Neutron noise-based core monitoring for Small Modular Reactors using Machine Learning

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Outline

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- Progress
  - Localization of AVS noise source in SMR using machine learning
  - Identification and localization of multiple noise source types in SMR using machine learning
- Conclusions
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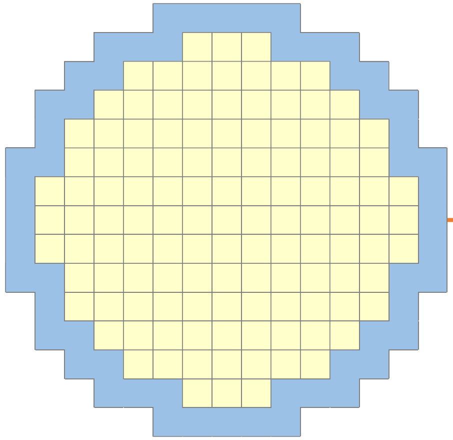
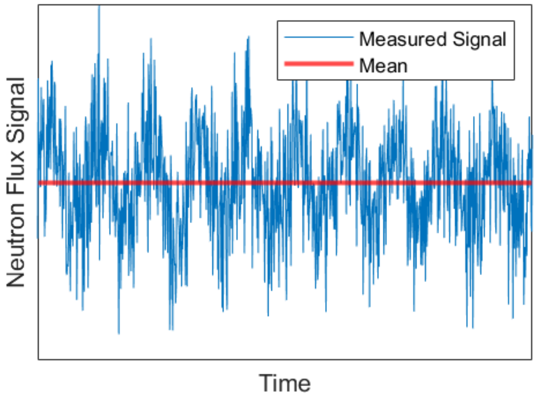
Introduction

Introduction

- Core monitoring and diagnostics via reactor neutron noise in SMRs

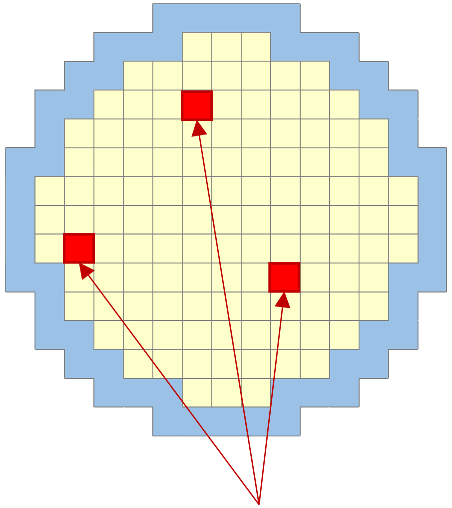


in-core + ex-core detectors



Reactor neutron noise

Unfolding



Identify and localize perturbations

We are using machine learning!

Introduction

Objectives of the project

- Characterize reactor neutron noise in SMRs
  - Assess the dominance of the non-point kinetic component with respect to point-kinetics?
- Develop ANN models to unfold the problem and identify perturbations in SMRs from reactor noise
  - Train and test using data from simulations
- Study detection system in SMRs for core monitoring via reactor noise

Localization of AVS noise source in SMR using machine learning

Neutron Noise model (AVS)

$$\{\boldsymbol{\nabla}.[\boldsymbol{D}(\boldsymbol{r})\boldsymbol{\nabla}] + \boldsymbol{\Sigma}_{\boldsymbol{dyn}}(\boldsymbol{r},\omega)\} \times \begin{bmatrix}\delta\phi_1(\boldsymbol{r},\omega)\\ \delta\phi_2(\boldsymbol{r},\omega)\end{bmatrix} = \begin{bmatrix}S_1(\boldsymbol{r},\omega)\\ S_2(\boldsymbol{r},\omega)\end{bmatrix} \tag{1}$$

$$\begin{bmatrix}S_1(\boldsymbol{r}',\omega)\\ S_2(\boldsymbol{r}',\omega)\end{bmatrix} = \boldsymbol{\phi}_r(\boldsymbol{r}')\delta\Sigma_r(\boldsymbol{r}',\omega) + \boldsymbol{\phi}_a(\boldsymbol{r}')\begin{bmatrix}\delta\Sigma_{a,1}(\boldsymbol{r}',\omega)\\ \delta\Sigma_{a,2}(\boldsymbol{r}',\omega)\end{bmatrix} + \boldsymbol{\phi}_f(\boldsymbol{r}',\omega)\begin{bmatrix}\delta\upsilon\Sigma_{f,1}(\boldsymbol{r}',\omega)\\ \delta\upsilon\Sigma_{f,2}(\boldsymbol{r}',\omega)\end{bmatrix} \tag{2}$$

$$\boldsymbol{\phi}_r(\boldsymbol{r}) = \begin{bmatrix}\phi_{1,0}(\boldsymbol{r})\\ -\phi_{1,0}(\boldsymbol{r})\end{bmatrix}, \tag{3}$$

$$\boldsymbol{\phi}_a(\boldsymbol{r}) = \begin{bmatrix}\phi_{1,0}(\boldsymbol{r}) & 0\\ 0 & \phi_{2,0}(\boldsymbol{r})\end{bmatrix}, \tag{4}$$

$$\boldsymbol{\phi}_f(\boldsymbol{r},\omega) = \begin{bmatrix}-\frac{\phi_{1,0}(\boldsymbol{r})}{k_{eff}}\left(1-\frac{i\omega\beta}{i\omega+\lambda}\right) & -\frac{\phi_{2,0}(\boldsymbol{r})}{k_{eff}}\left(1-\frac{i\omega\beta}{i\omega+\lambda}\right)\\ 0 & 0\end{bmatrix}. \tag{5}$$

$$\{\boldsymbol{\nabla}.[\boldsymbol{D}(\boldsymbol{r})\boldsymbol{\nabla}] + \boldsymbol{\Sigma}_{\boldsymbol{dyn}}(\boldsymbol{r},\omega)\} \times \begin{bmatrix}G_{g\to1}(\boldsymbol{r},\boldsymbol{r}',\omega)\\ G_{g\to2}(\boldsymbol{r},\boldsymbol{r}',\omega)\end{bmatrix} = \begin{bmatrix}\delta(\boldsymbol{r}-\boldsymbol{r}')\\ 0\end{bmatrix}_{g=1} or \begin{bmatrix}0\\ \delta(\boldsymbol{r}-\boldsymbol{r}')\end{bmatrix}_{g=2} \tag{6}$$

$$\begin{bmatrix}\delta\phi_1(\boldsymbol{r},\omega)\\ \delta\phi_2(\boldsymbol{r},\omega)\end{bmatrix} = \begin{bmatrix}\int\{G_{1\to1}(\boldsymbol{r},\boldsymbol{r}',\omega)S_1(\boldsymbol{r}',\omega) + G_{2\to1}(\boldsymbol{r},\boldsymbol{r}',\omega)S_2(\boldsymbol{r}',\omega)\}d^3\boldsymbol{r}'\\ \int\{G_{1\to2}(\boldsymbol{r},\boldsymbol{r}',\omega)S_1(\boldsymbol{r}',\omega) + G_{2\to2}(\boldsymbol{r},\boldsymbol{r}',\omega)S_2(\boldsymbol{r}',\omega)\}\,d^3\boldsymbol{r}'\end{bmatrix} \tag{7}$$

AVS sources are sampled with varying strengths and phases

For 1 AVS source at location (r):
S_1 is sampled from [-1,1]
S_2 is sampled from [-0.1,0.1]

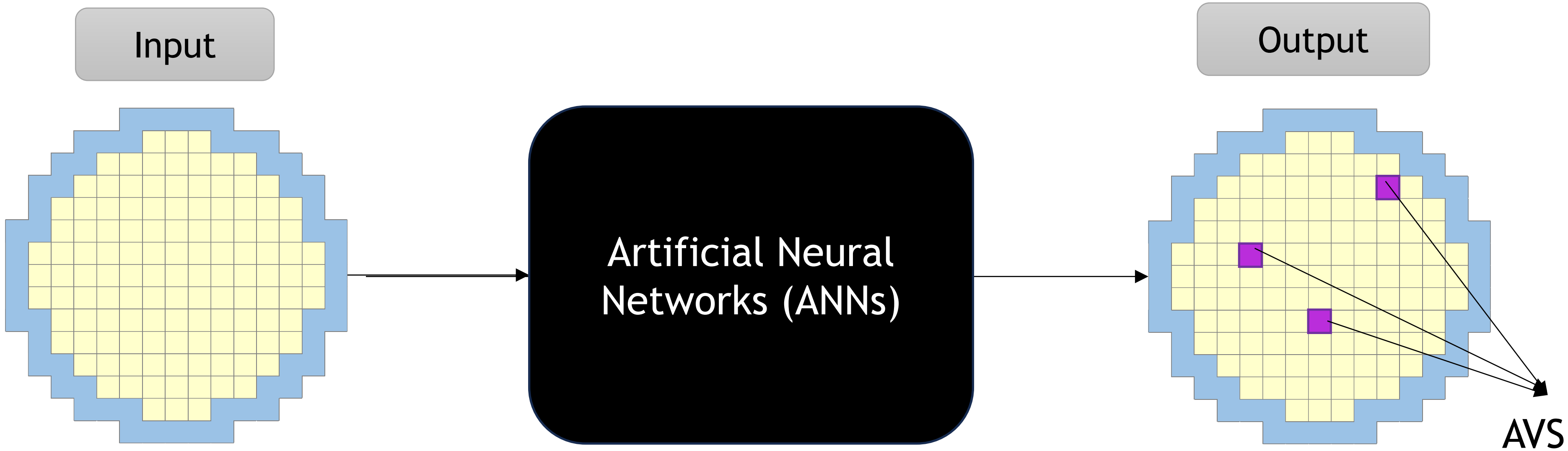
Localization of AVS noise source in 300-MWe SMR model using machine learning

For 300-MWe SMR model:

Objective: Detect locations for one or more AVS reactor noise source at f=1 Hz.

Diameter = 278 cm
Height = 366 cm

15 x 15 x 20 nodes



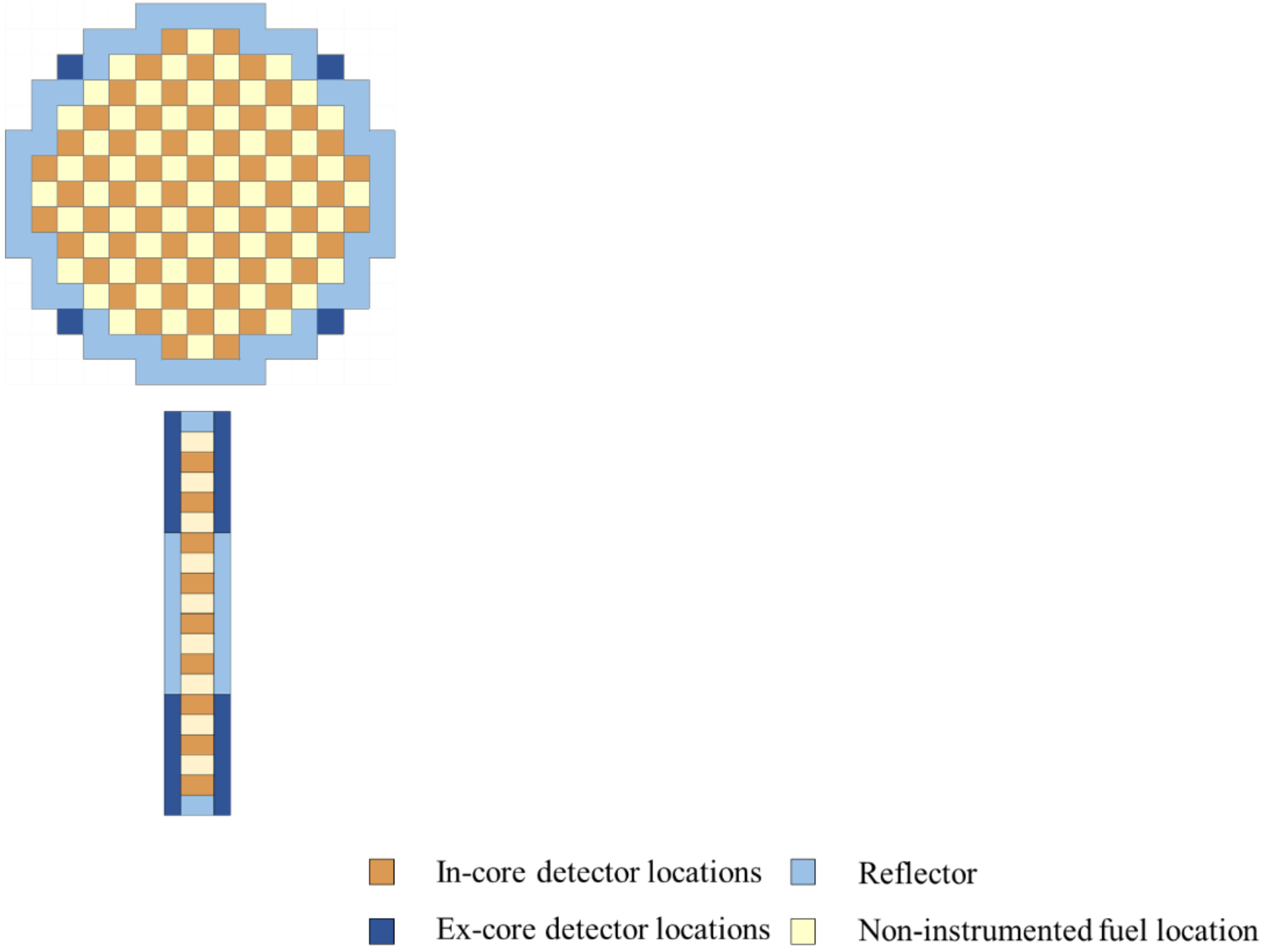
AVS Noise sources

Relative Thermal Neutron Noise at detector locations

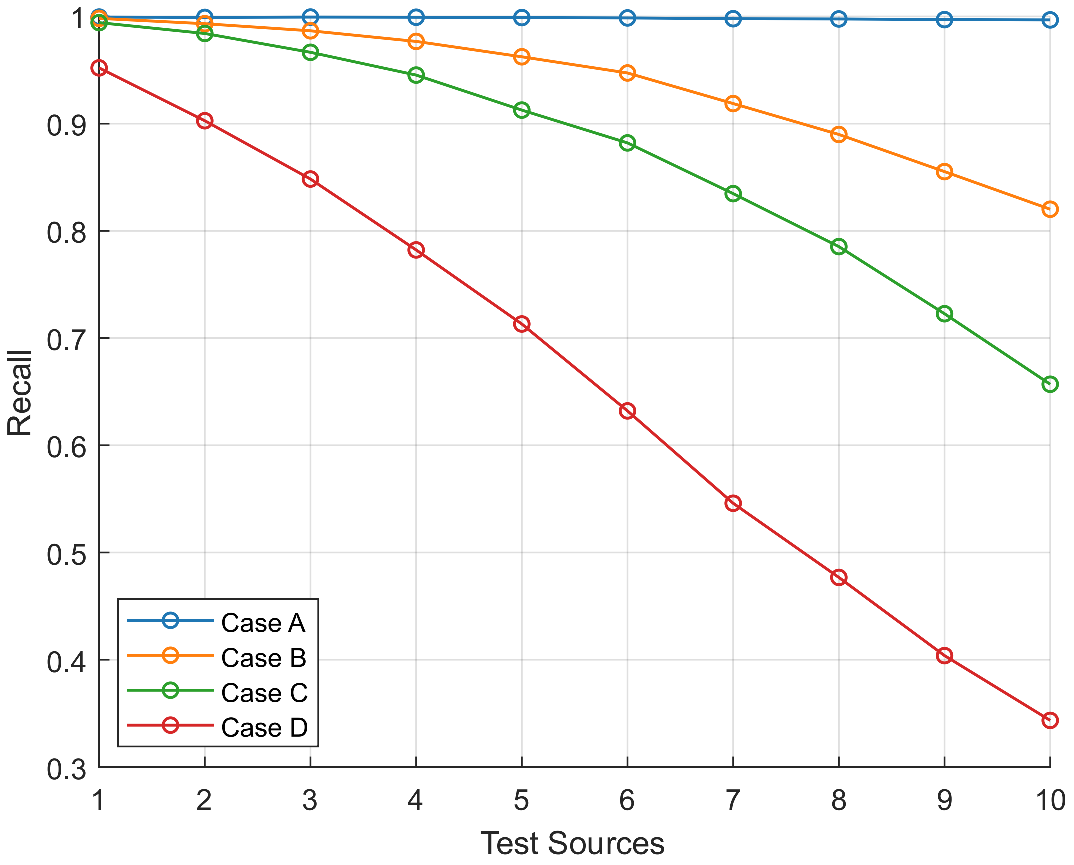
Approach: Train an ANN (CNN) model using simulated cases to classify each output node.

Localization of AVS noise source in 300-MWe SMR model using machine learning

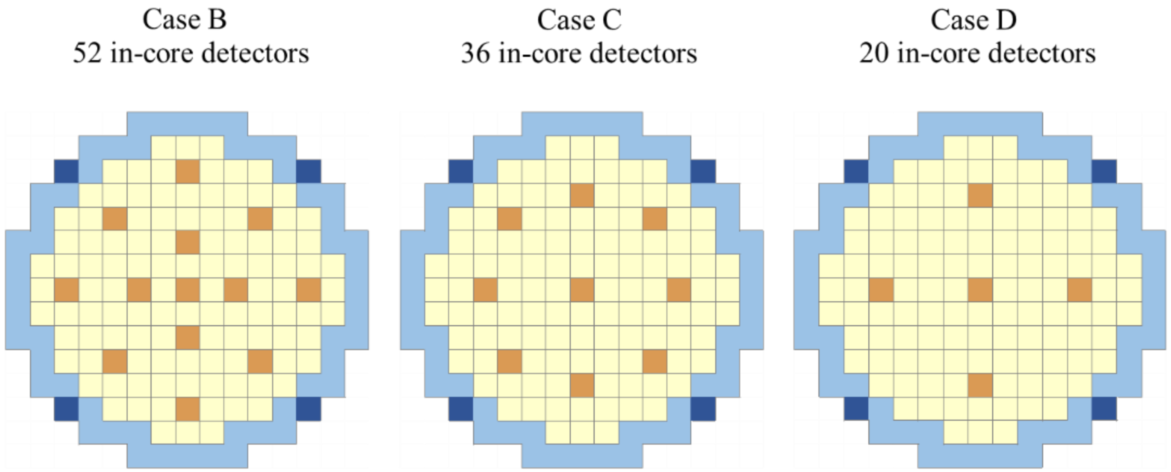
Case A
549 in-core detectors
25% core coverage



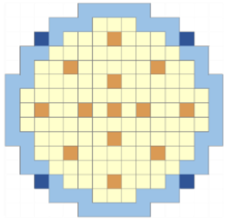
Localization of AVS noise source in 300-MWe SMR model using machine learning

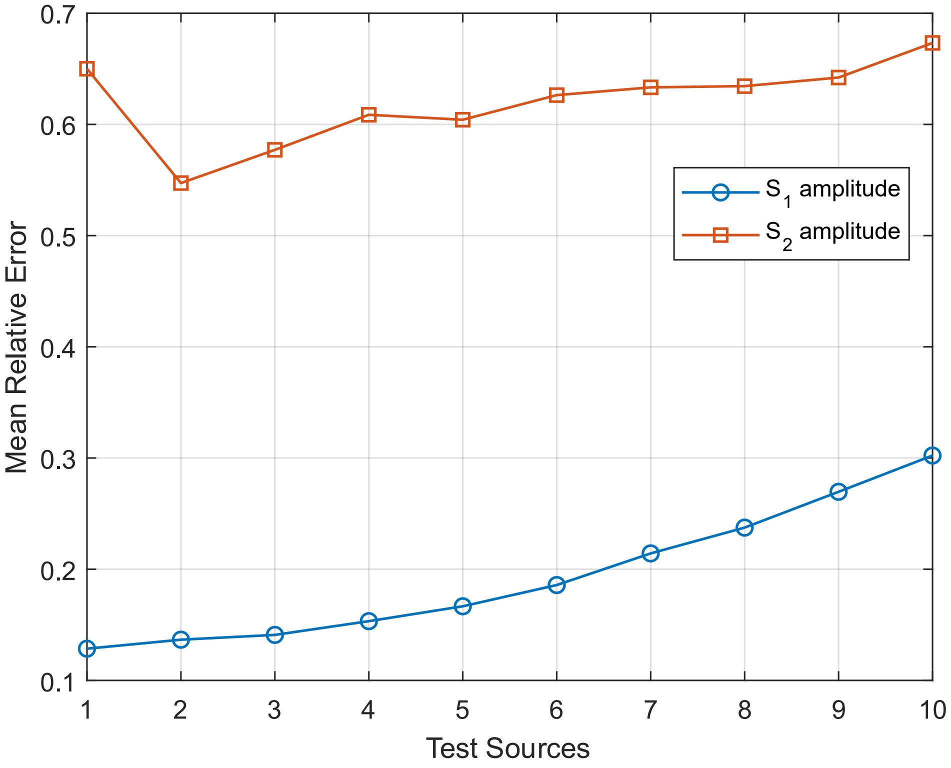


Recall measures prediction probability

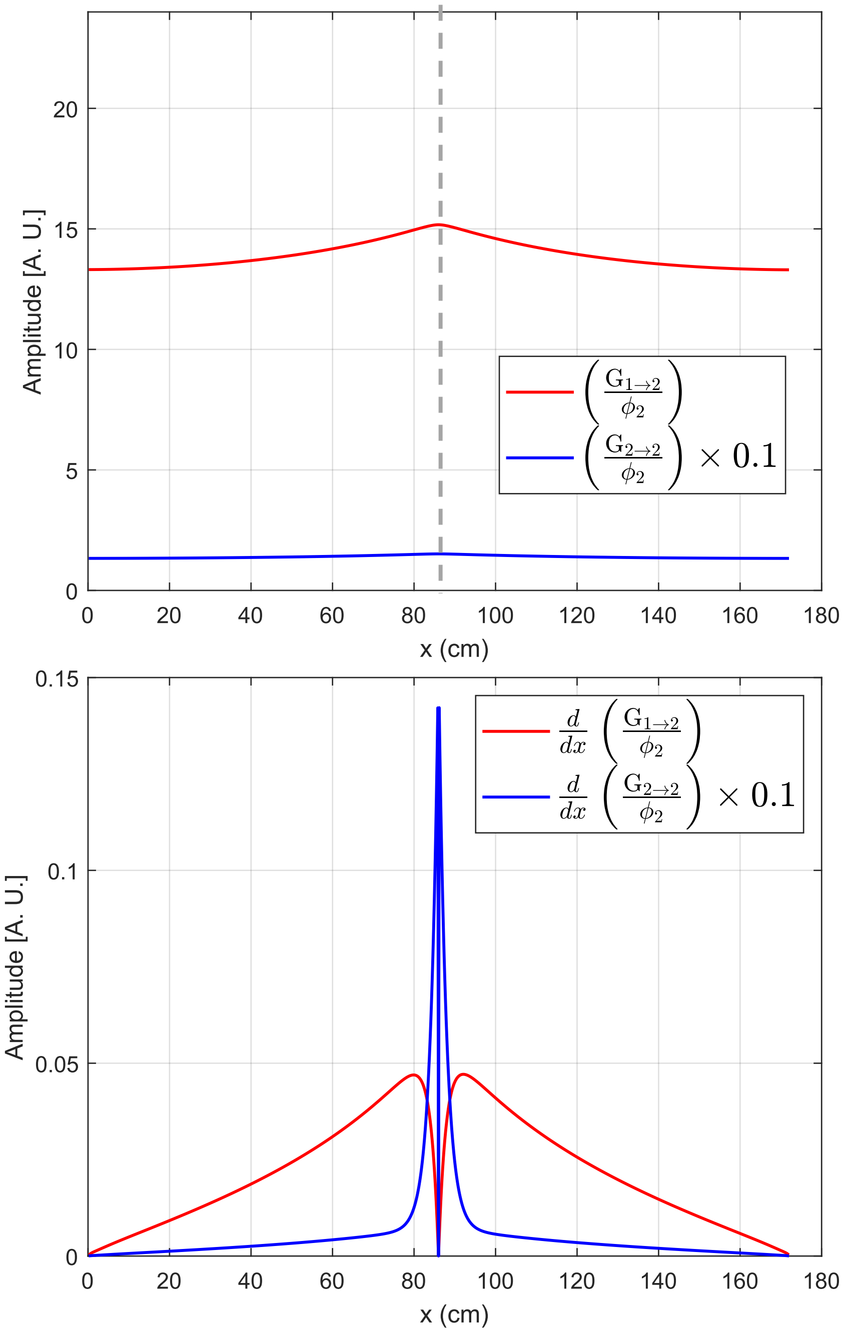


Retreiving S_1 and S_2 coefficients



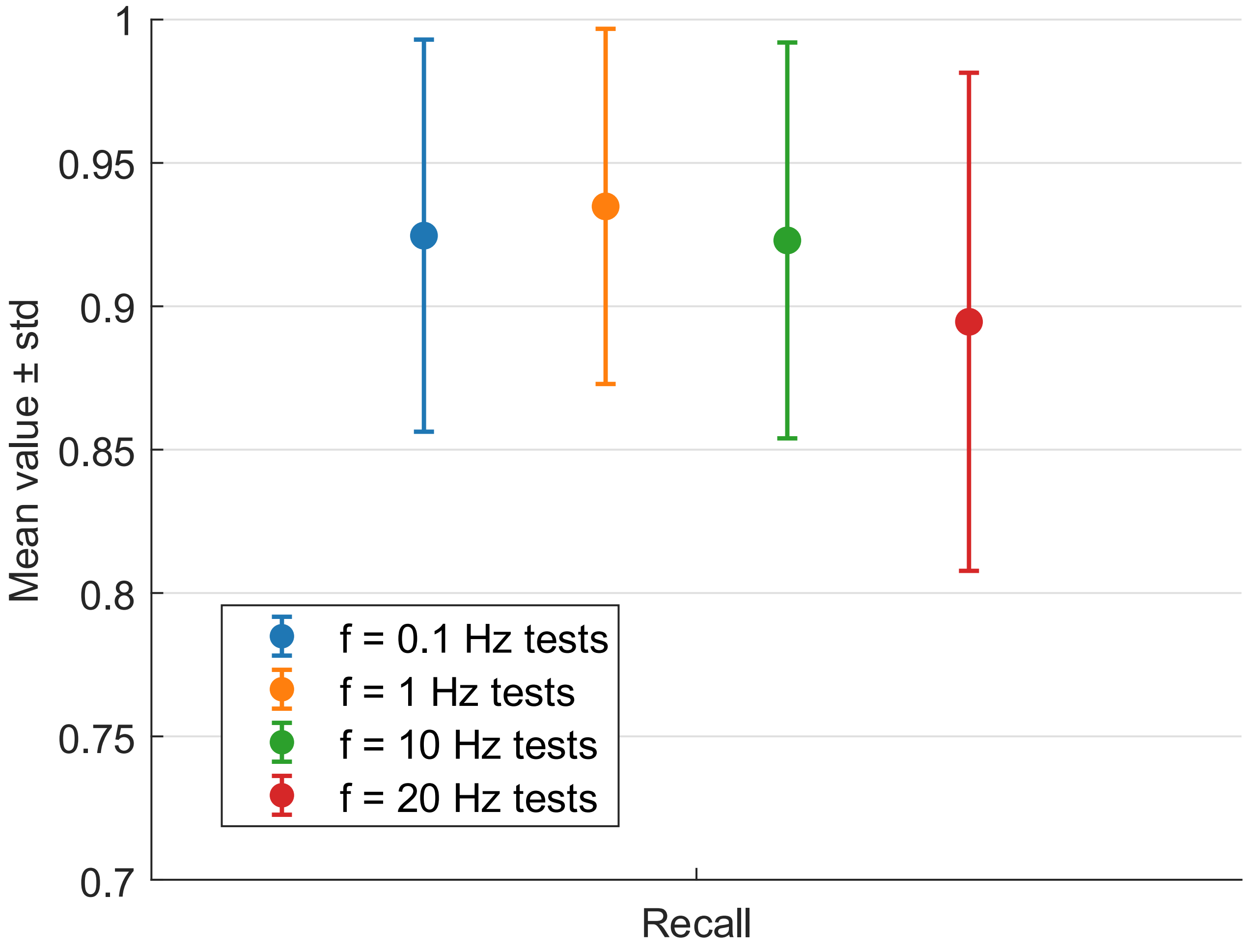


Relative noise resulting from S_1 =1 and S_2 = 0.1



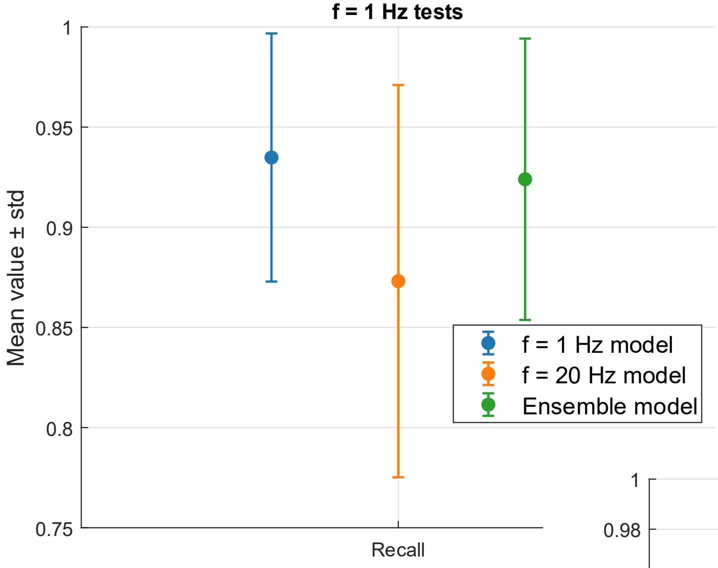
Frequency Generalization

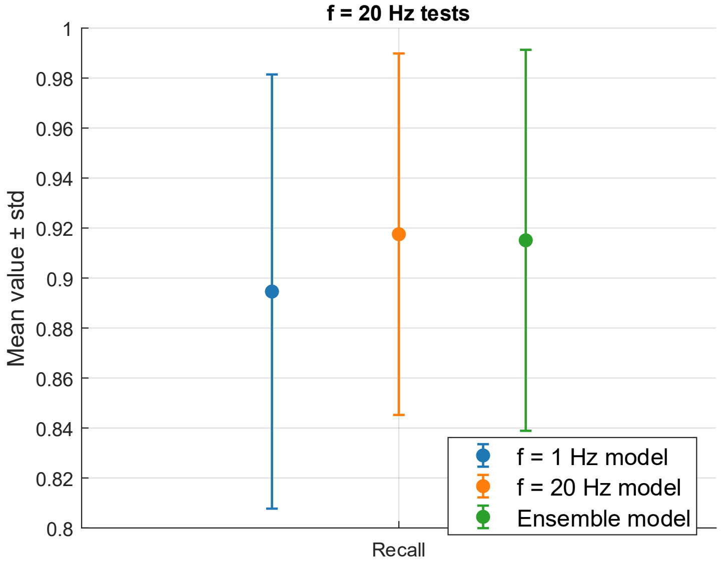
1 Model trained for 1 Hz AVS noise sources

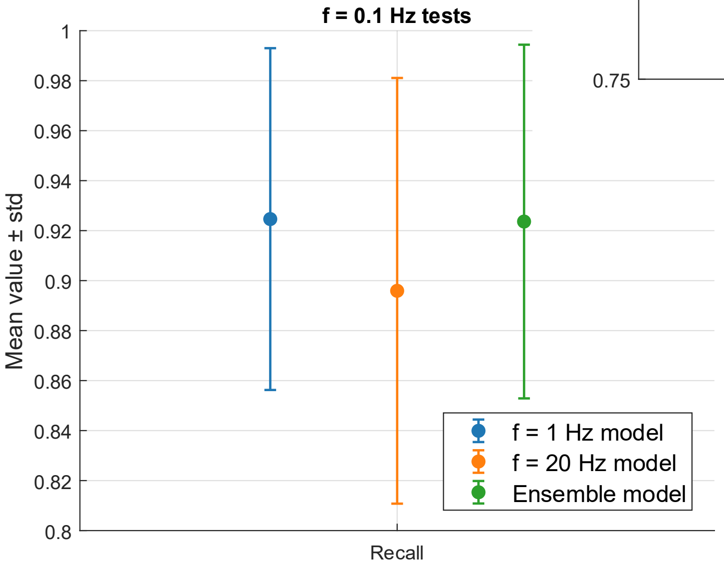


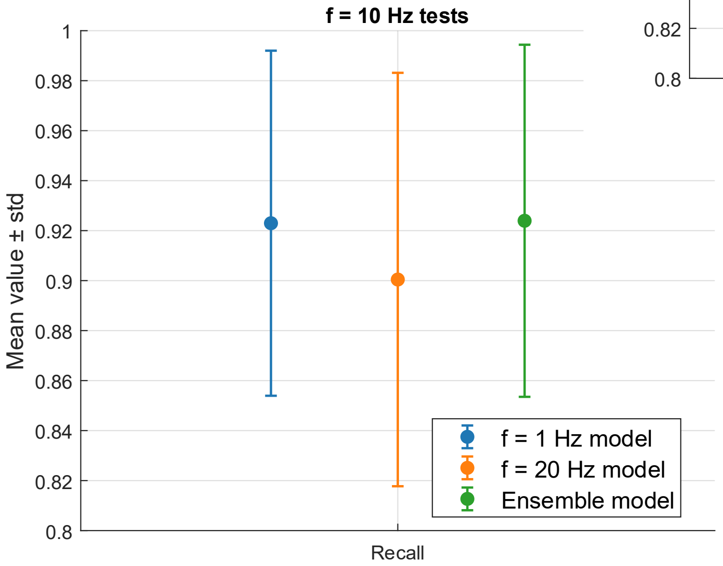
Frequency Generalization

- Model 1: trained for 1 Hz AVS noise sources
- Model 2: trained for 20 Hz AVS noise sources
- Model 3: ensemble model averaging the performance of Models 1 and 2



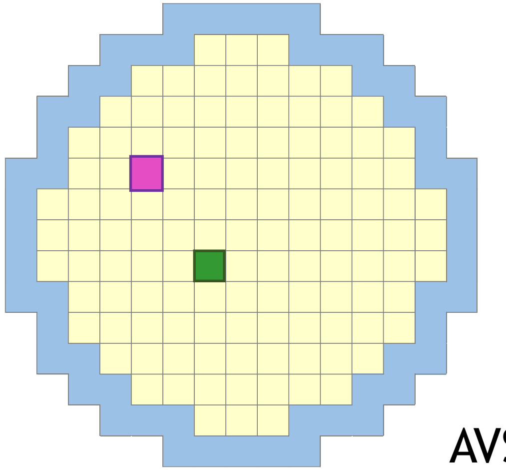






Identification and localization of multiple noise source types in SMR using machine learning

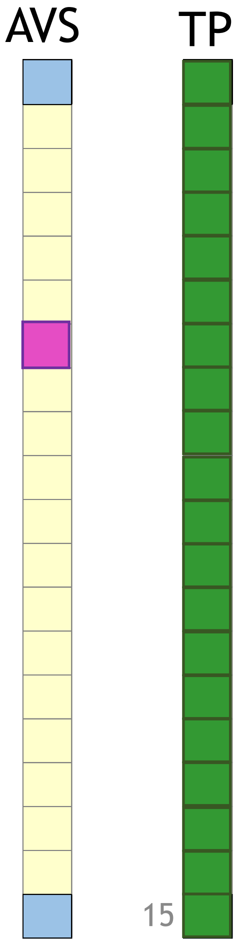
TP Neutron Noise model



$$\delta\Sigma_r(\mathbf{r},\omega) \equiv \delta\Sigma_r(x,y,z,\omega) = \begin{cases} 0, \text{ if } (x,y) \neq (x_0,y_0) \\ 0, \text{ if } (x,y) = (x_0,y_0) \text{ and } z < z_0 \\ \delta\Sigma_r(x_0,y_0,z_0,\omega)\exp\left[-\dfrac{i\omega(z-z_0)}{v}\right], \text{ if } (x,y) = (x_0,y_0) \text{ and } z \geq z_0 \end{cases} \quad (1)$$

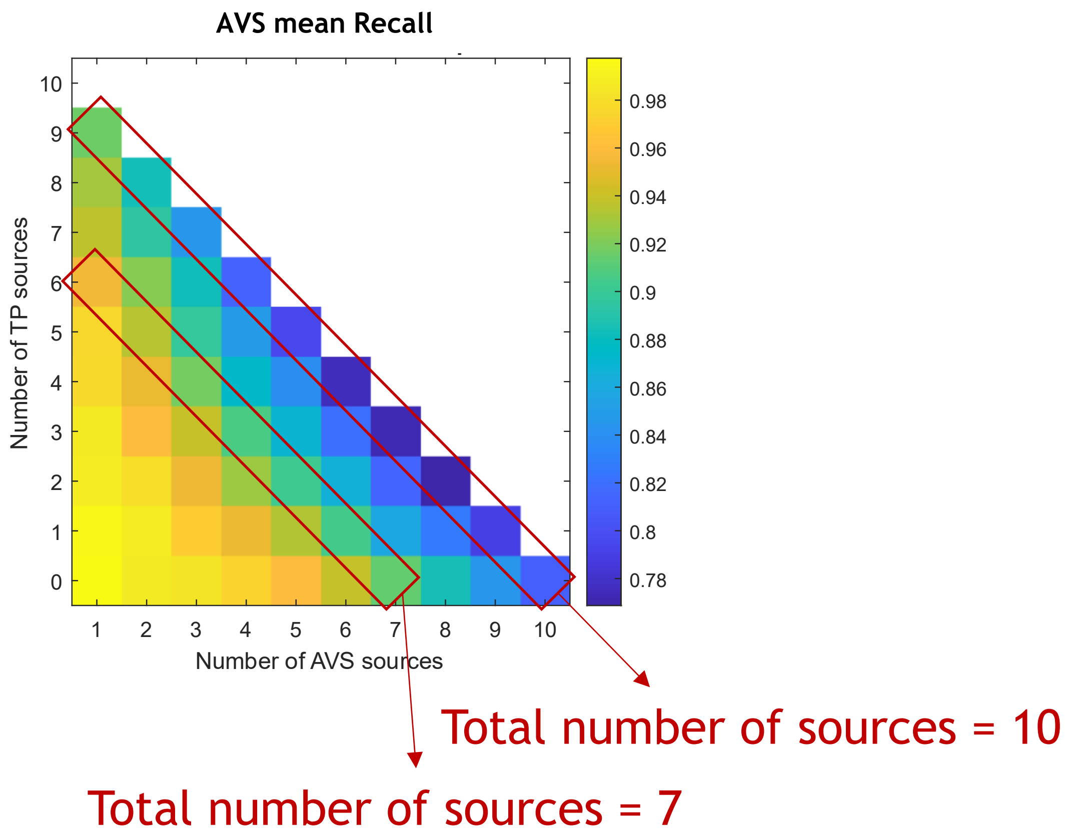
$$\begin{bmatrix} S_1(\boldsymbol{r}',\omega) \\ S_2(\boldsymbol{r}',\omega) \end{bmatrix} = \boldsymbol{\phi}_r(\boldsymbol{r}')\delta\Sigma_r(\boldsymbol{r}',\omega) \quad (2)$$

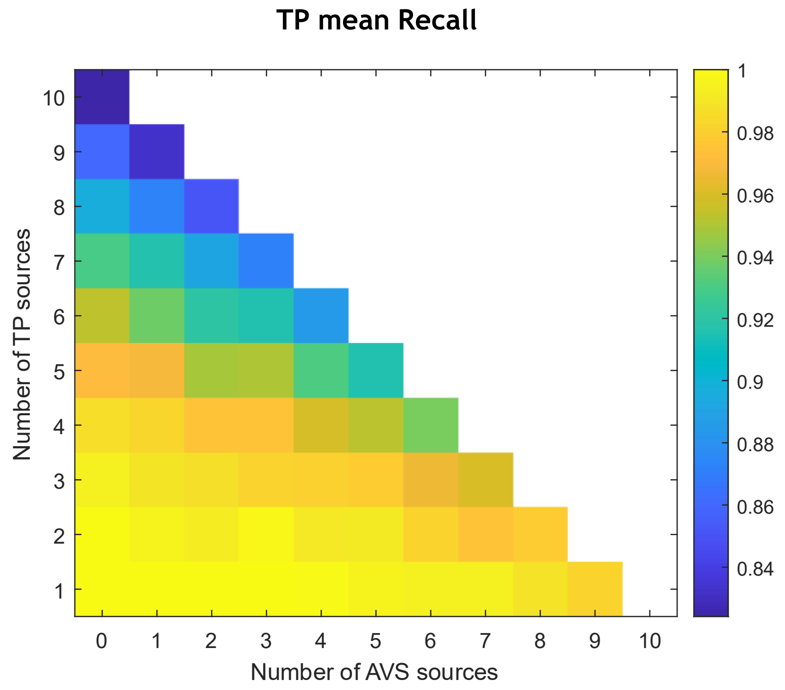
$$\begin{bmatrix} \delta\phi_1(\boldsymbol{r},\omega) \\ \delta\phi_2(\boldsymbol{r},\omega) \end{bmatrix} = \begin{bmatrix} \int\{G_{1\to1}(\boldsymbol{r},\boldsymbol{r}',\omega)S_1(\boldsymbol{r}',\omega) + G_{2\to1}(\boldsymbol{r},\boldsymbol{r}',\omega)S_2(\boldsymbol{r}',\omega)\}d^3\boldsymbol{r}' \\ \int\{G_{1\to2}(\boldsymbol{r},\boldsymbol{r}',\omega)S_1(\boldsymbol{r}',\omega) + G_{2\to2}(\boldsymbol{r},\boldsymbol{r}',\omega)S_2(\boldsymbol{r}',\omega)\}\,d^3\boldsymbol{r}' \end{bmatrix} \quad (3)$$



Prediction of AVS and TP

- Identification and localization
- Usage of transformers in the model





Conclusions and future work

Conclusions

- Development of CNN model to localize AVS in 300-MWe SMR
  - ➢ Able to detect locations of up to 10 AVS sources simultaneously.
  - ➢ Comparison of model performance using 549, 52, 36, and 20 in-core detectors + 8 ex-core detectors.
  - ➢ Studied the retrieval of S_1 and S_2 coefficients (S_1 overshadows S_2 contribution).
  - ➢ Developed an ensemble model to localize pertrubations at different frequencies using 2 frequency models.
- Development of ML model to identify and localize AVS and TP in 300-MWe SMR
  - ➢ Able to differentiate between AVS and TP neutron noise sources.
  - ➢ Able to localize each type separately.

Future work

- For the 300-MWe SMR:
  - Investigate different types of perturbations
  - Investigate different frequency ranges
  - Integrate uncertainty quantification into the different stages of this work
  - Effect of external background noise to the input data

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Thank you!

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