



# Automatic Estimation of Modulation Transfer Functions

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<sup>3</sup>Amazon Research

May 5, 2018

# Automatic Estimation of Modulation Transfer Functions

This project is joint work with



**Valentin Volchkov**



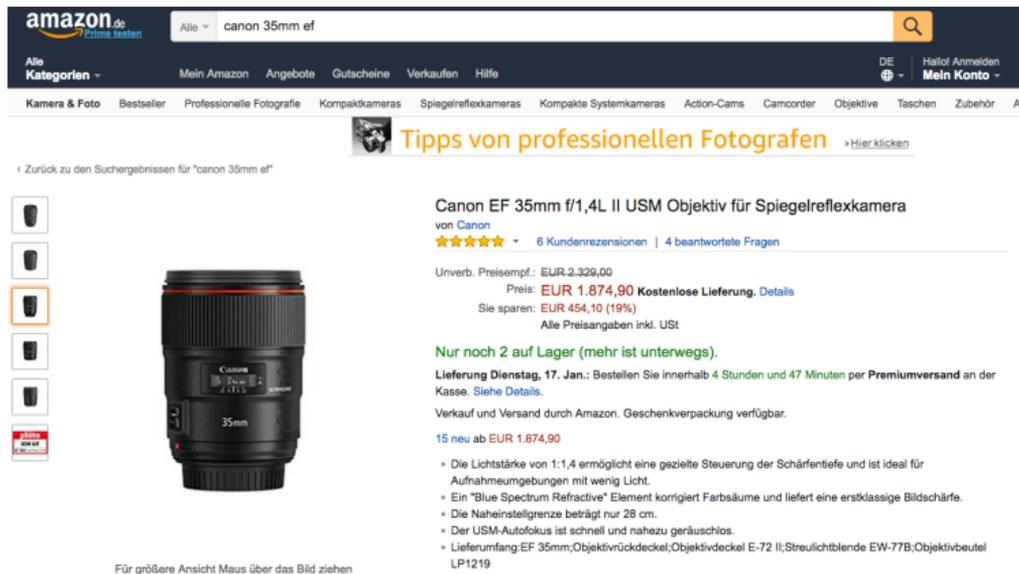
**Michael Hirsch**



**Bernhard Schölkopf**



# How good is this lens?



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Für größere Ansicht Maus über das Bild ziehen

**Canon EF 35mm f/1,4L II USM Objektiv für Spiegelreflexkamera**  
von Canon  
★★★★★ 6 Kundenrezensionen | 4 beantwortete Fragen

Unverb. Preisempf.: EUR 2.329,00  
Preis: **EUR 1.874,90** **Kostenlose Lieferung.** [Details](#)  
Sie sparen: **EUR 454,10 (19%)**  
Alle Preisangaben inkl. USt

**Nur noch 2 auf Lager (mehr ist unterwegs).**

**Lieferung Dienstag, 17. Jan.:** Bestellen Sie innerhalb **4 Stunden und 47 Minuten** per **Premiumversand** an der Kasse. [Siehe Details.](#)

Verkauf und Versand durch Amazon. Geschenkverpackung verfügbar.

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- Die Lichtstärke von 1:1,4 ermöglicht eine gezielte Steuerung der Schärfentiefe und ist ideal für Aufnahmeumgebungen mit wenig Licht.
- Ein "Blue Spectrum Refractive" Element korrigiert Farbsäume und liefert eine erstklassige Bildschärfe.
- Die Naheinstellgrenze beträgt nur 28 cm.
- Der USM-Autofokus ist schnell und nahezu geräuschlos.
- Lieferumfang: EF 35mm; Objektivrückdeckel; Objektivdeckel E-72 II; Streulichtblende EW-77B; Objektivbeutel LP1219

► Lens quality is determined by **optical aberrations**

# Optical aberrations are spatially varying

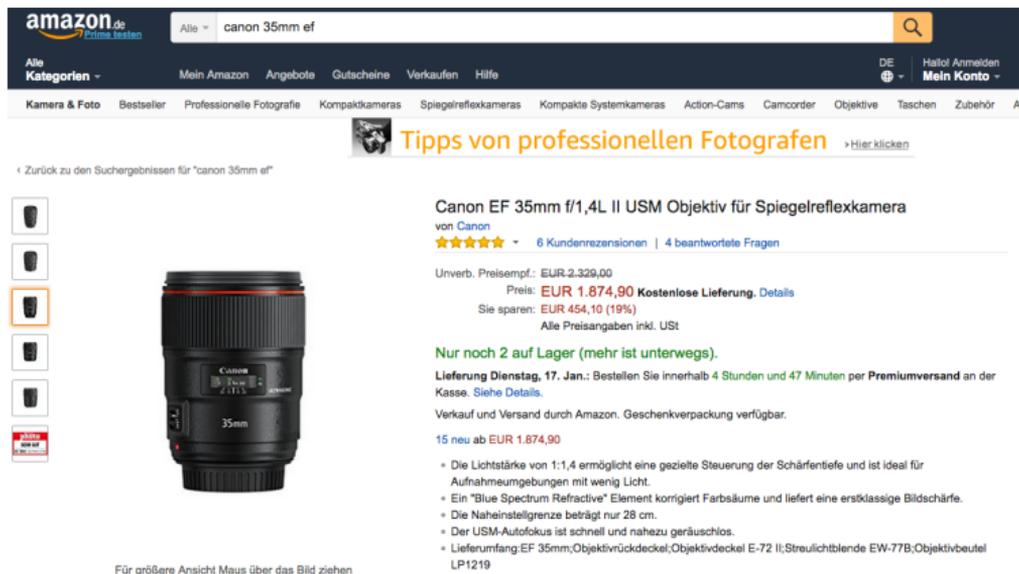


# Optical aberrations are spatially varying



Optical aberrations can be characterised by the *point spread function* (PSF)

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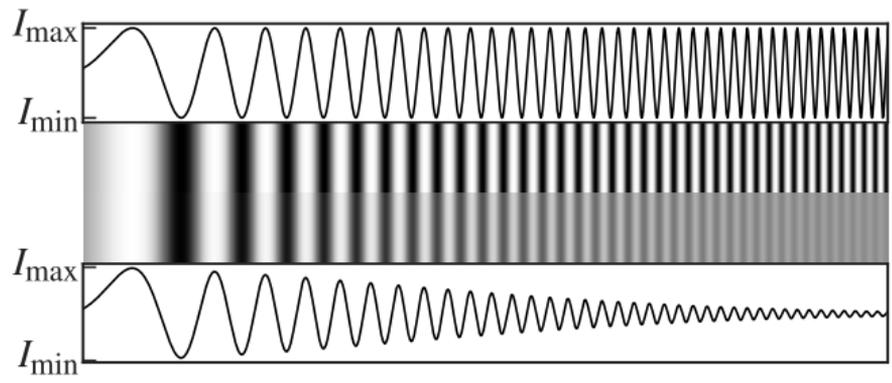
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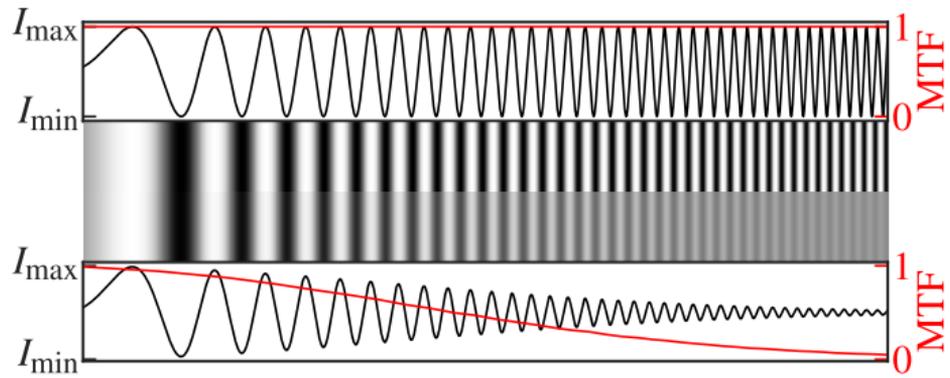
- ▶ Lens quality is determined by **optical aberrations** (spatially varying PSF)
- ▶ Related and normalised quality measure: **Modulation Transfer Function (MTF)**

**What is the MTF?**

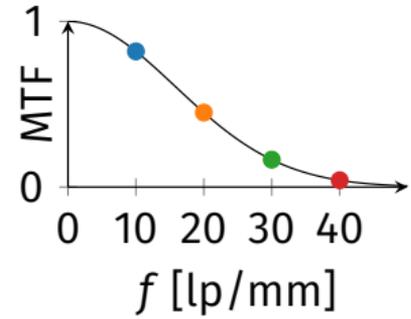
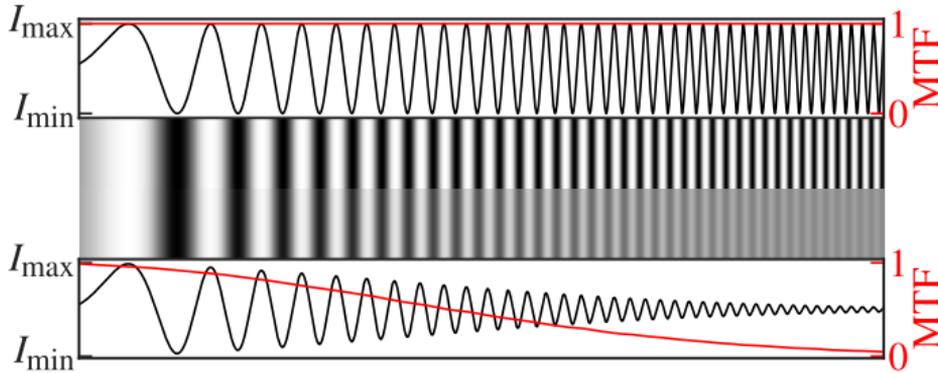
# The local MTF characterises diminished relative contrast



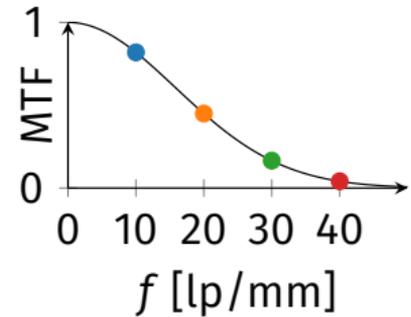
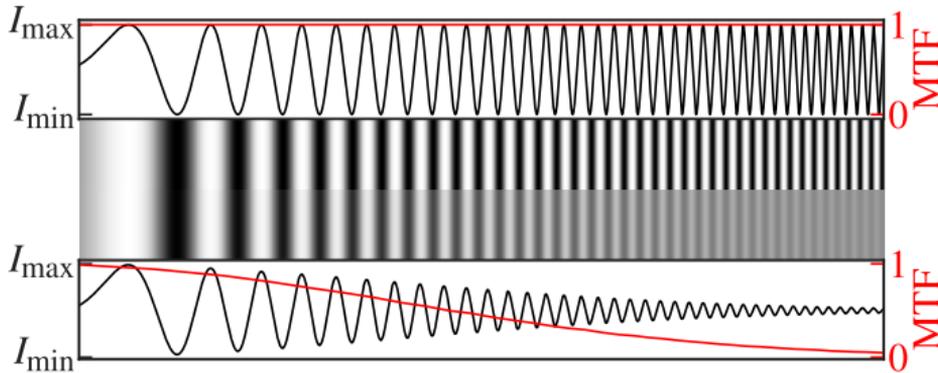
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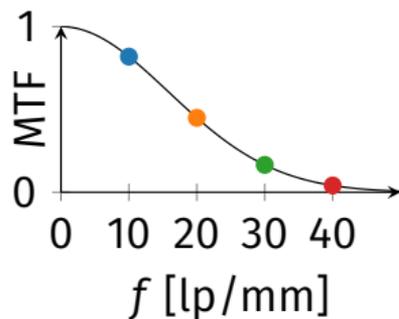
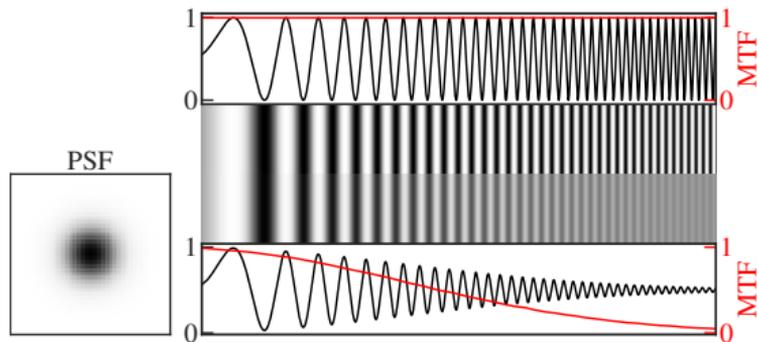
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## MTF as normalised diminished relative contrast

$$C(f) = \frac{I_{\max}(f) - I_{\min}(f)}{I_{\max}(f) + I_{\min}(f)} \quad \text{MTF}(f) = \frac{C(f)}{C(0)} \in [0, 1]$$

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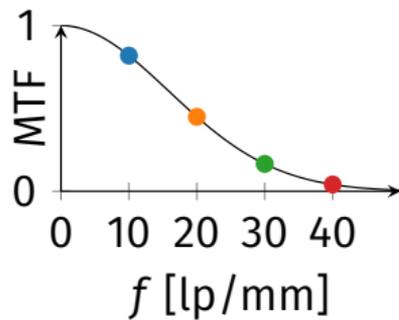
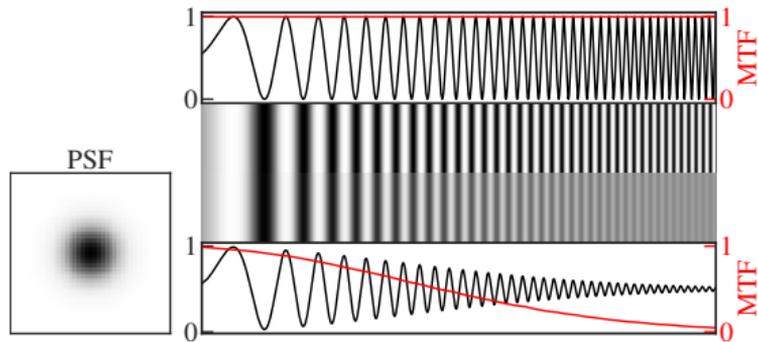
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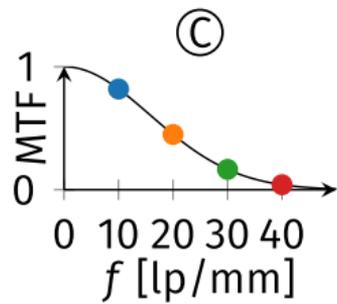
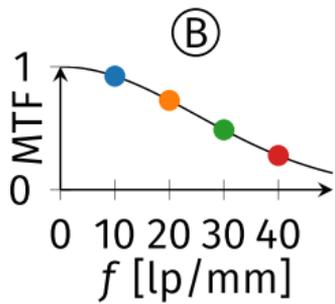
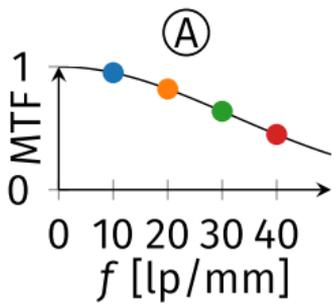
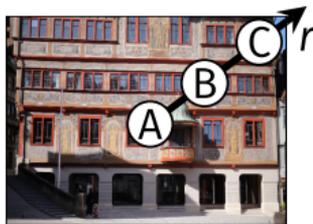
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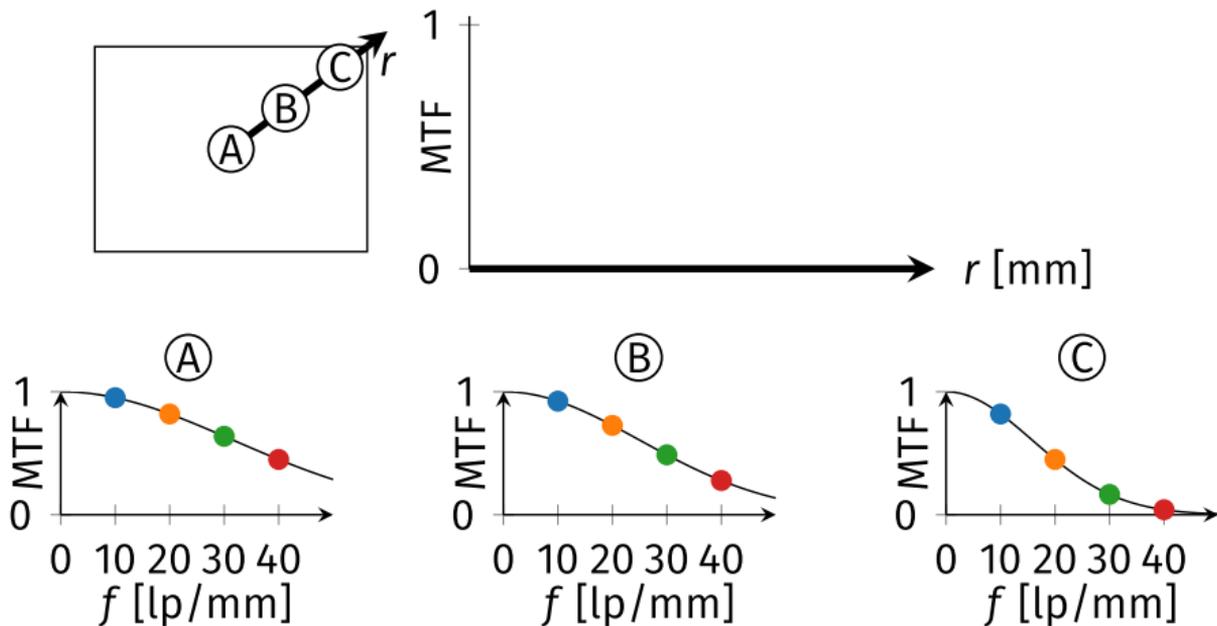
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Aggregate local MTF values into global MTF charts

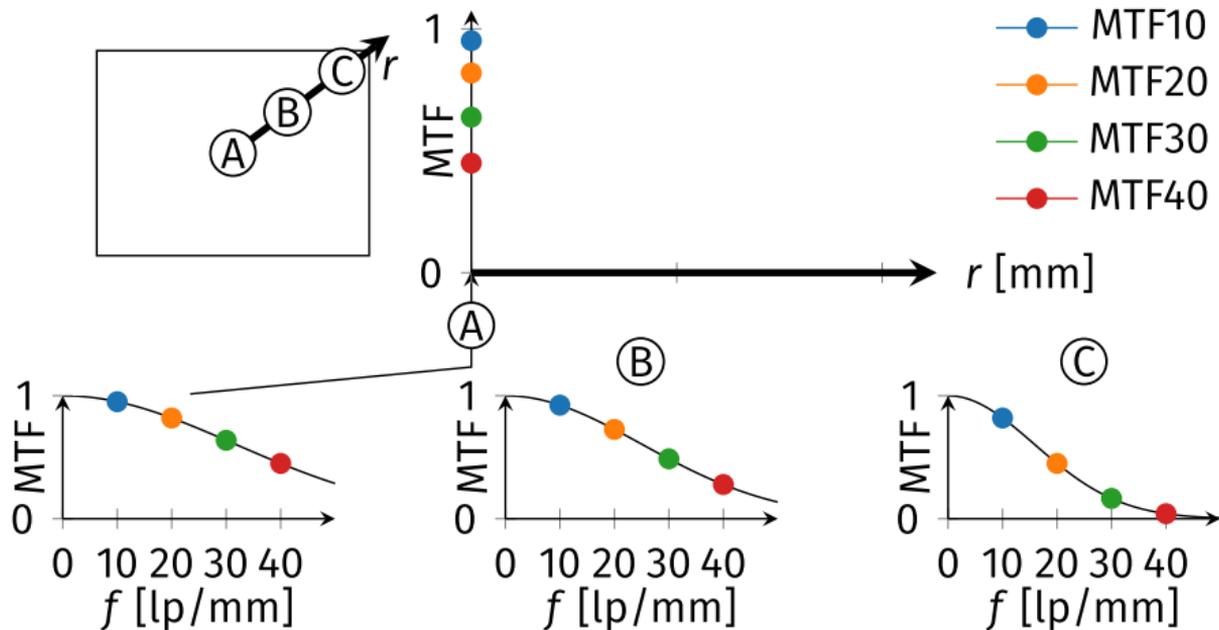
# Aggregate local MTF curves into global MTF charts



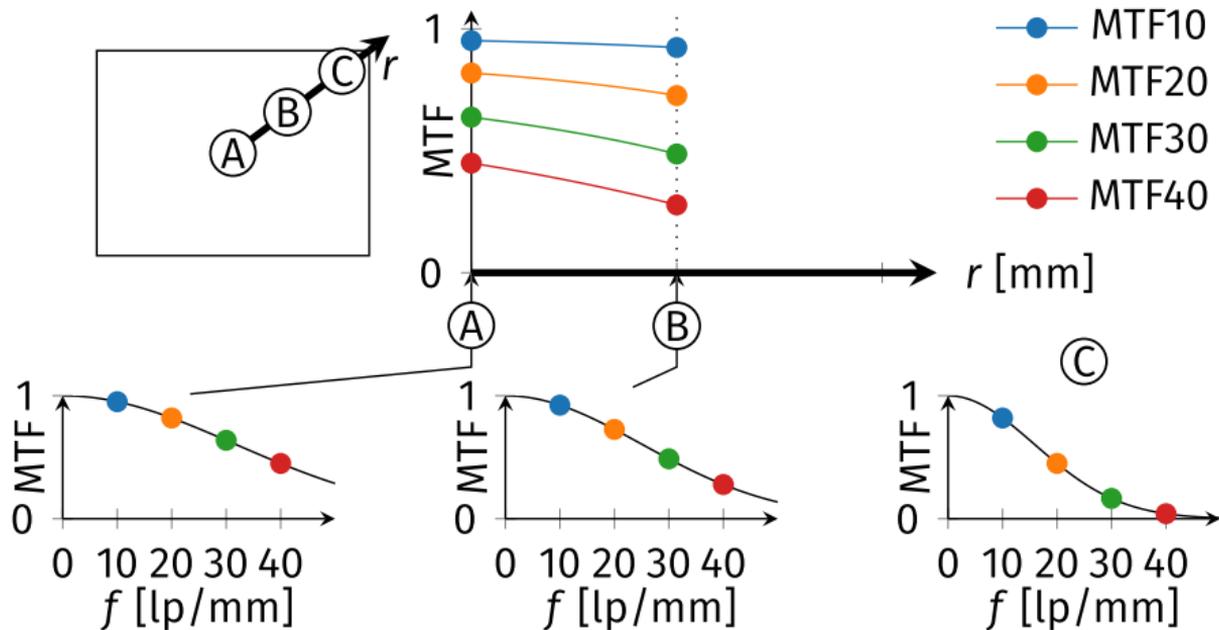
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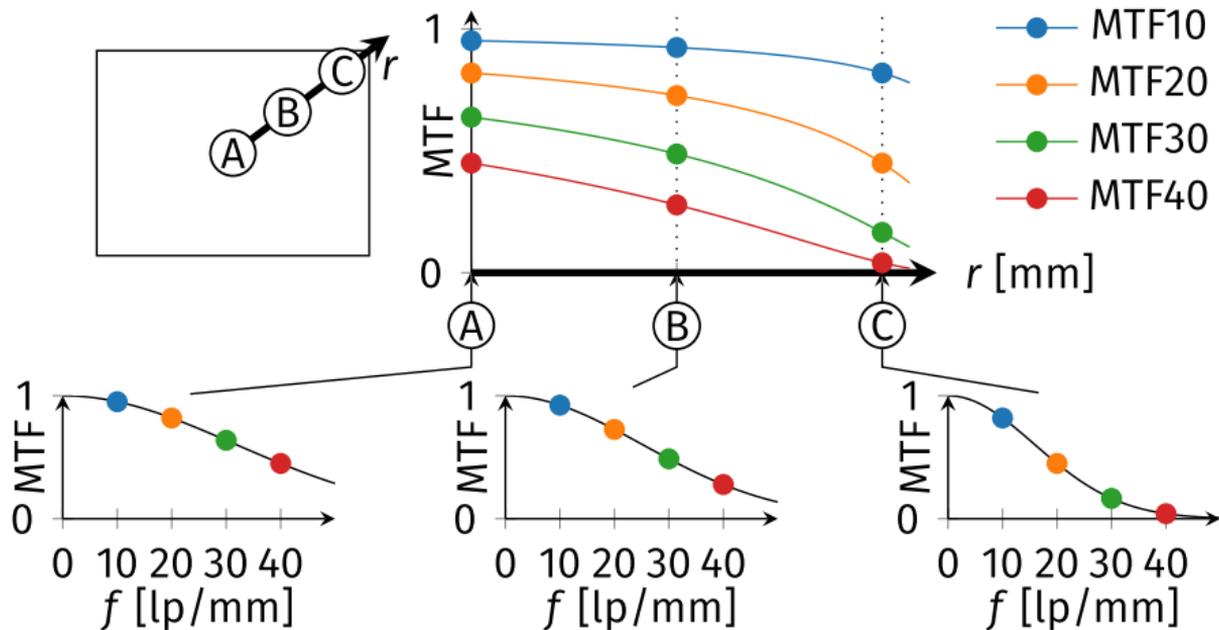
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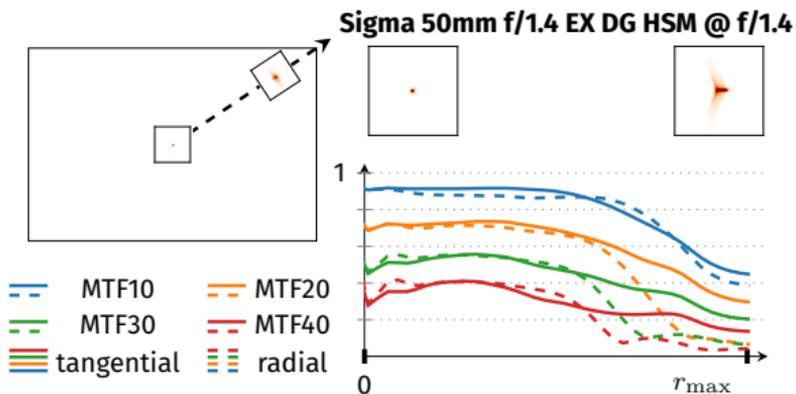
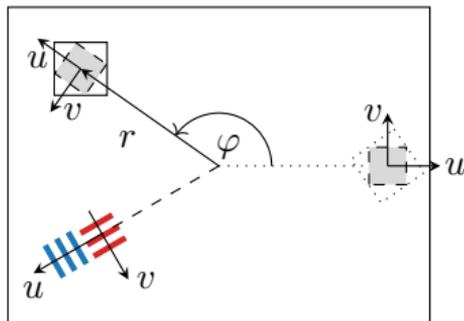
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# Global MTF Charts: Radial and Tangential MTF

 measure the *radial MTF* ()

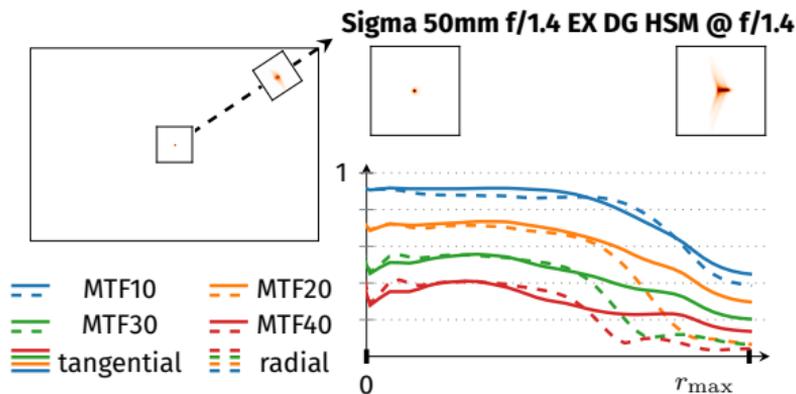
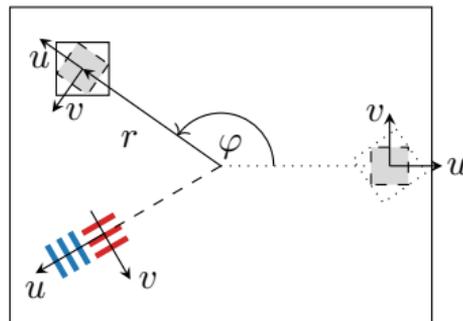
 measure the *tangential MTF* ()



# Global MTF Charts: Radial and Tangential MTF

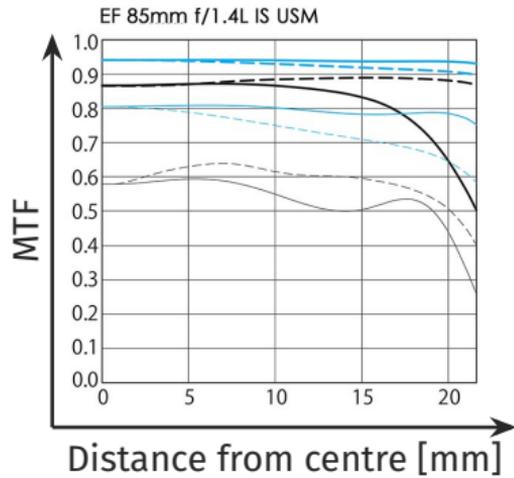
 measure the *radial MTF* ()

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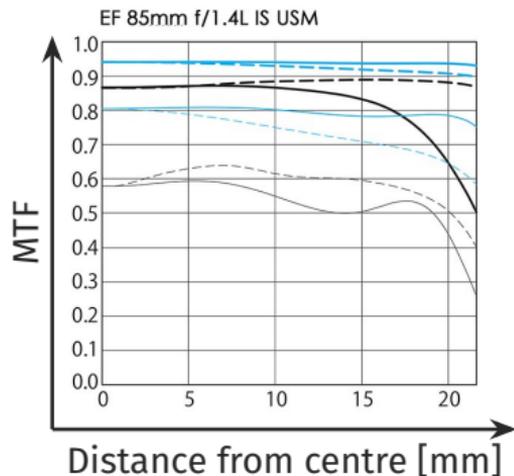


Lens manufacturers provide MTF charts

# How good is this lens?



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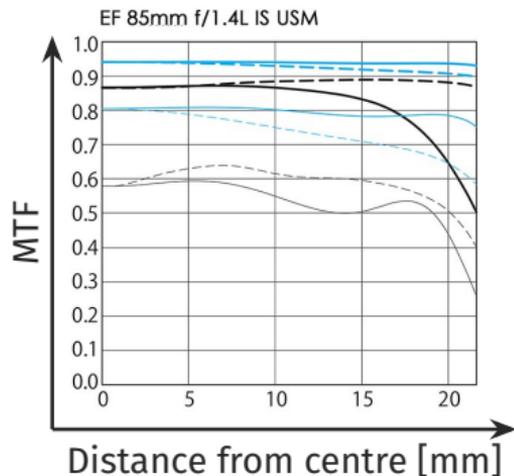


## How good is your lens? Assessing performance with MTF full-field displays

BRANDON DUBE,<sup>1,2,\*</sup> ROGER CICALA,<sup>1</sup> AARON CLOSZ,<sup>1</sup> AND JANNICK P. ROLLAND<sup>2</sup>

- ▶ Large variability between different specimens of the same lens
- ▶ Lenses often surprisingly asymmetric

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Want the MTF curve for a specific specimen of a lens

# Photometric MTF measurements

## Typical techniques used for lens quality assessment

← **simple/cheap**

- ▶ visual inspection of images

▶ **MTF test charts**

**complex/expensive** →

- ▶ wavefront sensor
- ▶ professional MTF testing station

← **qualitative**

**quantitative** →

### **MTF test charts**

- ▶ Several methods:
  - ▶ Slanted edge [Burns2000]
  - ▶ Dead leaves
  - ▶ Siemens stars [Loebich2007]
- ▶ DxO, imatest, Image Engineering, ...

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**Lens quality assessment is laborious and requires equipment**

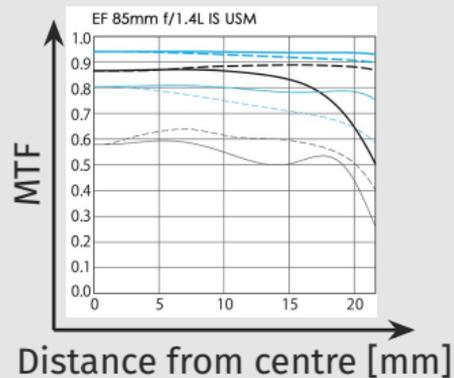
# Our approach: Estimate MTF blindly from photographs

This work: A learning system for MTF estimation from photographs



unprocessed photographs

Learning  
system



global MTF chart

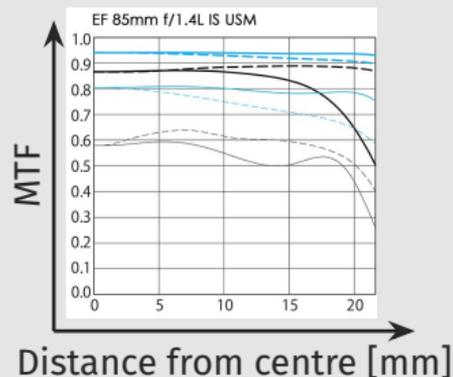
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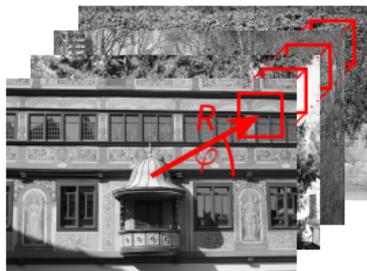
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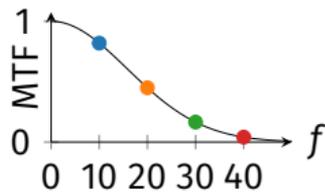
- ▶ Photographs contain ample information about lens properties
- ▶ Information is confounded with image statistics of unknown scenes
- ▶ Lens properties are the same for different motives

# Overview of our learning system



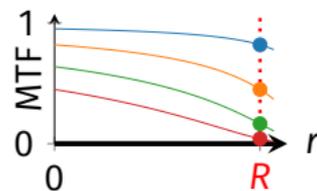
Patch extraction

at position  $(R, \varphi)$



Local MTF estimation

in direction  $\varphi$

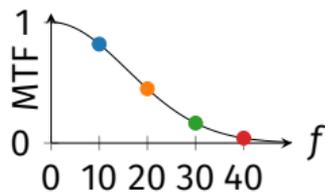


Global MTF aggregation

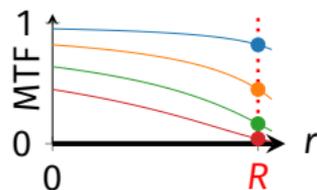
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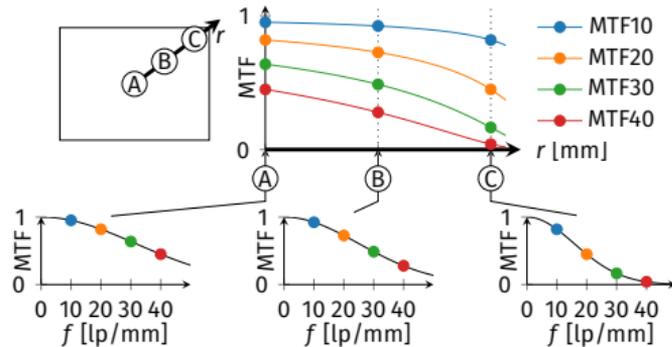
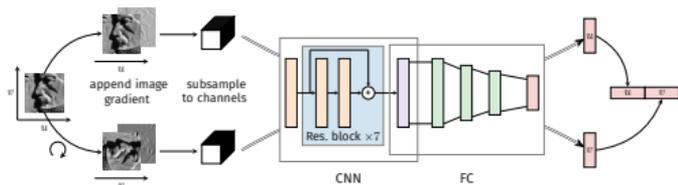
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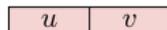
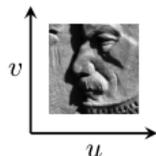
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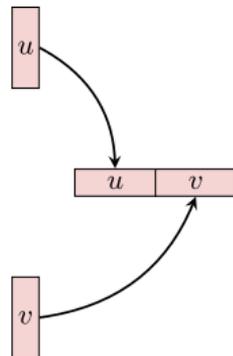
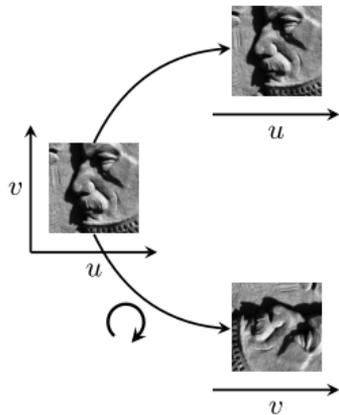


# Local MTF Estimation: Network Architecture



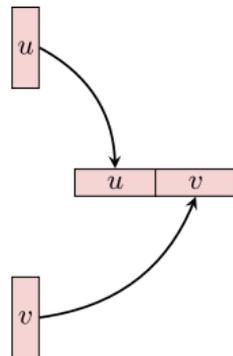
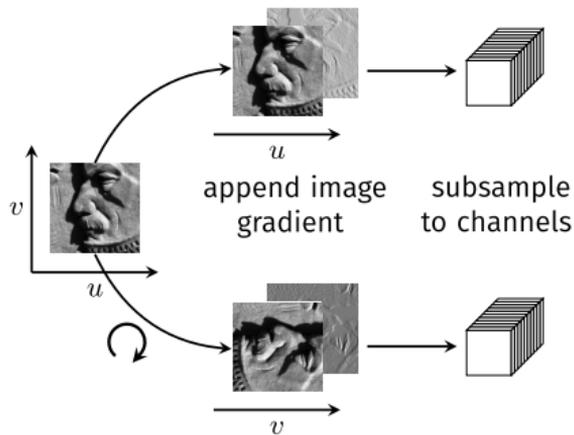
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- ▶ **Outputs:** MTF10, MTF20, MTF30, MTF40 (tangential and radial)

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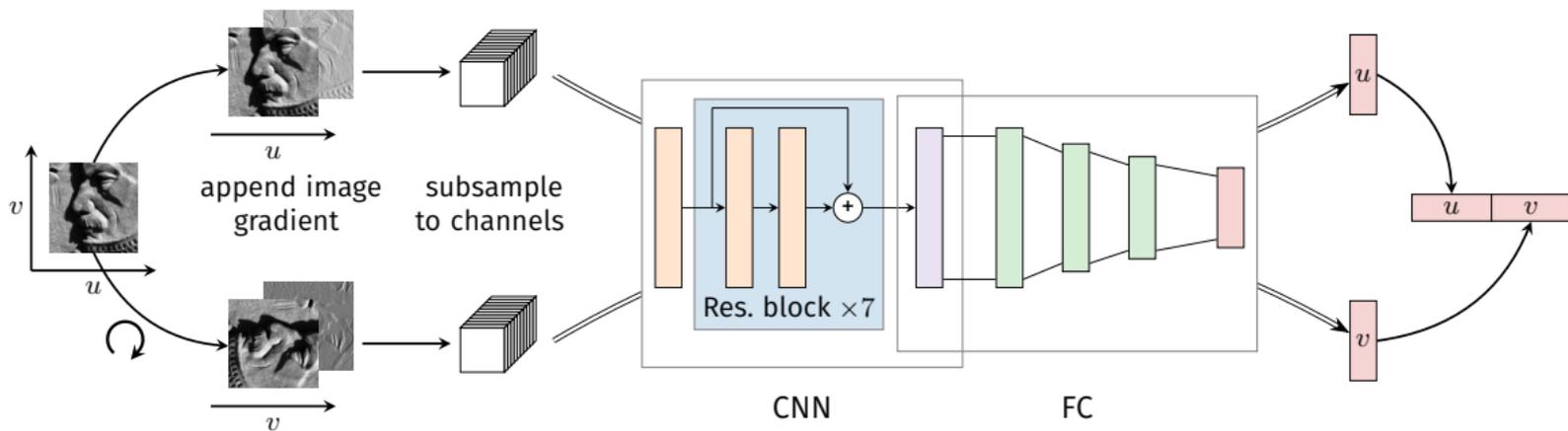
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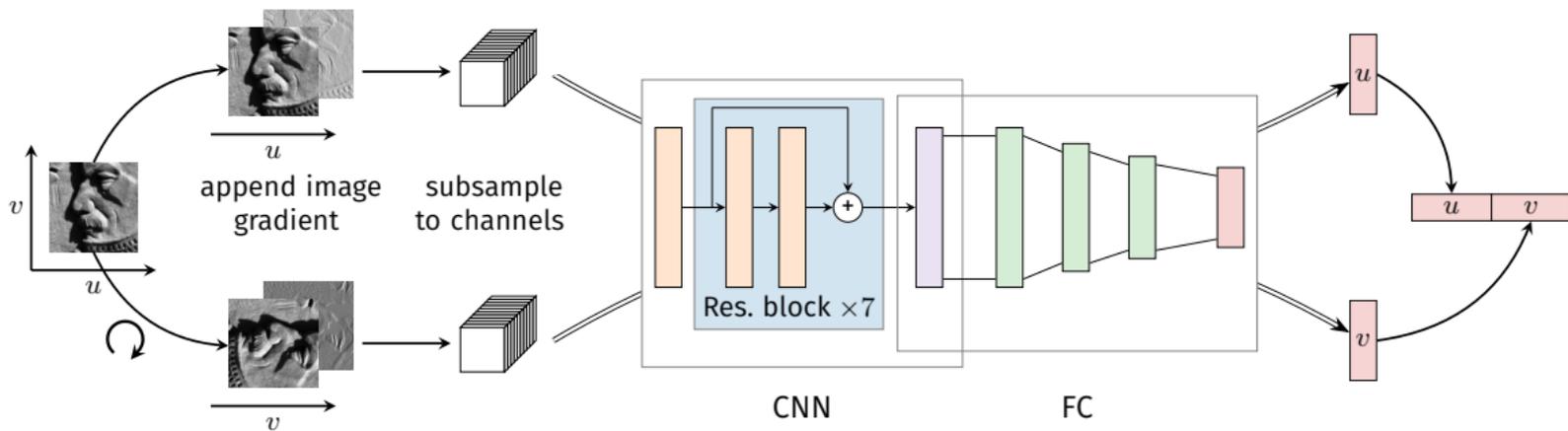
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- ▶ **Initial data processing:** Rotation, image gradient, subsampling into channels
- ▶ **DNN** with convolutional residual blocks and fully connected layers
- ▶ **Treat multiple input patches**  
Compute the intermediate feature representation separately and average them in feature space (similar to “Deep Sets” [Zaheer 2017])

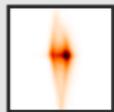
# Train the Local Estimation Network on synthetically blurred patches

## Set up a supervised training task

Input: Synthetically blurred patches



\*



Output: MTF values of the blur



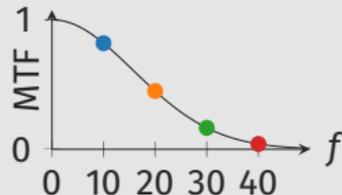
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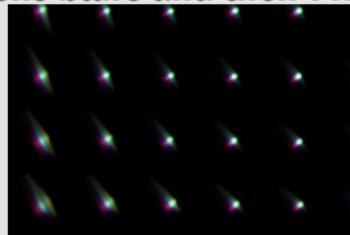
## Required training and validation data

Sharp image patches



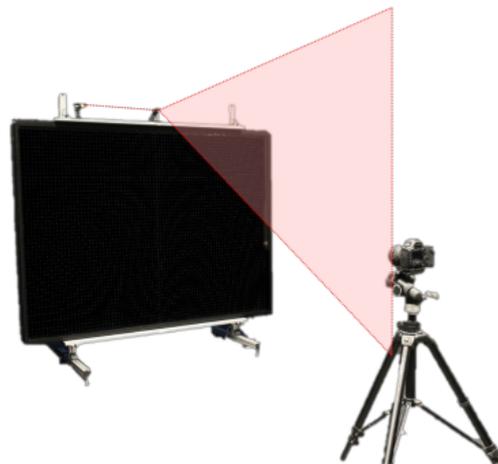
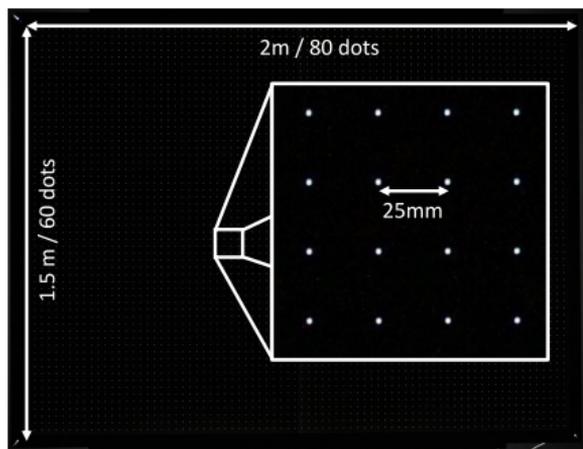
- ▶ regular patterns [Joshi 2008]
- ▶ patches from photos in the wild

Lens blurs and their MTFs



- ▶ Record lens blurs with custom pinhole array

# Record ground truth PSFs/MTFs using a self-made pinhole array



- ▶ Custom-built pinhole array to efficiently and accurately record PSFs
- ▶ Image of a point light source is the PSF
- ▶ Record  $80 \times 60 = 4800$  PSFs per lens and setting over the entire field of view

**New dataset of real PSFs for aberrated lenses**

# Experiments: Estimate MTF charts from three types of images

- ① **Synthetically blurred patterns** (same as training but with unseen blurs)
- ② **Photographs of printouts** of the test pattern (similar to a test chart)

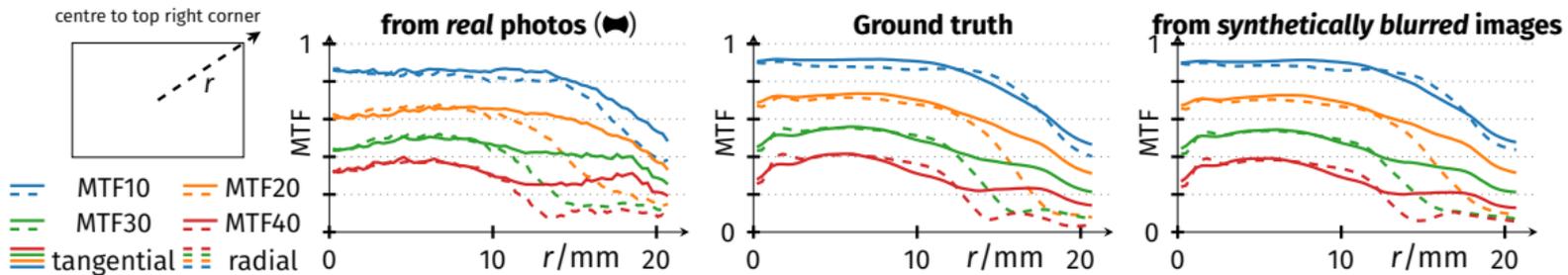


- ③ **Photographs of natural scenes** in the wild

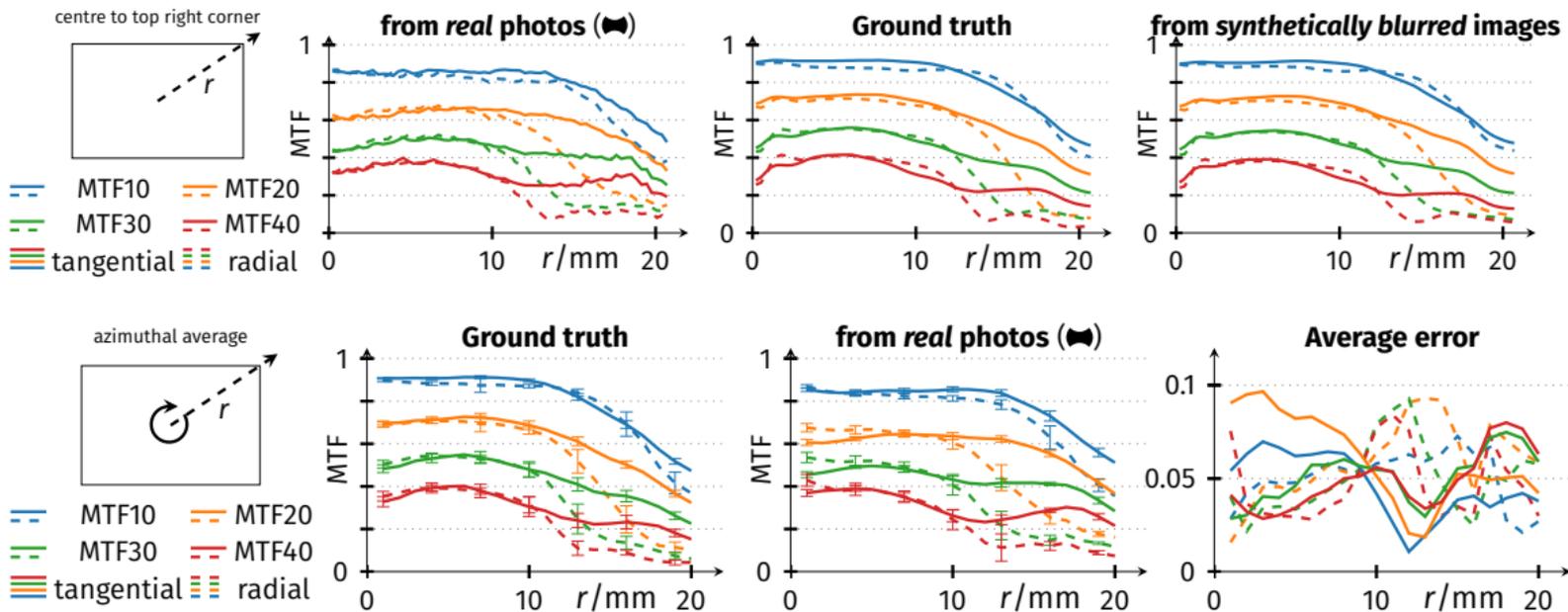


All results for the same lens (Sigma 50mm f/1.4 EX DG HSM @ f/1.4)

# 1 + 2 Results on the test pattern



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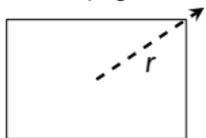


- ▶ Estimation from synthetically blurred patches almost perfect (for all lenses)
- ▶ Very good quantitative and qualitative agreement
- ▶ Estimation errors for other lenses typically similar

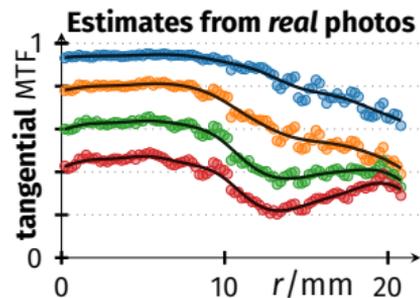
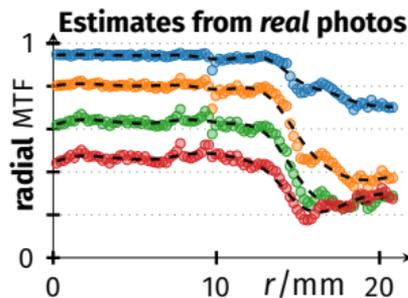
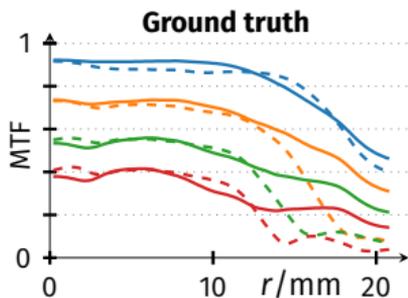
### 3 Results on natural scenes



centre to top right corner



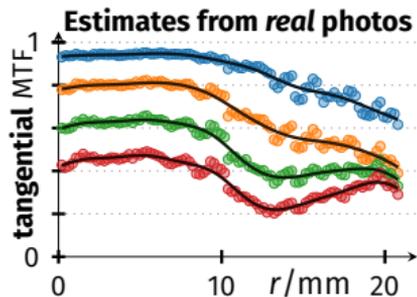
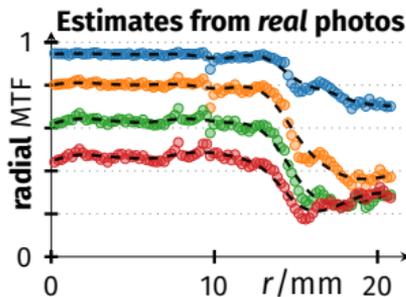
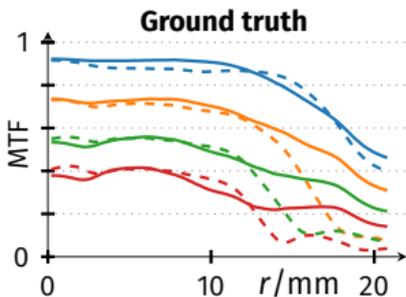
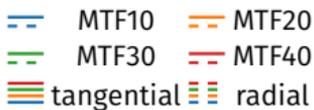
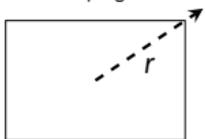
- MTF10
- MTF20
- MTF30
- MTF40
- tangential
- radial



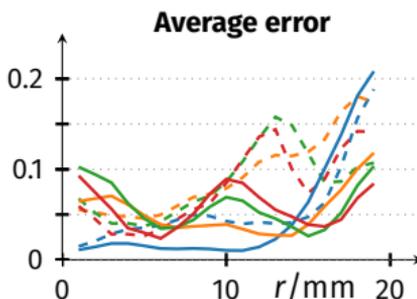
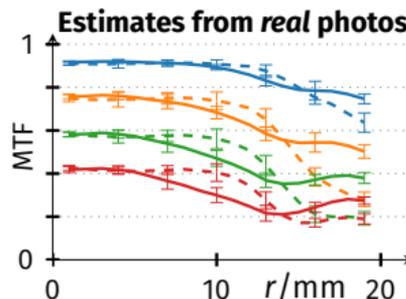
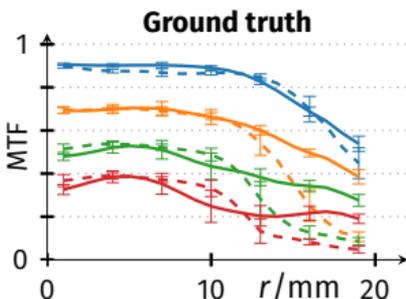
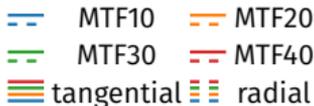
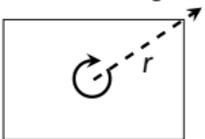
### 3 Results on natural scenes



centre to top right corner



azimuthal average



- ▶ Very good qualitative agreement
- ▶ Good quantitative agreement

# Limitations and discussion of discrepancies

## Main sources of discrepancies

- ▶ **Curvature of the focal plane**

the PSF panel is completely flat while real objects have depth variations

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- ▶ Objects not in focus
- ▶ homogeneous/texture less areas (e.g. sky)
- ▶ edges in only one direction

# Limitations and discussion of discrepancies

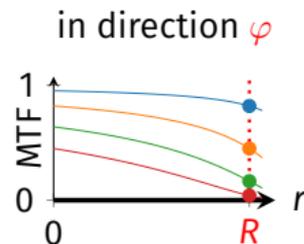
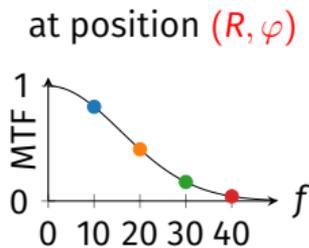
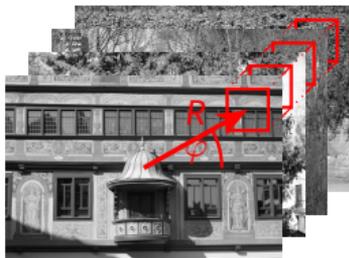
## Main sources of discrepancies

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the PSF panel is completely flat while real objects have depth variations
- ▶ **Not all patches suitable**
  - ▶ Objects not in focus
  - ▶ homogeneous/texture less areas (e.g. sky)
  - ▶ edges in only one direction

## Mitigation strategies

- ▶ *So far*: Select suitable photographs
- ▶ *Future work/Production system*: Automatic patch selection from photographs, similar to “*Finding good regions to deblur images*” [Hu 2012]

# We present a system for MTF estimation from real photographs



Patch extraction

Local MTF estimation

Global MTF aggregation

- ▶ Estimate entire MTF charts from a batch of photographs within minutes
- ▶ Good qualitative and quantitative results
- ▶ New dataset of real PSFs from aberrated lenses (available on the project website soon)

<https://ei.is.mpg.de/projects/mtf-estimation>

Questions?

# Questions? See you at the poster session!

## Automatic Estimation of Modulation Transfer Functions

Matthias Bauer<sup>1,2</sup>, Valentin Volchkov<sup>1</sup>, Michael Hirsch<sup>3</sup>, Bernhard Schölkopf<sup>1,3</sup>

<sup>1</sup>Max Planck Institute for Intelligent Systems, Tübingen, <sup>2</sup>University of Cambridge, <sup>3</sup>Amazon Research

### Motivation

Lens Quality Assessment is expensive and time consuming...

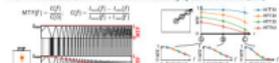
...but every photographer has access to photographs captured with that lens

- Photographs contain ample information about lens properties
- This information is confounded with the statistics of the images
- Lens properties are the same for different movies

The Modulation Transfer Function (MTF) is a standard measure for camera lens quality.

### What is the Modulation Transfer Function?

The MTF characterizes how contrast is diminished by optical aberrations (blur)

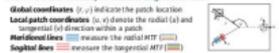


The Point Spread Function (PSF) characterizes the local blur and is spatially varying across the field of view. It is related to the MTF by a Fourier Transformation:

$$PSF(x, y) \cdot OTF(f_x, f_y) = MTF(f_x, f_y)$$

Global MTF charts summarize the MTF for fixed frequencies (10 cycles/mm, 20 cycles/mm, etc.) over the entire field of view and are typically provided by manufacturers.

The MTF is measured locally in radial and tangential direction



### Ground Truth PSF/MTF Measurements



- Custom-built pinhole array of  $20 \times 1.5$ mm to record the point spread function (PSF) at  $80 \times 80 \rightarrow 4800$  locations over the entire field of view
- The image of a point light source is a local measurement of PSF

### Set up a Supervised Training Task

Inputs: Systematically blurred patches

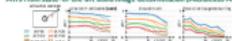
Outputs: MTF values of the blur (MTF<sub>R</sub>, MTF<sub>T</sub>)

Ground truth training and validation data

- Sharp image patches
- regular patches (Duch2005)
- real blur from pinhole array
- patches from photos in the wild
- artificial blurs (e.g. sum of Gaussians)

### Comparison to other Methods

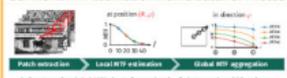
MTFs from state-of-the-art image deconvolution (Schickel2014)



Photons et al. MTF measurements from test charts (Baron2008, Leiblein2007)

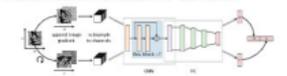


### Our work: MTF Estimation from a Batch of Photos



- Estimate on-line global MTF charts from a batch of photographs within minutes
- Good qualitative and quantitative agreement w/ photometric measurements

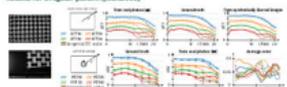
### Neural Network for Local MTF Estimation



- Inputs:  $100 \times 100 \times 3$  image patches
- Outputs: radial and tangential MTF values
- Input:  $100 \times 100 \times 3$  image patches
- Output: radial and tangential MTF values

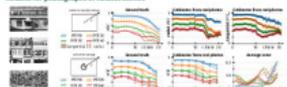
### Experimental Results

#### Results for regular pattern (Duch2005)



- Estimates from synthetically blurred patches are almost perfect (for all lenses)
- Very good qualitative and quantitative agreement (on some are similar for other lenses)

#### Results for photographs of natural scenes

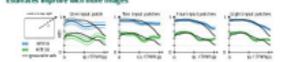


- Typically very good qualitative and good quantitative agreement: identification and recognition of discrepancies

**Curvature of the focal plane.** The PSF panel is completely flat, while natural scenes have depth variations, corners may appear sharper than PSF measurements

**Set of patches are suitable.** Objects not in focus (e.g. protruding object), homogeneous/texture-less areas (e.g. sky), edges in only one direction

**Integration strategy.** Carefully select photos, (start work: automatically select patches)



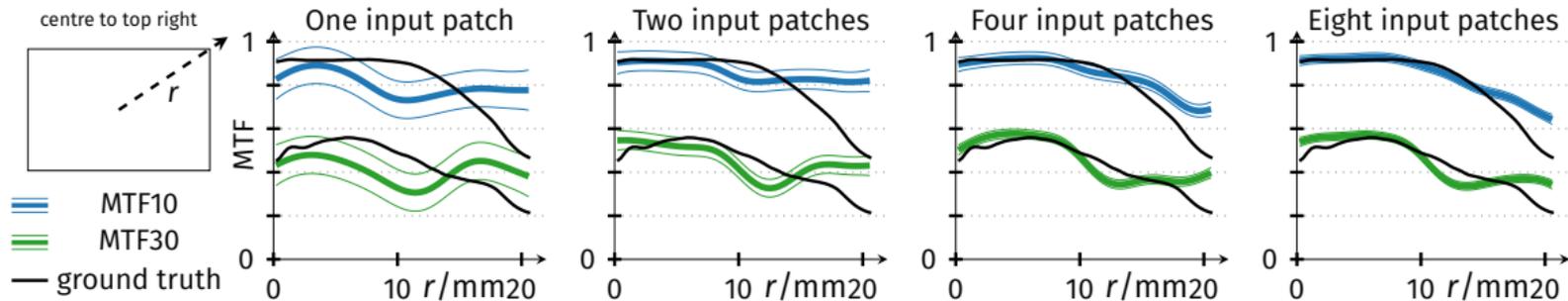
### References

- Baron2008: In a lens, "corner edge mtf for digital camera and source of analog" (2008)
- Schickel2014: In a lens, "MTF estimation using deconvolution" (2014)
- Leiblein2007: A review of "Digital camera resolution measurements using an artificial luminance chart" (2007)
- Duch2005: "A review of "Digital camera resolution measurements using an artificial luminance chart" (2005)

Poster P46

# Appendix/Backup

# Results improve with more data

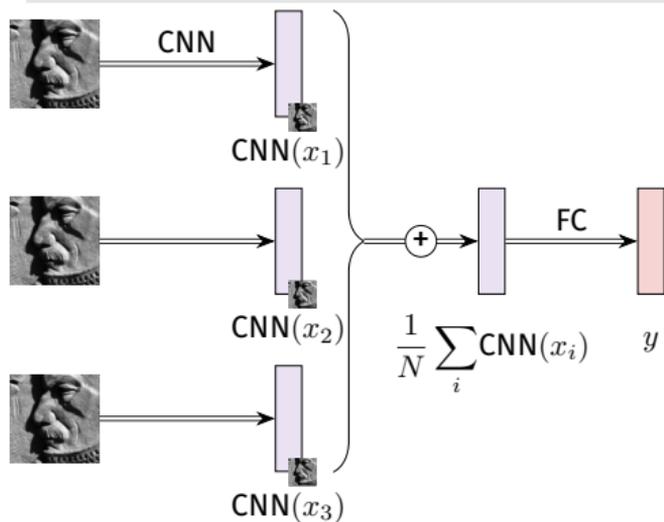


- ▶ Increase the number of input patches from the same location but different images
- ▶ Patches are averaged in feature space

# Treat multiple input patches

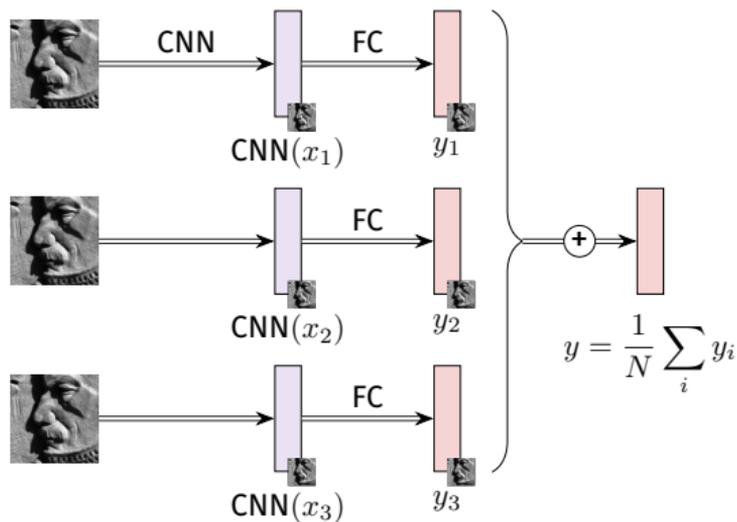
## Average in feature space

$$y = \text{FC} \left( \frac{1}{N} \sum_i \text{CNN}(x_i) \right)$$



## Average in output space

$$y = \frac{1}{N} \sum_i \text{FC}(\text{CNN}(x_i))$$



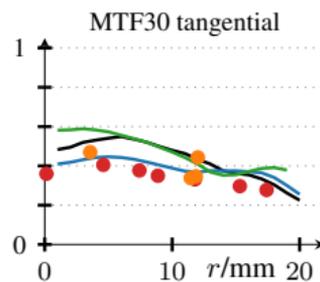
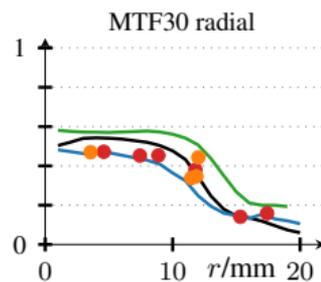
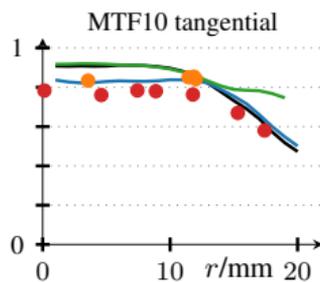
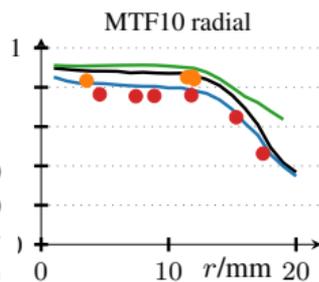
# Comparison to other methods

## Photometric measurements

azimuthal average

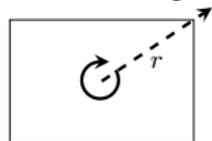


- PSF panel
- ours (pattern)
- ours (natural)
- Siemens Star
- Slanted Edge

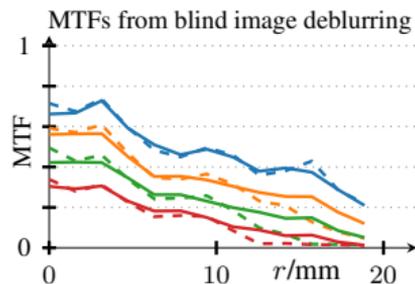
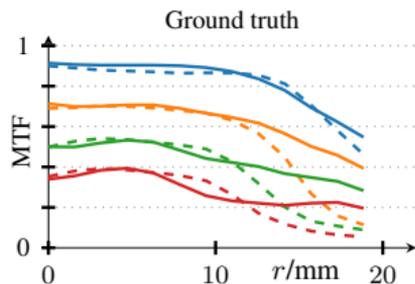
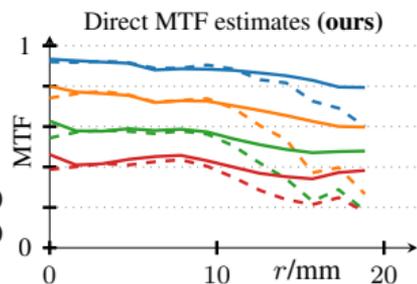


## State-of-the-art deblurring algorithm

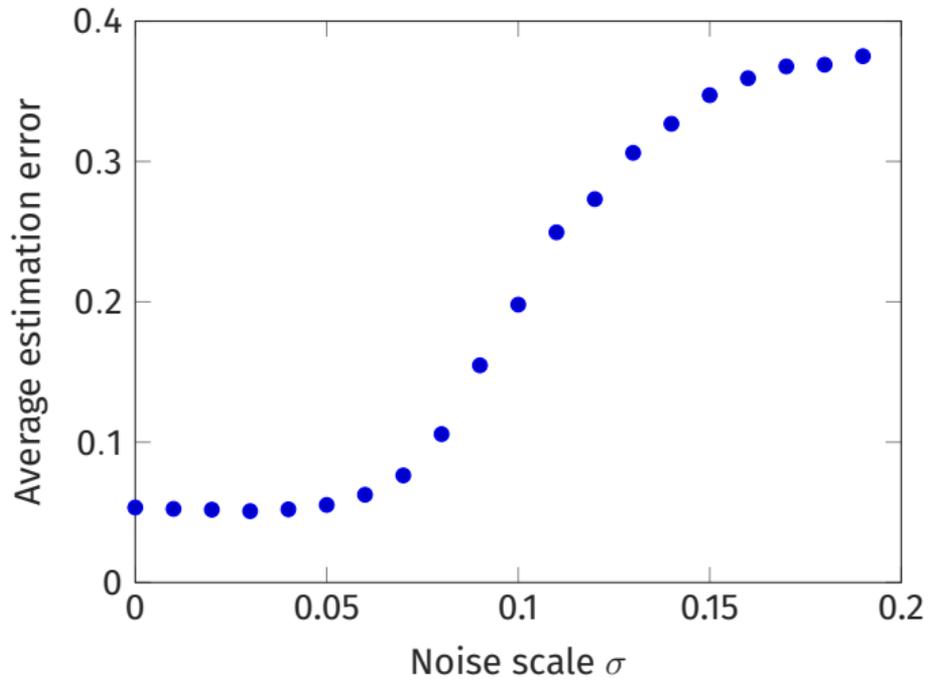
azimuthal average



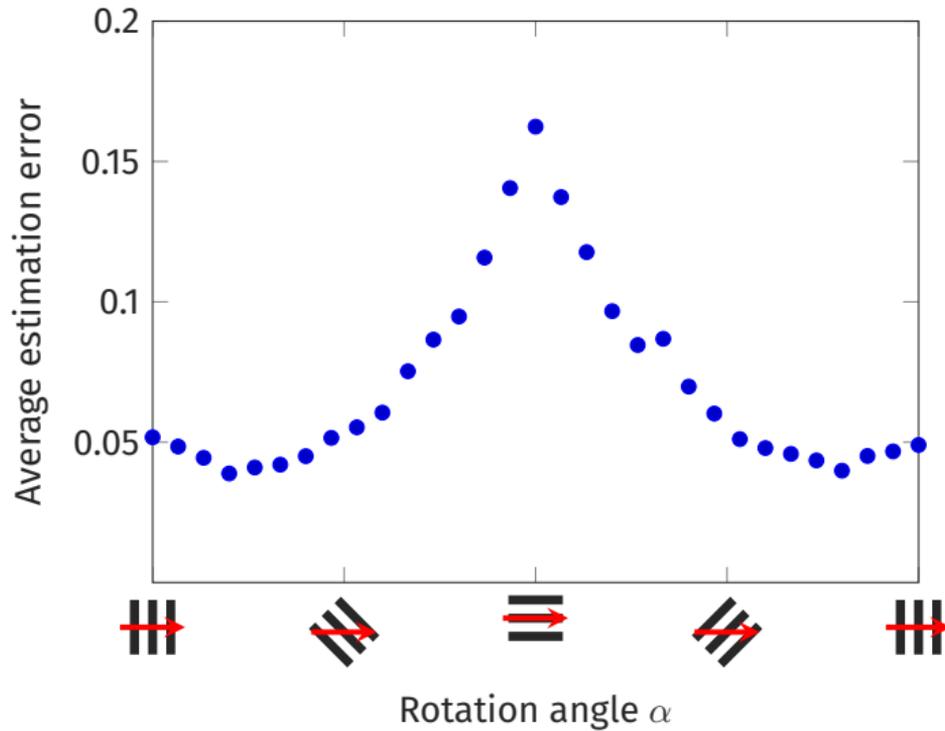
- MTF10
- MTF20
- MTF30
- MTF40
- tangential
- radial



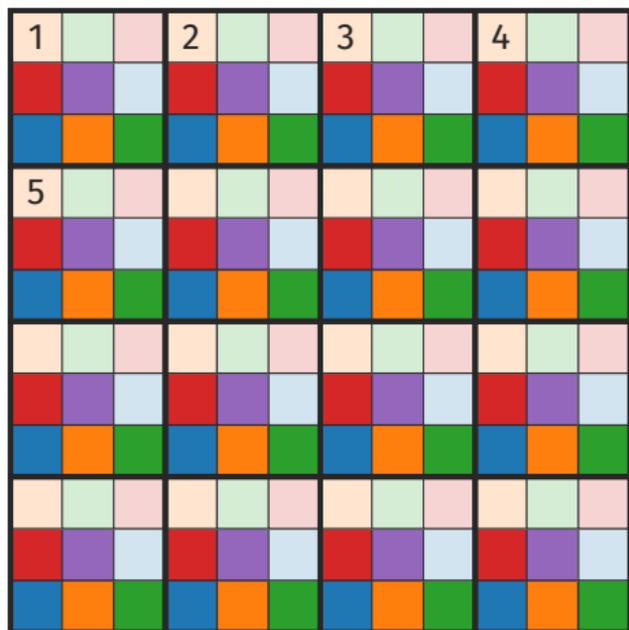
# Robustness to noise



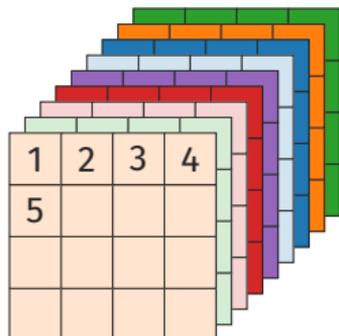
# Orientation of edges



# Subsampling into channels



Before subsampling:  $12 \times 12 \times 1$



After subsampling:  $4 \times 4 \times 9$