Denoising Radio Pulses From Air-Showers Using a Machine-Learning Method

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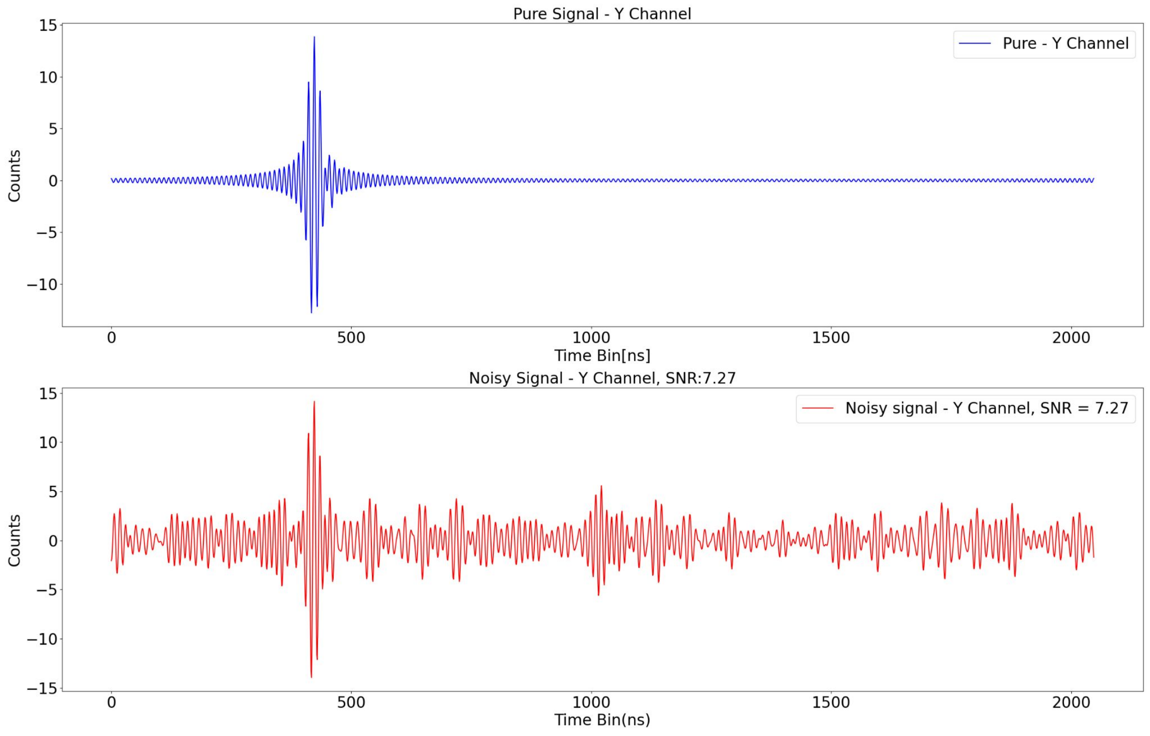
01
Data Processing

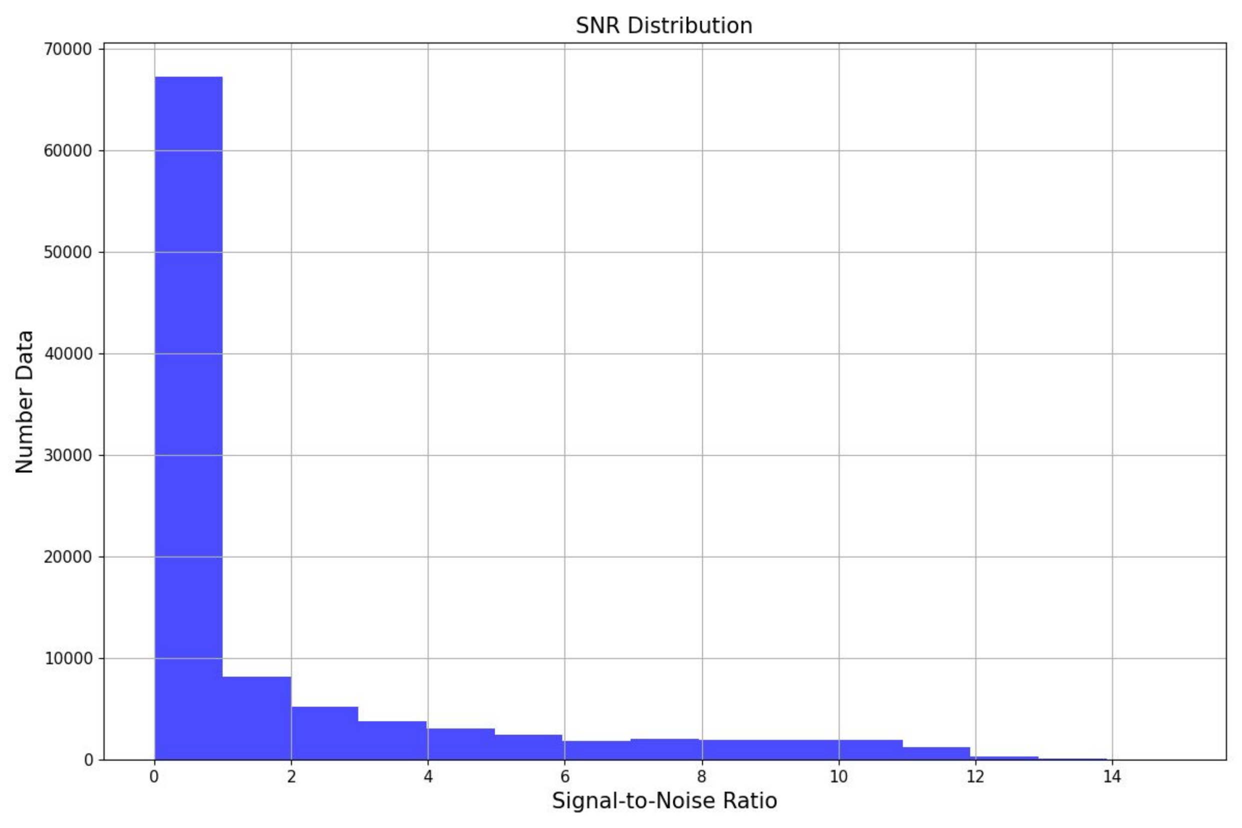
Introduction of ZHaires Data distribution,
Processing

Data Overview

- Dataset: Analog-to-Digital Converters counts (**ADC**) vs **time [ns]**
- **SNR:=** Max of Pure signal / Standard Deviation of Noisy Signal



Data Distribution for Various SNRs



- Number of Antennas **~ 300.**
- Many Signals with SNR < 1.
- **30,000** simulations (**80%** training, **10%** test, **10%** validation)

02

Introduction to the Autoencoder

Model Structure & Parameters

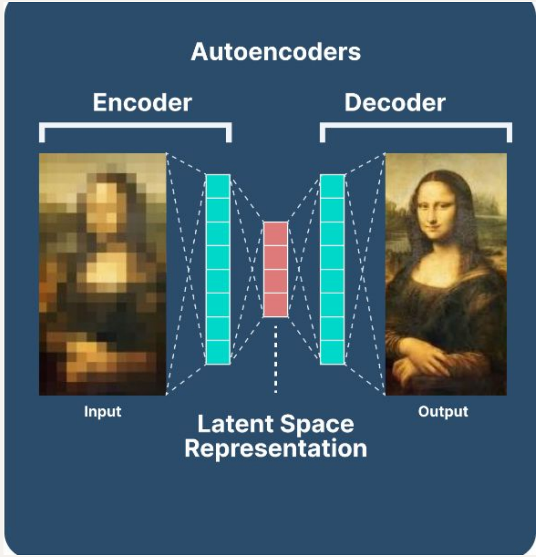
Motivation for the Autoencoder

General Structure

- **Encoder**: Compresses data, captures the essential features of the training data.

- **Latent Space Representation**: Stores the training data features.

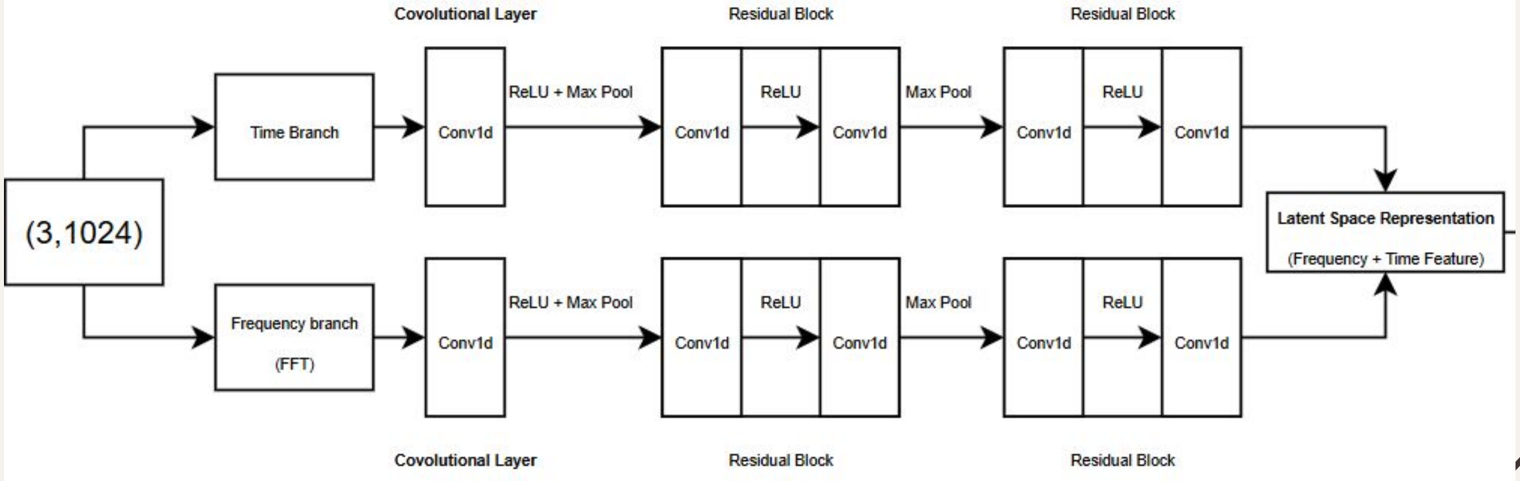
- **Decoder:** Reconstructs data based on the true signal characteristics while filtering out noise.



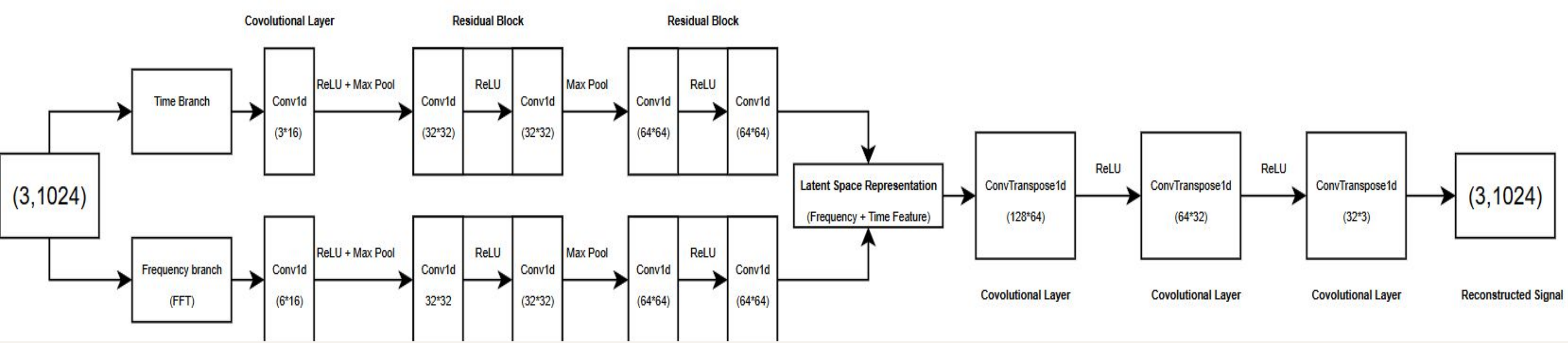
Encoder of Time Domain and Frequency Domain

Model Architecture:

- **Time Domain Branch**: Processes raw ADC counts (x, y, z channels) in the time domain
- **Frequency Domain Branch**: Processes frequency-transformed ADC data (via FFT).
- **Outputs of both branches** are concatenated to form the **latent space representation**.



Hyperparameters of the Model



Training Setup:

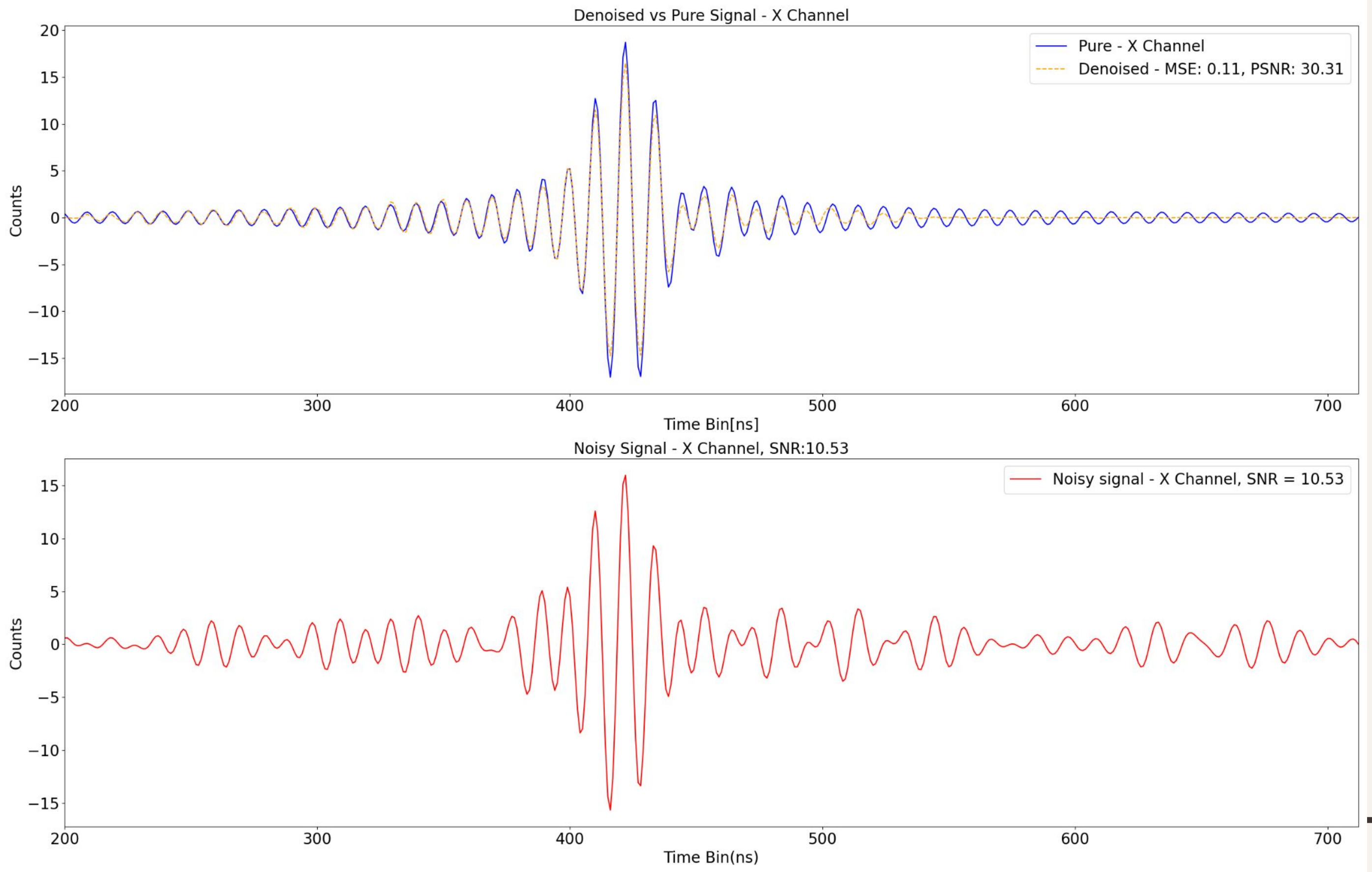
- **Epochs: 100**
- **Learning Rate: 0.0001**
- **Optimizer: AdamW**
- **Loss Function: MSELoss**
- **Performance Metrics: MSE & PSNR**

03

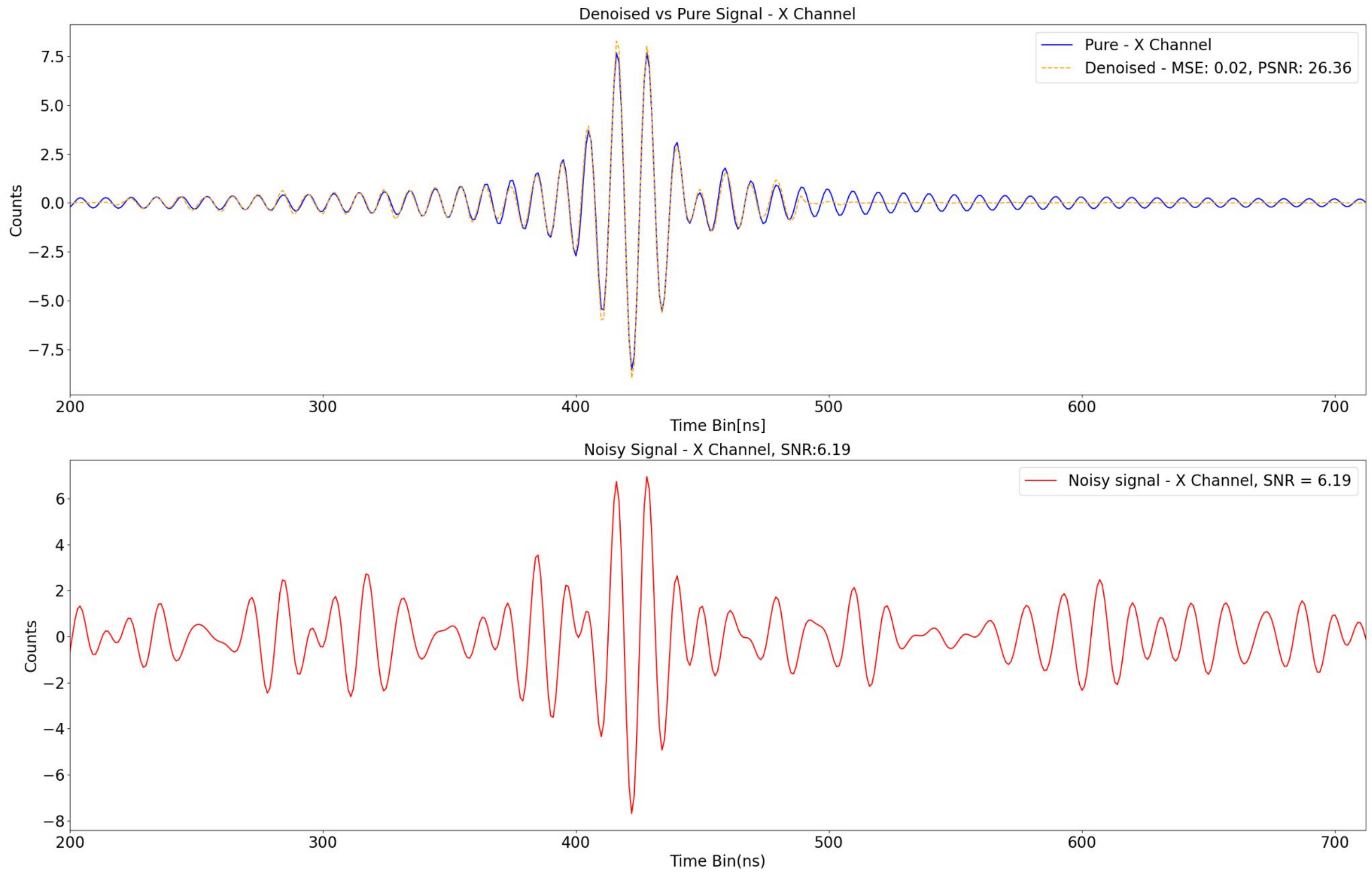
Results

Denoising Results and Analysis

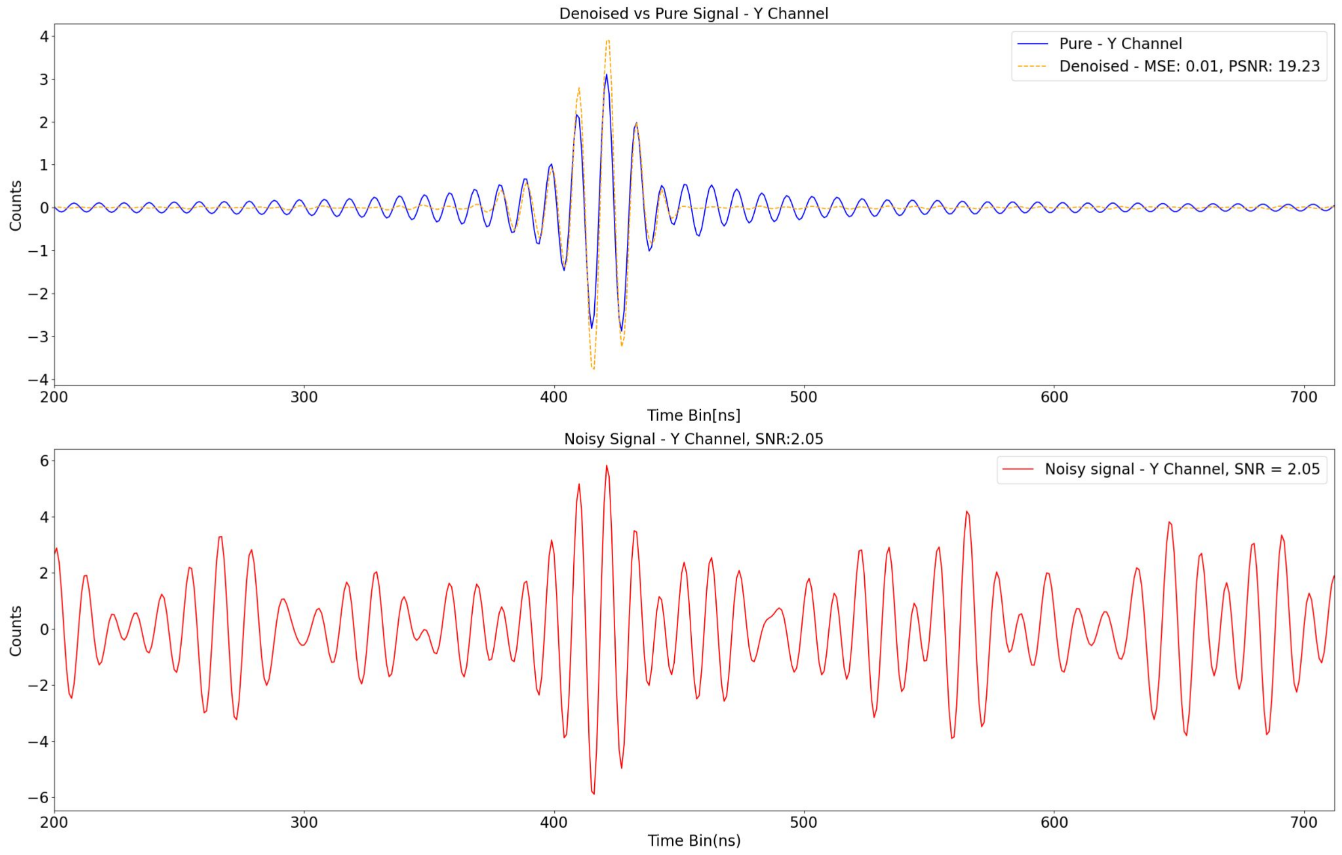
SNR > 10 (X-Channel)



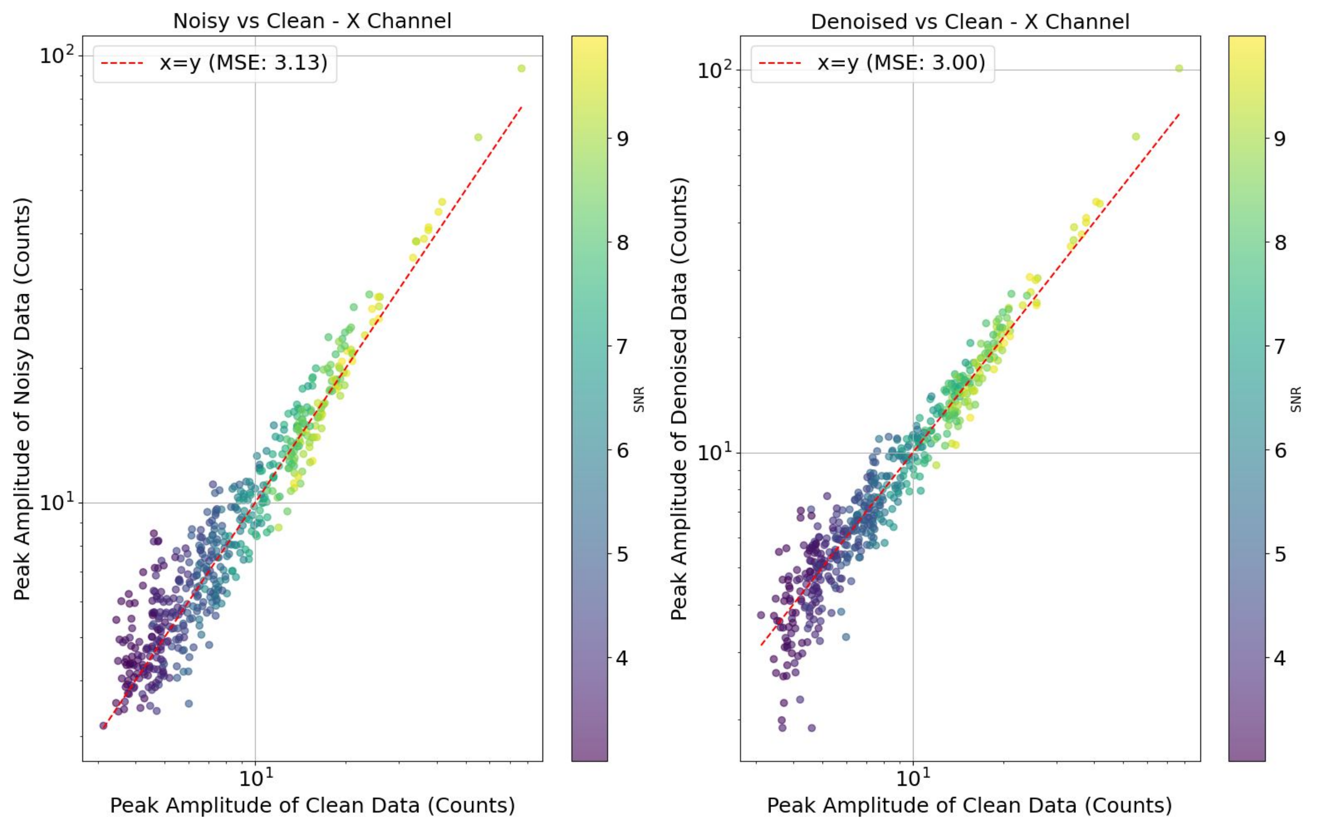
10> SNR > 3 (X-Channel)



SNR < 3 (X-Channel)



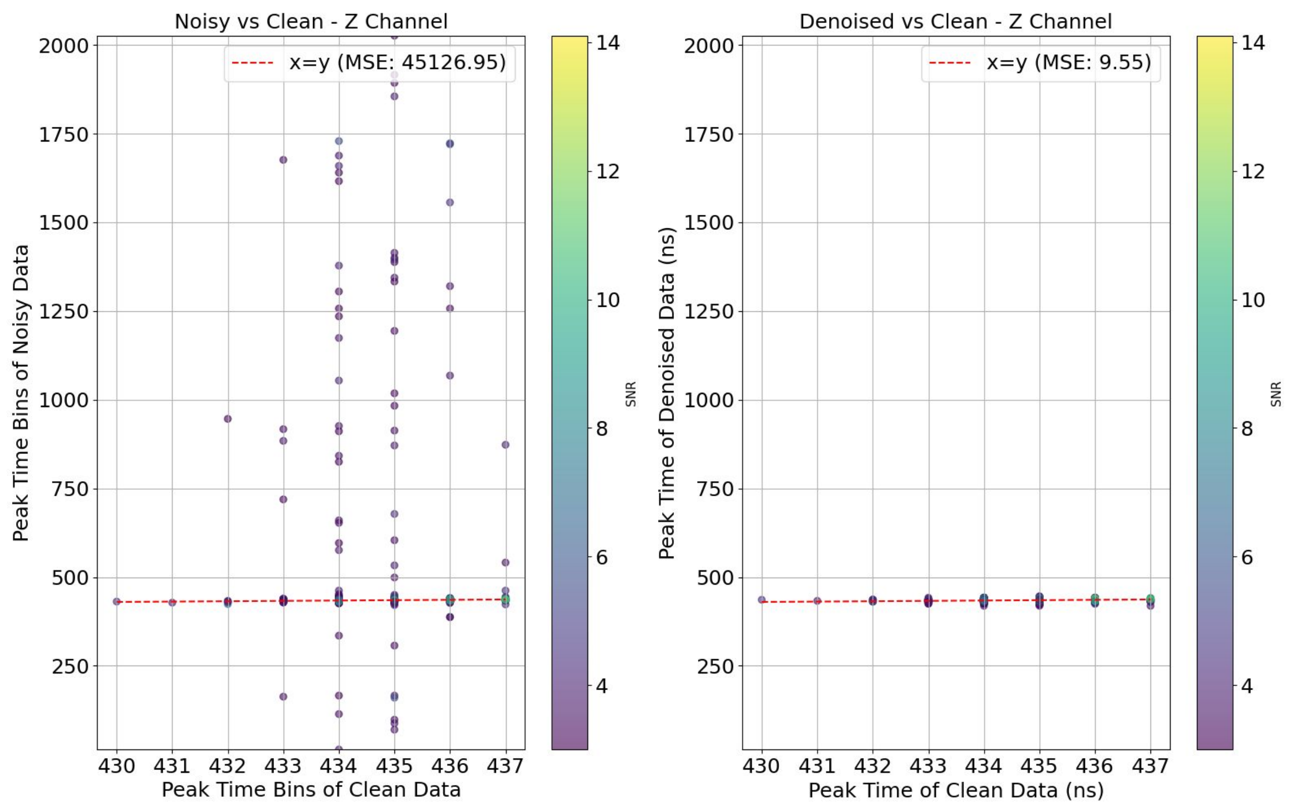
10>SNR > 3, Peak Amplitude (X-Channel)



X-Channel:

- **Left Panel:** Peak Amplitude of Noised Data (Y-Axis) vs Peak Amplitude of Clean Data (X-Axis). **MSE: 3.13**
- **Right Panel:** Peak Amplitude of Denoised Data (Y-Axis) vs Peak Amplitude of Clean Data (X-Axis). **MSE: 3.00**
- Data points are closer to the Red-dot line indicated the better reconstructions.

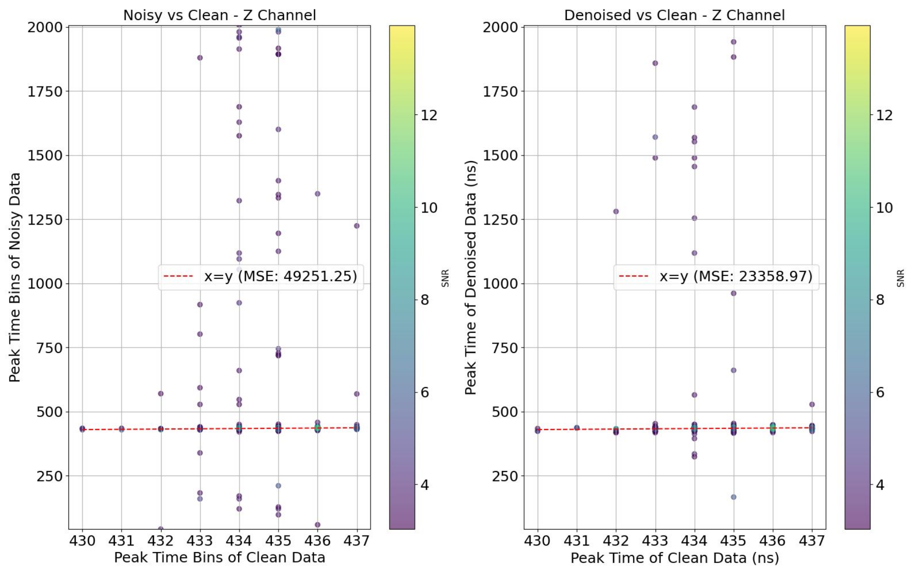
10>SNR > 3, Peak Time (Z-Channel)

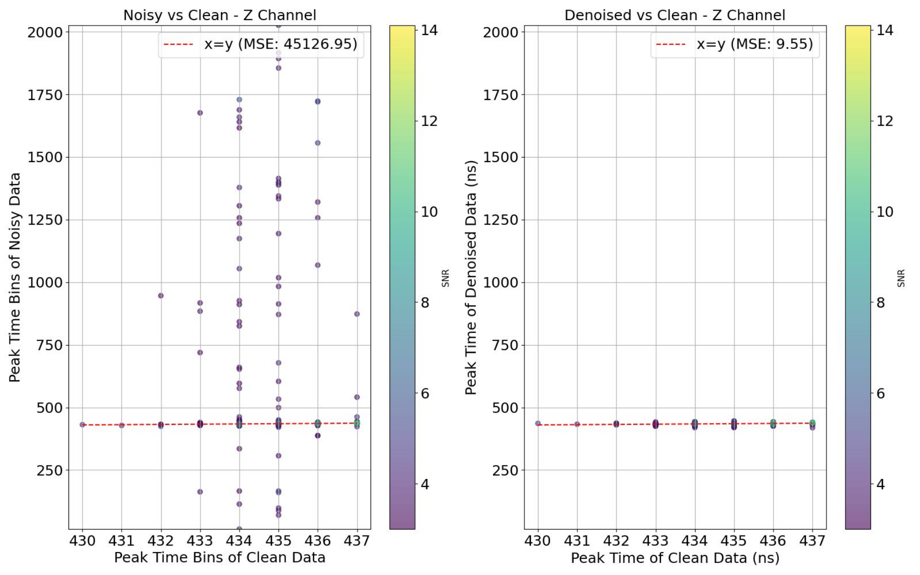


X-Channel:

- **Left Panel MSE: 45,126**
- **Right Panel MSE: 9.55.**
- There is a significant effect in peak time reconstruction for snr between 3 and 10.

10>SNR > 3, Peak Time (Z-Channel)

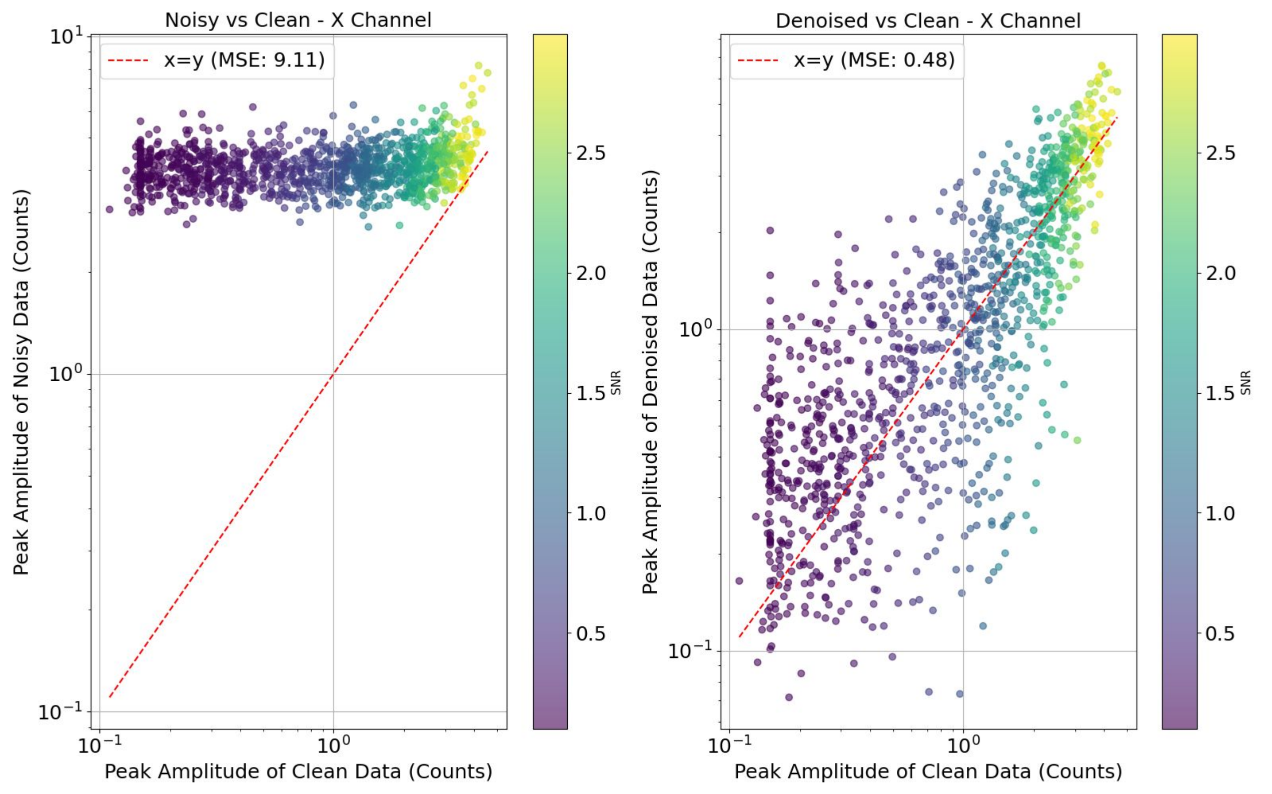




Left: Train with the Autoencoder model without frequency branch in the encoder

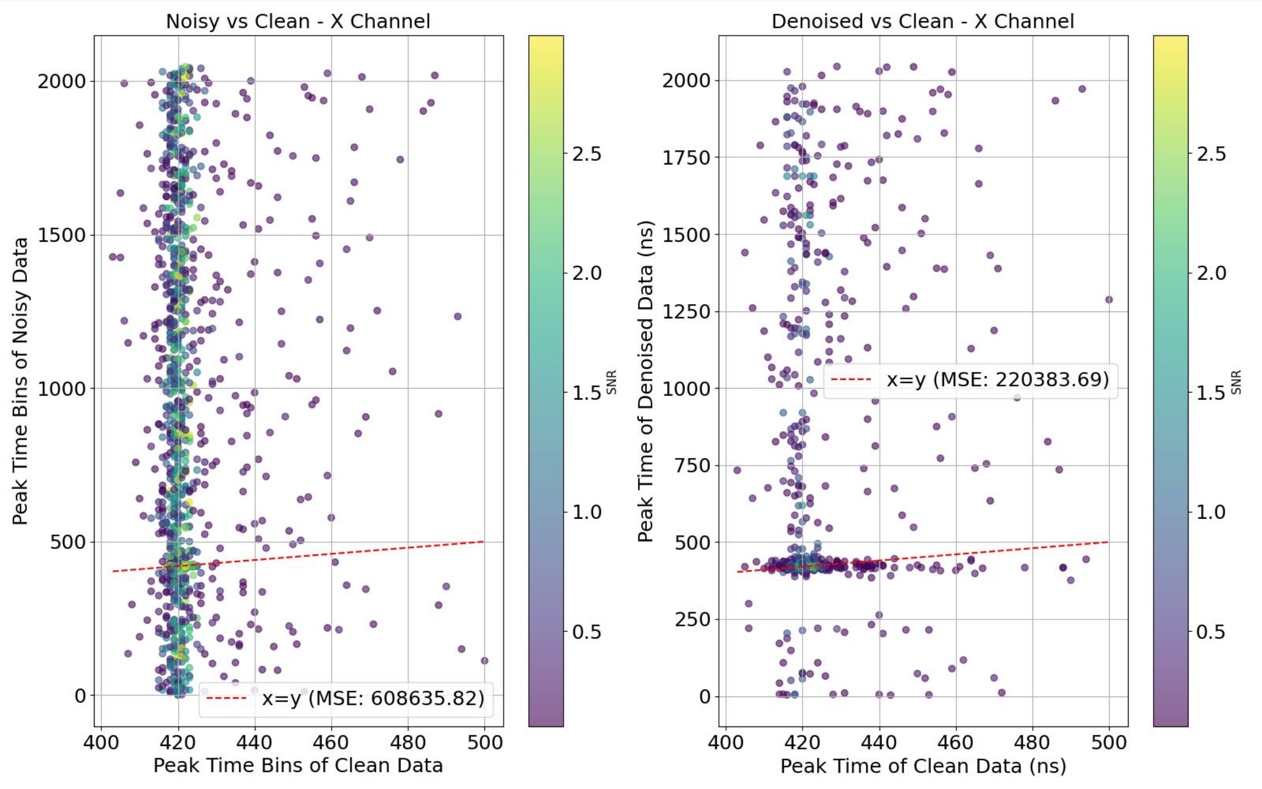
Right: Train with the Autoencoder model frequency branch in the encoder.

SNR <3, Peak Amplitude (X-Channel)



- Encouraging preliminary results, but large preliminary dispersion

SNR <3, Peak Time (X-Channel)



Summary and Future Work

- The Model works well for SNRs > 3, specially for the Peak Time Reconstruction.

  Encouraging for SNR < 3, but further work needed.

- Our most important results so far: Improved peak time reconstruction suggests a more accurate determination of the trigger time.

- Future work: Test the Autoencoder model with real data Tune the model for inclusion in the antenna hardware.

Backup slides (Would not be presented)

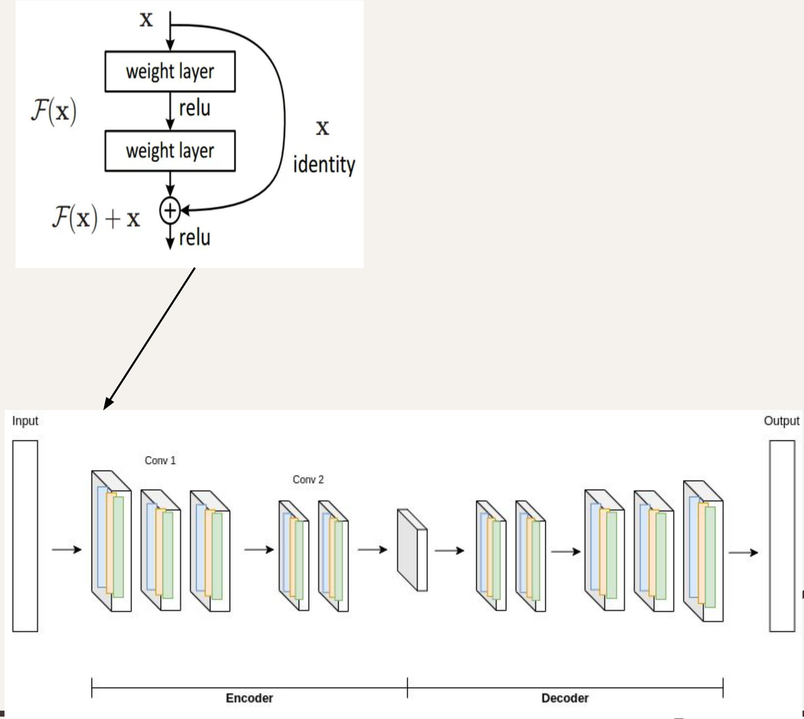
- Backup slides from 19 to 35 would be the additional information

Data Overview

- Data Criterion: zenith between **70** and **89** degrees and primary energy > **10^9 GeV**
- Total Data size: There are **33833 ADC** signals in X, Y, Z Channel, respectively. Each signal has **1024 time bins**.
- Signals in X, Y, Z Channel are combined into one for **27066** training data, **3384** validation data, and **3383** test data.
- Data is passed by a bandwidth filter to the signals with frequencies smaller than 50 MHz and greater than 200 MHz.

Enhancing Autoencoder with ResNet

- Residual Connection, or skip connection to improve learning
- Allow gradients to flow more easily through the network, solving vanishing gradient problem.
- **Benefit 1**: Improve learning efficiency
- **Benefit 2**: Enhance signal reconstruction



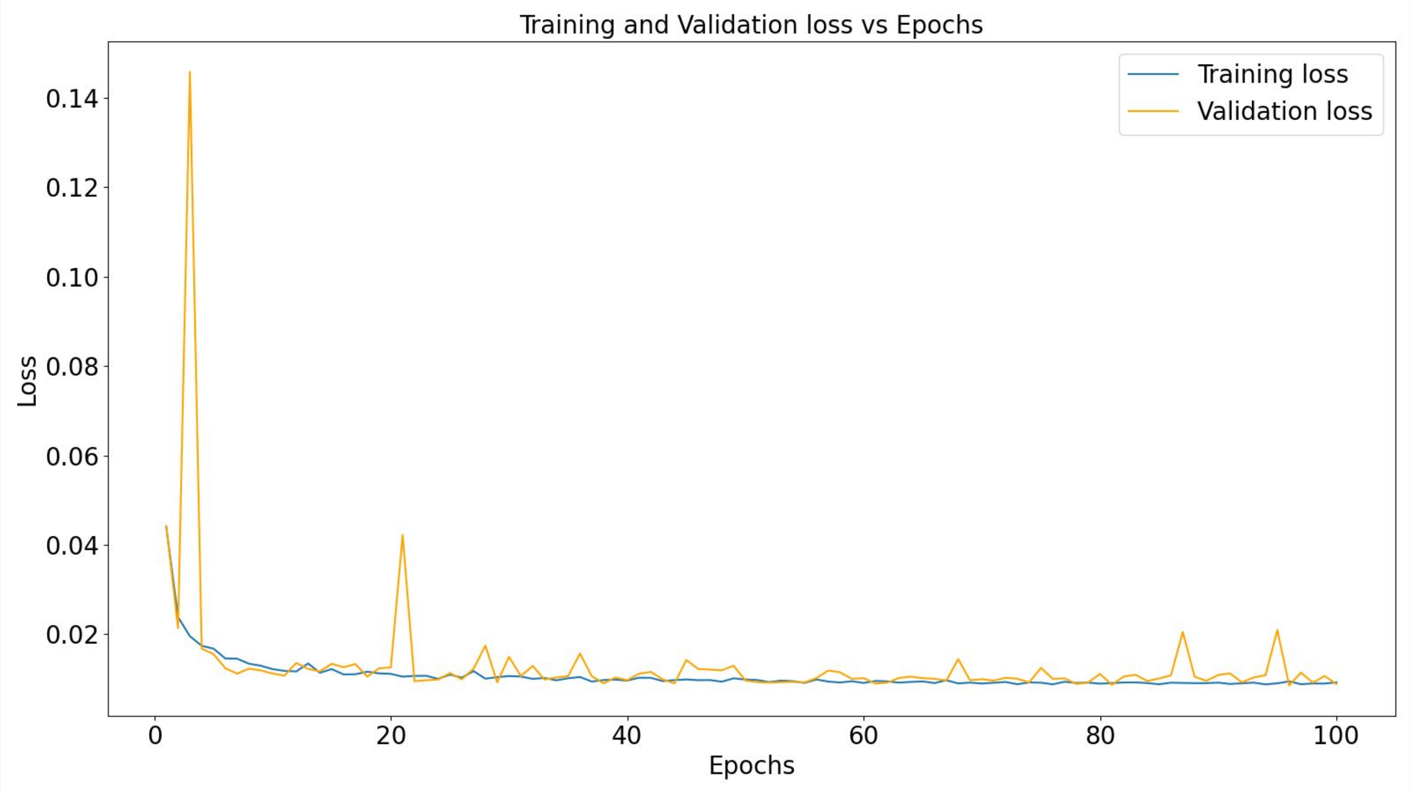
Training Setup

- Dataset split: **80%** training, **10%** validation, **10%** testing.
- Batch size: 4 samples.
- Training details:
    - 50 epochs on **GPU cluster** using PyTorch.
    - **Learning rate:** 0.0001.
    - **Optimizer:** AdamW, combining Adam optimization with weight regularization to enhance convergence and prevent overfitting.
    - **Loss Function:** Mean Squared Error Loss (MSE Loss)
    - **Performance Metrics:** Peak Signal-to-Noise Ratio(PSNR), Mean Squared Error(MSE)

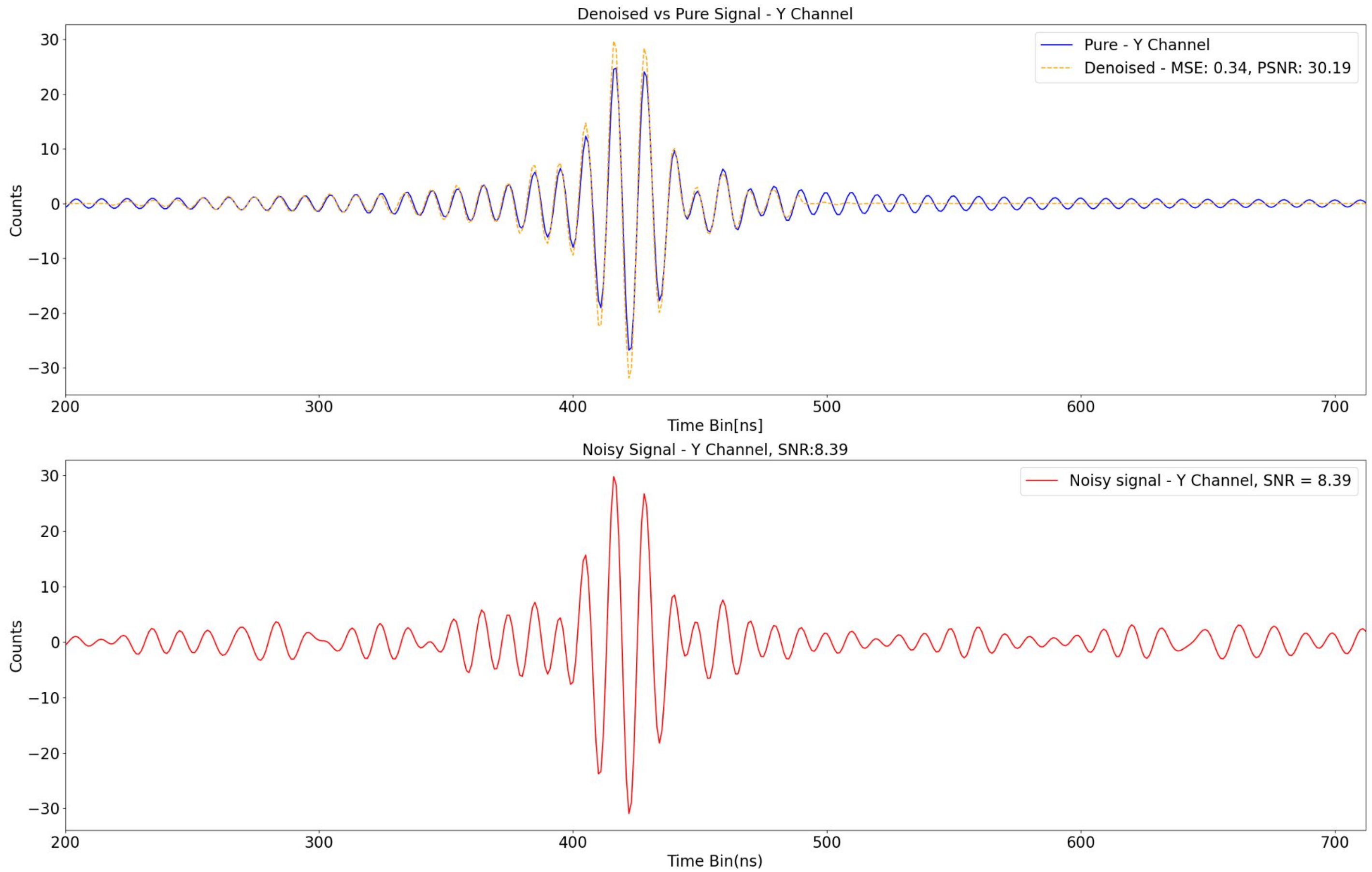
$$\text{MSE} = \frac{1}{N}\sum_{i=1}^{N}(y_i - \hat{y}_i)^2$$

$$PSNR = 10 \cdot \log_{10}\left(\frac{MAX^2}{MSE}\right)$$

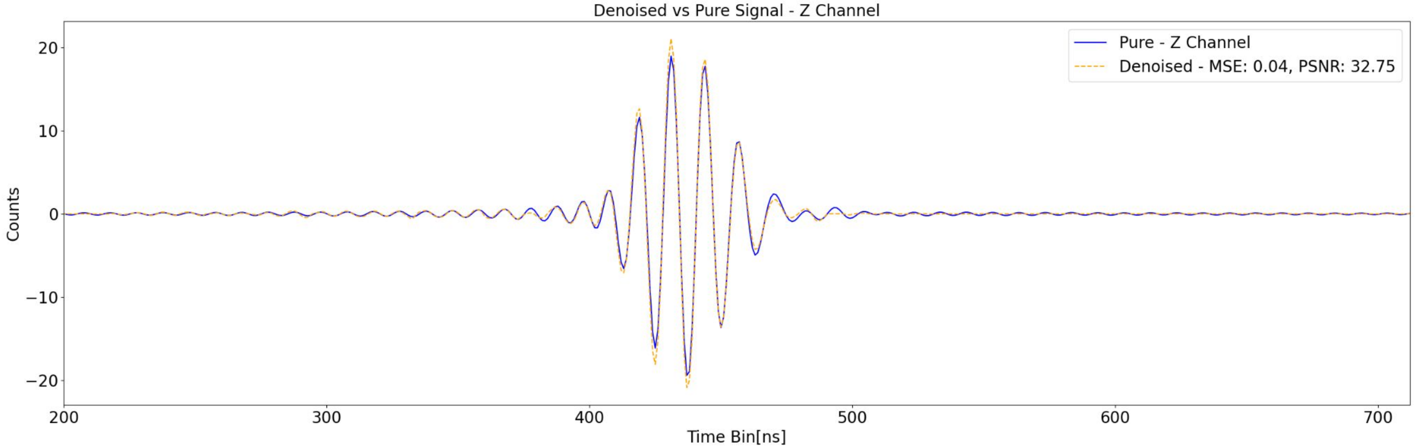
Training & Validation Loss

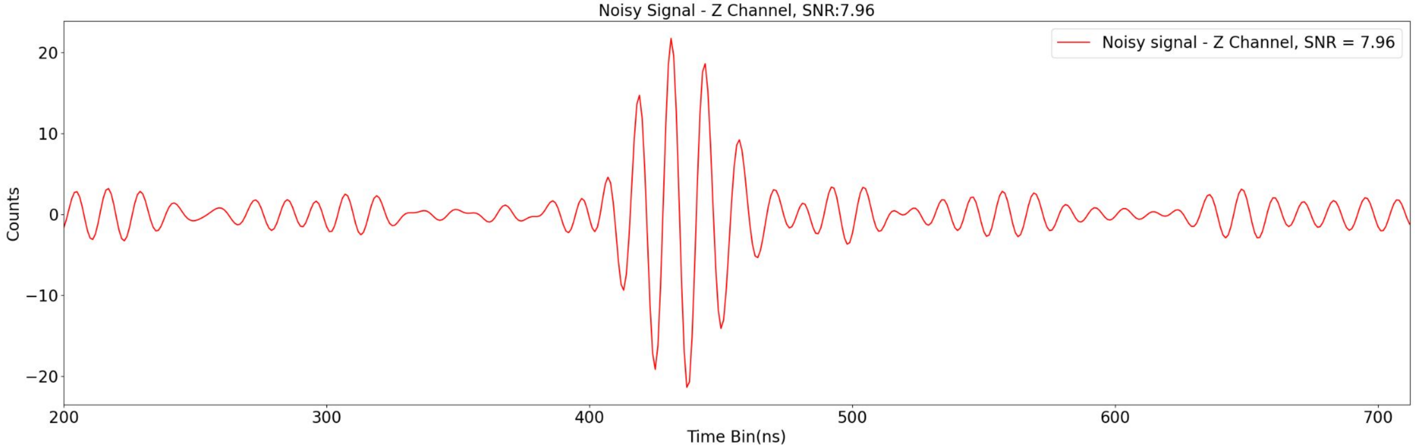


10> SNR > 3, Y-Channel

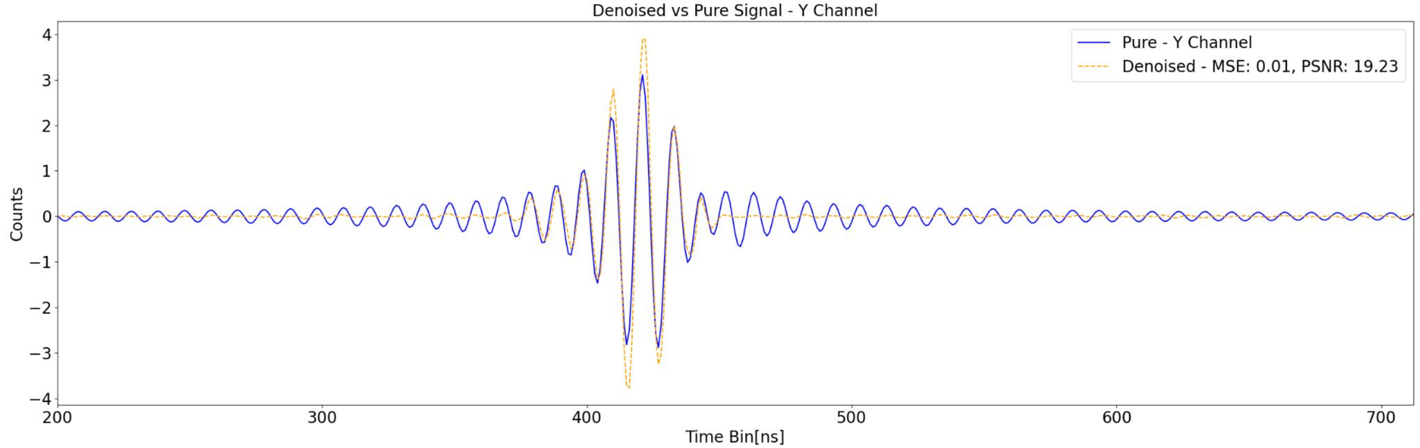


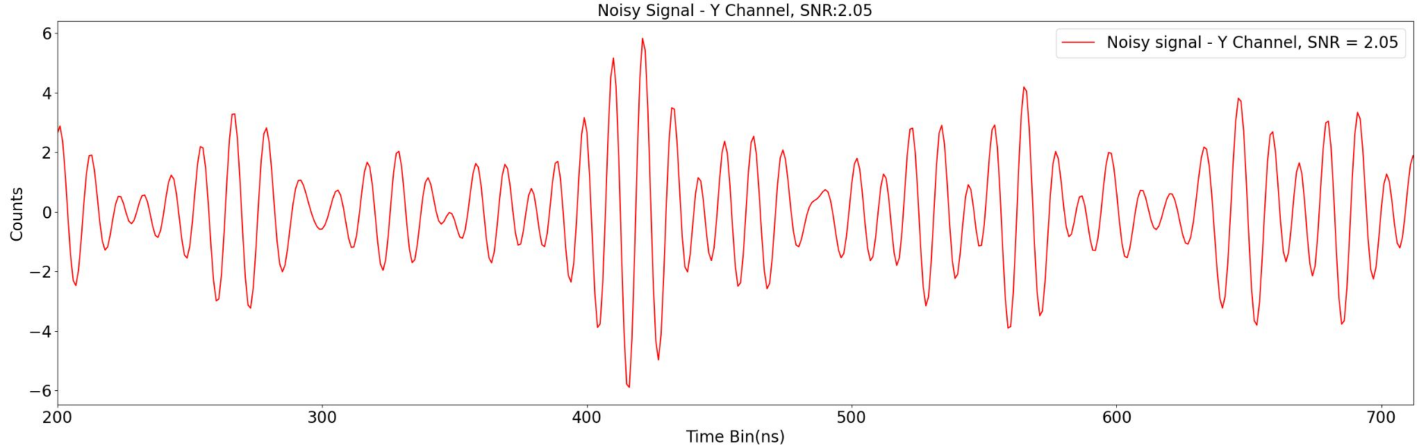
10> SNR > 3, Z-Channel



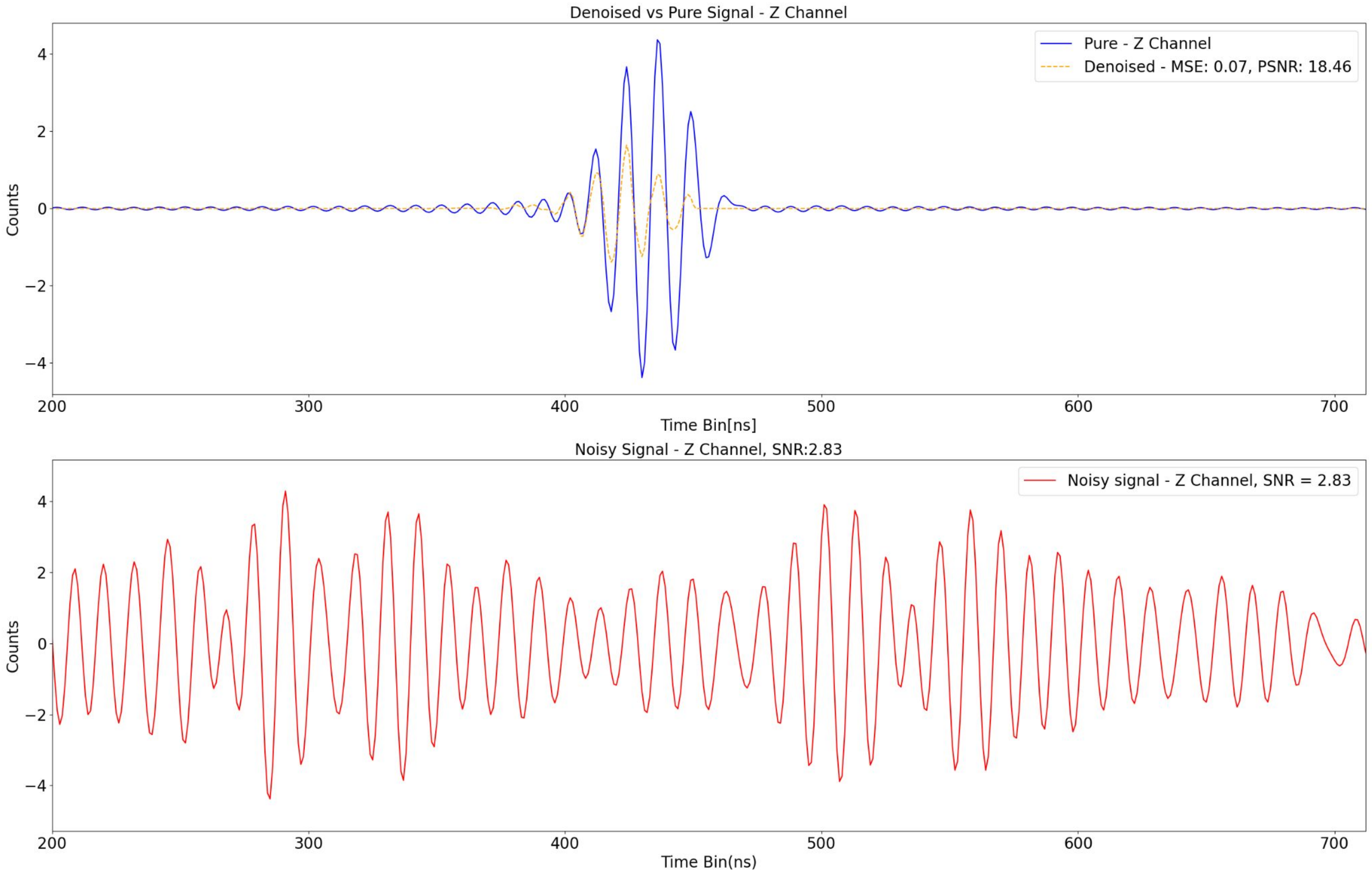


SNR < 3, Y-Channel

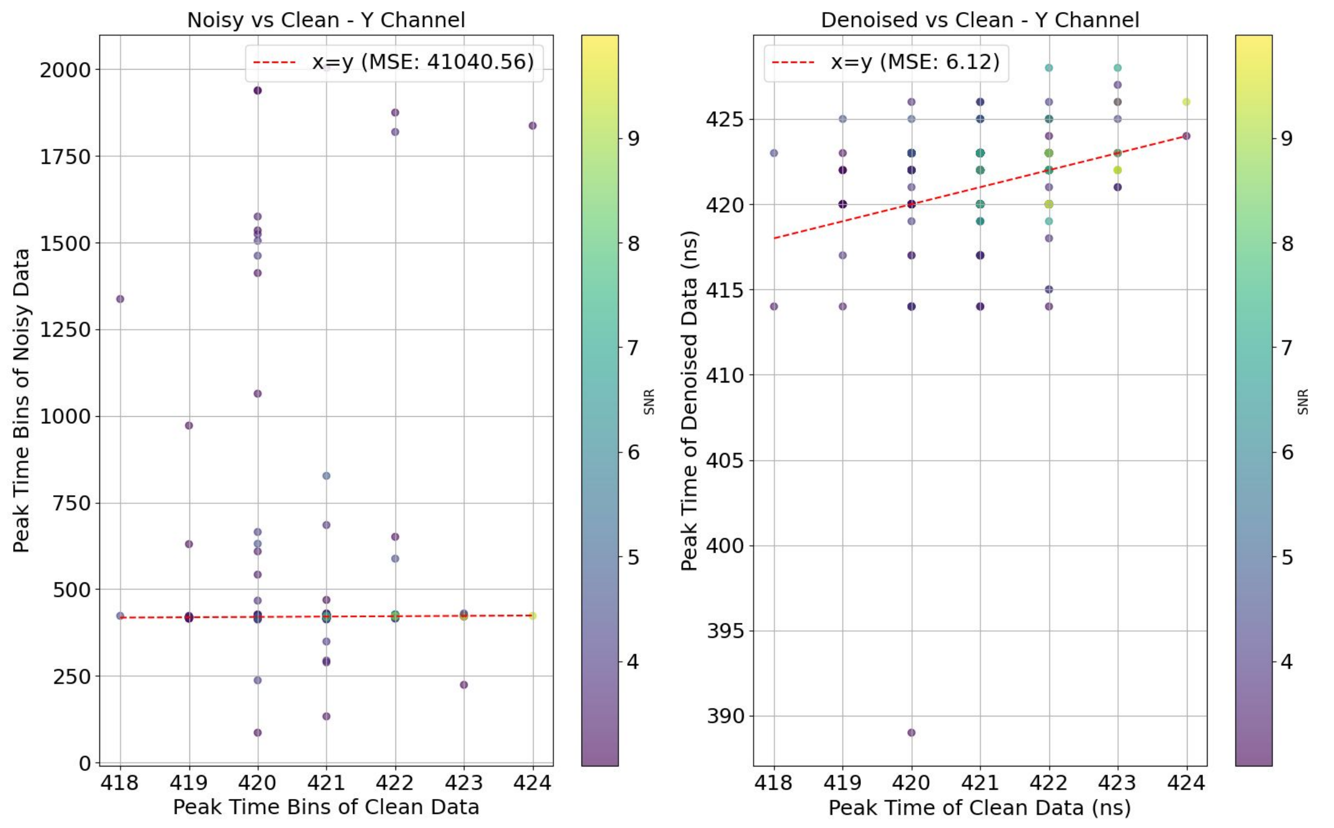




SNR < 3, Z-Channel



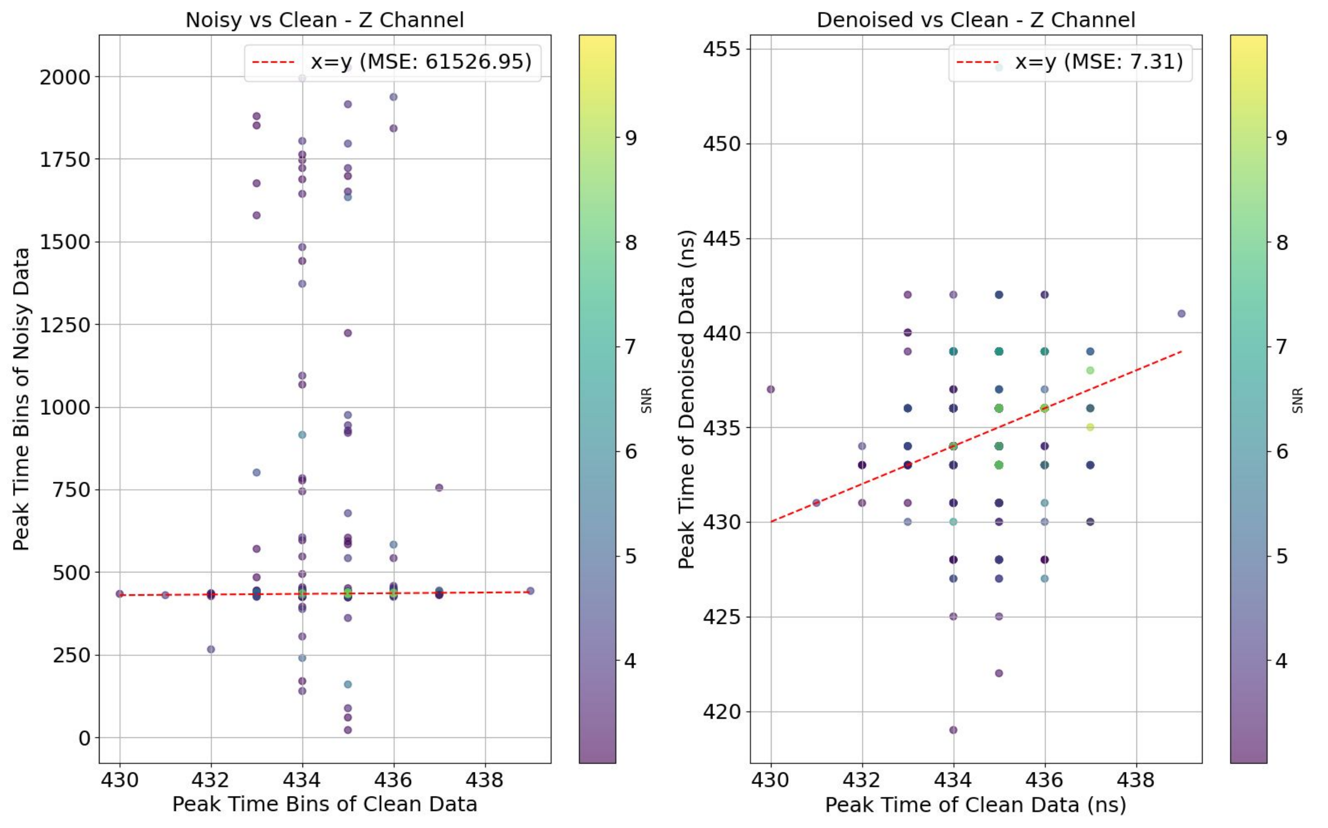
10>SNR > 3, Peak Time -Y



Y-Channel:

- **Left Panel MSE: 410,40**
- **Right Panel MSE: 6.12**

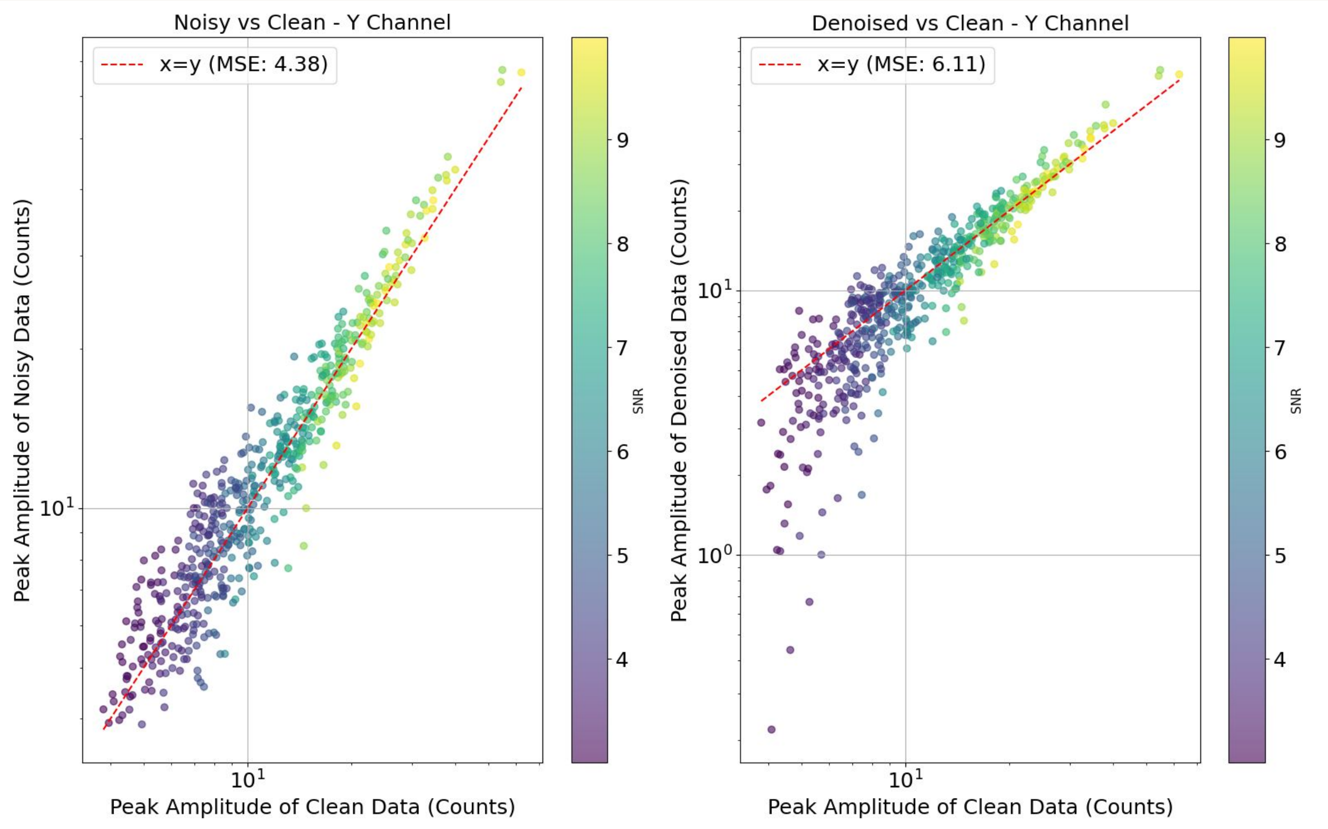
10>SNR > 3, Peak Time -Z



Z-Channel:

- **Left Panel MSE: 61,526**
- **Right Panel MSE: 7.31**

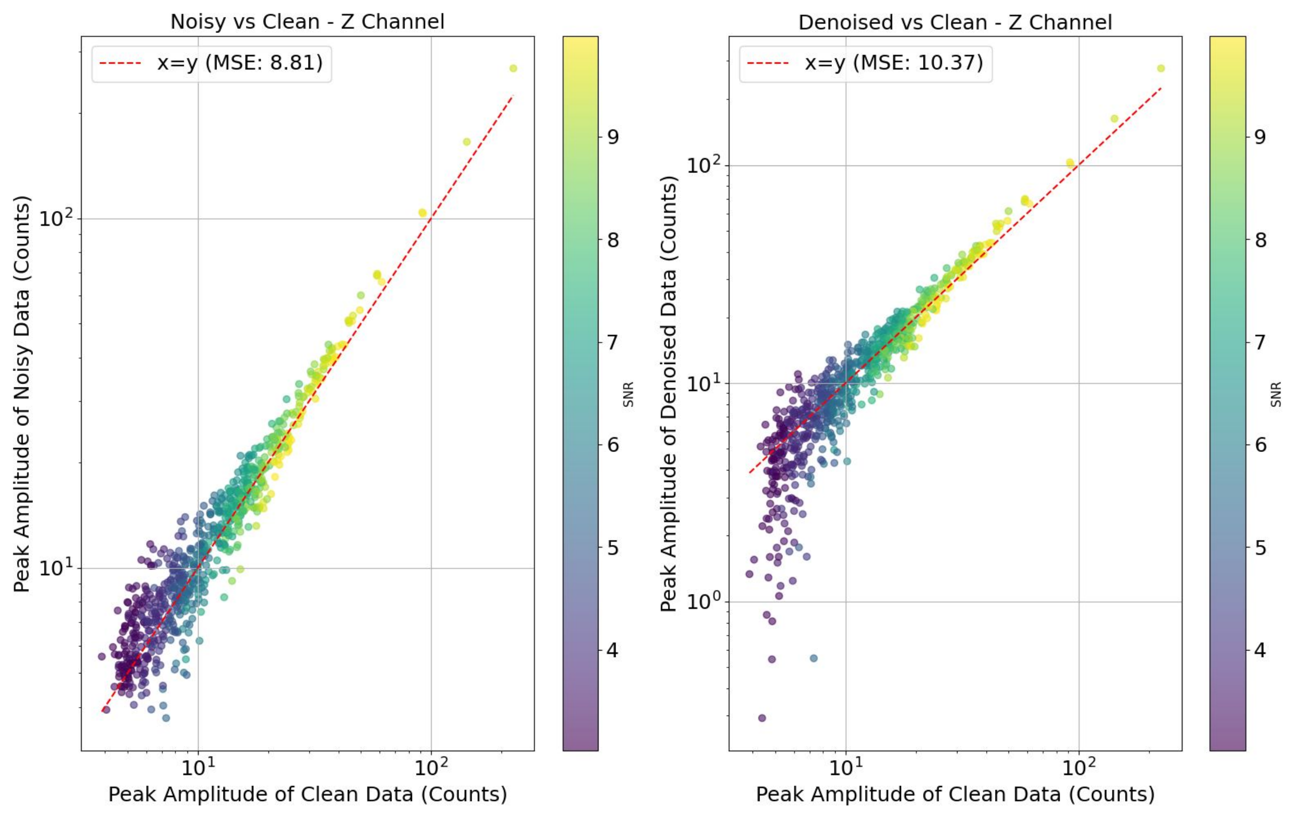
10>SNR > 3, Peak Amplitude (Y-Channel)



Y-Channel:

- **Left Panel MSE: 4.38**
- **Right Panel MSE: 6.11**
- Lower SNR's reconstruction still needed to improve

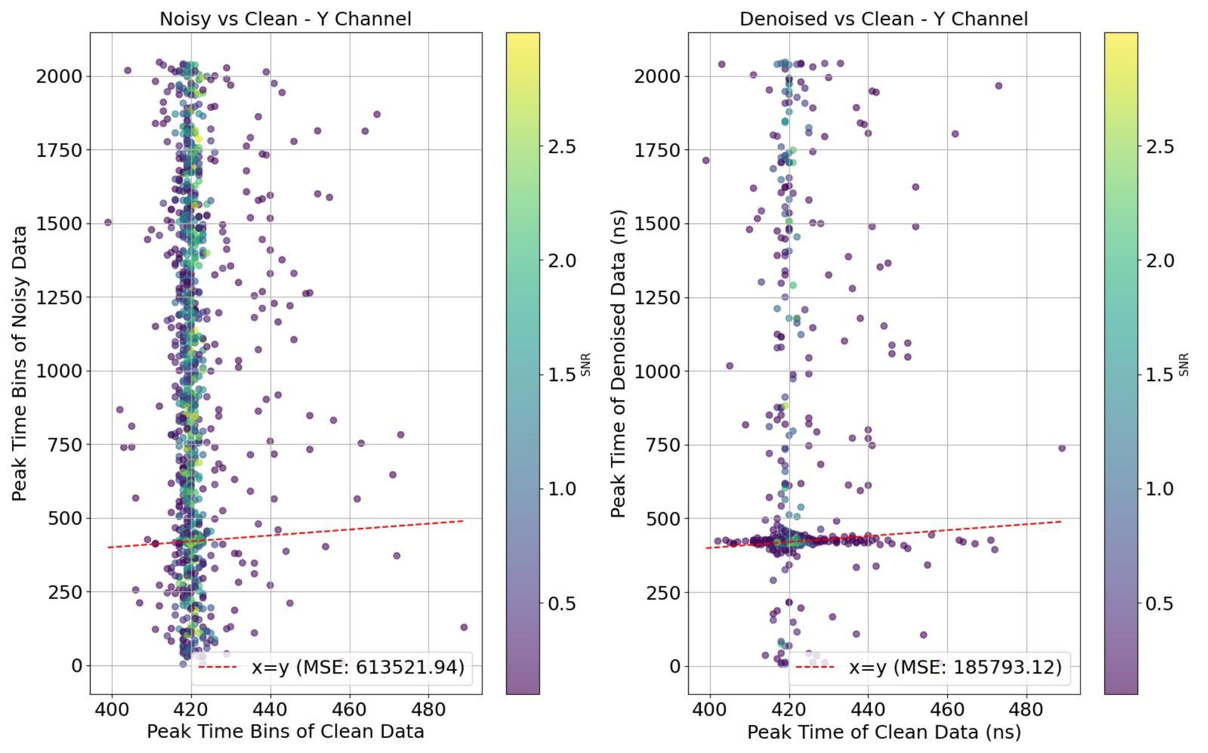
10>SNR > 3, Peak Amplitude (Z-Channel)



Z-Channel:

- **Left Panel MSE: 8.81**
- **Right Panel MSE: 10.37**

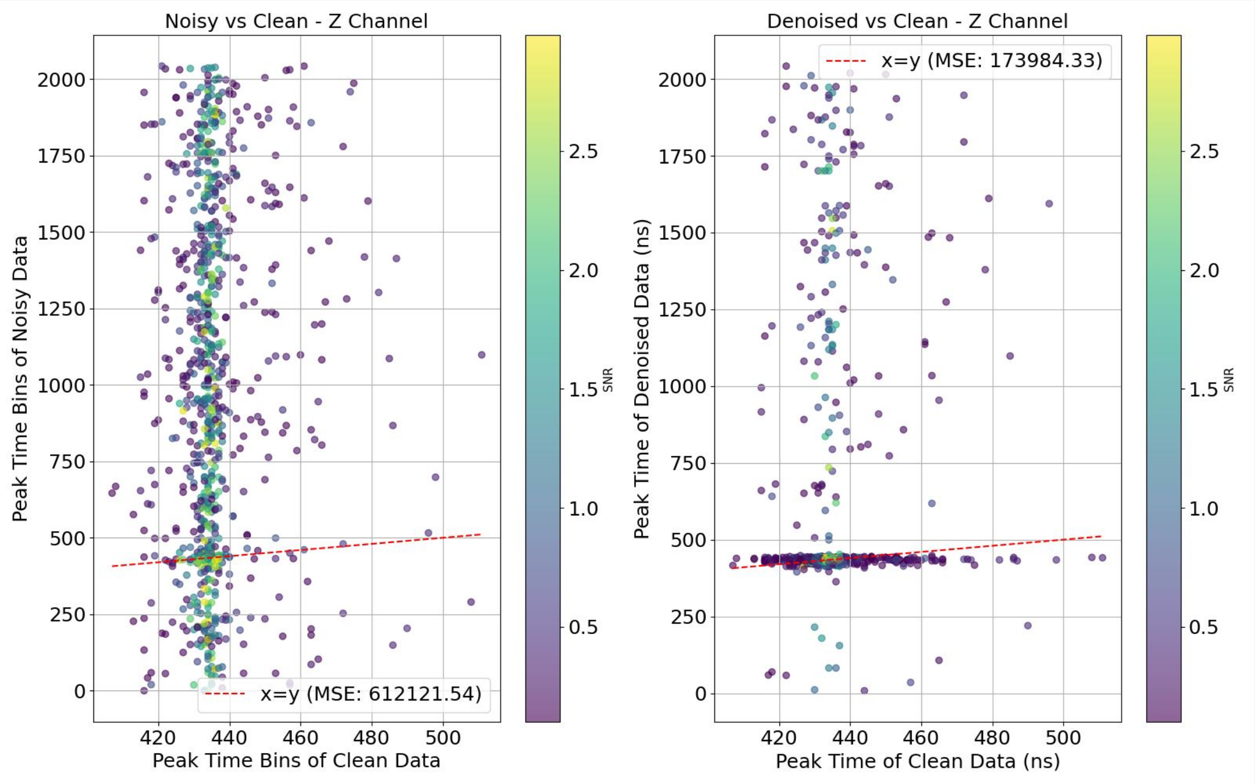
SNR <3, Peak Time - Y



Y-Channel:

- **Left Panel MSE: 613,521**
- **Right Panel MSE: 185,793**

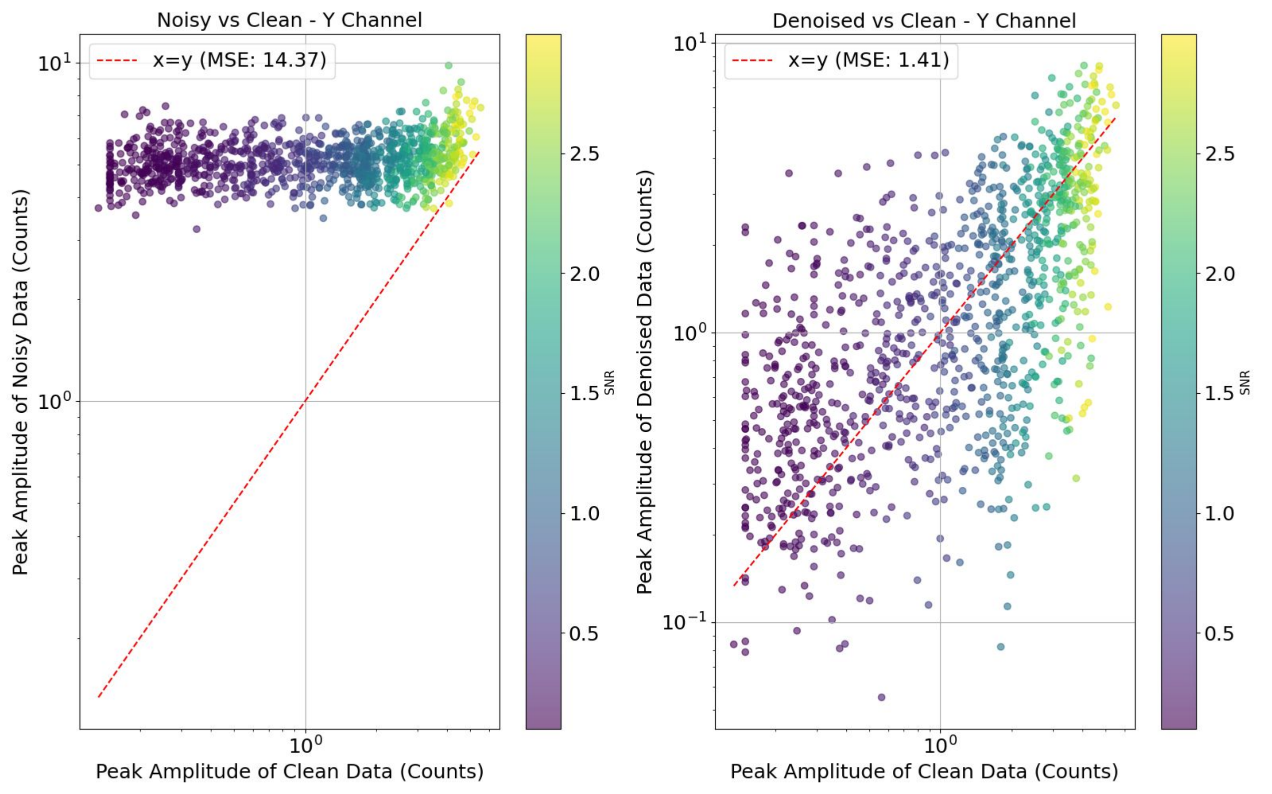
SNR <3, Peak Time - Z



Z-Channel:

- **Left Panel MSE: 612,121**
- **Right Panel MSE: 173,984**

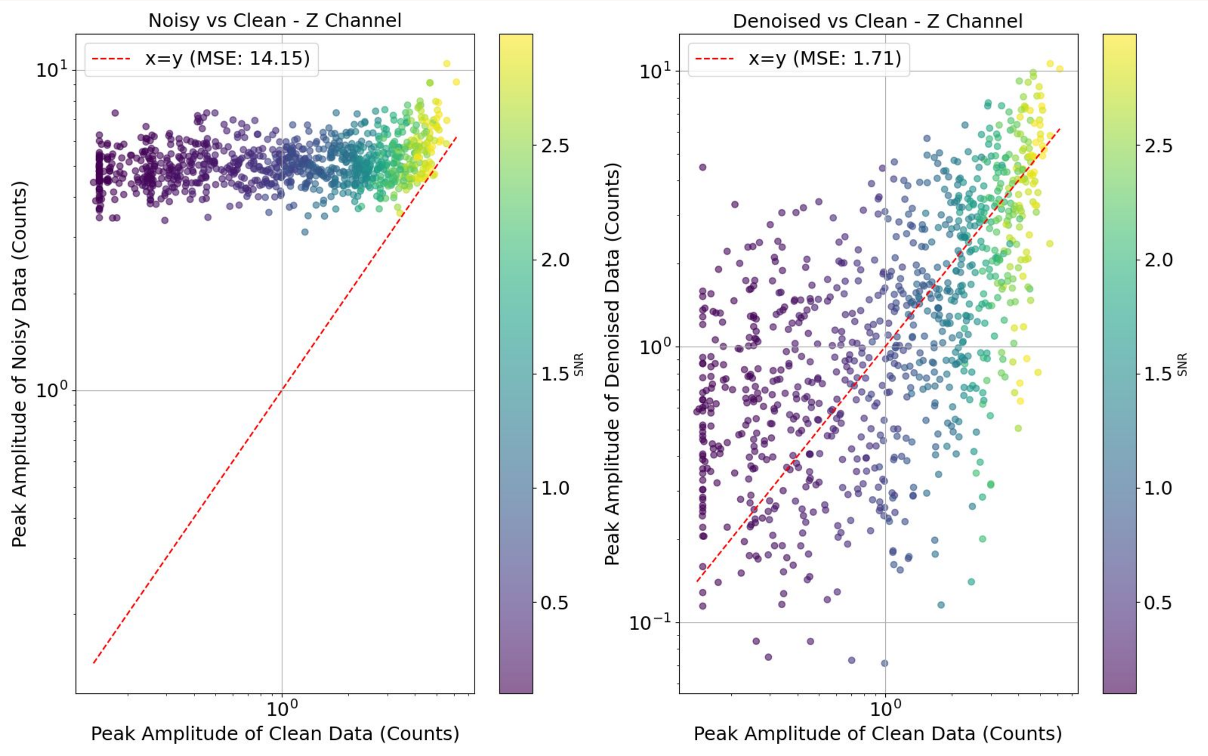
SNR <3, Peak Amplitude-Y



Y-Channel:

- **Left Panel MSE: 14.37**
- **Right Panel MSE: 1.41**

SNR <3, Peak Amplitude-Z



Z-Channel:

- **Left Panel MSE: 14.15**
- **Right Panel MSE: 1.71**