REMOVING RADIO FREQUENCY INTERFERENCE FROM AURORAL KILOMETRIC RADIATION WITH STACKED CONVOLUTIONAL DENOISING AUTOENCODERS

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AERO-VISTA missions will observe the Earth's auroral region.

- The dominant goal of the AERO-VISTA missions is to study the Earth's auroral zones
- One strong emission is auroral kilometric radiation (AKR), which comes from the electron cyclotron maser mechanism
- One way AKR is downlinked is in the form of time-frequency spectrograms
- However, spectrograms (both observed in space- and ground-level) contain harsh radio frequency interference (RFI) that obscure AKR

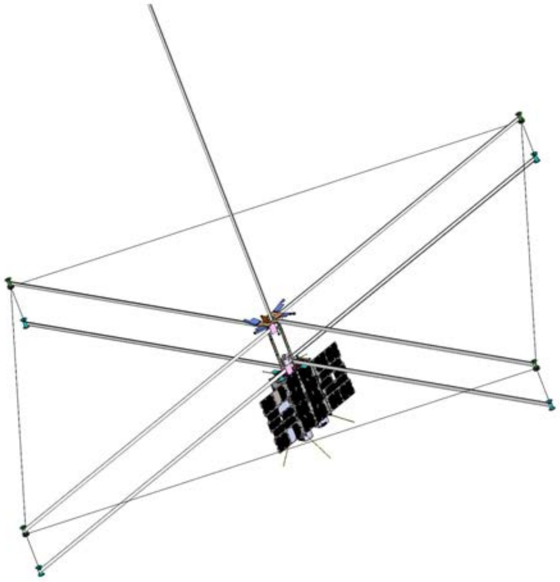


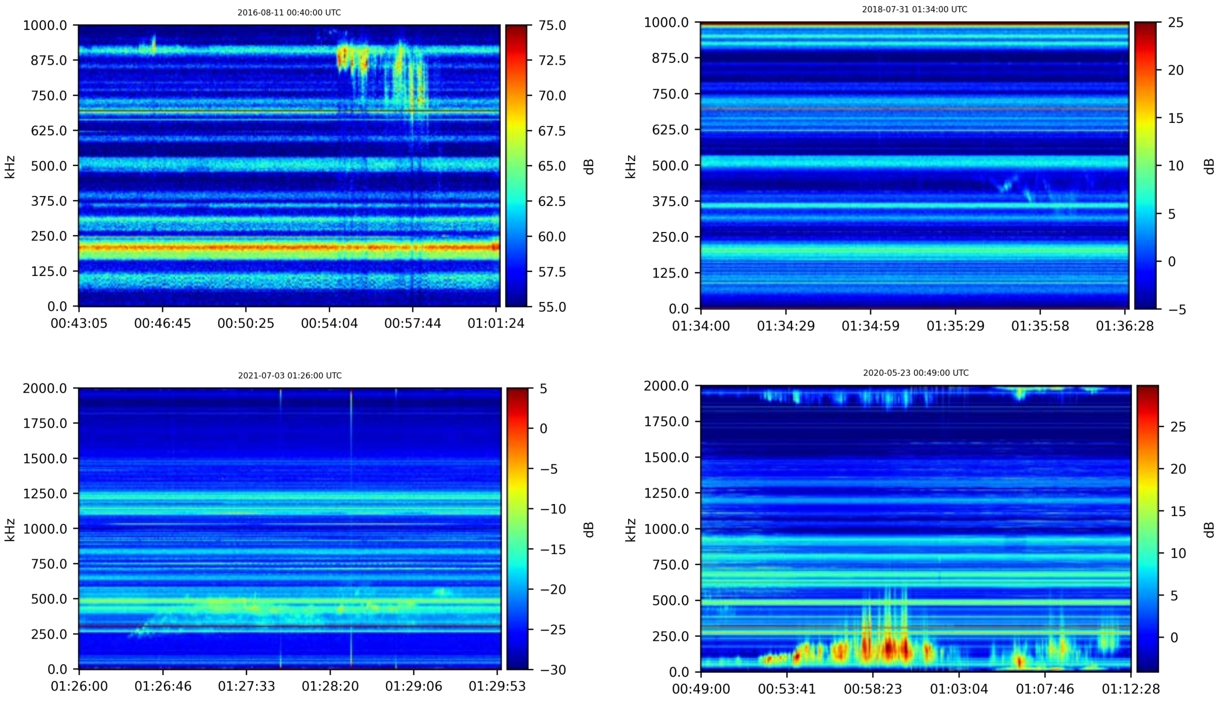
Fig 1. The AERO spacecraft

AERO-VISTA project

AKR observations are corrupted by electronic interference.

- y axis: frequency, typically in the ranges of (0 – 2000 kHz)
- x axis: time
- color: dB intensity

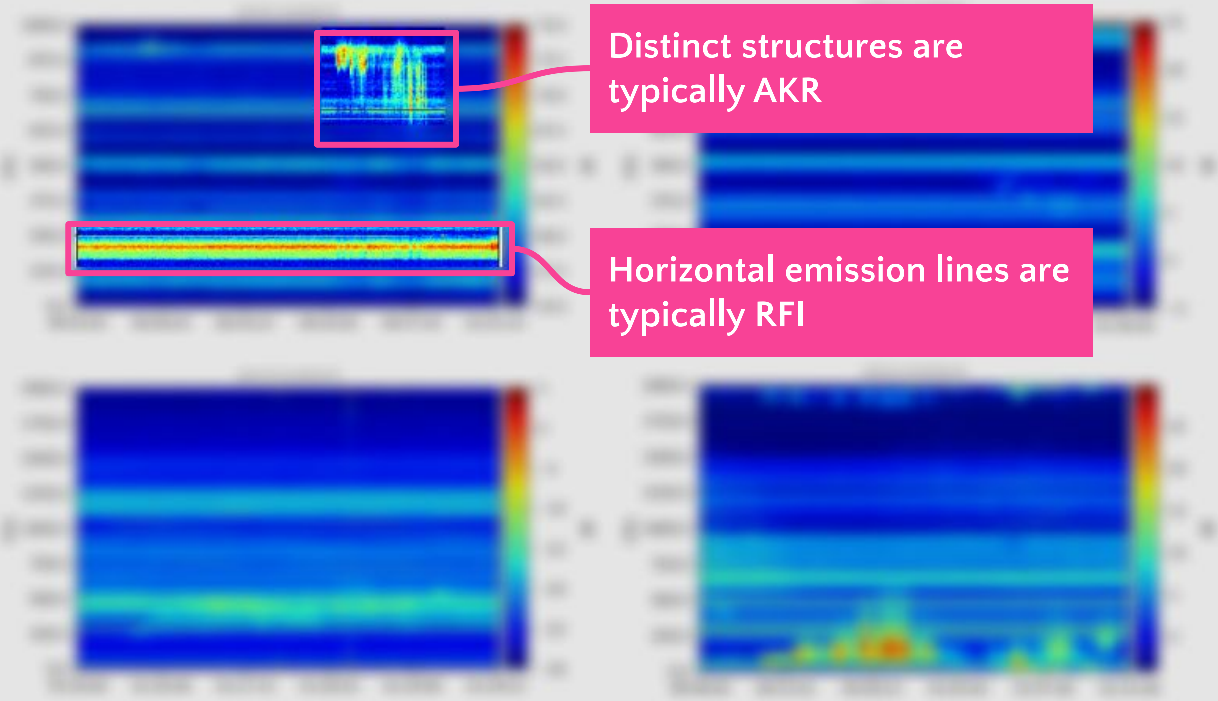
* plots have different scales



AKR observations are corrupted by electronic interference.

- y axis: frequency typically in the ranges of 10 - 2000 kHz
- x axis: time
- color: dB intensity

* plots have different scales



Several motivations exist for noise removal.

- Visual analysis by scientists
- Automatic detection and categorization of auroral radiation
- Unsupervised clustering of emissions with similar characteristics
- Forecasting of future AKR events
- Comparison of AKR across long geographical distances
- Comparison to AKR above the ionosphere
- **(+ any other downstream applications and analysis of AKR data)**

What can be done about noise?

Data collection

- Operate somewhere more silent (such as the South Pole or space)
    - Not a foolproof solution, as seen in the previous plots

Post-processing

- Physical cancellation applying convolutions with wavelets (requires knowledge of the exact structure of the noise, assuming the noise structure is constant)
- Manual instance removal of noise (costly)
- **Apply existing image denoising techniques to spectrograms (this project)**

Main computational image denoising methods.

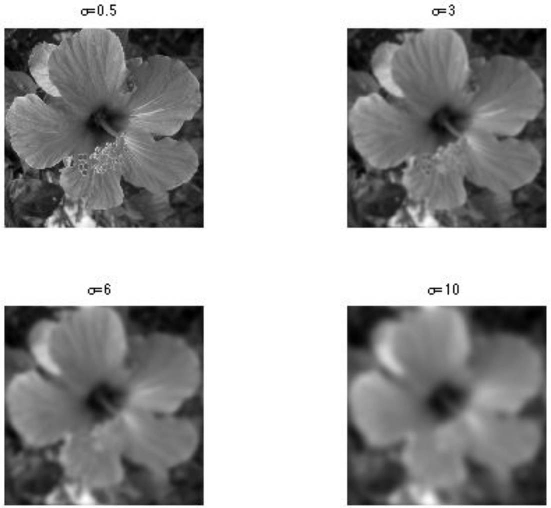


Fig 2. A filtering method

https://www.numerical-tours.com/matlab/denoising adv_8_bilateral/

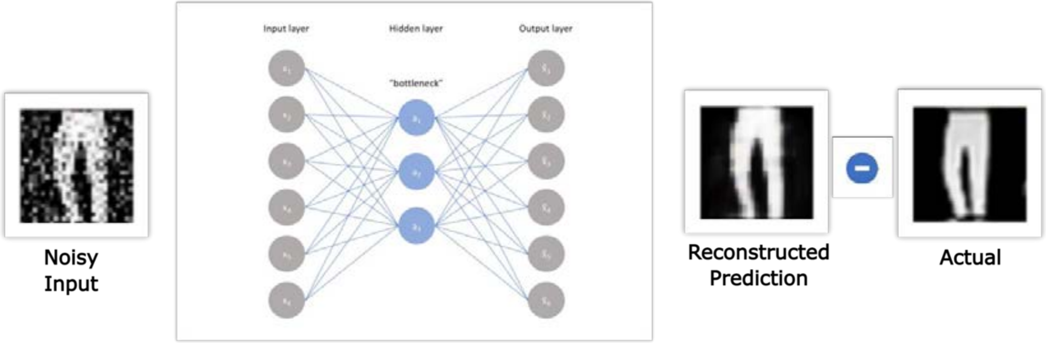


Fig 3. A deep-learning method

https://towardsdatascience.com/6-applications-of-auto-encoders-every-data-scientist-should-know-dc703cbc89 2b

Main steps in a deep-learning approach.

1. We need a dataset for the denoising model to train from
2. Choose an architecture to denoise with
3. Compare across other denoising algorithms to see if our approach is good

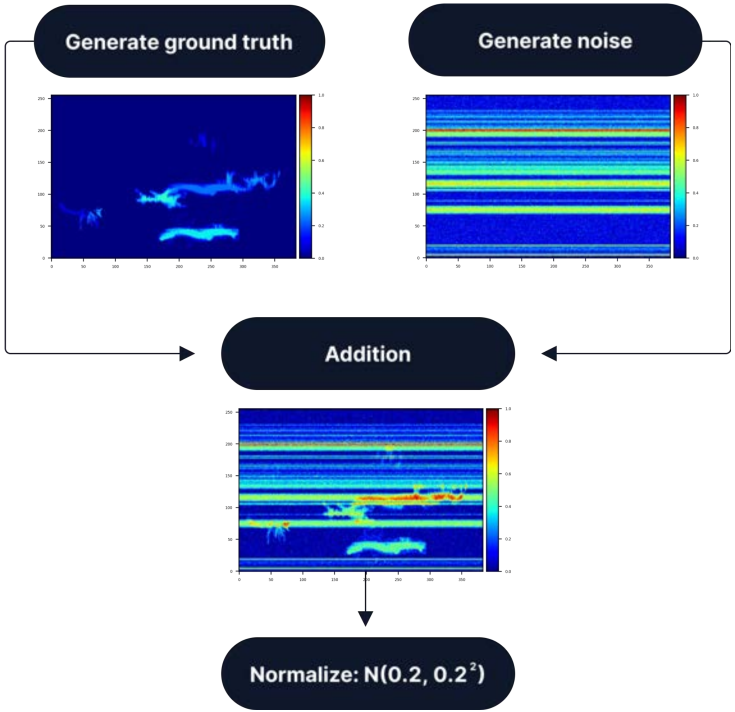
We synthesized random AKR samples to train from.

Variables used to randomize our ground truths include:

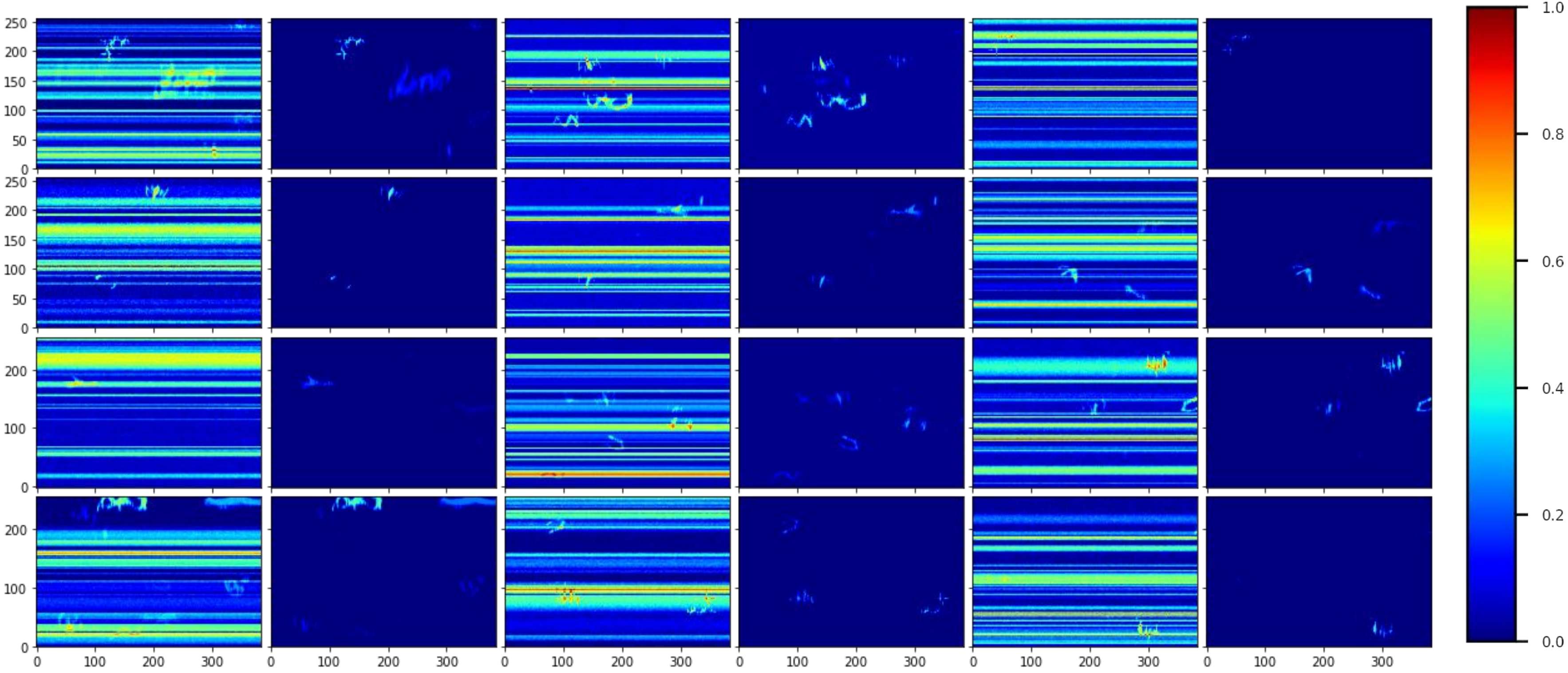
- Background intensity
- Number of AKR
- $AKR^{(i)}$ position
- $AKR^{(i)}$ intensity
- $AKR^{(i)}$ mirroring

Variables used to randomize our noise include:

- Gaussian noise intensity
- Overall channel intensity
- $Channel^{(i)}$ height
- $Channel^{(i)}$ position
- $Channel^{(i)}$ intensity



Sample of training data generated with this method.



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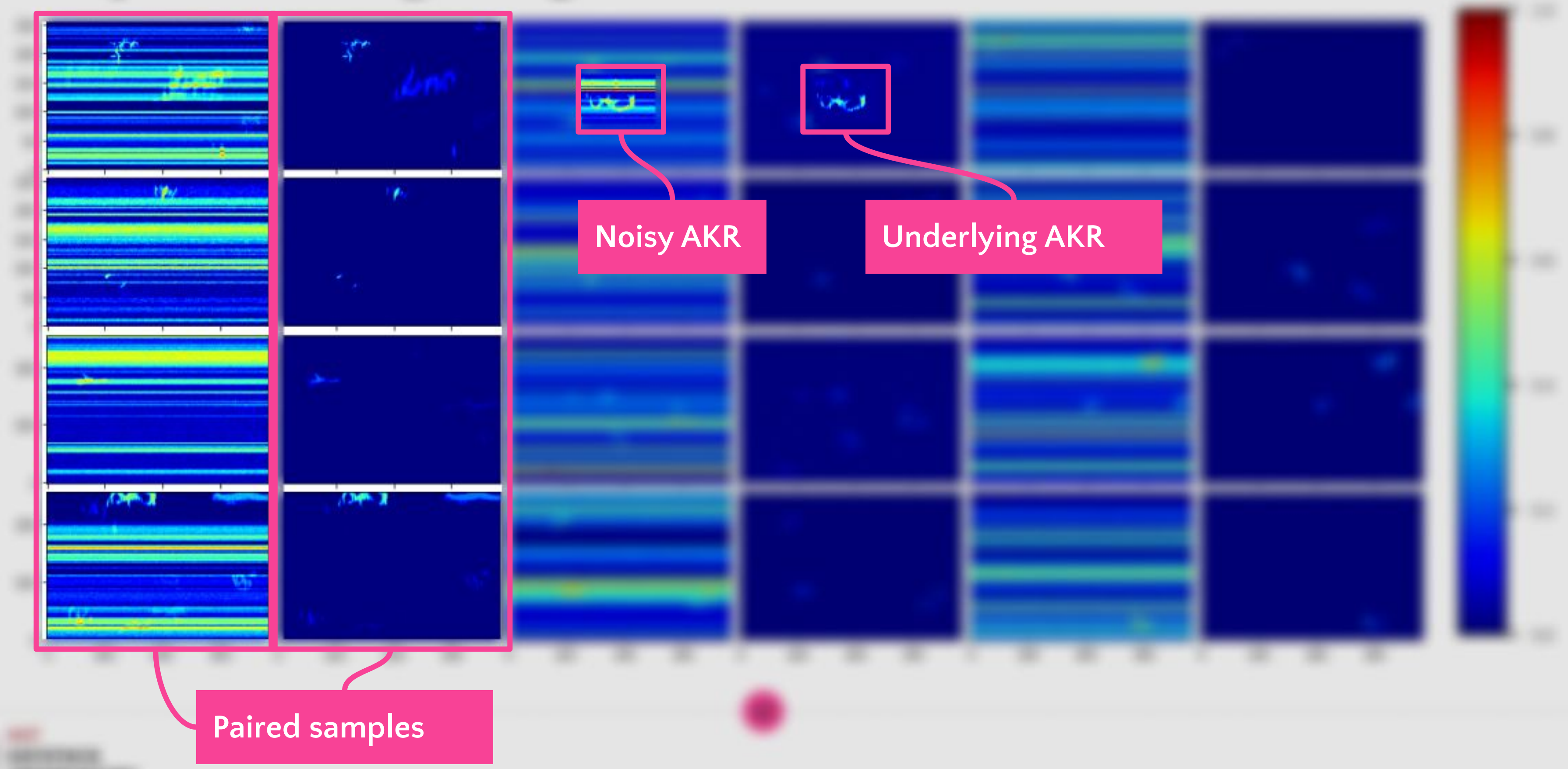
Sample of training data generated with this method.



We chose to use a denoising autoencoder, which is the following:

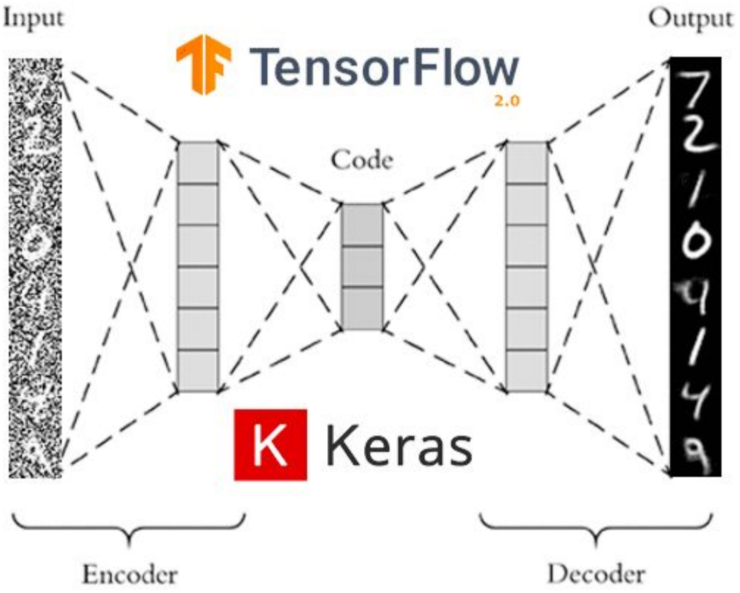
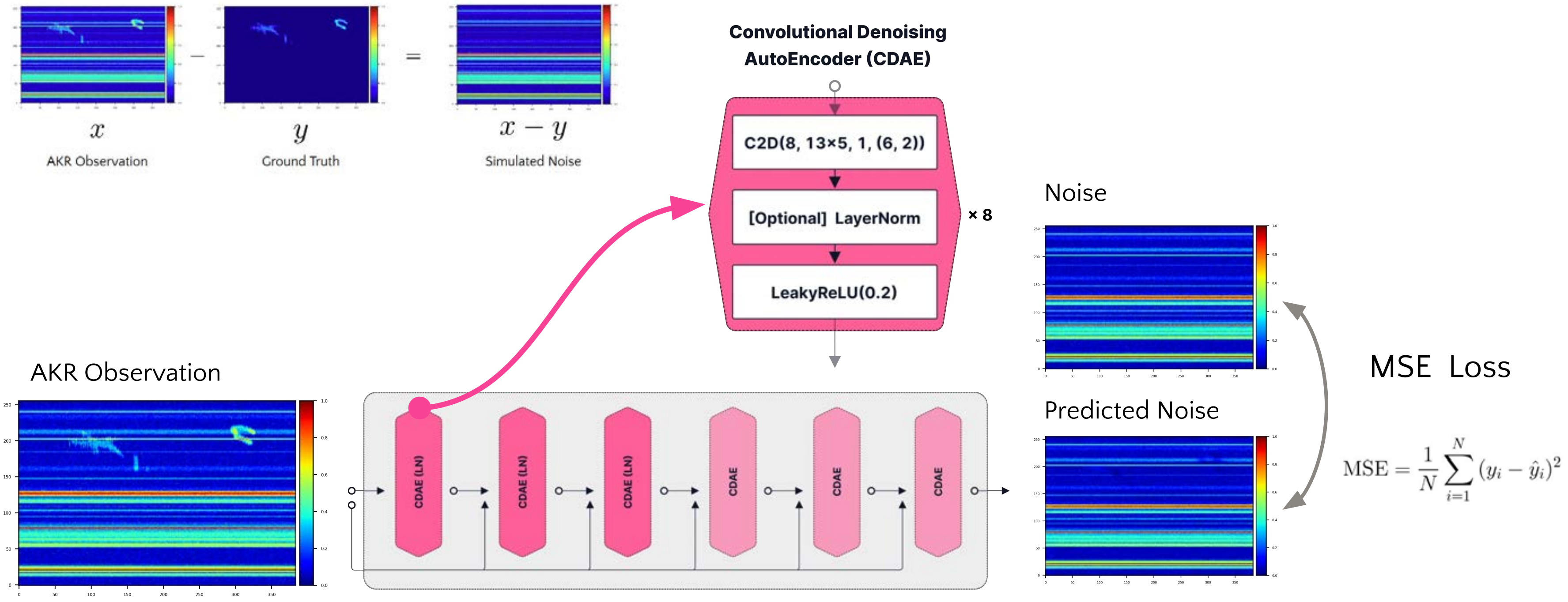


Fig 4. Denoising AutoEncoder

https://pyimagesearch.com/2020/02/24/denoising-autoencoders-with-keras-tensorflow-and-deep-learning/

Denoising Autoencoder for Auroral Radio Emissions (DAARE)

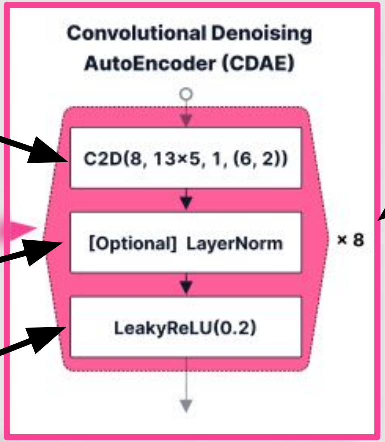


Denoising Autoencoder for Auroral Radio Emissions (DAARE)

Convolutional layer:
- 8 output channels
- 13 x 5 kernel size
- 1 stride
- 6 x 2 padding

Layer normalization

LeakyReLU activation



Stacked 8 times

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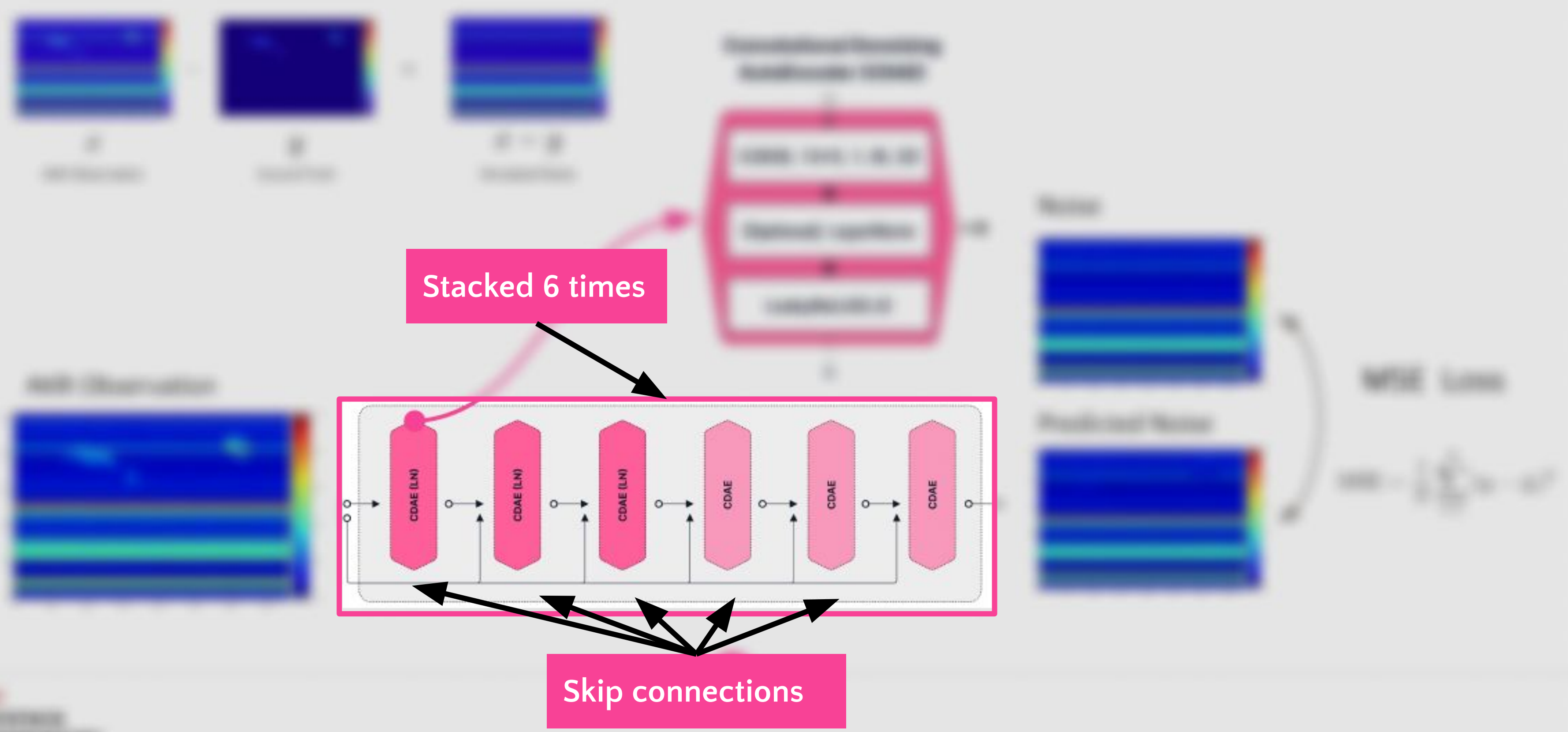
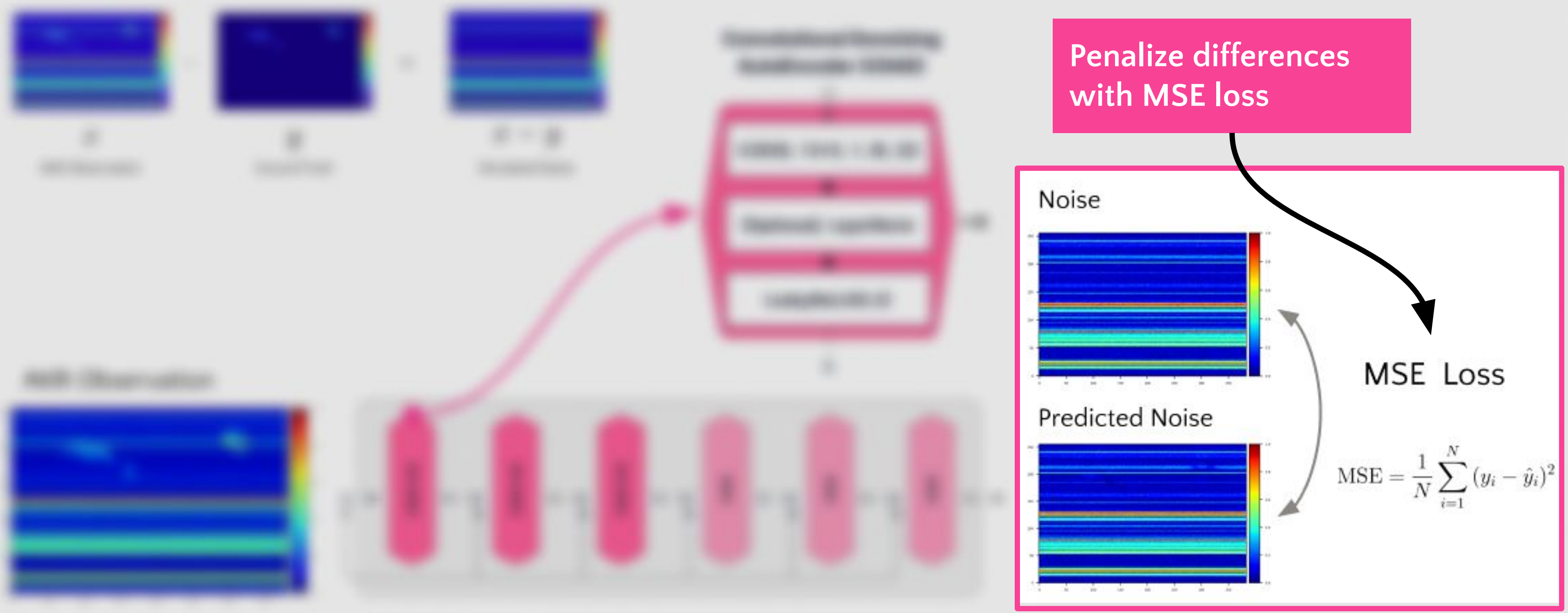


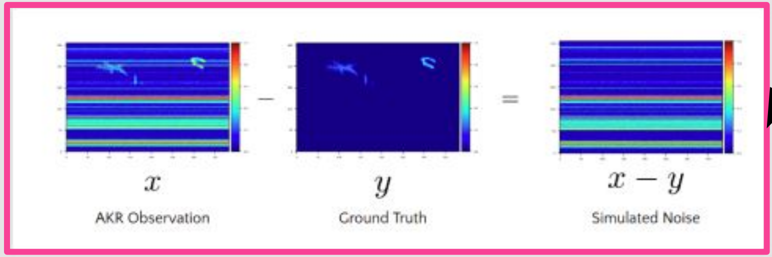
Denoising Autoencoder for Auroral Radio Emissions (DAARE)

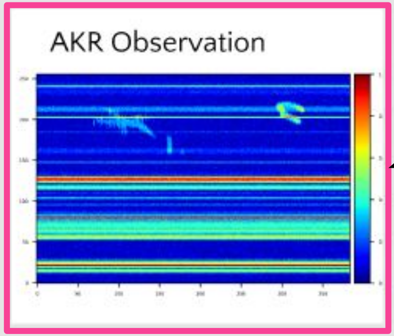
Penalize differences with MSE loss



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

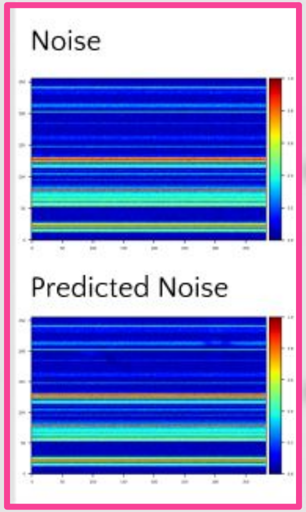
As long as you have 2, you can calculate the last



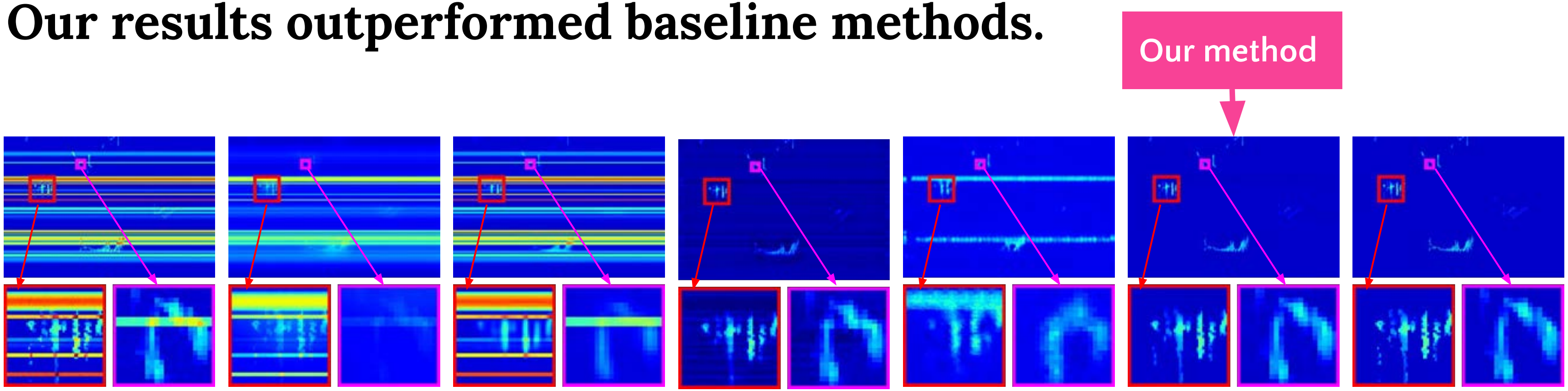


DAARE(Observation) → Noise

AKR = Observation – Noise

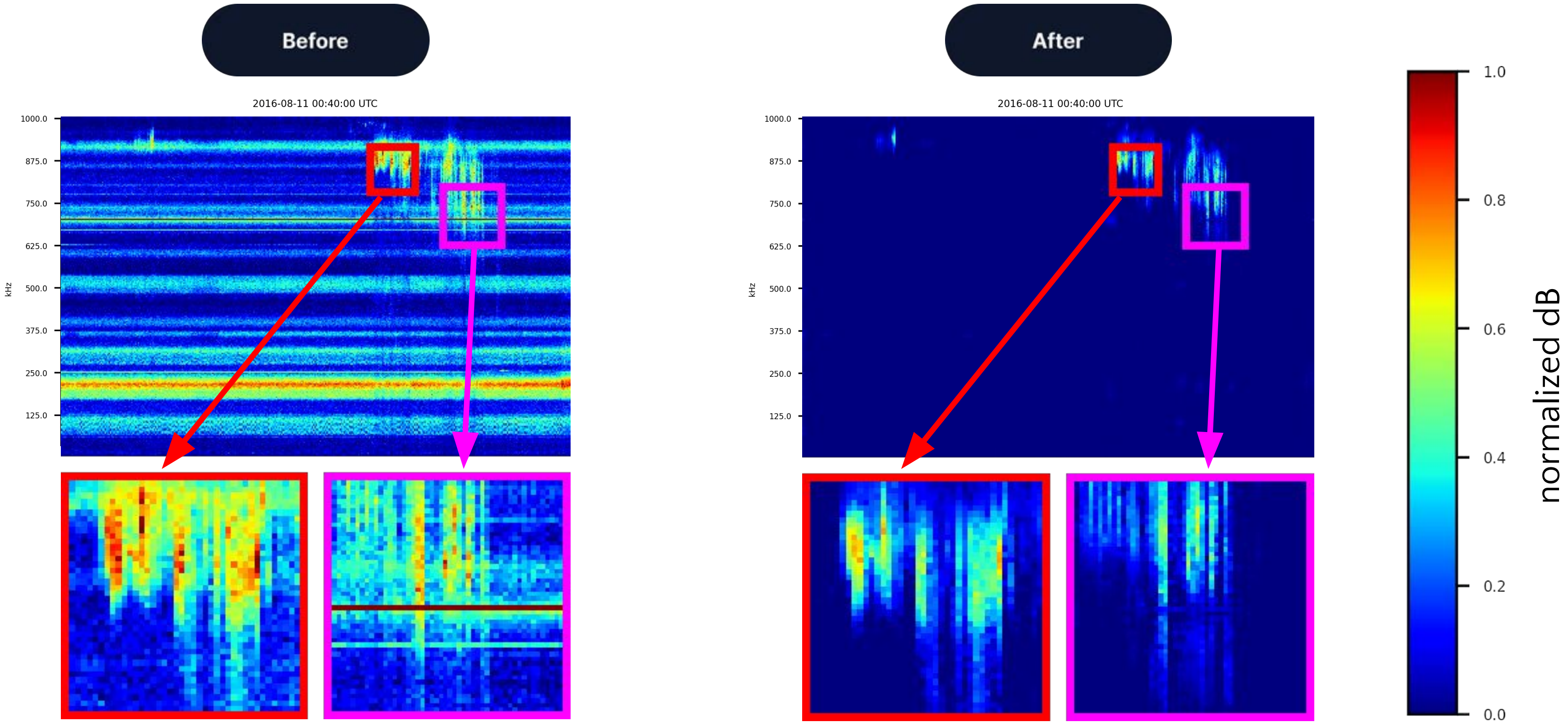


Our results outperformed baseline methods.

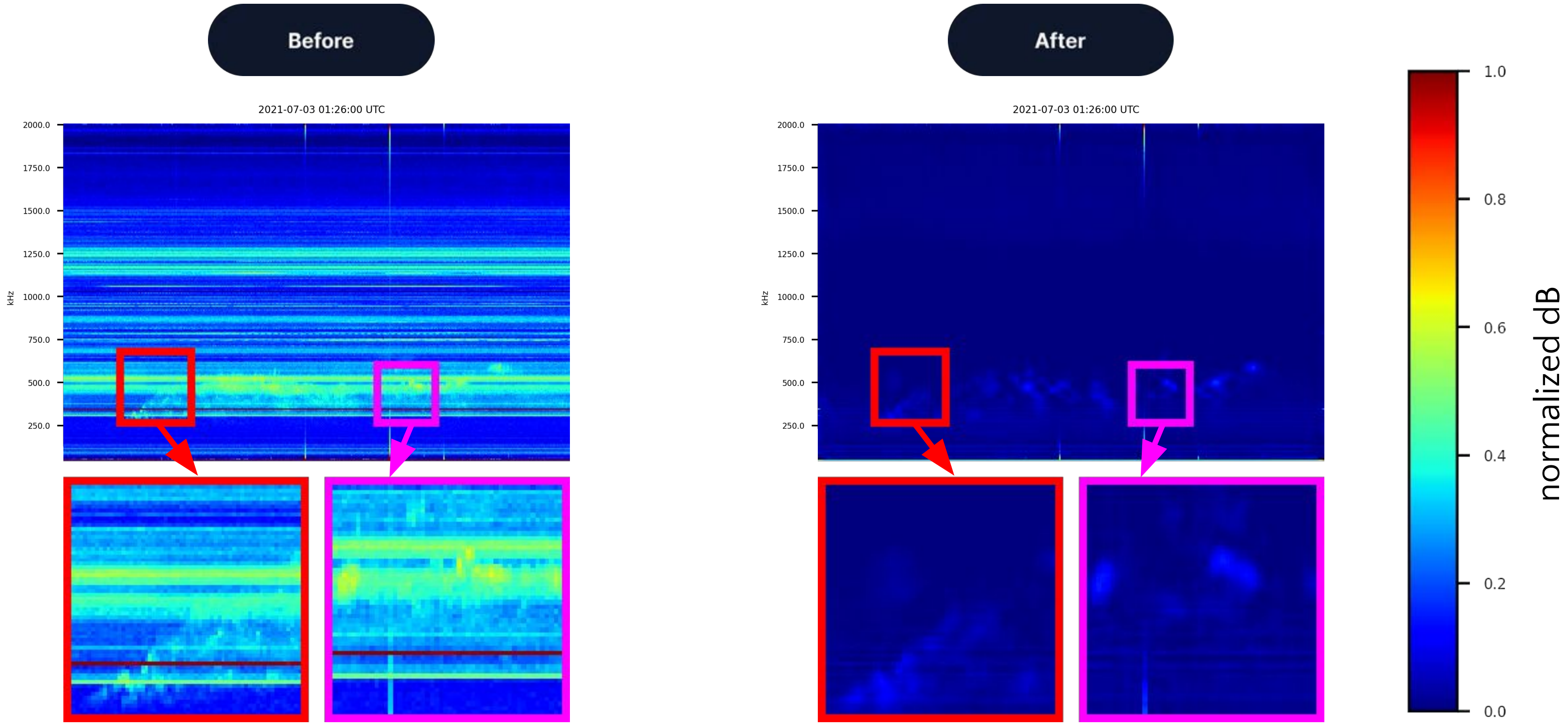


	AKR Observation	Bilateral Filtering	Block-matching and 3D filtering	Fast and Flexible Denoising Network	Vision Transformer	DAARE	Ground Truth
PSNR (dB) 0 Optimal PSNR (dB) ∞	19.8	17.7	38.3	23.5	**42.2**	∞	
SSIM 0 Optimal SSIM 1	0.773	0.555	0.917	0.817	**0.981**	1.00	

Real AKR observation: 08-11-2016 00:40 UT



Real AKR observation: 07-03-2021 01:26 UT



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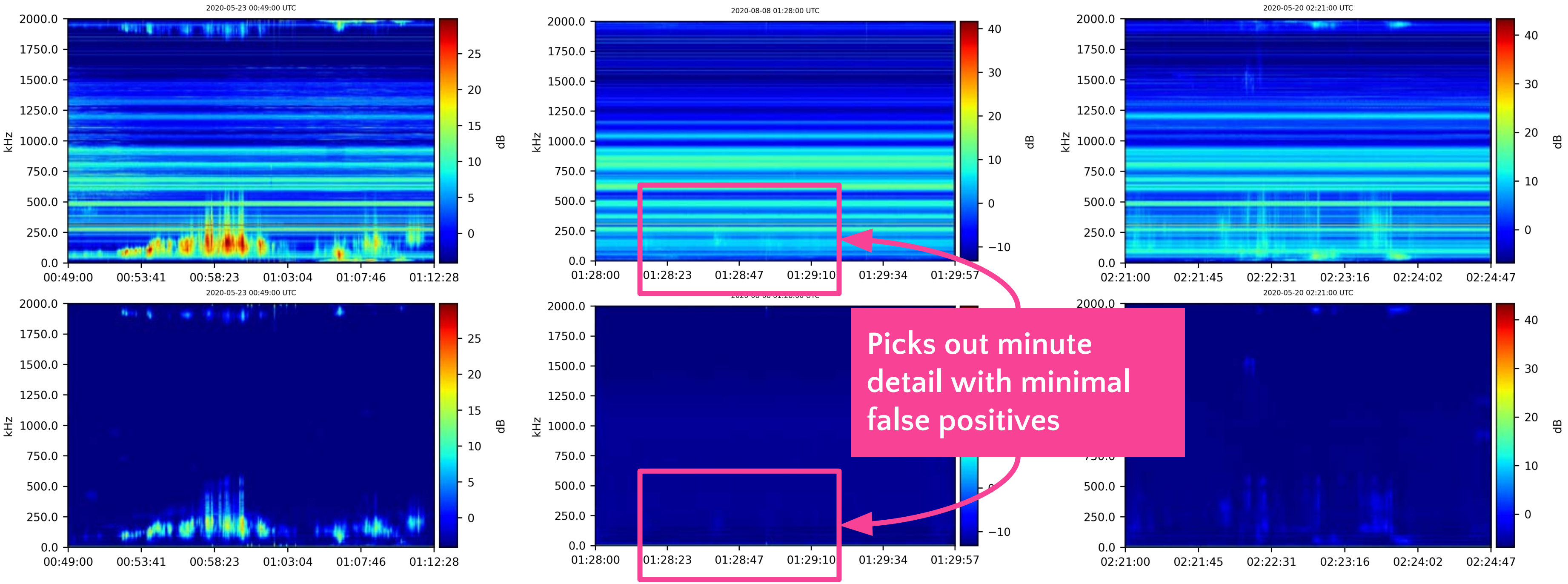
Denoised spectrograms of other AKR observations



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Main strengths of DAARE:

- Automated algorithm to denoise AKR spectrograms
- Efficient
  - Can run in batches and be parallelized
  - Each spectrogram can be processed in **< 1 second** (A batch of 16 spectrograms processed in 3.314 seconds without the use of a GPU)

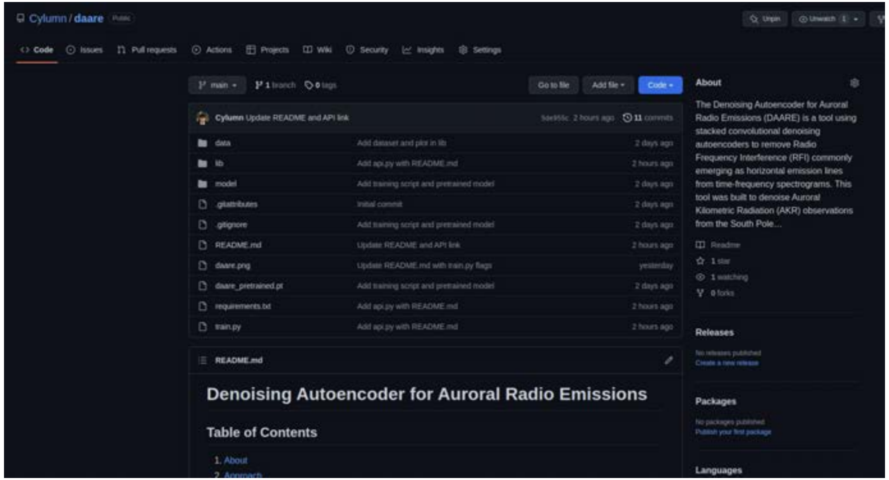
Main limitations of DAARE:

- Change in AKR spectra intensity
- Potential change or loss in AKR features

Open-Sourcing DAARE

Detailed code and documentation for DAARE can be accessed at: https://github.com/Cylumn/daare.

The repository contains detailed comments and instruction to train and use the model, as well as an API to simplify using DAARE without prior knowledge of PyTorch.



How do we improve DAARE?

- Improve the training set
  - Manually remove noise for the training set
  - Increase simulation fidelity
- Specific preprocessing of spectrograms
- Model architecture search

Takeaways

- Though AKR observations often contain noise that occlude data, it is possible to remove noise from the data for downstream applications and analysis
- Other radio data with RFI could potentially benefit from applying DAARE
- Future work can apply machine learning to auroral data and ionospheric sciences which has (for the most part) been left untouched

https://clipart.me/free-vector/aurora

Thank you!

Mentors
Mary Knapp
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