Lab Notebook

Photonic Lantern Information Determination

Contents

Part I

Normalized Mutual Information Analysis

1 The data

1.1 Zernike coefficients dataset

5 datasets of zernike coefficients are created, each of the dataset contain 5000 datapoints

- **2 mode dataset**: 2 Zernike modes coefficients, their RMSE in the range [-2, 2]
- **5 mode dataset**: 5 Zernike modes coefficients, their RMSE in the range:
  - Modes 2 and 3: [-2, 2]
  - Modes 4, 5 and 6: [-1.5, 1.5]
- **9 mode dataset**: 9 Zernike mode coefficients, their RMSE in the range:
  - Modes 2 and 3: [-2, 2]
  - Modes 4, 5 and 6: [-1.5, 1.5]
  - Modes 7, 8, 9 and 10: [-1, 1]
- **14 mode dataset**: 2 Zernike mode coefficients, their RMSE in the range:
  - Modes 2 and 3: [-2, 2]
  - Modes 4, 5 and 6: [-1.5, 1.5]
  - Modes 7, 8, 9 and 10: [-1, 1]

  - Modes 11, 12, 13, 14 and 15: [-0.5, 0.5]

- **2 0mode dataset**: 2 Zernike mode coefficients, their RMSE in the range:
  - Modes 2 and 3: [-2, 2]
  - Modes 4, 5 and 6: [-1.5, 1.5]
  - Modes 7, 8, 9 and 10: [-1, 1]
  - Modes 11, 12, 13, 14 and 15: [-0.5, 0.5]
  - Modes 16, 17, 18, 19, 20 and 21: [-0.2, 0.2]

1.2 PSFs intensities dataset

5 datasets of 5000 PSF intensities are created from the 5 zernike coefficients dataset, each datapoint being a 128x128 matrix

1.3 LP mode coefficients dataset

5 datasets of 5000 LP coefficients are created from the 5 zernike coefficients dataset, each datapoint being a 19x2 matrix dividing the real and imaginary part of the LP coefficients

1.4 Output fluxes dataset

The output fluxes are obtained using the 19 mode PL transfer matrix. 5 datasets of 5000 Output fluxes are created from the 5 zernike coefficients dataset, each datapoint being a 19x1 vector

2 Preprocessing

2.1 PSF Intensities

The 5000x128x128 PSF intensities datasets are dimensionally reduced using UMAP giving an array of 5000x19 projections of the PSF Intensities for each dataset.

Number of neighbors	Min distance	Number of components
15	0.3	19

Table 1: UMAP hyperparameter configurations for PSF Intensities dimensionality reduction

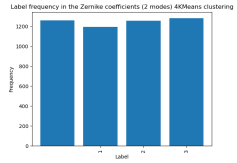
2.2 Clustering

K-Means is used to find clusters in all the datasets. KMeans is set to produce the following number of clusters:

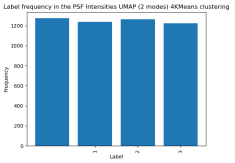
- 4
- 8
- 16
- 32
- 64
- 100
- 250
- 500
- 1000

The results are the following:

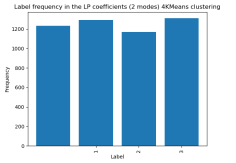
2.2.1 2 Zernike modes datasets clusters densities



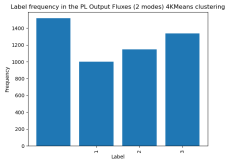
(a) 4KMeans for Zernike coefficients



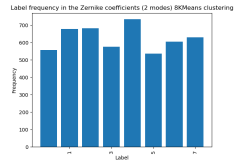
(b) 4KMeans PSF Intensities UMAP



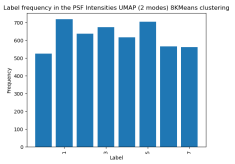
(c) 4KMeans LP coefficients



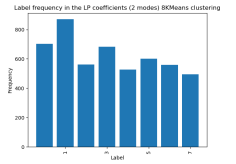
(d) 4KMeans Output Fluxes



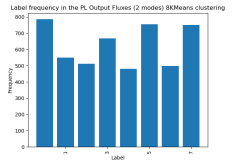
(a) 8KMeans for Zernike coefficients



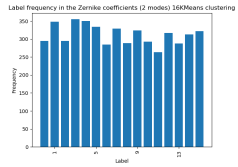
(b) 8KMeans PSF Intensities UMAP



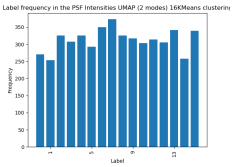
(c) 8KMeans LP coefficients



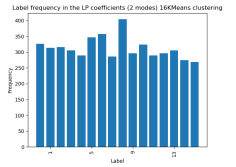
(d) 8KMeans Output Fluxes



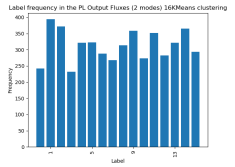
(a) 16KMeans for Zernike coefficients



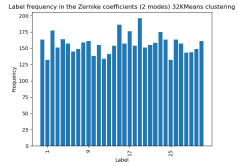
(b) 16KMeans PSF Intensities UMAP



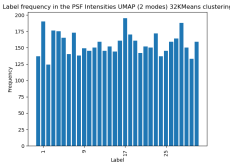
(c) 16KMeans LP coefficients



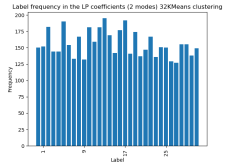
(d) 16KMeans Output Fluxes



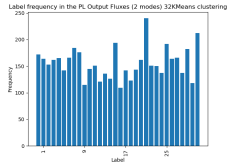
(a) 32KMeans for Zernike coefficients



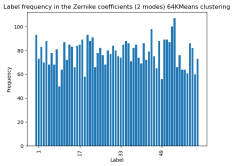
(b) 32KMeans PSF Intensities UMAP



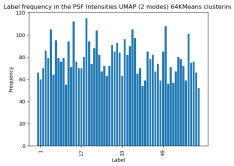
(c) 32KMeans LP coefficients



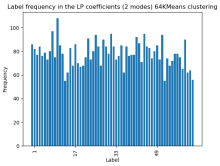
(d) 32KMeans Output Fluxes



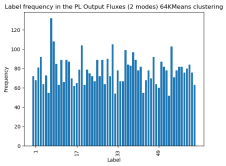
(a) 64KMeans for Zernike coefficients



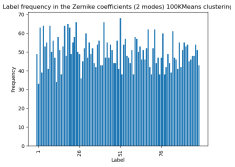
(b) 64KMeans PSF Intensities UMAP



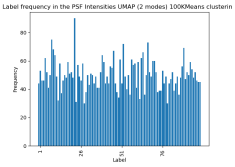
(c) 64KMeans LP coefficients



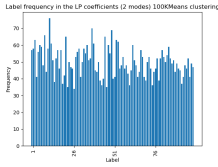
(d) 64KMeans Output Fluxes



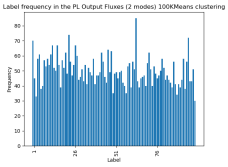
(a) 100KMeans for Zernike coefficients



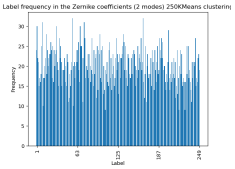
(b) 100KMeans PSF Intensities UMAP



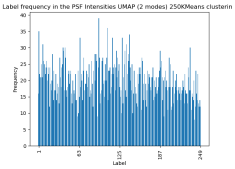
(c) 100KMeans LP coefficients



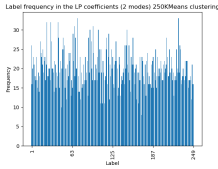
(d) 100KMeans Output Fluxes



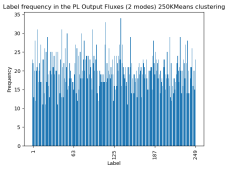
(a) 250KMeans for Zernike coefficients



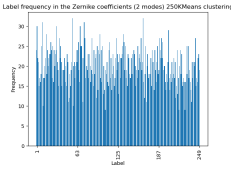
(b) 250KMeans PSF Intensities UMAP



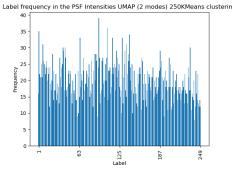
(c) 250KMeans LP coefficients



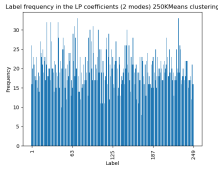
(d) 250KMeans Output Fluxes



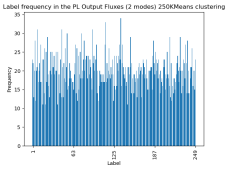
(a) 250KMeans for Zernike coefficients



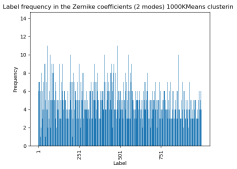
(b) 250KMeans PSF Intensities UMAP



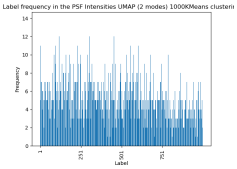
(c) 250KMeans LP coefficients



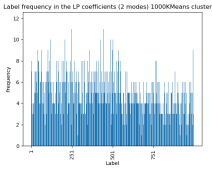
(d) 250KMeans Output Fluxes



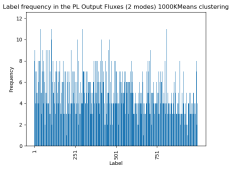
(a) 1000KMeans for Zernike coefficients



(b) 250KMeans PSF Intensities UMAP

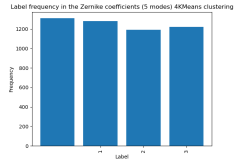


(c) 250KMeans LP coefficients

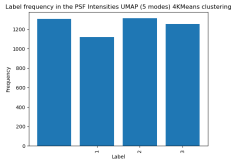


(d) 250KMeans Output Fluxes

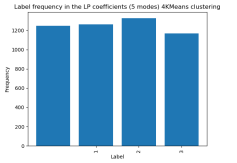
2.2.2 5 Zernike modes datasets clusters densities



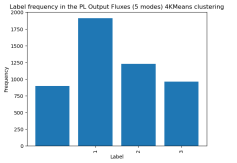
(a) 4KMeans for Zernike coefficients



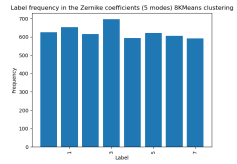
(b) 4KMeans PSF Intensities UMAP



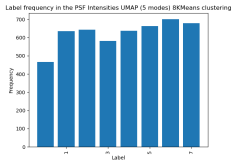
(c) 4KMeans LP coefficients



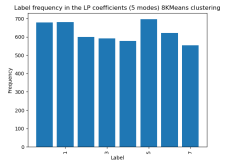
(d) 4KMeans Output Fluxes



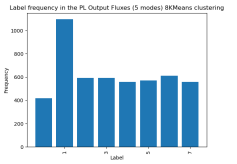
(a) 8KMeans for Zernike coefficients



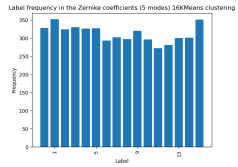
(b) 8KMeans PSF Intensities UMAP



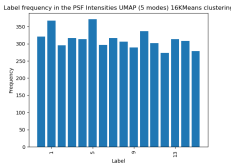
(c) 8KMeans LP coefficients



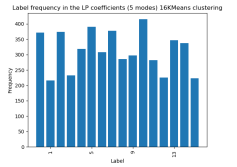
(d) 8KMeans Output Fluxes



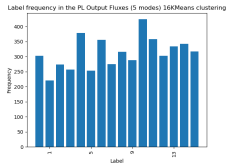
(a) 16KMeans for Zernike coefficients



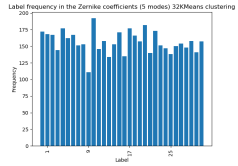
(b) 16KMeans PSF Intensities UMAP



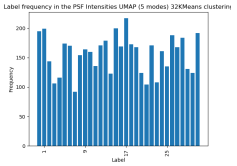
(c) 16KMeans LP coefficients



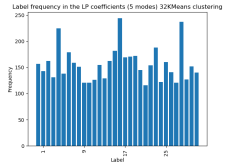
(d) 16KMeans Output Fluxes



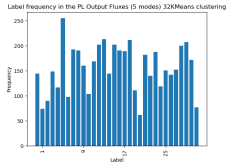
(a) 32KMeans for Zernike coefficients



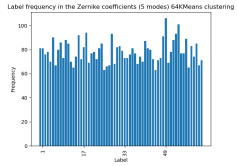
(b) 32KMeans PSF Intensities UMAP



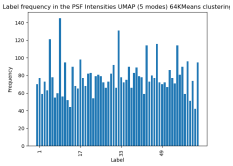
(c) 32KMeans LP coefficients



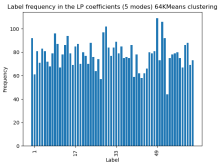
(d) 32KMeans Output Fluxes



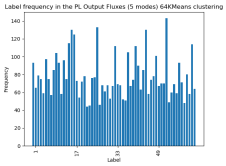
(a) 64KMeans for Zernike coefficients



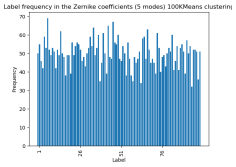
(b) 64KMeans PSF Intensities UMAP



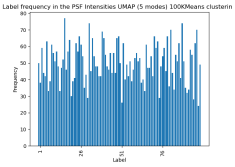
(c) 64KMeans LP coefficients



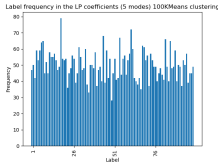
(d) 64KMeans Output Fluxes



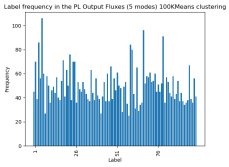
(a) 100KMeans for Zernike coefficients



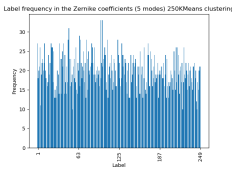
(b) 100KMeans PSF Intensities UMAP



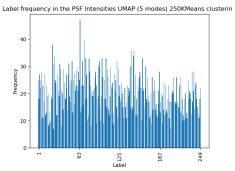
(c) 100KMeans LP coefficients



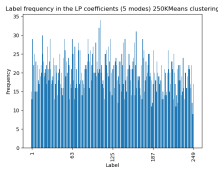
(d) 100KMeans Output Fluxes



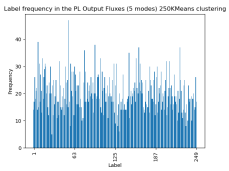
(a) 250KMeans for Zernike coefficients



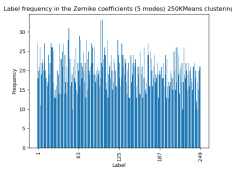
(b) 250KMeans PSF Intensities UMAP



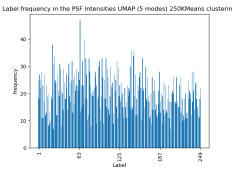
(c) 250KMeans LP coefficients



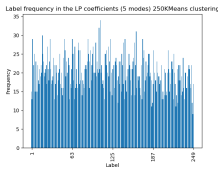
(d) 250KMeans Output Fluxes



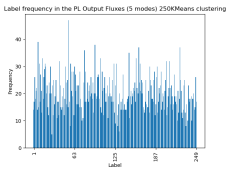
(a) 250KMeans for Zernike coefficients



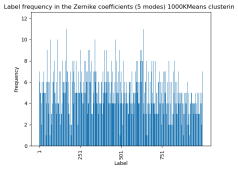
(b) 250KMeans PSF Intensities UMAP



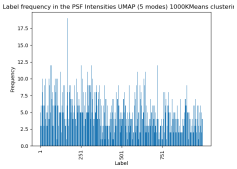
(c) 250KMeans LP coefficients



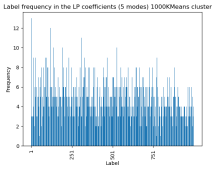
(d) 250KMeans Output Fluxes



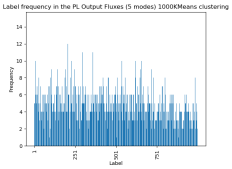
(a) 1000KMeans for Zernike coefficients



(b) 250KMeans PSF Intensities UMAP

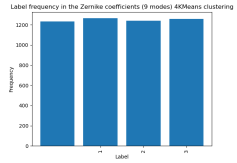


(c) 250KMeans LP coefficients

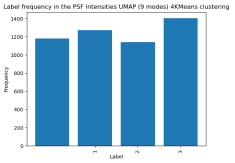


(d) 250KMeans Output Fluxes

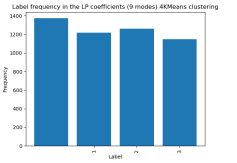
2.2.3 9 Zernike modes datasets clusters densities



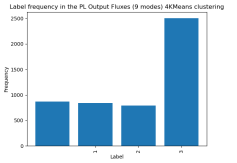
(a) 4KMeans for Zernike coefficients



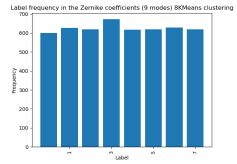
(b) 4KMeans PSF Intensities UMAP



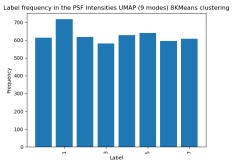
(c) 4KMeans LP coefficients



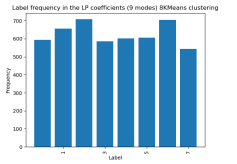
(d) 4KMeans Output Fluxes



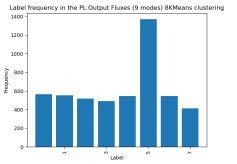
(a) 8KMeans for Zernike coefficients



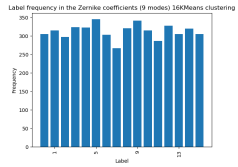
(b) 8KMeans PSF Intensities UMAP



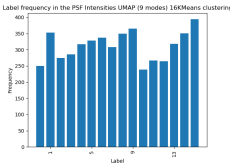
(c) 8KMeans LP coefficients



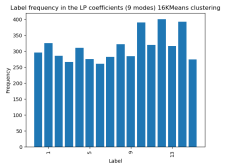
(d) 8KMeans Output Fluxes



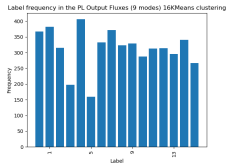
(a) 16KMeans for Zernike coefficients



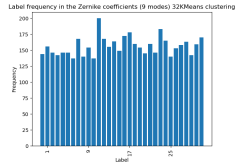
(b) 16KMeans PSF Intensities UMAP



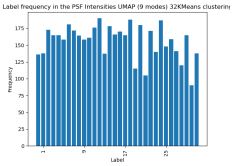
(c) 16KMeans LP coefficients



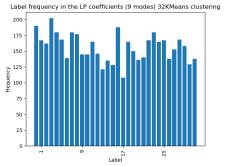
(d) 16KMeans Output Fluxes



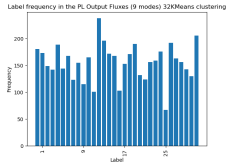
(a) 32KMeans for Zernike coefficients



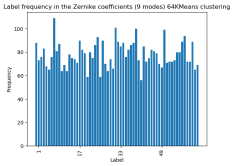
(b) 32KMeans PSF Intensities UMAP



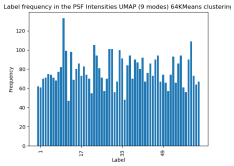
(c) 32KMeans LP coefficients



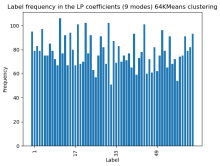
(d) 32KMeans Output Fluxes



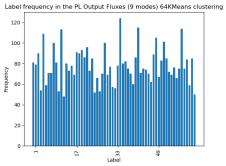
(a) 64KMeans for Zernike coefficients



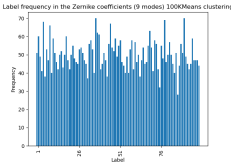
(b) 64KMeans PSF Intensities UMAP



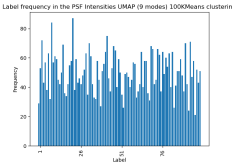
(c) 64KMeans LP coefficients



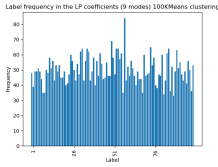
(d) 64KMeans Output Fluxes



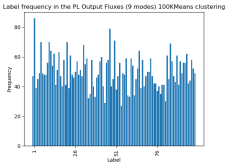
(a) 100KMeans for Zernike coefficients



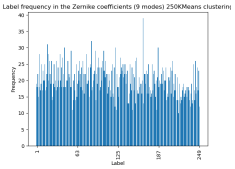
(b) 100KMeans PSF Intensities UMAP



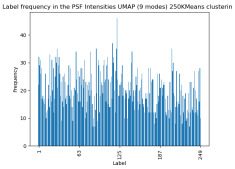
(c) 100KMeans LP coefficients



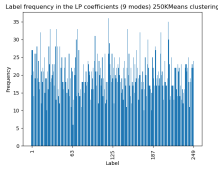
(d) 100KMeans Output Fluxes



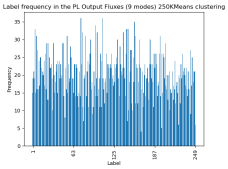
(a) 250KMeans for Zernike coefficients



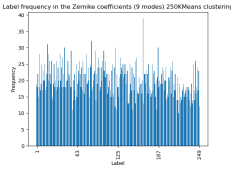
(b) 250KMeans PSF Intensities UMAP



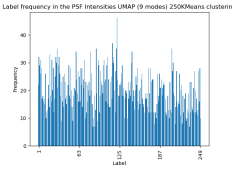
(c) 250KMeans LP coefficients



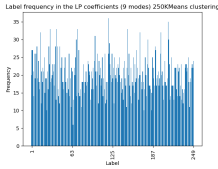
(d) 250KMeans Output Fluxes



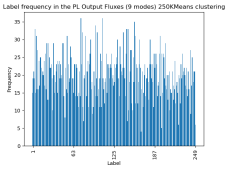
(a) 250KMeans for Zernike coefficients



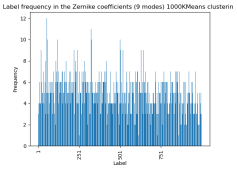
(b) 250KMeans PSF Intensities UMAP



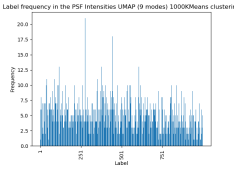
(c) 250KMeans LP coefficients



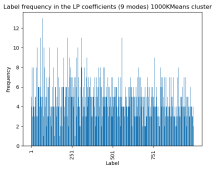
(d) 250KMeans Output Fluxes



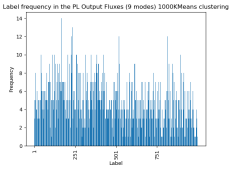
(a) 1000KMeans for Zernike coefficients



(b) 250KMeans PSF Intensities UMAP

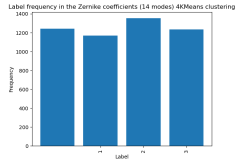


(c) 250KMeans LP coefficients

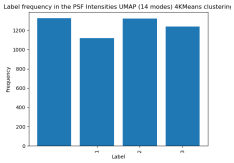


(d) 250KMeans Output Fluxes

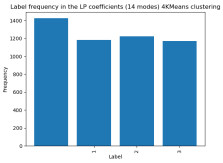
2.2.4 14 Zernike modes datasets clusters densities



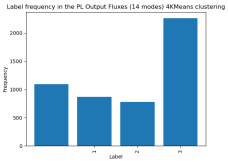
(a) 4KMeans for Zernike coefficients



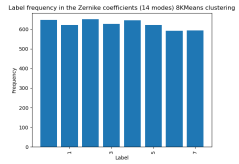
(b) 4KMeans PSF Intensities UMAP



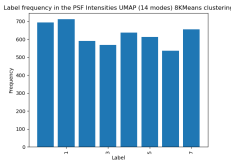
(c) 4KMeans LP coefficients



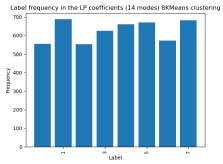
(d) 4KMeans Output Fluxes



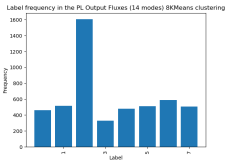
(a) 8KMeans for Zernike coefficients



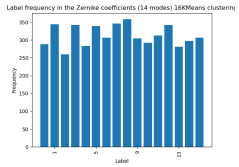
(b) 8KMeans PSF Intensities UMAP



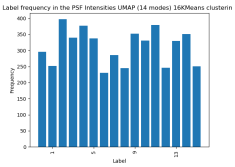
(c) 8KMeans LP coefficients



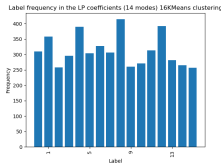
(d) 8KMeans Output Fluxes



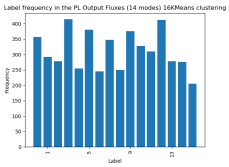
(a) 16KMeans for Zernike coefficients



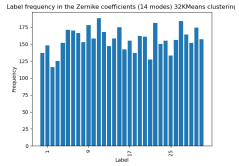
(b) 16KMeans PSF Intensities UMAP



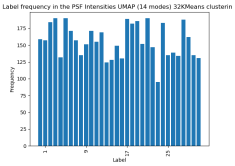
(c) 16KMeans LP coefficients



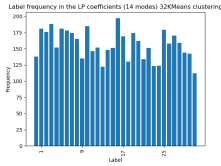
(d) 16KMeans Output Fluxes



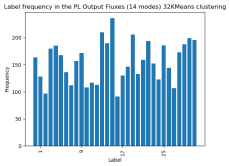
(a) 32KMeans for Zernike coefficients



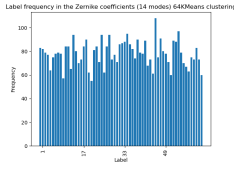
(b) 32KMeans PSF Intensities UMAP



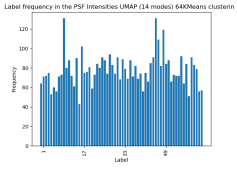
(c) 32KMeans LP coefficients



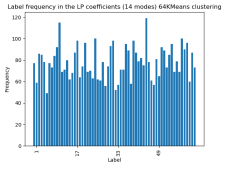
(d) 32KMeans Output Fluxes



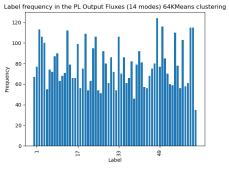
(a) 64KMeans for Zernike coefficients



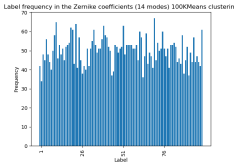
(b) 64KMeans PSF Intensities UMAP



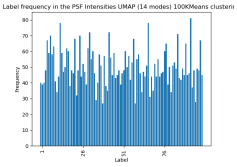
(c) 64KMeans LP coefficients



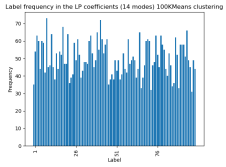
(d) 64KMeans Output Fluxes



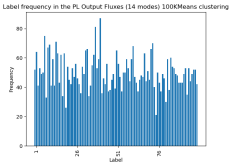
(a) 100KMeans for Zernike coefficients



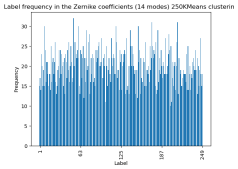
(b) 100KMeans PSF Intensities UMAP



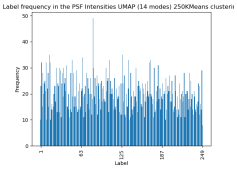
(c) 100KMeans LP coefficients



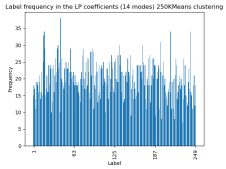
(d) 100KMeans Output Fluxes



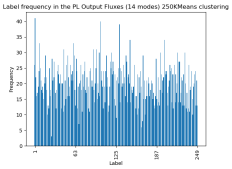
(a) 250KMeans for Zernike coefficients



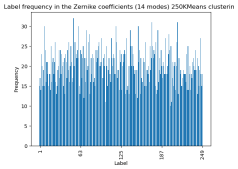
(b) 250KMeans PSF Intensities UMAP



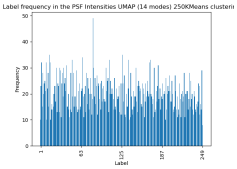
(c) 250KMeans LP coefficients



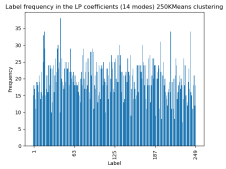
(d) 250KMeans Output Fluxes



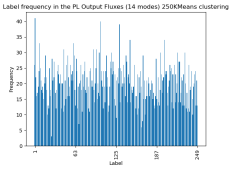
(a) 250KMeans for Zernike coefficients



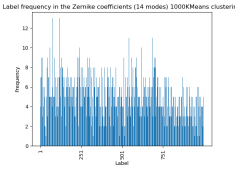
(b) 250KMeans PSF Intensities UMAP



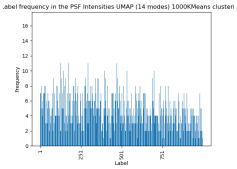
(c) 250KMeans LP coefficients



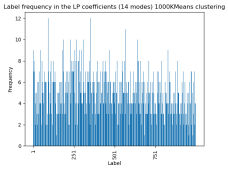
(d) 250KMeans Output Fluxes



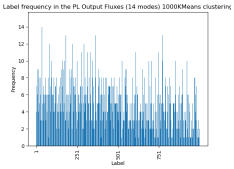
(a) 1000KMeans for Zernike coefficients



(b) 250KMeans PSF Intensities UMAP

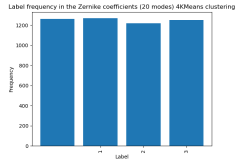


(c) 250KMeans LP coefficients

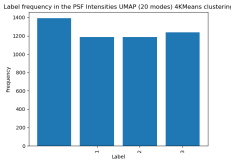


(d) 250KMeans Output Fluxes

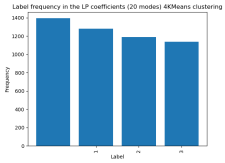
2.2.5 20 Zernike modes datasets clusters densities



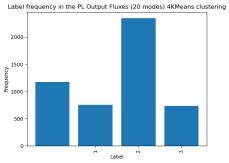
(a) 4KMeans for Zernike coefficients



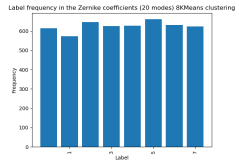
(b) 4KMeans PSF Intensities UMAP



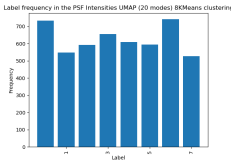
(c) 4KMeans LP coefficients



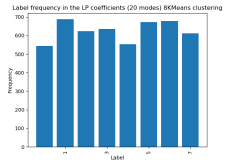
(d) 4KMeans Output Fluxes



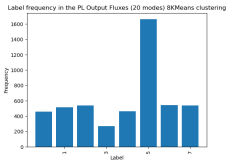
(a) 8KMeans for Zernike coefficients



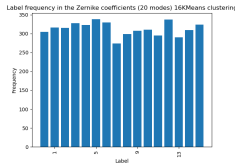
(b) 8KMeans PSF Intensities UMAP



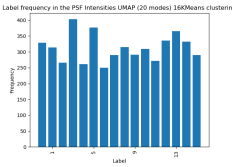
(c) 8KMeans LP coefficients



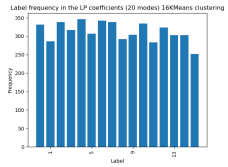
(d) 8KMeans Output Fluxes



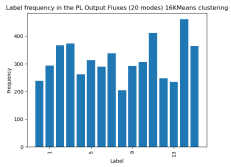
(a) 16KMeans for Zernike coefficients



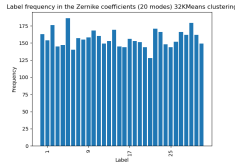
(b) 16KMeans PSF Intensities UMAP



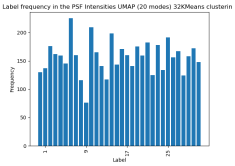
(c) 16KMeans LP coefficients



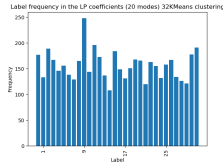
(d) 16KMeans Output Fluxes



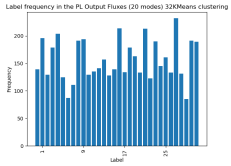
(a) 32KMeans for Zernike coefficients



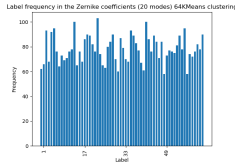
(b) 32KMeans PSF Intensities UMAP



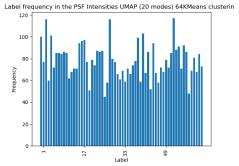
(c) 32KMeans LP coefficients



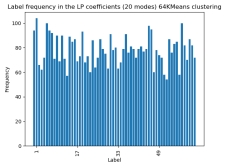
(d) 32KMeans Output Fluxes



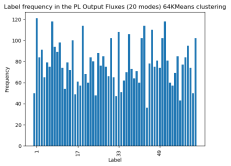
(a) 64KMeans for Zernike coefficients



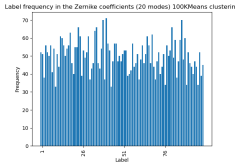
(b) 64KMeans PSF Intensities UMAP



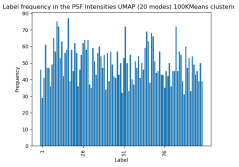
(c) 64KMeans LP coefficients



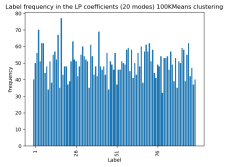
(d) 64KMeans Output Fluxes



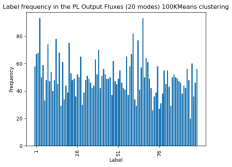
(a) 100KMeans for Zernike coefficients



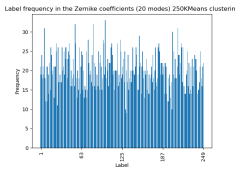
(b) 100KMeans PSF Intensities UMAP



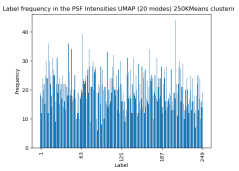
(c) 100KMeans LP coefficients



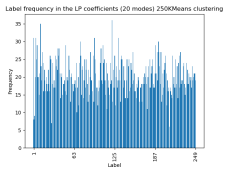
(d) 100KMeans Output Fluxes



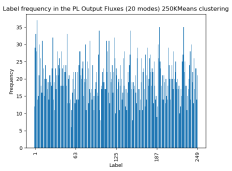
(a) 250KMeans for Zernike coefficients



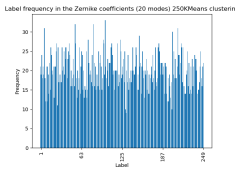
(b) 250KMeans PSF Intensities UMAP



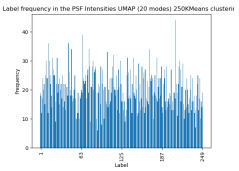
(c) 250KMeans LP coefficients



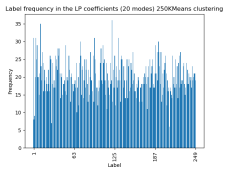
(d) 250KMeans Output Fluxes



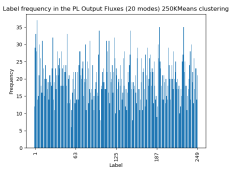
(a) 250KMeans for Zernike coefficients



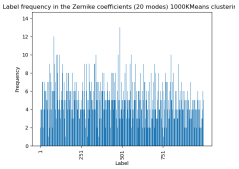
(b) 250KMeans PSF Intensities UMAP



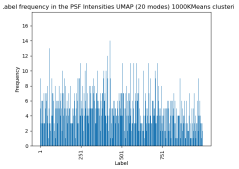
(c) 250KMeans LP coefficients



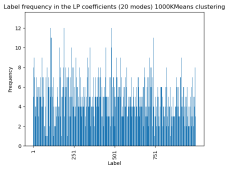
(d) 250KMeans Output Fluxes



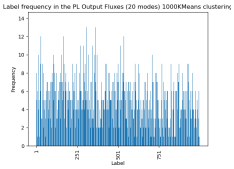
(a) 1000KMeans for Zernike coefficients



(b) 250KMeans PSF Intensities UMAP



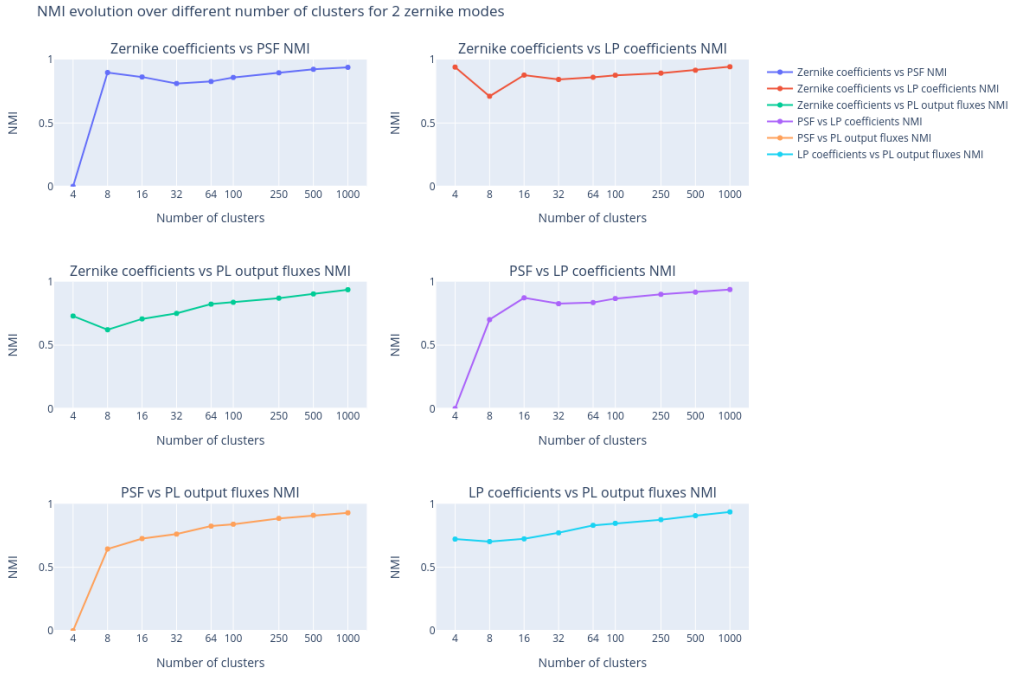
(c) 250KMeans LP coefficients



(d) 250KMeans Output Fluxes

2.3 Normalized Mutual Information evolution

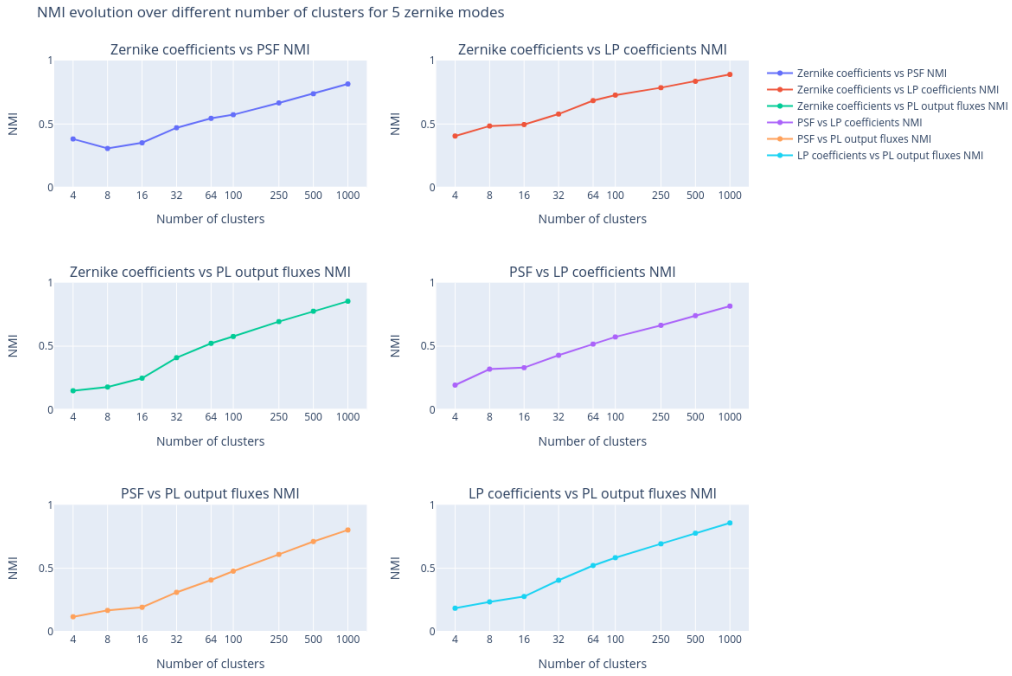
2.3.1 NMI evolution over number of clusters for 2 zernike mode related datasets



Clusters	Z vs PSF	Z vs LP	Z vs PL	PSF vs LP	PSF vs PL	LP vs PL
4	0.001	0.940	0.730	0.001	0.001	0.722
8	0.898	0.711	0.621	0.701	0.644	0.703
16	0.863	0.877	0.707	0.873	0.726	0.724
32	0.811	0.843	0.750	0.827	0.761	0.772
64	0.827	0.860	0.823	0.836	0.824	0.830
100	0.859	0.876	0.838	0.867	0.839	0.847
250	0.895	0.893	0.870	0.900	0.885	0.875
500	0.923	0.916	0.903	0.918	0.910	0.907
1000	0.939	0.943	0.937	0.938	0.929	0.936

Table 2: NMI Analysis for Different Numbers of Clusters

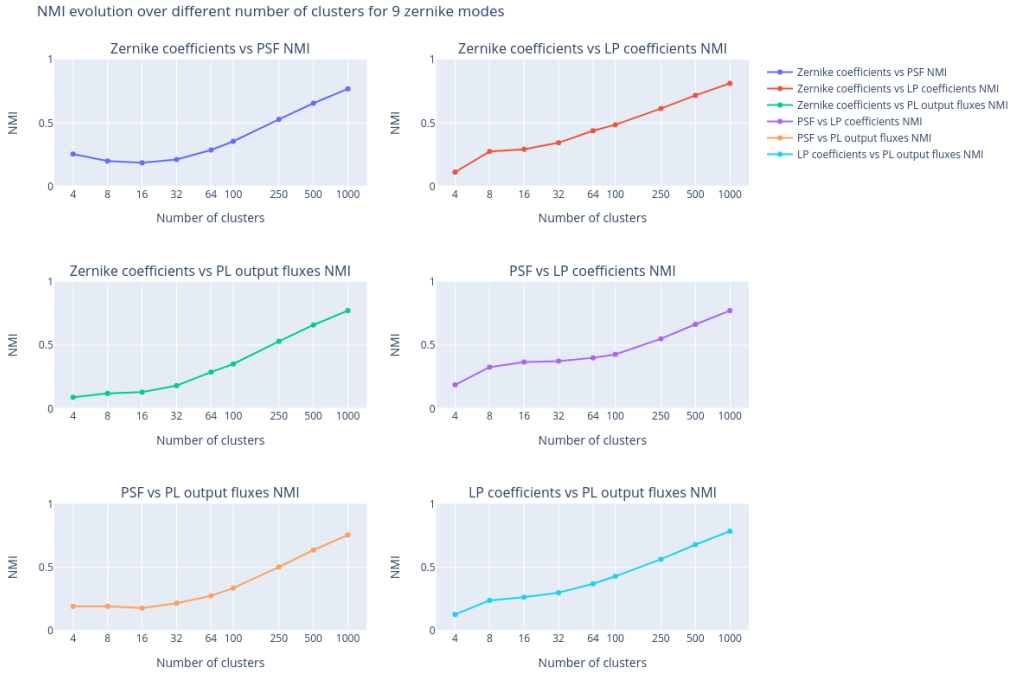
2.3.2 NMI evolution over number of clusters for 5 zernike mode related datasets



Clusters	Z vs PSF	Z vs LP	Z vs PL	PSF vs LP	PSF vs PL	LP vs PL
4	0.382	0.406	0.149	0.193	0.118	0.186
8	0.307	0.484	0.178	0.319	0.168	0.236
16	0.352	0.496	0.248	0.330	0.193	0.278
32	0.470	0.579	0.409	0.428	0.311	0.406
64	0.545	0.684	0.522	0.516	0.407	0.522
100	0.573	0.728	0.576	0.572	0.477	0.583
250	0.666	0.786	0.693	0.664	0.609	0.693
500	0.738	0.836	0.775	0.740	0.711	0.776
1000	0.815	0.890	0.854	0.815	0.802	0.857

Table 3: NMI Analysis for Different Numbers of Clusters

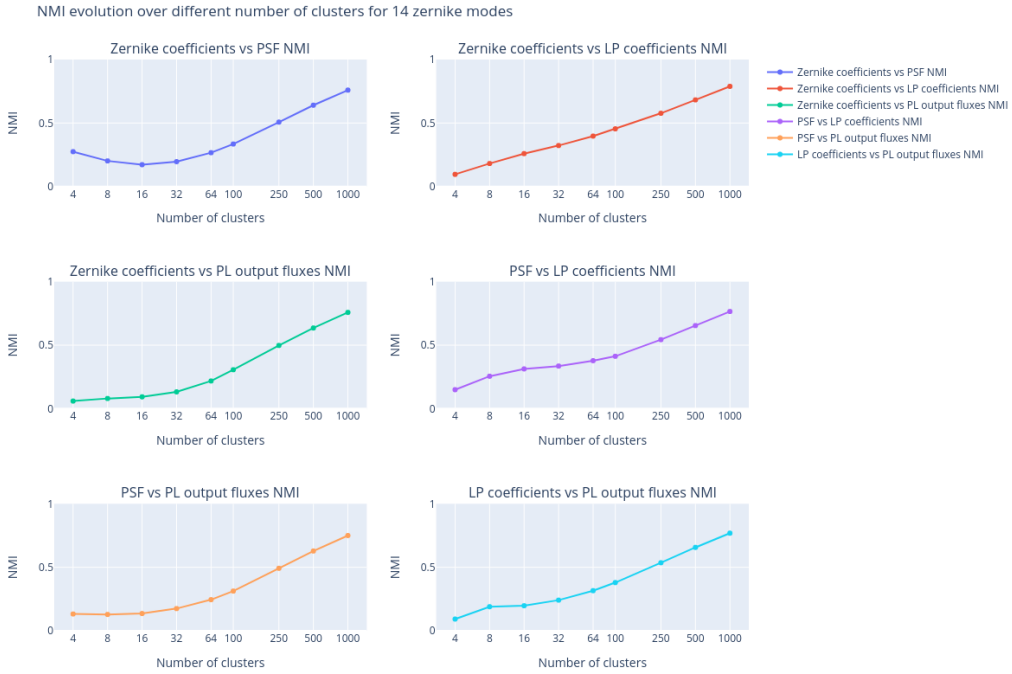
2.3.3 NMI evolution over number of clusters for 9 zernike mode related datasets



Clusters	Z vs PSF	Z vs LP	Z vs PL	PSF vs LP	PSF vs PL	LP vs PL
4	0.256	0.113	0.090	0.188	0.192	0.128
8	0.201	0.276	0.120	0.326	0.193	0.239
16	0.187	0.293	0.130	0.367	0.178	0.265
32	0.212	0.345	0.181	0.374	0.217	0.300
64	0.288	0.439	0.288	0.400	0.275	0.370
100	0.356	0.486	0.352	0.427	0.336	0.429
250	0.529	0.614	0.530	0.550	0.502	0.563
500	0.656	0.718	0.659	0.664	0.636	0.678
1000	0.769	0.813	0.772	0.772	0.755	0.784

Table 4: NMI Analysis for Different Numbers of Clusters

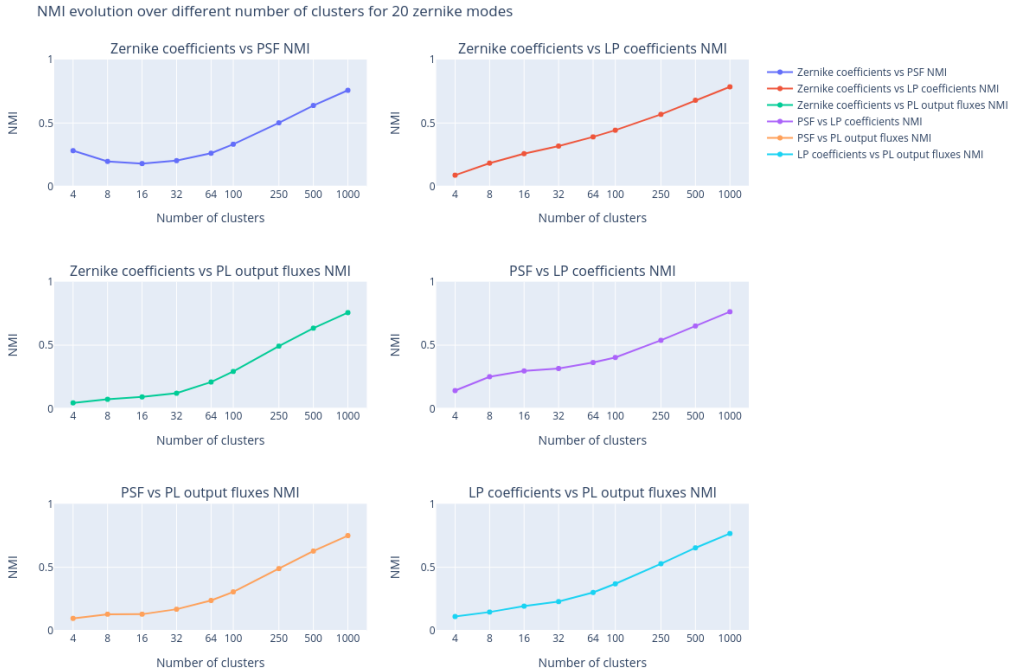
2.3.4 NMI evolution over number of clusters for 14 zernike mode related datasets



Clusters	Z vs PSF	Z vs LP	Z vs PL	PSF vs LP	PSF vs PL	LP vs PL
4	0.274	0.096	0.060	0.149	0.132	0.092
8	0.201	0.181	0.080	0.255	0.128	0.189
16	0.172	0.259	0.093	0.313	0.136	0.197
32	0.196	0.323	0.132	0.335	0.175	0.241
64	0.266	0.397	0.218	0.378	0.245	0.316
100	0.335	0.454	0.306	0.412	0.313	0.380
250	0.507	0.577	0.498	0.543	0.492	0.536
500	0.640	0.682	0.635	0.654	0.628	0.657
1000	0.759	0.789	0.758	0.765	0.750	0.769

Table 5: NMI Analysis for Different Numbers of Clusters

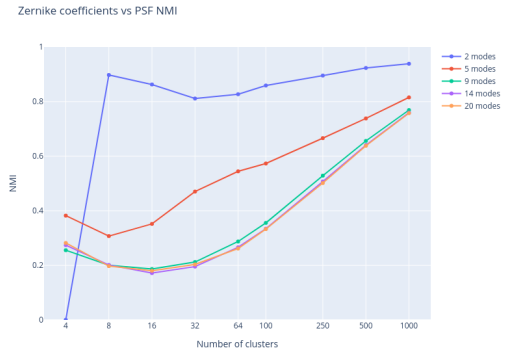
2.3.5 NMI evolution over number of clusters for 20 zernike mode related datasets



Clusters	Z vs PSF	Z vs LP	Z vs PL	PSF vs LP	PSF vs PL	LP vs PL
4	0.282	0.089	0.045	0.142	0.097	0.112
8	0.197	0.184	0.074	0.251	0.130	0.147
16	0.180	0.259	0.092	0.297	0.130	0.194
32	0.203	0.318	0.121	0.316	0.170	0.230
64	0.262	0.391	0.210	0.363	0.239	0.302
100	0.333	0.443	0.293	0.403	0.306	0.370
250	0.502	0.568	0.492	0.538	0.490	0.528
500	0.638	0.679	0.634	0.651	0.628	0.653
1000	0.758	0.785	0.756	0.763	0.750	0.766

Table 6: NMI Analysis for Different Numbers of Clusters

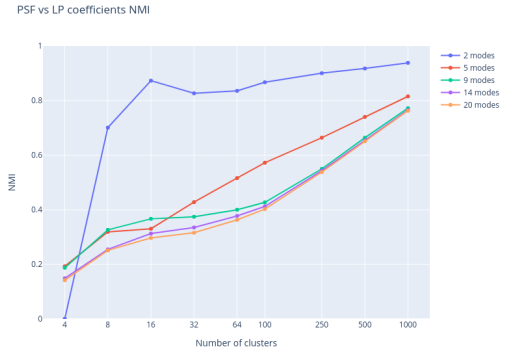
2.3.6 NMI evolution over number of zernike modes



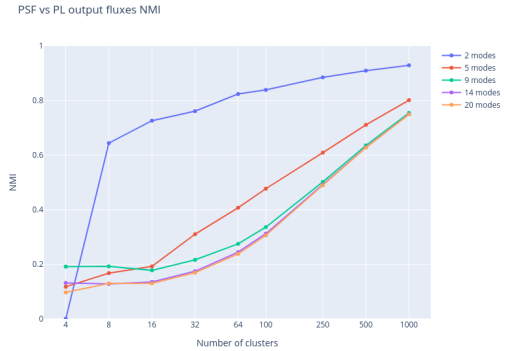
(a) NMI evolution over number of clusters for Zernike coefficients vs PSF

(b) NMI evolution over number of clusters for Zernike coefficients vs LP coefficients

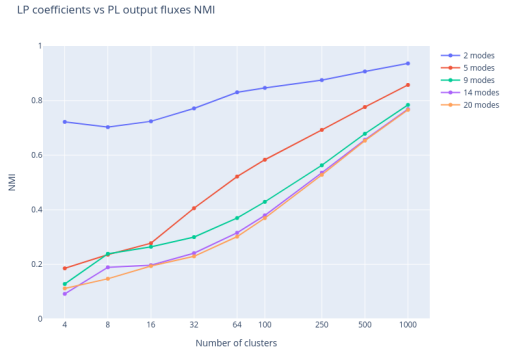
(c) NMI evolution over number of clusters for Zernike coefficients vs PL output fluxes



(d) NMI evolution over number of clusters for PSF vs LP coefficients



(e) NMI evolution over number of clusters for PSF vs PL output fluxes



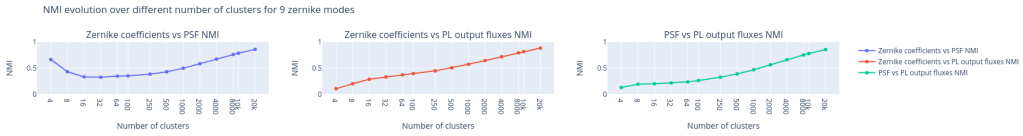
(f) NMI evolution over number of clusters for LP coefficients vs PL output fluxes

2.4 Normalized Mutual Information evolution for a big dataset

This dataset is made from 75000 combinations of 9 zernike modes their RMSE ranging from:

- Modes 2,3 between [-0.8, 0.8]
- Modes 4,5,6 between [-0.6, 0.6]
- Modes 7,8,9,10 between [-0.4, 0.4]

2.4.1 NMI evolution over number of clusters for 9 zernike mode related datasets



Clusters	Z vs PSF	Z vs PL	PSF vs PL
4	0.667	0.109	0.133
8	0.433	0.205	0.196
16	0.336	0.291	0.205
32	0.329	0.334	0.220
64	0.351	0.375	0.240
100	0.356	0.399	0.267
250	0.389	0.452	0.331
500	0.433	0.510	0.393
1000	0.501	0.577	0.472
2000	0.588	0.648	0.567
4000	0.677	0.722	0.664
8000	0.763	0.796	0.755
10000	0.789	0.819	0.782
20000	0.863	0.886	0.859

Table 7: NMI Analysis for Different Numbers of Clusters