Lab Notebook

Pupil Reconstruction

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Contents

1 Amplitude and Phase Reconstruction

16 February 2024

- Create new github branch: `AmpPhaseReconstructionRetraining`
- Download the following the files from Morgana:
  - `superK_slmcube_20230625_complsines-01sp_07`
  - `slmcube_20230625_complsines-01sp_07_PSFWFs_file00`
  - `slmcube_20230625_complsines-01sp_07_PSFWFs_file01`
  - `slmcube_20230625_complsines-01sp_07_PSFWFs_file02`
  - `slmcube_20230625_complsines-01sp_07_PSFWFs_file03`
  - `slmcube_20230625_complsines-01sp_07_PSFWFs_file04`
  - `slmcube_20230625_complsines-01sp_07_PSFWFs_file05`
  - `slmcube_20230625_complsines-01sp_07_PSFWFs_file06`
  - `slmcube_20230625_complsines-01sp_07_PSFWFs_file07`
  - `slmcube_20230625_complsines-01sp_07_PSFWFs_file08`
  - `slmcube_20230625_complsines-01sp_07_PSFWFs_file09`
- Data processing for Fully Convolutional NN training
- One fast experiment for each file: very good results, around 0.05 validation mse

19 February 2024

- Remove normalization from amplitude and phase for the fully connected experiments

---

EXPERIMENT NewFC10000-Processed 2

HYPERPARAMETERS:

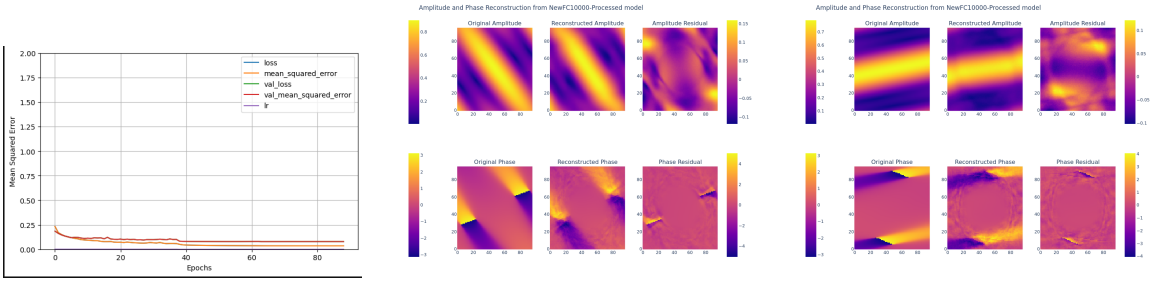
```
*ARCHITECTURE HYPERPARAMETERS:
  -Fully Connected
  -Input shape: 1320
  -Output shape: (2, 96, 96)
  -Hidden layers: [2000, 2000, 2000, 2000]
  -Regularizer: None
  -Hidden Layers Activation: relu
  -Output Layer Activation: linear
  -Batch Normalization: False
  -Dropout: False, 0.2

*COMPILATION HYPERPARAMETERS:
  -Optimizer: ADAM lr=0.001, beta_1=0.9, beta_2=0.999
  -Loss Function: MSE
  -Metric: MSE
```

```
*TRAINING HYPERPARAMETERS:
  -Epochs: 200
  -Batch size: 64
  -Callbacks:
    -ReduceLROnPlateau: MSE 10 x0.1
    -Early Stop: MSE 25
```

VISUALIZATION:

```
*RESULTS:
      -Train MSE: 0.035130929201841354
      -Validation MSE: 0.0786573588848114
```



(a) Training Evolution (b) Validation example (c) Train example

Figure 1: Results of training the model NewFC10000-Processed 2

EXPERIMENT NewFC30000-Processed-1

HYPERPARAMETERS:

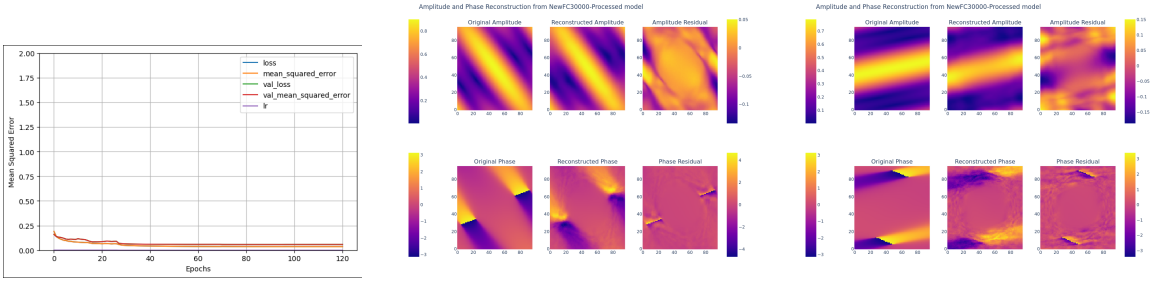
```
*ARCHITECTURE HYPERPARAMETERS:
  -Fully Connected
  -Input shape: 1320
  -Output shape: (2, 96, 96)
  -Hidden layers: [2000, 2000, 2000, 2000]
  -Regularizer: None
  -Hidden Layers Activation: relu
  -Output Layer Activation: linear
  -Batch Normalization: False
  -Dropout: False, 0.2

*COMPILATION HYPERPARAMETERS:
  -Optimizer: ADAM lr=0.001, beta_1=0.9, beta_2=0.999
  -Loss Function: MSE
  -Metric: MSE

*TRAINING HYPERPARAMETERS:
  -Epochs: 200
  -Batch size: 64
  -Callbacks:
    -ReduceLROnPlateau: MSE 10 x0.1
    -Early Stop: MSE 25
```

VISUALIZATION:

```
*RESULTS:
      -Train MSE: 0.0357743538916111
      -Validation MSE: 0.057852283120155334
```



(a) Training Evolution (b) Validation example (c) Train example

Figure 2: Results of training the model NewFC30000-Processed-1

EXPERIMENT NewFC80000-Processed-1

HYPERPARAMETERS:

```
*ARCHITECTURE HYPERPARAMETERS:
  -Fully Connected
  -Input shape: 1320
  -Output shape: (2, 96, 96)
  -Hidden layers: [2000, 2000, 2000, 2000]
  -Regularizer: None
  -Hidden Layers Activation: relu
```

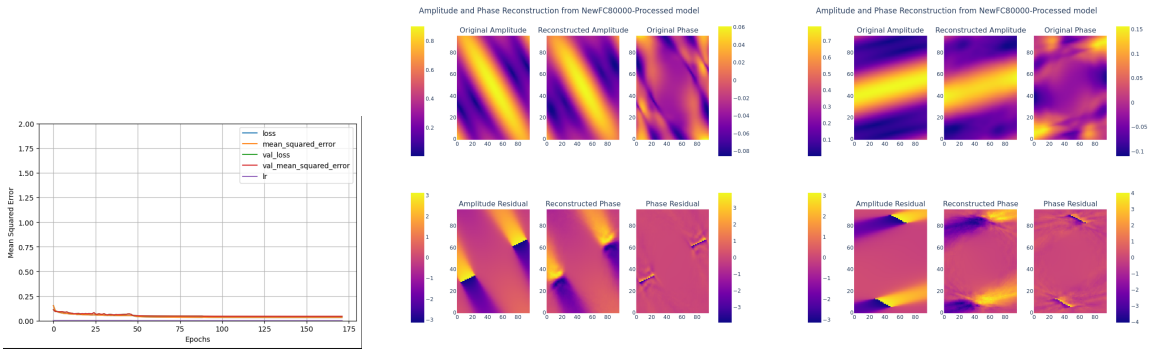
```
  -Output Layer Activation: linear
  -Batch Normalization: False
  -Dropout: False, 0.2

*COMPILATION HYPERPARAMETERS:
  -Optimizer: ADAM lr=0.001, beta_1=0.9, beta_2=0.999
  -Loss Function: MSE
  -Metric: MSE

*TRAINING HYPERPARAMETERS:
  -Epochs: 200
  -Batch size: 64
  -Callbacks:
    -ReduceLROnPlateau: MSE 10 x0.1
    -Early Stop: MSE 25
```

VISUALIZATION:

```
*RESULTS:
      -Train MSE: 0.03301804140210152
      -Validation MSE: 0.04487497732043266
```



(a) Training Evolution (b) Validation example (c) Train example

Figure 3: Results of training the model NewFC80000-Processed-1

- Normalize and split fluxes in train, validation and test files
- Stack amplitude and phase arrays and save in train, validation and test files

---

EXPERIMENT NewConv10000-1

HYPERPARAMETERS:

```
*ARCHITECTURE HYPERPARAMETERS:
  -Convolutional
  -Input shape: (55, 24, 1)
  -Output shape: (96, 96, 2)
  -Convolutional Layers: [128, 256, 512]
  -Convolutonal Kernels: [(3, 3), (3, 3), (3, 3)]
```

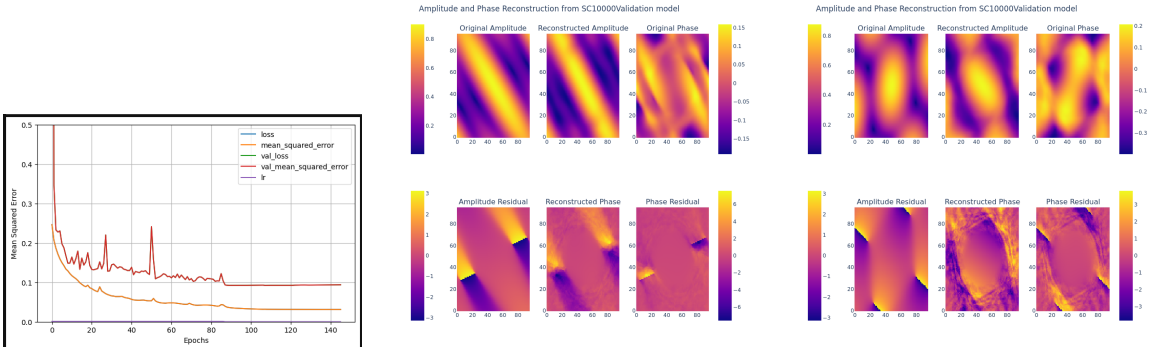
```
  -Fully Connected Hidden layers: [4096, 2048, 2048,
  1024, 1024, 1024]
  -Regularizer: None
  -Convolutional Activation: relu
  -Hidden Layers Activation: relu
  -Output Layer Activation: linear
  -Batch Normalization: True

*COMPILATION HYPERPARAMETERS:
  -Optimizer: ADAM lr=0.001, beta_1=0.9, beta_2=0.999
  -Loss Function: MSE
  -Metric: MSE

* TRAINING HYPERPARAMETERS:
  -Epochs: 200
  -Batch size: 32
  -Callbacks:
    -ReduceLROnPlateau: MSE 15 x0.1
    -Early Stop: MSE 50
```

VISUALIZATION:

```
*RESULTS:
      -Train MSE: 0.031087761744856834
      -Validation MSE: 0.09376049041748047
```



(a) Training Evolution (b) Validation example (c) Train example

Figure 4: Results of training the model NewConv10000-1

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EXPERIMENT NewConv30000-1

HYPERPARAMETERS:

```
*ARCHITECTURE HYPERPARAMETERS:
  -Convolutional
  -Input shape: (55, 24, 1)
  -Output shape: (96, 96, 2)
  -Convolutional Layers: [128, 256, 512]
  -Convolutonal Kernels: [(3, 3), (3, 3), (3, 3)]
```

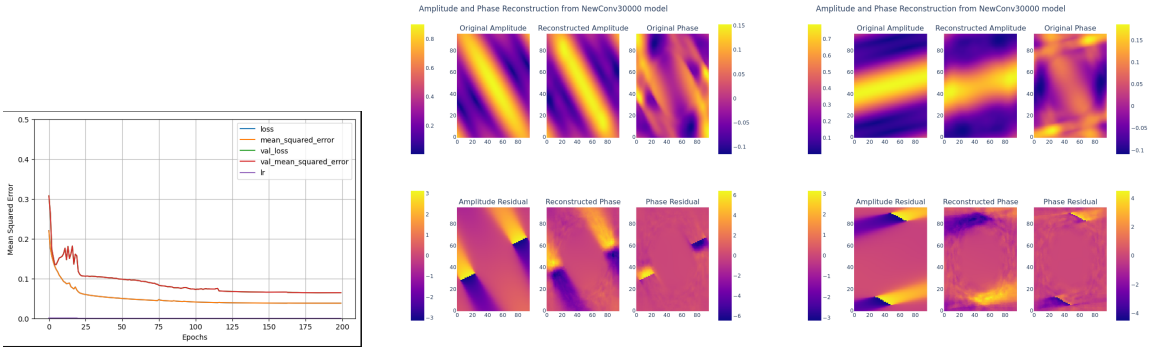
```
  -Fully Connected Hidden layers: [4096, 2048, 2048, 1024, 1024, 102
  -Regularizer: None
  -Convolutional Activation: relu
  -Hidden Layers Activation: relu
  -Output Layer Activation: linear
  -Batch Normalization: True

*COMPILATION HYPERPARAMETERS:
  -Optimizer: ADAM lr=0.001, beta_1=0.9, beta_2=0.999
  -Loss Function: MSE
  -Metric: MSE

* TRAINING HYPERPARAMETERS:
  -Epochs: 200
  -Batch size: 32
  -Callbacks:
    -ReduceLROnPlateau: MSE 15 x0.1
    -Early Stop: MSE 50
```

VISUALIZATION:

```
*RESULTS:
      -Train MSE: 0.03819489851593971
      -Validation MSE: 0.06443119794130325
```



(a) Training Evolution (b) Validation example (c) Train example

Figure 5: Results of training the model NewConv30000-1

EXPERIMENT NewConv30000-1

HYPERPARAMETERS:

```
*ARCHITECTURE HYPERPARAMETERS:
  -Convolutional
  -Input shape: (55, 24, 1)
  -Output shape: (96, 96, 2)
  -Convolutional Layers: [128, 256, 512]
  -Convolutonal Kernels: [(3, 3), (3, 3), (3, 3)]
  -Fully Connected Hidden layers: [4096, 2048, 2048, 1024, 1024, 102
  -Regularizer: None
  -Convolutional Activation: relu
  -Hidden Layers Activation: relu
```

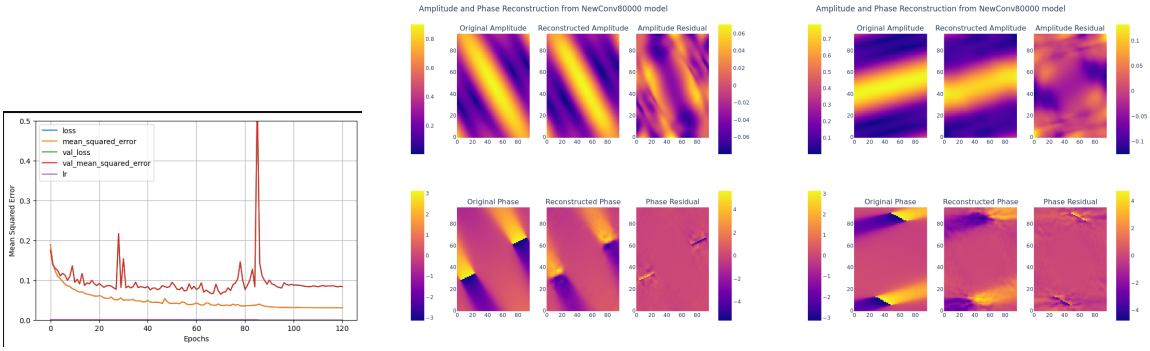
```
  -Output Layer Activation: linear
  -Batch Normalization: True

*COMPILATION HYPERPARAMETERS:
  -Optimizer: ADAM lr=0.001, beta_1=0.9, beta_2=0.999
  -Loss Function: MSE
  -Metric: MSE

* TRAINING HYPERPARAMETERS:
  -Epochs: 200
  -Batch size: 32
  -Callbacks:
    -ReduceLROnPlateau: MSE 15 x0.1
    -Early Stop: MSE 50
```

VISUALIZATION:

```
*RESULTS:
      -Train MSE: 0.030630357563495636
      -Validation MSE: 0.08355200290679932
```



(a) Training Evolution (b) Validation example (c) Train example

Figure 6: Results of training the model NewConv80000-1

- Normalize flux data and add padding for flux autoencoder
- Stack amplitude and phase and add padding for encoder+convolutional model

---

EXPERIMENT NewFluxAutoencoder10000-1

HYPERPARAMETERS:

```
*ARCHITECTURE HYPERPARAMETERS:
  -Autoencoder
  -Input shape: (56, 24, 1)
  -Convolutional Layers: [512, 128, 64, 8]
    (Inverse in the decoder)
  -Convolutonal Kernels: [(3, 3), (3, 3), (3, 3), (3, 3)]
```

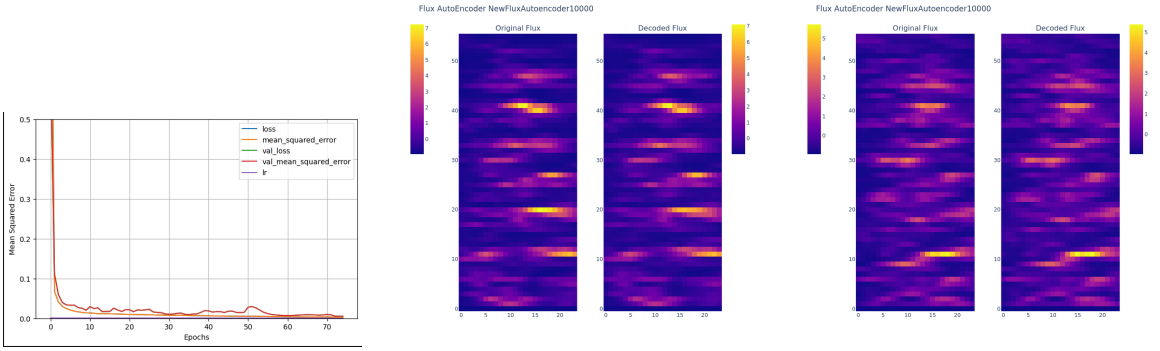
```
    (Inverse in the decoder)
  -Convolutional Activation: relu
  -Output Layer Activation: linear
  -Padding: same
  -Use Batch Normalization: True

*COMPILATION HYPERPARAMETERS:
  -Optimizer: ADAM lr=0.001, beta_1=0.9, beta_2=0.999
  -Loss Function: MSE
  -Metric: MSE

*TRAINING HYPERPARAMETERS:
  -Epochs: 75
  -Batch size: 32
  -Callbacks:
    -ReduceLROnPlateau: MSE 8 x0.1
    -Early Stop: MSE 15
```

VISUALIZATION:

```
*RESULTS:
      -Train MSE: 0.0018673702143132687
      -Validation MSE: 0.005482238717377186
```



(a) Training Evolution (b) Validation example (c) Train example

Figure 7: Results of training the model NewFluxAutoencoder10000-1

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EXPERIMENT NewFluxAutoencoder80000-1

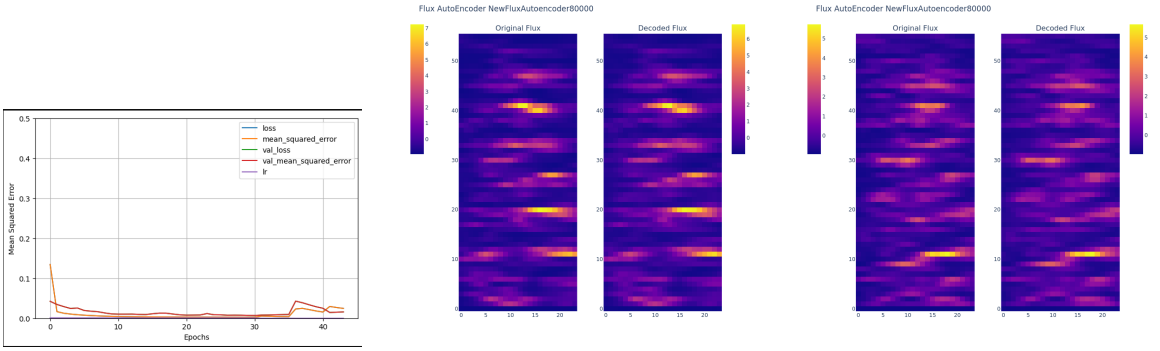
HYPERPARAMETERS:

```
*ARCHITECTURE HYPERPARAMETERS:
  -Autoencoder
  -Input shape: (56, 24, 1)
  -Convolutional Layers: [512, 128, 64, 8]
    (Inverse in the decoder)
```

```
  -Convolutonal Kernels: [(3, 3), (3, 3), (3, 3), (3, 3)]
    (Inverse in the decoder)
  -Convolutional Activation: relu
  -Output Layer Activation: linear
  -Padding: same
  -Use Batch Normalization: True

*COMPILATION HYPERPARAMETERS:
  -Optimizer: ADAM lr=0.001, beta_1=0.9, beta_2=0.999
  -Loss Function: MSE
  -Metric: MSE

*TRAINING HYPERPARAMETERS:
  -Epochs: 75
  -Batch size: 32
  -Callbacks:
    -ReduceLROnPlateau: MSE 8 x0.1
    -Early Stop: MSE 15
```

VISUALIZATION:

```
      -Train MSE: 0.024667566642165184
      -Validation MSE: 0.0158506091684103
```



(a) Training Evolution (b) Validation example (c) Train example

Figure 8: Results of training the model NewFluxAutoencoder10000-1

EXPERIMENT NewEncConv10000-1

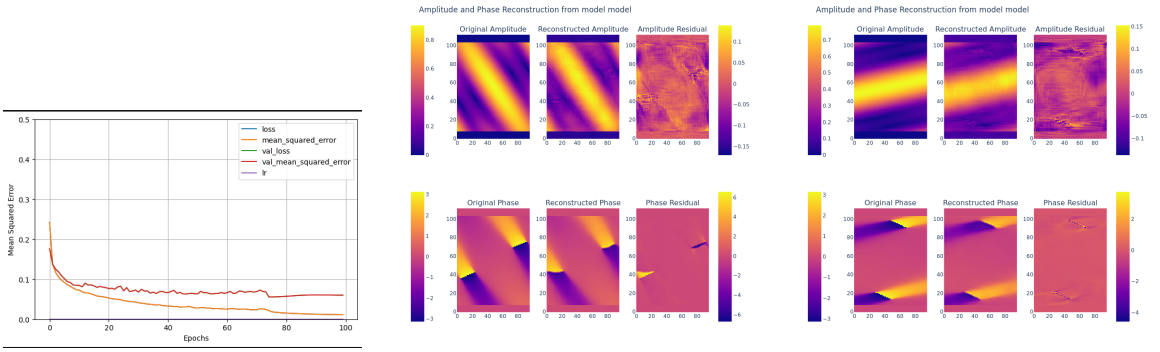
HYPERPARAMETERS:

```
*ARCHITECTURE HYPERPARAMETERS:
  -Encoder + Convolutional
  -Convolutional Layers: [1024, 512, 256, 256]
  -Convolutonal Kernels: [(3, 3), (3, 3), (3, 3), (3, 3)]
  -Convolutional Activation: relu
  -Output Layer Activation: linear

*COMPILATION HYPERPARAMETERS:
  -Optimizer: ADAM lr=0.0001, beta_1=0.9, beta_2=0.999
  -Loss Function: MSE
```

```
   -Metric: MSE


* TRAINING HYPERPARAMETERS:
   -Epochs: 100
   -Batch size: 32
   -Callbacks:
      -ReduceLROnPlateau: MSE 8 x0.1
      -Early Stop: MSE 15
```

VISUALIZATION:

```
*RESULTS:
       -Train MSE: 0.011328332126140594
       -Validation MSE: 0.06024651601910591
```



(a) Training Evolution (b) Validation example (c) Train example

Figure 9: Results of training the model NewEncConv10000-1

EXPERIMENT NewEncConv30000-1

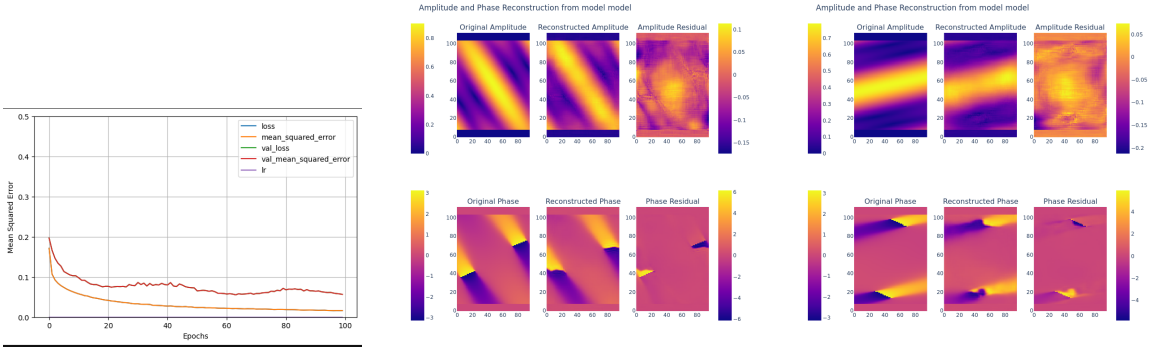
HYPERPARAMETERS:

```
*ARCHITECTURE HYPERPARAMETERS:
  -Encoder + Convolutional
  -Convolutional Layers: [1024, 512, 256, 256]
  -Convolutonal Kernels: [(3, 3), (3, 3), (3, 3), (3, 3)]
  -Convolutional Activation: relu
  -Output Layer Activation: linear

*COMPILATION HYPERPARAMETERS:
  -Optimizer: ADAM lr=0.0001, beta_1=0.9, beta_2=0.999
  -Loss Function: MSE
  -Metric: MSE

* TRAINING HYPERPARAMETERS:
  -Epochs: 100
  -Batch size: 32
  -Callbacks:
    -ReduceLROnPlateau: MSE 8 x0.1
    -Early Stop: MSE 15
```

VISUALIZATION:

```
*RESULTS:
      -Train MSE: 0.016221819445490837
```

```
-Validation MSE: 0.05662507936358452
```



(a) Training Evolution (b) Validation example (c) Train example

Figure 10: Results of training the model NewEncConv30000-1

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EXPERIMENT NewEncConv80000-1

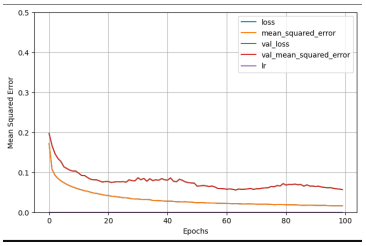
HYPERPARAMETERS:

```
*ARCHITECTURE HYPERPARAMETERS:
  -Encoder + Convolutional
  -Convolutional Layers: [1024, 512, 256, 256]
```

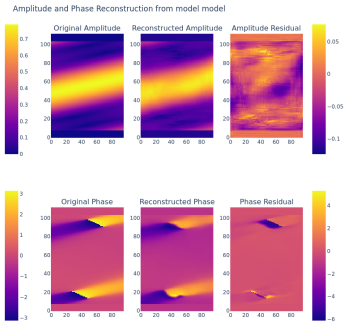
```
  -Convolutonal Kernels: [(3, 3), (3, 3), (3, 3), (3, 3)]
  -Convolutional Activation: relu
  -Output Layer Activation: linear

*COMPILATION HYPERPARAMETERS:
  -Optimizer: ADAM lr=0.0001, beta_1=0.9, beta_2=0.999
  -Loss Function: MSE
  -Metric: MSE

* TRAINING HYPERPARAMETERS:
  -Epochs: 100
  -Batch size: 32
  -Callbacks:
    -ReduceLROnPlateau: MSE 8 x0.1
    -Early Stop: MSE 15
```

VISUALIZATION:

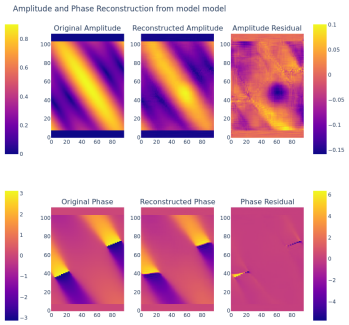
```
*RESULTS:
      -Train MSE: 0.0163
      -Validation MSE: 0.0369
```



(a) IGNORE THIS EVOLUTION FIGURE, TRAINING FINISHED BEFORE STORING THE HISTORY, THIS IS FROM THE PREVIOUS EXPERIMENT



(b) Validation example



(c) Train example

Figure 11: Results of training the model NewEncConv80000-1

2 PSF Reconstruction

20 February 2024

- Create custom dynamic dataloader for PL output flux and PSF complex field for PSF reconstruction

26 February 2024

- Create a dataloader to dynamically load flux and psf
- Normalize electric fields, real and imaginary parts independently
- Normalize PL output fluxes
- Train a fully connected nn with horrible results, train mse keeps stable at 1, will have to look at the data

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27 February 2024

- Create plotting functions to show amplitude, phase and intensity from an electric field
- Normalize electric field, this time dividing the complex number matrix by a constant (50.000 in this case)
- Redo output flux calculation with the normalized electric fields through the transfer matrix of the 19 fibre PL

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28 February 2024

EXPERIMENT PSF-FC-Reconstructor-1

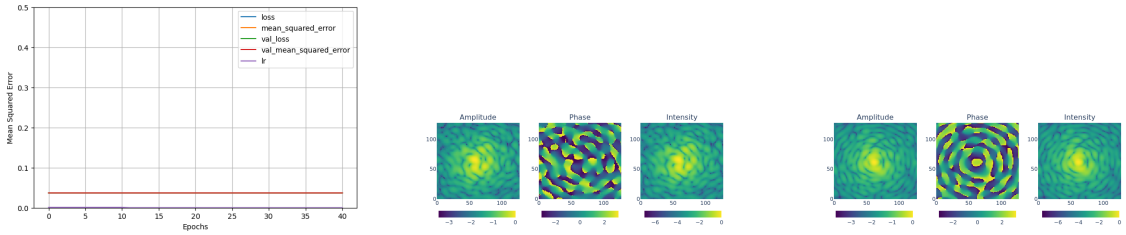
HYPERPARAMETERS:

```
*ARCHITECTURE HYPERPARAMETERS:
  -Fully Connected
  -Input shape: 19
  -Output shape: 32768
  -Hidden layers: [2000, 2000, 2000, 2000]
  -Regularizer: None
  -Hidden Layers Activation: relu
  -Output Layer Activation: linear
  -Batch Normalization: False
  -Dropout: False, 0.2

*COMPILATION HYPERPARAMETERS:
  -Optimizer: ADAM lr=0.001, beta_1=0.9, beta_2=0.999
  -Loss Function: MSE
  -Metric: MSE

*TRAINING HYPERPARAMETERS:
  -Epochs: 200
```

```
-Batch size: 64
-Callbacks:
  -ReduceLROnPlateau: MSE 10 x0.1
  -Early Stop: MSE 25
```

VISUALIZATION:

```
    -Train MSE: 0.03701553866267204
    -Validation MSE: 0.03701810911297798
```



(a) Training Evolution (b) Validation prediction (c) Validation original

Figure 12: Results of training the model PSF-FC-Reconstructor-1

29 February 2024

- Create a function to plot amplitude and phase predictions and residuals from a complex field
- Create evaluation notebook
- Since in yesterdays experiment the model does not learn at all, I design two different experiments, to check if there is a problem with the network:

1. A model that sums the output flux of the PL
2. A model that sums the scalars of the complex numbers array containing the electric fields at the pupil.

EXPERIMENT Flux-Sum-1

This model performs a sum of all the output fluxes from the PL

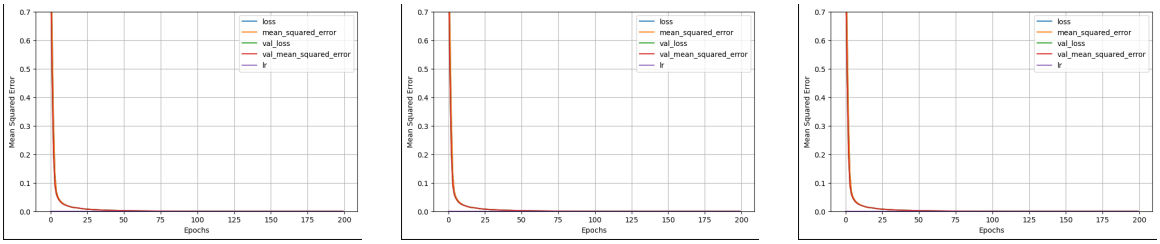
HYPERPARAMETERS:

```
*ARCHITECTURE HYPERPARAMETERS:
  -Fully Connected
  -Input shape: 19
  -Output shape: 1
  -Hidden layers: [100, 100]
  -Regularizer: None
  -Hidden Layers Activation: relu
  -Output Layer Activation: linear
  -Batch Normalization: False
  -Dropout: False, 0.2

*COMPILATION HYPERPARAMETERS:
  -Optimizer: ADAM lr=0.0001, beta_1=0.9, beta_2=0.999
  -Loss Function: MSE
  -Metric: MSE
```

```
*TRAINING HYPERPARAMETERS:
  -Epochs: 200
  -Batch size: 64
  -Callbacks:
    -ReduceLROnPlateau: MSE 10 x0.1
    -Early Stop: MSE 25
```

VISUALIZATION:

```
  *RESULTS:
      -Train MSE: 0.00018273142632097006
      -Validation MSE: 0.00018727070710156113
```



(a) Training Evolution (b) Training Evolution (c) Training Evolution

Figure 13: Results of training the model Flux-Sum-1

EXPERIMENT ElectricField-Sum-1

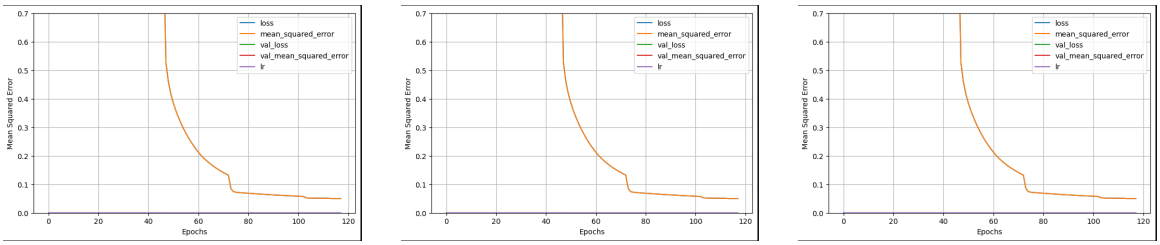
This model performs a sum of all the output fluxes from the PL

HYPERPARAMETERS:

```
*ARCHITECTURE HYPERPARAMETERS:
  -Fully Connected
  -Input shape: 32768
  -Output shape: 1
  -Hidden layers: [100, 100, 100]
  -Regularizer: None
  -Hidden Layers Activation: relu
  -Output Layer Activation: linear
  -Batch Normalization: False
  -Dropout: False, 0.2

*COMPILATION HYPERPARAMETERS:
  -Optimizer: ADAM lr=0.0001, beta_1=0.9, beta_2=0.999
  -Loss Function: MSE
  -Metric: MSE

*TRAINING HYPERPARAMETERS:
  -Epochs: 200
  -Batch size: 64
  -Callbacks:
    -ReduceLROnPlateau: MSE 10 x0.1
    -Early Stop: MSE 25
```

VISUALIZATION:

```
*RESULTS:
    -Train MSE: 0.050156451761722565
    -Validation MSE: 0.8189939856529236
```



(a) Training Evolution (b) Training Evolution (c) Training Evolution

Figure 14: Results of training the model ElectricField-Sum-1

---

01 March 2024

- Today I decide to train a model with just one datapoint and see if is able to learn the PSF from one flux and one electric field

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EXPERIMENT TestWith1DataPoint-1

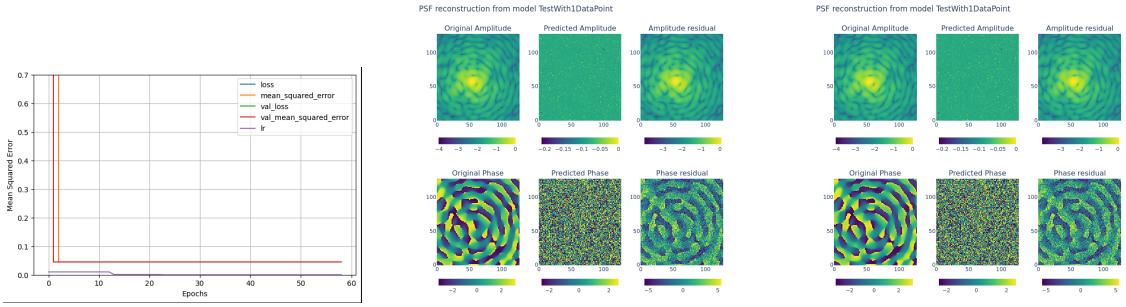
HYPERPARAMETERS:

```
*ARCHITECTURE HYPERPARAMETERS:
```

```
  -Fully Connected
  -Input shape: 19
  -Output shape: 32768
  -Hidden layers: [1000, 1000, 1000, 1000]
  -Regularizer: None
  -Hidden Layers Activation: relu
  -Output Layer Activation: linear
  -Batch Normalization: False
  -Dropout: False, 0.2

*COMPILATION HYPERPARAMETERS:
  -Optimizer: ADAM lr=0.01, beta_1=0.9, beta_2=0.999
  -Loss Function: MSE
  -Metric: MSE

*TRAINING HYPERPARAMETERS:
  -Epochs: 1000
  -Batch size: 64
  -Callbacks:
    -ReduceLROnPlateau: MSE 10 x0.1
    -Early Stop: MSE 25
```

VISUALIZATION:

```
      -Train MSE: 0.03701553866267204
      -Validation MSE: 0.03701810911297798
```



(a) Training Evolution (b) Train datapoint (c) Train datapoint

Figure 15: Results of training the model TestWith1DataPoint-1

- Something is wrong, going try with a bigger NN, don't think this will change anything but I have to try just in case.

EXPERIMENT TestWith1DataPoint-2

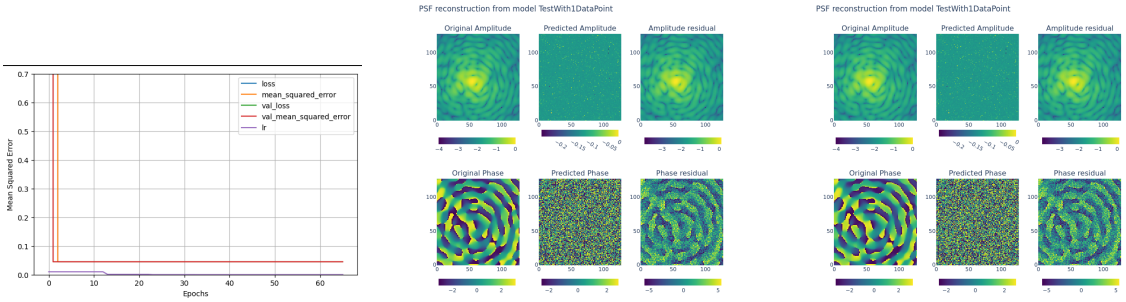
HYPERPARAMETERS:

```
*ARCHITECTURE HYPERPARAMETERS:
  -Fully Connected
  -Input shape: 19
  -Output shape: 32768
  -Hidden layers: [128, 128, 128, 128, 256,
          256, 512, 2000, 4000]
  -Regularizer: None
```

```
  -Hidden Layers Activation: relu
  -Output Layer Activation: linear
  -Batch Normalization: False
  -Dropout: False, 0.2

*COMPILATION HYPERPARAMETERS:
  -Optimizer: ADAM lr=0.01, beta_1=0.9, beta_2=0.999
  -Loss Function: MSE
  -Metric: MSE

*TRAINING HYPERPARAMETERS:
  -Epochs: 1000
  -Batch size: 64
  -Callbacks:
    -ReduceLROnPlateau: MSE 10 x0.1
    -Early Stop: MSE 25
```

VISUALIZATION:

```
*RESULTS:
      -Train MSE: 0.04261719062924385
      -Validation MSE: 0.04261719062924385
```



(a) Training Evolution (b) Train datapoint (c) Train datapoint

Figure 16: Results of training the model TestWith1DataPoint-2

---

04 March 2024

- After seeing that with 1 datapoint the model does not learn I decide to make some simpler tests, I will train a model that from a 19 element array predicts images with 2 channels and see if the input is too small for the model to predict anything. Three experiments will be performed:
  - From a 19 elements array to a 2x128x128 image
  - From a 19 elements array to a 2x64x64 image
  - From a 19 elements array to a 2x32x32 image

EXPERIMENT FromArrayToImage128-1

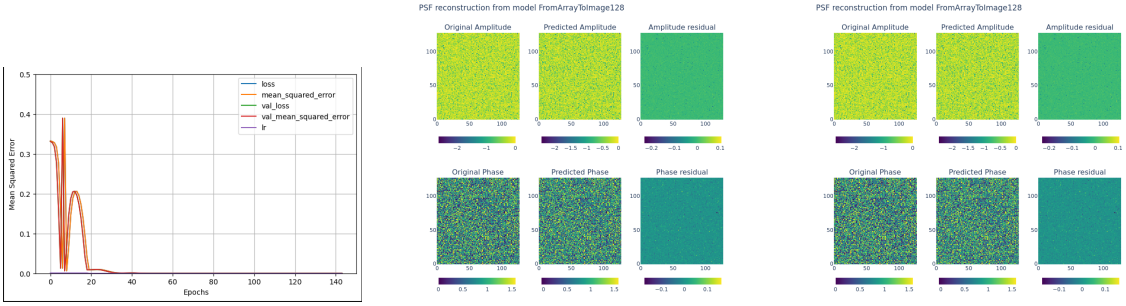
HYPERPARAMETERS:

```
*ARCHITECTURE HYPERPARAMETERS:
  -Fully Connected
  -Input shape: 19
  -Output shape: 32768
  -Hidden layers: [128, 128, 128, 128, 256, 256, 512, 2000, 4000]
  -Regularizer: None
  -Hidden Layers Activation: relu
  -Output Layer Activation: linear
  -Batch Normalization: False
  -Dropout: False, 0.2

*COMPILATION HYPERPARAMETERS:
  -Optimizer: ADAM lr=0.001, beta_1=0.9, beta_2=0.999
  -Loss Function: MSE
  -Metric: MSE

*TRAINING HYPERPARAMETERS:
  -Epochs: 10000
  -Batch size: 1
  -Callbacks:
    -ReduceLROnPlateau: MSE 10 x0.1
    -Early Stop: MSE 25
```

VISUALIZATION:

```
*RESULTS:
```

```
-Train MSE: 0.00010900569031946361
```



(a) Training Evolution (b) Train example (c) Train example

Figure 17: Results of training the model FromArrayToImage128-1

- From the previous experiment it is clear that a 19 element array as input is enough to reconstruct a random image of 2x128x128 resolution, what is happening for the psf reconstruction?.

  I will perform the other 2 stated experiments because it is quite fast.

EXPERIMENT FromArrayToImage64-1

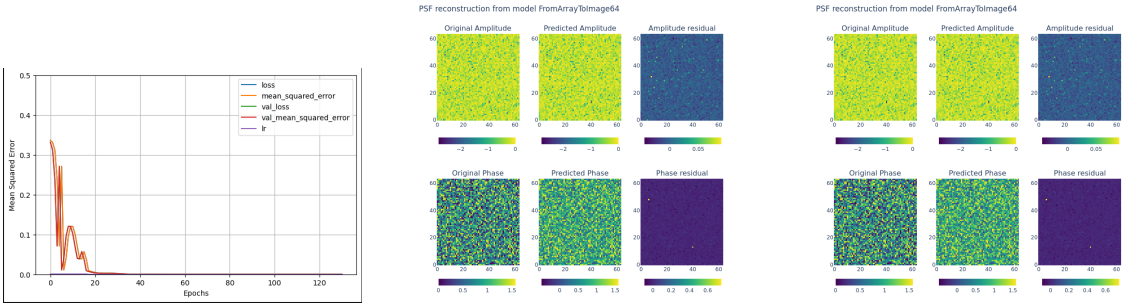
HYPERPARAMETERS:

```
*ARCHITECTURE HYPERPARAMETERS:
  -Fully Connected
```

```
  -Input shape: 19
  -Output shape: 8192
  -Hidden layers: [128, 128, 128, 128, 256, 256, 512, 2000, 4000]
  -Regularizer: None
  -Hidden Layers Activation: relu
  -Output Layer Activation: linear
  -Batch Normalization: False
  -Dropout: False, 0.2

*COMPILATION HYPERPARAMETERS:
  -Optimizer: ADAM lr=0.001, beta_1=0.9, beta_2=0.999
  -Loss Function: MSE
  -Metric: MSE

*TRAINING HYPERPARAMETERS:
  -Epochs: 10000
  -Batch size: 1
  -Callbacks:
    -ReduceLROnPlateau: MSE 10 x0.1
    -Early Stop: MSE 25
```

VISUALIZATION:

```
*RESULTS:
      -Train MSE: 0.00012627203250303864
```



(a) Training Evolution (b) Train example (c) Train example

Figure 18: Results of training the model FromArrayToImage64-1

EXPERIMENT FromArrayToImage32-1

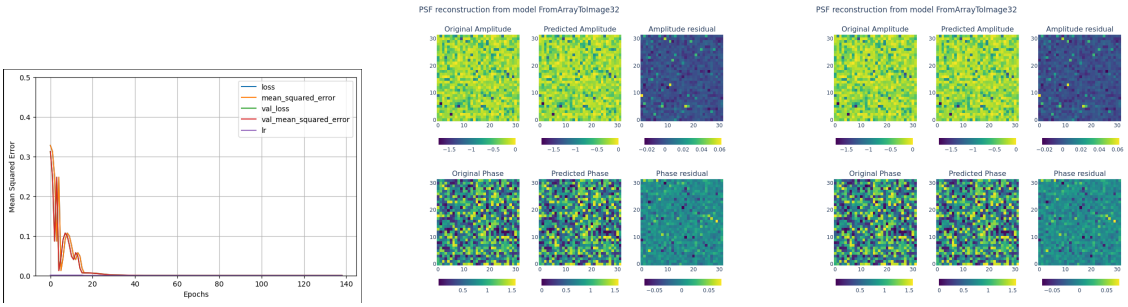
HYPERPARAMETERS:

```
*ARCHITECTURE HYPERPARAMETERS:
  -Fully Connected
  -Input shape: 19
  -Output shape: 2048
  -Hidden layers: [128, 128, 128, 128, 256, 256, 512, 2000, 4000]
  -Regularizer: None
  -Hidden Layers Activation: relu
  -Output Layer Activation: linear
  -Batch Normalization: False
  -Dropout: False, 0.2
```

```
*COMPILATION HYPERPARAMETERS:
  -Optimizer: ADAM lr=0.001, beta_1=0.9, beta_2=0.999
  -Loss Function: MSE
  -Metric: MSE

*TRAINING HYPERPARAMETERS:
  -Epochs: 10000
  -Batch size: 1
  -Callbacks:
    -ReduceLROnPlateau: MSE 10 x0.1
    -Early Stop: MSE 25
```

VISUALIZATION:

```
*RESULTS:
      -Train MSE: 5.556200267164968e-05
```



(a) Training Evolution (b) Train example (c) Train example

Figure 19: Results of training the model FromArrayToImage32-1

- The results are satisfactory, I am going to try the exact same configuration for one data point of the PSF dataset and see what happens

---

EXPERIMENT TestWith1DataPoint-3

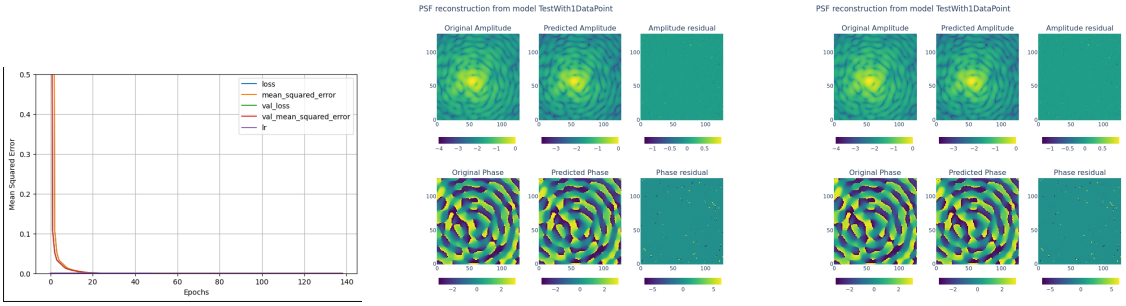
HYPERPARAMETERS:

```
*ARCHITECTURE HYPERPARAMETERS:
  -Fully Connected
  -Input shape: 19
  -Output shape: 32768
  -Hidden layers: [128, 128, 128, 128, 256, 256, 512, 2000, 4000]
  -Regularizer: None
  -Hidden Layers Activation: relu
  -Output Layer Activation: linear
  -Batch Normalization: False
  -Dropout: False, 0.2

*COMPILATION HYPERPARAMETERS:
  -Optimizer: ADAM lr=0.001, beta_1=0.9, beta_2=0.999
  -Loss Function: MSE
  -Metric: MSE
```

```
*TRAINING HYPERPARAMETERS:
  -Epochs: 10000
  -Batch size: 1
  -Callbacks:
    -ReduceLROnPlateau: MSE 10 x0.1
    -Early Stop: MSE 25
```

VISUALIZATION:

```
*RESULTS:
      -Train MSE: 1.2409615010255948e-05
```



(a) Training Evolution (b) Train datapoint (c) Train datapoint

Figure 20: Results of training the model TestWith1DataPoint-3

- The result has improved incredibly compared to the TestWith1DataPoint-1 and TestWith1DataPoint-2. The only difference I can see are the learning rates and the batch size. I will perform a series of experiments varying batch size: 100 datapoints with 64, 32 and 16 batch size

EXPERIMENT PSFReconstructor-100-64-1

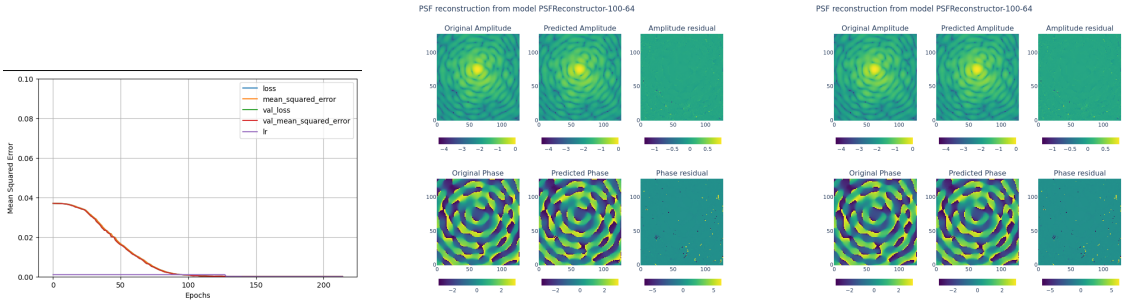
HYPERPARAMETERS:

```
*ARCHITECTURE HYPERPARAMETERS:
  -Fully Connected
  -Input shape: 19
  -Output shape: 32768
  -Hidden layers: [128, 128, 128, 128, 256,
          256, 512, 2000, 4000]
  -Regularizer: None
  -Hidden Layers Activation: relu
  -Output Layer Activation: linear
  -Batch Normalization: False
  -Dropout: False, 0.2

*COMPILATION HYPERPARAMETERS:
  -Optimizer: ADAM lr=0.001, beta_1=0.9, beta_2=0.999
  -Loss Function: MSE
  -Metric: MSE

*TRAINING HYPERPARAMETERS:
  -Epochs: 10000
  -Batch size: 64
```

```
  -Callbacks:
    -ReduceLROnPlateau: MSE 10 x0.1
    -Early Stop: MSE 25
```

VISUALIZATION:

```
*RESULTS:
      -Train MSE: 1.7399888747604564e-05
```



(a) Training Evolution (b) Train datapoint (c) Train datapoint

Figure 21: Results of training the model PSFReconstructor-100-64-1

---

05 March 2024

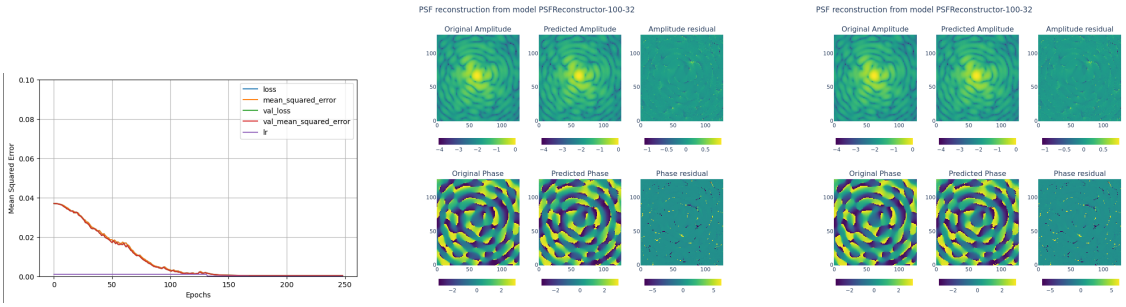
EXPERIMENT PSFReconstructor-100-32-1

HYPERPARAMETERS:

```
*ARCHITECTURE HYPERPARAMETERS:
  -Fully Connected
  -Input shape: 19
  -Output shape: 32768
  -Hidden layers: [128, 128, 128, 128, 256,
          256, 512, 2000, 4000]
  -Regularizer: None
  -Hidden Layers Activation: relu
  -Output Layer Activation: linear
  -Batch Normalization: False
  -Dropout: False, 0.2

*COMPILATION HYPERPARAMETERS:
  -Optimizer: ADAM lr=0.001, beta_1=0.9, beta_2=0.999
  -Loss Function: MSE
  -Metric: MSE

*TRAINING HYPERPARAMETERS:
  -Epochs: 10000
  -Batch size: 32
  -Callbacks:
    -ReduceLROnPlateau: MSE 10 x0.1
    -Early Stop: MSE 25
```

VISUALIZATION:

```
*RESULTS:
      -Train MSE: 0.00033666446688584983
```



(a) Training Evolution (b) Train datapoint (c) Train datapoint

Figure 22: Results of training the model PSFReconstructor-100-32-1

EXPERIMENT PSFReconstructor-100-16-1

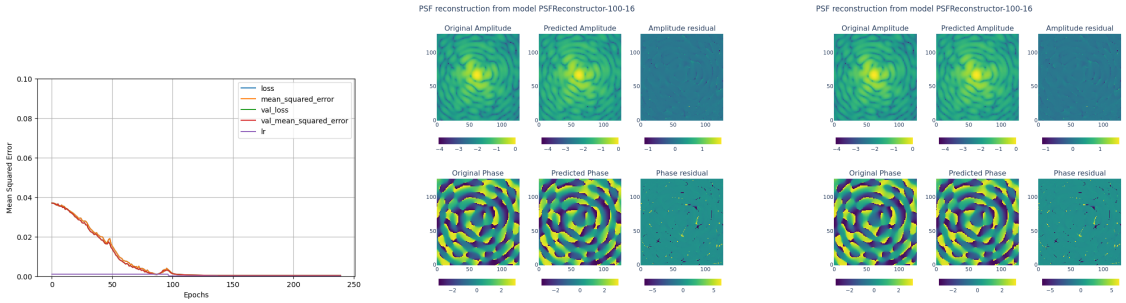
HYPERPARAMETERS:

```
*ARCHITECTURE HYPERPARAMETERS:
  -Fully Connected
  -Input shape: 19
  -Output shape: 32768
  -Hidden layers: [128, 128, 128, 128, 256,
          256, 512, 2000, 4000]
  -Regularizer: None
```

```
  -Hidden Layers Activation: relu
  -Output Layer Activation: linear
  -Batch Normalization: False
  -Dropout: False, 0.2

*COMPILATION HYPERPARAMETERS:
  -Optimizer: ADAM lr=0.001, beta_1=0.9, beta_2=0.999
  -Loss Function: MSE
  -Metric: MSE

*TRAINING HYPERPARAMETERS:
  -Epochs: 10000
  -Batch size: 16
  -Callbacks:
    -ReduceLROnPlateau: MSE 10 x0.1
    -Early Stop: MSE 25
```

VISUALIZATION:

```
*RESULTS:
      -Train MSE: 0.0003098844608757645
```



(a) Training Evolution (b) Train datapoint (c) Train datapoint

Figure 23: Results of training the model PSFReconstructor-100-16-1

- Apart from the mse, no significant difference can be appreciated for different batch sizes using 100 datapoints.

- The goal for today is to study the correlation between the L2 norm of the pupil plane electric field and the L2 norm of the LP modes complex coefficients.

- First compute the L2 norm of the LP modes complex coefficients from the validation psf electric fields.

- Done!, here it is what it looks like

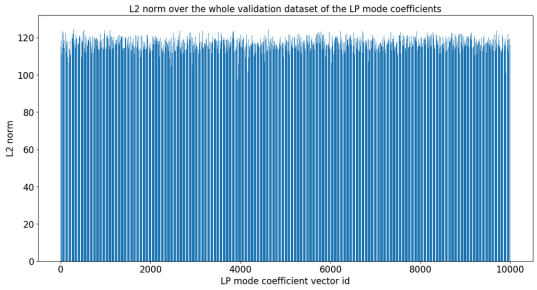


Figure 24: L2 norms for the overlap integral mode coefficients of the validation PSFs

- Let's do the same for the electric fields of the PSF
- Done!, here are the results:

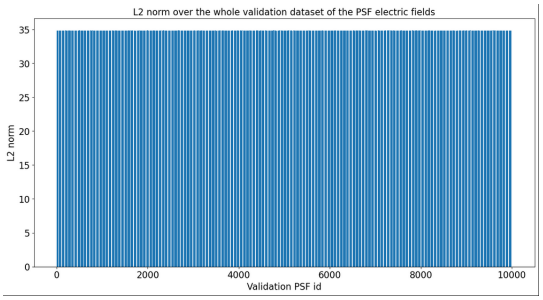


Figure 25: L2 norms of the validation PSFs electric fields

- After doing a correlation analysis the result is the following:
  `Pearson correlation coefficient:  0.1451513895198259`
  Which means that there is no correlation

---

06 March 2024

- Today I will be looking at the code from the `lantern_fiber_utils.py` file looking for the place where the LP mode coefficients are normalized

- Found it, in the function `make_fiber_modes()` used to compute de coefficients, there is a parameter called `normtosum` that is set to True by default, it looks as it normalizes the coefficients after the overlap integral is computed.

- Set `normtosum` to False, and compute 10000 output fluxes.

---

07 March 2024

- I will test a model with the new generated unnormalized output fluxes

---

EXPERIMENT UnnormalizedCoefficients-1

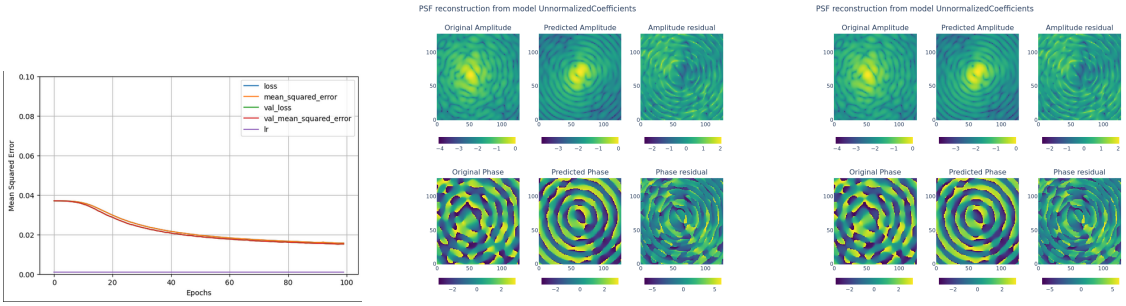
HYPERPARAMETERS:

```
*ARCHITECTURE HYPERPARAMETERS:
  -Fully Connected
  -Input shape: 19
  -Output shape: 32768
  -Hidden layers: [256, 256, 256]
  -Regularizer: None
  -Hidden Layers Activation: relu
  -Output Layer Activation: linear
  -Batch Normalization: False
```

```
  -Dropout: False, 0.2


*COMPILATION HYPERPARAMETERS:
  -Optimizer: ADAM lr=0.001, beta_1=0.9, beta_2=0.999
  -Loss Function: MSE
  -Metric: MSE


*TRAINING HYPERPARAMETERS:
  -Epochs: 100
  -Batch size: 64
  -Callbacks:
    -ReduceLROnPlateau: MSE 10 x0.1
    -Early Stop: MSE 25
```

VISUALIZATION:

```
  *RESULTS:
      -Train MSE: 0.01565057598054409
```



(a) Training Evolution (b) Train datapoint (c) Train datapoint

Figure 26: Results of training the model UnnormalizedCoefficientsS-1

- Looks like the problem with the data was in the normalization of the coefficients, I will reprocess the output fluxes again and then test with a bigger dataset.

- While, the processing is running I create two new functions to plot, amplitude-phase-intensity and output flux of the PL.

---

08 March 2024

- FUCK, When processing the data I forgot to disable the `normtosum` variable. Have to repeat the process again

---

11 March 2024

- Finally got the output fluxes from the unnormalized mode coefficients

---

EXPERIMENT PSFRecontructorFC10000-1

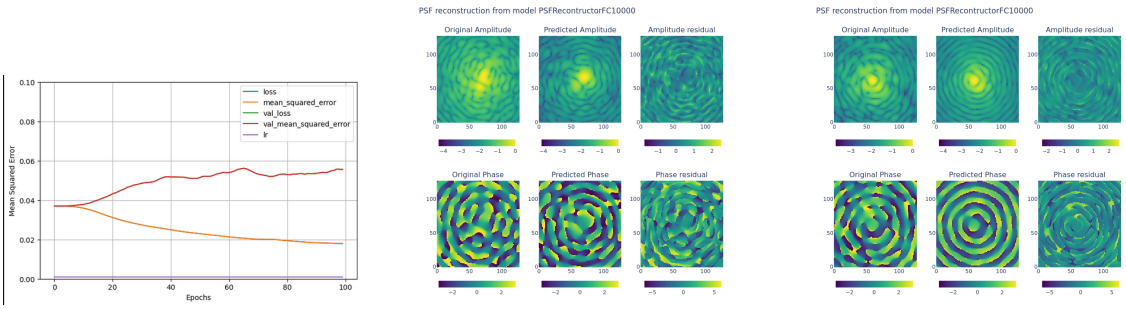
HYPERPARAMETERS:

```
*ARCHITECTURE HYPERPARAMETERS:
  -Fully Connected
  -Input shape: 19
  -Output shape: 32768
  -Hidden layers: [256, 256, 256]
  -Regularizer: None
  -Hidden Layers Activation: relu
  -Output Layer Activation: linear
  -Batch Normalization: False
  -Dropout: False, 0.2

*COMPILATION HYPERPARAMETERS:
  -Optimizer: ADAM lr=0.001, beta_1=0.9, beta_2=0.999
  -Loss Function: MSE
  -Metric: MSE

*TRAINING HYPERPARAMETERS:
  -Epochs: 100
  -Batch size: 64
  -Callbacks:
    -ReduceLROnPlateau: MSE 10 x0.1
    -Early Stop: MSE 25
```

VISUALIZATION:

```
  *RESULTS:
```

```
        -Train MSE: 0.017938978970050812
        -Validation MSE: 0.055591899901628494
```



(a) Training Evolution (b) Validation datapoint (c) Train datapoint

Figure 27: Results of training the model PSFRecontructorFC10000-1

EXPERIMENT PSFRecontructorFC30000-1

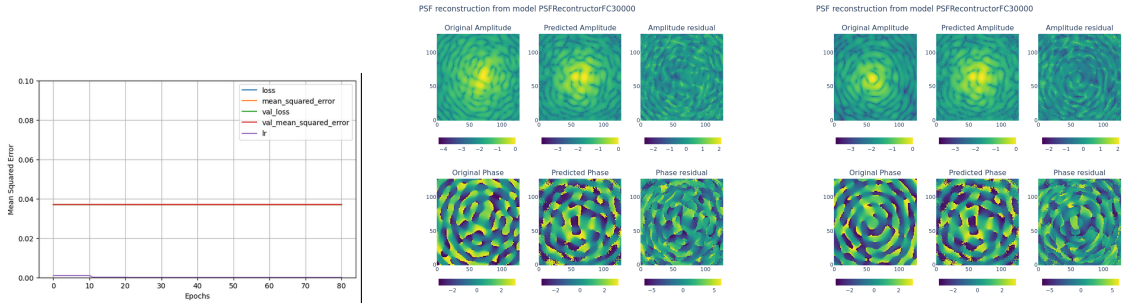
HYPERPARAMETERS:

```
*ARCHITECTURE HYPERPARAMETERS:
  -Fully Connected
  -Input shape: 19
  -Output shape: 32768
  -Hidden layers: [256, 256, 256]
  -Regularizer: None
  -Hidden Layers Activation: relu
  -Output Layer Activation: linear
```

```
  -Batch Normalization: False
  -Dropout: False, 0.2

*COMPILATION HYPERPARAMETERS:
  -Optimizer: ADAM lr=0.001, beta_1=0.9, beta_2=0.999
  -Loss Function: MSE
  -Metric: MSE

*TRAINING HYPERPARAMETERS:
  -Epochs: 100
  -Batch size: 64
  -Callbacks:
    -ReduceLROnPlateau: MSE 10 x0.1
    -Early Stop: MSE 25
```

VISUALIZATION:

```
  *RESULTS:
      -Train MSE: 0.03696389123797417
      -Validation MSE: 0.03704820200800896
```



(a) Training Evolution (b) Validation datapoint (c) Train datapoint

Figure 28: Results of training the model PSFRecontructorFC30000-1

- Again, flatline, and same output for any input. I will try with all the train dataset and then start using different batch sizes, see how this works

---

EXPERIMENT PSFRecontructorFC70000-1

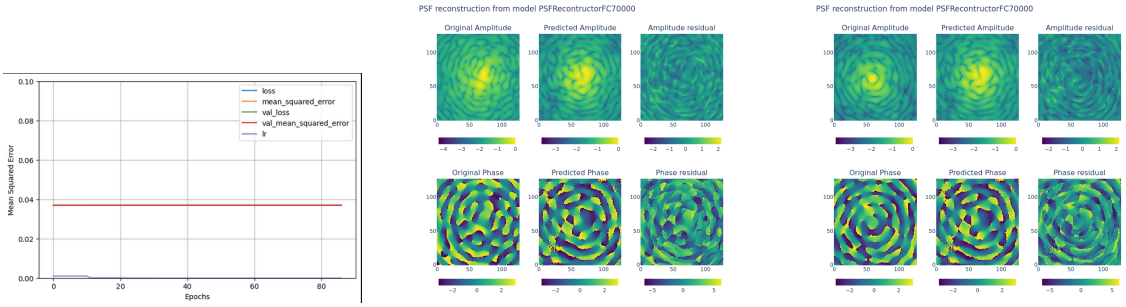
HYPERPARAMETERS:

```
*ARCHITECTURE HYPERPARAMETERS:
  -Fully Connected
  -Input shape: 19
  -Output shape: 32768
  -Hidden layers: [256, 256, 256]
  -Regularizer: None
  -Hidden Layers Activation: relu
```

```
  -Output Layer Activation: linear
  -Batch Normalization: False
  -Dropout: False, 0.2

*COMPILATION HYPERPARAMETERS:
  -Optimizer: ADAM lr=0.001, beta_1=0.9, beta_2=0.999
  -Loss Function: MSE
  -Metric: MSE

*TRAINING HYPERPARAMETERS:
  -Epochs: 100
  -Batch size: 64
  -Callbacks:
    -ReduceLROnPlateau: MSE 10 x0.1
    -Early Stop: MSE 25
```

VISUALIZATION:

```
  *RESULTS:
      -Train MSE: 0.03700976073741913
      -Validation MSE: 0.0370212197303772
```



(a) Training Evolution (b) Validation datapoint (c) Train datapoint

Figure 29: Results of training the model PSFRecontructorFC70000-1

- Batch size for these experiments is 64, maybe it is too big , let's try with 32

EXPERIMENT PSFRecontructorFC10000-32-1

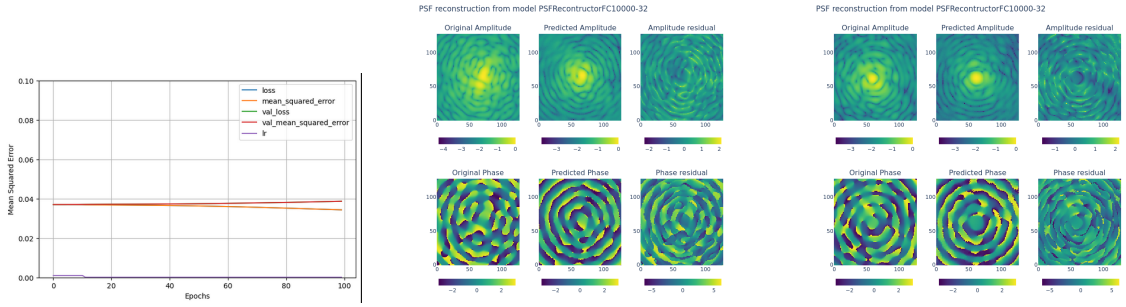
HYPERPARAMETERS:

```
*ARCHITECTURE HYPERPARAMETERS:
  -Fully Connected
  -Input shape: 19
  -Output shape: 32768
  -Hidden layers: [256, 256, 256]
  -Regularizer: None
  -Hidden Layers Activation: relu
  -Output Layer Activation: linear
```

```
  -Batch Normalization: False
  -Dropout: False, 0.2

*COMPILATION HYPERPARAMETERS:
  -Optimizer: ADAM lr=0.001, beta_1=0.9, beta_2=0.999
  -Loss Function: MSE
  -Metric: MSE

*TRAINING HYPERPARAMETERS:
  -Epochs: 100
  -Batch size: 32
  -Callbacks:
    -ReduceLROnPlateau: MSE 10 x0.1
    -Early Stop: MSE 25
```

VISUALIZATION:

```
  *RESULTS:
      -Train MSE: 0.03432031720876694
      -Validation MSE: 0.038697339594364166
```



(a) Training Evolution (b) Validation datapoint (c) Train datapoint

Figure 30: Results of training the model PSFRecontructorFC10000-32-1

- Interesting, slower convergence but less overfitting

EXPERIMENT PSFRecontructorFC30000-32-1

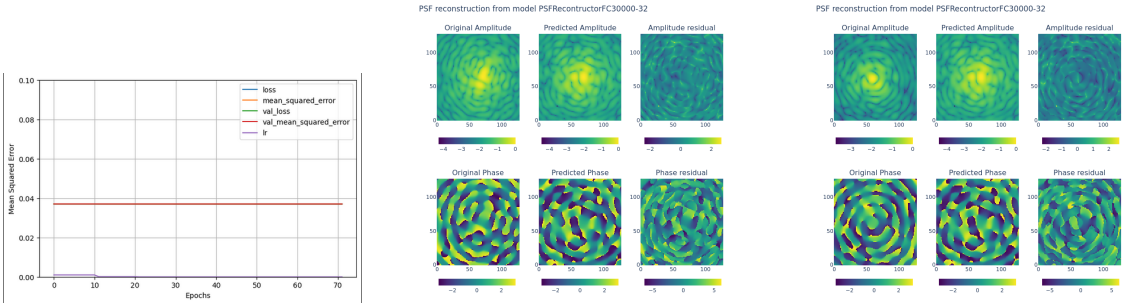
HYPERPARAMETERS:

```
*ARCHITECTURE HYPERPARAMETERS:
  -Fully Connected
  -Input shape: 19
  -Output shape: 32768
  -Hidden layers: [256, 256, 256]
  -Regularizer: None
  -Hidden Layers Activation: relu
  -Output Layer Activation: linear
```

```
  -Batch Normalization: False
  -Dropout: False, 0.2

*COMPILATION HYPERPARAMETERS:
  -Optimizer: ADAM lr=0.001, beta_1=0.9, beta_2=0.999
  -Loss Function: MSE
  -Metric: MSE

*TRAINING HYPERPARAMETERS:
  -Epochs: 100
  -Batch size: 32
  -Callbacks:
    -ReduceLROnPlateau: MSE 10 x0.1
    -Early Stop: MSE 25
```

VISUALIZATION:

```
  *RESULTS:
      -Train MSE: 0.03701305016875267
      -Validation MSE: 0.03701600059866905
```



(a) Training Evolution (b) Validation datapoint (c) Train datapoint

Figure 31: Results of training the model PSFRecontructorFC30000-32-1

EXPERIMENT PSFRecontructorFC70000-32-1

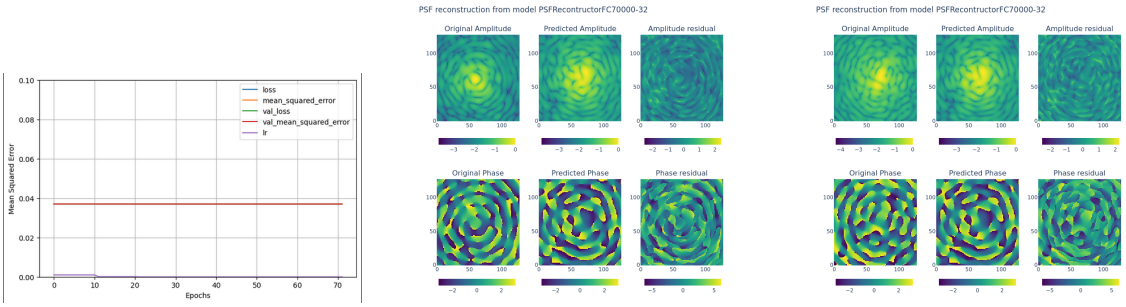
HYPERPARAMETERS:

```
*ARCHITECTURE HYPERPARAMETERS:
  -Fully Connected
  -Input shape: 19
  -Output shape: 32768
  -Hidden layers: [256, 256, 256]
  -Regularizer: None
  -Hidden Layers Activation: relu
  -Output Layer Activation: linear
  -Batch Normalization: False
  -Dropout: False, 0.2
```

```
*COMPILATION HYPERPARAMETERS:
  -Optimizer: ADAM lr=0.001, beta_1=0.9, beta_2=0.999
  -Loss Function: MSE
  -Metric: MSE

*TRAINING HYPERPARAMETERS:
  -Epochs: 100
  -Batch size: 32
  -Callbacks:
    -ReduceLROnPlateau: MSE 10 x0.1
    -Early Stop: MSE 25
```

VISUALIZATION:

```
  *RESULTS:
      -Train MSE: 0.037016756832599 64
      -Validation MSE: 0.037016723304986954
```



(a) Training Evolution (b) Validation datapoint (c) Train datapoint

Figure 32: Results of training the model PSFRecontructorFC70000-32-1

- So no good results, what I saw is that the lower the batch size, the longer it takes to coverge. Options now are:
  - Bigger NN
  - Bigger Batch size
  - Longer training

  I will start with 10000 datapoints and a bigger NN

EXPERIMENT PSFRecontructorBigFC10000-32-1

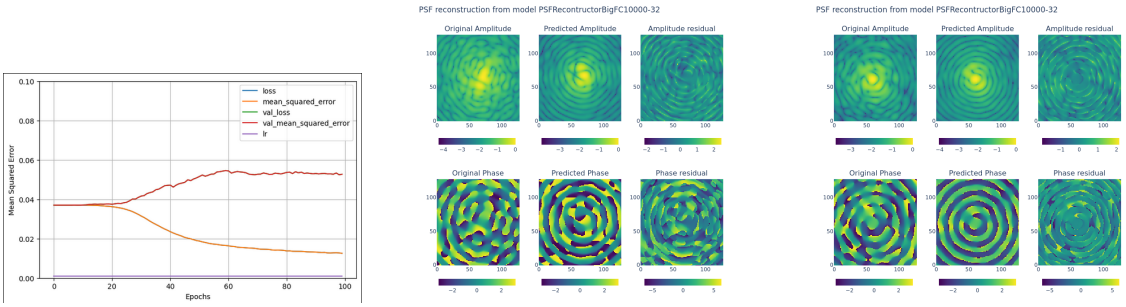
HYPERPARAMETERS:

```
*ARCHITECTURE HYPERPARAMETERS:
  -Fully Connected
  -Input shape: 19
  -Output shape: 32768
  -Hidden layers: [256, 256, 256, 256, 256, 256]
  -Regularizer: None
  -Hidden Layers Activation: relu
  -Output Layer Activation: linear
  -Batch Normalization: False
  -Dropout: False, 0.2
```

```
*COMPILATION HYPERPARAMETERS:
  -Optimizer: ADAM lr=0.001, beta_1=0.9, beta_2=0.999
  -Loss Function: MSE
  -Metric: MSE

*TRAINING HYPERPARAMETERS:
  -Epochs: 100
  -Batch size: 32
  -Callbacks:
    -ReduceLROnPlateau: MSE 20 x0.1
    -Early Stop: MSE 50
```

VISUALIZATION:

```
*RESULTS:
      -Train MSE: 0.012548761442303658
      -Validation MSE: 0.0527174137532711
```



(a) Training Evolution (b) Validation example (c) Train example

Figure 33: Results of training the model psf-PSFRecontructorBigFC10000-32-1

EXPERIMENT PSFRecontructorBigFC30000-32-1

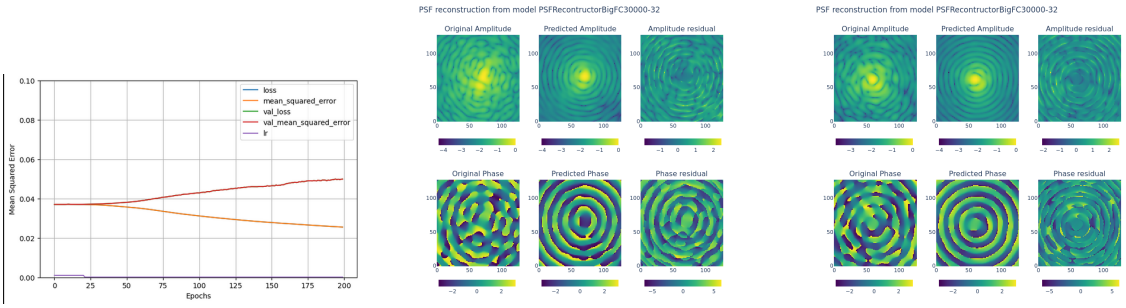
HYPERPARAMETERS:

```
*ARCHITECTURE HYPERPARAMETERS:
  -Fully Connected
  -Input shape: 19
  -Output shape: 32768
  -Hidden layers: [256, 256, 256, 256, 256, 256]
  -Regularizer: None
  -Hidden Layers Activation: relu
  -Output Layer Activation: linear
  -Batch Normalization: False
  -Dropout: False, 0.2

*COMPILATION HYPERPARAMETERS:
  -Optimizer: ADAM lr=0.001, beta_1=0.9, beta_2=0.999
  -Loss Function: MSE
  -Metric: MSE

*TRAINING HYPERPARAMETERS:
  -Epochs: 200
  -Batch size: 32
```

```
  -Callbacks:
    -ReduceLROnPlateau: MSE 20 x0.1
    -Early Stop: MSE 50
```

VISUALIZATION:

```
*RESULTS:
      -Train MSE: 0.025507930666208267
      -Validation MSE: 0.04988955706357956
```



(a) Training Evolution (b) Validation example (c) Train example

Figure 34: Results of training the model PSFRecontructorBigFC30000-32-1

- With respect to the last to experiments, a bigger neural network seems to work better, with more datapoints the learning is delayed a bit, and the overfitting slightly improves, let's check with 70000 datapoints.

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EXPERIMENT PSFRecontructorBigFC70000-32-1

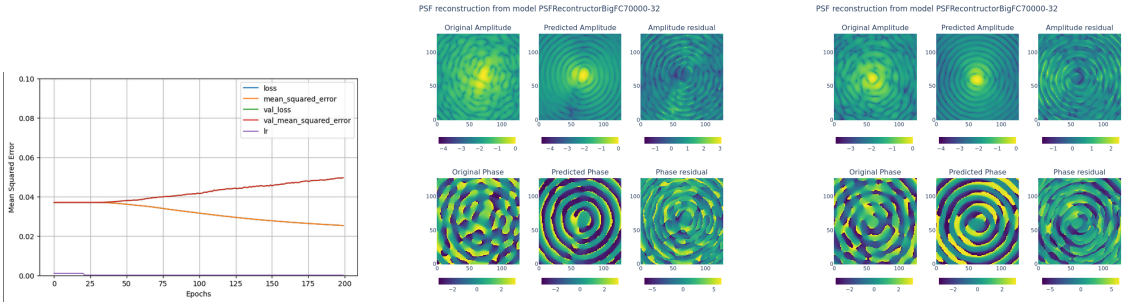
HYPERPARAMETERS:

```
*ARCHITECTURE HYPERPARAMETERS:
  -Fully Connected
  -Input shape: 19
  -Output shape: 32768
  -Hidden layers: [256, 256, 256, 256, 256, 256]
  -Regularizer: None
  -Hidden Layers Activation: relu
  -Output Layer Activation: linear
  -Batch Normalization: False
  -Dropout: False, 0.2

*COMPILATION HYPERPARAMETERS:
  -Optimizer: ADAM lr=0.001, beta_1=0.9, beta_2=0.999
  -Loss Function: MSE
  -Metric: MSE

*TRAINING HYPERPARAMETERS:
  -Epochs: 200
```

```
  -Batch size: 32
  -Callbacks:
    -ReduceLROnPlateau: MSE 20 x0.1
    -Early Stop: MSE 50
```

VISUALIZATION:

```
*RESULTS:
      -Train MSE: 0.025293584913015366
      -Validation MSE: 0.04955973103642464
```



(a) Training Evolution (b) Validation example (c) Train example

Figure 35: Results of training the model PSFRecontructorBigFC70000-32-1

- There is barely any difference in training with 30000 and 70000 datapoints. I think I will make a final set of experiments with an even bigger neural network before addressing the overfitting.

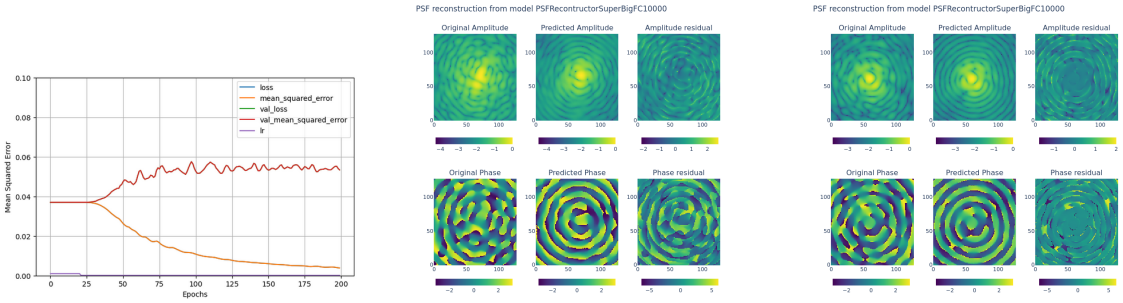
EXPERIMENT PSFRecontructorSuperBigFC10000-1

HYPERPARAMETERS:

```
*ARCHITECTURE HYPERPARAMETERS:
  -Fully Connected
  -Input shape: 19
  -Output shape: 32768
  -Hidden layers: [1024, 1024, 1024, 1024, 1024, 1024]
  -Regularizer: None
  -Hidden Layers Activation: relu
  -Output Layer Activation: linear
  -Batch Normalization: False
  -Dropout: False, 0.2

*COMPILATION HYPERPARAMETERS:
  -Optimizer: ADAM lr=0.001, beta_1=0.9, beta_2=0.999
  -Loss Function: MSE
  -Metric: MSE

*TRAINING HYPERPARAMETERS:
  -Epochs: 200
  -Batch size: 32
  -Callbacks:
    -ReduceLROnPlateau: MSE 20 x0.1
    -Early Stop: MSE 50
```

VISUALIZATION:

```
*RESULTS:
      -Train MSE: 0.00384897249750793
      -Validation MSE: 0.05339088663458824
```



(a) Training Evolution (b) Validation example (c) Train example

Figure 36: Results of training the model PSFRecontructorSuperBigFC10000-1

EXPERIMENT PSFRecontructorSuperBigFC30000-1

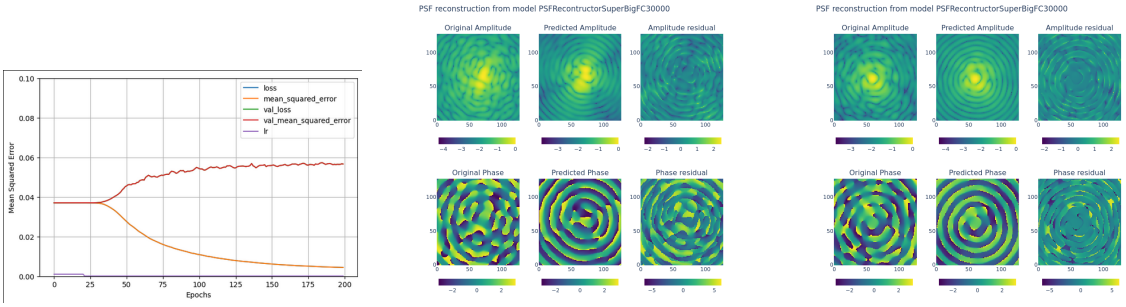
HYPERPARAMETERS:

```
*ARCHITECTURE HYPERPARAMETERS:
  -Fully Connected
  -Input shape: 19
  -Output shape: 32768
  -Hidden layers: [1024, 1024, 1024, 1024, 1024, 1024]
  -Regularizer: None
```

```
  -Hidden Layers Activation: relu
  -Output Layer Activation: linear
  -Batch Normalization: False
  -Dropout: False, 0.2

*COMPILATION HYPERPARAMETERS:
  -Optimizer: ADAM lr=0.001, beta_1=0.9, beta_2=0.999
  -Loss Function: MSE
  -Metric: MSE

*TRAINING HYPERPARAMETERS:
  -Epochs: 200
  -Batch size: 32
  -Callbacks:
    -ReduceLROnPlateau: MSE 20 x0.1
    -Early Stop: MSE 50
```

VISUALIZATION:

```
*RESULTS:
      -Train MSE: 0.004385718610137701
      -Validation MSE: 0.056627288460731506
```



(a) Training Evolution (b) Validation example (c) Train example

Figure 37: Results of training the model PSFRecontructorSuperBigFC30000-1

---

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EXPERIMENT PSFRecontructorSuperBigFC70000-1

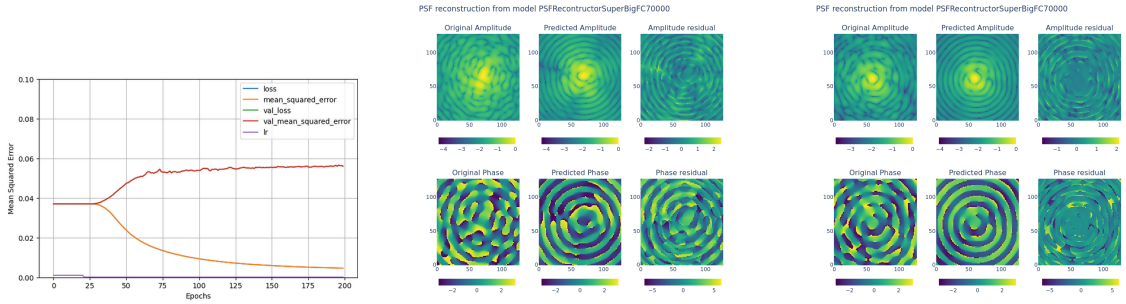
HYPERPARAMETERS:

```
*ARCHITECTURE HYPERPARAMETERS:
  -Fully Connected
  -Input shape: 19
  -Output shape: 32768
  -Hidden layers: [1024, 1024, 1024, 1024, 1024, 1024]
  -Regularizer: None
```

```
  -Hidden Layers Activation: relu
  -Output Layer Activation: linear
  -Batch Normalization: False
  -Dropout: False, 0.2

*COMPILATION HYPERPARAMETERS:
  -Optimizer: ADAM lr=0.001, beta_1=0.9, beta_2=0.999
  -Loss Function: MSE
  -Metric: MSE

*TRAINING HYPERPARAMETERS:
  -Epochs: 200
  -Batch size: 32
  -Callbacks:
    -ReduceLROnPlateau: MSE 20 x0.1
    -Early Stop: MSE 50
```

VISUALIZATION:

```
*RESULTS:
      -Train MSE: 0.004607476759701967
      -Validation MSE: 0.056021399796009064
```



(a) Training Evolution (b) Validation example (c) Train example

Figure 38: Results of training the model PSFRecontructorSuperBigFC70000-1

EXPERIMENT PSF-FCDR01-10000-1

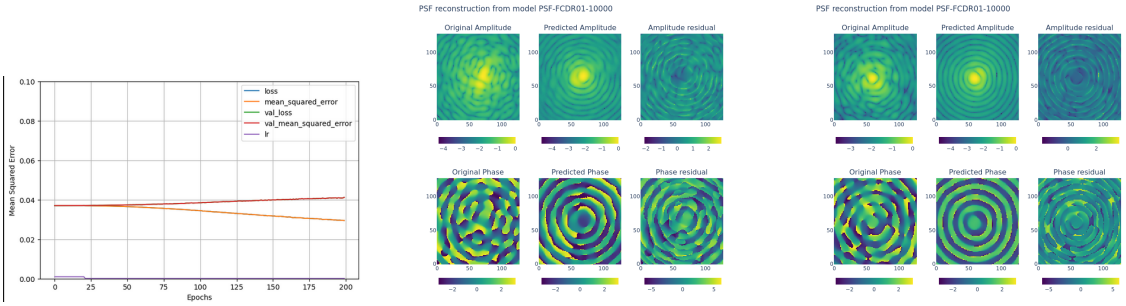
HYPERPARAMETERS:

```
*ARCHITECTURE HYPERPARAMETERS:
  -Fully Connected
  -Input shape: 19
  -Output shape: 32768
  -Hidden layers: [256, 256, 256, 256, 256, 256]
  -Regularizer: None
  -Hidden Layers Activation: relu
  -Output Layer Activation: linear
  -Batch Normalization: False
  -Dropout: True, 0.1
```

```
*COMPILATION HYPERPARAMETERS:
  -Optimizer: ADAM lr=0.001, beta_1=0.9, beta_2=0.999
  -Loss Function: MSE
  -Metric: MSE

*TRAINING HYPERPARAMETERS:
  -Epochs: 200
  -Batch size: 32
  -Callbacks:
    -ReduceLROnPlateau: MSE 20 x0.1
    -Early Stop: MSE 50
```

VISUALIZATION:

```
*RESULTS:
      -Train MSE: 0.029477272182703018
      -Validation MSE: 0.04117809608578682
```



(a) Training Evolution (b) Validation example (c) Train example

Figure 39: Results of training the model PSF-FCDR01-10000-1

EXPERIMENT PSF-FCBN-10000-1

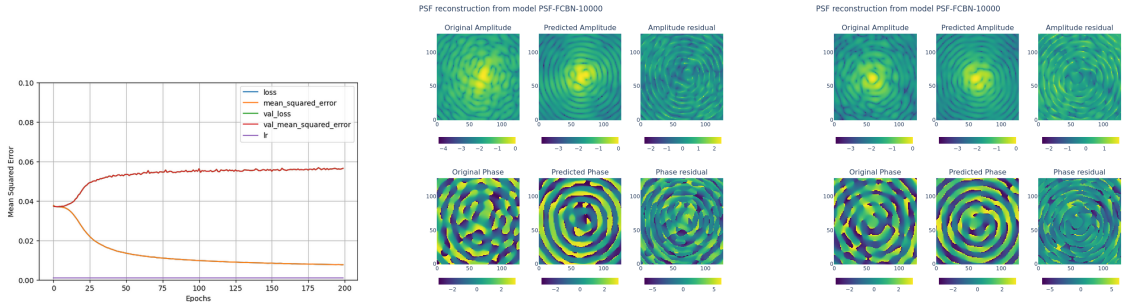
HYPERPARAMETERS:

```
*ARCHITECTURE HYPERPARAMETERS:
  -Fully Connected
  -Input shape: 19
  -Output shape: 32768
  -Hidden layers: [256, 256, 256, 256, 256, 256]
  -Regularizer: None
  -Hidden Layers Activation: relu
  -Output Layer Activation: linear
  -Batch Normalization: True
  -Dropout: False, 0.1

*COMPILATION HYPERPARAMETERS:
  -Optimizer: ADAM lr=0.001, beta_1=0.9, beta_2=0.999
  -Loss Function: MSE
  -Metric: MSE

*TRAINING HYPERPARAMETERS:
  -Epochs: 200
```

```
-Batch size: 32
-Callbacks:
  -ReduceLROnPlateau: MSE 20 x0.1
  -Early Stop: MSE 50
```

VISUALIZATION:

```
*RESULTS:
      -Train MSE: 0.007657112553715706
      -Validation MSE: 0.05646741762757301
```



(a) Training Evolution (b) Validation example (c) Train example

Figure 40: Results of training the model PSF-FCBN-10000-1

EXPERIMENT PSF-FCL1001-10000-1

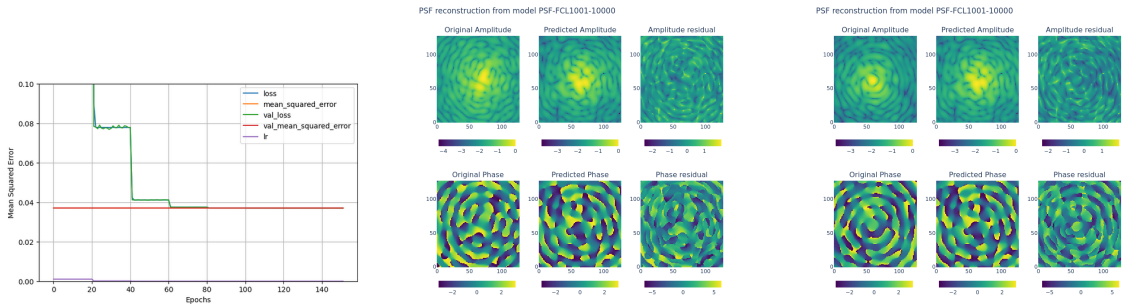
HYPERPARAMETERS:

```
*ARCHITECTURE HYPERPARAMETERS:
  -Fully Connected
  -Input shape: 19
  -Output shape: 32768
  -Hidden layers: [256, 256, 256, 256, 256, 256]
  -Regularizer: L1 0.01
  -Hidden Layers Activation: relu
  -Output Layer Activation: linear
  -Batch Normalization: False
  -Dropout: False, 0.1

*COMPILATION HYPERPARAMETERS:
  -Optimizer: ADAM lr=0.001, beta_1=0.9, beta_2=0.999
  -Loss Function: MSE
  -Metric: MSE

*TRAINING HYPERPARAMETERS:
  -Epochs: 200
  -Batch size: 32
  -Callbacks:
    -ReduceLROnPlateau: MSE 20 x0.1
    -Early Stop: MSE 50
```

VISUALIZATION:

```
*RESULTS:
```

```
        -Train MSE: 0.03701375797390938
        -Validation MSE: 0.037019241601228714
```



(a) Training Evolution (b) Validation example (c) Train example

Figure 41: Results of training the model PSF-FCL1001-10000-1

EXPERIMENT PSF-FCL10001-10000-1

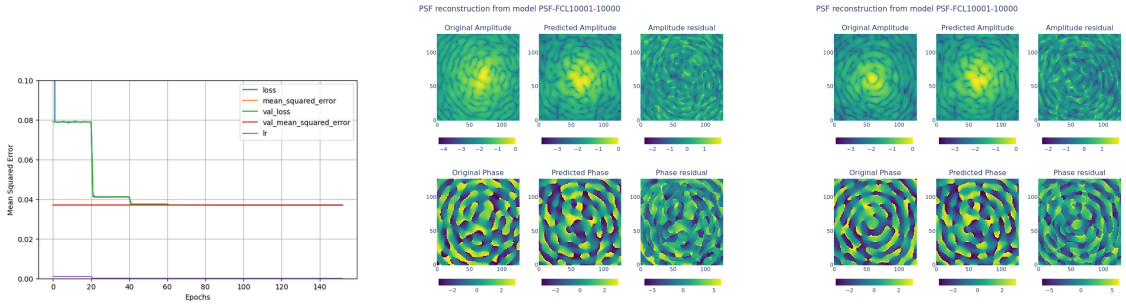
HYPERPARAMETERS:

```
*ARCHITECTURE HYPERPARAMETERS:
  -Fully Connected
  -Input shape: 19
  -Output shape: 32768
  -Hidden layers: [256, 256, 256, 256, 256, 256]
  -Regularizer: L1 0.001
  -Hidden Layers Activation: relu
```

```
  -Output Layer Activation: linear
  -Batch Normalization: False
  -Dropout: False, 0.1

*COMPILATION HYPERPARAMETERS:
  -Optimizer: ADAM lr=0.001, beta_1=0.9, beta_2=0.999
  -Loss Function: MSE
  -Metric: MSE

*TRAINING HYPERPARAMETERS:
  -Epochs: 200
  -Batch size: 32
  -Callbacks:
    -ReduceLROnPlateau: MSE 20 x0.1
    -Early Stop: MSE 50
```

VISUALIZATION:

```
*RESULTS:
      -Train MSE: 0.03701375797390938
      -Validation MSE: 0.037019241601228714
```



(a) Training Evolution (b) Validation example (c) Train example

Figure 42: Results of training the model PSF-FCL10001-10000-1

---

22 March 2024

EXPERIMENT PSF-FCDR02-10000-2

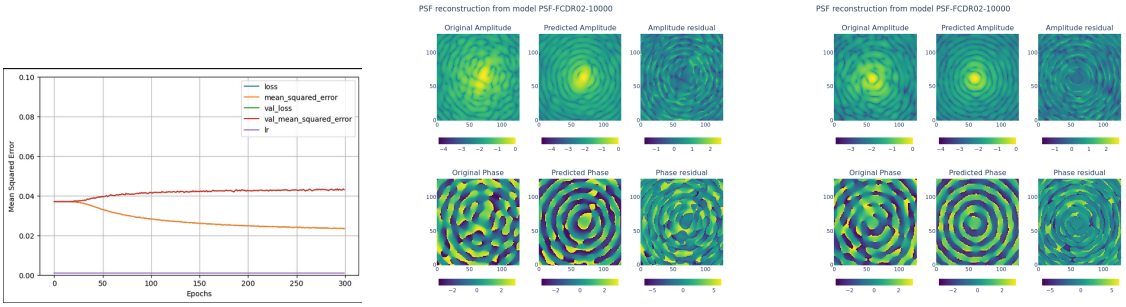
HYPERPARAMETERS:

```
*ARCHITECTURE HYPERPARAMETERS:
  -Fully Connected
  -Input shape: 19
  -Output shape: 32768
  -Hidden layers: [256, 256, 256, 256, 256, 256]
  -Regularizer: None
```

```
  -Hidden Layers Activation: relu
  -Output Layer Activation: linear
  -Batch Normalization: False
  -Dropout: True, 0.2

*COMPILATION HYPERPARAMETERS:
  -Optimizer: ADAM lr=0.001, beta_1=0.9, beta_2=0.999
  -Loss Function: MSE
  -Metric: MSE

*TRAINING HYPERPARAMETERS:
  -Epochs: 300
  -Batch size: 32
  -Callbacks:
    -ReduceLROnPlateau: MSE 50 x0.1
    -Early Stop: MSE 70
```

VISUALIZATION:

```
*RESULTS:
      -Train MSE: 0.0234194565564394
      -Validation MSE: 0.043008171021938324
```



(a) Training Evolution (b) Validation example (c) Train example

Figure 43: Results of training the model PSF-FCDR02-10000-2

EXPERIMENT PSF-FCDR02-30000-1

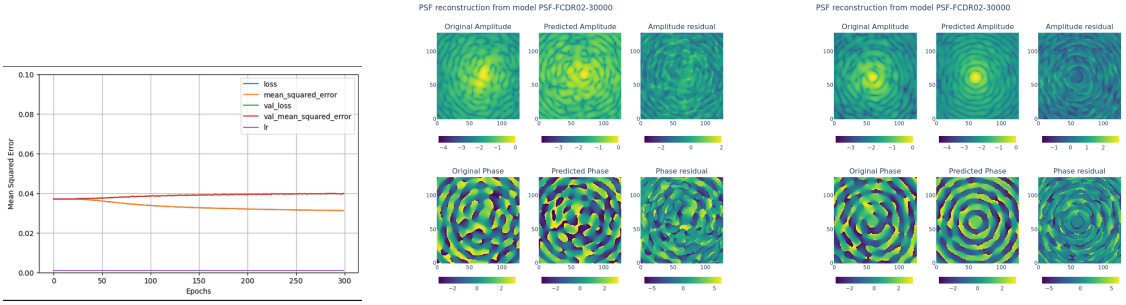
HYPERPARAMETERS:

```
*ARCHITECTURE HYPERPARAMETERS:
  -Fully Connected
  -Input shape: 19
  -Output shape: 32768
  -Hidden layers: [256, 256, 256, 256, 256, 256]
  -Regularizer: None
  -Hidden Layers Activation: relu
  -Output Layer Activation: linear
  -Batch Normalization: False
  -Dropout: True, 0.2
```

```
*COMPILATION HYPERPARAMETERS:
  -Optimizer: ADAM lr=0.001, beta_1=0.9, beta_2=0.999
  -Loss Function: MSE
  -Metric: MSE

*TRAINING HYPERPARAMETERS:
  -Epochs: 300
  -Batch size: 32
  -Callbacks:
    -ReduceLROnPlateau: MSE 20 x0.1
    -Early Stop: MSE 50
```

VISUALIZATION:

```
*RESULTS:
      -Train MSE: 0.03109411522746086
      -Validation MSE: 0.03979235887527466
```



(a) Training Evolution (b) Validation example (c) Train example

Figure 44: Results of training the model PSF-FCDR02-30000-1

EXPERIMENT PSF-FCDR02-70000-2

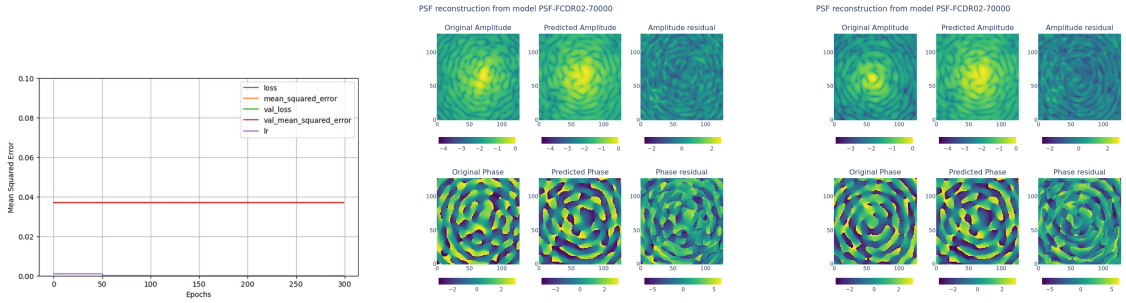
HYPERPARAMETERS:

```
*ARCHITECTURE HYPERPARAMETERS:
  -Fully Connected
  -Input shape: 19
  -Output shape: 32768
  -Hidden layers: [256, 256, 256, 256, 256, 256]
  -Regularizer: None
  -Hidden Layers Activation: relu
  -Output Layer Activation: linear
  -Batch Normalization: False
  -Dropout: True, 0.2

*COMPILATION HYPERPARAMETERS:
  -Optimizer: ADAM lr=0.001, beta_1=0.9, beta_2=0.999
  -Loss Function: MSE
  -Metric: MSE

*TRAINING HYPERPARAMETERS:
  -Epochs: 300
  -Batch size: 32
  -Callbacks:
```

```
    -ReduceLROnPlateau: MSE 20 x0.1
    -Early Stop: MSE 50
```

VISUALIZATION:

```
*RESULTS:
      -Train MSE: 0.03701671585440636
      -Validation MSE: 0.03701670467853546
```



(a) Training Evolution (b) Validation example (c) Train example

Figure 45: Results of training the model PSF-FCDR02-30000-1

25 March 2024

- Regularizations:
  - Dropout, the best results altough not enough
  - Batch normalization makes the convergence faster but makes overfitting worse

  - Kernel regularizers, they don't help, the model does not learn.

- Apart from the overfitting, the predictions made from the training samples are accurate but just in the center of the pupil, as we go away from the center the ripples become more regular

- My guess is either we need more fibers on the PL or a lower resolution image

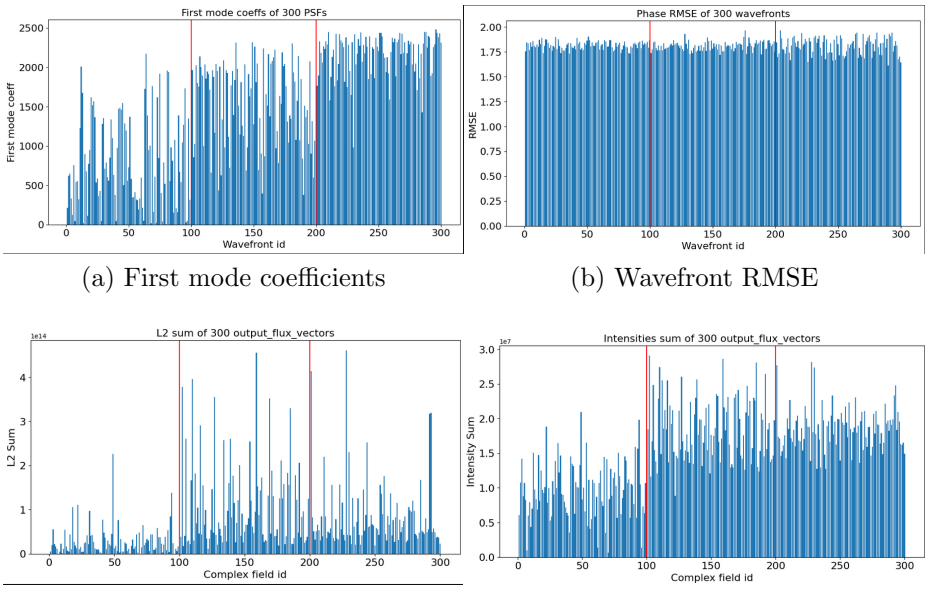
---

26 March 2024

- Perform a correlation analysis: In the figures the red line indicate a change in the fried parameter, from left to right it incresases from 0.1 to 0.2 and then 0.4. There are 100 wavefronts per fried parameter, it looks like the data correlates in all the graphs except for the phase RMSE which does not vary too much

---

CORRELATION ANALYSIS



(a) First mode coefficients (b) Wavefront RMSE

(c) PSF L2 sum (d) PSF Intensity sum

Figure 46: Correlation analysis

---

02 April 2024

EXPERIMENT CroppedSimpleFC10000-1

HYPERPARAMETERS:

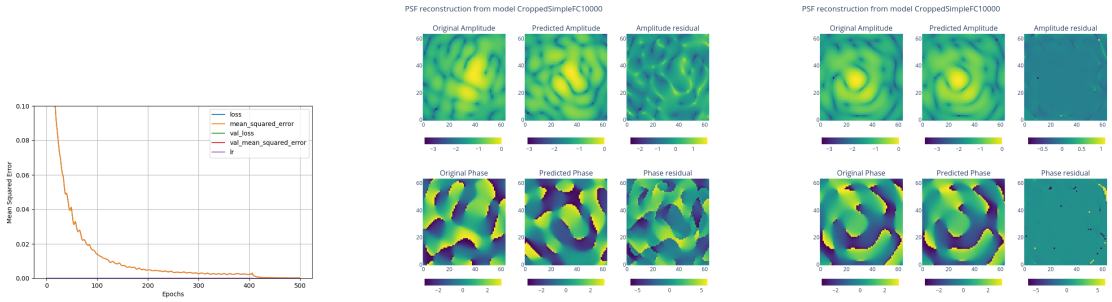
```
*ARCHITECTURE HYPERPARAMETERS:
```

```
  -Fully Connected
  -Input shape: 19
  -Output shape: 8192
  -Hidden layers: [1024, 1024, 1024, 1024, 1024, 1024]
  -Regularizer: None
  -Hidden Layers Activation: relu
  -Output Layer Activation: linear
  -Batch Normalization: False
  -Dropout: False, 0.2

*COMPILATION HYPERPARAMETERS:
  -Optimizer: ADAM lr=0.0001, beta_1=0.9, beta_2=0.999
  -Loss Function: MSE
  -Metric: MSE

*TRAINING HYPERPARAMETERS:
  -Epochs: 500
  -Samples: 10000
  -Batch size: 32
  -Callbacks:
    -ReduceLROnPlateau: MSE 50 x0.1
    -Early Stop: MSE 70
```

VISUALIZATION:

```
*RESULTS:
```

```
        -Train MSE: 0.00028163602109998465
        -Validation MSE: 0.1800803393125534
```



(a) Training Evolution (b) Validation example (c) Train example

Figure 47: Results of training the model CroppedSimpleFC10000-1

EXPERIMENT CroppedSimpleFC30000-1

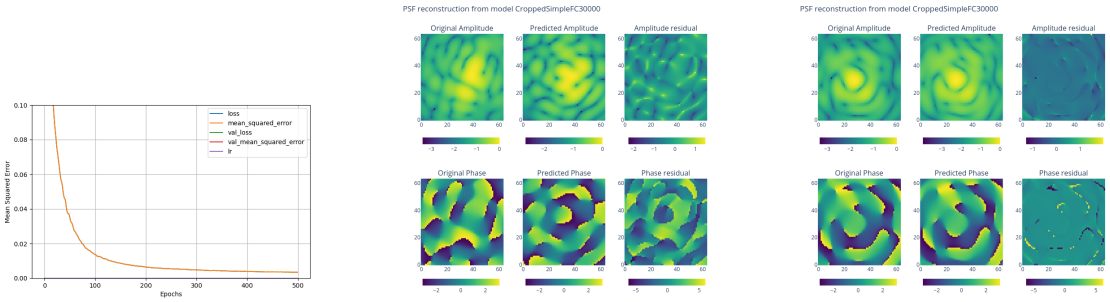
HYPERPARAMETERS:

```
*ARCHITECTURE HYPERPARAMETERS:
  -Fully Connected
  -Input shape: 19
  -Output shape: 8192
  -Hidden layers: [1024, 1024, 1024, 1024, 1024, 1024]
  -Regularizer: None
  -Hidden Layers Activation: relu
```

```
  -Output Layer Activation: linear
  -Batch Normalization: False
  -Dropout: False, 0.2

*COMPILATION HYPERPARAMETERS:
  -Optimizer: ADAM lr=0.0001, beta_1=0.9, beta_2=0.999
  -Loss Function: MSE
  -Metric: MSE

*TRAINING HYPERPARAMETERS:
  -Epochs: 500
  -Samples: 30000
  -Batch size: 32
  -Callbacks:
    -ReduceLROnPlateau: MSE 50 x0.1
    -Early Stop: MSE 70
```

VISUALIZATION:

```
*RESULTS:
      -Train MSE: 0.0034643723629415035
      -Validation MSE: 0.1996324509382248
```



(a) Training Evolution (b) Validation example (c) Train example

Figure 48: Results of training the model CroppedSimpleFC30000-1

EXPERIMENT CroppedSimpleFC70000-1

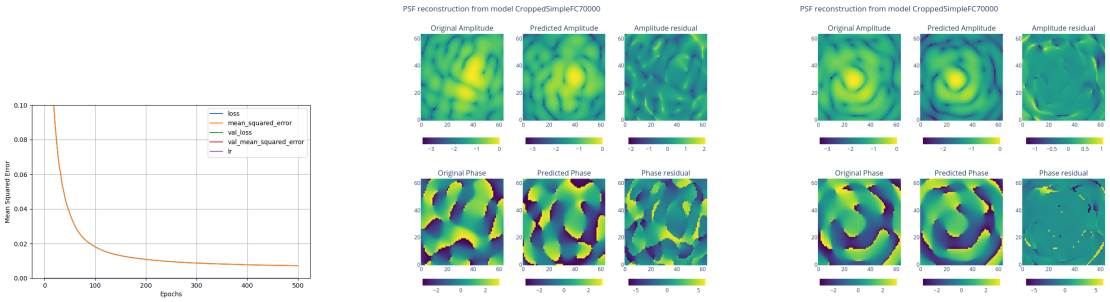
HYPERPARAMETERS:

```
*ARCHITECTURE HYPERPARAMETERS:
  -Fully Connected
  -Input shape: 19
  -Output shape: 8192
  -Hidden layers: [1024, 1024, 1024, 1024, 1024, 1024]
  -Regularizer: None
  -Hidden Layers Activation: relu
  -Output Layer Activation: linear
  -Batch Normalization: False
  -Dropout: False, 0.2
```

```
*COMPILATION HYPERPARAMETERS:
  -Optimizer: ADAM lr=0.0001, beta_1=0.9, beta_2=0.999
  -Loss Function: MSE
  -Metric: MSE

*TRAINING HYPERPARAMETERS:
  -Epochs: 500
  -Samples: 30000
  -Batch size: 32
  -Callbacks:
    -ReduceLROnPlateau: MSE 50 x0.1
    -Early Stop: MSE 70
```

VISUALIZATION:

```
*RESULTS:
      -Train MSE: 0.007220898289233446
      -Validation MSE: 0.20809102058410645
```



(a) Training Evolution (b) Validation example (c) Train example

Figure 49: Results of training the model CroppedSimpleFC70000-1

EXPERIMENT CroppedDR01FC10000-1

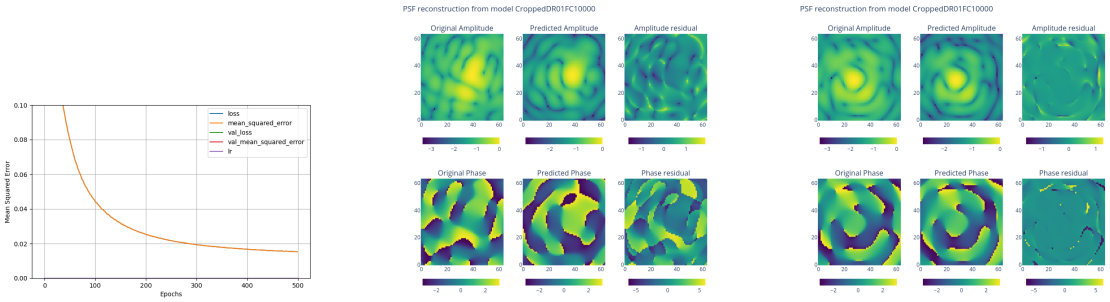
HYPERPARAMETERS:

```
*ARCHITECTURE HYPERPARAMETERS:
  -Fully Connected
  -Input shape: 19
  -Output shape: 8192
  -Hidden layers: [1024, 1024, 1024, 1024, 1024, 1024]
  -Regularizer: None
  -Hidden Layers Activation: relu
  -Output Layer Activation: linear
  -Batch Normalization: False
  -Dropout: True, 0.1
```

```
*COMPILATION HYPERPARAMETERS:
  -Optimizer: ADAM lr=0.0001, beta_1=0.9, beta_2=0.999
  -Loss Function: MSE
  -Metric: MSE

*TRAINING HYPERPARAMETERS:
  -Epochs: 500
  -Samples: 10000
  -Batch size: 32
  -Callbacks:
    -ReduceLROnPlateau: MSE 50 x0.1
    -Early Stop: MSE 70
```

VISUALIZATION:

```
*RESULTS:
      -Train MSE: 0.0152916694059968
      -Validation MSE: 0.18240582942962646
```



(a) Training Evolution (b) Validation example (c) Train example

Figure 50: Results of training the model CroppedDR01FC10000-1

EXPERIMENT CroppedDR01FC30000-1

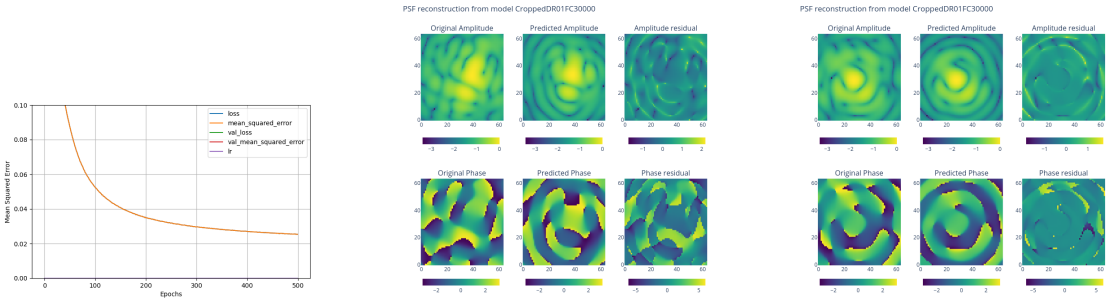
HYPERPARAMETERS:

```
*ARCHITECTURE HYPERPARAMETERS:
  -Fully Connected
  -Input shape: 19
  -Output shape: 8192
  -Hidden layers: [1024, 1024, 1024, 1024, 1024, 1024]
  -Regularizer: None
  -Hidden Layers Activation: relu
  -Output Layer Activation: linear
  -Batch Normalization: False
  -Dropout: True, 0.1
```

```
*COMPILATION HYPERPARAMETERS:
  -Optimizer: ADAM lr=0.0001, beta_1=0.9, beta_2=0.999
  -Loss Function: MSE
  -Metric: MSE

*TRAINING HYPERPARAMETERS:
  -Epochs: 500
  -Samples: 30000
  -Batch size: 32
  -Callbacks:
    -ReduceLROnPlateau: MSE 50 x0.1
    -Early Stop: MSE 70
```

VISUALIZATION:

```
*RESULTS:
      -Train MSE: 0.025341492146253586
      -Validation MSE: 0.18506889045238495
```



(a) Training Evolution (b) Validation example (c) Train example

Figure 51: Results of training the model CroppedDR01FC30000-1

EXPERIMENT CroppedDR01FC70000-1

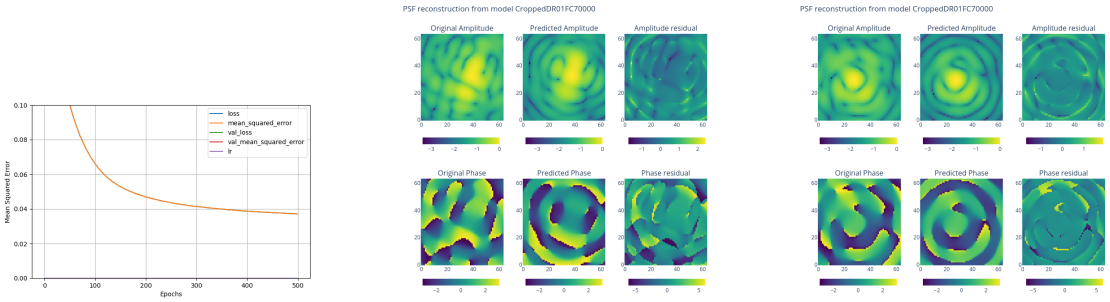
HYPERPARAMETERS:

```
*ARCHITECTURE HYPERPARAMETERS:
  -Fully Connected
  -Input shape: 19
  -Output shape: 8192
  -Hidden layers: [1024, 1024, 1024, 1024, 1024, 1024]
  -Regularizer: None
  -Hidden Layers Activation: relu
  -Output Layer Activation: linear
  -Batch Normalization: False
  -Dropout: True, 0.1
```

```
*COMPILATION HYPERPARAMETERS:
  -Optimizer: ADAM lr=0.0001, beta_1=0.9, beta_2=0.999
  -Loss Function: MSE
  -Metric: MSE

*TRAINING HYPERPARAMETERS:
  -Epochs: 500
  -Samples: 70000
  -Batch size: 32
  -Callbacks:
    -ReduceLROnPlateau: MSE 50 x0.1
    -Early Stop: MSE 70
```

VISUALIZATION:

```
*RESULTS:
      -Train MSE: 0.03703419491648674
      -Validation MSE: 0.18717476725578308
```



(a) Training Evolution (b) Validation example (c) Train example

Figure 52: Results of training the model CroppedDR01FC70000-1

EXPERIMENT CroppedDR02FC10000-1

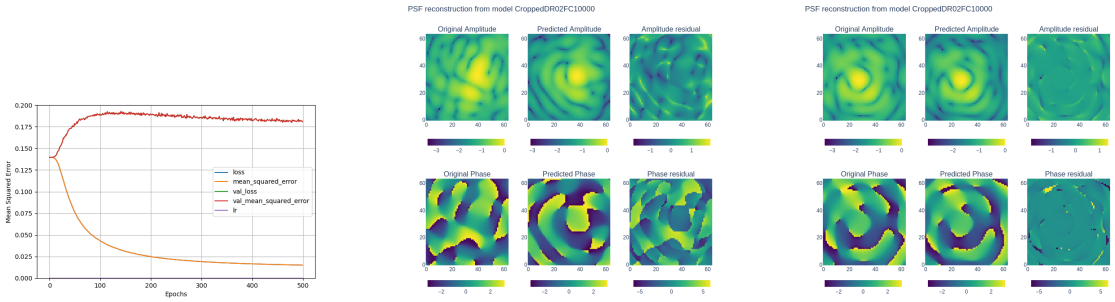
HYPERPARAMETERS:

```
*ARCHITECTURE HYPERPARAMETERS:
  -Fully Connected
  -Input shape: 19
  -Output shape: 8192
  -Hidden layers: [1024, 1024, 1024, 1024, 1024, 1024]
  -Regularizer: None
  -Hidden Layers Activation: relu
  -Output Layer Activation: linear
  -Batch Normalization: False
  -Dropout: True, 0.2
```

```
*COMPILATION HYPERPARAMETERS:
  -Optimizer: ADAM lr=0.0001, beta_1=0.9, beta_2=0.999
  -Loss Function: MSE
  -Metric: MSE

*TRAINING HYPERPARAMETERS:
  -Epochs: 500
  -Samples: 30000
  -Batch size: 32
  -Callbacks:
    -ReduceLROnPlateau: MSE 50 x0.1
    -Early Stop: MSE 70
```

VISUALIZATION:

```
*RESULTS:
      -Train MSE: 0.01520285103470087
      -Validation MSE: 0.18062736093997955
```



(a) Training Evolution (b) Validation example (c) Train example

Figure 53: Results of training the model CroppedDR02FC10000-1

EXPERIMENT CroppedDR02FC30000-1

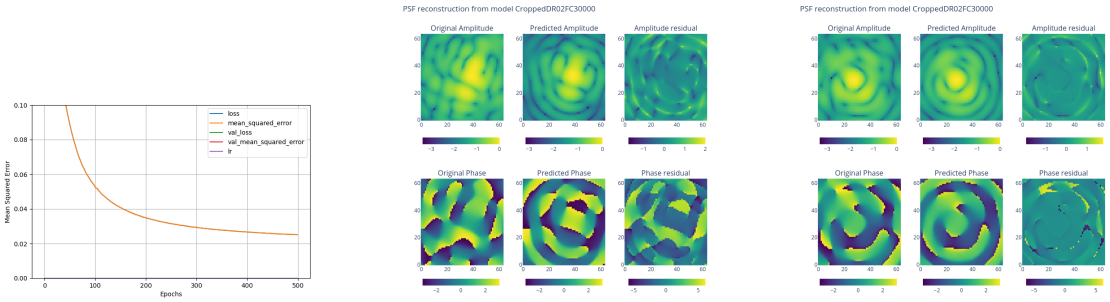
HYPERPARAMETERS:

```
*ARCHITECTURE HYPERPARAMETERS:
  -Fully Connected
  -Input shape: 19
  -Output shape: 8192
  -Hidden layers: [1024, 1024, 1024, 1024, 1024, 1024]
  -Regularizer: None
  -Hidden Layers Activation: relu
  -Output Layer Activation: linear
  -Batch Normalization: False
  -Dropout: True, 0.2
```

```
*COMPILATION HYPERPARAMETERS:
  -Optimizer: ADAM lr=0.0001, beta_1=0.9, beta_2=0.999
  -Loss Function: MSE
  -Metric: MSE

*TRAINING HYPERPARAMETERS:
  -Epochs: 500
  -Samples: 30000
  -Batch size: 32
  -Callbacks:
    -ReduceLROnPlateau: MSE 50 x0.1
    -Early Stop: MSE 70
```

VISUALIZATION:

```
*RESULTS:
      -Train MSE: 0.025196749716997147
      -Validation MSE: 0.1864871084690094
```



(a) Training Evolution (b) Validation example (c) Train example

Figure 54: Results of training the model CroppedDR02FC30000-1

EXPERIMENT CroppedDR02FC70000-1

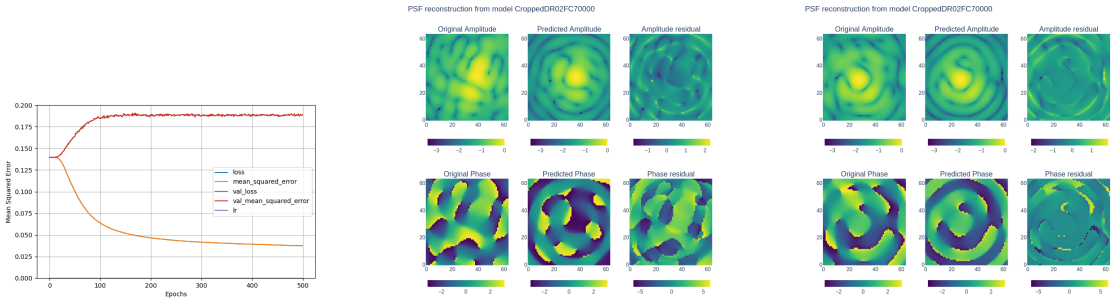
HYPERPARAMETERS:

```
*ARCHITECTURE HYPERPARAMETERS:
  -Fully Connected
  -Input shape: 19
  -Output shape: 8192
  -Hidden layers: [1024, 1024, 1024, 1024, 1024, 1024]
  -Regularizer: None
  -Hidden Layers Activation: relu
  -Output Layer Activation: linear
  -Batch Normalization: False
  -Dropout: True, 0.2
```

```
*COMPILATION HYPERPARAMETERS:
  -Optimizer: ADAM lr=0.0001, beta_1=0.9, beta_2=0.999
  -Loss Function: MSE
  -Metric: MSE

*TRAINING HYPERPARAMETERS:
  -Epochs: 500
  -Samples: 30000
  -Batch size: 32
  -Callbacks:
    -ReduceLROnPlateau: MSE 50 x0.1
    -Early Stop: MSE 70
```

VISUALIZATION:

```
*RESULTS:
      -Train MSE: 0.03758401796221733
      -Validation MSE: 0.1887626349925995
```



(a) Training Evolution (b) Validation example (c) Train example

Figure 55: Results of training the model CroppedDR02FC70000-1

EXPERIMENT CroppedBNFC10000-1

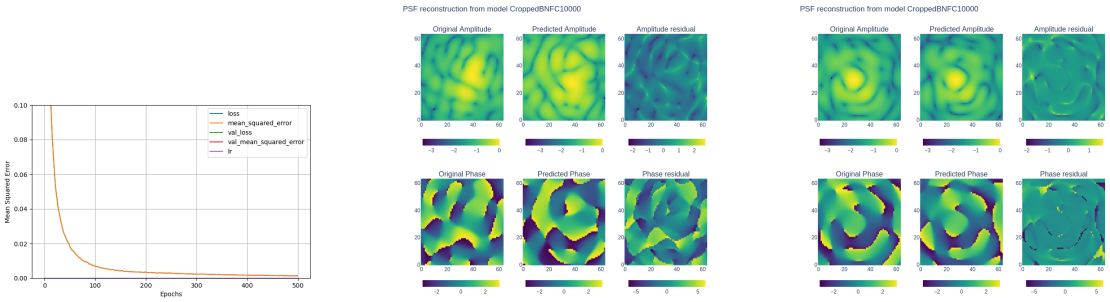
HYPERPARAMETERS:

```
*ARCHITECTURE HYPERPARAMETERS:
  -Fully Connected
  -Input shape: 19
  -Output shape: 8192
  -Hidden layers: [1024, 1024, 1024, 1024, 1024, 1024]
  -Regularizer: None
  -Hidden Layers Activation: relu
  -Output Layer Activation: linear
  -Batch Normalization: True
  -Dropout: False, 0.2
```

```
*COMPILATION HYPERPARAMETERS:
  -Optimizer: ADAM lr=0.0001, beta_1=0.9, beta_2=0.999
  -Loss Function: MSE
  -Metric: MSE

*TRAINING HYPERPARAMETERS:
  -Epochs: 500
  -Samples: 10000
  -Batch size: 32
  -Callbacks:
    -ReduceLROnPlateau: MSE 50 x0.1
    -Early Stop: MSE 70
```

VISUALIZATION:

```
*RESULTS:
      -Train MSE: 0.001437550876289606
      -Validation MSE: 0.18398649990558624
```



(a) Training Evolution (b) Validation example (c) Train example

Figure 56: Results of training the model CroppedBNFC10000-1

EXPERIMENT CroppedBNFC30000-1

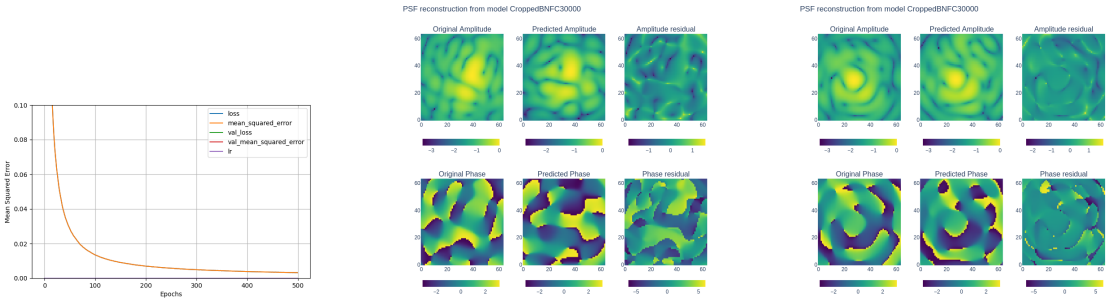
HYPERPARAMETERS:

```
*ARCHITECTURE HYPERPARAMETERS:
  -Fully Connected
  -Input shape: 19
  -Output shape: 8192
  -Hidden layers: [1024, 1024, 1024, 1024, 1024, 1024]
  -Regularizer: None
  -Hidden Layers Activation: relu
  -Output Layer Activation: linear
  -Batch Normalization: True
  -Dropout: False, 0.2
```

```
*COMPILATION HYPERPARAMETERS:
  -Optimizer: ADAM lr=0.0001, beta_1=0.9, beta_2=0.999
  -Loss Function: MSE
  -Metric: MSE

*TRAINING HYPERPARAMETERS:
  -Epochs: 500
  -Samples: 30000
  -Batch size: 32
  -Callbacks:
    -ReduceLROnPlateau: MSE 50 x0.1
    -Early Stop: MSE 70
```

VISUALIZATION:

```
*RESULTS:
      -Train MSE: 0.0032125315628945827
      -Validation MSE: 0.1955052763223648
```



(a) Training Evolution (b) Validation example (c) Train example

Figure 57: Results of training the model CroppedBNFC30000-1

EXPERIMENT CroppedBNFC70000-1

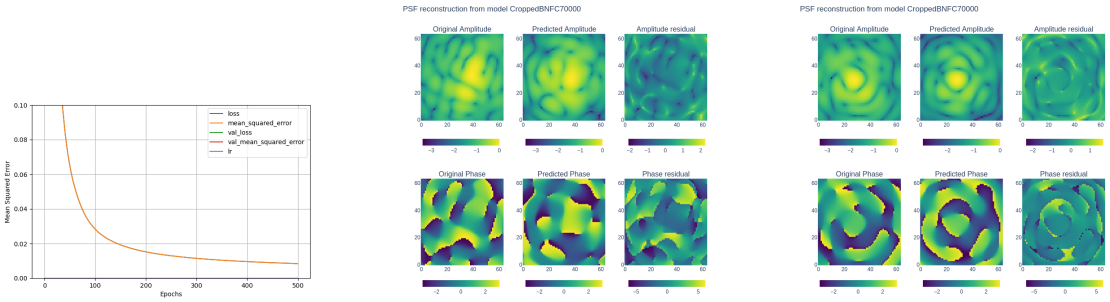
HYPERPARAMETERS:

```
*ARCHITECTURE HYPERPARAMETERS:
  -Fully Connected
  -Input shape: 19
  -Output shape: 8192
  -Hidden layers: [1024, 1024, 1024, 1024, 1024, 1024]
  -Regularizer: None
  -Hidden Layers Activation: relu
  -Output Layer Activation: linear
  -Batch Normalization: True
  -Dropout: False, 0.2
```

```
*COMPILATION HYPERPARAMETERS:
  -Optimizer: ADAM lr=0.0001, beta_1=0.9, beta_2=0.999
  -Loss Function: MSE
  -Metric: MSE

*TRAINING HYPERPARAMETERS:
  -Epochs: 500
  -Samples: 70000
  -Batch size: 32
  -Callbacks:
    -ReduceLROnPlateau: MSE 50 x0.1
    -Early Stop: MSE 70
```

VISUALIZATION:

```
*RESULTS:
      -Train MSE: 0.008466990664601326
      -Validation MSE: 0.20970138907432556
```



(a) Training Evolution (b) Validation example (c) Train example

Figure 58: Results of training the model CroppedBNFC70000-1

---

09 April 2024

- PL information determination

- Given some set of data containing the inputs (eg mode coeffs or images) X and outputs (eg PL fluxes) y of a photonic lantern, quantify the amount of information preserved by the encoding, independent of any assumptions about the transfer function or reconstruction algorithm.

- First create files with the predictions from the models `PSFRecontructorSuperBigFC70000-1` (for the original sized complex fields predictions) and `CroppedBNFC70000-1` (for the cropped complex fields predictions). The predictions are made for the whole train dataset.

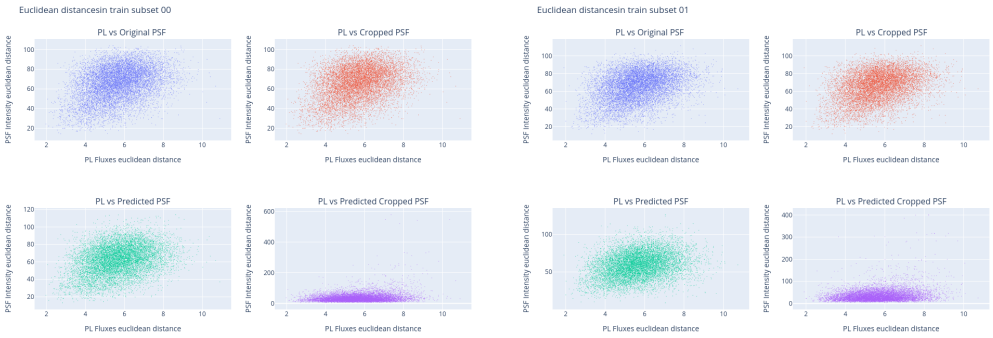
- **BRUTE FORCE ANALYSIS**:

  - Pick 70000 random pair of frames
  - Save euclidean distances for each of them
  - Plot euclidean distances
  - See if PSF similarity implies PL similarity
  - Metric will be the ratio between PL output distances and PSF distances
  - Perform ANOVA test for Uncropped, Cropped, PredictedUncropped, PredictedCropped pairs.

- I compute the euclidean distances between pairs and store the pairs in `pairsxx.npy` and `euclidean_distancesxx.npy` . The `euclidean_distancesxx.npy` array has shape of 1000x5, each column being the distance between pairs of psf fluxes, original complex fields, cropped complex fields, predicted complex fields and predicted cropped complex fields.

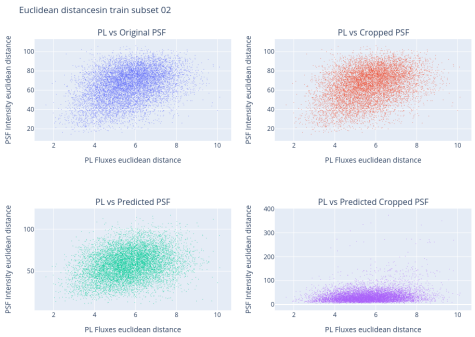
- The complex fields are 2x128x128 and the cropped complex fields are 2x64x64, when I say predicted I mean the complex generated by the models.

EXPERIMENT Euclidean distances

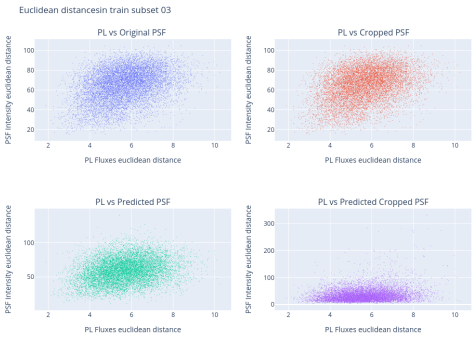


(a) Train subset 0

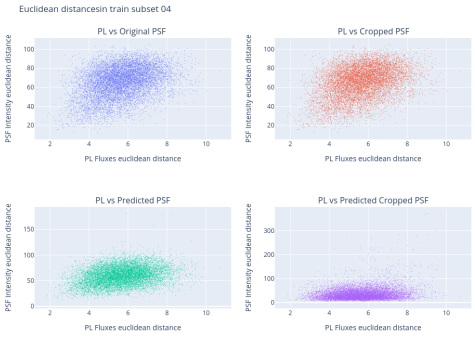
(b) Train subset 1



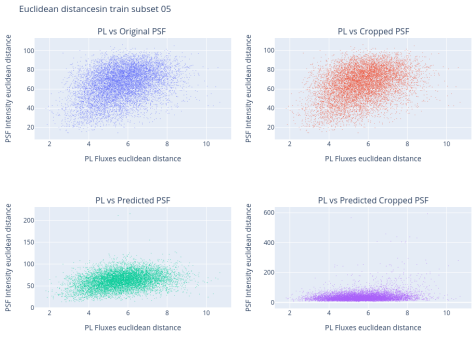
(c) Train subset 2



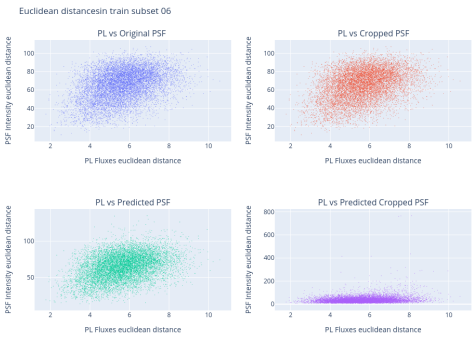
(d) Train subset 3



(e) Train subset 4



(f) Train subset 5



(g) Train subset 6

Figure 59: Euclidean distances between PL and PSF pairs

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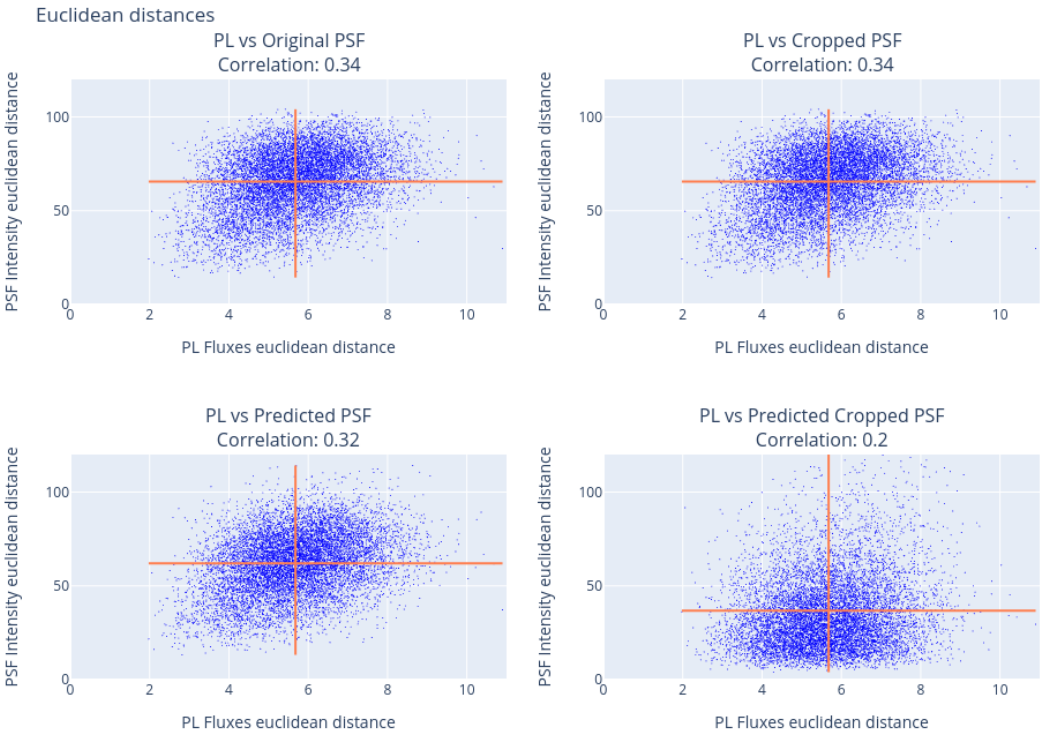
- Repeat the same analysis but this time for the whole train dataset

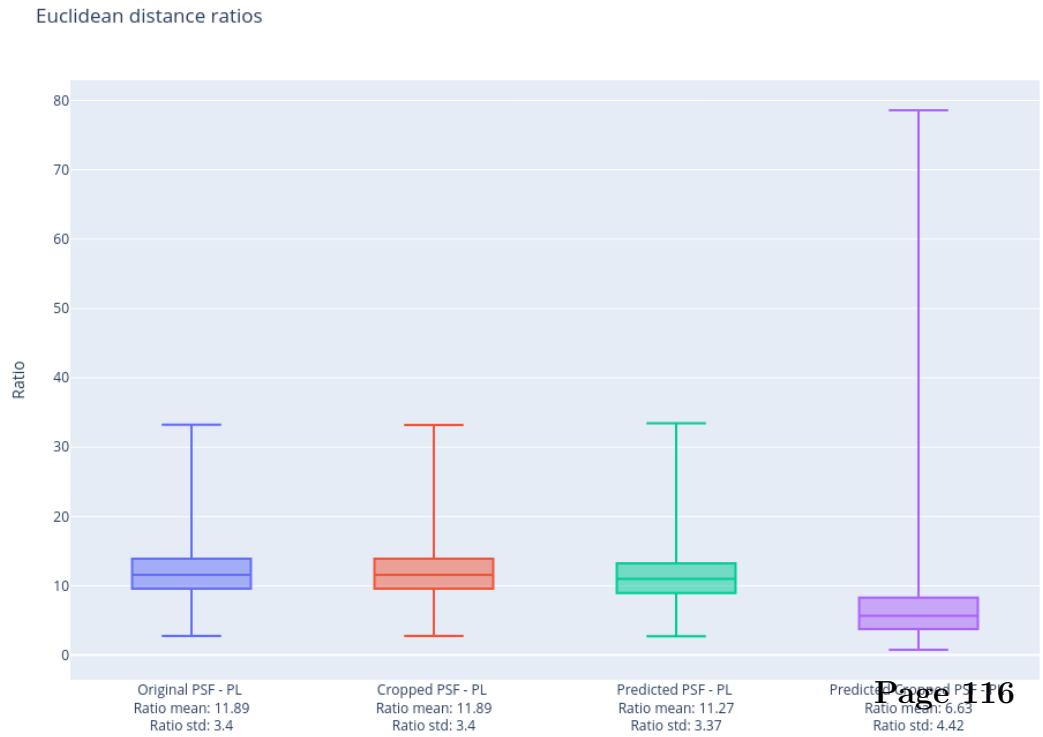
- The correlation is 0.3 which indicates a slightly positive linear relationship between the PL flux and PSF in all caes except for the cropped predictions which has a 0.2 correlation rate.

  The cropped predictions seem to be closer between them than in the rest of the cases, the model that predicts the original sized PSFs has a very similar cloud structure to the one composed of the PL and original dataset.

EXPERIMENT Euclidean distances for the whole dataset



(a) Euclidean distance cloud



(b) Euclidean distance ratios

Figure 60: Euclidean distances ratios between PL and PSF pairs