Microseismic Source Localization Using Fourier Neural Operators

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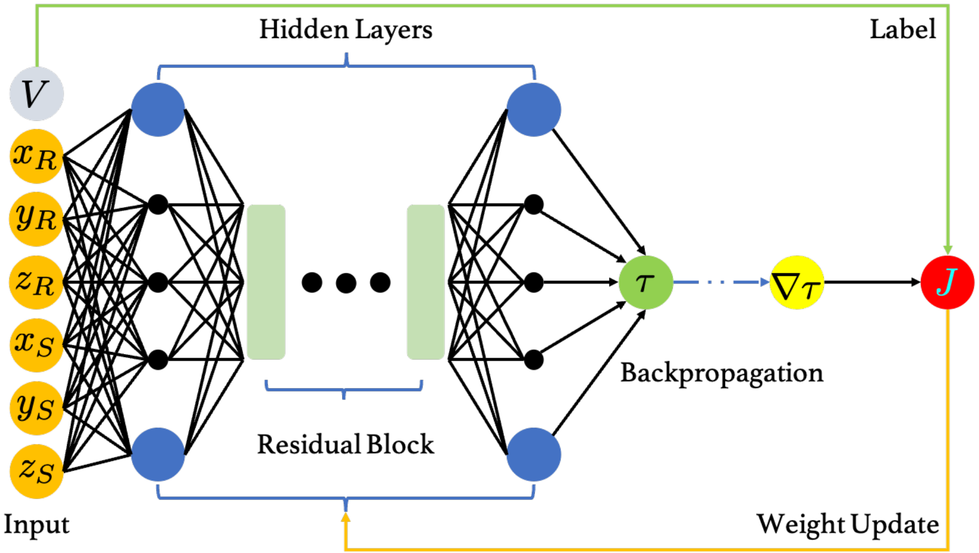
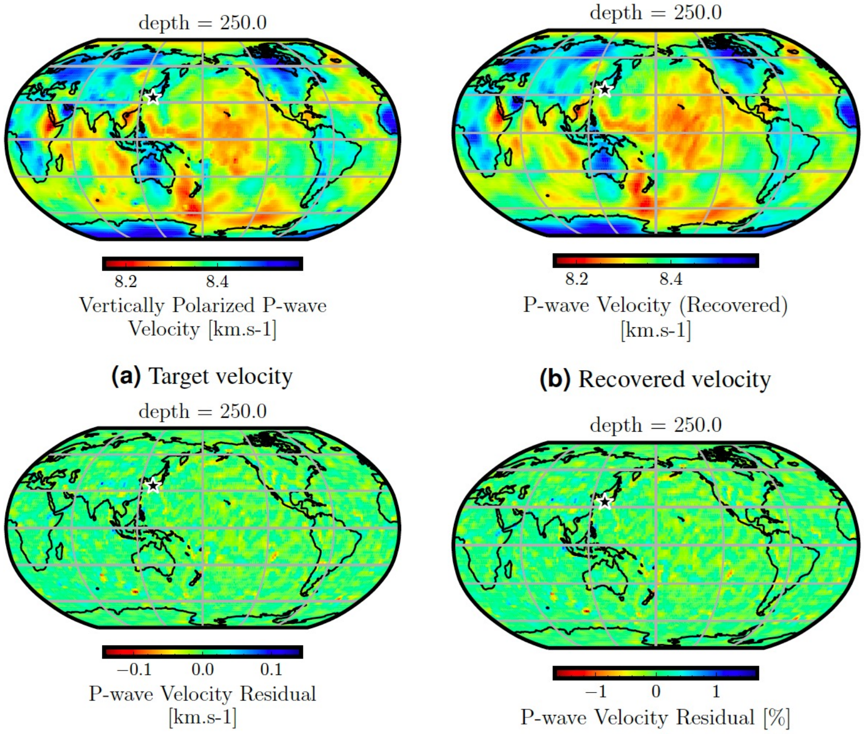
GlobeNN: Global Earth traveltime modeling





(a) Target velocity

(b) Recovered velocity

(c) Recovered velocity residual

(d) Relative recovered velocity residual

https://github.com/hatsyim/globenn

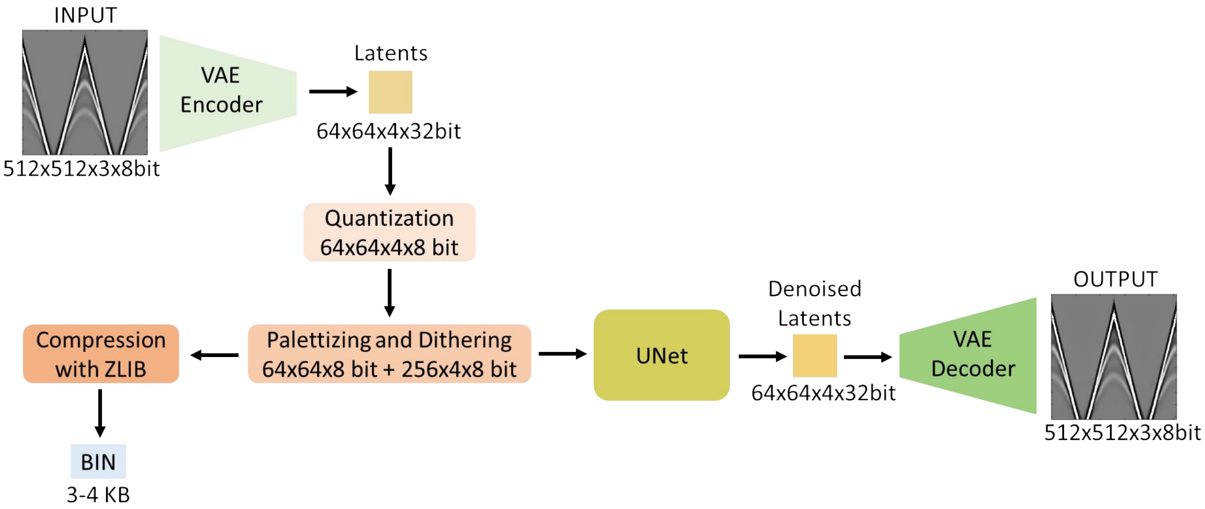
Taufik et al. (2023); *Scientific Reports*

Stable Diffusion NN for data compression

“A road diverging in two different direction”

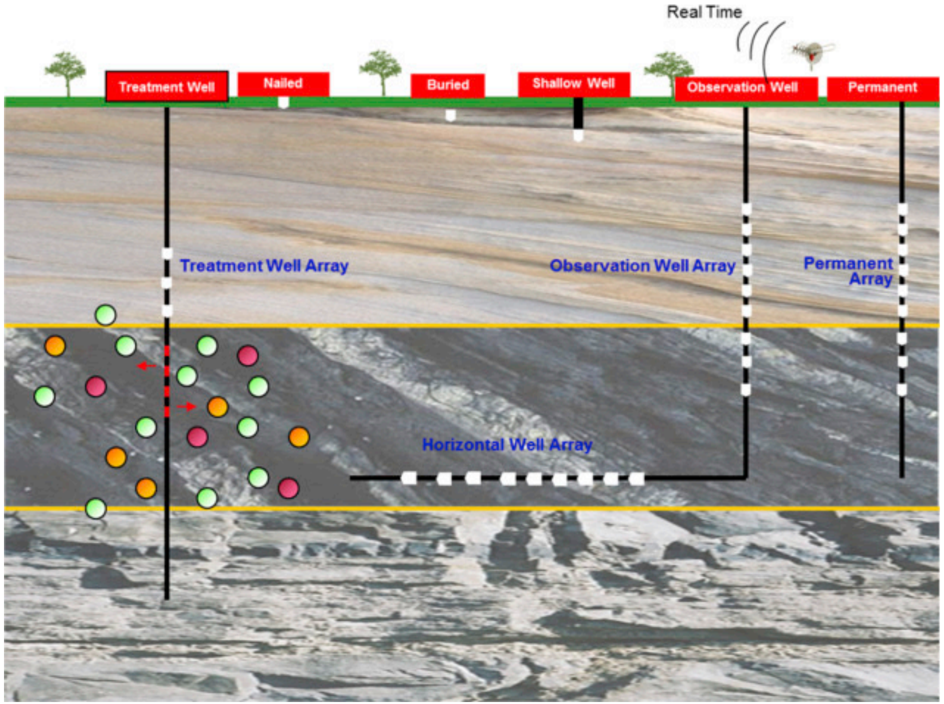
Stable Diffusion NN for data compression

"A polar bear in a Saudi desert"

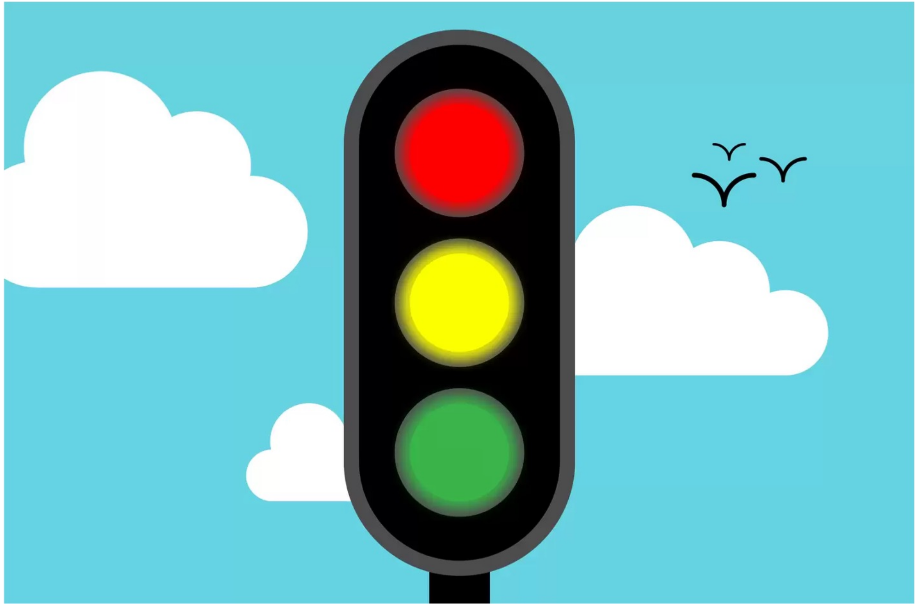


Abdullin et al. (2023); *IMAGE 2023*

Motivation



Real-time optimization of industrial operations

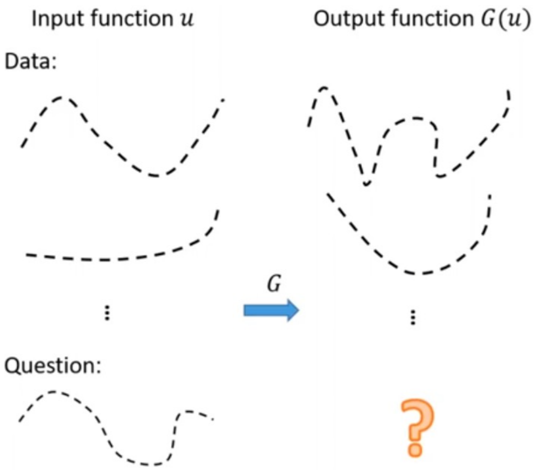


Seismic hazard mitigation

Operator learning using NNs

- Function: $\mathbb{R}^{d_1} \rightarrow \mathbb{R}^{d_2}$
  - Universal approximation theorem
  - Image classification  $\rightarrow 5$
- Operator: function $(\infty - \text{dimension}) \rightarrow (\infty - \text{dimension})$
  - Derivative
  - Integral
  - Dynamic system

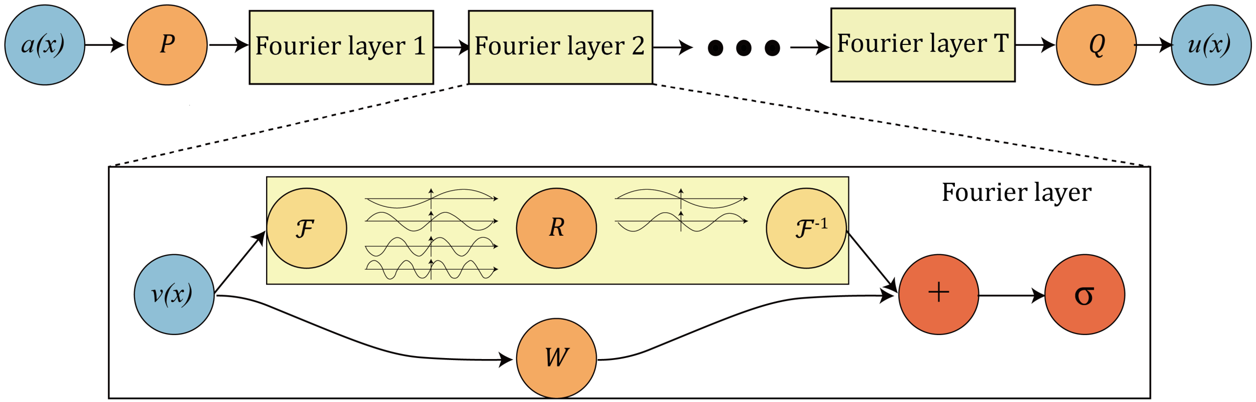
  …



- Can we learn operators using NNs? Yes (Chen and Chen, 1995)

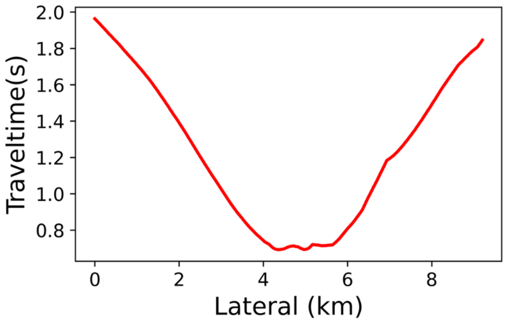
Fourier Neural Operators (FNOs)

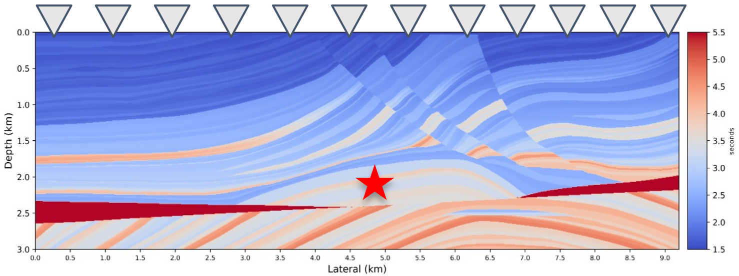
- FNOs are composed of two parts: a Fourier layer and a neural network. The Fourier layer decomposes the input function into its constituent frequencies. The neural network then learns how to transform these frequencies into the desired output function.

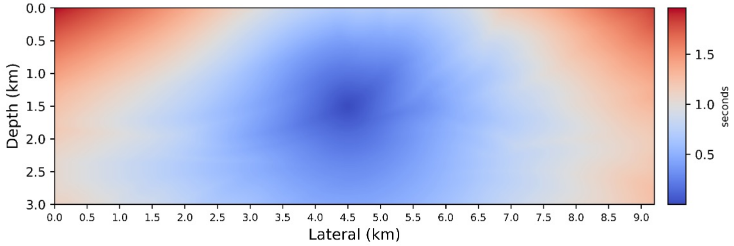


Li et al. (2021)

Localization Methodology





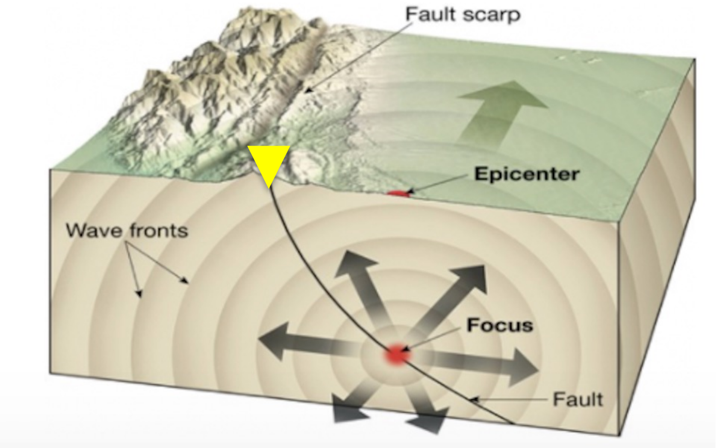


The eikonal equation

- Eikonal equation is a non-linear, first-order, hyperbolic PDE of the form:

$$|\nabla T(\mathbf{x})|^2 = \frac{1}{v^2(\mathbf{x})}, \forall\, \mathbf{x} \in \Omega$$

$$T(\mathbf{x}_s) = 0$$



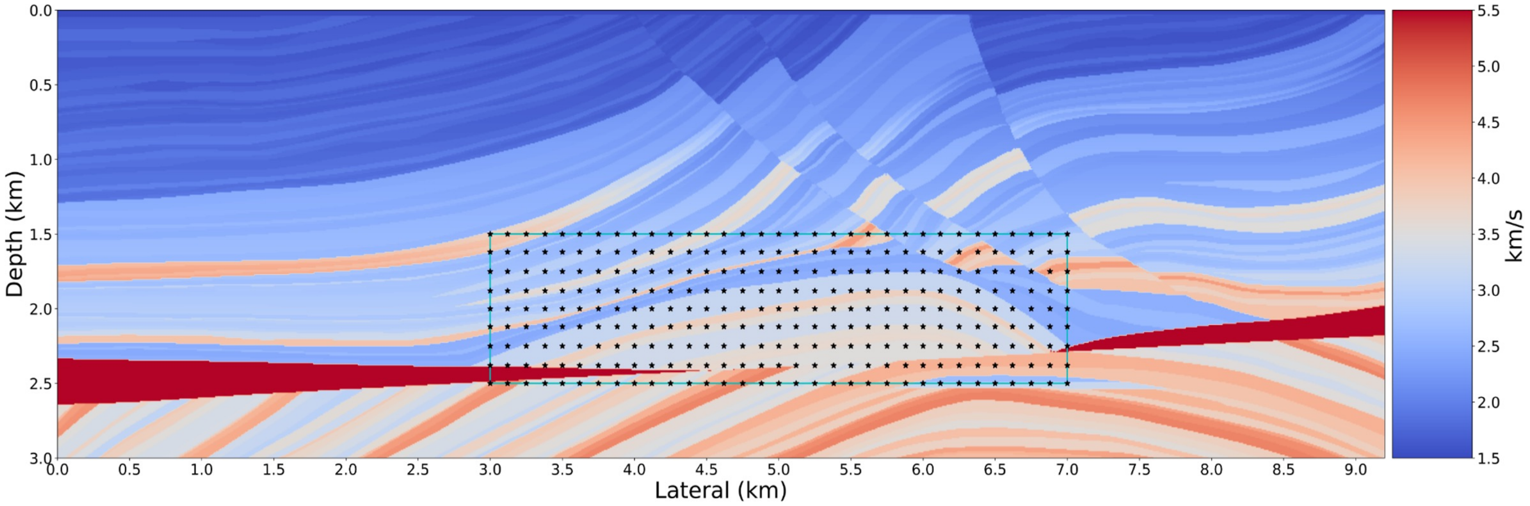
T = Traveltime

v = Phase velocity

$\mathbf{x}_s$ = Source location

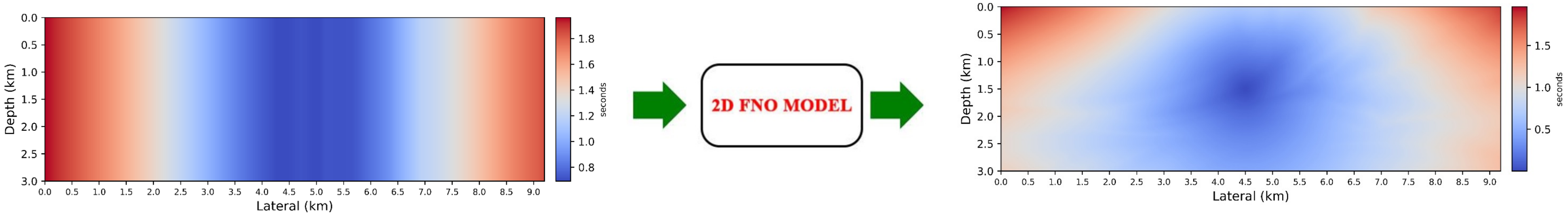
http://wwwchristianblog-christian.blogspot.com/2012/02/earthquakes.html

FNO Training Process



Source point spacing: 125m
Total number of training points: 297

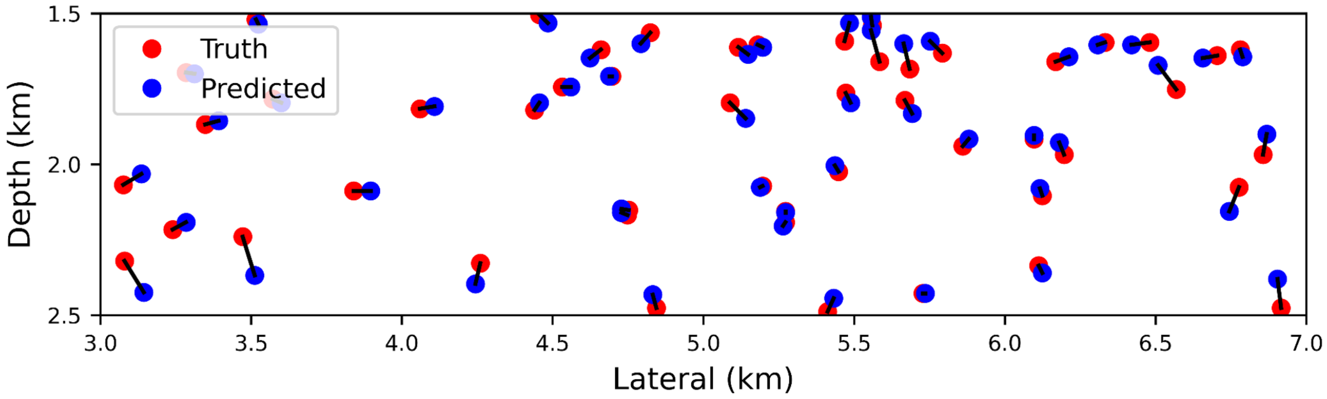
FNO Training Process



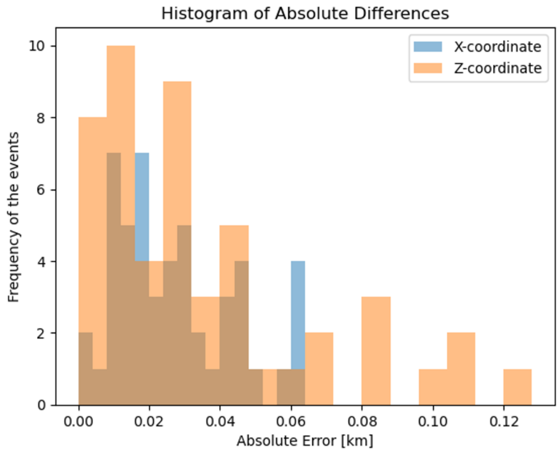
$$Source\,location: \ \min(T)$$

- All the trainings are done with a single A5000 24GB GPU

Error Analysis



True vs. predicted locations



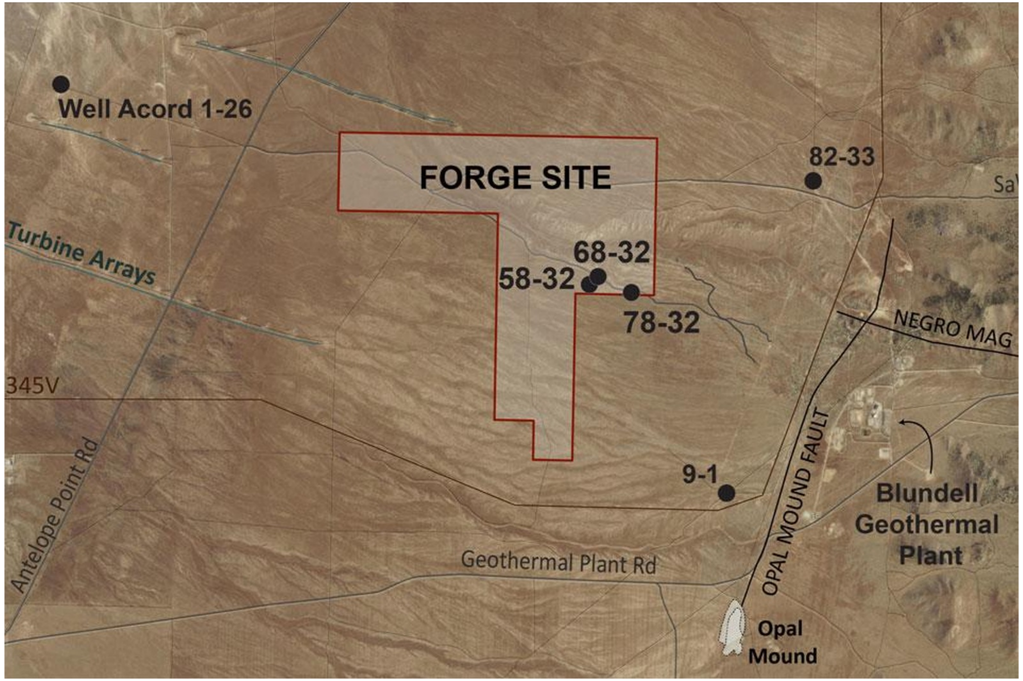
Error histogram

Utah FORGE Site

- FORGE is an initiative that facilitates the controlled development and experimentation of EGS reservoir technologies.

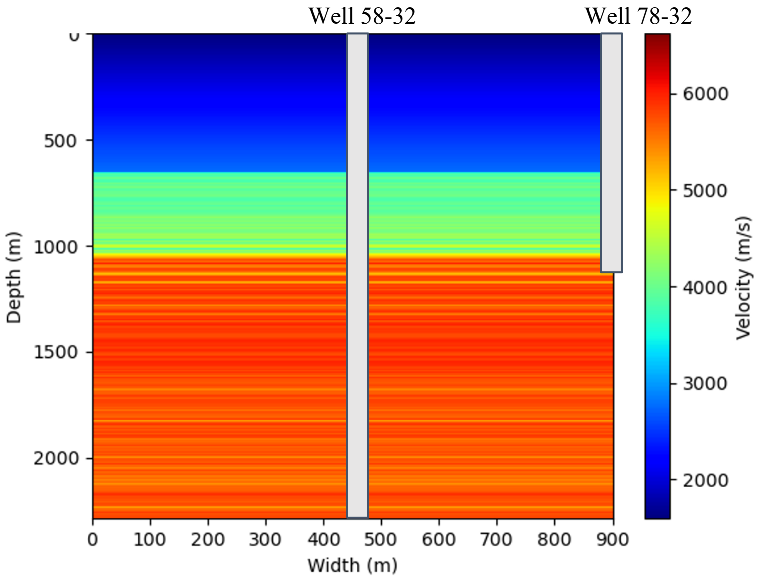
- The main purposes of drilling **58–32 (stimulation well)** is to directly measure reservoir properties including temperature, rock type, permeability and stress in the reservoir

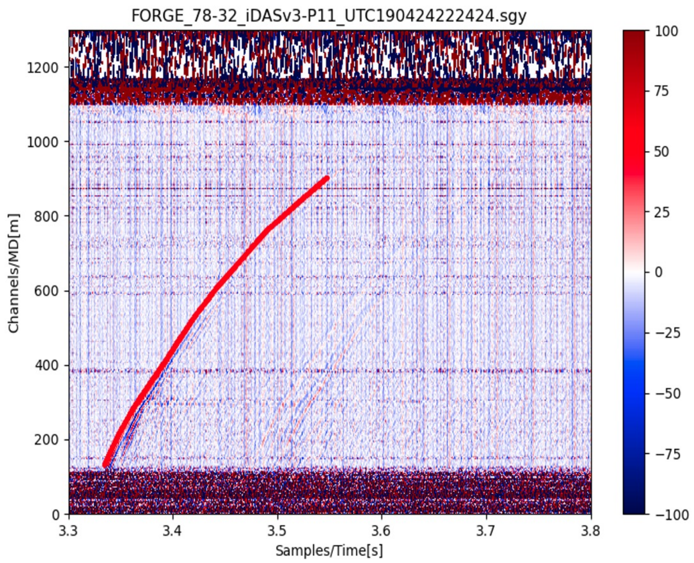
- Well **78-32 is the monitoring well**



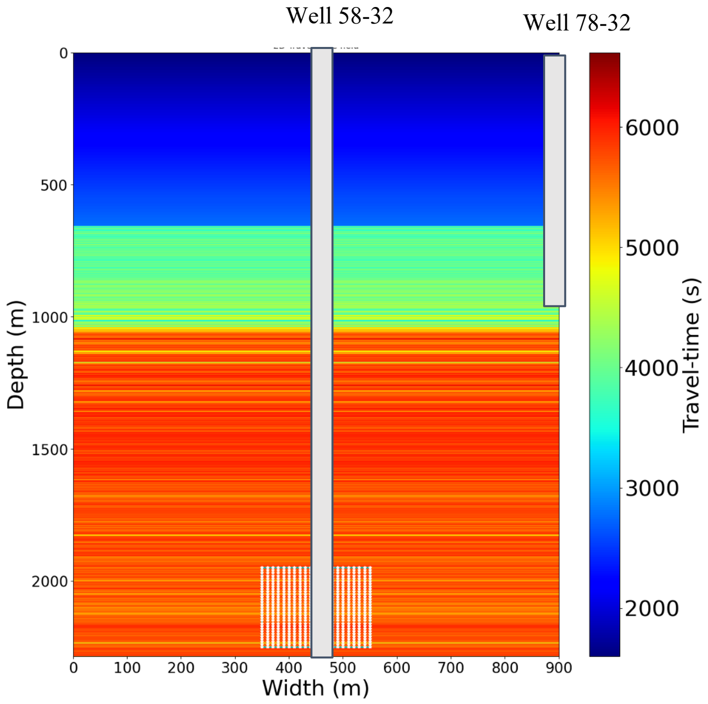
utahforge.com

Velocity model and picking example





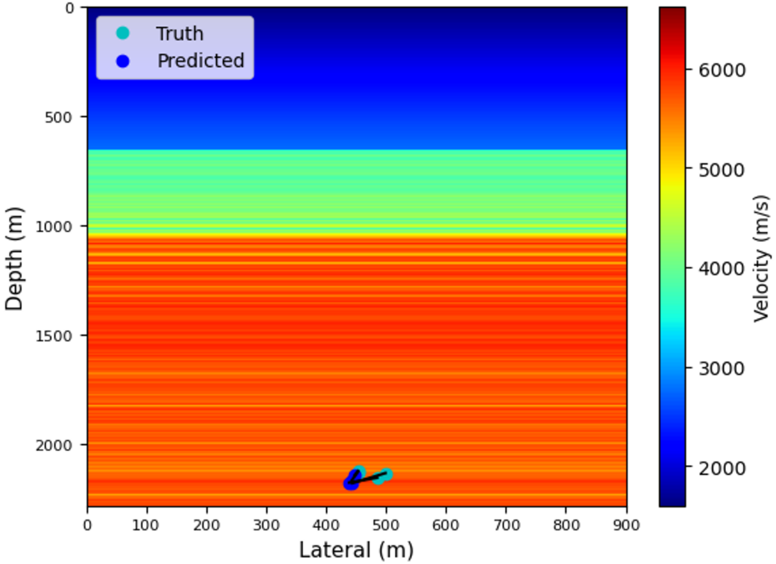
Training configuration



Source point spacing: 125m

Total number of training points: 627

Catalog vs. Predicted Locations



	X_{true} (m)	X_{pred} (m)	Z_{true} (m)	Z_{pred} (m)	$Error_X$ (m)	$Error_Z$ (m)
Perforation	453.016	447.615	2126	2145.71	5.4	19.71
Event 1	484.954	438.48	2157.243	2179.205	46.47	21.96
Event 2	453.214	442.54	2129.52	2170.07	10.67	40.55
Event 3	498.95	443.55	2135.823	2182.25	55.4	46.42

Summary

- We developed an FNO-based framework for hypocenter localization
- Achieved robust results in the presence of noisy arrival times or when picks are missing
- Can be applied for real-time localization of microseismic events
- Flexible for different types of monitoring arrays and data types (surface/boreholes, geophones/DAS, dense/sparse)

Acknowledgements

- SEEM research group and KFUPM for support

SMART
EARTH
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SEEM

KING FAHD UNIVERSITY OF PETROLEUM & MINERALS
College of Petroleum
Engineering & Geosciences

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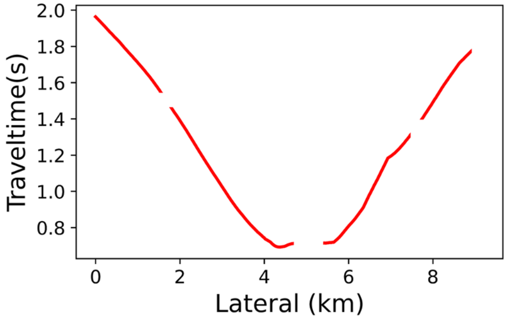
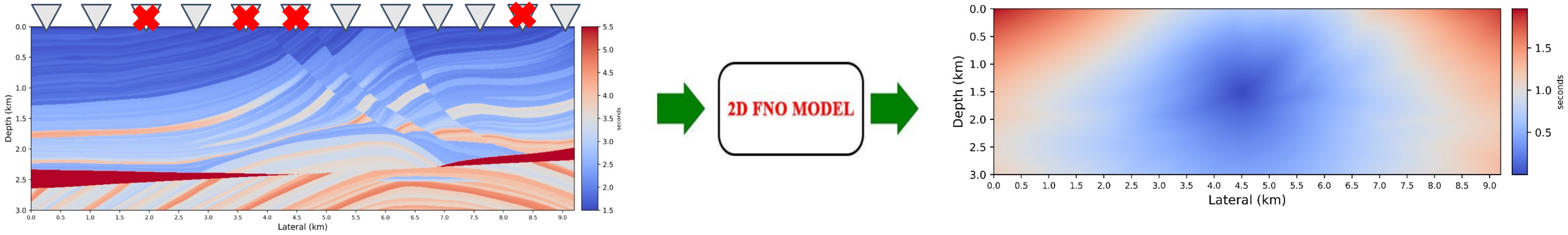
Dealing With Missing Data



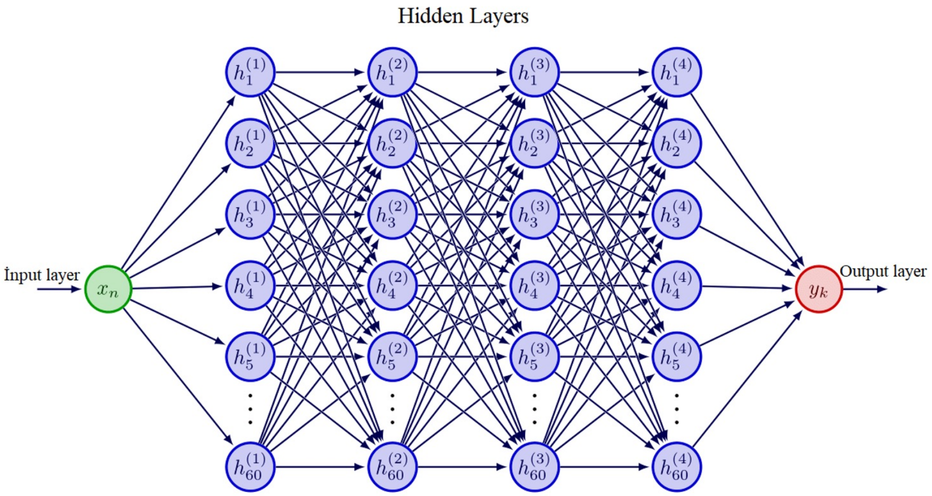


ANN for Interpolation/Extrapolation

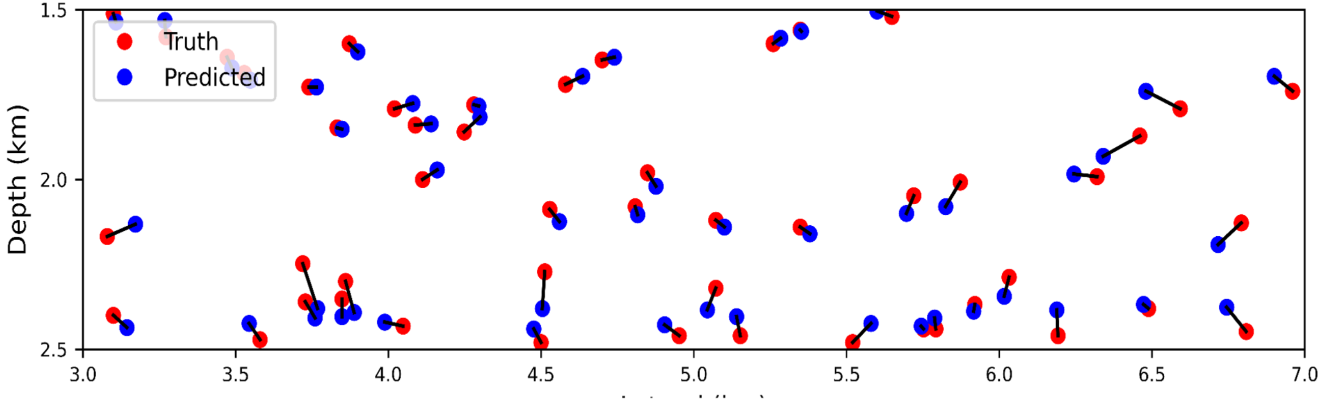
Input: spatial coordinates of the available receivers

Output: Corresponding travel-time for the receivers

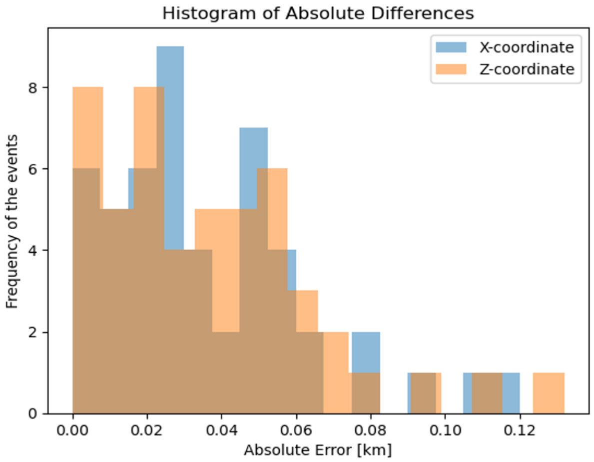
The model is used to construct missing receivers' values by interpolation/extrapolation



Error Analysis

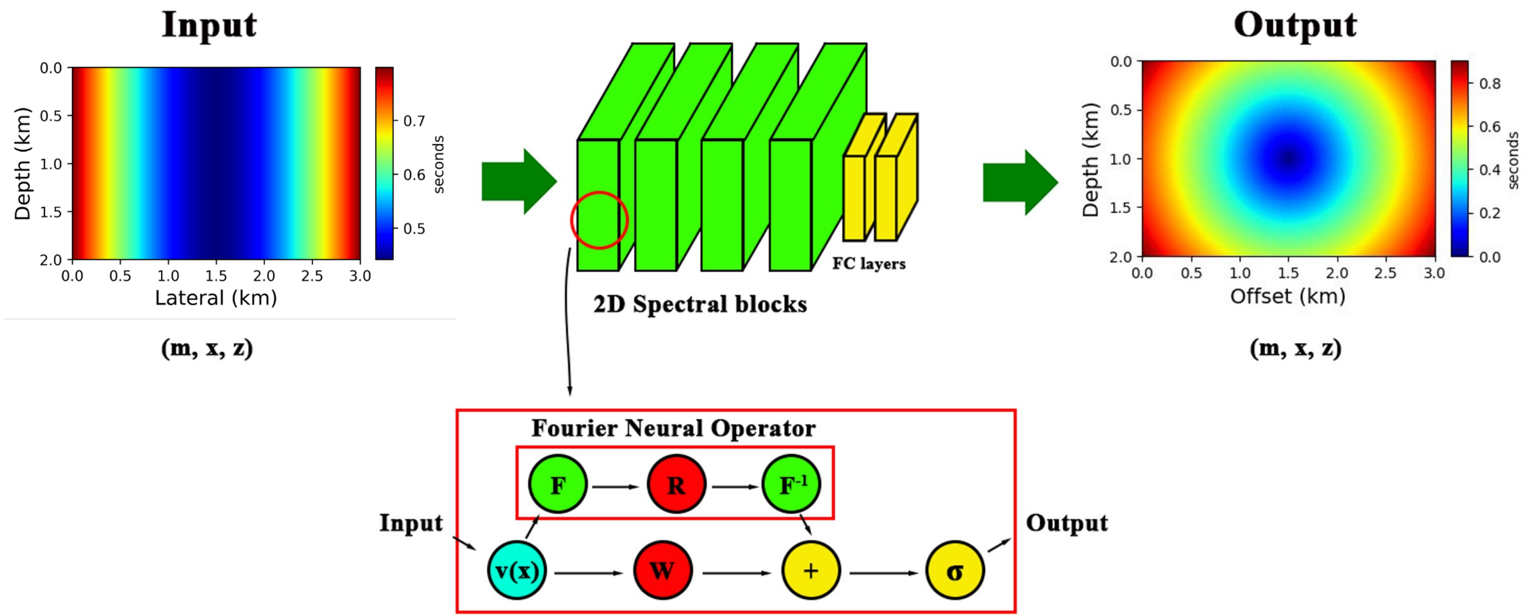


True vs. predicted locations



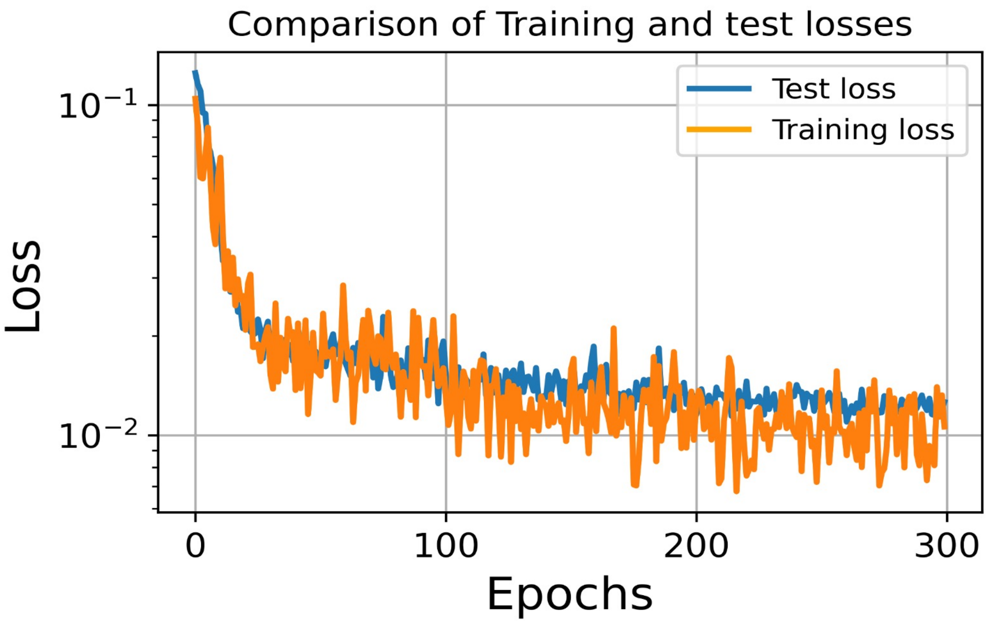
Error histogram

2D FNO Model

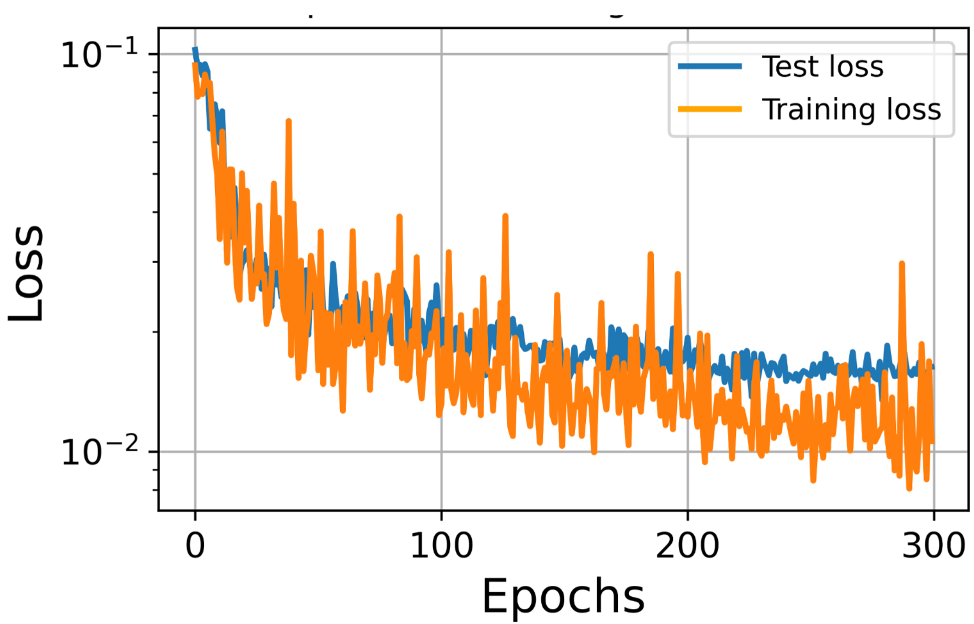


- All the trainings are done with a single A5000 24GB GPU

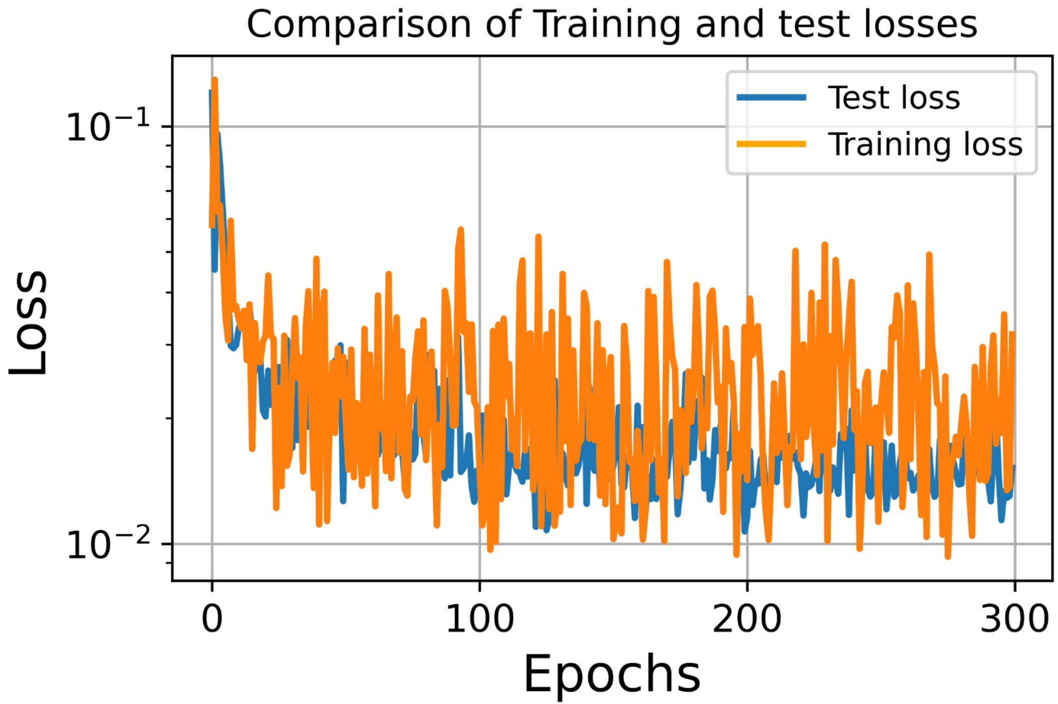
Marmousi Loss Curve



50% Missing Loss curve



Forge Loss Curve



Prior approaches for hypocenter localization

- ➔ Conventional travel time & wavefield methods
  - ◆ **Computationally slow: For each point new modelling needed**

- ➔ ML-based travel time & wavefield methods
  - ◆ **Huge amount of data needed to have better generalization**

- ➔ PINN-based travel time & wavefield methods
  - ◆ **Retraining needed for each new source, non-uniqueness of the solution**