

Lab Notebook

Photonic Lantern Information Determination

Contents

1 PL Information Determination	2
1.1 The data	2
1.1.1 Atmospheric aberration related	2
1.1.2 Zernike modes related	4
1.2 The models	14
1.2.1 Atmospheric aberration related models	16
1.2.2 Zernike modes related models	17
1.3 Euclidean distances analysis for atmospheric aberration PSFs	29
1.3.1 Preprocessing	29
1.3.2 Results	29
1.3.3 Analysis	30

1 PL Information Determination

1.1 The data

There are two groups of datasets.

1.1.1 Atmospheric aberration related

There are 4 datasets composed by PSFs and their corresponding PL intensities.

PSFs The PSFs' electric fields are stored in a 3d matrix of depth 2: depth 1 and 2 represent the real and imaginary value of the electric field in a point.

- **Original sized PSFs:** Two datasets of 70000 electric fields and corresponding intensities stored in 128x128x2 and 128x128 matrices respectively.

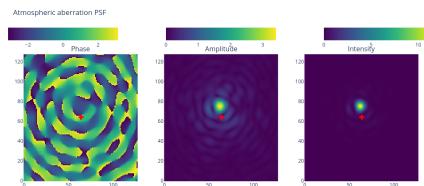


Figure 1: Example original sized PSF

- **Cropped sized PSFs:** Two datasets of 70000 electric fields and corresponding intensities stored in 64x64x2 and 64x64 matrices respectively. These cropped PSFs correspond to the central pixels from the Original sized PSFs.
- **Original sized predicted PSFs:** Two datasets of 70000 predicted electric fields and predicted intensities stored in 128x128x2 and 128x128 matrices respectively. These predicted PSFs are the outputs of a model trained with the Original PSFs dataset and their corresponding PL intensities.

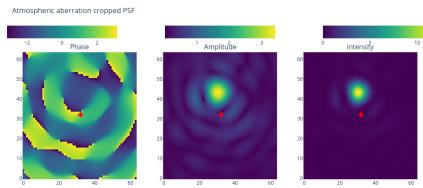


Figure 2: Example Cropped sized PSF

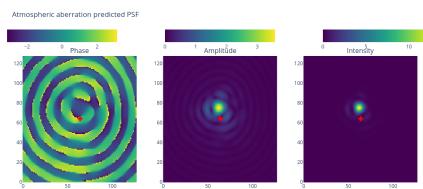


Figure 3: Example original sized predicted PSF

- **Cropped sized predicted PSF:** Two datasets of 70000 predicted electric fields and predicted intensities stored in 64x64x2 and 64x64 matrices respectively. These cropped predicted PSFs are the outputs of a model trained with the Cropped sized PSFs dataset and their corresponding PL intensities (which are the same output intensities from the Original sized PSFs dataset).

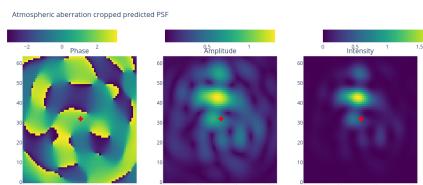


Figure 4: Example cropped sized predicted PSF

PL intensities The same dataset of PL output intensities are used for every PSF dataset. The intensities are computed multiplying the LP coefficients by the transfer matrix of the **19 mode PL**. This dataset has 70000 datapoints, each datapoint being

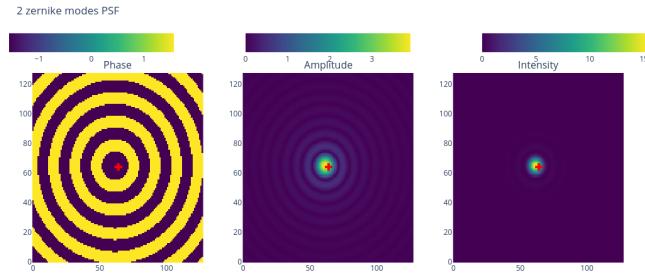
a vector of 19 elements.

1.1.2 Zernike modes related

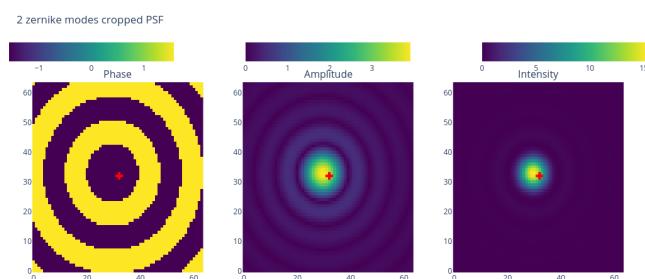
There are 5 subgroups of datasets: PSFs generated with 2, 5, 9, 14 and 20 zernike modes. Each subgroup is divided in original sized, cropped sized, predicted and cropped predicted as in the case of the atmospheric aberration PSFs.

2 Zernike modes PSFs

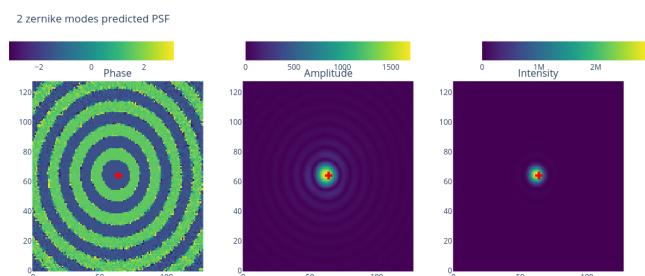
- **Original sized 2 modes PSFs:** Two datasets of 70000 electric fields and corresponding intensities stored in 128x128x2 and 128x128 matrices respectively. The aberration by a 2 modes zernike basis.
- **Cropped sized 2 modes PSFs:** Two datasets of 70000 electric fields and corresponding intensities stored in 64x64x2 and 64x64 matrices respectively. These cropped PSFs correspond to the central pixels from the Original sized 2 modes PSFs.
- **Original sized predicted 2 modes PSFs:** Two datasets of 70000 predicted electric fields and predicted intensities stored in 128x128x2 and 128x128 matrices respectively. These predicted PSFs are the outputs of a model trained with the Original sized 2 modes PSFs dataset and their corresponding PL intensities.
- **Cropped sized predicted 2 modes PSF:** Two datasets of 70000 predicted electric fields and predicted intensities stored in 64x64x2 and 64x64 matrices respectively. These cropped predicted PSFs are the outputs of a model trained with the Cropped sized 2 modes PSFs dataset and their corresponding PL intensities (which are the same ouput intensities from the Original sized 2 modes PSFs dataset).



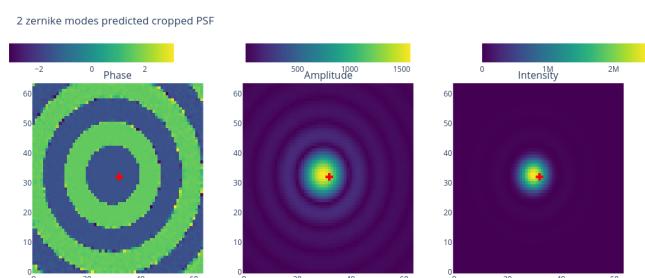
(a) Original sized 2 modes PSF example



(b) Cropped sized 2 modes PSF example



(c) Original sized predicted 2 modes PSF example

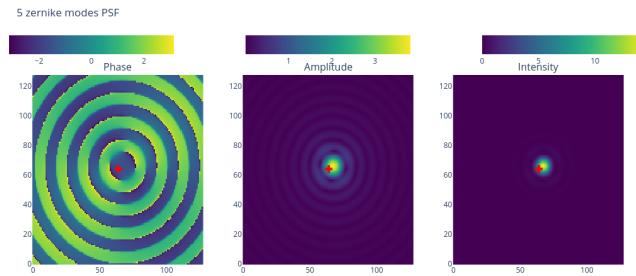


(d) cropped sized predicted 2 modes PSF example

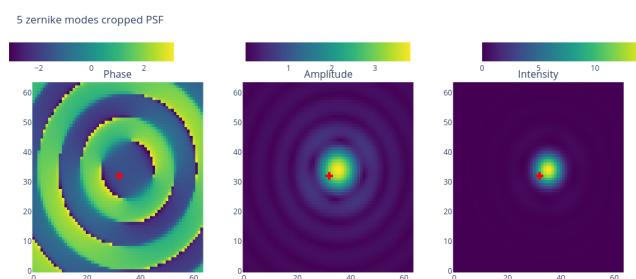
Figure 5: 2 Zernike modes PSF datasets examples

5 Zernike modes PSFs

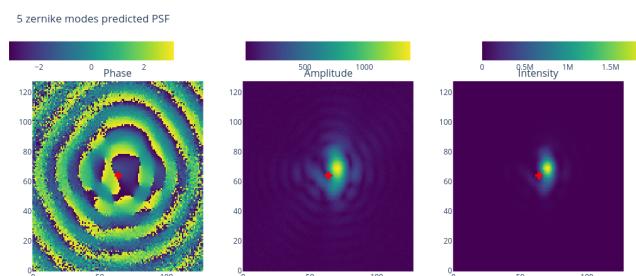
- **Original sized 5 modes PSFs:** Two datasets of 70000 electric fields and corresponding intensities stored in 128x128x2 and 128x128 matrices respectively. The aberration by a 5 modes zernike basis.
- **Cropped sized 5 modes PSFs:** Two datasets of 70000 electric fields and corresponding intensities stored in 64x64x2 and 64x64 matrices respectively. These cropped PSFs correspond to the central pixels from the Original sized 5 modes PSFs.
- **Original sized predicted 5 modes PSFs:** Two datasets of 70000 predicted electric fields and predicted intensities stored in 128x128x2 and 128x128 matrices respectively. These predicted PSFs are the outputs of a model trained with the Original sized 5 modes PSFs dataset and their corresponding PL intensities.
- **Cropped sized predicted 5 modes PSF:** Two datasets of 70000 predicted electric fields and predicted intensities stored in 64x64x2 and 64x64 matrices respectively. These cropped predicted PSFs are the outputs of a model trained with the Cropped sized 5 modes PSFs dataset and their corresponding PL intensities (which are the same ouput intensities from the Original sized 5 modes PSFs dataset).



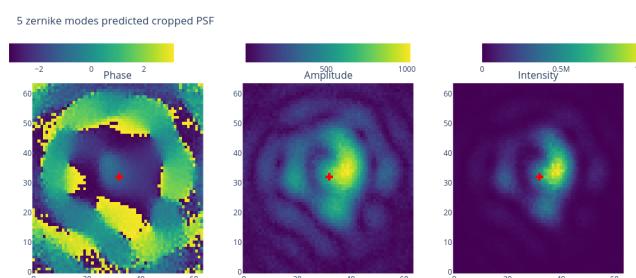
(a) Original sized 5 modes PSF example



(b) Cropped sized 5 modes PSF example



(c) Original sized predicted 5 modes PSF example

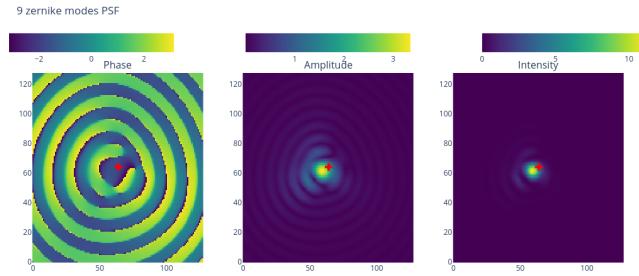


(d) cropped sized predicted 5 modes PSF example

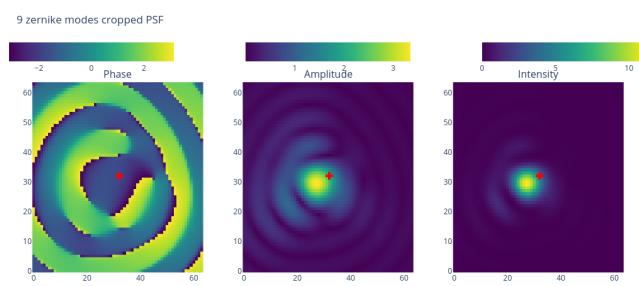
Figure 6: 5 Zernike modes PSF datasets examples

9 Zernike modes PSFs

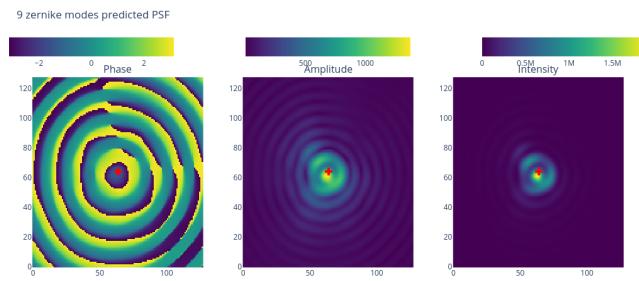
- **Original sized 9 modes PSFs:** Two datasets of 70000 electric fields and corresponding intensities stored in 128x128x2 and 128x128 matrices respectively. The aberration by a 9 modes zernike basis.
- **Cropped sized 9 modes PSFs:** Two datasets of 70000 electric fields and corresponding intensities stored in 64x64x2 and 64x64 matrices respectively. These cropped PSFs correspond to the central pixels from the Original sized 9 modes PSFs.
- **Original sized predicted 9 modes PSFs:** Two datasets of 70000 predicted electric fields and predicted intensities stored in 128x128x2 and 128x128 matrices respectively. These predicted PSFs are the outputs of a model trained with the Original sized 9 modes PSFs dataset and their corresponding PL intensities.
- **Cropped sized predicted 9 modes PSF:** Two datasets of 70000 predicted electric fields and predicted intensities stored in 64x64x2 and 64x64 matrices respectively. These cropped predicted PSFs are the outputs of a model trained with the Cropped sized 9 modes PSFs dataset and their corresponding PL intensities (which are the same ouput intensities from the Original sized 9 modes PSFs dataset).



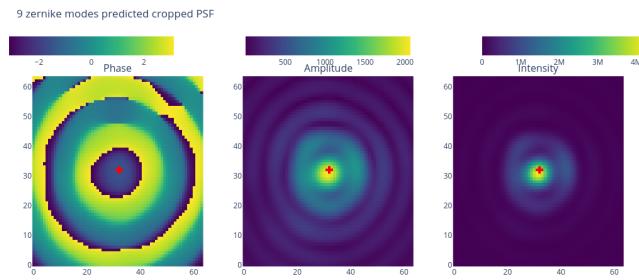
(a) Original sized 9 modes PSF example



(b) Cropped sized 9 modes PSF example



(c) Original sized predicted 9 modes PSF example

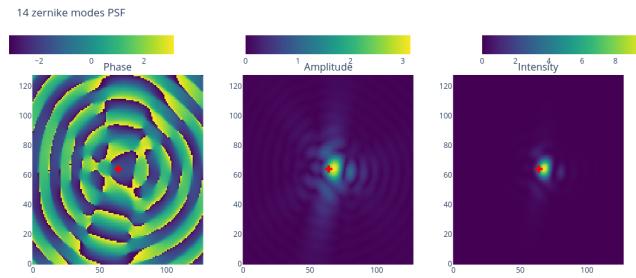


(d) cropped sized predicted 9 modes PSF example

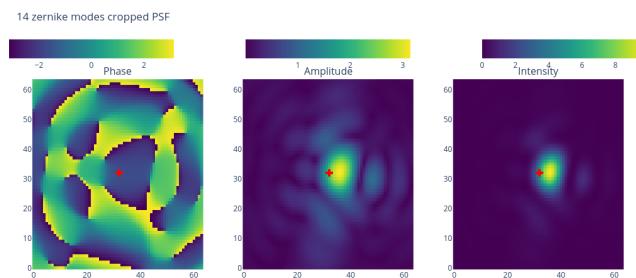
Figure 7: 9 Zernike modes PSF datasets examples

14 Zernike modes PSFs

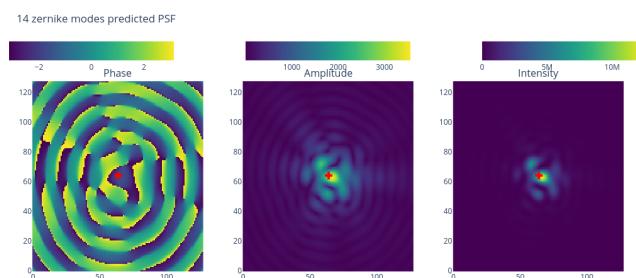
- **Original sized 14 modes PSFs:** Two datasets of 70000 electric fields and corresponding intensities stored in 128x128x2 and 128x128 matrices respectively. The aberration by a 14 modes zernike basis.
- **Cropped sized 14 modes PSFs:** Two datasets of 70000 electric fields and corresponding intensities stored in 64x64x2 and 64x64 matrices respectively. These cropped PSFs correspond to the central pixels from the Original sized 14 modes PSFs.
- **Original sized predicted 14 modes PSFs:** Two datasets of 70000 predicted electric fields and predicted intensities stored in 128x128x2 and 128x128 matrices respectively. These predicted PSFs are the outputs of a model trained with the Original sized 14 modes PSFs dataset and their corresponding PL intensities.
- **Cropped sized predicted 14 modes PSF:** Two datasets of 70000 predicted electric fields and predicted intensities stored in 64x64x2 and 64x64 matrices respectively. These cropped predicted PSFs are the outputs of a model trained with the Cropped sized 14 modes PSFs dataset and their corresponding PL intensities (which are the same ouput intensities from the Original sized 14 modes PSFs dataset).



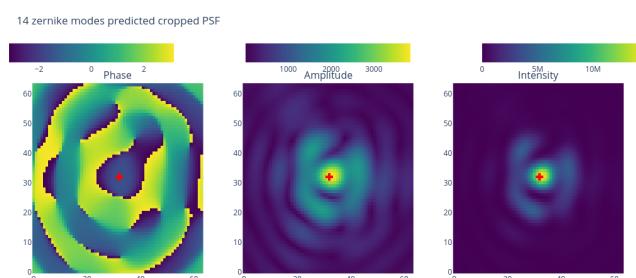
(a) Original sized 14 modes PSF example



(b) Cropped sized 14 modes PSF example



(c) Original sized 14 modes PSF example

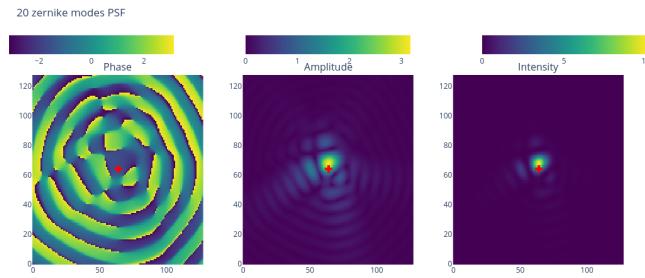


(d) cropped sized predicted 14 modes PSF example

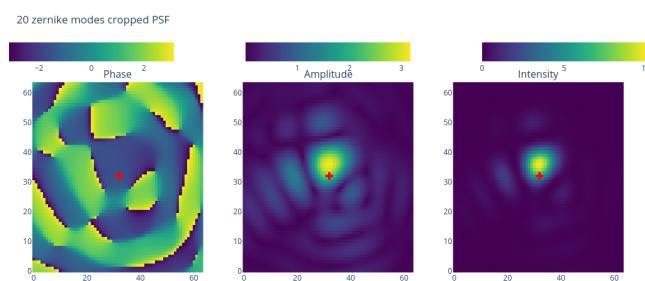
Figure 8: 14 Zernike modes PSF datasets examples

20 Zernike modes PSFs

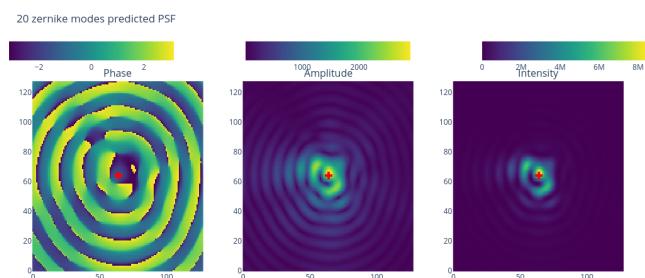
- **Original sized 20 modes PSFs:** Two datasets of 70000 electric fields and corresponding intensities stored in 128x128x2 and 128x128 matrices respectively. The aberration by a 20 modes zernike basis.
- **Cropped sized 20 modes PSFs:** Two datasets of 70000 electric fields and corresponding intensities stored in 64x64x2 and 64x64 matrices respectively. These cropped PSFs correspond to the central pixels from the Original sized 20 modes PSFs.
- **Original sized predicted 20 modes PSFs:** Two datasets of 70000 predicted electric fields and predicted intensities stored in 128x128x2 and 128x128 matrices respectively. These predicted PSFs are the outputs of a model trained with the Original sized 20 modes PSFs dataset and their corresponding PL intensities.
- **Cropped sized predicted 20 modes PSF:** Two datasets of 70000 predicted electric fields and predicted intensities stored in 64x64x2 and 64x64 matrices respectively. These cropped predicted PSFs are the outputs of a model trained with the Cropped sized 20 modes PSFs dataset and their corresponding PL intensities (which are the same ouput intensities from the Original sized 20 modes PSFs dataset).



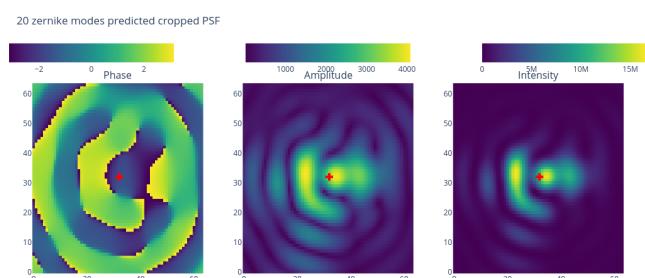
(a) Original sized 20 modes PSF example



(b) Cropped sized 20 modes PSF example



(c) Original sized 20 modes PSF example



(d) cropped sized predicted 20 modes PSF example

Figure 9: 20 Zernike modes PSF datasets examples

LP mode coefficients There are two PL intensities dataset per Zernike aberration PSF subgroup: LP modes coefficients for 2, 5, 9, 14, 20 modes PSFs. Each of the dataset has 70000 datapoints each datapoint being the complex coefficients stored in a 19x2 matrix that separates the real and imaginary part of the coefficients.

The two datasets correspond to the LP coefficients that are computed in the multimode end of Photonic Lanterns. The PLs are:

- 19 mode supporting multimode end with 19 waveguides in the single mode end.
- 42 mode supporting multimode end with 42 waveguides in the single mode end.

PL intensities There is one PL intensities dataset per Zernike aberration PSF subgroup: PL intensities for 2, 5, 9, 14, 20 modes PSFs. Each of the dataset has 70000 datapoints each datapoint being the 19 intensities corresponding to the PSF

The two datasets correspond to the single mode end intensities of Photonic Lanterns. The PLs are:

- 19 mode supporting multimode end with 19 waveguides in the single mode end.
 - 42 mode supporting multimode end with 42 waveguides in the single mode end.
-

1.2 The models

For all the datasets a model with the following configuration has been trained. The inputs of the model are the PL intensities and the outputs are the flattened matrices that represent the PSFs' complex fields.

HYPERPARAMETERS:***ARCHITECTURE HYPERPARAMETERS :**

- Fully Connected
- Input shape: 19
- Output shape:
 - 32768 for original sized PSF electric field
 - 16384 for original sized PSF intensity
 - 8192 for cropped sized PSF electric field
 - 4096 for cropped sized PSF intensity
- 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

***COMPILE 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
```

The exception is the model trained for the Atmospheric Aberration Cropped PSF which has Batch Normalization activated.

1.2.1 Atmospheric aberration related models

Original sized PSF :

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

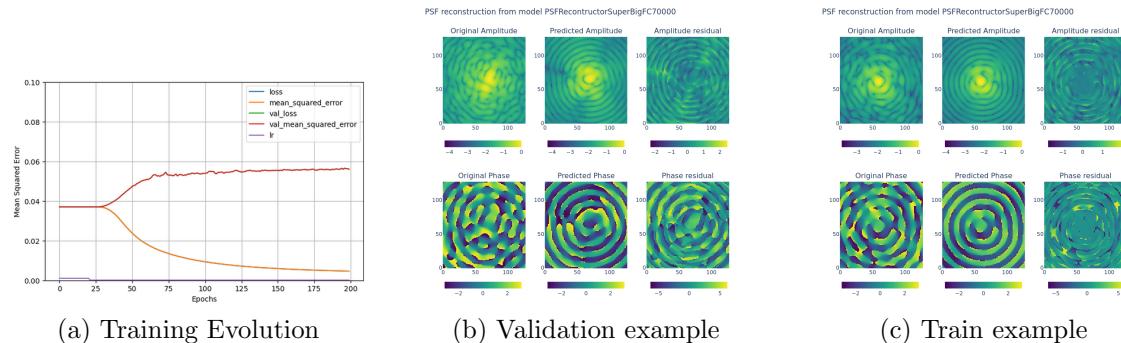


Figure 10: Results of training the model PSFReconstructorSuperBigFC70000-1

Cropped sized PSF :

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

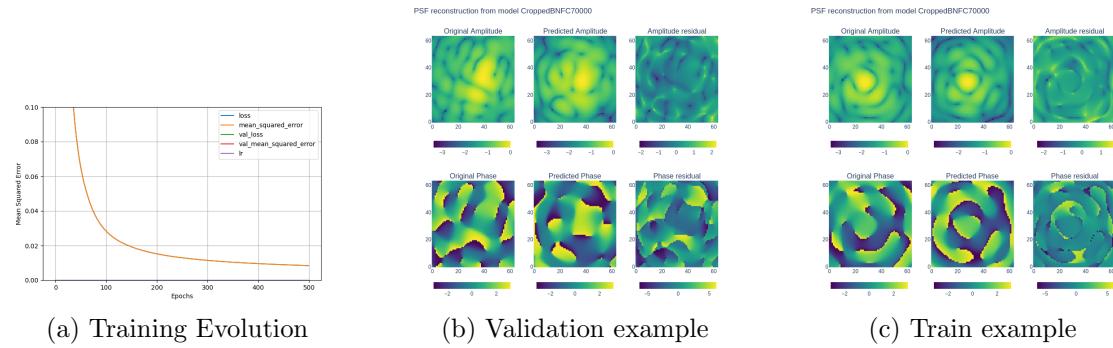


Figure 11: Results of training the model PSFReconstructorSuperBigFC70000-1

1.2.2 Zernike modes related models

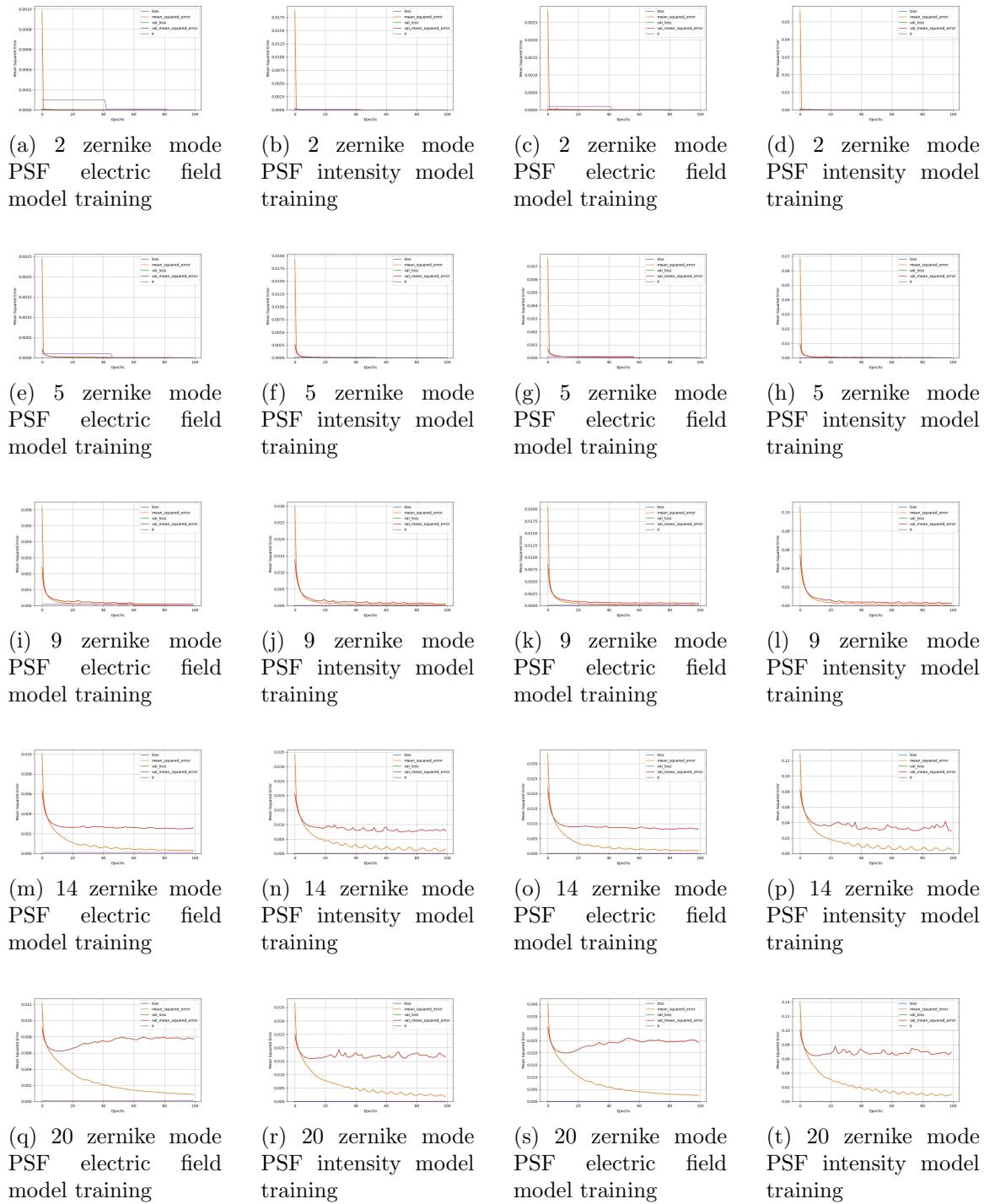
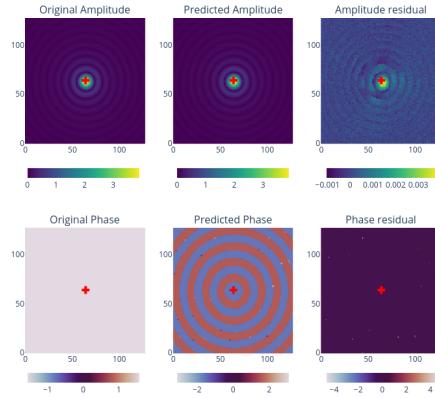


Figure 12: Training evolution comparison for the different Zernike datasets

2 modes PSF datasets :

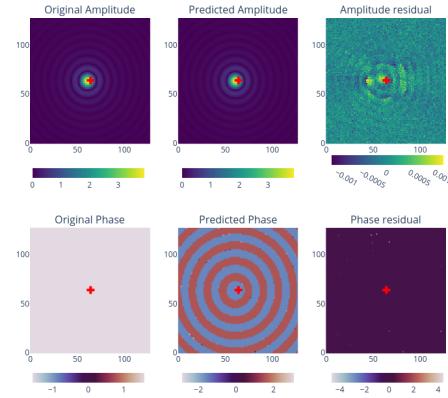
```
-Train MSE: 0.0000000895368188480461  
-Validation MSE: 0.034455109387636185
```

PSF reconstruction from model SuperBigZernike2MFC70000



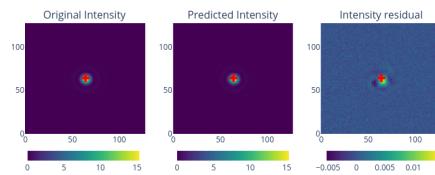
(a) Train example from electric field model

PSF reconstruction from model SuperBigZernike2MFC70000



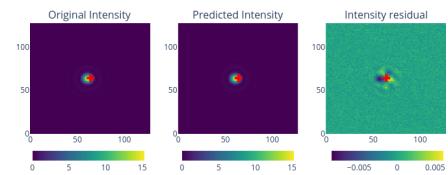
(b) Validation example from electric field model

PSF reconstruction from model SuperBigZernike2MFCIntensity70000



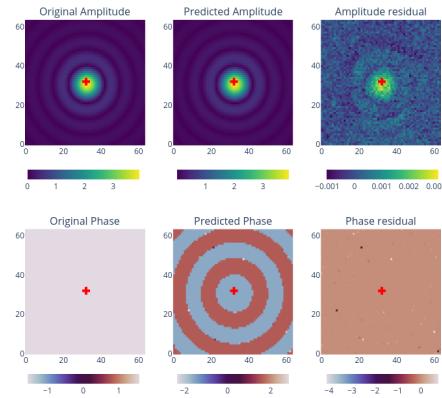
(c) Train example from intensity model

PSF reconstruction from model SuperBigZernike2MFCIntensity70000



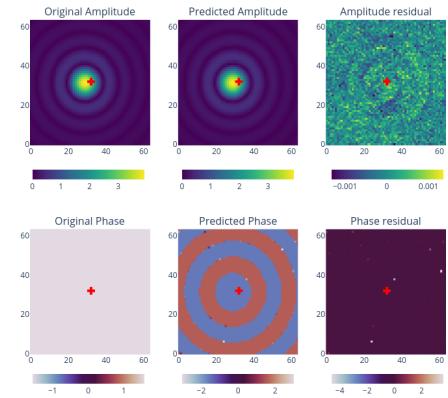
(d) Validation example from intensity model

PSF reconstruction from model SuperBigCroppedZernike2MFC70000



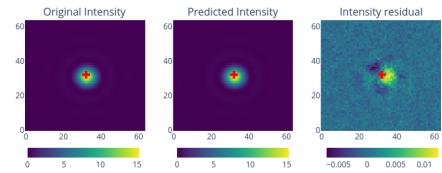
(e) Train example from cropped electric field model

PSF reconstruction from model SuperBigCroppedZernike2MFC70000



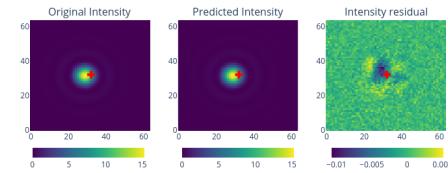
(f) Validation example cropped from electric field model

PSF reconstruction from model SuperBigCroppedZernike2MFCIntensity70000



(g) Train example from cropped intensity model

PSF reconstruction from model SuperBigCroppedZernike2MFCIntensity70000



(h) Validation example from cropped model

Figure 13: Model outputs for 2 mode PSF datasets

5 modes PSFs :

```
-Train MSE: 0.0000018320155277251615  
-Validation MSE: 0.0000026587338197714416
```

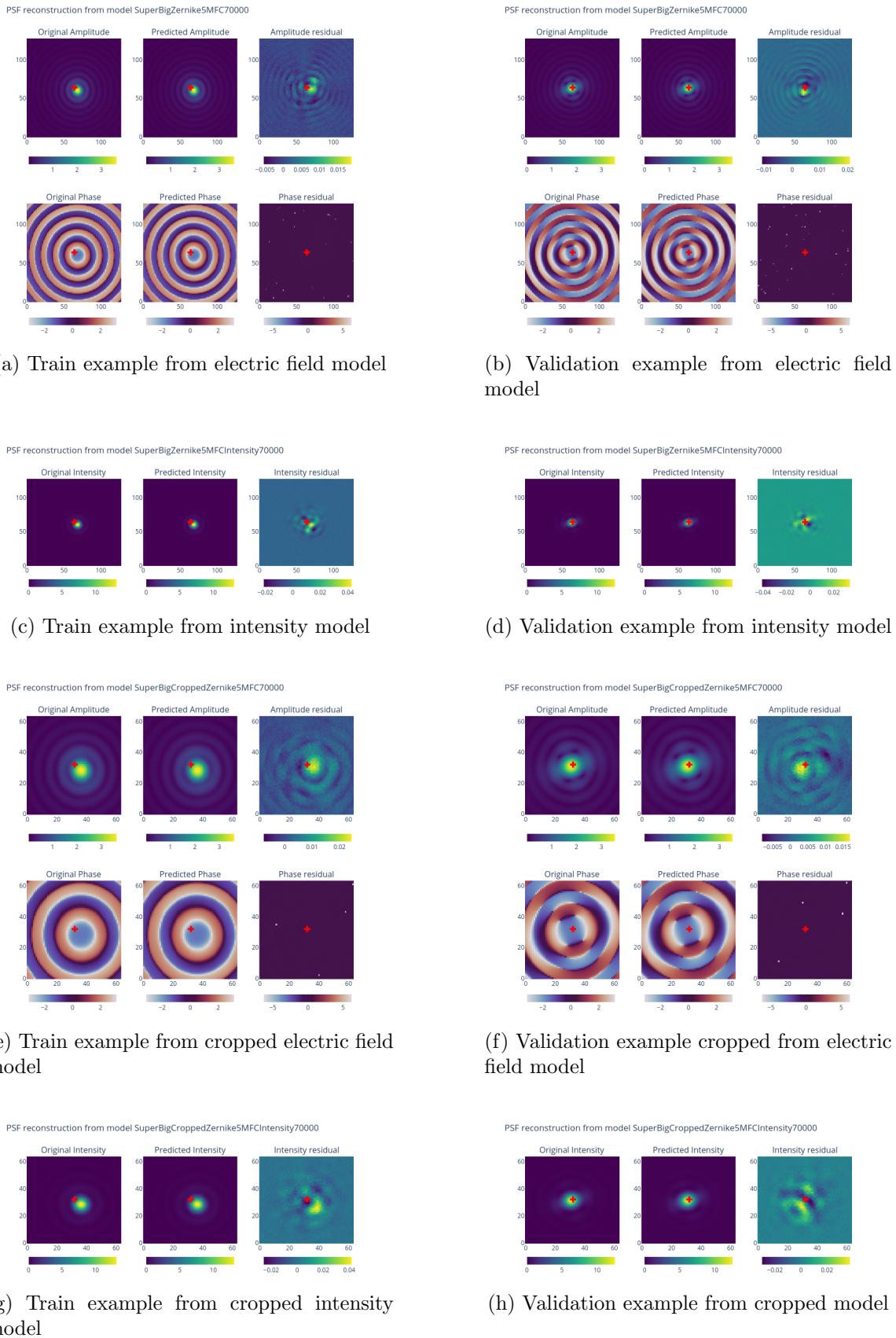


Figure 14: Model outputs for 5 mode PSF datasets

9 modes PSF datasets :

```
-Train MSE: 0.000016877984307939187  
-Validation MSE: 0.00010731885413406417
```

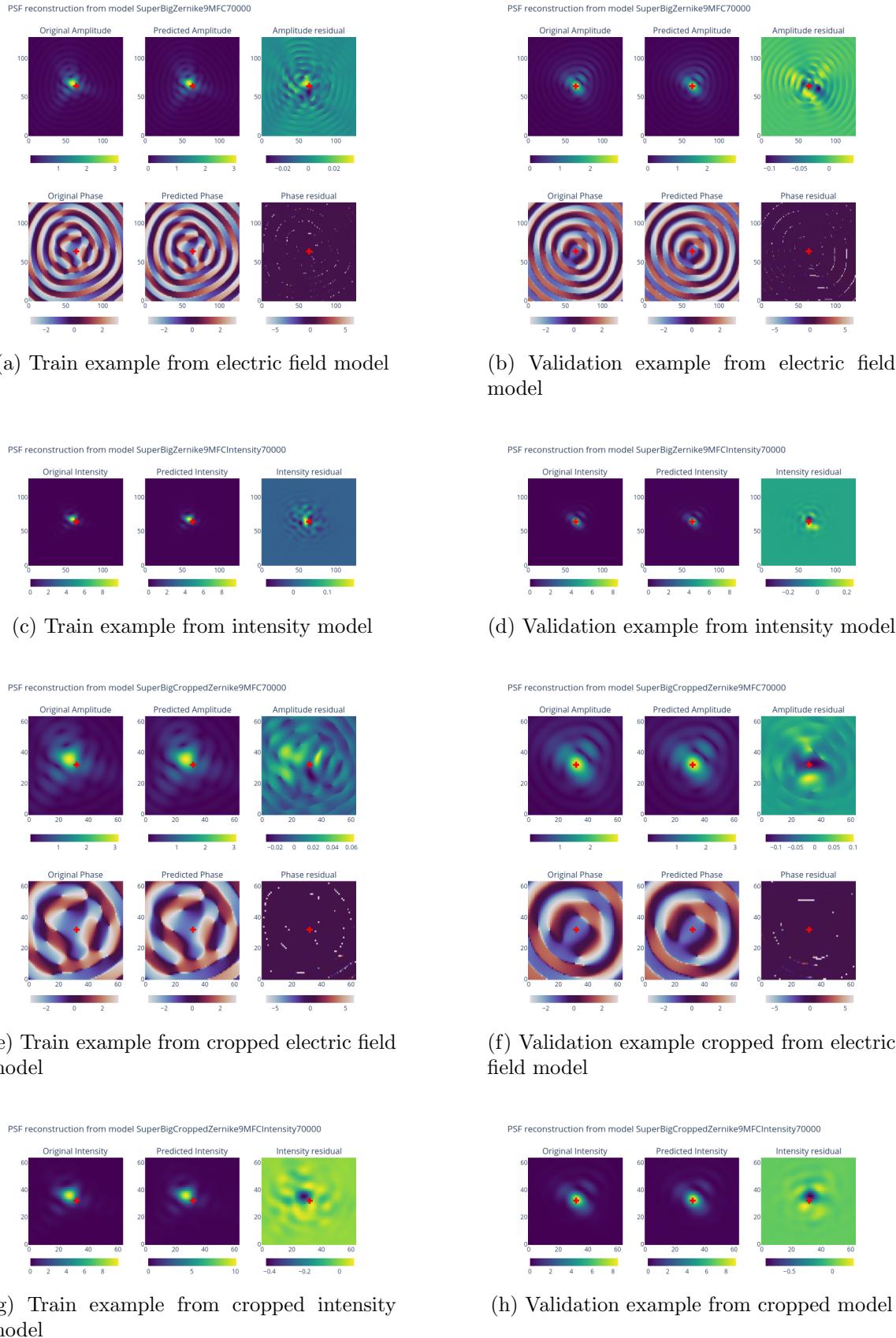


Figure 15: Model outputs for 9 mode PSF datasets

Original sized 14 modes PSFs :

```
-Train MSE: 0.00008819704817142338  
-Validation MSE: 0.002211778424680233
```

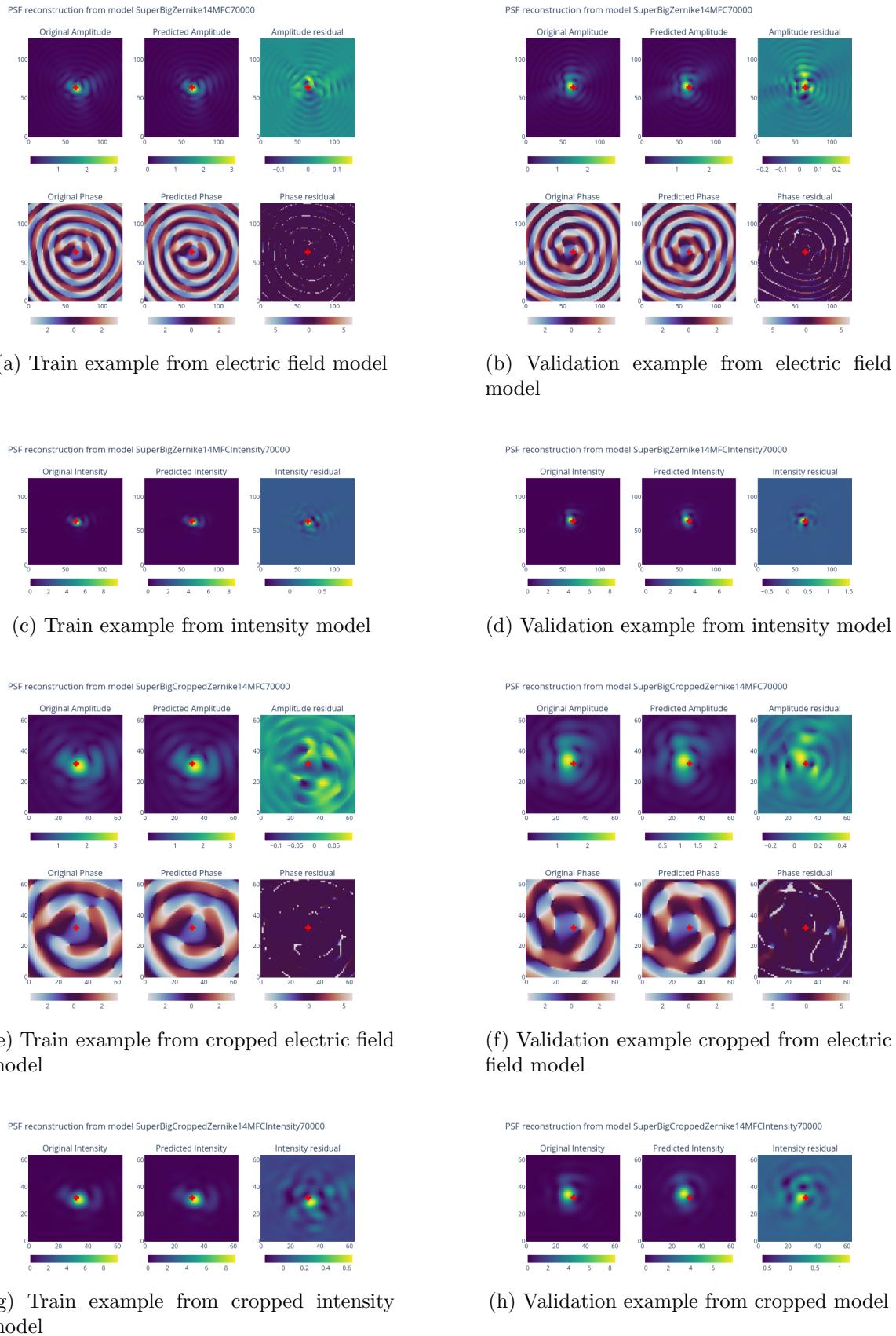
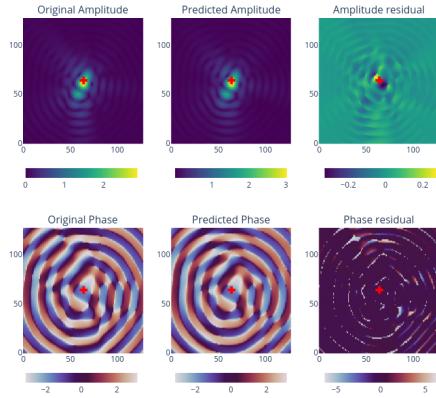


Figure 16: Model outputs for 14 mode PSF datasets

20 modes PSF datasets :

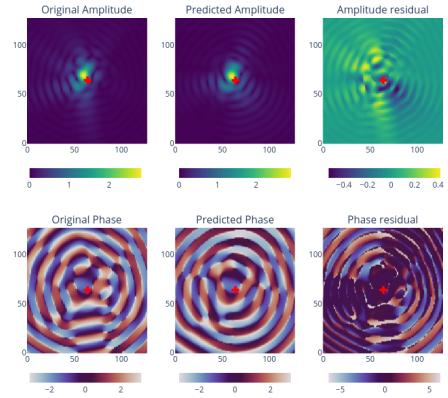
```
-Train MSE: 0.0002106916217599064  
-Validation MSE: 0.007495625875890255
```

PSF reconstruction from model SuperBigZernike20MFC70000



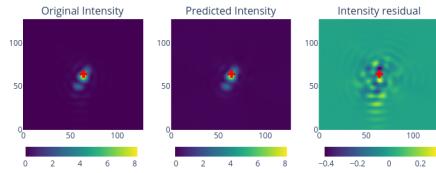
(a) Train example from electric field model

PSF reconstruction from model SuperBigZernike20MFC70000



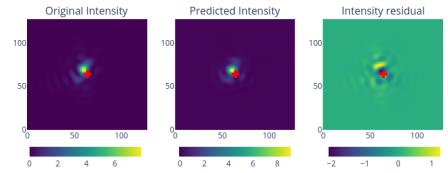
(b) Validation example from electric field model

PSF reconstruction from model SuperBigZernike20MFCIntensity70000



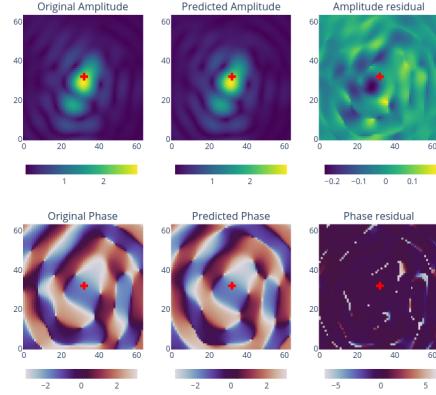
(c) Train example from intensity model

PSF reconstruction from model SuperBigZernike20MFCIntensity70000



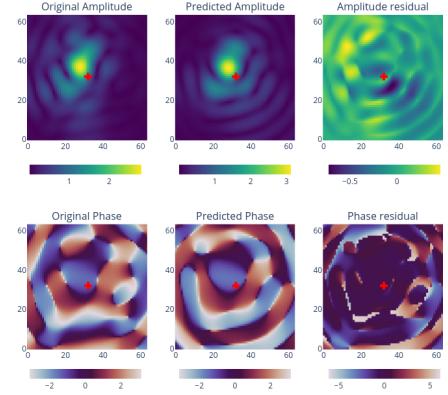
(d) Validation example from intensity model

PSF reconstruction from model SuperBigCroppedZernike20MFC70000



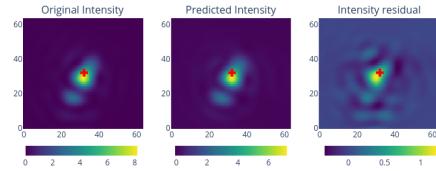
(e) Train example from cropped electric field model

PSF reconstruction from model SuperBigCroppedZernike20MFC70000



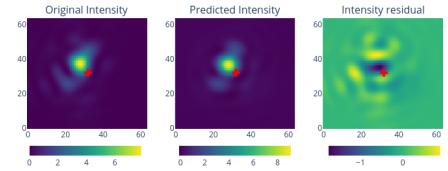
(f) Validation example cropped from electric field model

PSF reconstruction from model SuperBigCroppedZernike20MFCIntensity70000



(g) Train example from cropped intensity model

PSF reconstruction from model SuperBigCroppedZernike20MFCIntensity70000



(h) Validation example from cropped model

Figure 17: Model outputs for 20 mode PSF datasets

A summary of the MSE evolution over the Zernike PSFs datasets is shown below. The fact that the validation MSE for 2 modes is the worse may be because the neural network is not able to understand traslations.



Figure 18: MSE evolution over the Zernike PSFs datasets

1.3 Euclidean distances analysis for atmospheric aberration PSFs

1.3.1 Preprocessing

- The PSF electric fields are converted to a matrix of intensities of 128x128 size and the flattened to calculate the euclidean distances between them.
- 70000 datapoint pairs are defined for which the euclidean distances will be calculated.

1.3.2 Results

After performing an ANOVA test on the euclidean distances from the selected pairs of the 4 datasets obtaining a p-value of 0 and F-statistic of 4789.1531.

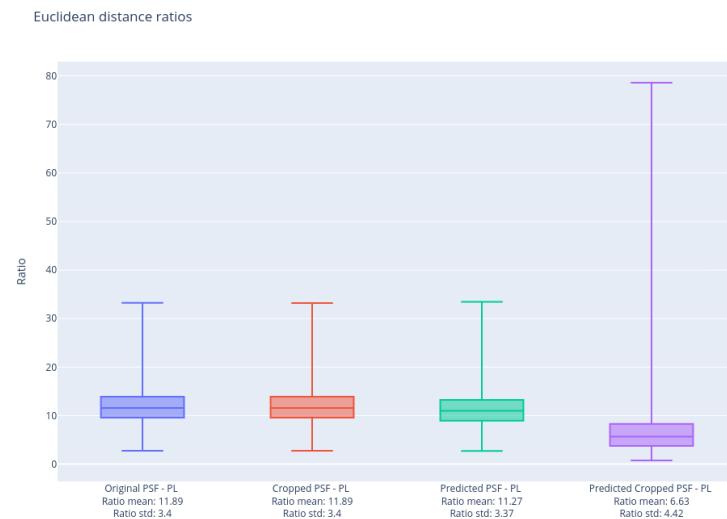
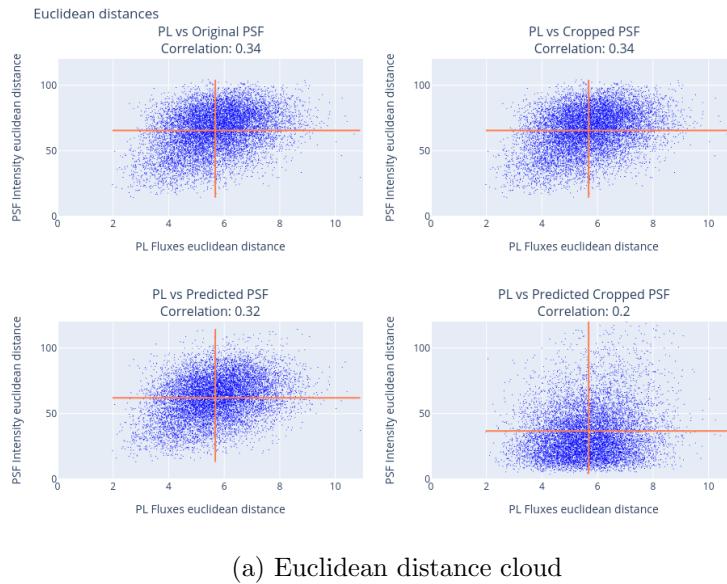


Figure 19: Euclidean distances ratios between PL and PSF pairs

1.3.3 Analysis

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

0.2 correlation rate. This makes sense as the model that predicted those PSFs is more overfitted than the model that predicts the original sized PSFs. The clouds are dispersed almost equally from the center of mass which may indicate that a 19 mode PL may not be enough to encode all PSF information.