WAVEFRONT SENSING WITH DEEP LEARNING

Esteban Vera

School of Electrical Engineering

PONTIFICIA UNIVERSIDAD CATOLICA DE VALPARAISO


CHILE
International boundary
Expressway
Road
Railroad
National capital
Major airport
Major port
0 100 200 300 Kilometers
0 100 200 300 Miles
Scale 1:18,950,000
PERU
BOLIVIA
PARAGUAY
ARGENTINA
BRAZ.
URU.
Arequipa
Matarani
La Paz
Cochabamba
Santa Cruz
Oruro
Sucre
Potosí
Uyuni
Villamontes
Tarija
Filadelfia
Pozo Colorado
Tacna
Arica
Colchane
Iquique
Tocopilla
Mejillones
Calama
Antofagasta
Socompa
Salta
San Salvador de Jujuy
San Miguel de Tucumán
Formosa
Santiago del Estero
Resistencia
Corrientes
Catamarca
La Rioja
Caldera
Copiapó
Huasco
La Serena
Coquimbo
Ovalle
San Juan
Córdoba
Santa Fe
Concordia
Paraná
Viña del Mar
Valparaíso
Santiago
San Antonio
Mendoza
San Luis
Río Cuarto
Rosario
San Nicolás de los Arroyos
Fray Bentos
Colonia
Buenos Aires
La Plata
Rancagua
Curicó
Constitución
Talca
San Rafael
Malargüe
Chillán
San Vicente
Concepción
Santa Isabel
Santa Rosa
Olavarría
Tandil
Temuco
Zapala
Neuquén
Bahía Blanca
Necochea
Mar del Plata
Valdivia
Osorno
San Carlos de Bariloche
Puerto Montt
Viedma
Ingeniero Jacobacci
Isla Chiloé
Quellón
Puerto Madryn
Esquel
Rawson
Puerto Aisén
Coihaique
Las Heras
Comodoro Rivadavia
Golfo San Jorge
Punta Yungay
Villa O'Higgins
Puerto Deseado
San Julián
Puerto Natales
El Turbio
Río Gallegos
Strait of Magellan
Punta Arenas
Porvenir
Tierra del Fuego
Ushuaia
Puerto Williams
Beagle Channel
Cape Horn
Islas Diego Ramírez
Stanley
Falkland Islands (Islas Malvinas)
(overseas territory of the UK; claimed by ARGENTINA)
SOUTH PACIFIC OCEAN
SOUTH ATLANTIC OCEAN
Isla San Félix
Isla San Ambrosio
ARCHIPIÉLAGO JUAN FERNÁNDEZ
Isla Róbinson Crusoe
Isla Alejandro Selkirk
Isla Sala y Gómez (uninhabited)
0 0.25 Kilometer
0 0.25 Mile
Easter Island
Hanga Roa
0 5 Kilometers
0 5 Miles
Isla Sala y Gómez
Easter Island
CHILE
ARG.
0 1000 Kilometers
0 1000 Miles
TRANSVERSE MERCATOR PROJECTION; CENTRAL MERIDIAN 71° W
803265AI (G00923) 1-09


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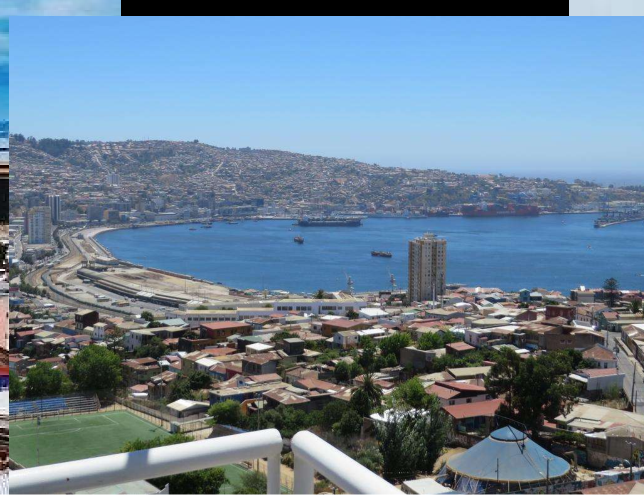
0.25 Mile
Easter Island
Hanga Roa
5 Kilometers
5 Miles
1000 Kilometers
1000 Miles
TRANSVERSE MERCATOR PROJECTION; CENTRAL MERIDIAN 71° W
803265AI (G00923) 1-09



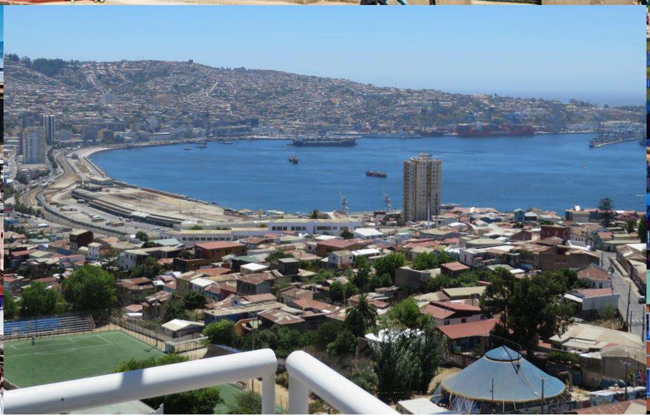


Viña del Mar
Valparaíso
Santiago
San Antonio
Rancagua
Curicó
Constitución




90 AÑOS 1928 - 2018

PONTIFICIA UNIVERSIDAD CATÓLICA DE VALPARAÍSO

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1000 Kilometers
1000 Miles
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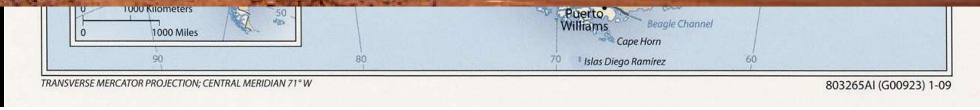
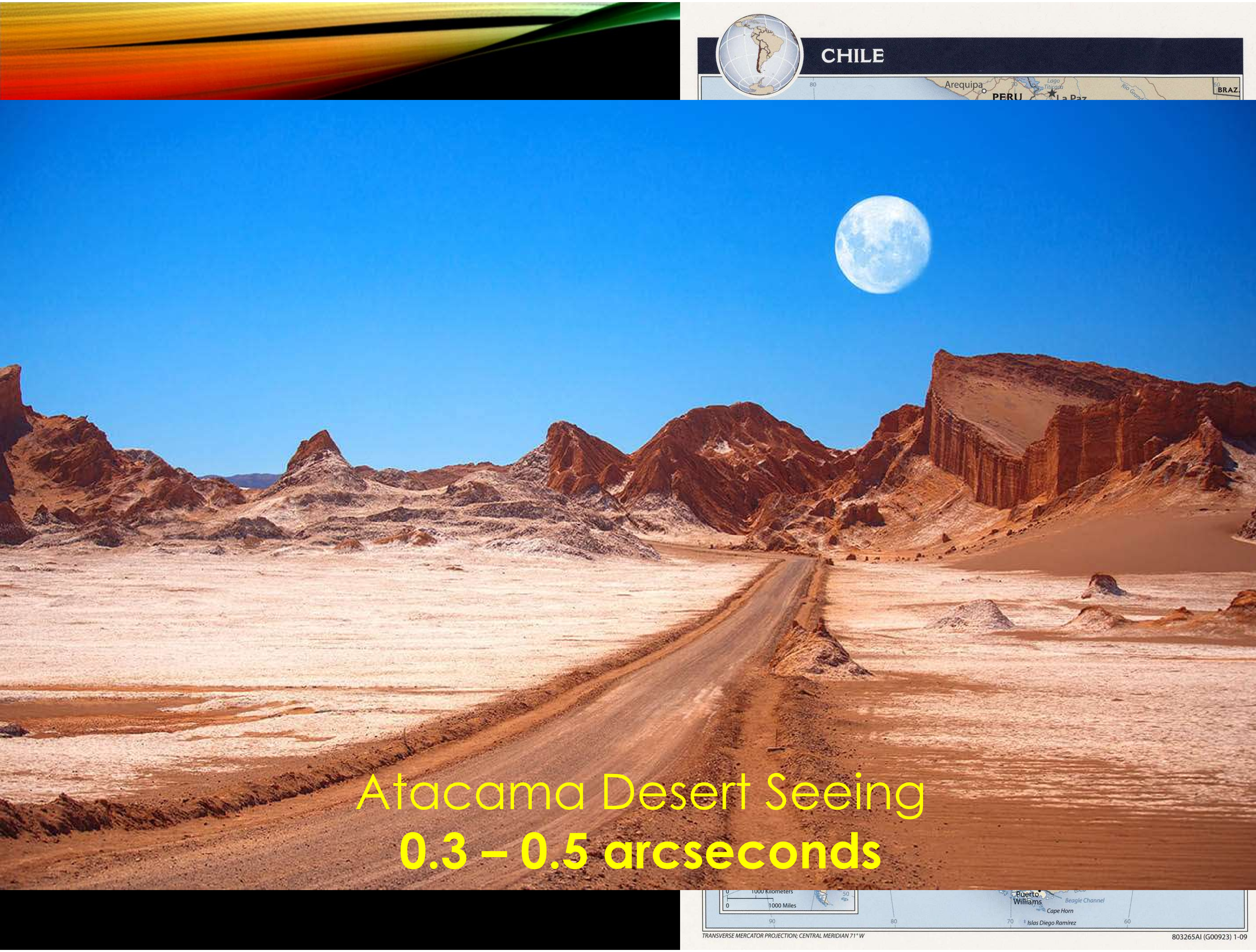
803265AI (G00923) 1-09


CHILE
Arequipa
PERU
La Paz
Lago Titicaca
BRAZ.


1000 Kilometers
1000 Miles
Puerto Williams
Beagle Channel
Cape Horn
Islas Diego Ramírez
TRANSVERSE MERCATOR PROJECTION; CENTRAL MERIDIAN 71° W
803265AI (G00923) 1-09



Atacama Desert Seeing

0.3 – 0.5 arcseconds

ASTRONOMY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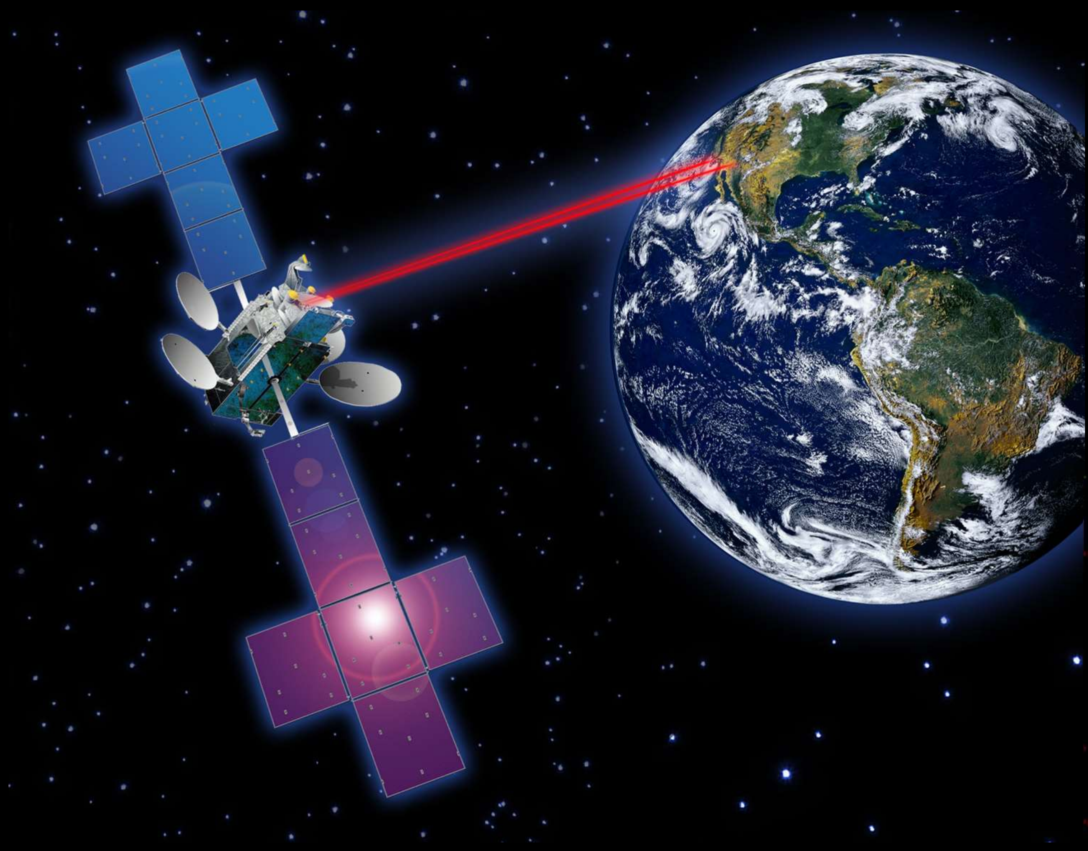
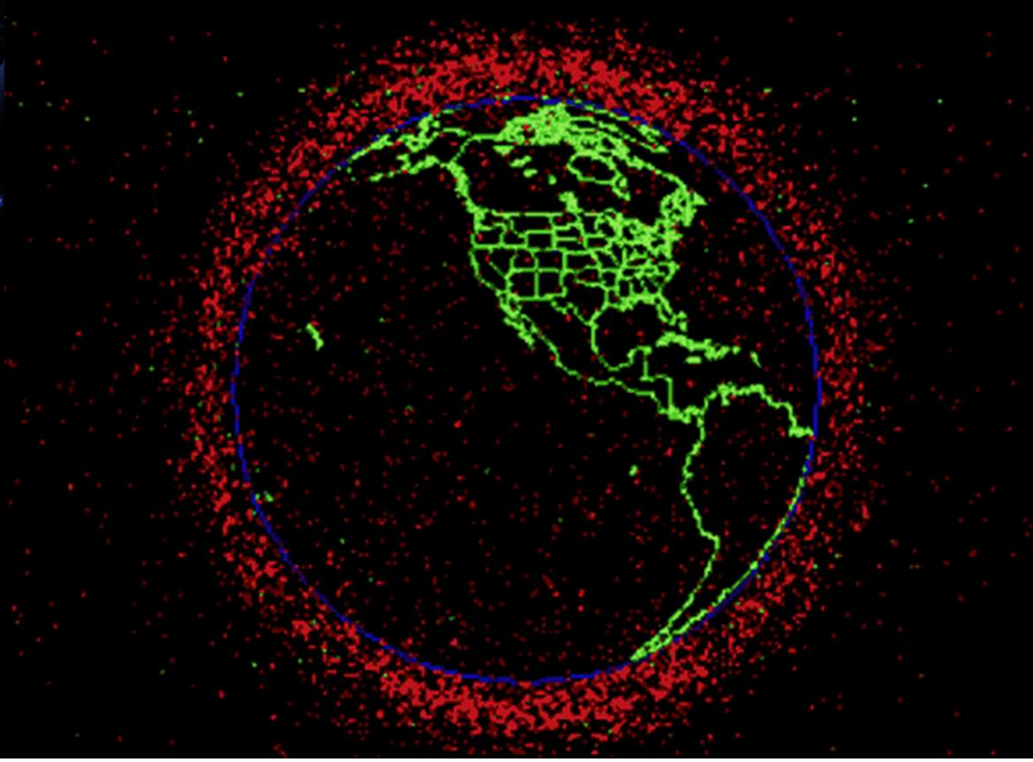
STRATEGIC Applications

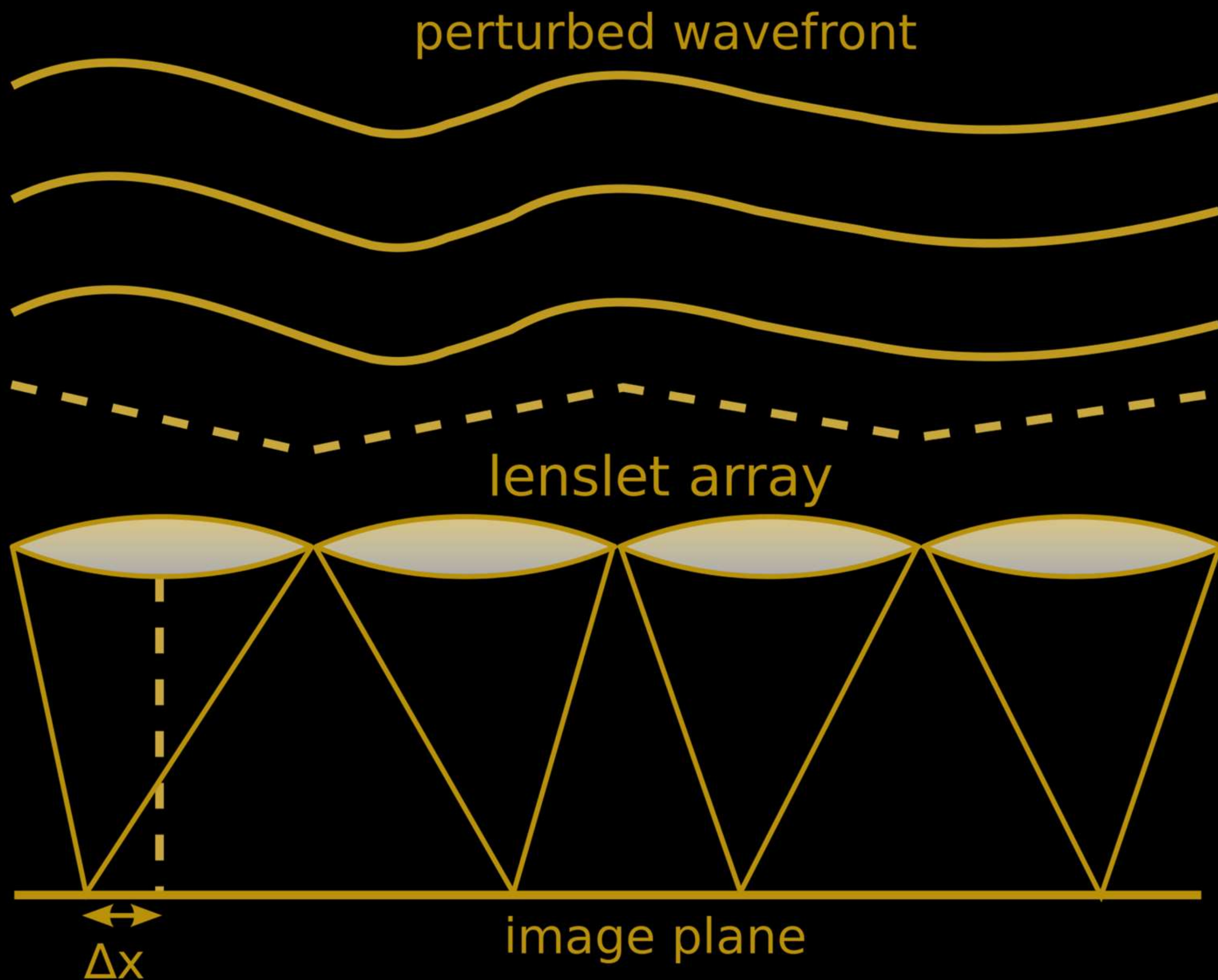
OPTICAL COMMUNICATIONS



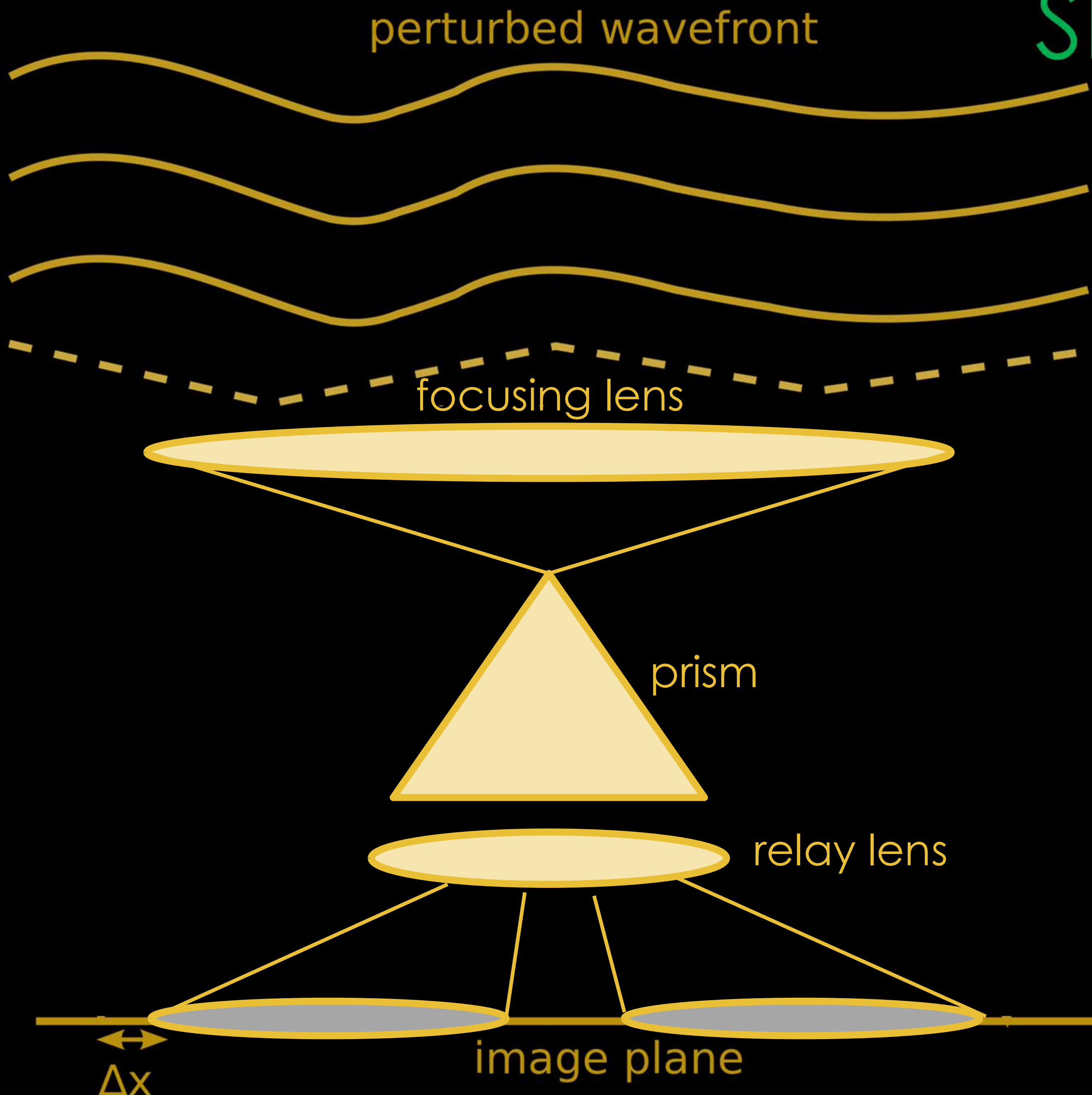
SPACE SITUATIONAL AWARENESS



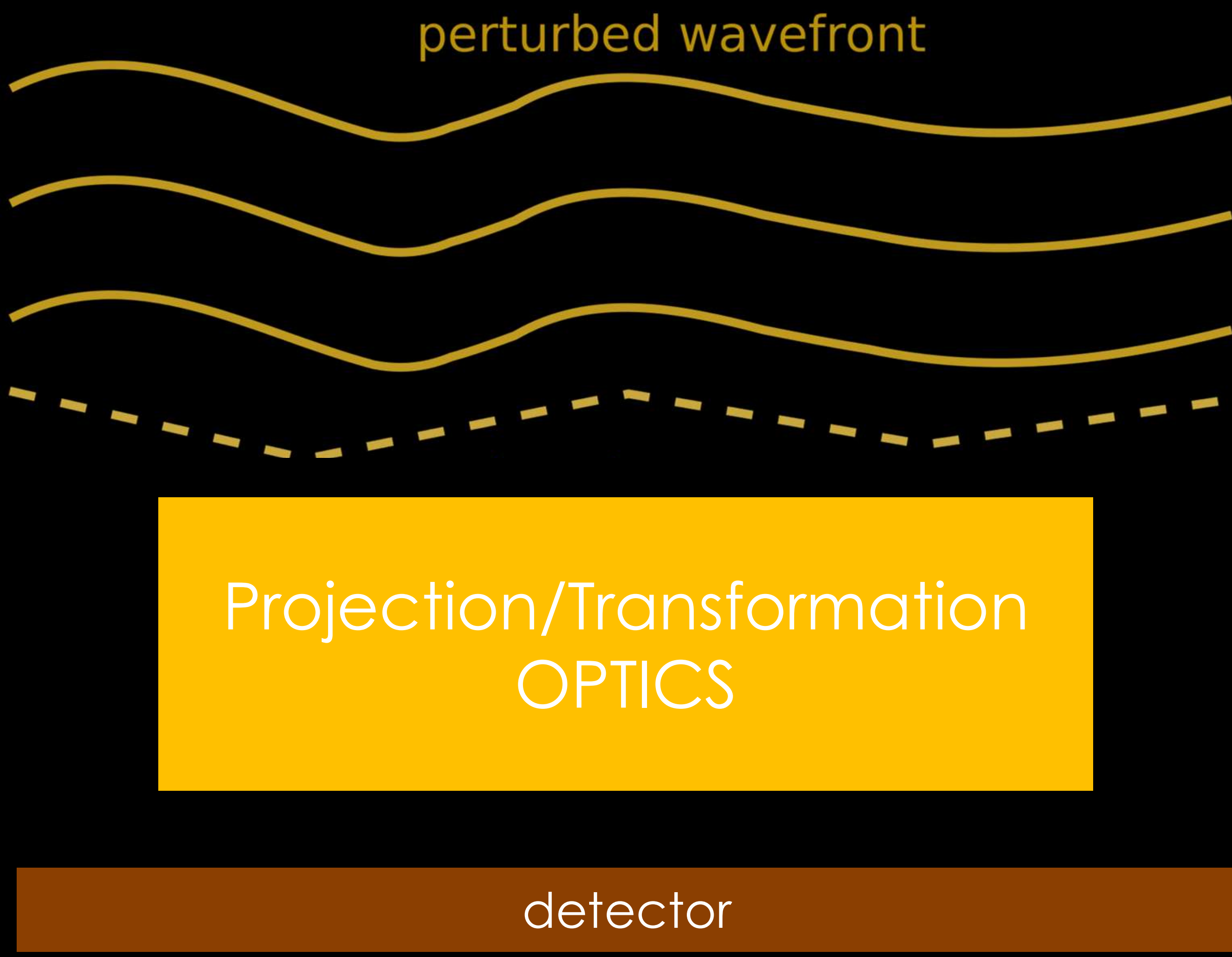
SHACK-HARTMANN WAVEFRONT SENSOR



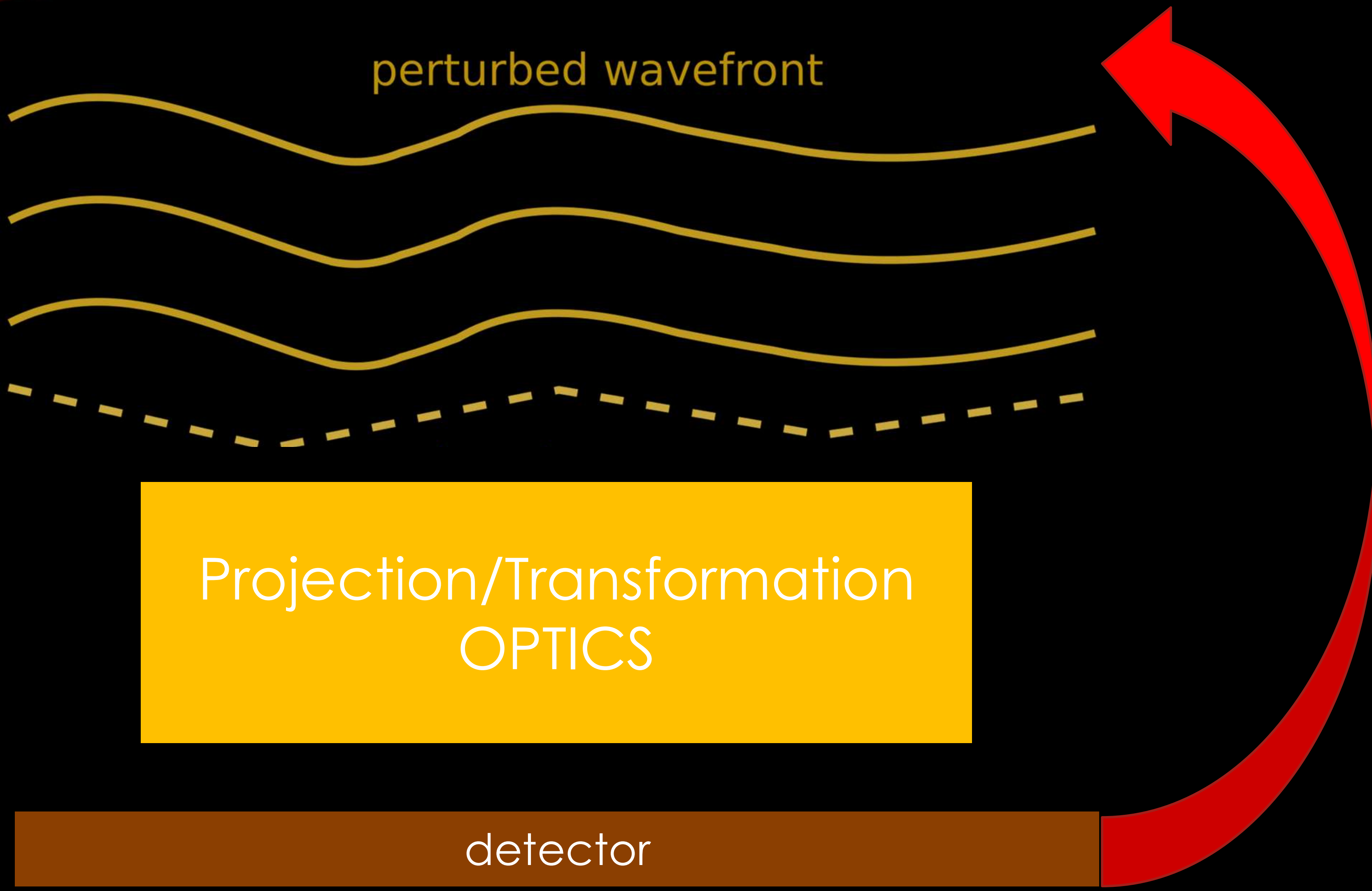
PYRAMID WAVEFRONT SENSOR



WAVEFRONT SENSING



WAVEFRONT SENSING

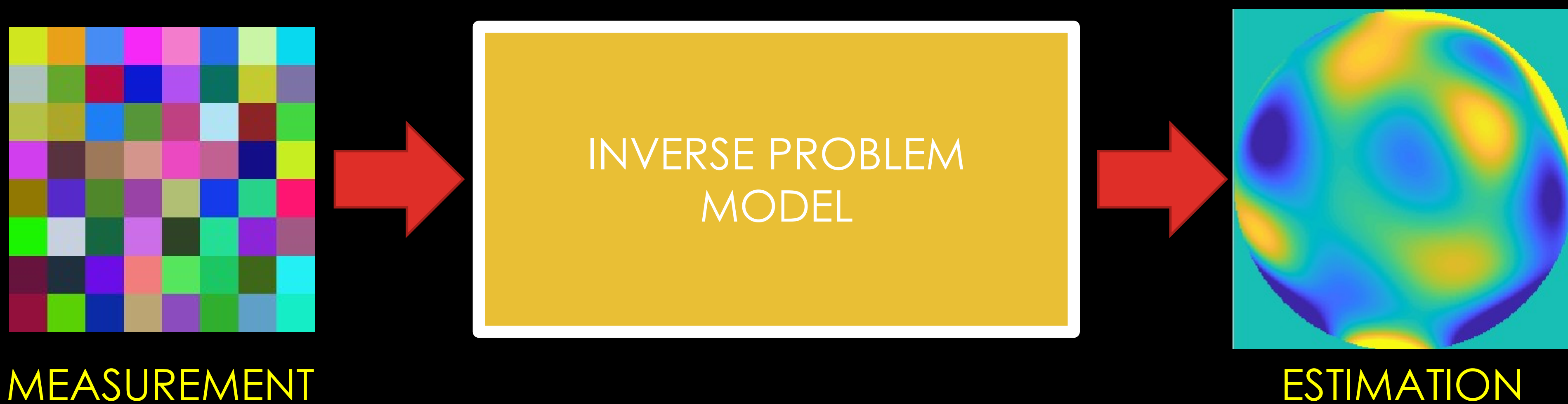


INVERSE PROBLEMS

- Follow a cause-effect explanation
  - What is the cause given an observed effect?
  - What are the parameters?

- Problems without a unique solution
  - Hadamard: Ill-posed/Ill-conditioned

INVERSE PROBLEM

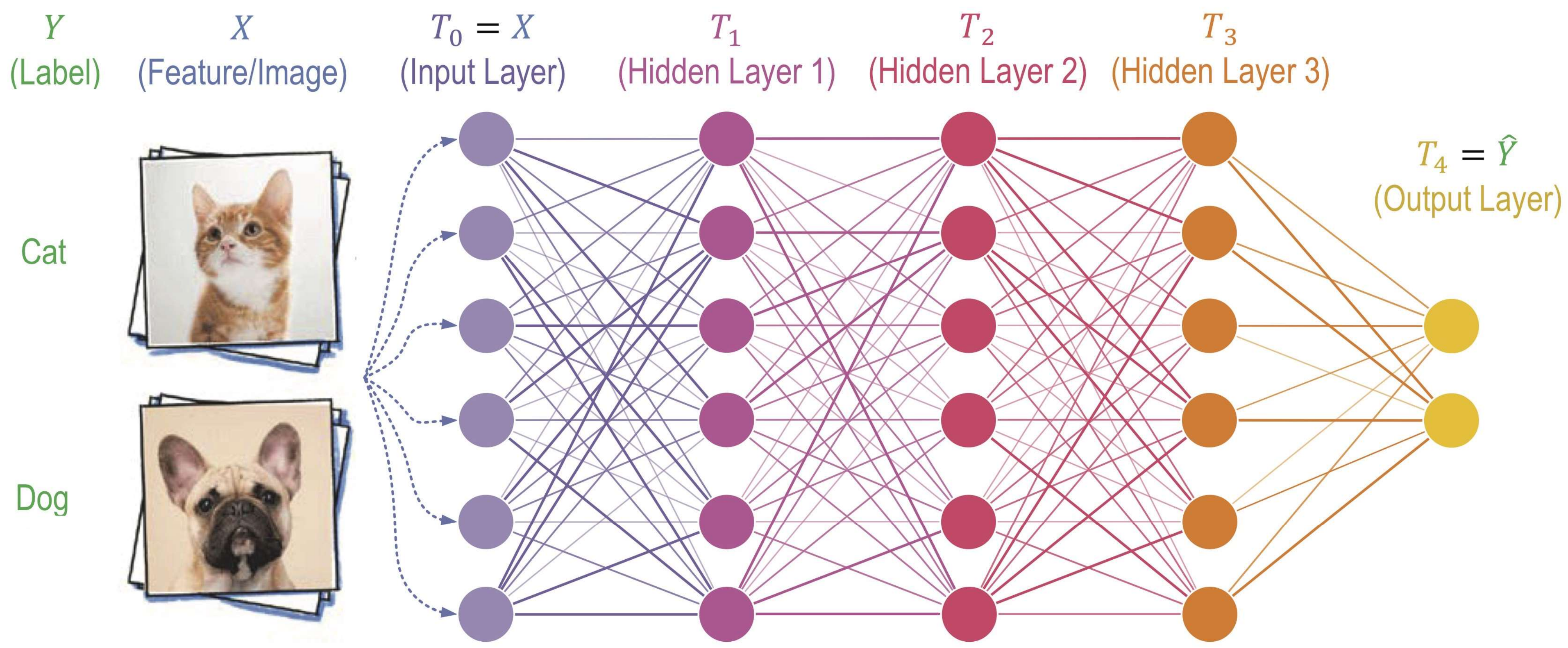


INVERSE PROBLEM

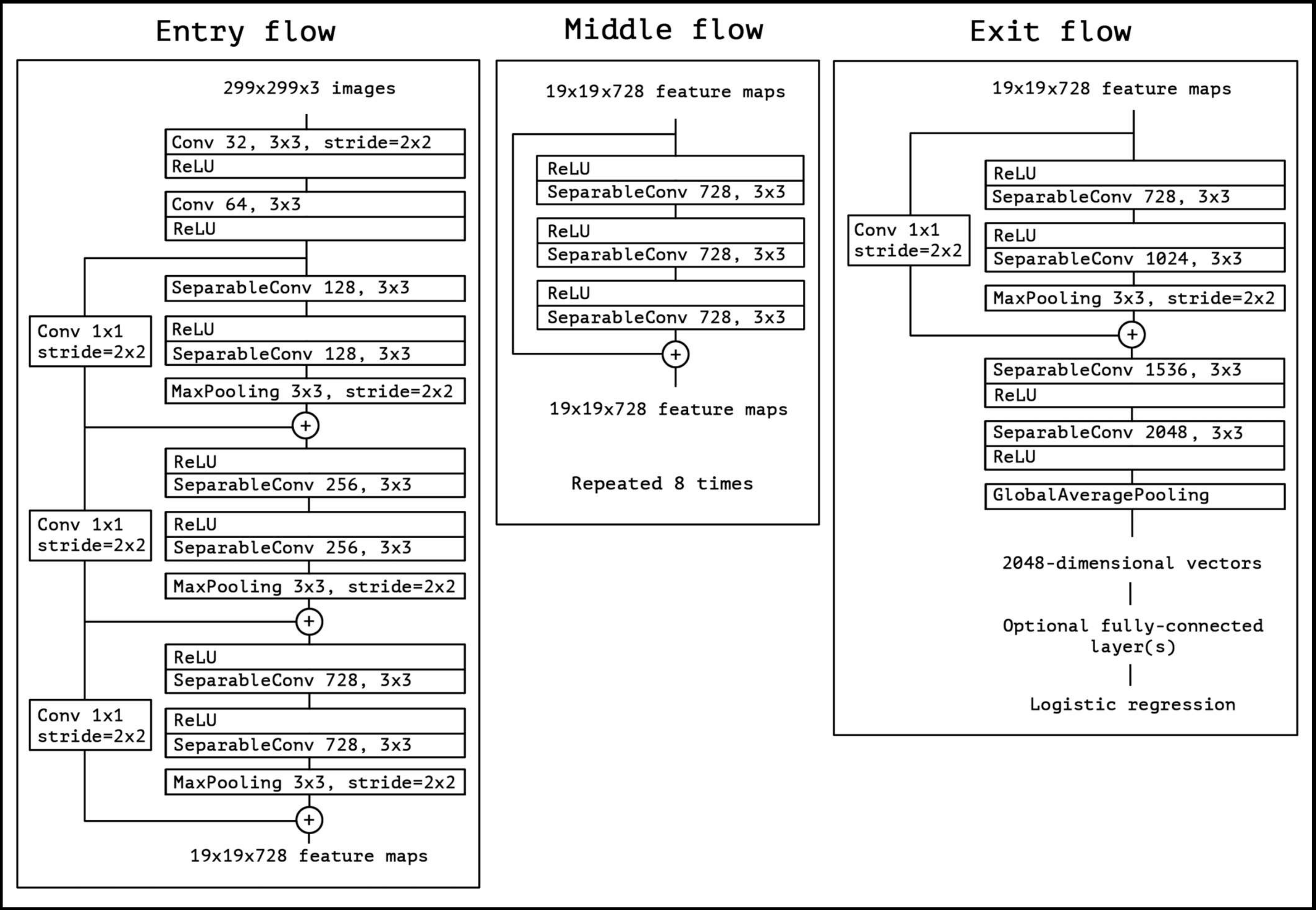
MEASUREMENT

ESTIMATION

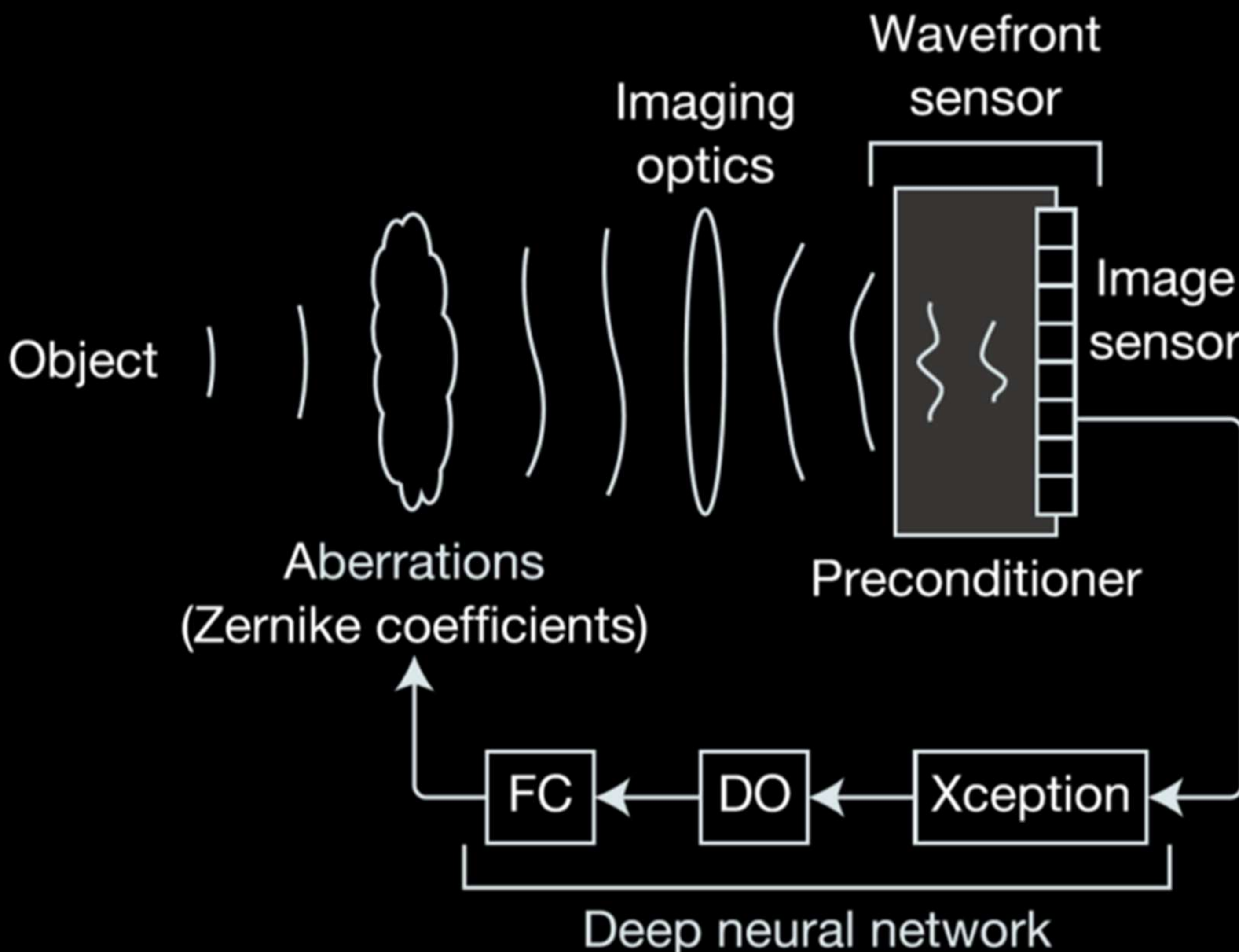
DEEP NEURAL NETWORKS



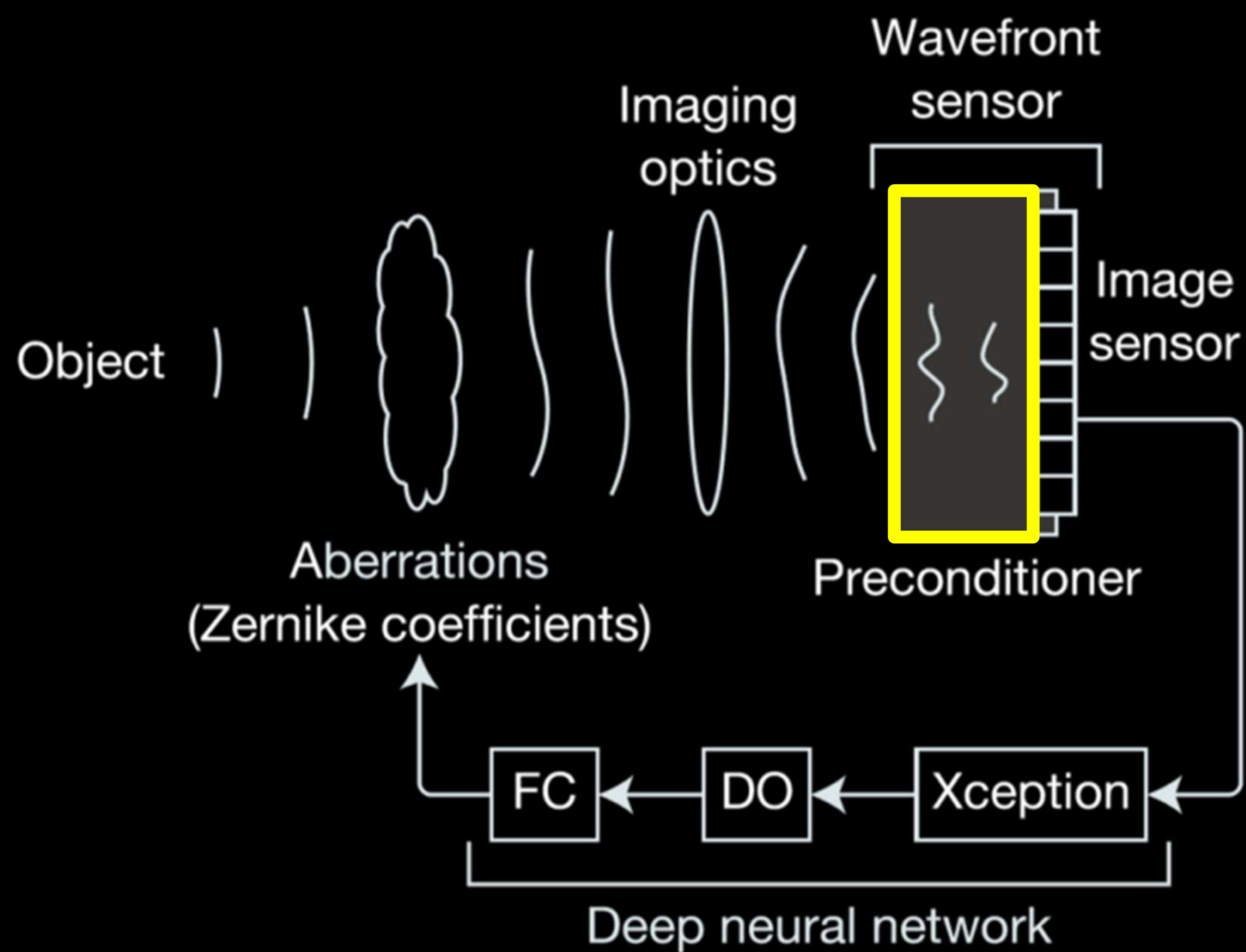
XCEPTION CNN



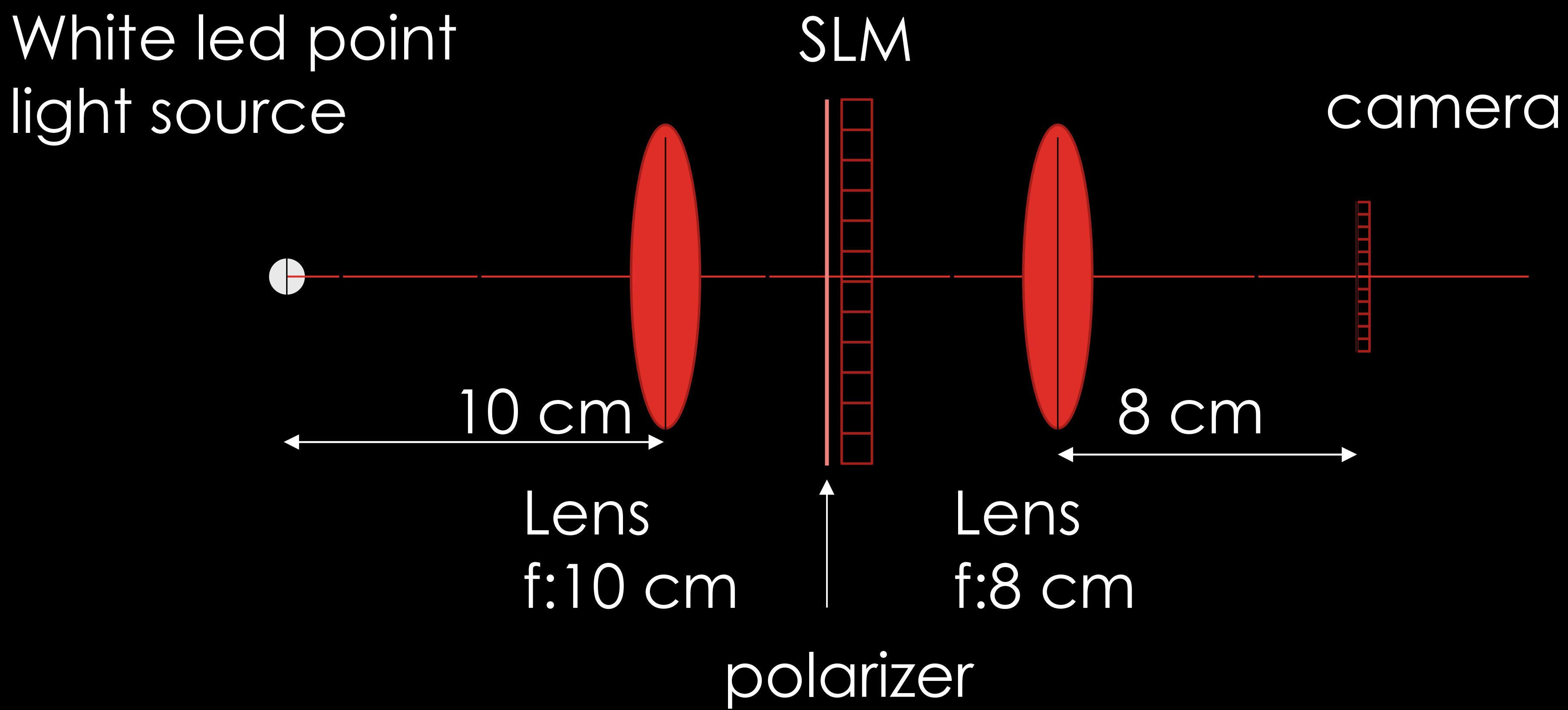
DEEP LEARNING WAVEFRONT SENSOR



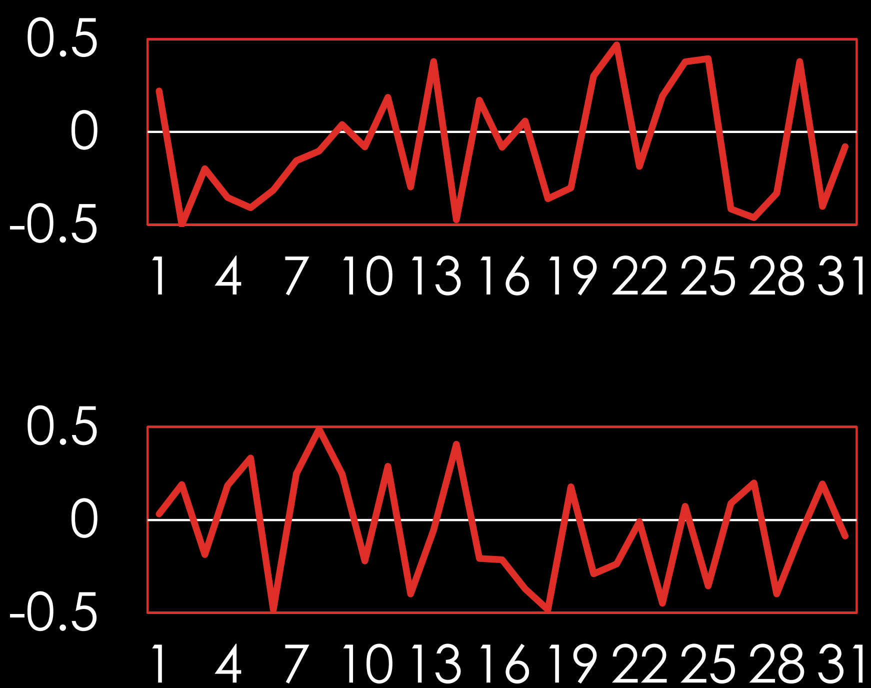
DEEP LEARNING WAVEFRONT SENSOR



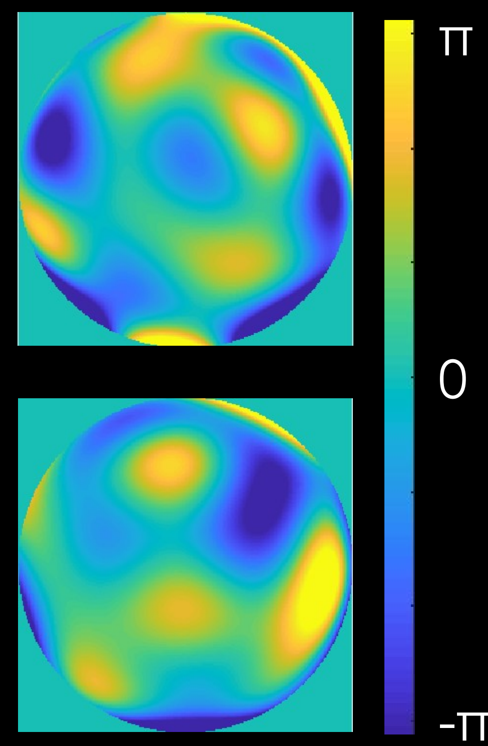
INFOCUS


White led point
light source
SLM
camera
10 cm
8 cm
Lens
f:10 cm
Lens
f:8 cm
polarizer

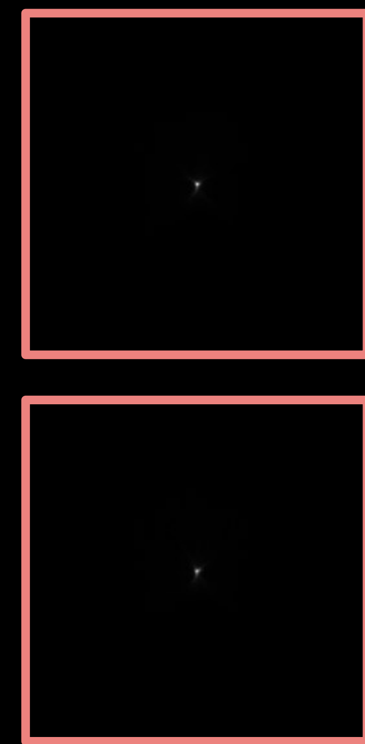
INFOCUS TRAINING



Given Zernike coefficients



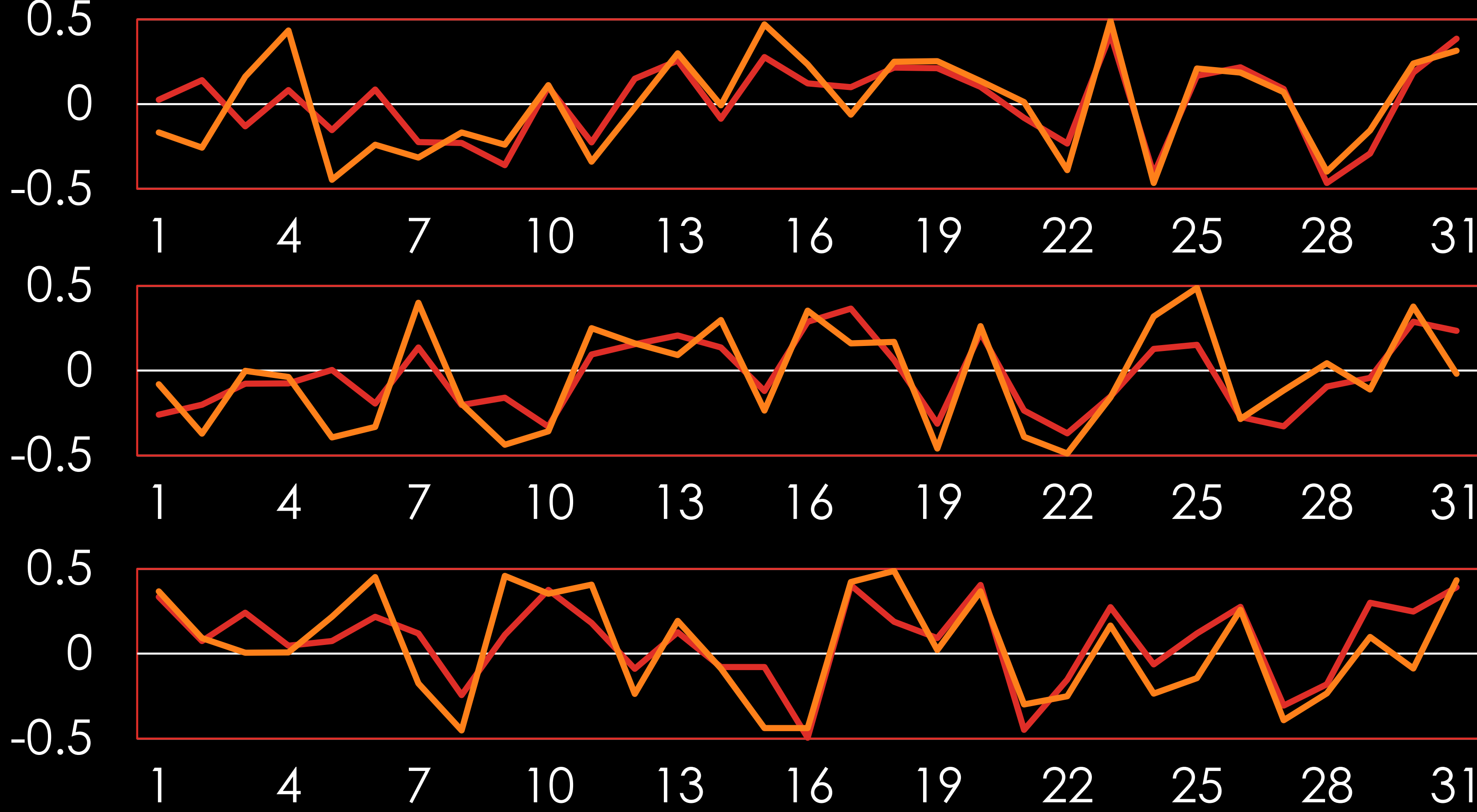
Phase patterns on SLM



Captured images

Number of training images:100,000 and 1,000,000
Number of Zernike coefficient: 31

INFOCUS RESULTS:100,000



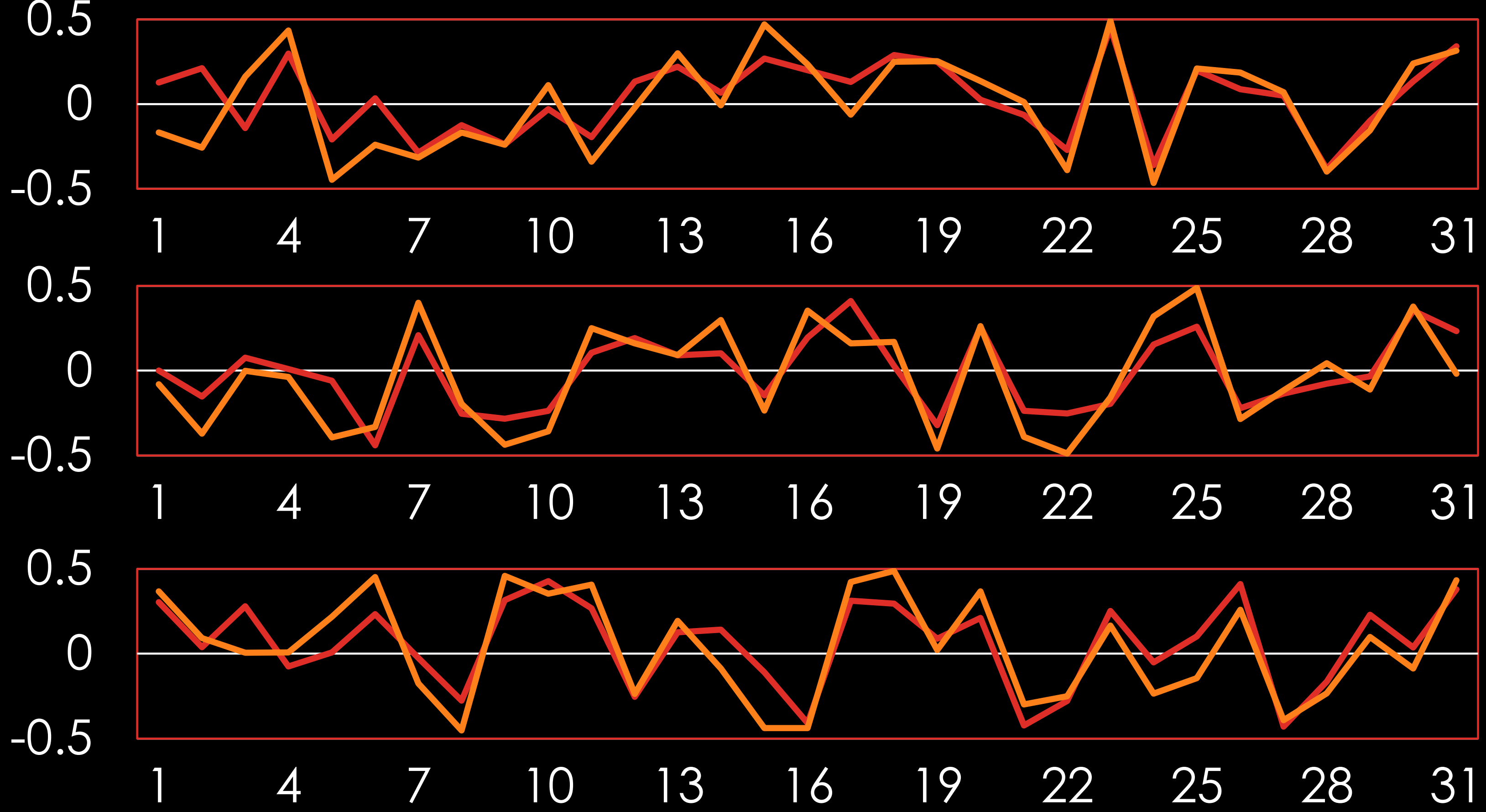
Zernike coefficient(red:true, orange:estimated)

RMSE(number of test images:1000)

train:0.160

test:0.177

INFOCUS RESULTS:1,000,000



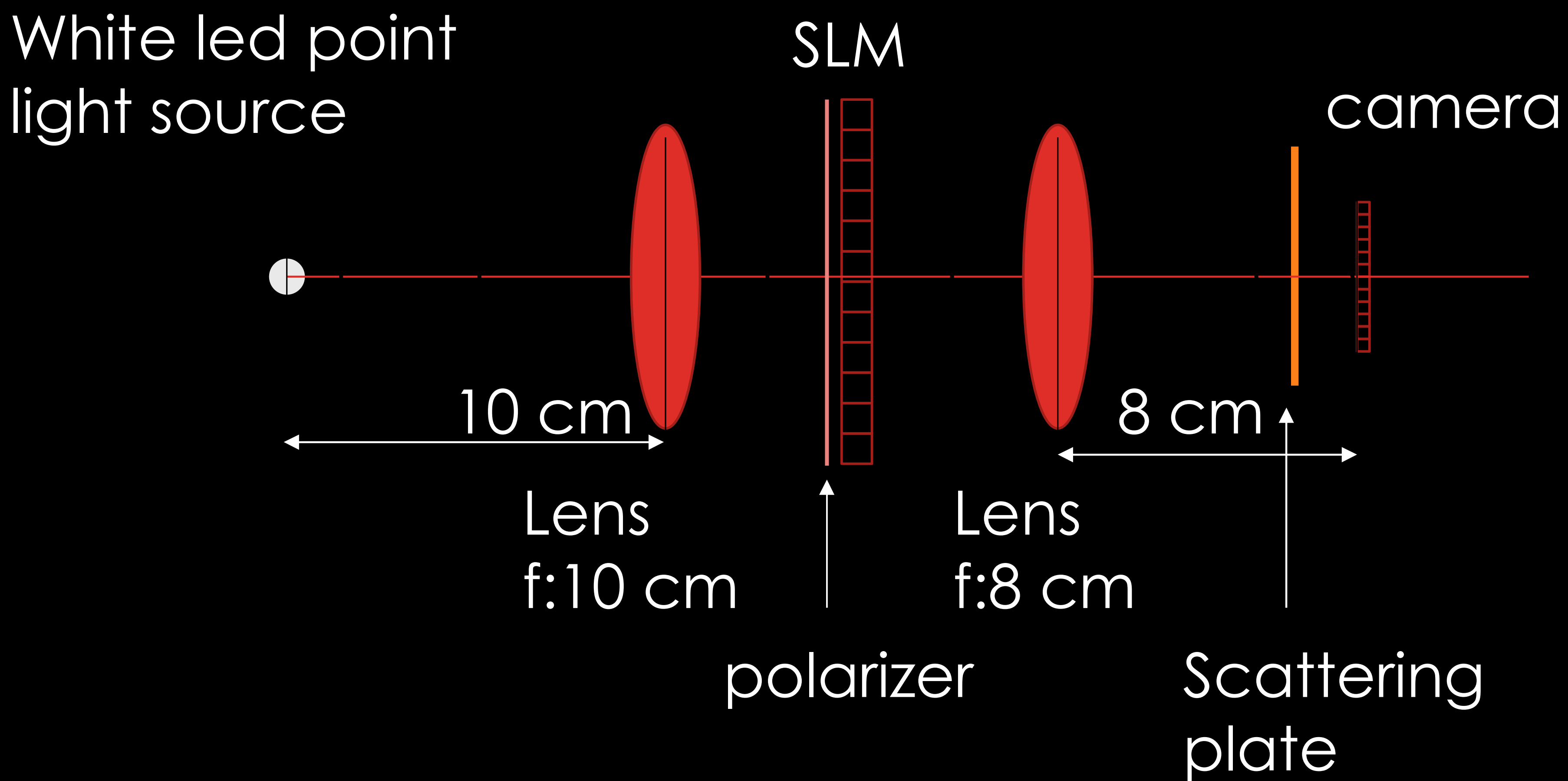
Zernike coefficient(red : true, orange : estimated)

RMSE(number of test images:1000)

train : 0.151

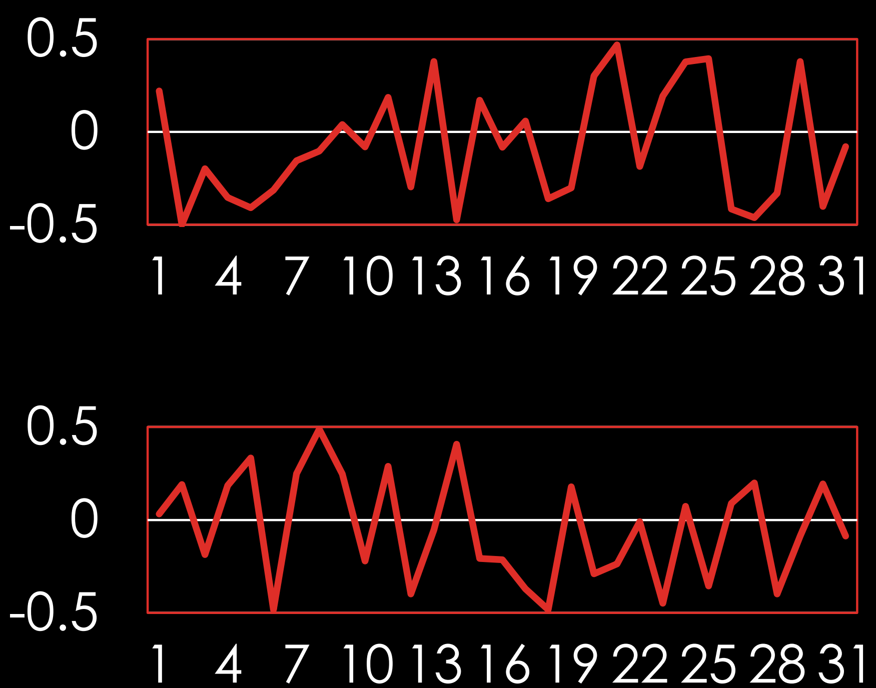
test : 0.154

SCATTERING

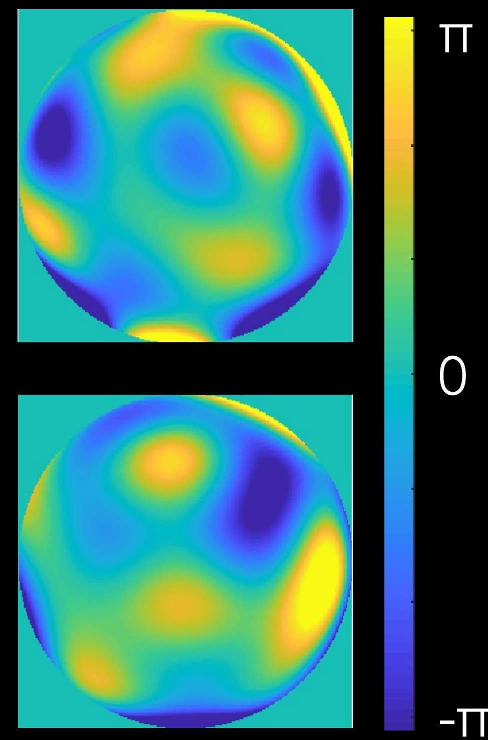


White led point
light source
SLM
camera
10 cm
8 cm
Lens
f:10 cm
Lens
f:8 cm
polarizer
Scattering
plate

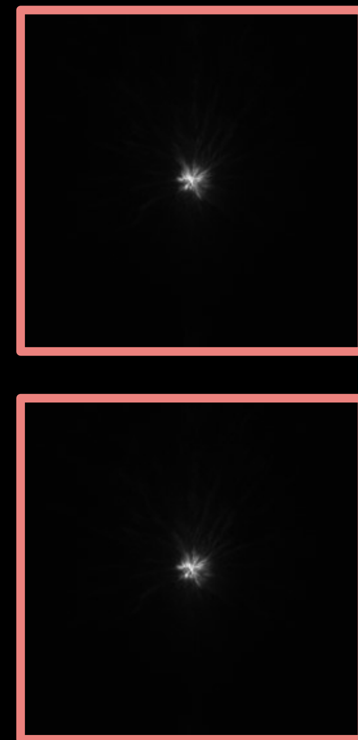
SCATTERING TRAINING



Given zernike coefficients



Phase patterns on SLM



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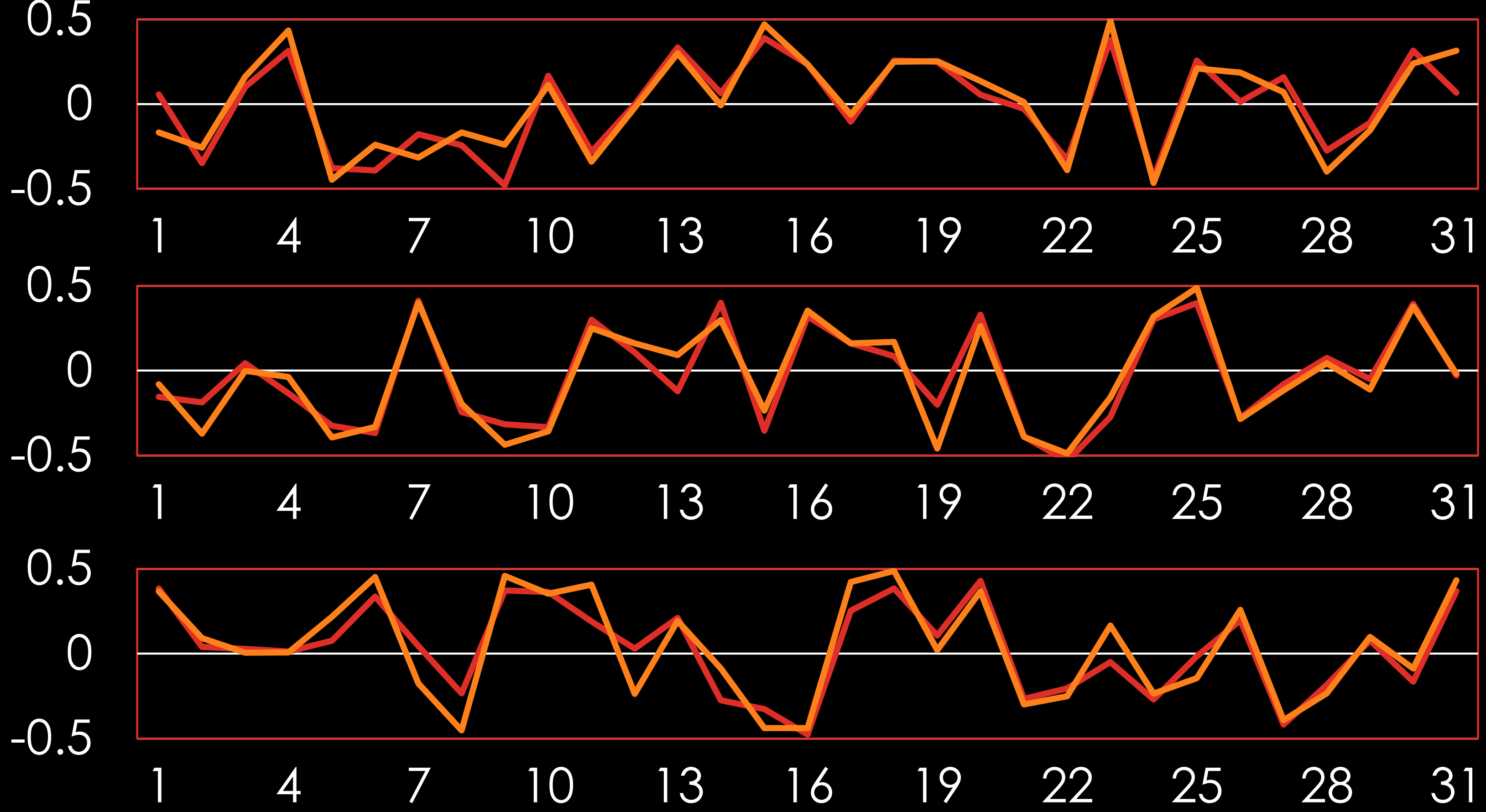
Number of Zernike coefficients: 31

SCATTERING RESULTS:100,000



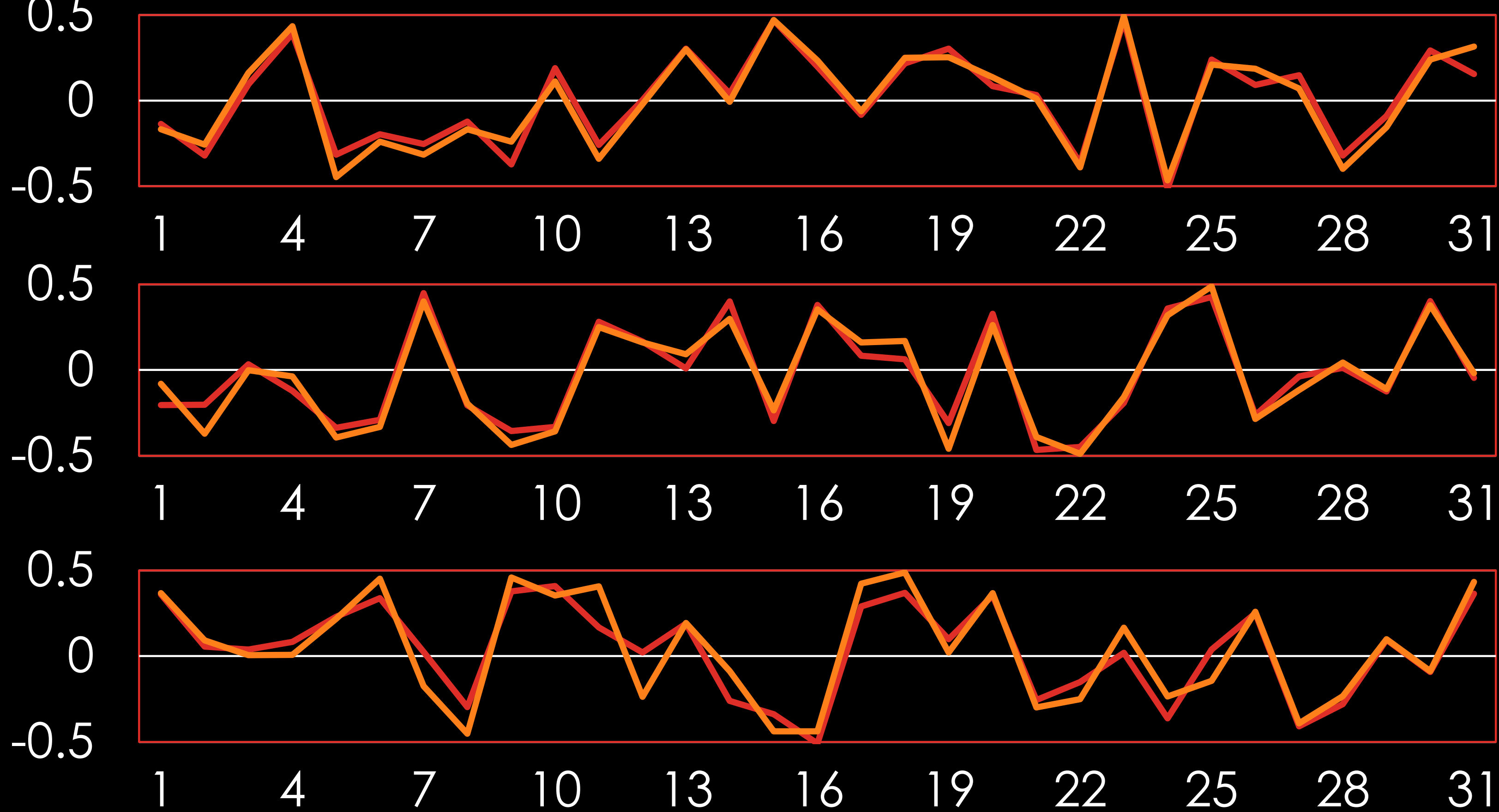
Zernike coefficient(red:true, orange:estimated)

RMSE(number of test images:1000)

train:0.079

test:0.103

SCATTERING RESULTS:1,000,000



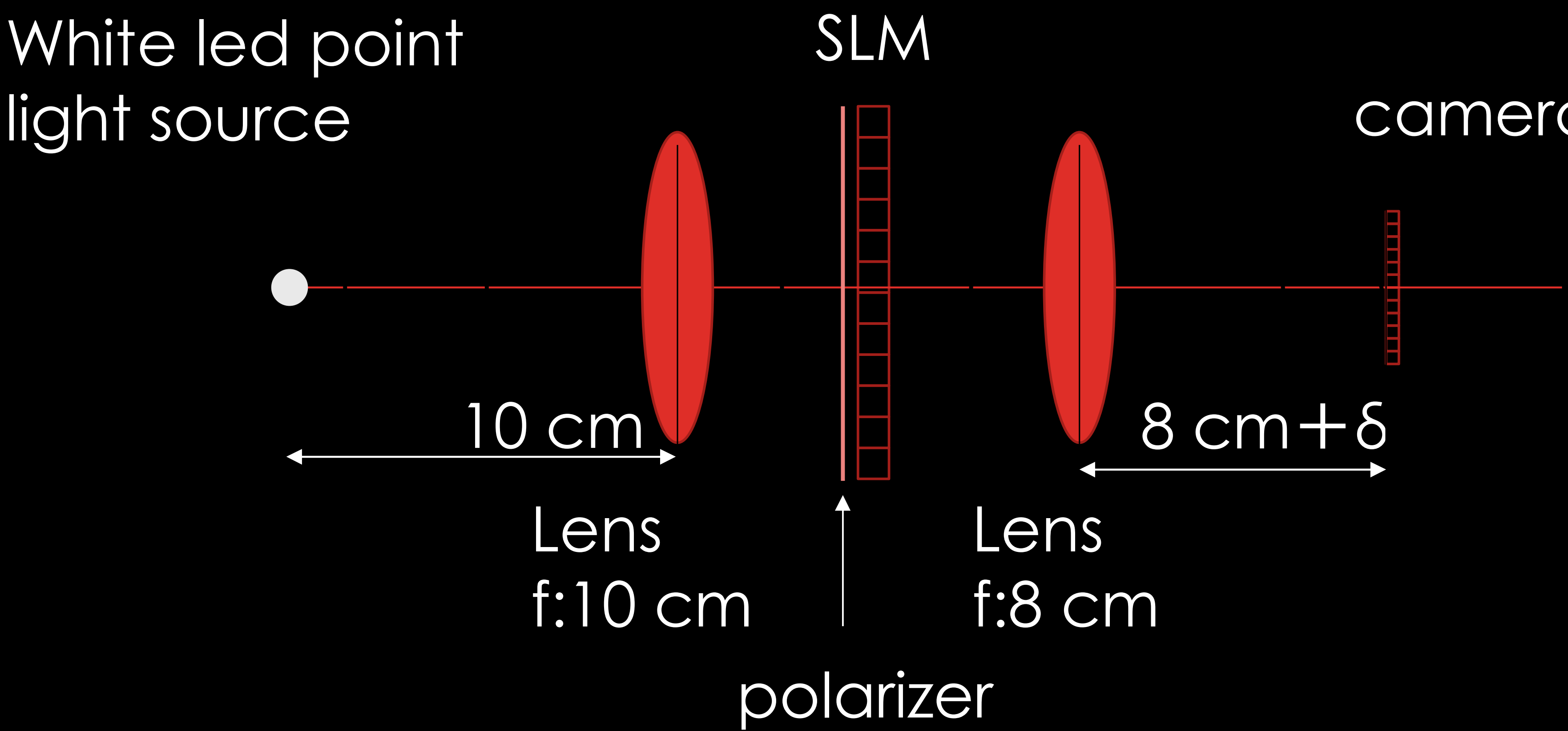
Zernike coefficient(red : true, blue : estimated)

RMSE(number of test images:1000)

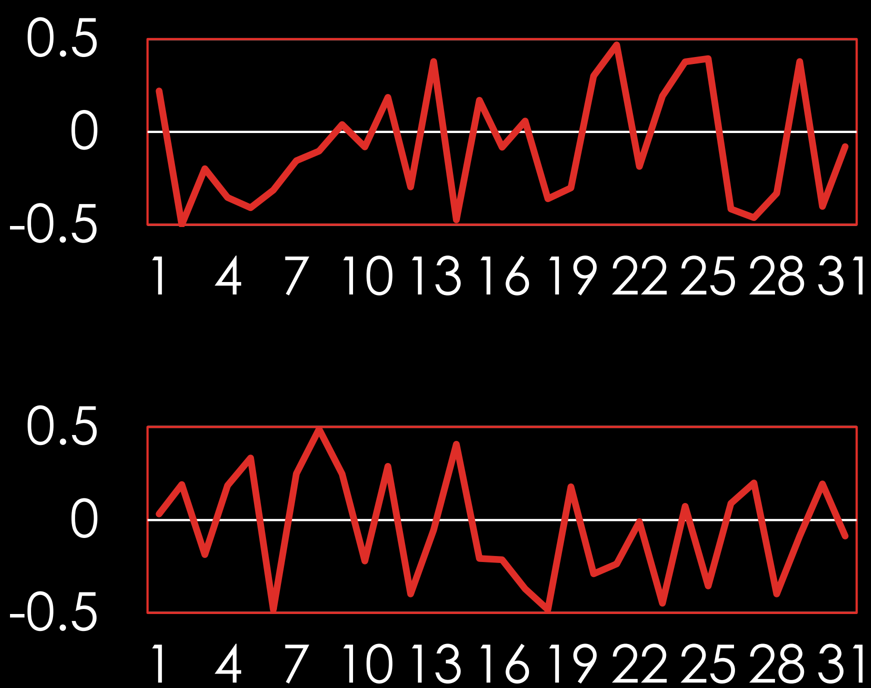
train : 0.077

test : 0.079

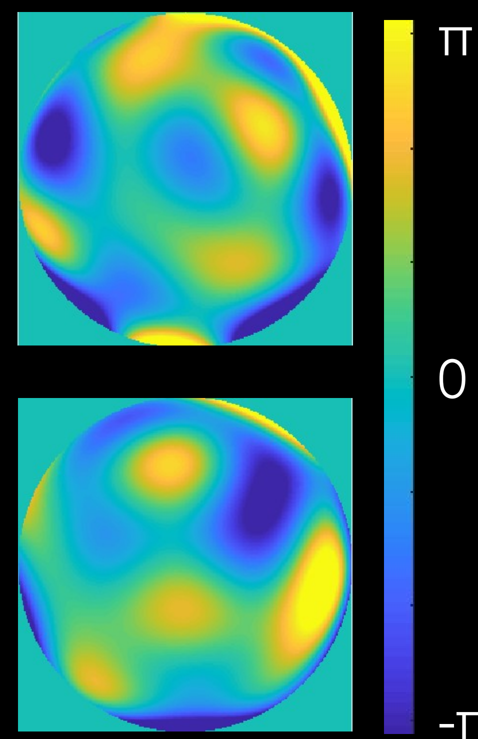
DEFOCUS


White led point
light source
SLM
camera
10 cm
8 cm+δ
Lens
f:10 cm
Lens
f:8 cm
polarizer

DEFOCUS TRAINING



Given Zernike coefficients



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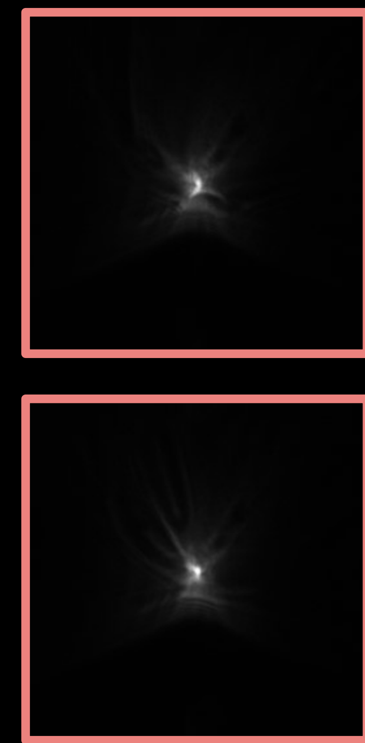

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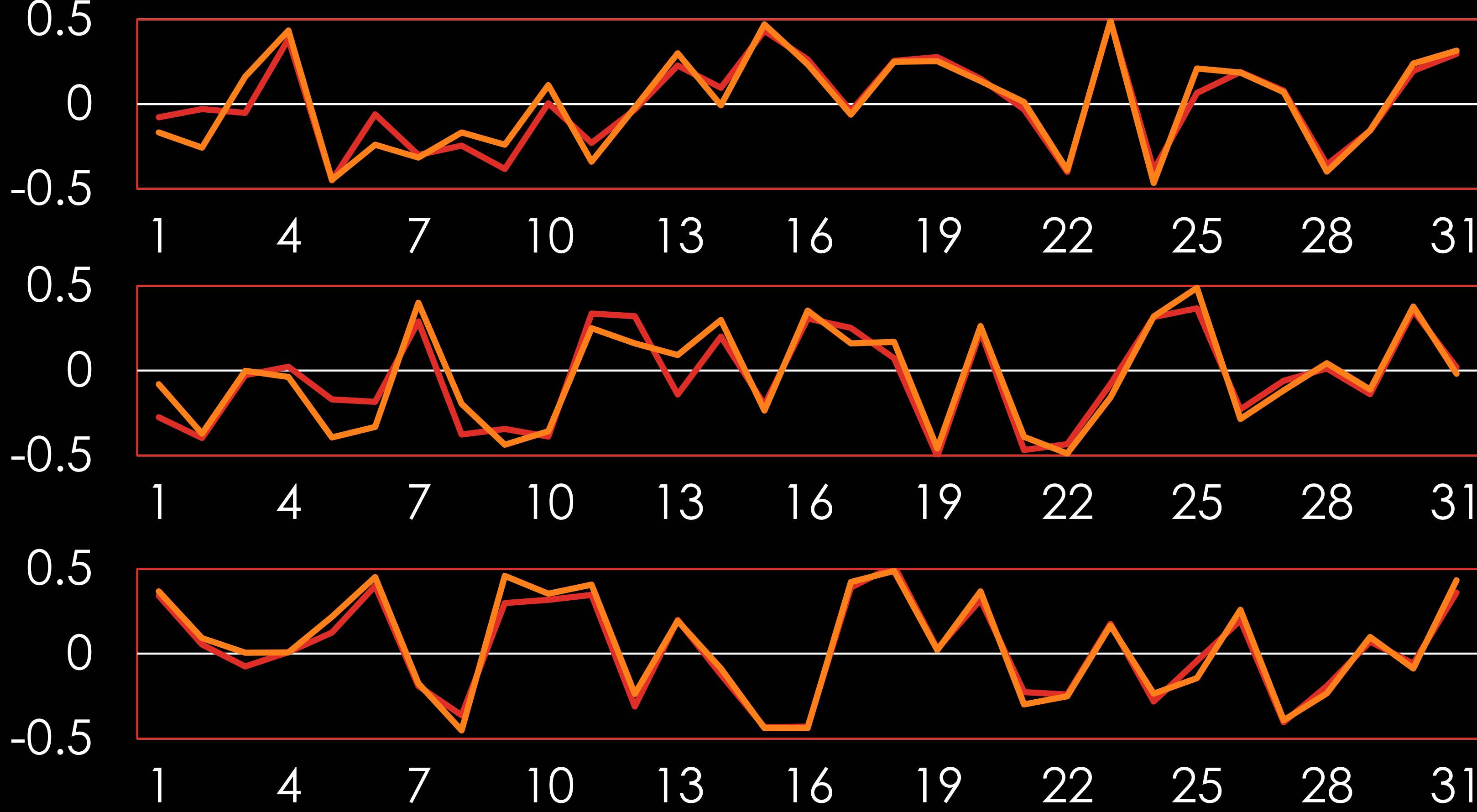
DEFOCUS RESULTS:100,000



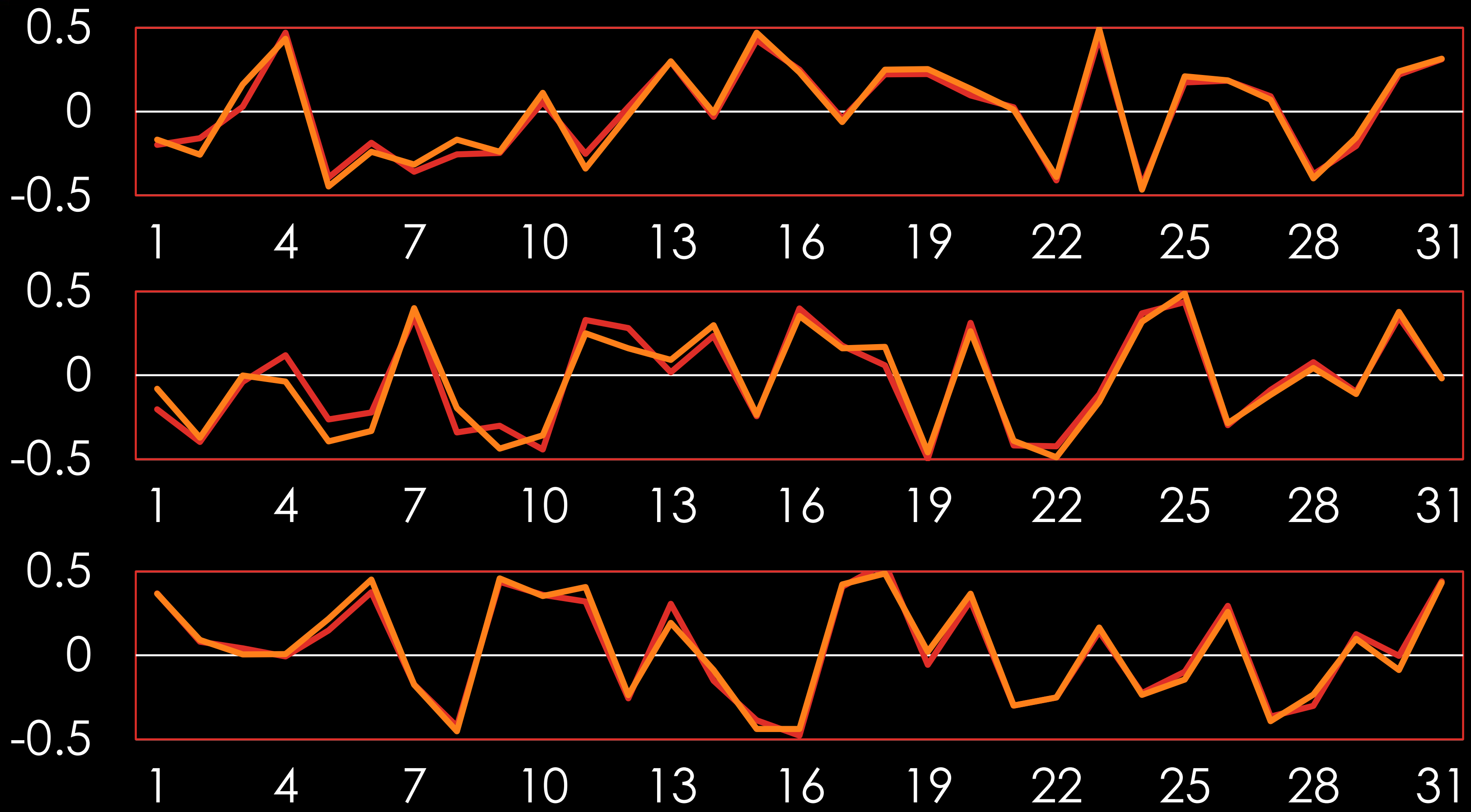
Zernike coefficient(red:true, orange:estimated)

RMSE(number of test images:1,000)

train:0.068

test:0.086

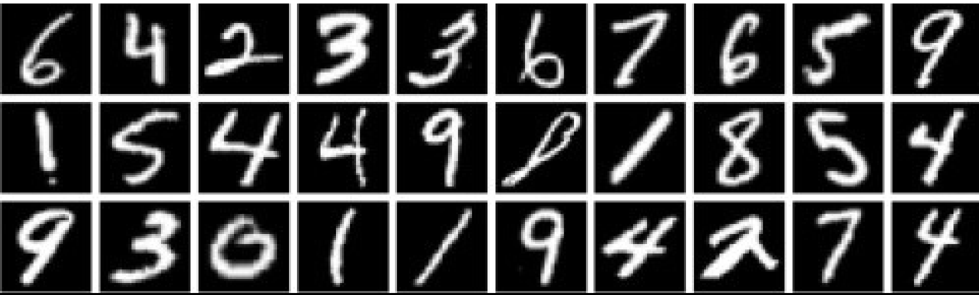
DEFOCUS RESULTS:1,000,000



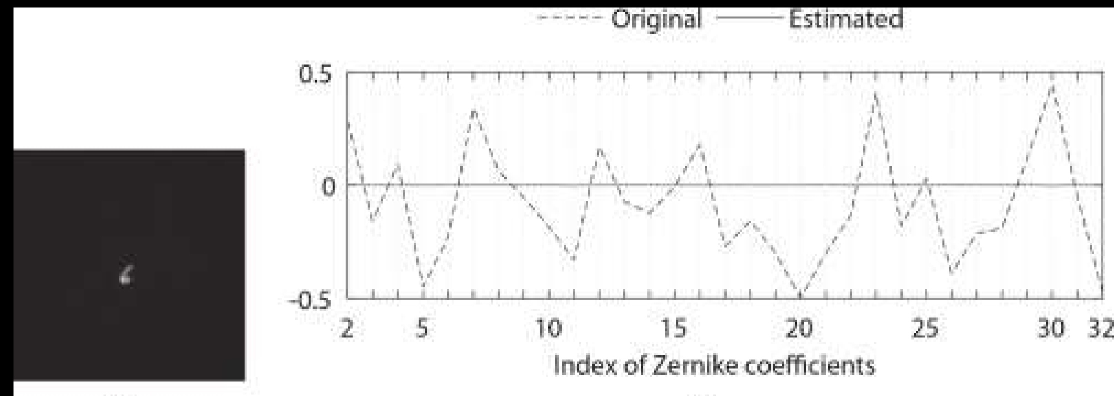
Zernike coefficient(red : true, orange : estimated)

RMSE(number of test images:1,000)
train : 0.062
test : 0.065

EXTENDED OBJECTS

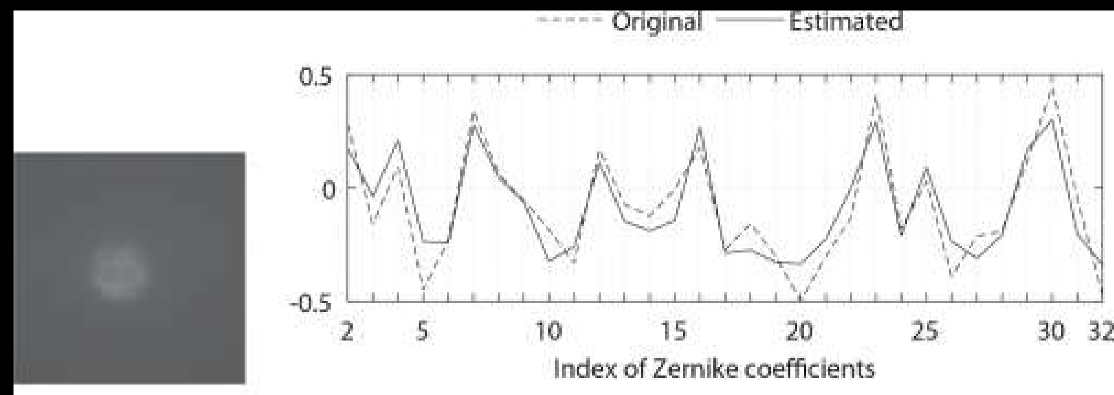


INFOCUS



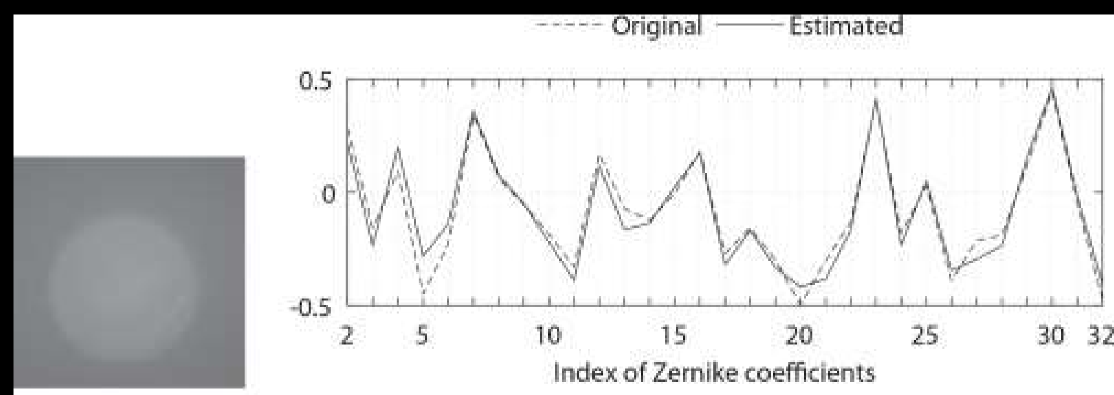
(a) (b)

SCATTER



(a) (b)

DEFOCUS

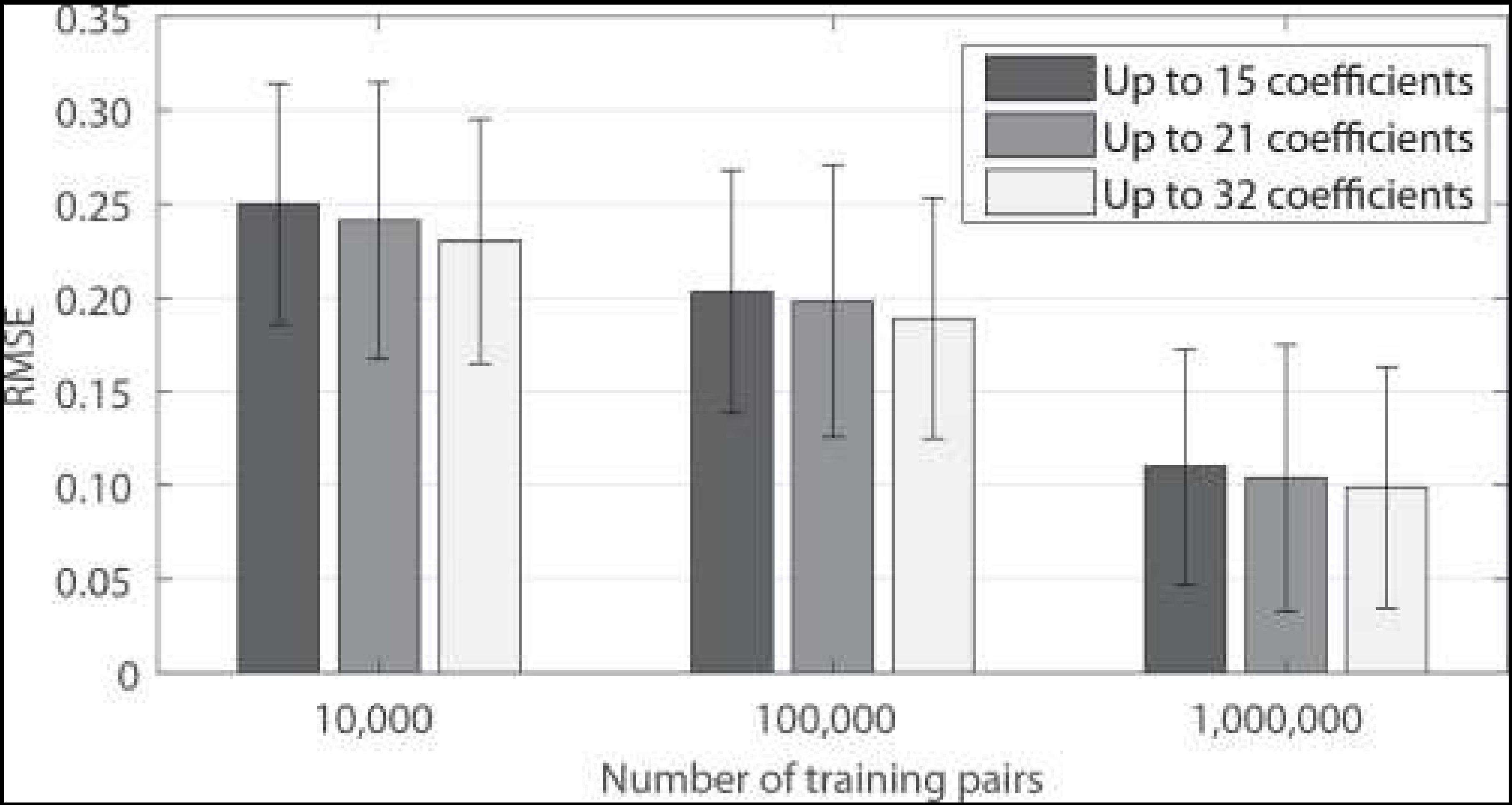


(a) (b)

SUMMARIZED RESULTS

	In-focus	Overexposure	Defocus	Scatter
Point source	0.142 ± 0.032	0.036 ± 0.013	0.040 ± 0.016	0.057 ± 0.018
Extended sources	0.288 ± 0.024	0.214 ± 0.051	0.099 ± 0.064	0.195 ± 0.064

SUMMARIZED RESULTS



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wavefront sensing

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About 901,000 results (0.51 seconds)

Wavefront sensor - Wikipedia

https://en.wikipedia.org › wiki › Wavefront_sensor

A **wavefront sensor** is a device for measuring the aberrations of an optical wavefront. Although an amplitude splitting interferometer such as the Michelson interferometer could be called a **wavefront sensor**, the term is normally applied to instruments that do not require an unaberrated reference beam to interfere with.

AO tutorial 3: wave-front sensors

www.ctio.noao.edu › ~atokovin › tutorial › part3 › wfs

Why do not use standard laser interferometers in Adaptive Optics **Wave-Front Sensors** (WFSs)?. First, an AO system must use the light of stars passing through ...

Requirements to wave ... · Shack-Hartmann WFS · Curvature sensors

People also ask

- How does a wavefront sensor work?
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https://en.wikipedia.org › wiki › Wavefront_sensor
A **wavefront sensor** is a device for measuring the aberrations of an optical wavefront. Altho an amplitude splitting interferometer such as the Michelson interferometer could be called a **wavefront sensor**, the term is normally applied to instruments that do not require an unaberrated reference beam to interfere with.

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www.ctio.noao.edu › ~atokovin › tutorial › part3 › wfs
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Optics Express **in the News:**
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The Optical Society (OSA) is pleased to announce two new editors-in-chief. Kurt Busch and James Leger have been appointed as the new editors-in-chief of the *Journal of the Optical Society of America B* and *Optics Express*, respectively. Read the Press Release for more details.

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Yohei Nishizaki, Matias Valdivia, Ryoichi Horisaki, Katsuhisa Kitaguchi, Mamoru Saito, Jun Tanida, and Esteban Vera
Opt. Express 27(1) 240-251 (2019) View: HTML | PDF

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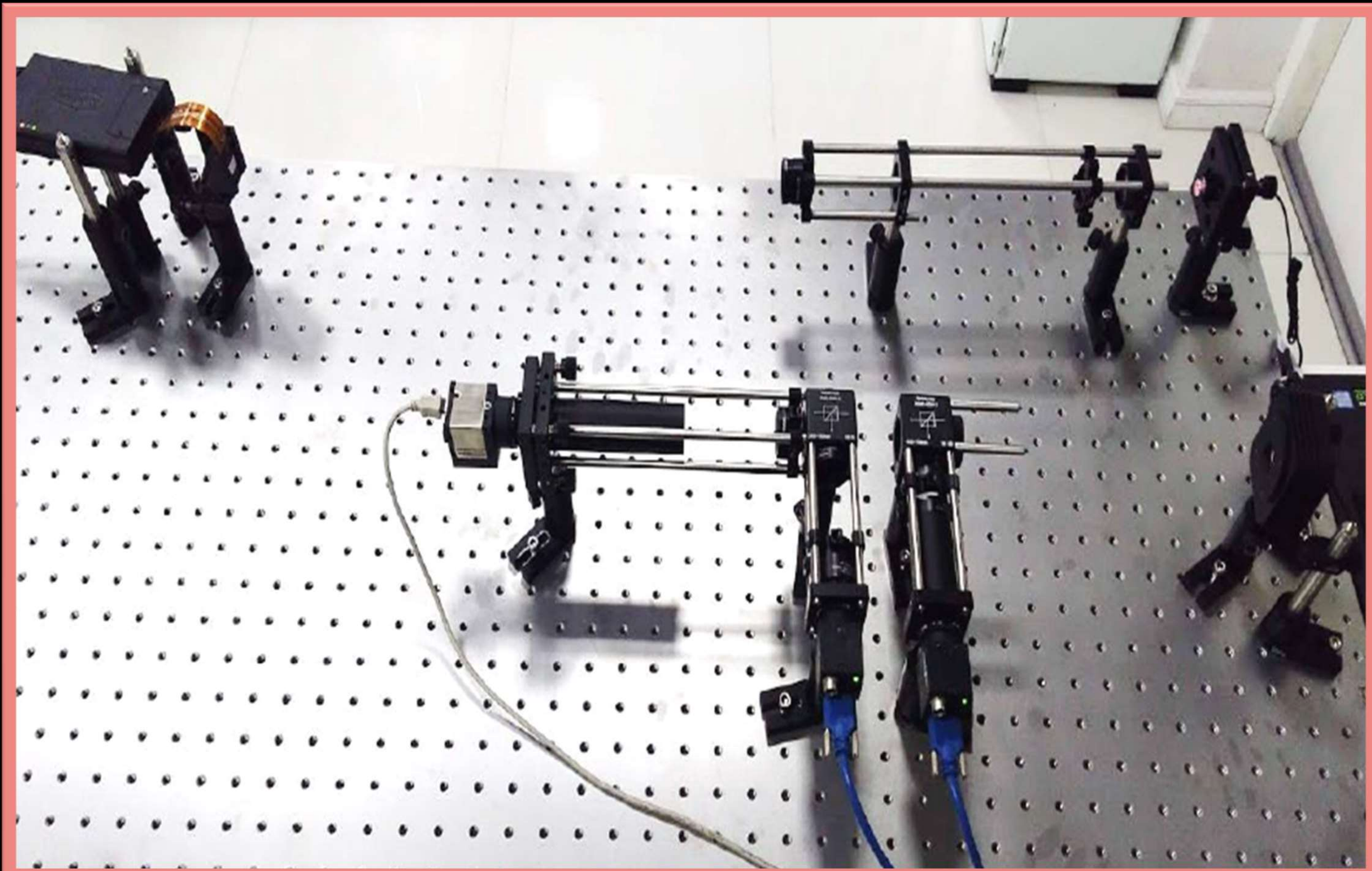
DLWFS IN ACTION



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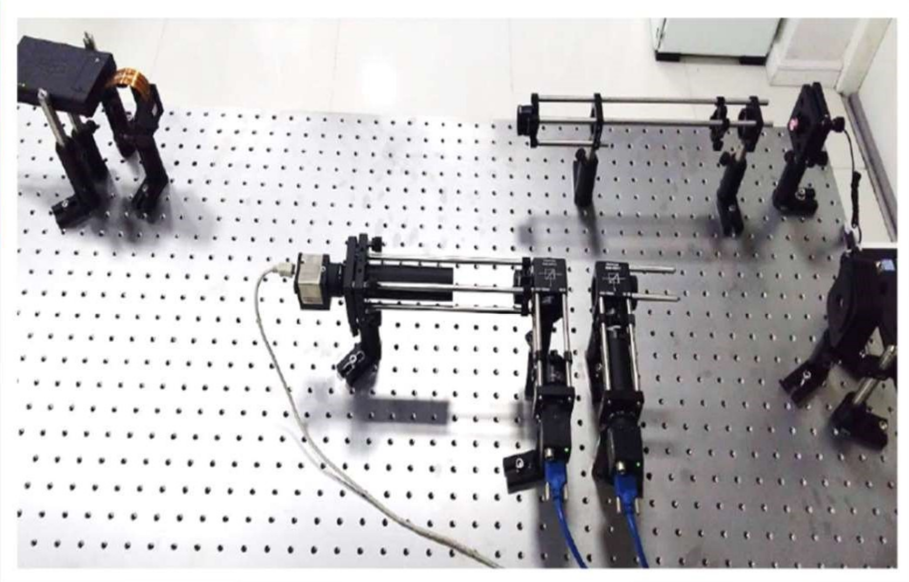

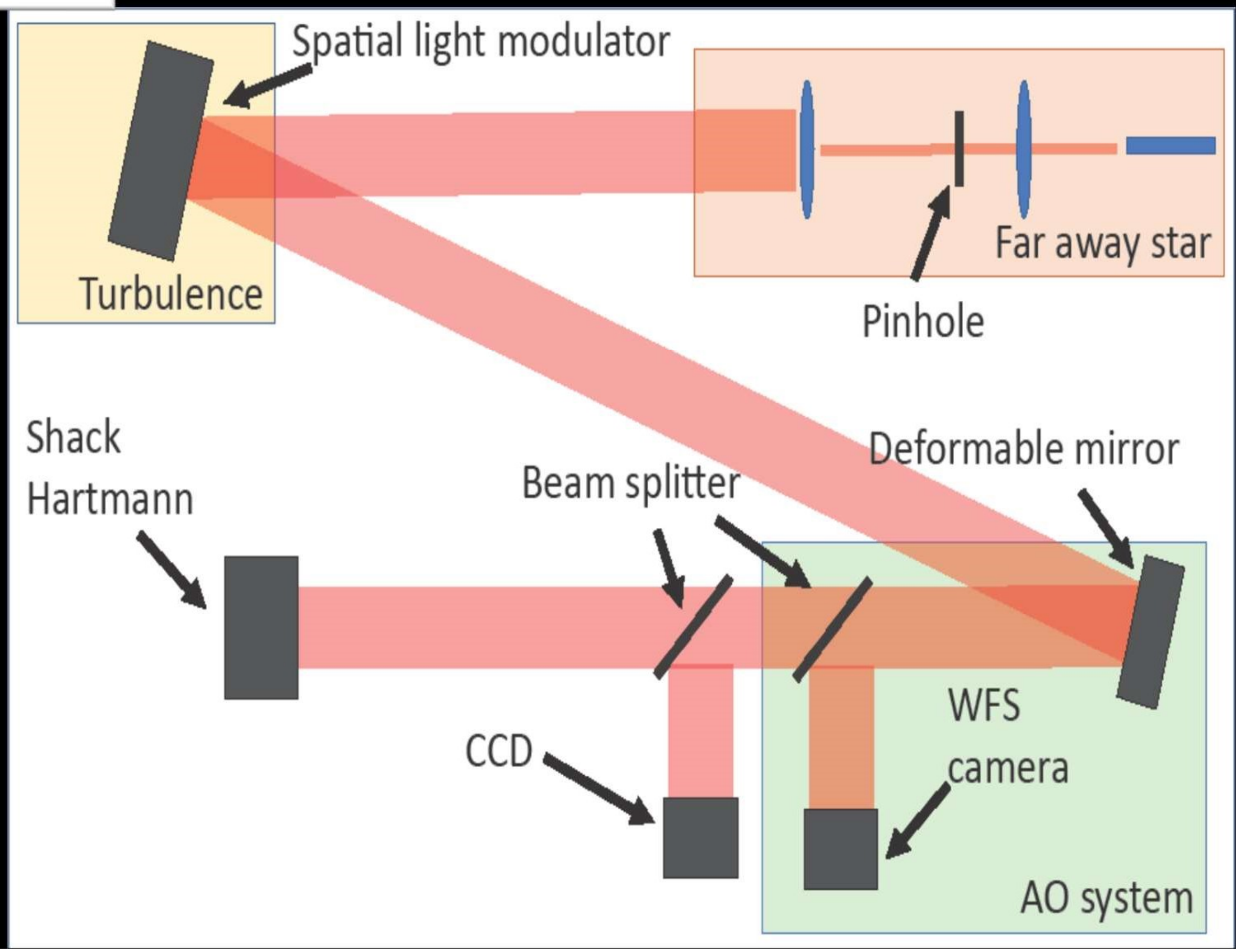

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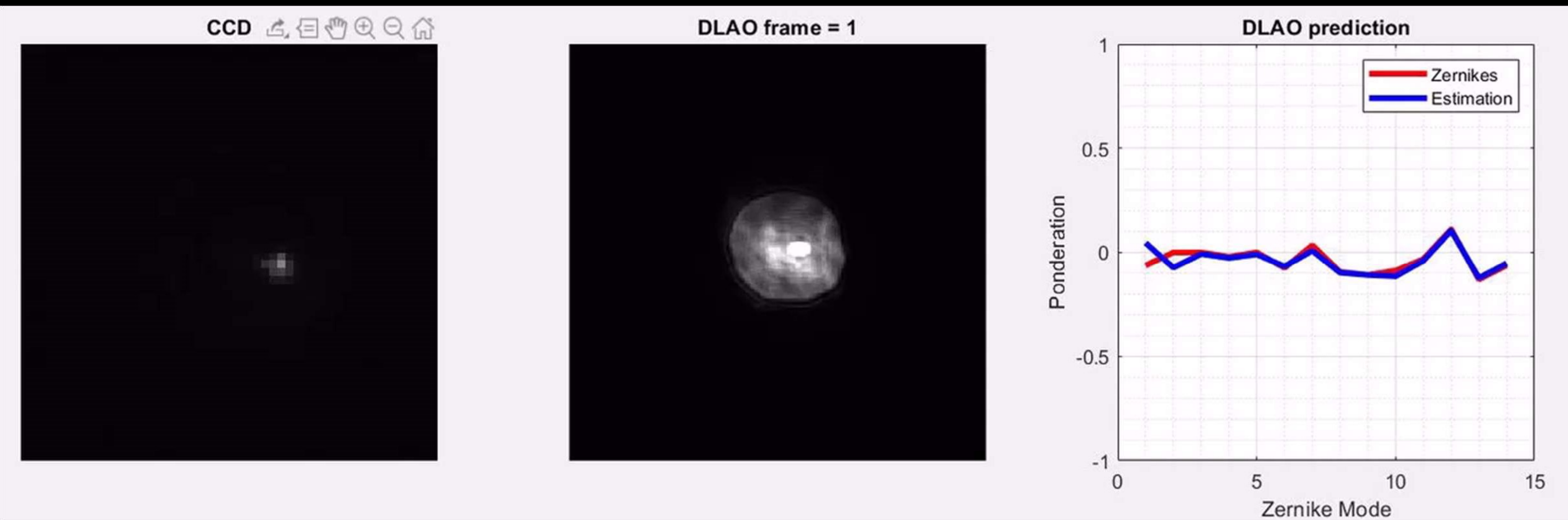
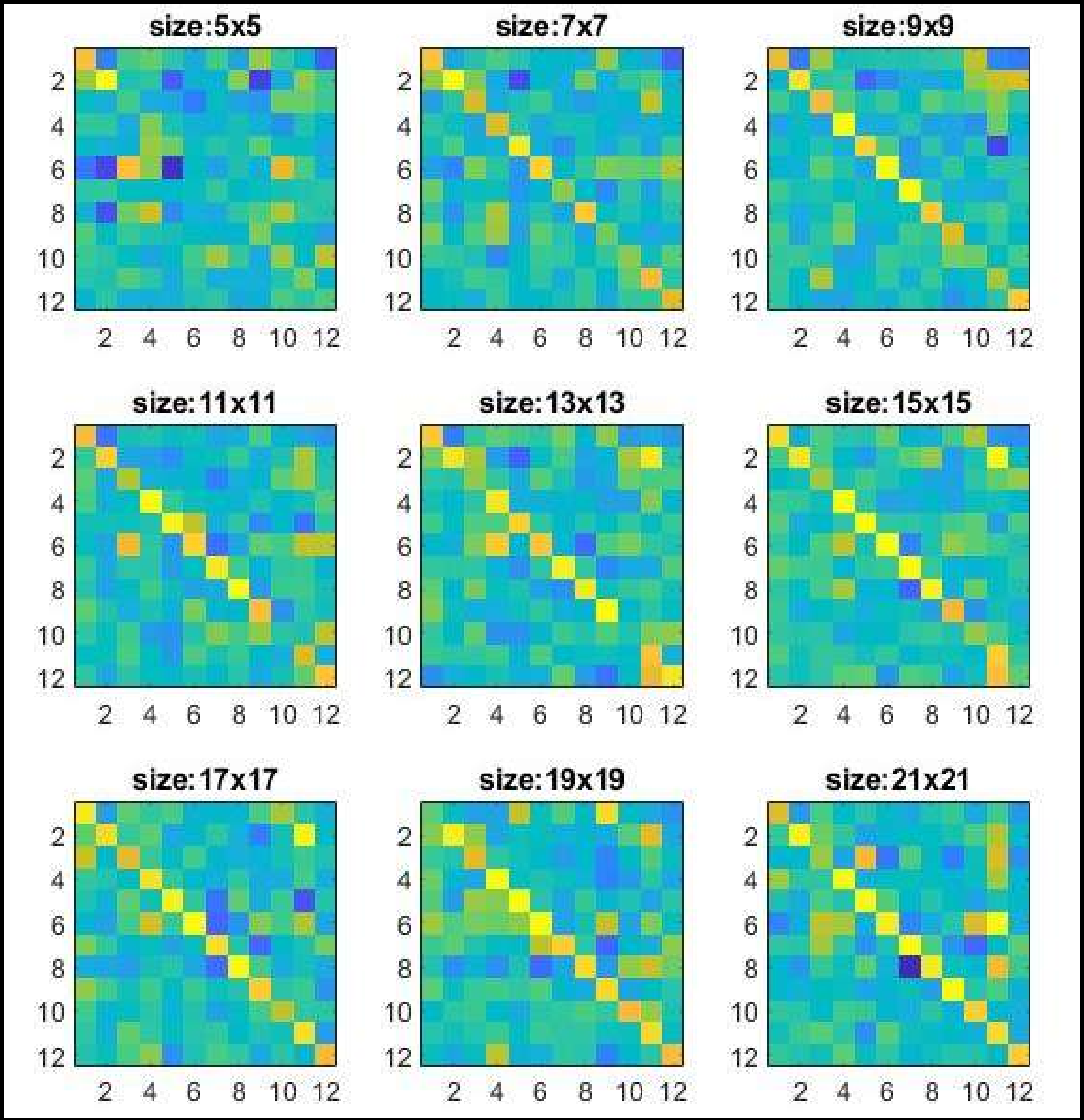


FASTER TRAINING?

ARE THERE SIMPLER CONVOLUTIONAL NEURAL NETWORKS?
3DNET

HOW MANY PIXELS WE ACTUALLY NEED?
RELATED TO NUMBER OF ZERNIKE MODES?

DWLFS WITH 3DNET: 50.000 TRAINING SAMPLES



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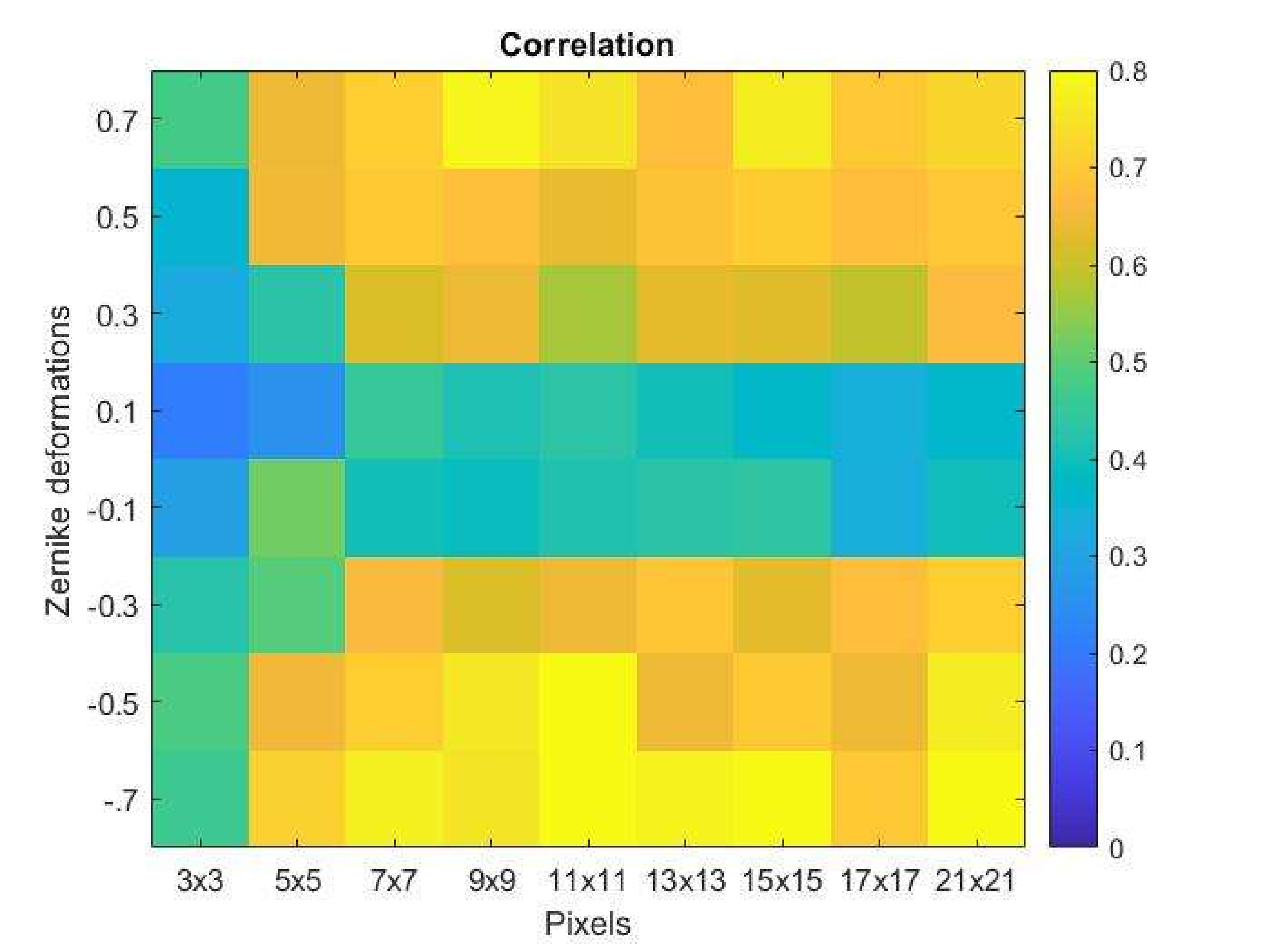

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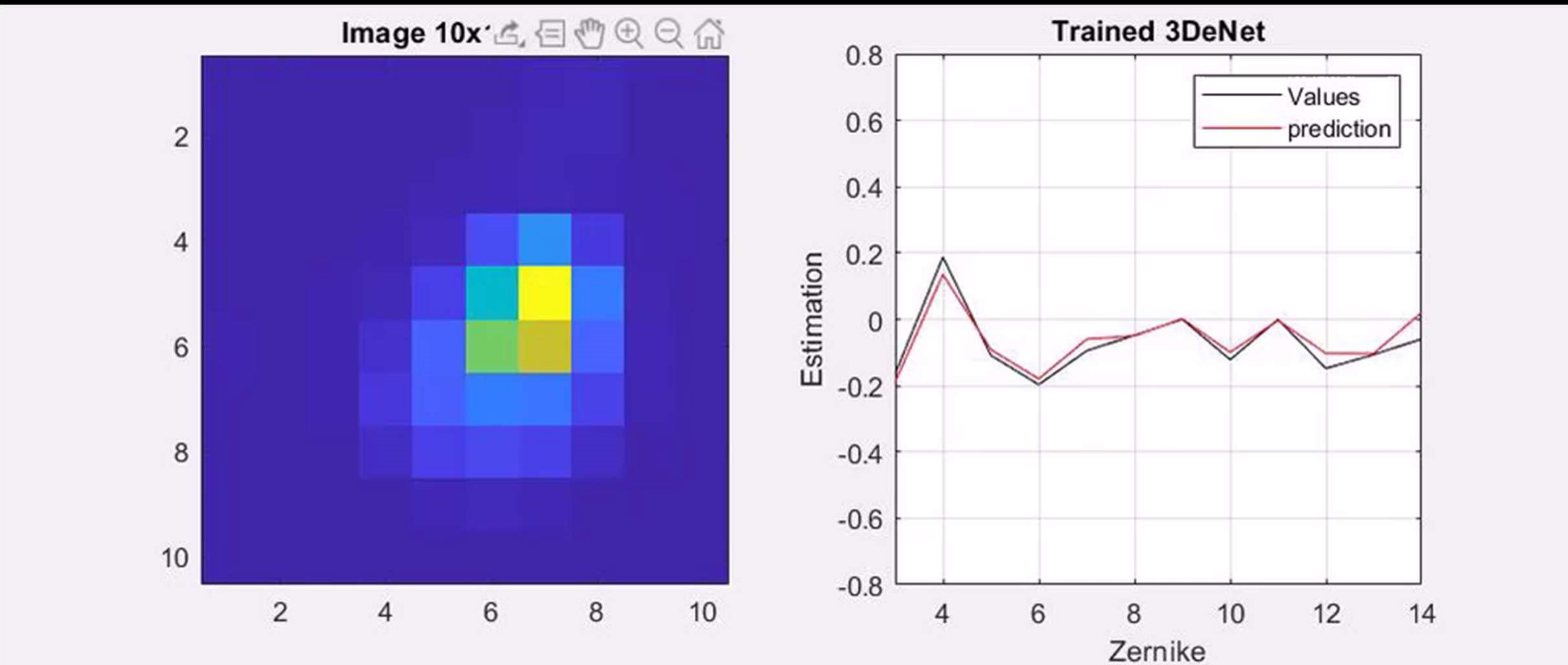

CONCLUSIONS

- Wavefront sensing can be seen as the retrieval of a phase fluctuation from an intensity measurement
- As an inverse problem, it can be solved by mathematical modeling or machine learning (black box modeling)
- Deep neural networks are novel modeling tools for a variety of tasks such as detection, classification and regression, requiring an intensive training stage
- We can use deep learning to train a model that is able to estimate Zernike modes out from intensity measurements, which gives flexibility to the optical system design
- We demonstrate that deep learning can become useful for image-based WFS, while simple optical transformations such as defocus can dramatically boost the performance
- The DLWFS can even be train to estimate wavefront disturbances even if the incoming light came from extended objects

FURTHER WORK

- SPEED or ACCURACY?
- Explore novel neural network architectures that may alleviate training time without sacrificing accuracy
- Understand the balance of sampling pixels and phase resolution, or number of Zernike modes
- Use pretrained neural networks using simulations, then update weights based in just a few as-built training samples
- Explore what could be the best optical transformation or plane where to make the most informative measurements
- Close the loop

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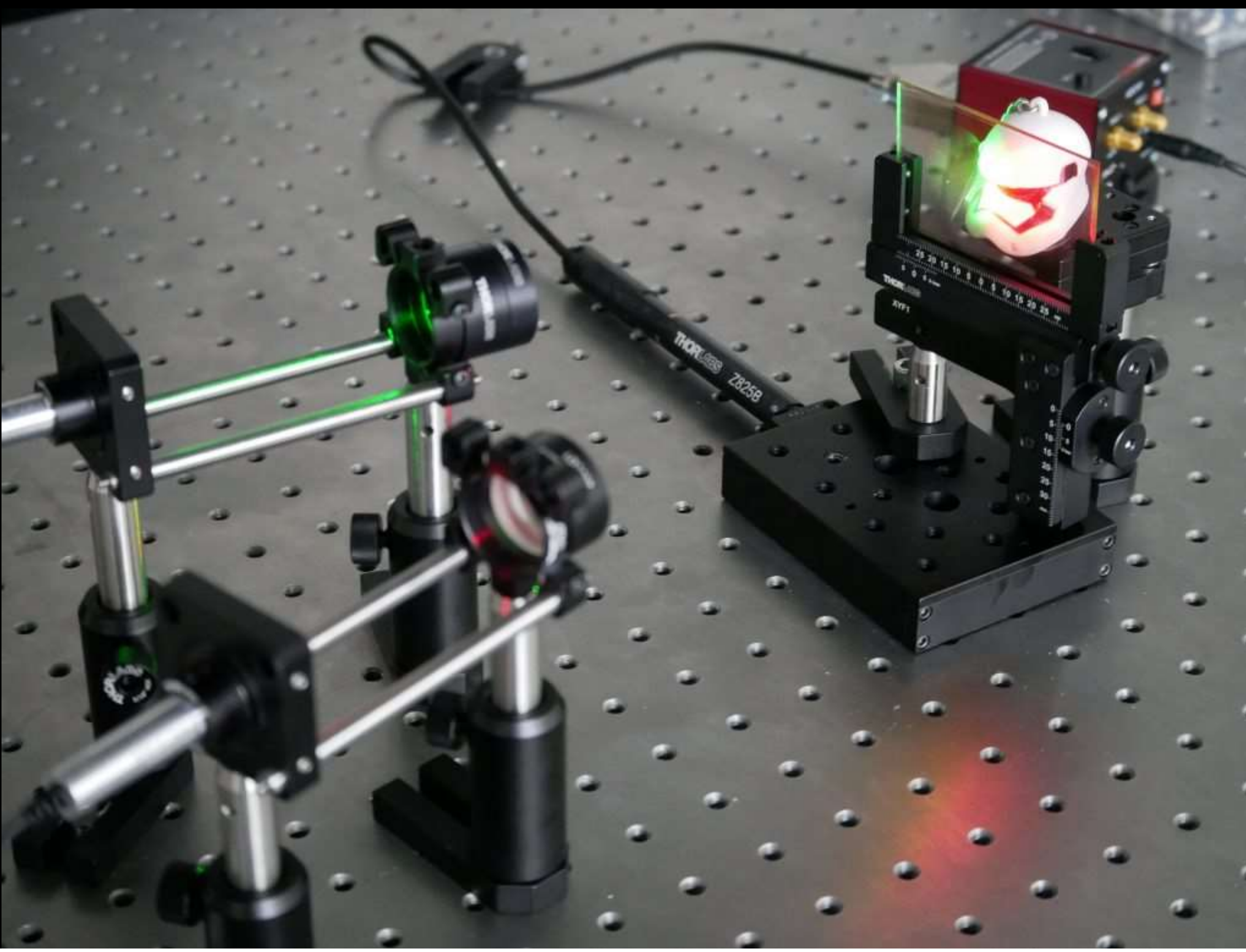

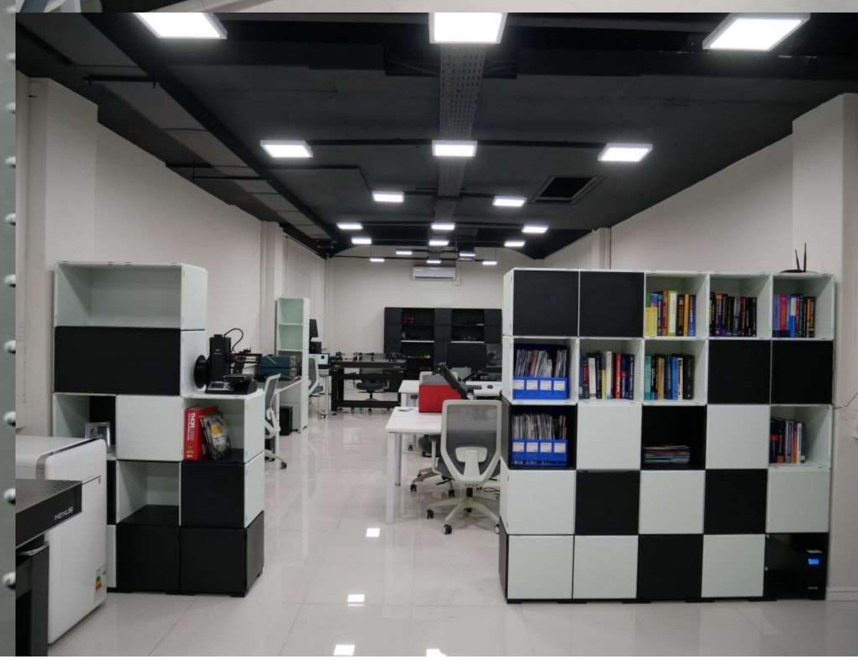

OPTOELECTRONICS LAB VISION

Research and Development of Computational Imaging Systems

Design of disruptive, non-traditional imaging systems to efficiently capture the maximum amount of optical information

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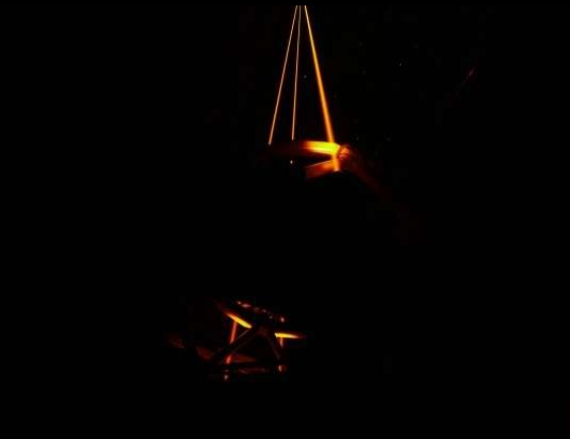

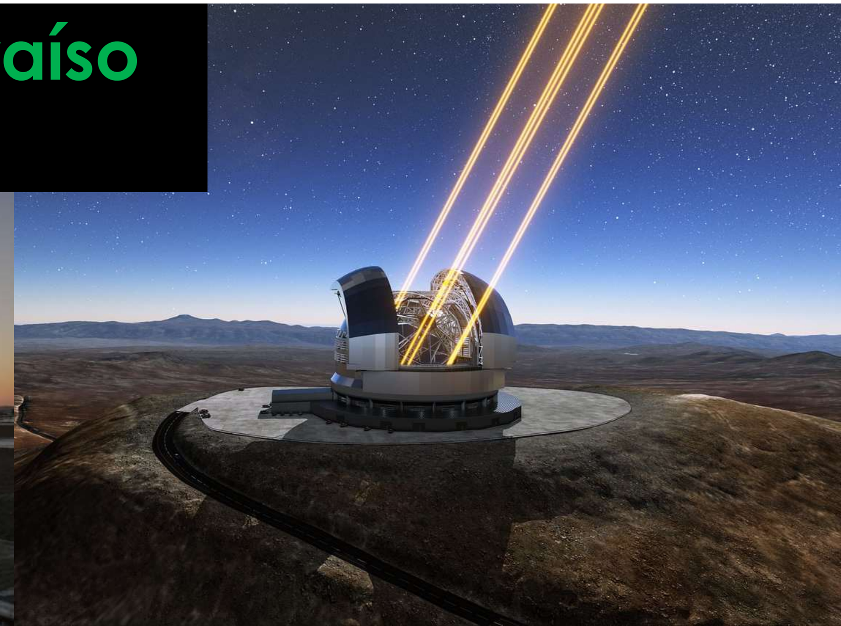

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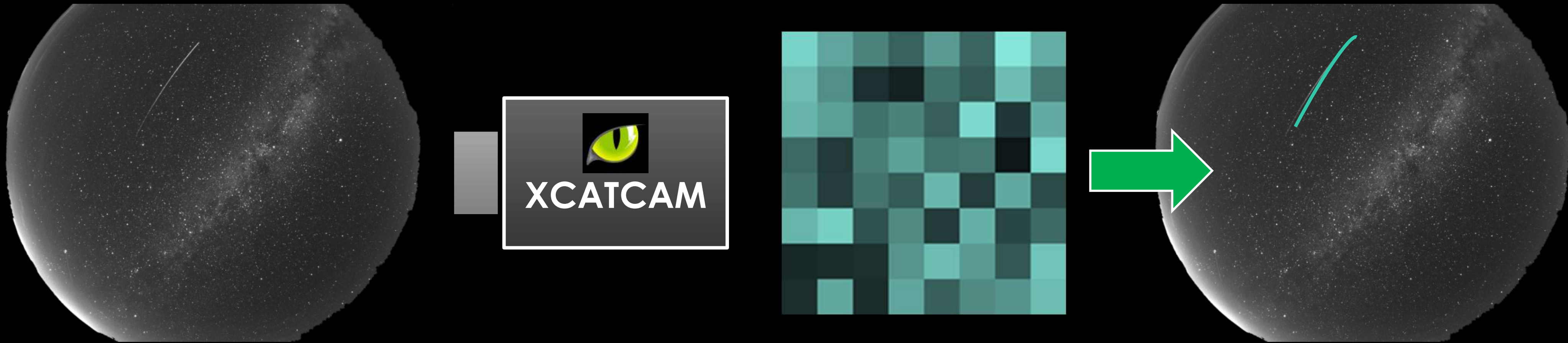

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