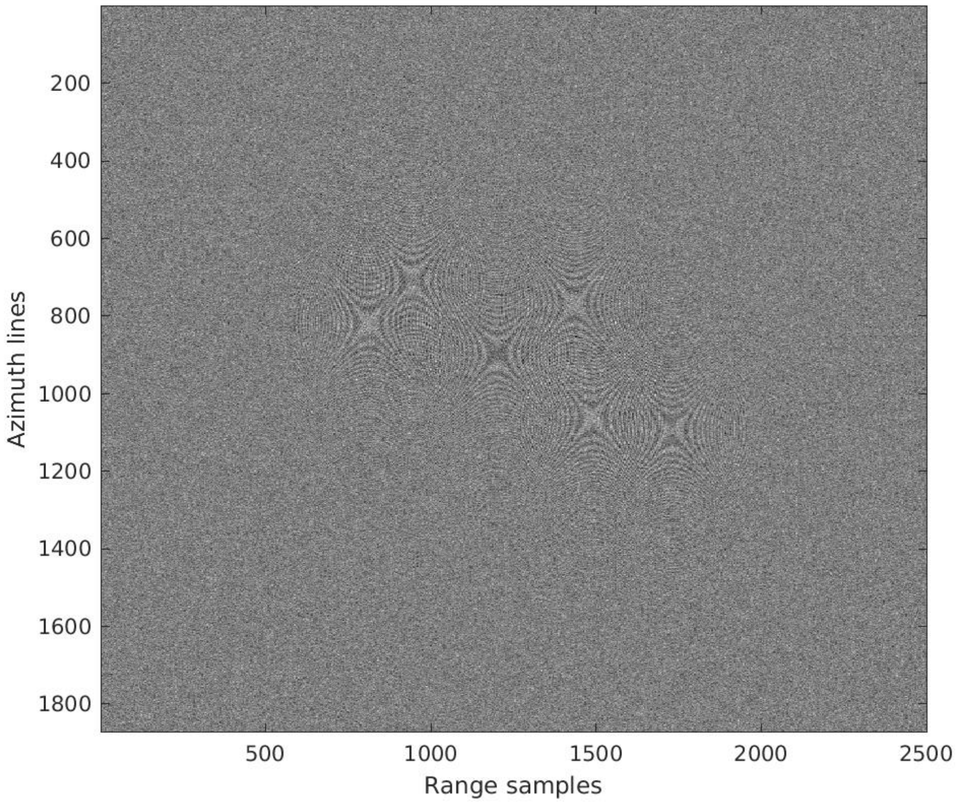
Custom point target SAR raw data simulator

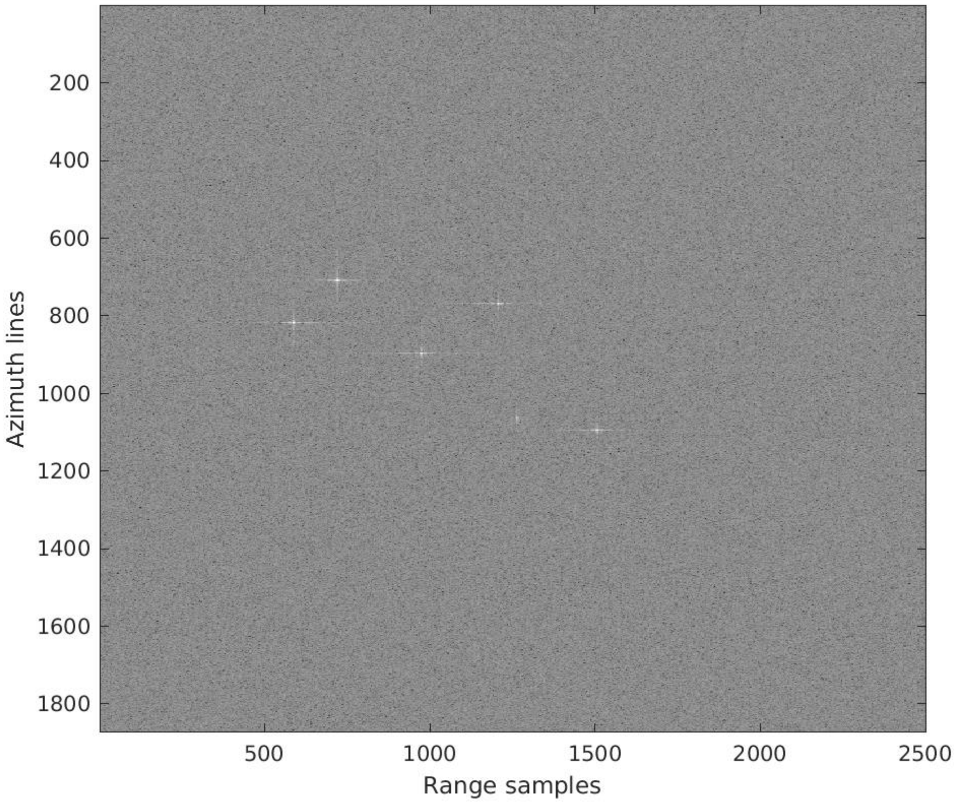


- **Centre frequency:** 5.405 GHz
- **Chirp bandwidth:** 50 MHz
- **Chirp pulse duration:** 3 μs
- **Range sampling frequency:** 150 MHz
- **Pulse Repetition Frequency:** 1871
- **Antenna length:** 12 metres
- **Platform height:** 690 km

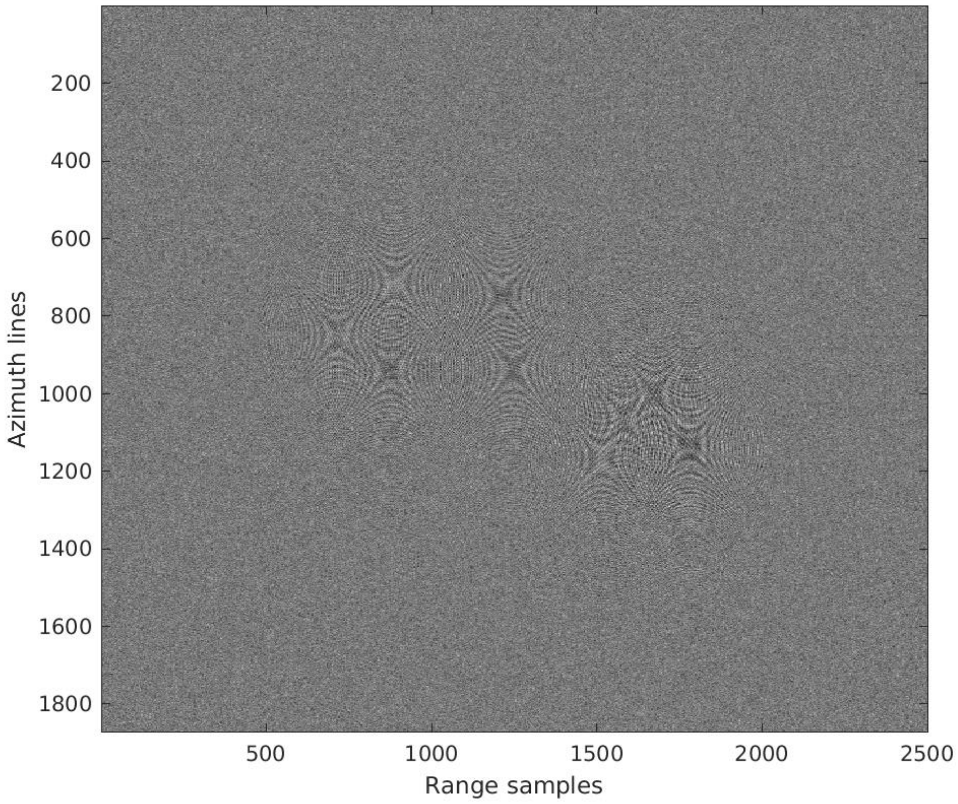
Note: These do not correspond to any actual Sentinel-1 acquisition mode, chosen for simplicity and ease of experiments.

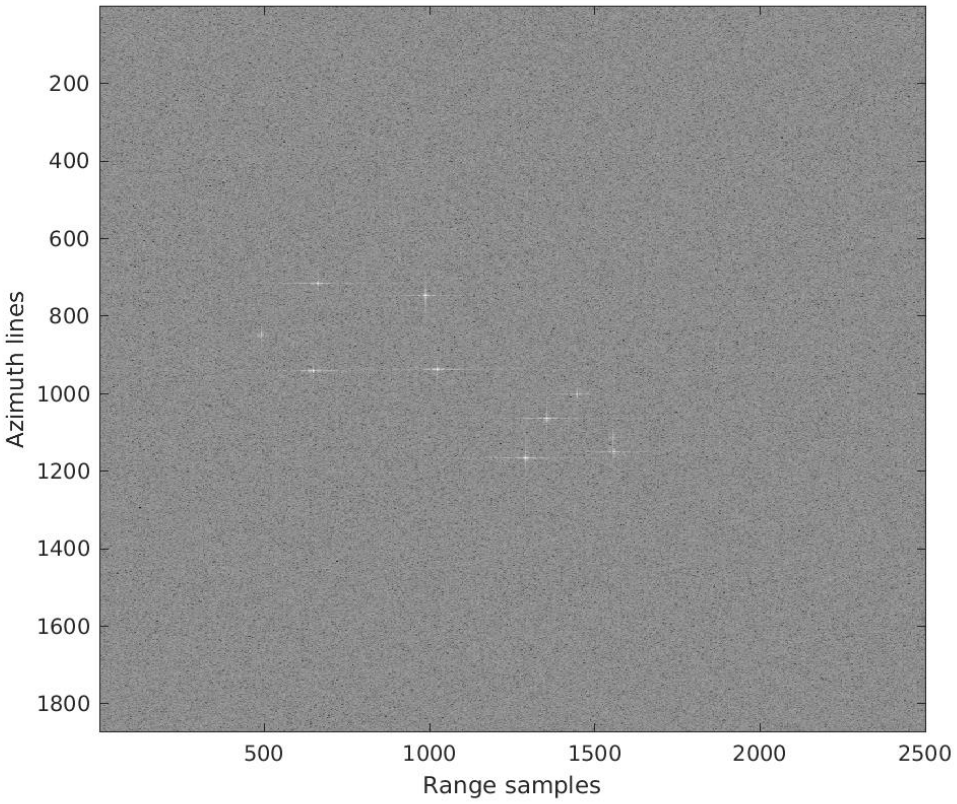
Custom point target SAR raw data simulator





Custom point target SAR raw data simulator





Training data from simulations

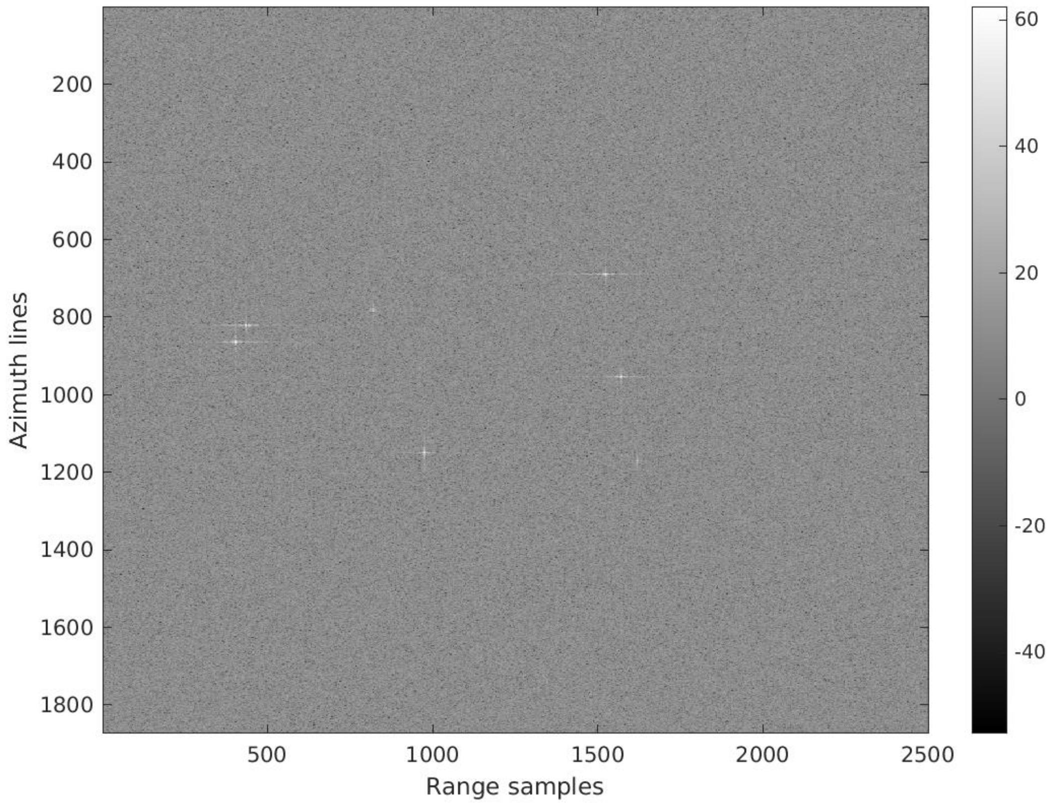
- 300 raw data volumes (1871, 2500, 2), 300 SLC images,
- 250 training data, 50 test data.
- Raw data normalized between -1 and 1, by dividing with maximum absolute value.

Bits per sample

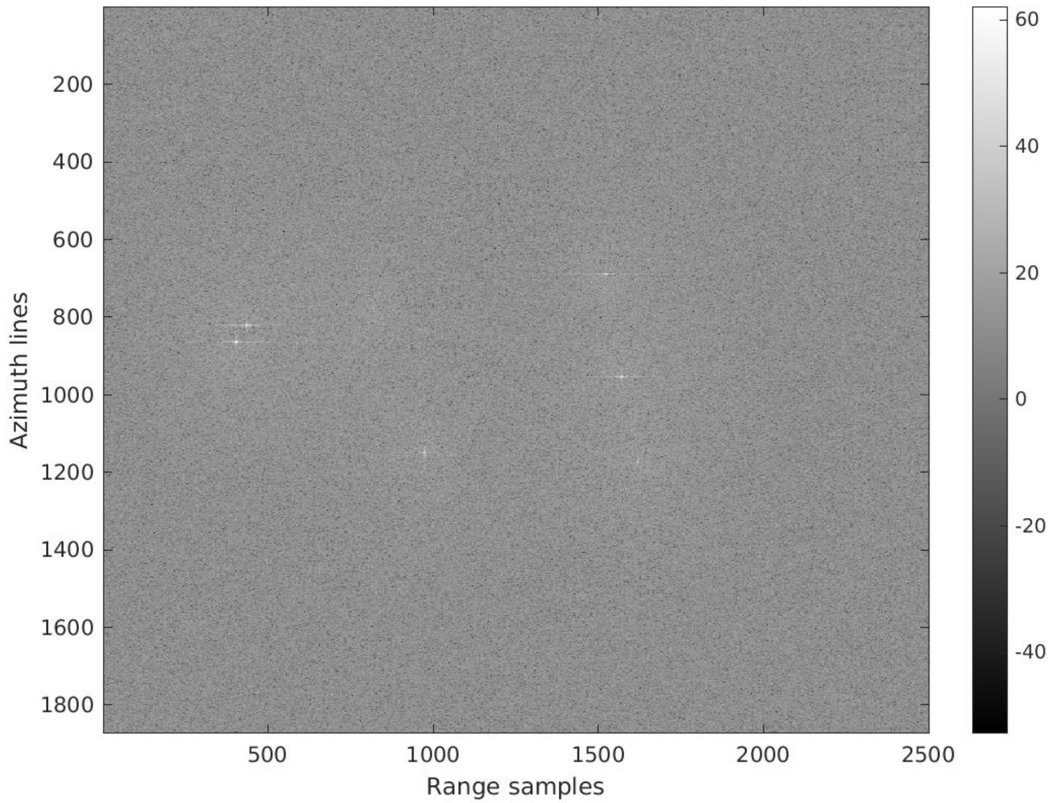
- Bits/sample = (first dimension of indices*second dimension of indices*9)/(azimuth lines*range samples*2),
- where **9 bits per index are used** (codebook size = 512), **2 is for real and imaginary** parts of raw data.
- Indices dimensions (935, 1249)
- **Bit-rate = 1.12 bits/sample**.

Examples

Original SLC image

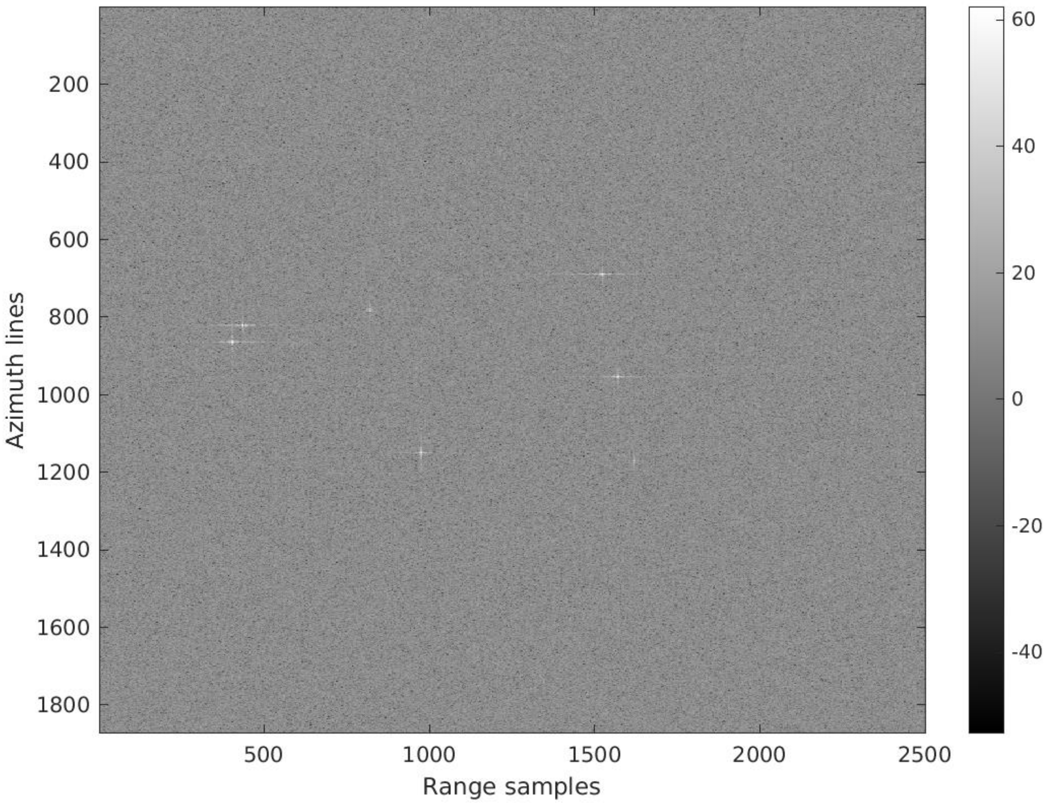


SLC image formed from VQVAE-recovered data

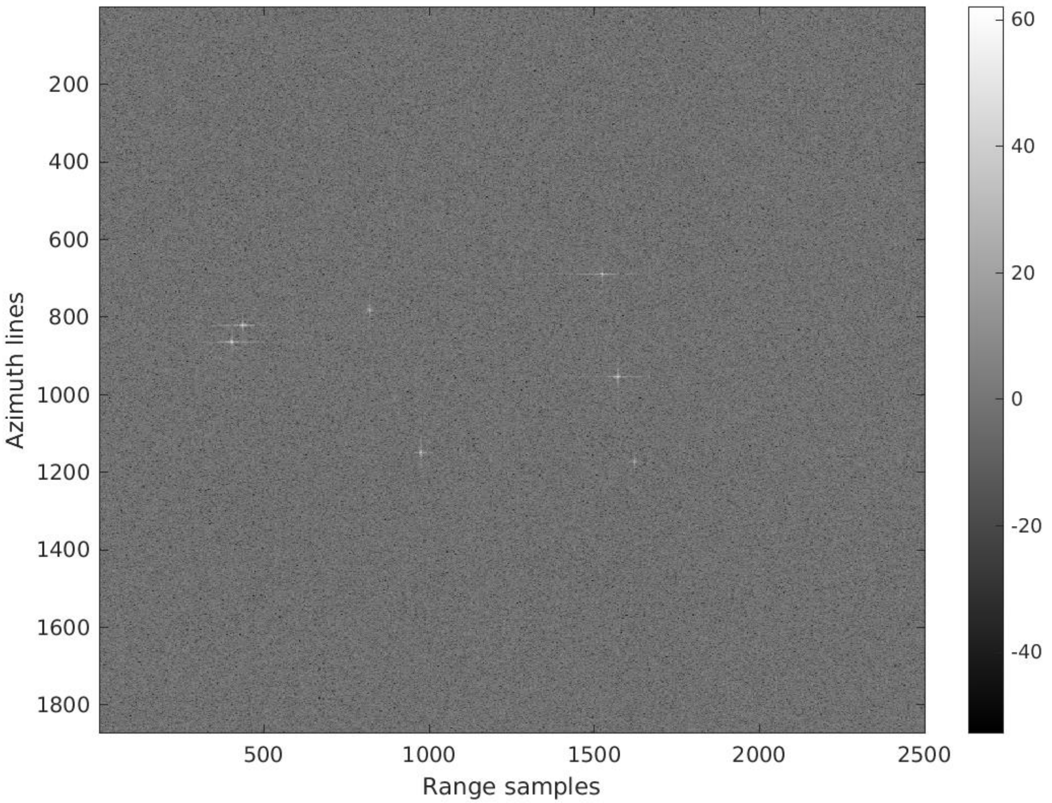


Examples

Original SLC image



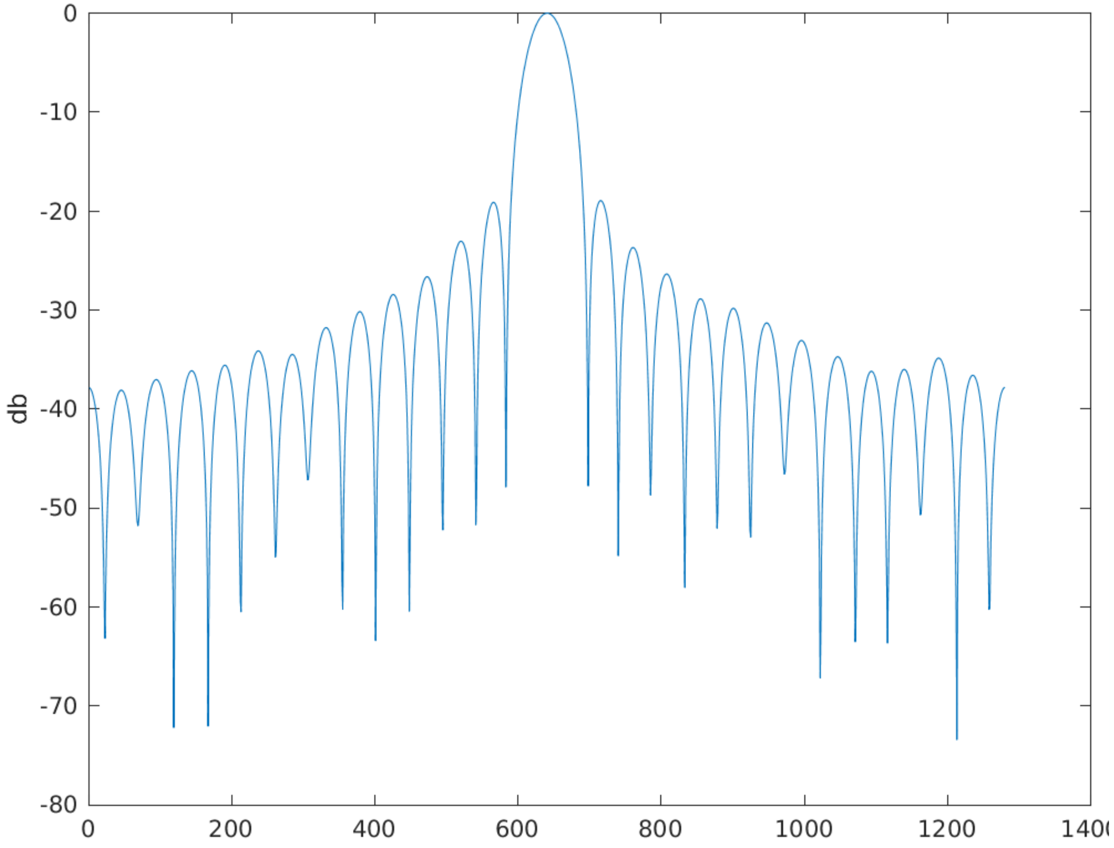
SLC image formed from VQVAE-RDA



Data normalization and image bias

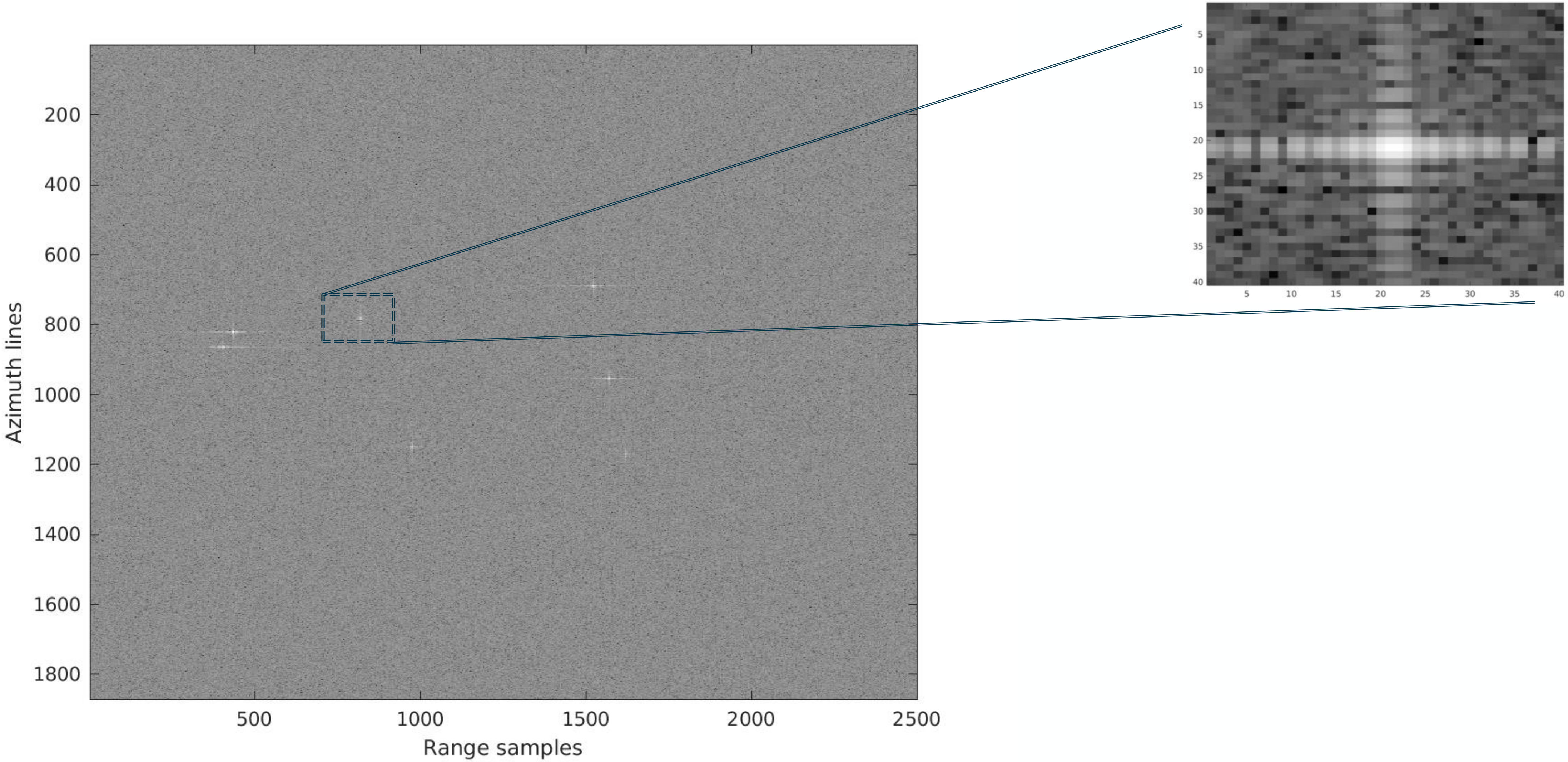
- **Image bias** issues.
- **Data normalization** during pre-processing.
- **Normalization** within each **network layer**.
- We continue with **Impulse Response Function (IRF)** analysis.

Impulse Response Function (IRF) metrics

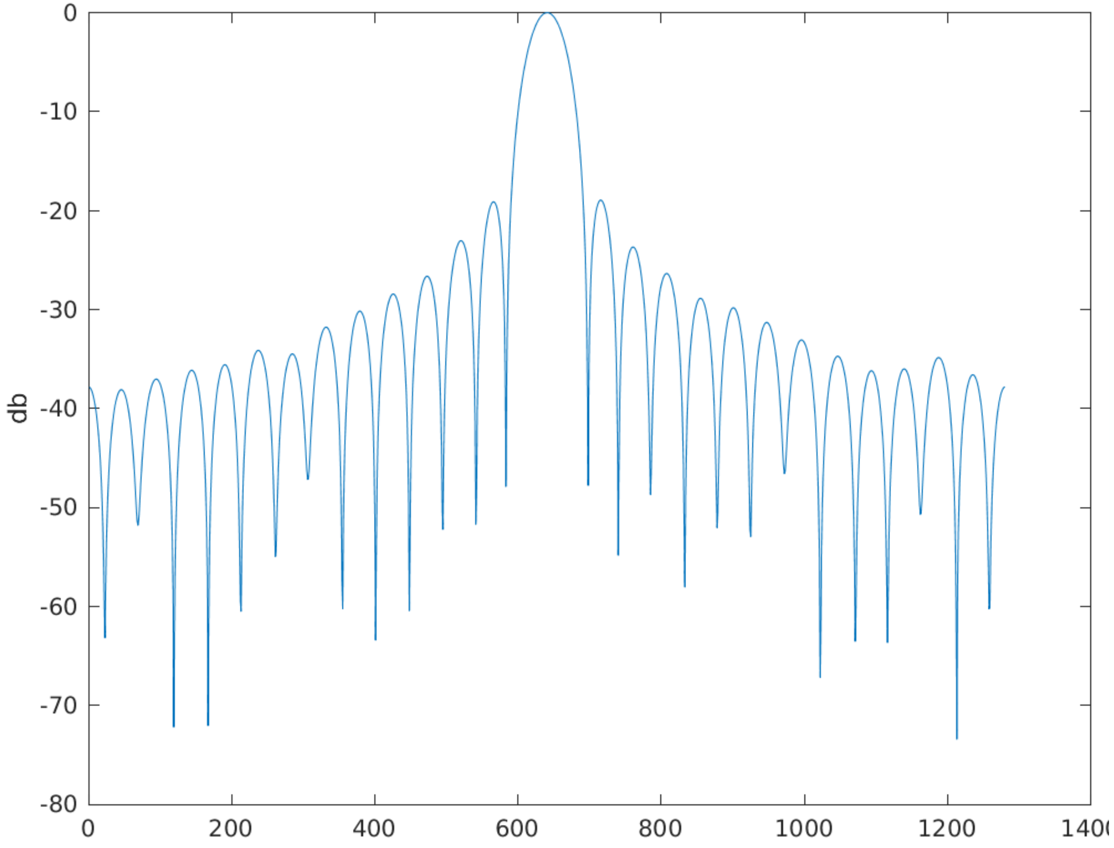


1. **Spatial resolution:** -3dB IRF widths in both azimuth and range.
2. **Peak side-lobe ratio (PSLR):** ratio of intensity of the largest peak outside the main-lobe to main-lobe [in dB].

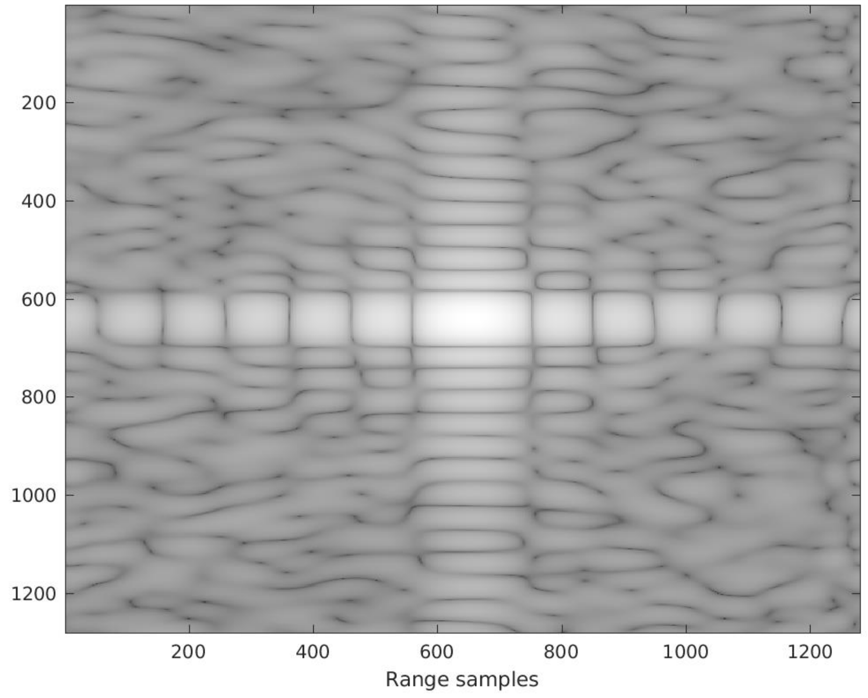
Impulse Response Function (IRF) metrics



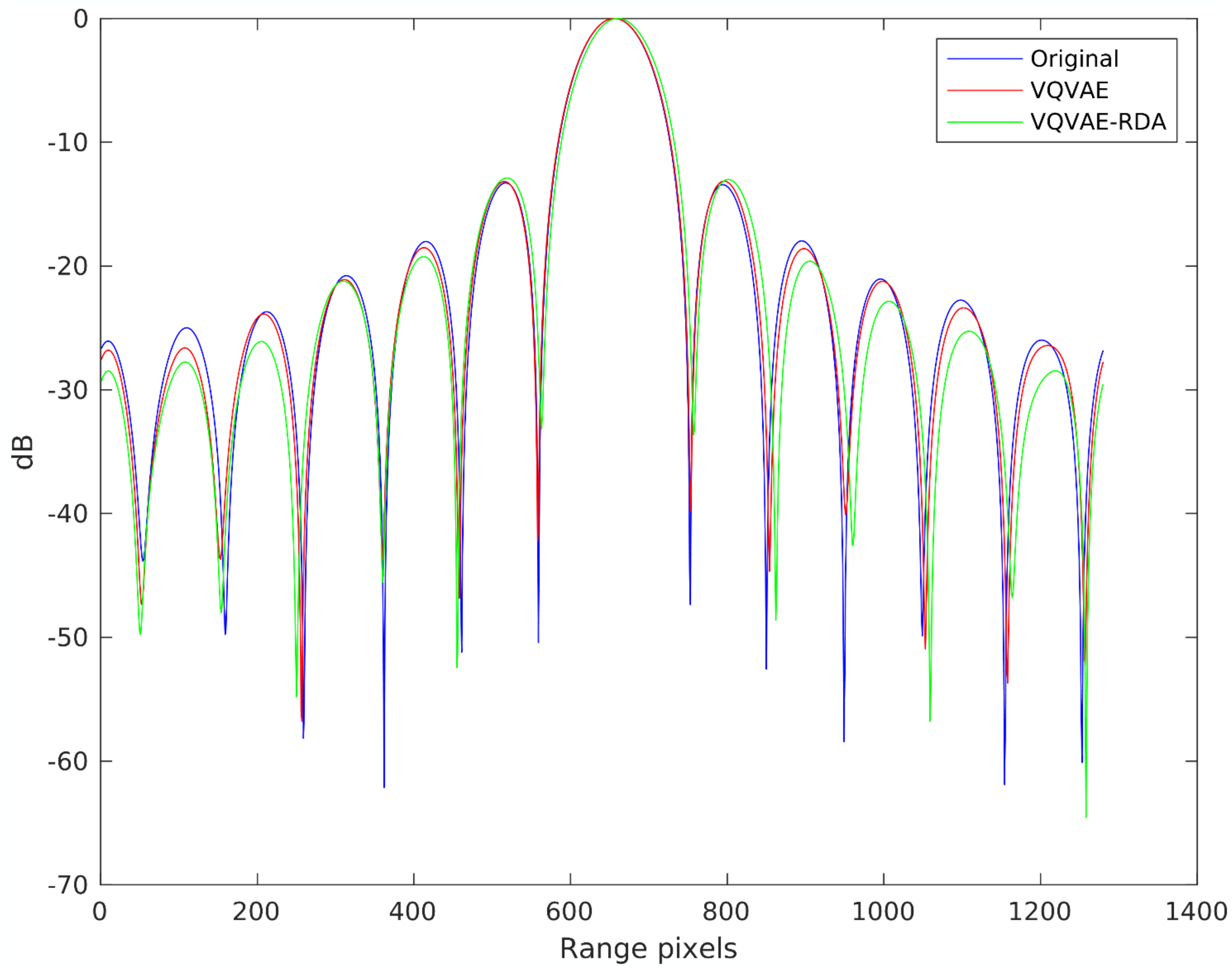
Impulse Response Function (IRF) in azimuth



Interpolation



Range Impulse Response Function (IRF)



Original Range IRF:

Resolution **= 2.62 m**
PSLR **= -13.29 dB**

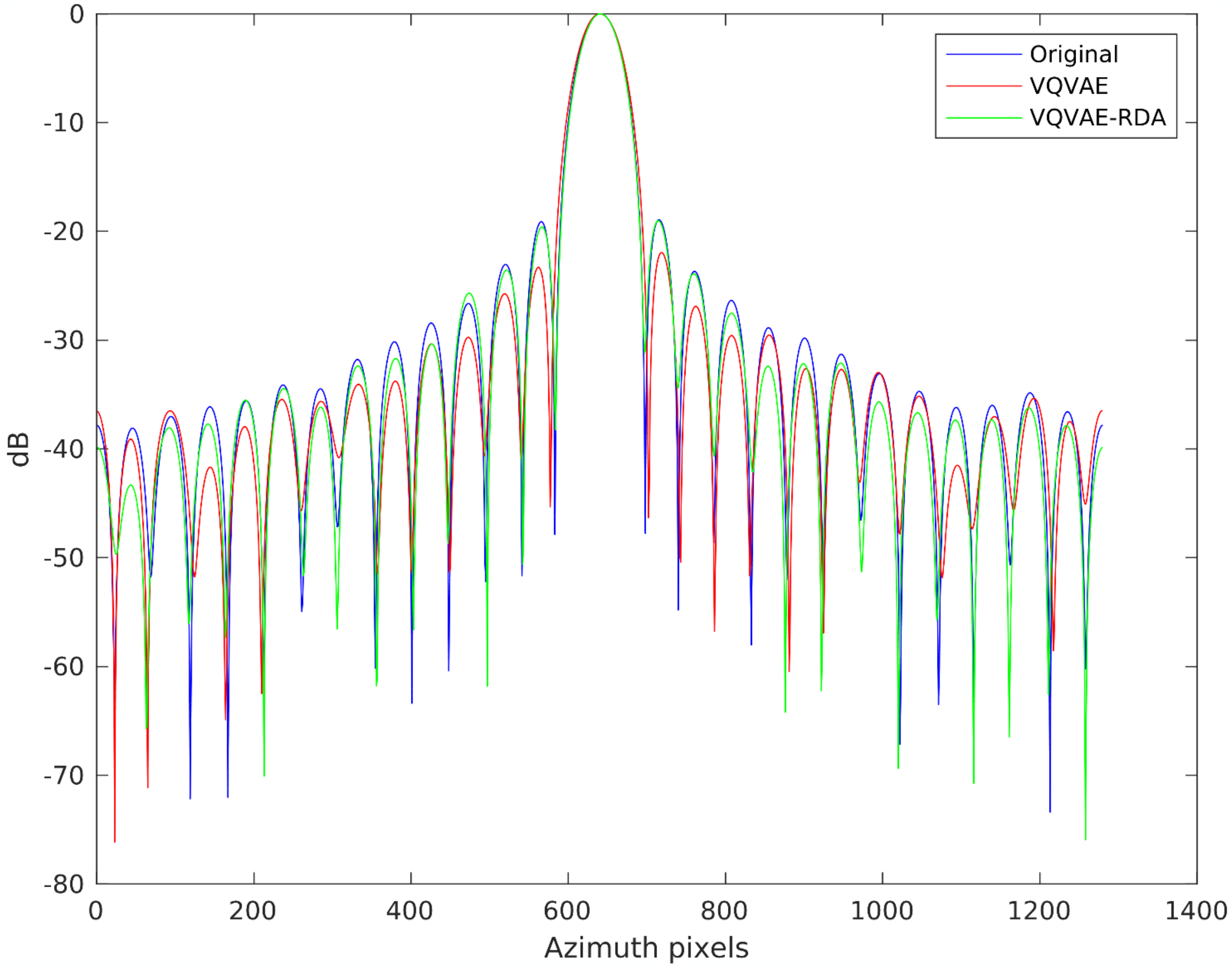
VQVAE Range IRF:

Resolution **= 2.65 m**
PSLR **= -13.14 dB**

VQVAE-RDA Range IRF:

Resolution **= 2.65 m**
PSLR **= -12.89 dB**

Azimuth Impulse Response Function (IRF)



Original Azimuth IRF:

Resolution = **5.95 m**
PSLR = **-18.94 dB**

VQVAE Azimuth IRF:

Resolution = **6.21 m**
PSLR = **-21.95 dB**

VQVAE-RDA Azimuth IRF:

Resolution = **5.83 m**
PSLR = **-19.02 dB**

Rate, Resolution & Inference Time (averaged 50 images)

Input size (azimuth lines = 1871, range samples = 2500, 2)

	Bit-Rate [bits/samples]	Mean Resolution (Rg\Az) [metres]	Mean PSLR (Rg\Az) [dB]	Mean Compression time [seconds]	Mean De-Compression time [seconds]
Original	-	2.62 \ 5.91	-13.32 \ -19.30	-	-
VQVAE	1.12	2.67 \ 6.28	-13.39 \ **-22.48**	0.29	0.28
VQVAE-RDA	1.12	2.67 \ **5.83**	**-13.60** \ -18.99	0.21	1.71

Inference time was calculated on an NVIDIA Tesla T4.

We continue the experiments with VQVAE

Sentinel-1 Instrument simulator

- **Stripmap mode**, emulates the **Sentinel-1 SAR instrument**.
- **Random location of point targets** across 2 datasets (1 for training, 1 for testing).
- (Azimuth line: **16659**, Range samples: **25742, 2**).
- **Entire azimuth line** during testing VQVAE, less image biases
- **FDBAQ** implemented nominally for **Sentinel-1**.
- **Custom RDA implementation** for image focusing.

Sentinel-1 Instrument simulator – Range IRF

Original Range IRF:

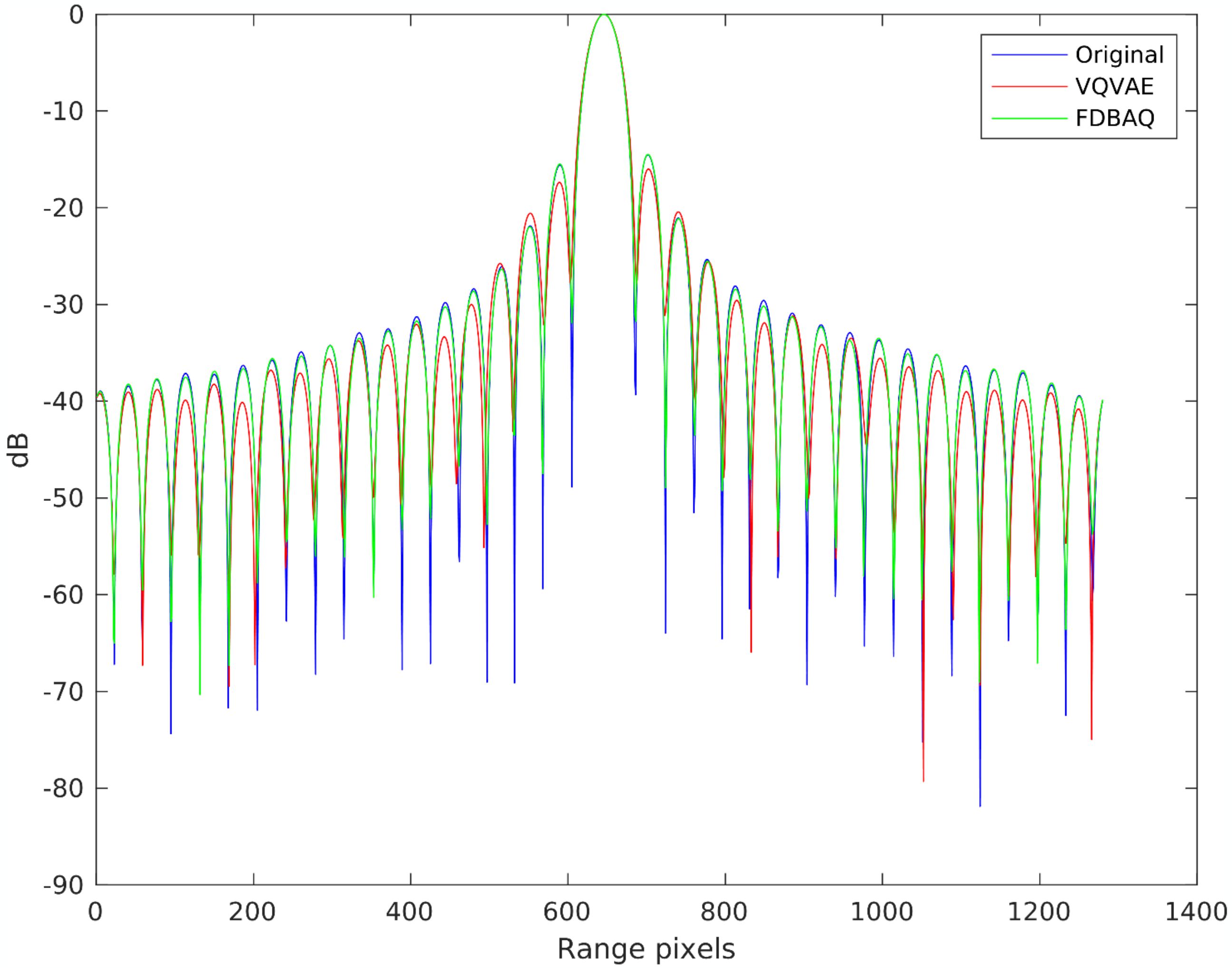
Resolution **= 1.59 m**
PSLR **= -14.54 dB**

VQVAE Range IRF:

Resolution **= 1.64 m**
PSLR **= -16.00 dB**
Bit-rate = **1.12 bits/sample**

FDBAQ Range IRF:

Resolution **= 1.59 m**
PSLR **= -14.49 dB**
Bit-rate = **2.77 bits/sample**



Approximately 60% data reduction using VQVAE

Sentinel-1 Instrument simulator – Azimuth IRF

Original Azimuth IRF:

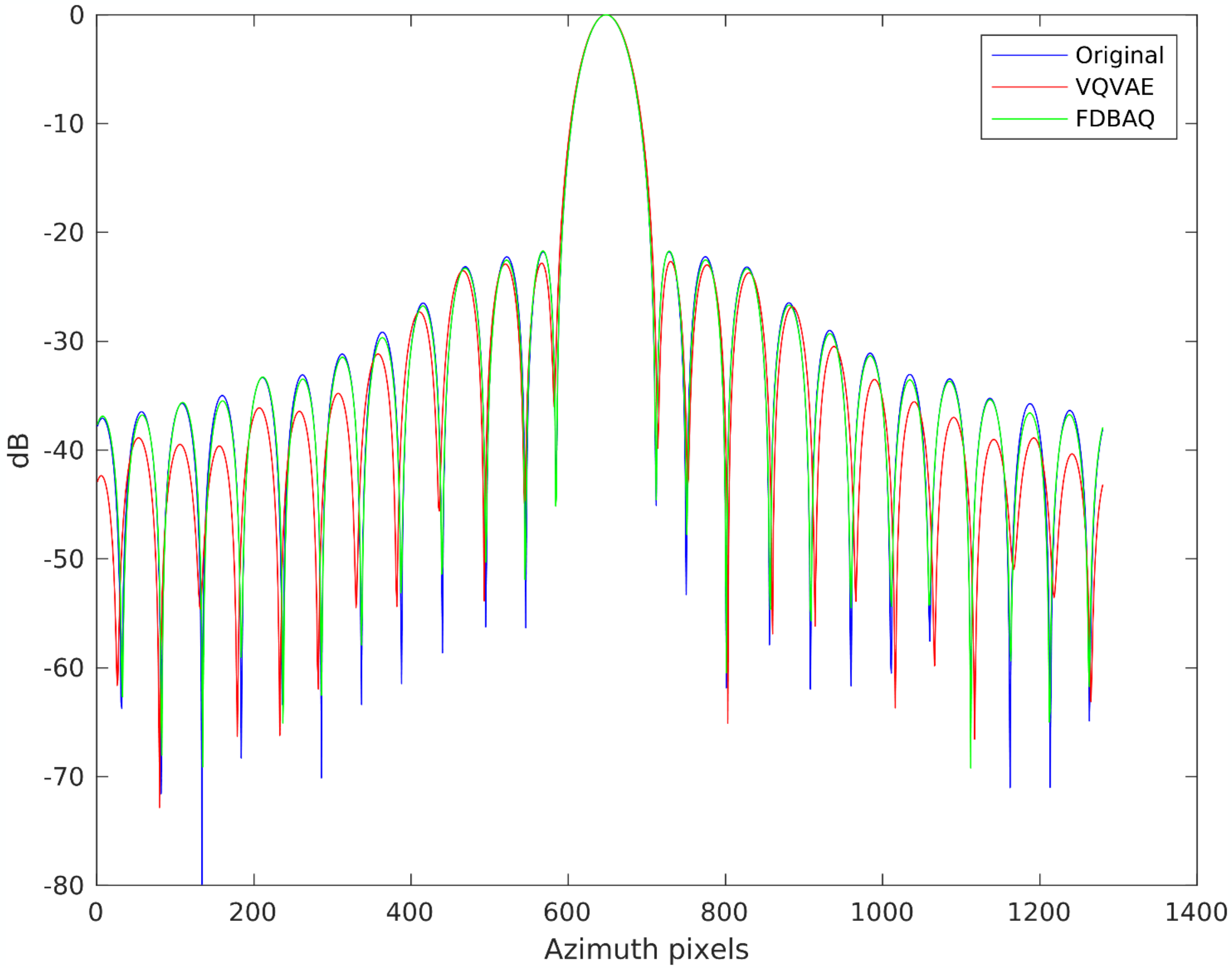
Resolution **= 6.01 m**
PSLR **= -21.77 dB**

VQVAE Azimuth IRF:

Resolution **= 6.25 m**
PSLR **= -22.67 dB**
Bit-rate = **1.12 bits/sample**

FDBAQ Azimuth IRF:

Resolution **= 6.01 m**
PSLR **= -21.71 dB**
Bit-rate = **2.77 bits/sample**



Approximately 60% data reduction using VQVAE

FDBAQ-processed raw data from Sentinel-1 acquisition

- **Data** acquired by **Sentinel-1 available** from **Copernicus Open Access Hub** (Copernicus Service Information, 2022).
- Data already **FDBAQ-processed (quantized, de-quantized).**
- Goal to **test VQVAE on more realistic scenes**, albeit already processed.
- **Stripmap-6 Mode**, Sao Paulo, Brazil (sea, ships, land, mountains, city).

FDBAQ-processed raw data from Sentinel-1 acquisition

- **Four large data** volumes (three for training, one for testing).
- (**Azimuth lines** = 29934, **Range samples** = 19950, 2).
- Experimented **with and without splitting** into range blocks.
- Results with **input size (2000, 2500, 2).**
- Choice of **range block size is not trivial**, effect on image quality and resources needs to be studied further.

FDBAQ-processed raw data from Sentinel-1 acquisition

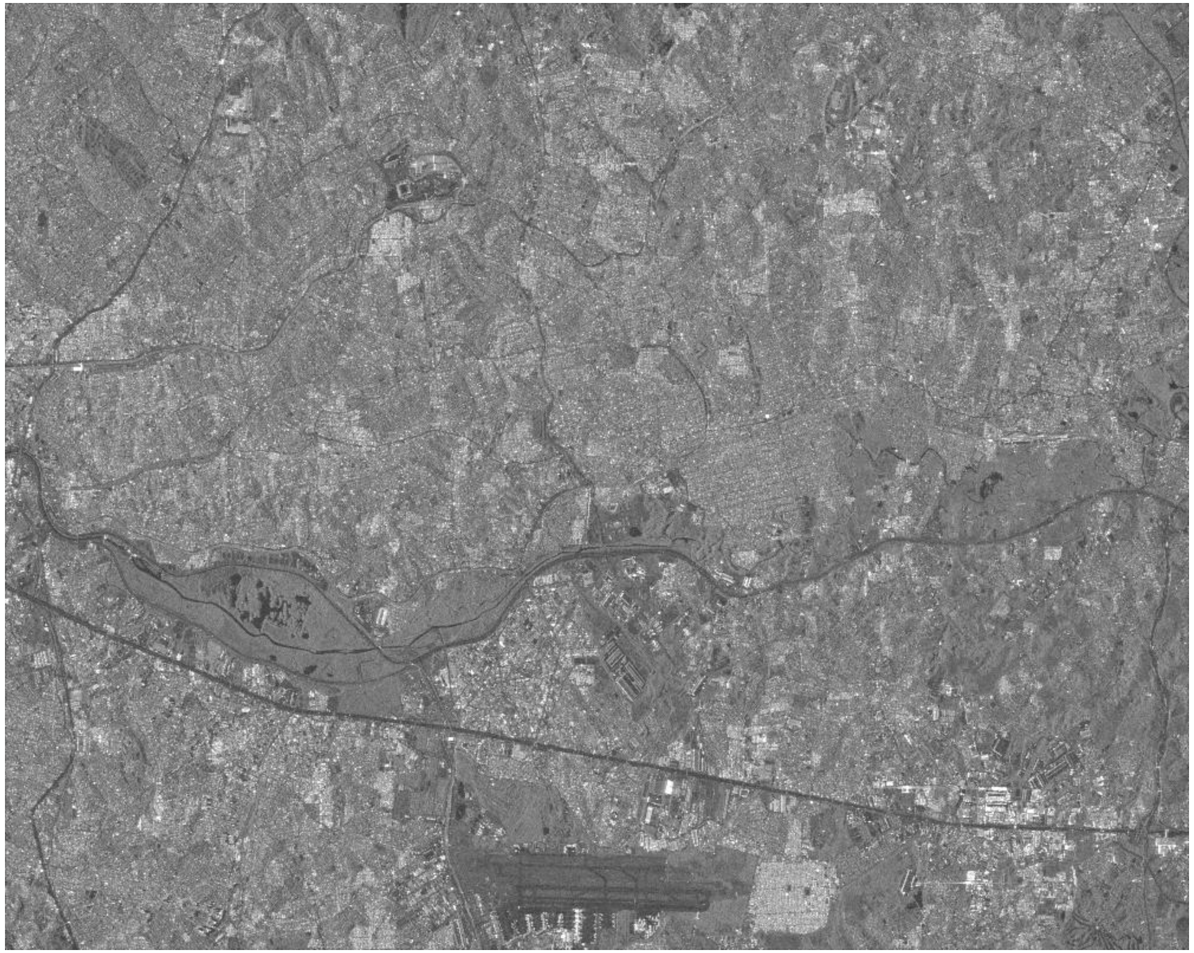
Focused from FDBAQ-processed data

Focused from VQVAE-recovered data (1.12 bits/sample)

Contains modified Copernicus Sentinel Data [2022].

FDBAQ-processed raw data from Sentinel-1 acquisition

Focused from FDBAQ-processed data



Focused from VQVAE-recovered data (1.12 bits/sample)

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Conclusions

- **Lossy SAR data compression** methodology proposed.
- **VQVAE** and **VQVAE-RDA** performed similarly on IRF metrics.
- **Image biases** were observed in image formed from recovered data. **Further studies on data normalization** are essential.
- **Range block size** investigation is required.
- **Entropy coding not used**. This could further decrease bit-rate.

Conclusions

- **Architecture choices** and their effect on **bit-rate**, **image quality** and inference **time** need to be studied.
- **Quality of phase** component in image to be investigated.
- **Greater generalizability** has **not been tested**. Experiments with **data from different regions** of the world are required.
- **Preliminary results** illustrate the **potential** of **deep learning** for **lossy SAR raw data compression**.