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

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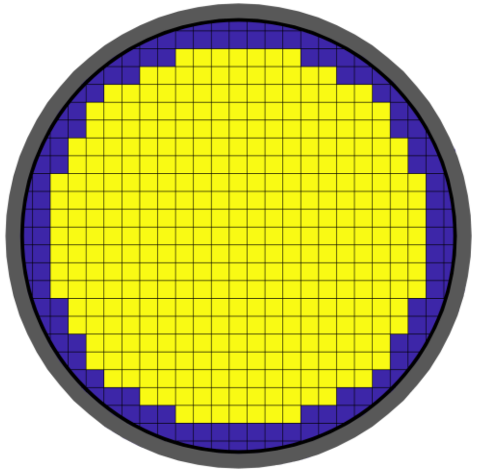
Outline

- Introduction
- Objectives
- Work done so far
  - Fuel Assembly Vibrations in small VS large reactors
  - Machine learning for noise source location detection
- Conclusions
- Future work

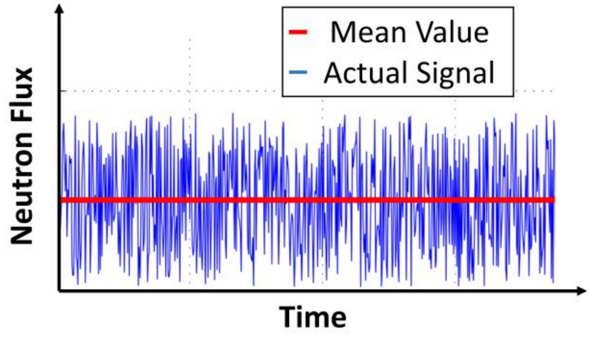
Introduction

Introduction

- Concept for core monitoring and diagnostics via reactor neutron noise



Neutron flux measurements in normal operations from ex-core and in-core detectors



Reactor neutron noise

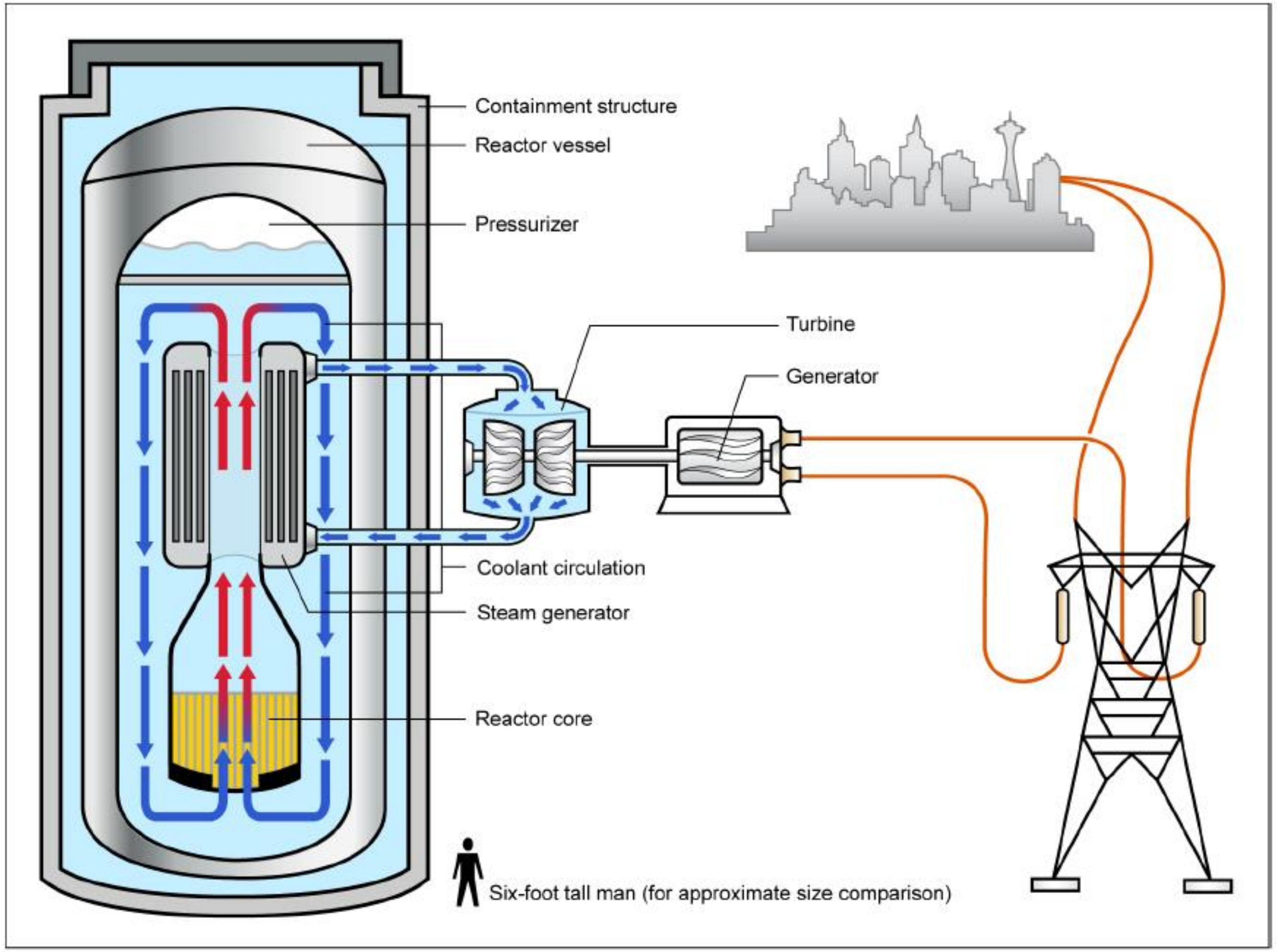
Unfolding technique: from the effect to the cause

Identification and localization of perturbations

Introduction (SMRs)

Easier to meet the safety requirements

Standardized and modular core components



Source: GAO, based on Department of Energy documentation. | GAO-15-652

Economically competitive

Reduced power level

Introduction

Objectives of the project

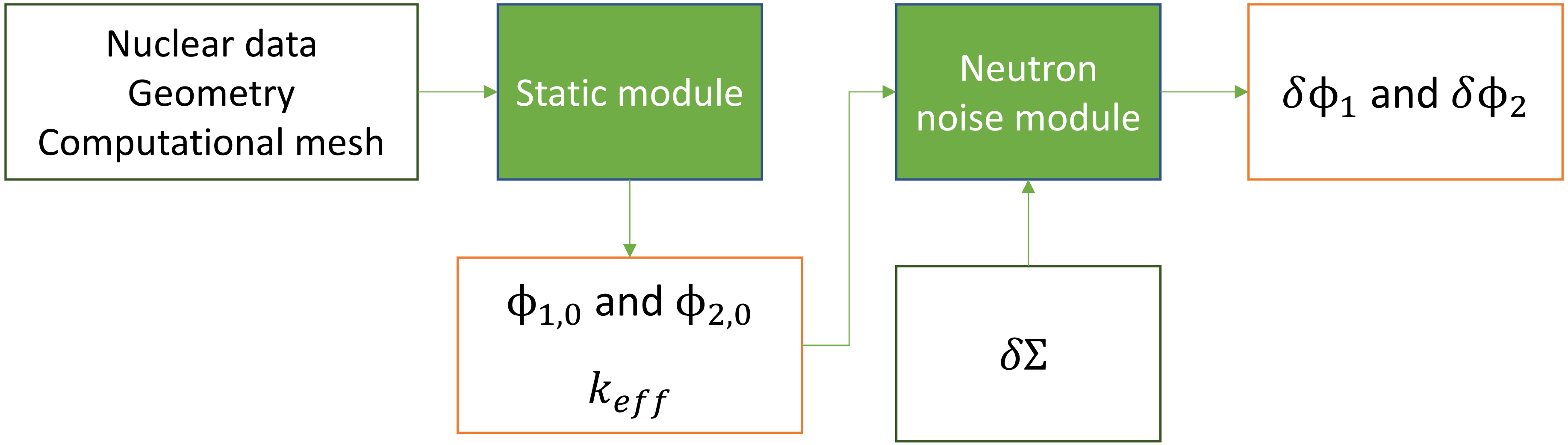
- Characterize reactor neutron noise in SMRs
  - In small systems such as SMRs:
    How strong is the spatial component with respect to point-kinetics?

- 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

Introduction

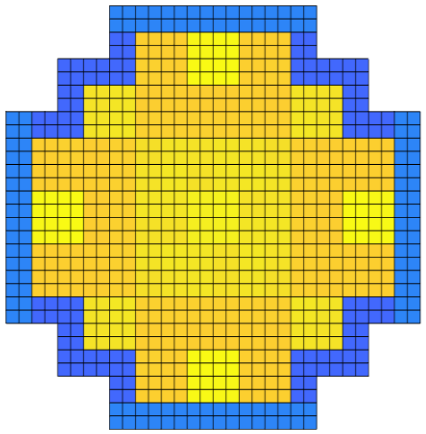
- Frequency-domain, 2-group diffusion-based solver CORE SIM+
    - Characterization of reactor noise in SMR
    - Generation of synthetic dataset for training and test of ANN models



Characterization of reactor neutron noise in SMRs

Reactor neutron noise in SMRs

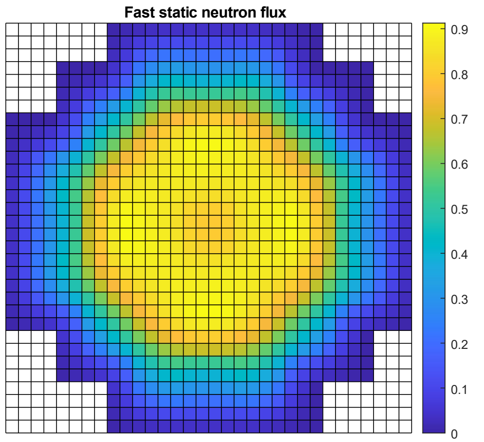
- Small water-cooled reactor core model developed for the study
  - Derived from a typical large PWR



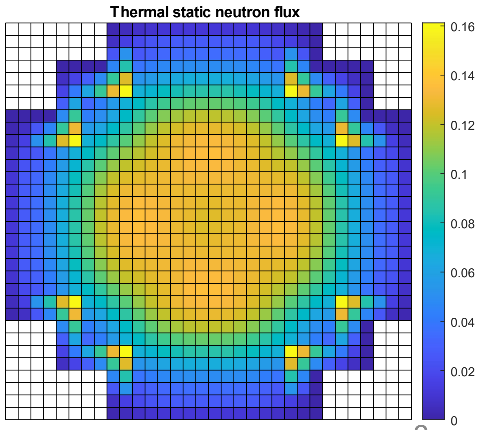
Diameter = 150.5 cm
Height = 200 cm

k_{eff}=1.0052

Fast
static flux



Thermal
static flux



Reactor neutron noise in SMRs

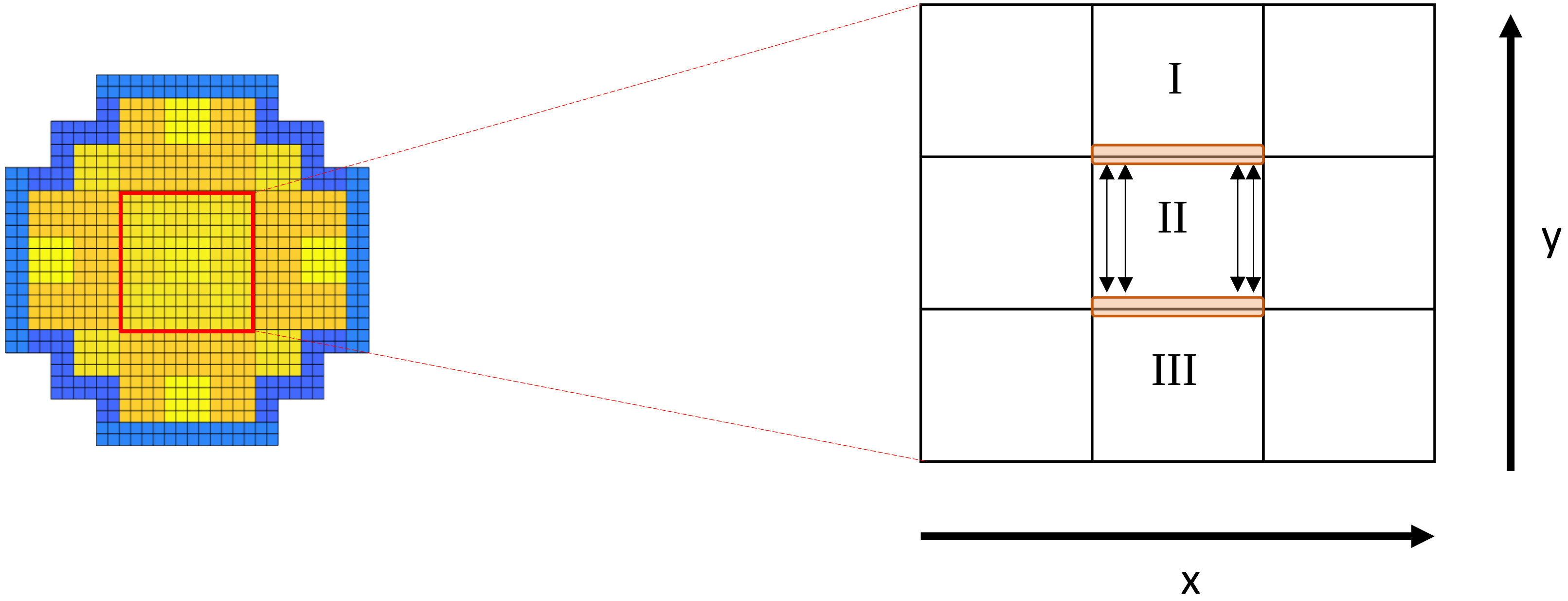
- Investigation of noise induced by
  - Absorber of Variable Strength (AVS)
  - Fuel Assembly Vibration (FAV)

$$\left\{\nabla.\begin{bmatrix} D_{1,0}(r) & 0 \\ 0 & D_{2,0}(r) \end{bmatrix}\nabla + \boldsymbol{\Sigma_{dyn}}(\boldsymbol{r},\boldsymbol{\omega})\right\} \times \begin{bmatrix} \delta\phi_1(r,\omega) \\ \delta\phi_2(r,\omega) \end{bmatrix} = \begin{bmatrix} S_1(r,\omega) \\ S_2(r,\omega) \end{bmatrix}$$

$$\begin{bmatrix} S_1(r,\omega) \\ S_2(r,\omega) \end{bmatrix} = \boldsymbol{\phi_r}(\boldsymbol{r})\,\delta\Sigma_r(r,\omega) + \boldsymbol{\phi_a}(\boldsymbol{r})\begin{bmatrix} \delta\Sigma_{a,1}(r,\omega) \\ \delta\Sigma_{a,2}(r,\omega) \end{bmatrix} + \boldsymbol{\phi_f}(\boldsymbol{r},\boldsymbol{\omega})\begin{bmatrix} \delta\upsilon\Sigma_{f,1}(r,\omega) \\ \delta\upsilon\Sigma_{f,2}(r,\omega) \end{bmatrix}$$

Reactor neutron noise in SMRs

- Fuel Assembly Vibration (FAV)
  - Modeling of the vibration along the y-direction



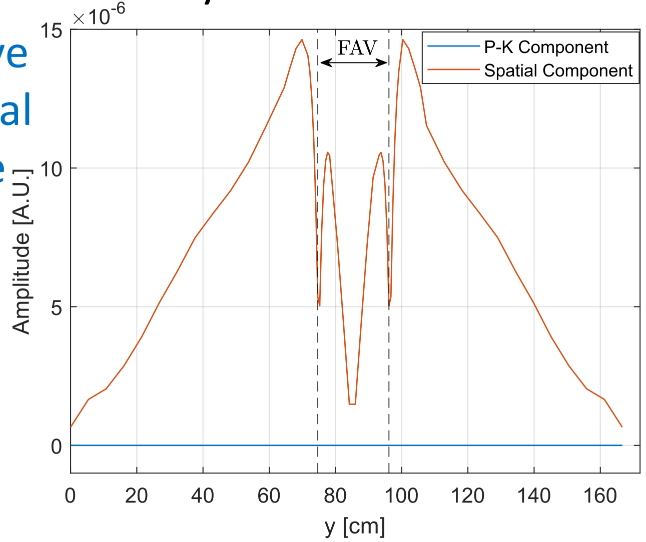
$$\delta\Sigma_{\alpha,g}(y,\omega) = \begin{cases} -i\,\frac{\pi}{2}\,\Delta\Sigma_{\alpha,g}\,\delta(\omega-\omega_0), & with\ \ y_0-\epsilon \le y \le y_0+\epsilon \\ 0, & otherwise \end{cases}$$

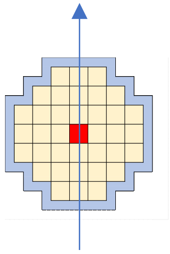
$\Delta\Sigma_{\alpha,g}$ is the difference between the $\Sigma_{\alpha,g}$ associated with the two regions separated by the boundary.

Central vibration

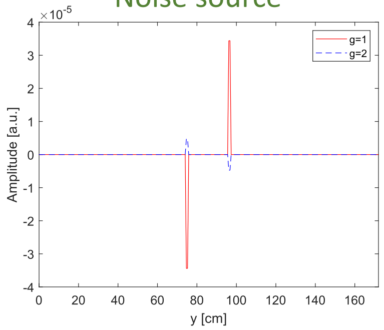
Relative Thermal Noise

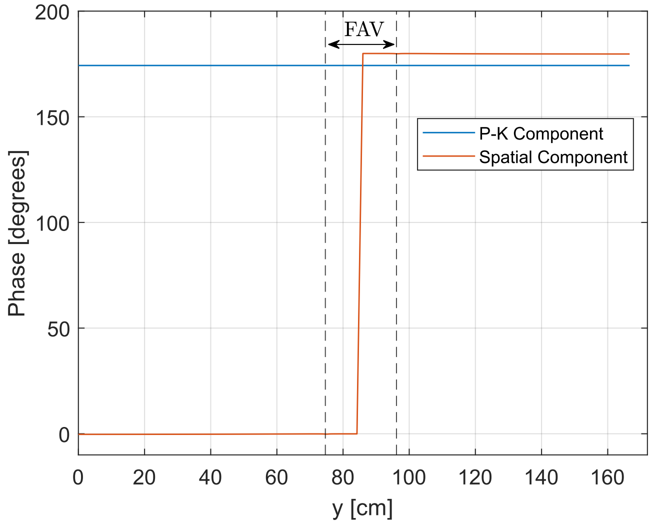
Symmetric SMR



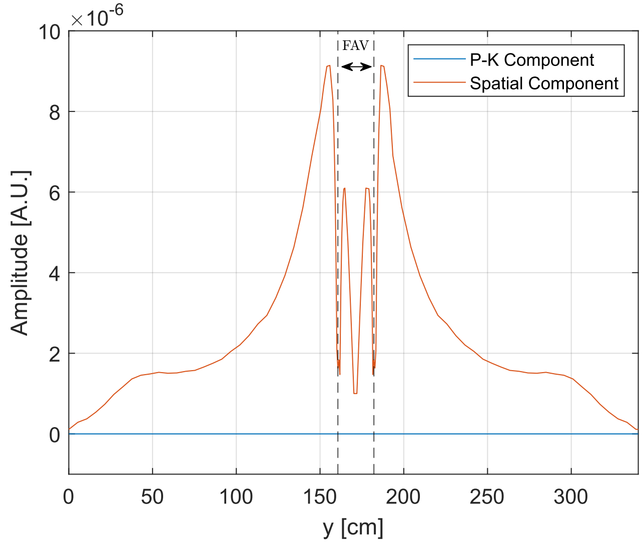


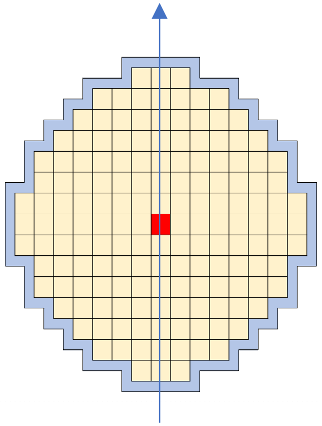
Noise source



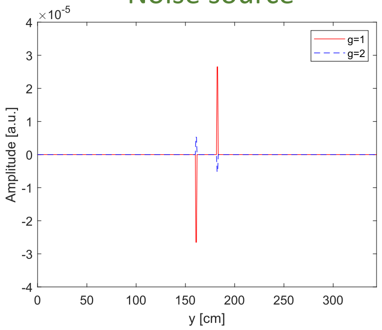


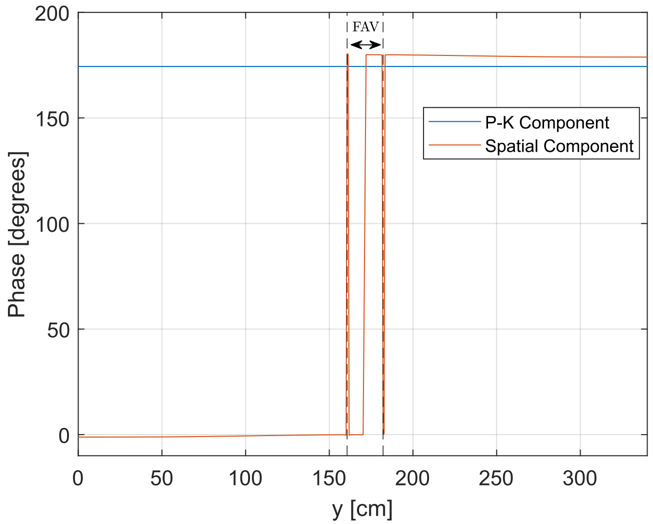
Symmetric large PWR





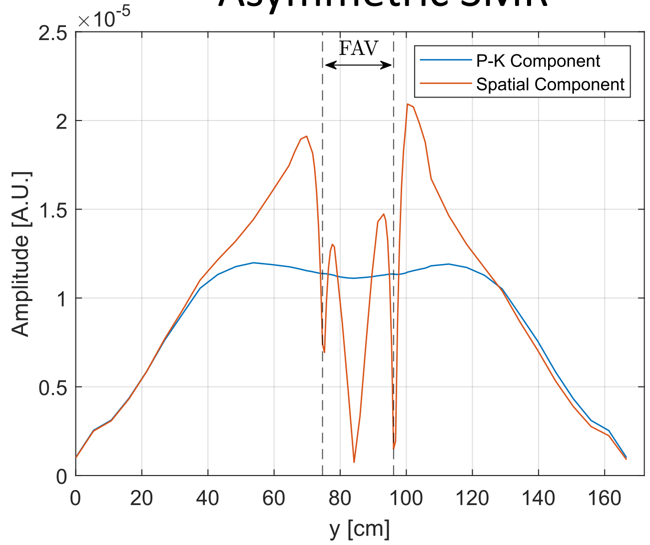
Noise source

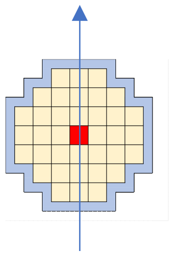




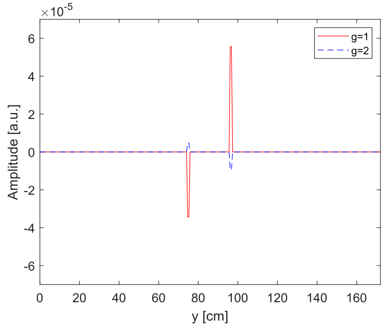
Central vibration

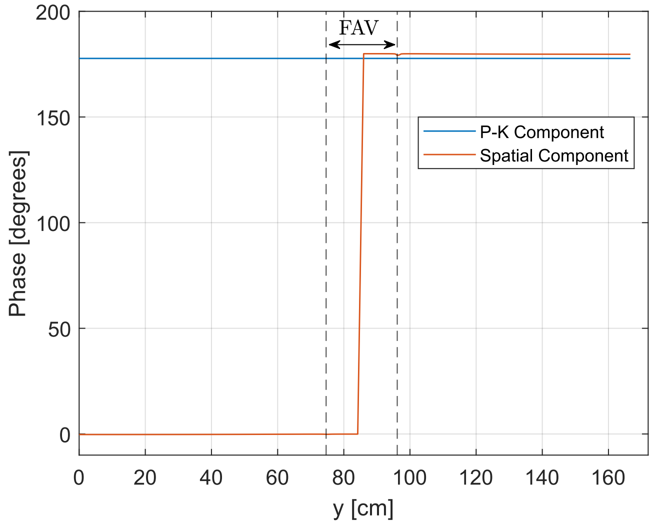
Asymmetric SMR



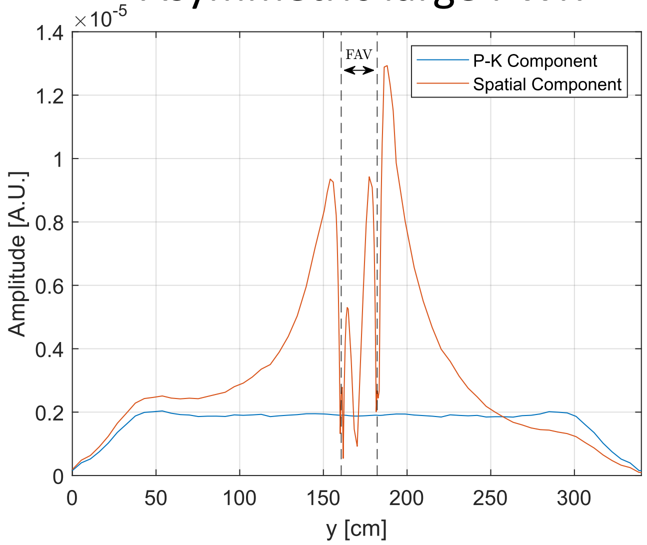


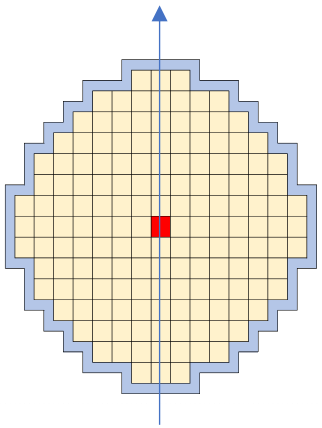
Noise source



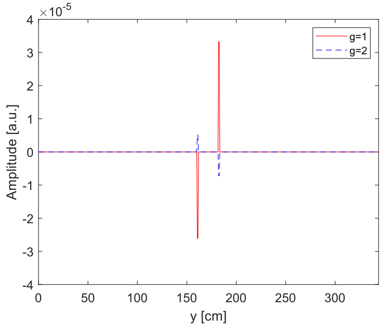


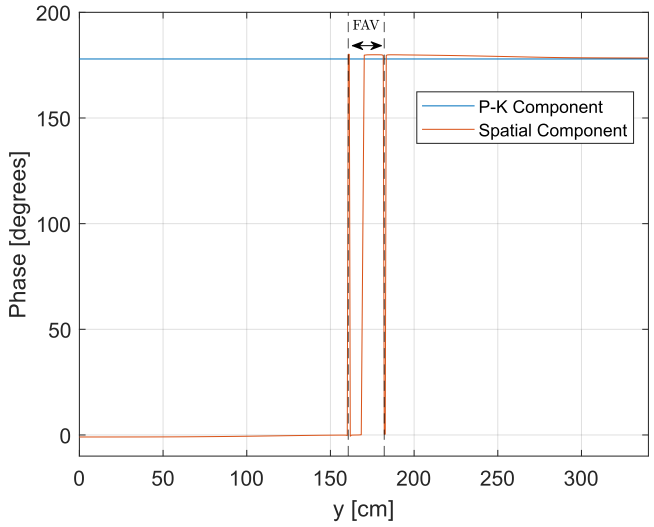
Asymmetric large PWR





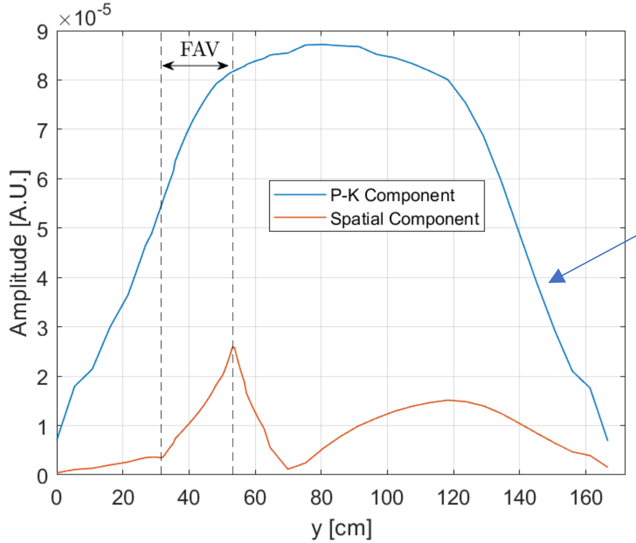
Noise source

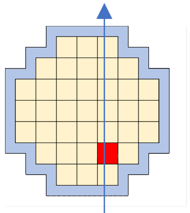




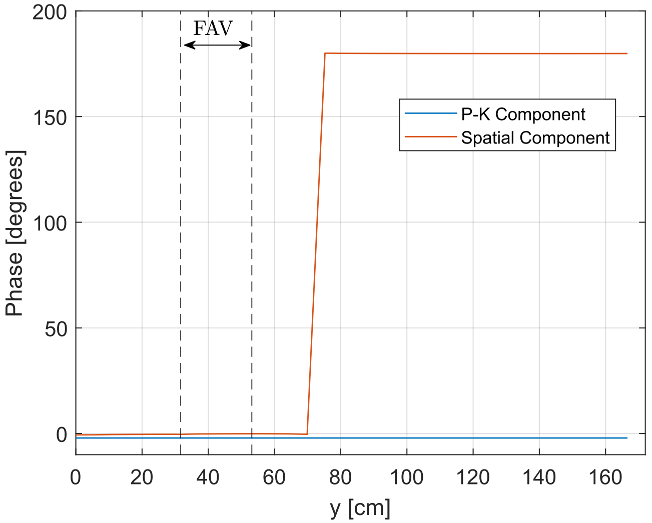
Periphery vibration 1

Asymmetric SMR

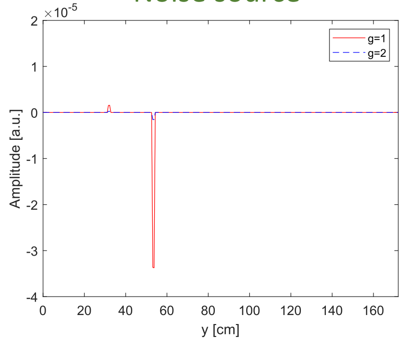




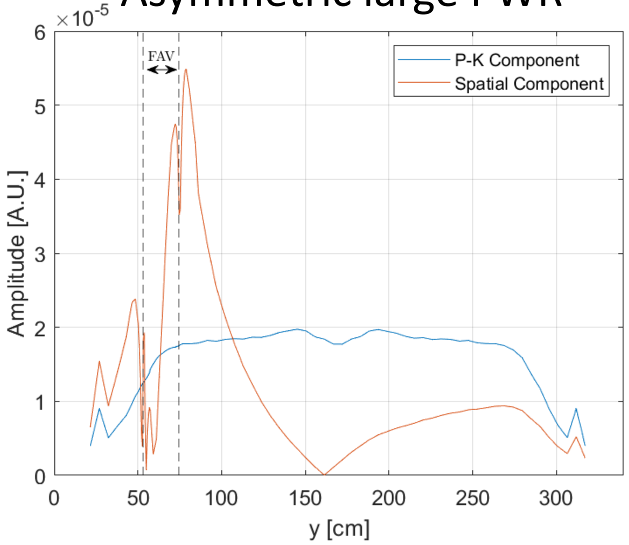
Overwhelming PK-component

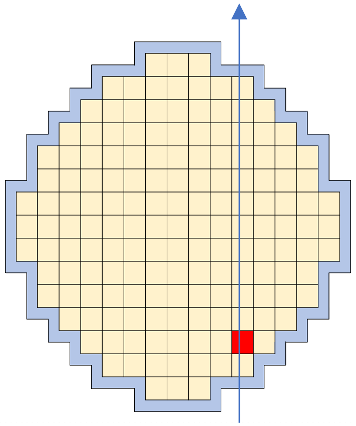


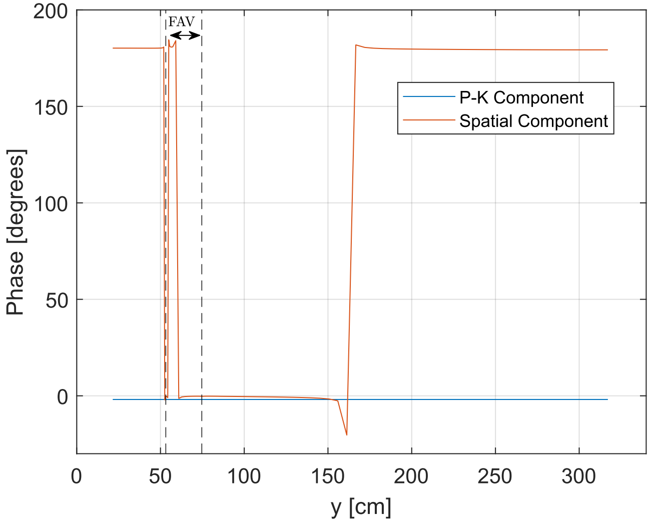
Noise source



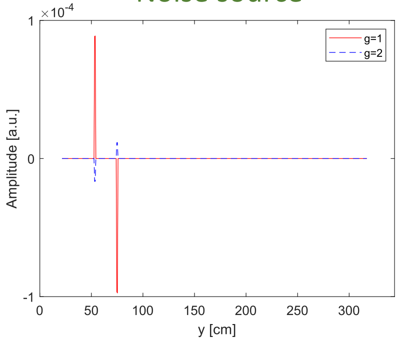
Asymmetric large PWR





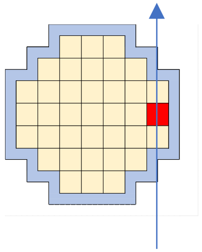


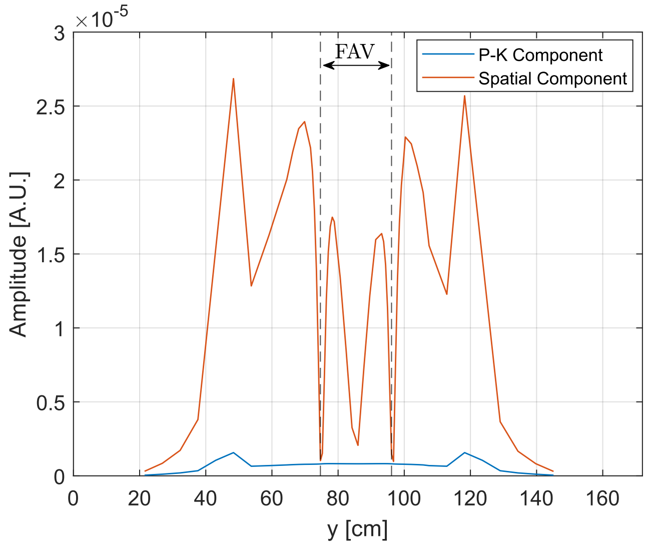
Noise source

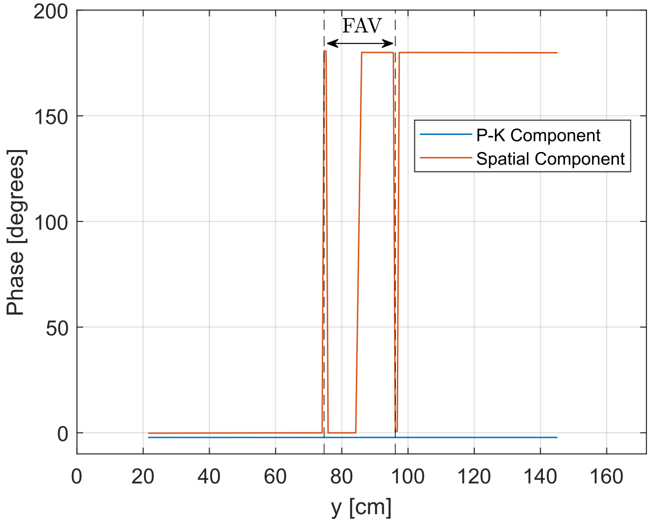


Periphery vibration 2

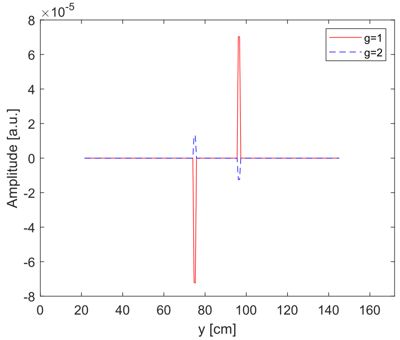
Asymmetric SMR





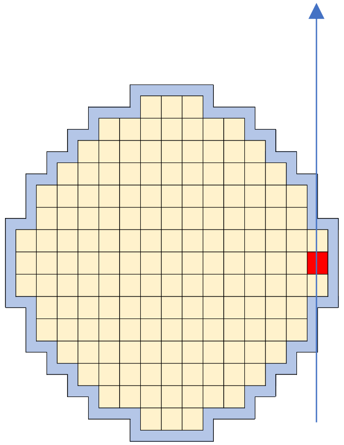


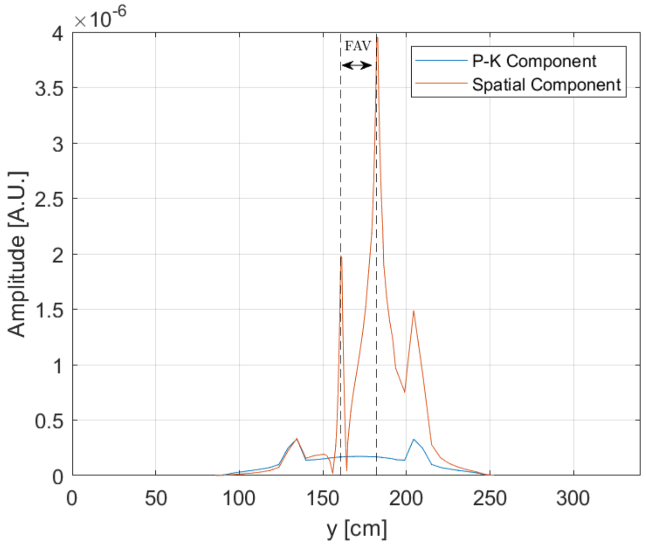
Noise source

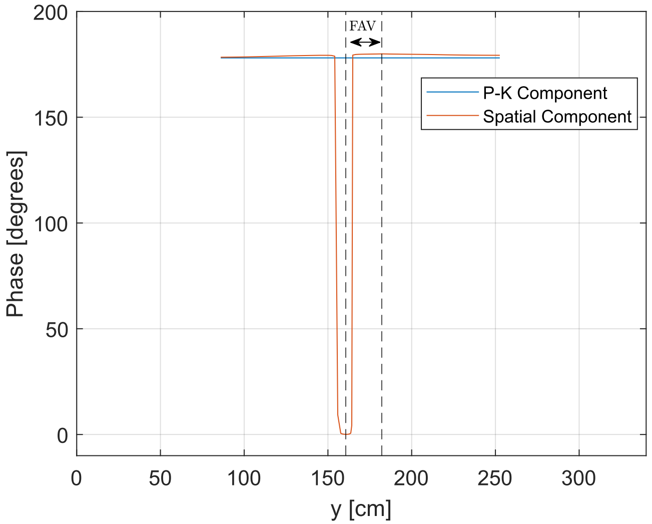


Behavior highly dependent on Σ not only reactor size

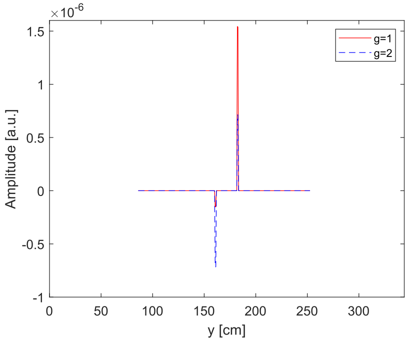
Asymmetric large PWR







Noise source

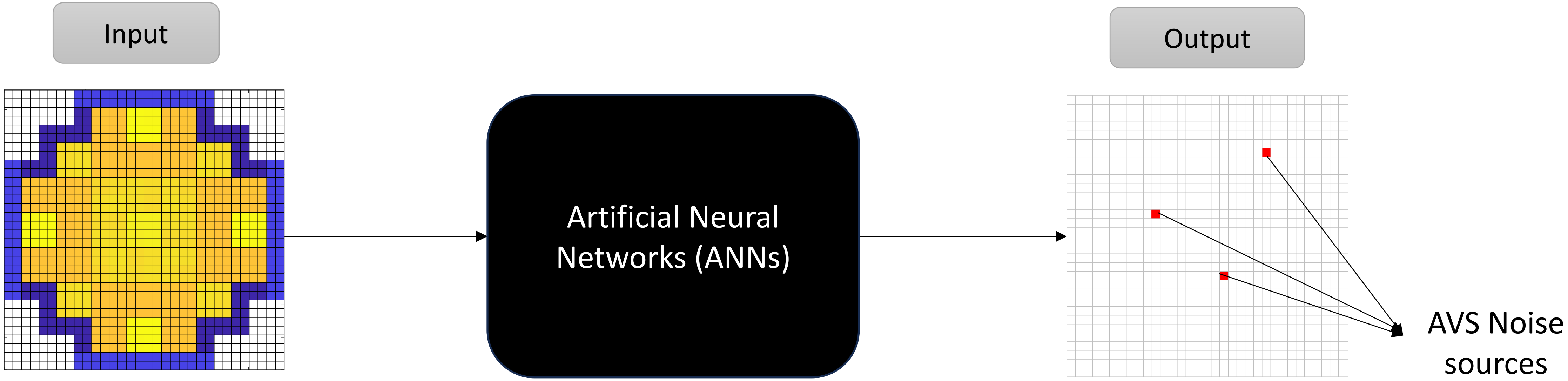


ML for detecting reactor noise source location in SMRS

Machine learning for reactor noise source location detection

For 2D SMR:

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



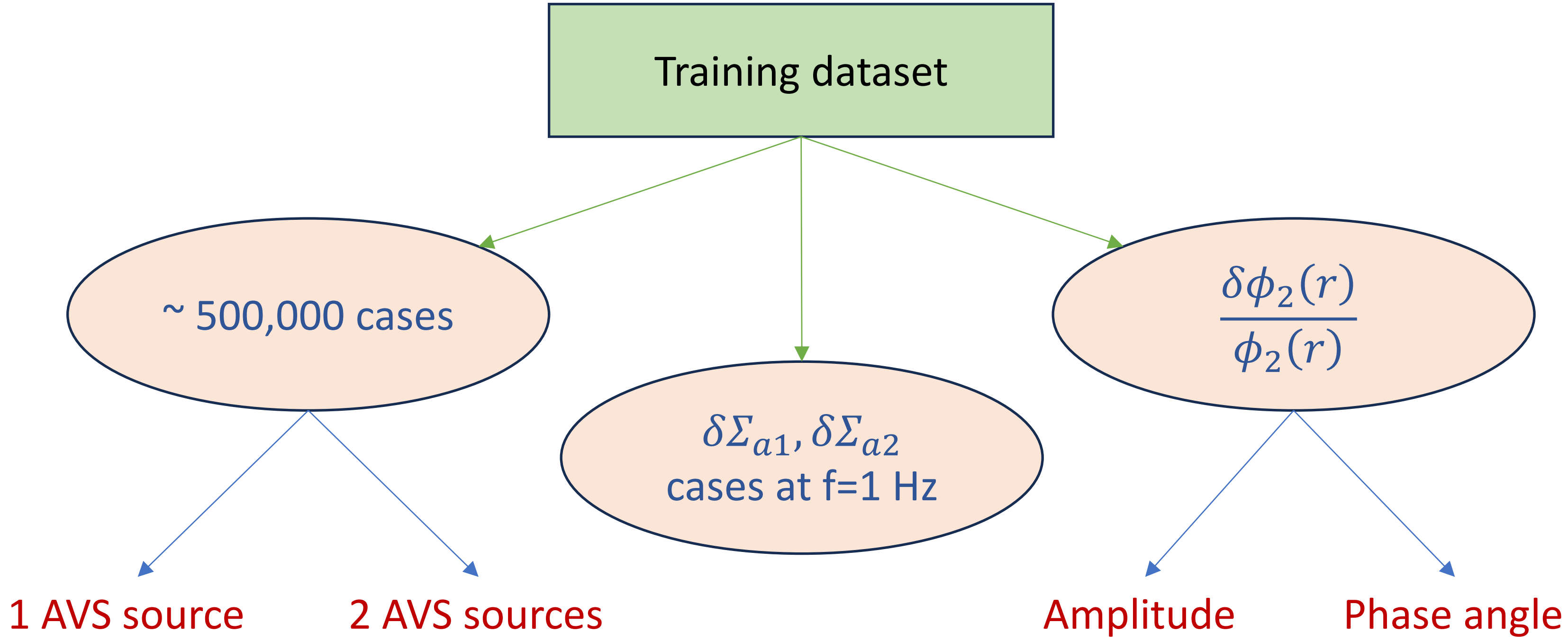
Relative Thermal Noise distribution

Approach: Train an ANN model using simulated cases.

Machine learning for reactor noise source location detection

Approach:

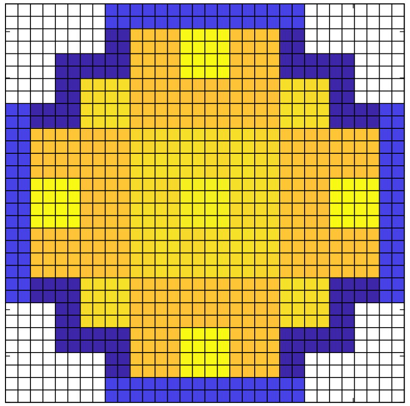
- Train an ANN model using cases with 1 or 2 AVS reactor noise sources



- Test the ANN model on cases with 1 or multiple AVS reactor noise sources

ANNs: Feed- Foward NN

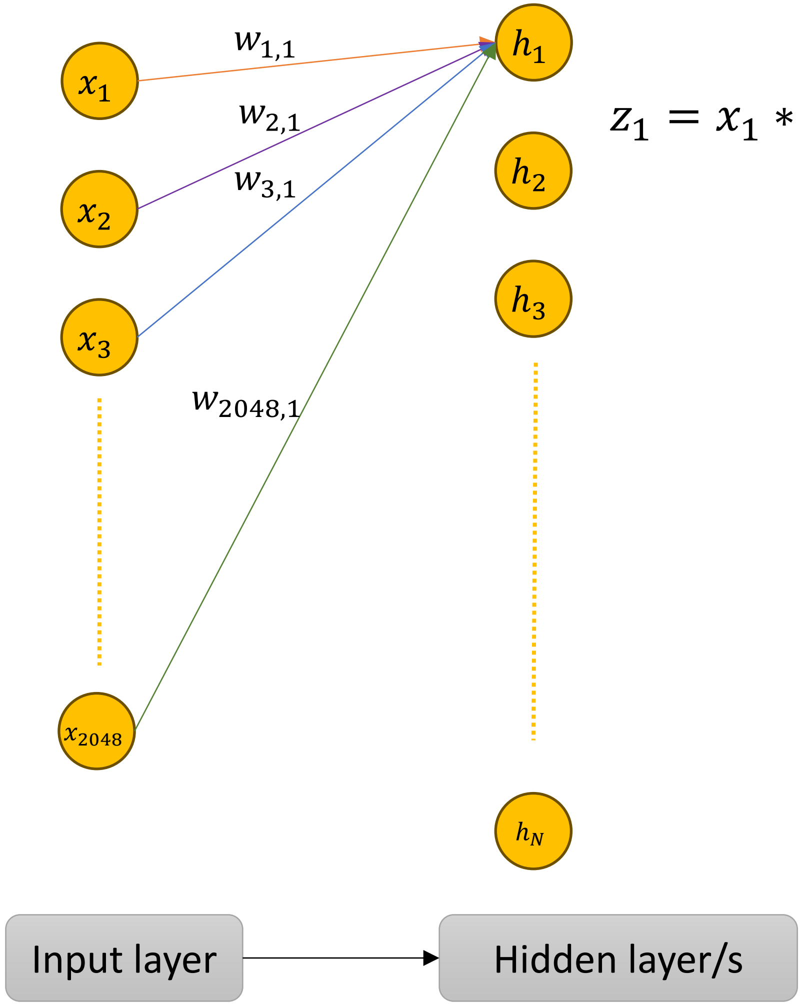
32



32

32 x 32 = 1024 nodes

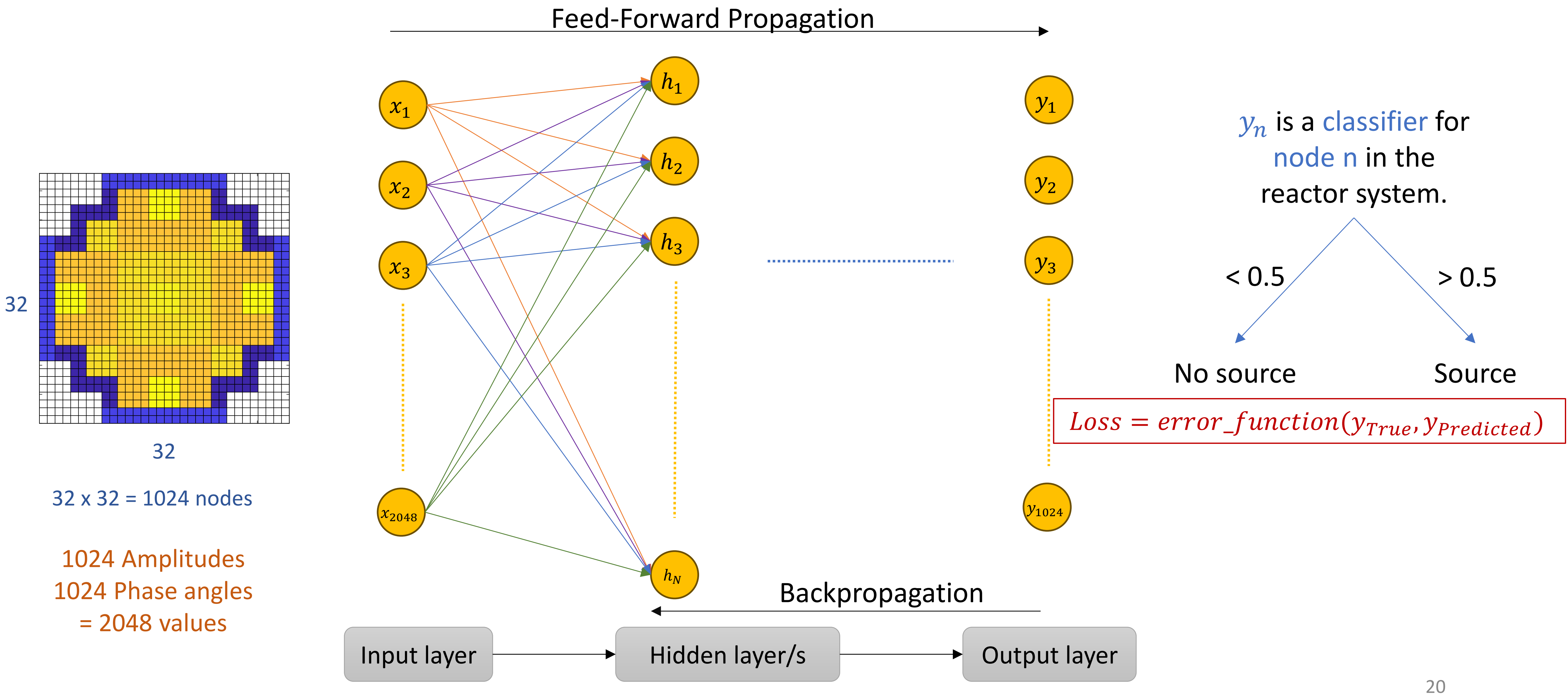
1024 Amplitudes
1024 Phase angles
= 2048 values



$$z_1 = x_1 * w_{1,1} + x_2 * w_{2,1} + x_3 * w_{3,1} + \ \ldots + x_{2048} * w_{2048,1} + b_1$$

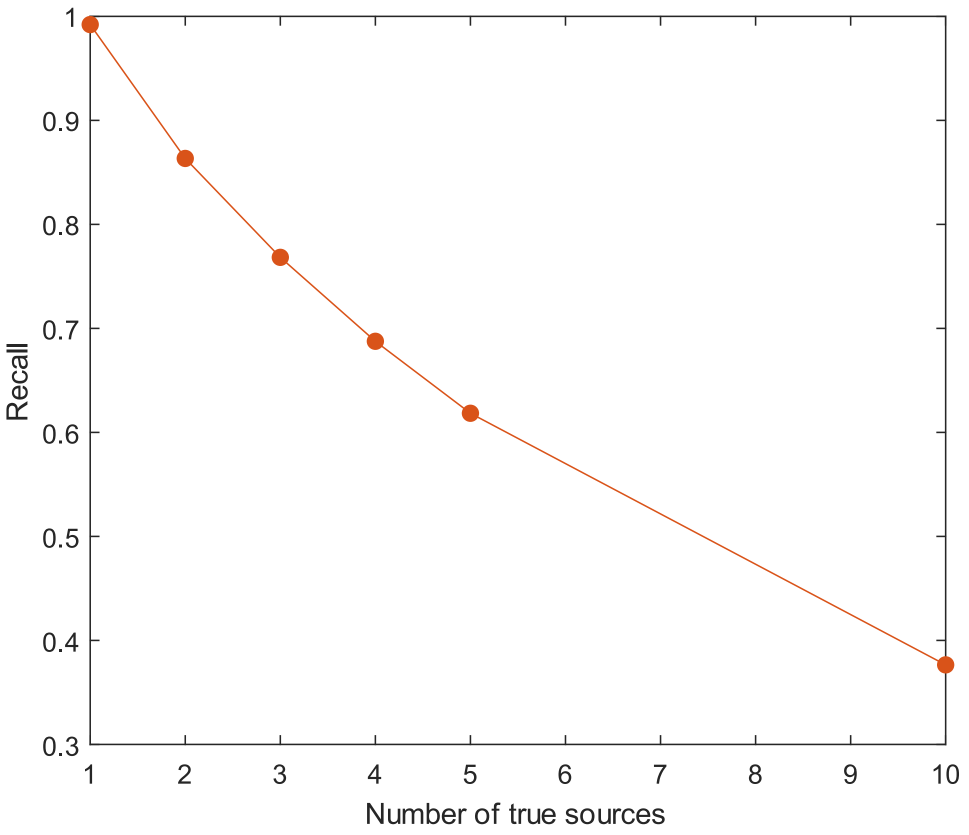
$$h_1 = activation\_function(z_1)$$

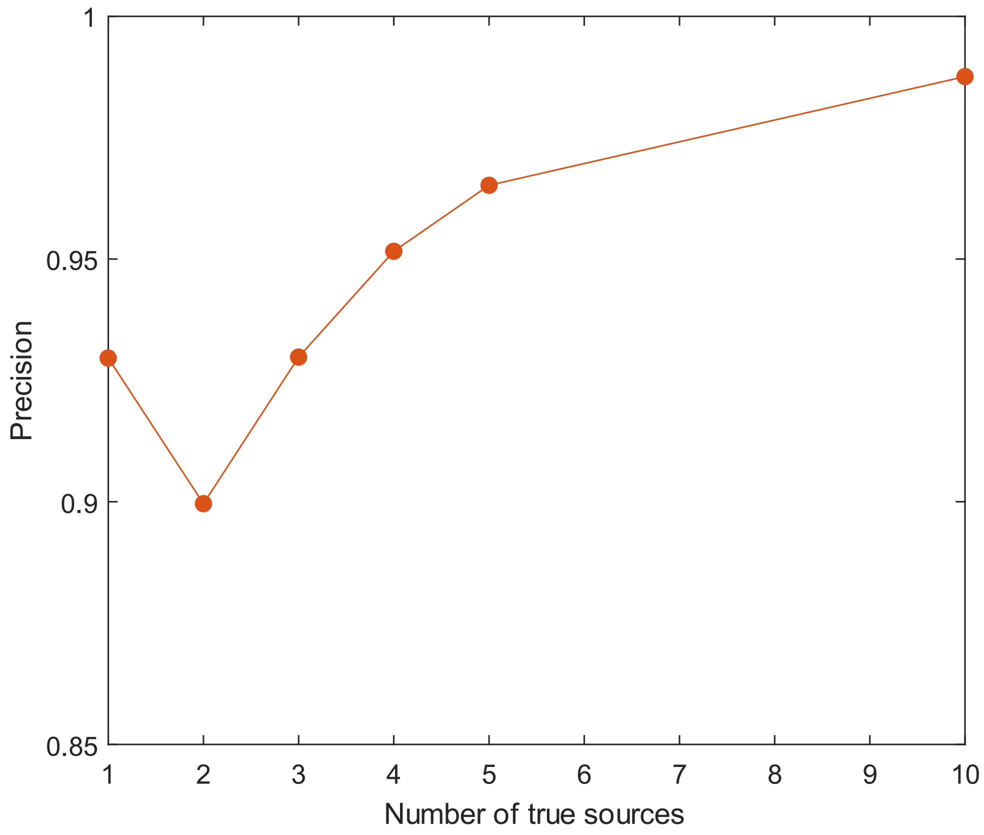
ANNs: Feed- Foward NN



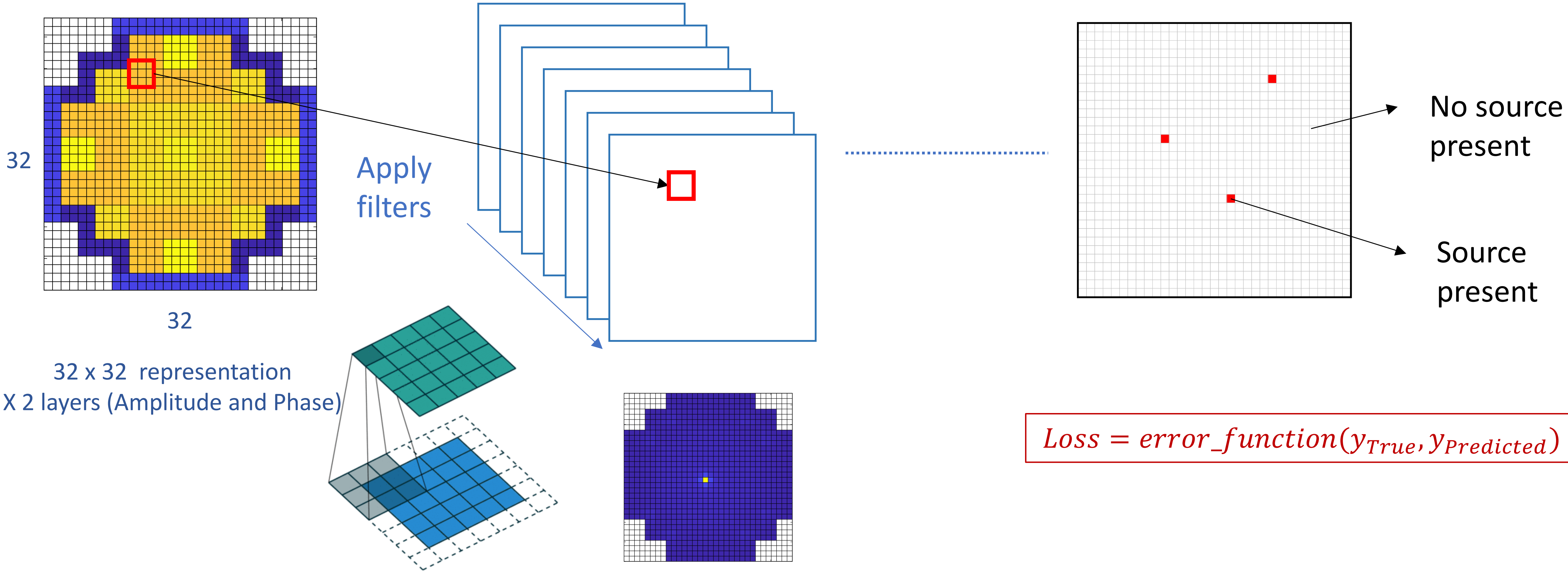
Results for Feed-Forward NN

Predicting cases with $\delta\Sigma_{a1}, \delta\Sigma_{a2}$ at f=1 Hz





ANNs: Convolutional NN(CNNs)

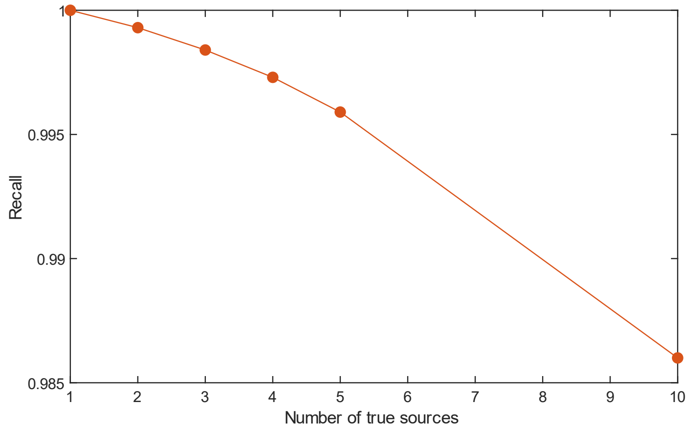


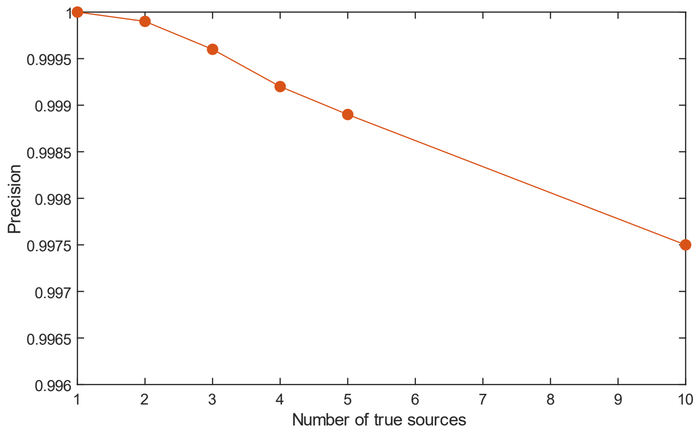
$$Loss = error\_function(y_{True}, y_{Predicted})$$

Input layer → Hidden layer/s → Output layer

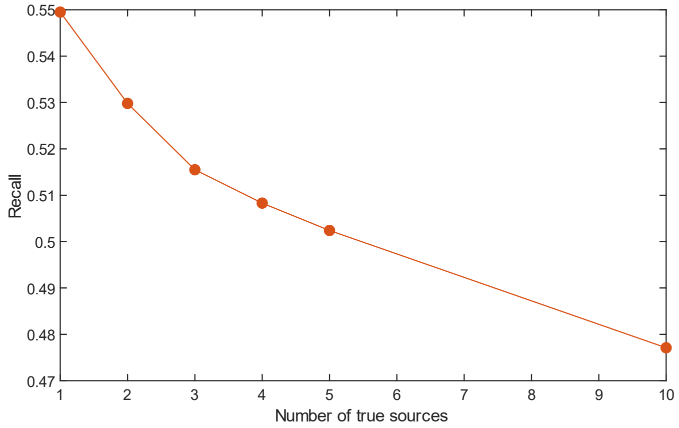
Results for CNN

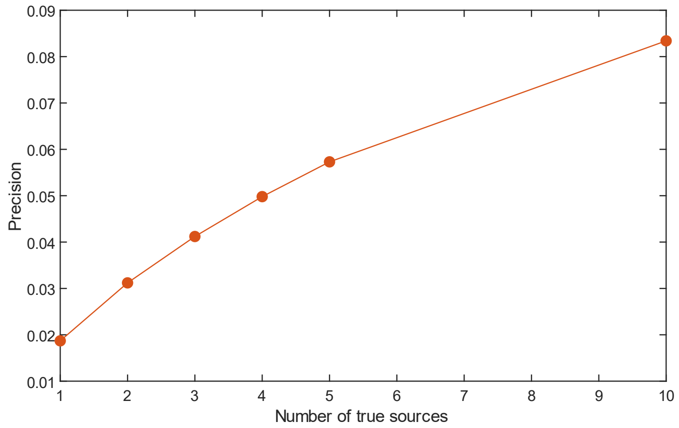
Predicting cases with $\delta\Sigma_{a1}, \delta\Sigma_{a2}$ at f=1 Hz





Predicting general cases with $\delta\Sigma_{a1}, \delta\Sigma_{a2}, \delta\nu\Sigma_{f1}, \delta\nu\Sigma_{f2}, \delta\Sigma_{rem}$ at f=1 Hz

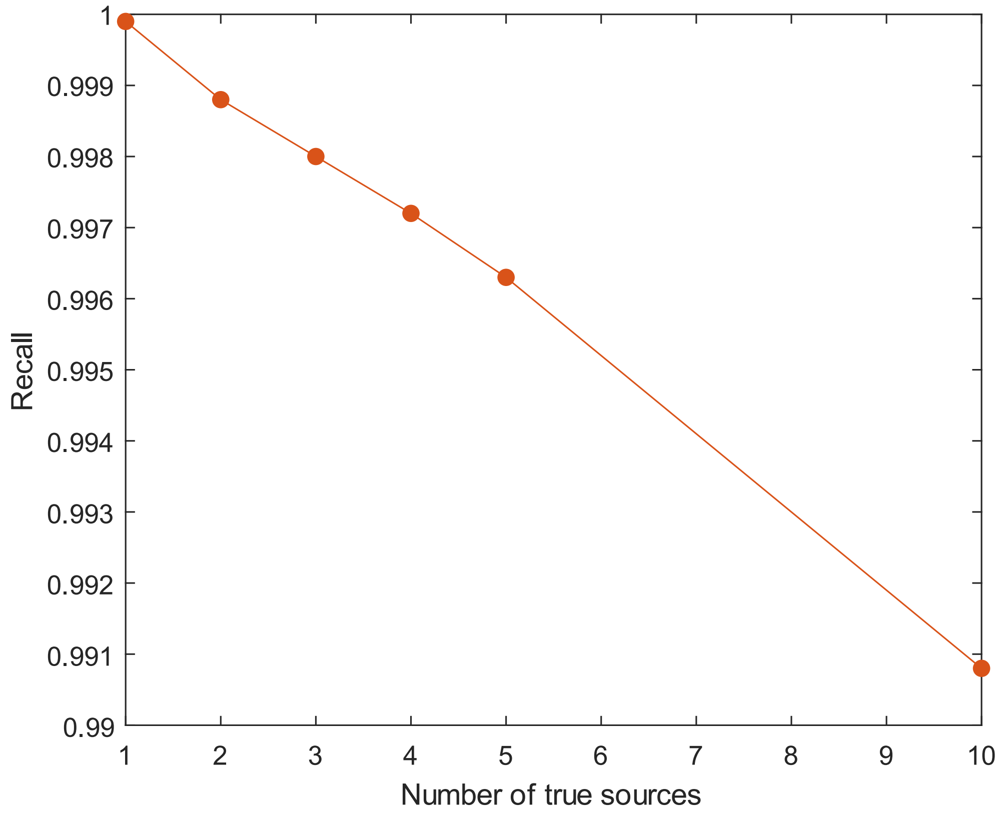


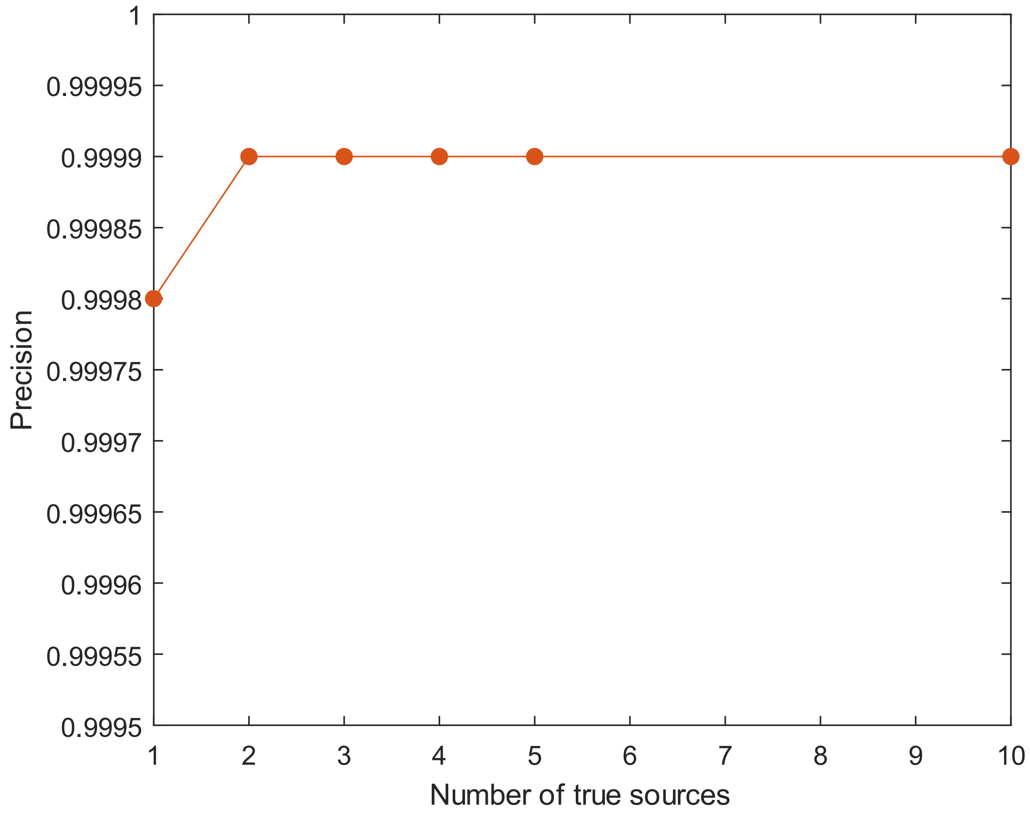


Results for CNN

New model: Trained using general cases with $\delta\Sigma_{a1}, \delta\Sigma_{a2}, \delta\nu\Sigma_{f1}, \delta\nu\Sigma_{f2}, \delta\Sigma_{rem}$ cases at f=1 Hz

Results for testing on general cases





Conclusions and future work

Conclusions

- Characterization of reactor neutron noise in SMRs
  - Comparison of FAV between large and small water-cooled reactors.
- Spatial component in SMRs leads to deviations from point-kinetics
  - Possibility of retrieving information about type and location of perturbations
- Development of ANN models for the inverse task to detect AVS locations in 2D
  - Results indicate ability to detect locations of up to 10 AVS sources simultaneously by training on only 1 and 2 sources.

Future work

- Further characterization of the reactor neutron noise types in SMRs.
  - Travelling perturbations with coolant flow
- Expand ANN models to 3D SMRs.
- Train ANN models to generalize over different types of noise and include more frequency ranges.

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Thank you!

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