Automatic Estimation of Modulation Transfer Functions

Matthias Bauer[1,2], Valentin Volchkov[1], Michael Hirsch[3], Bernhard Schölkopf[1,3]

[1]Max Planck Institute for Intelligent Systems, Tübingen, Germany
[2]University of Cambridge, UK
[3]Amazon Research

May 5, 2018

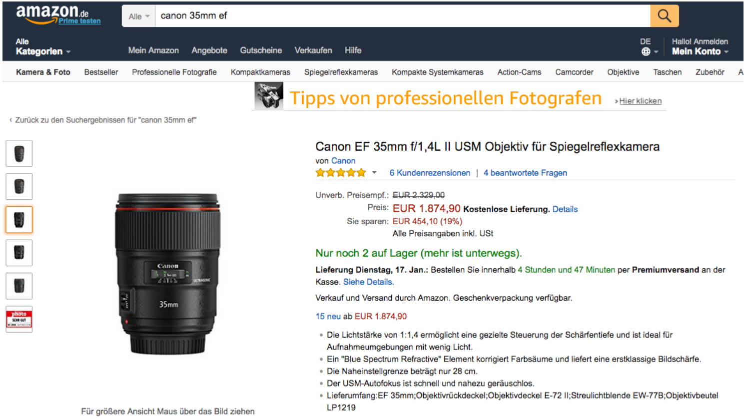
This project is joint work with

Valentin Volchkov

Michael Hirsch

Bernhard Schölkopf

How good is this lens?



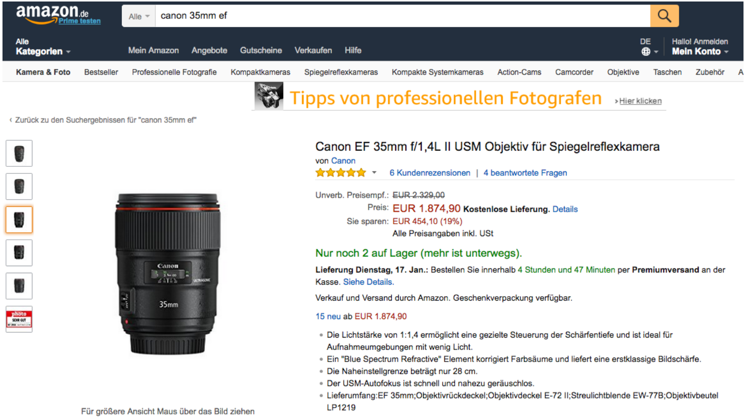
- Lens quality is determined by **optical aberrations**

Optical aberrations are spatially varying

Optical aberrations are spatially varying

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

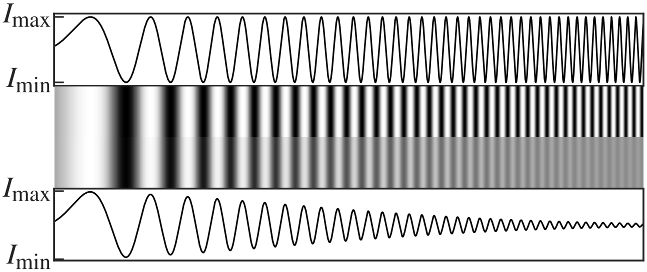
How good is this lens?



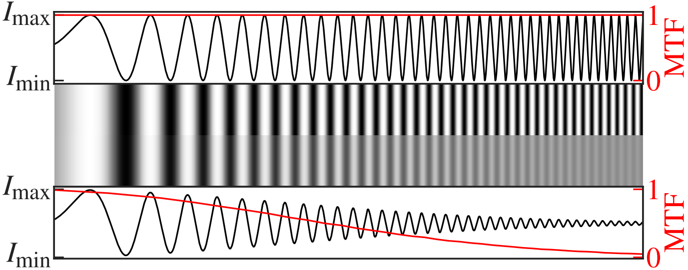
- Lens quality is determined by **optical aberrations** (spatially varying PSF)
- Related and normalised quality measure: **Modulation Transfer Function (MTF)**

What is the MTF?

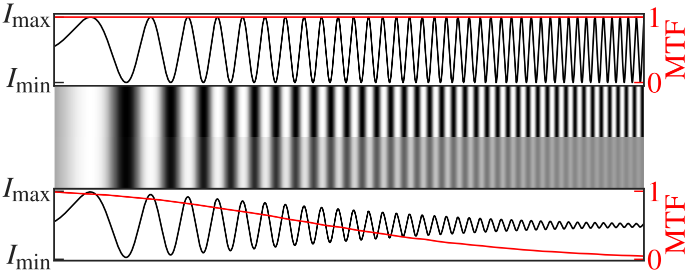
The local MTF characterises diminished relative contrast

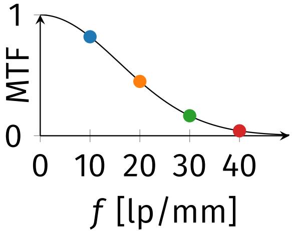


The local MTF characterises diminished relative contrast

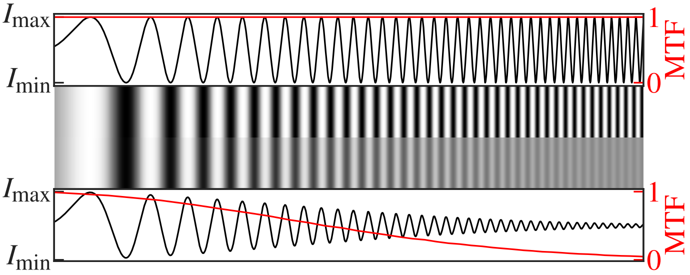


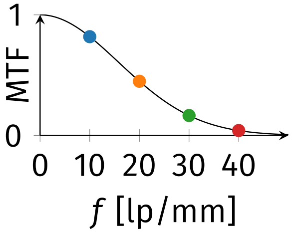
The local MTF characterises diminished relative contrast





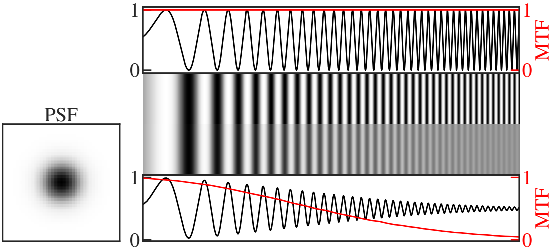
The local MTF characterises diminished relative contrast

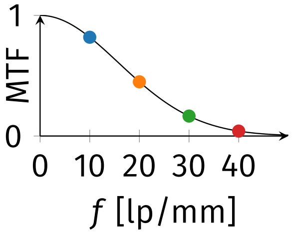




MTF as normalised diminished relative contrast

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





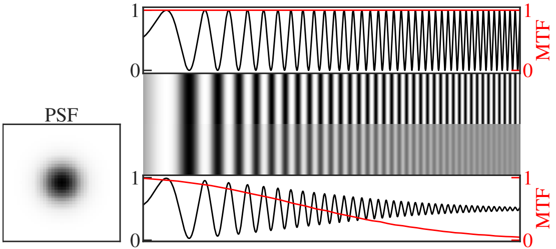
MTF as normalised diminished relative contrast

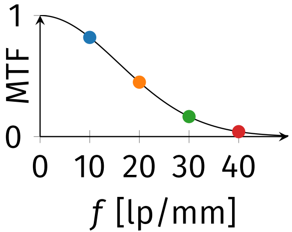
$$C(f) = \frac{I_{\max}(f) - I_{\min}(f)}{I_{\max}(f) + I_{\min}(f)} \qquad \mathrm{MTF}(f) = \frac{C(f)}{C(0)} \in [0, 1]$$

MTF as Fourier Transform of the Point Spread Function

$$\mathrm{PSF}(x) \xrightarrow{\mathcal{FT}} \mathrm{OTF}(f) \propto \mathrm{MTF}(f)\, \mathrm{e}^{i\,\mathrm{PhTF}(f)}$$

The local MTF characterises diminished relative contrast





MTF as normalised diminished relative contrast

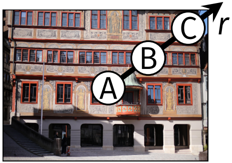
$$C(f) = \frac{I_{\mathrm{max}}(f) - I_{\mathrm{min}}(f)}{I_{\mathrm{max}}(f) + I_{\mathrm{min}}(f)} \qquad \mathrm{MTF}(f) = \frac{C(f)}{C(0)} \in [0, 1]$$

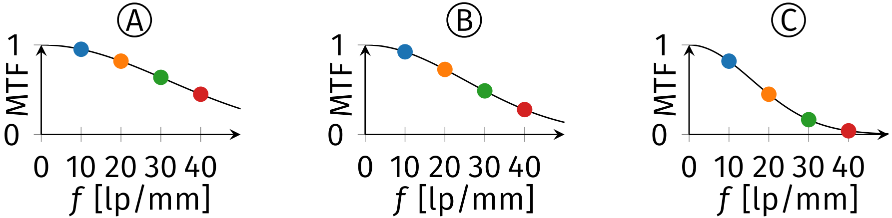
MTF as Fourier Transform of the Point Spread Function

$$\mathrm{PSF}(x) \xrightarrow{\mathcal{FT}} \mathrm{OTF}(f) \propto \mathrm{MTF}(f)\, \mathrm{e}^{i\, \mathrm{PhTF}(f)}$$

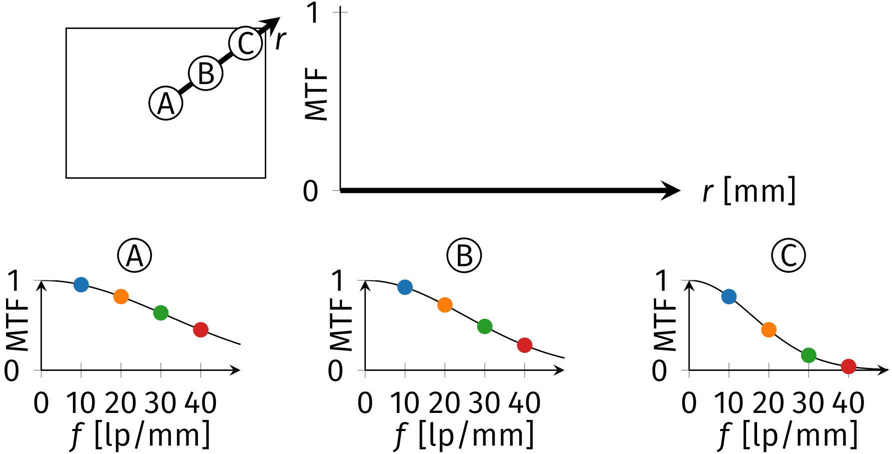
Aggregate local MTF values into *global MTF charts*

Aggregate local MTF curves into global MTF charts

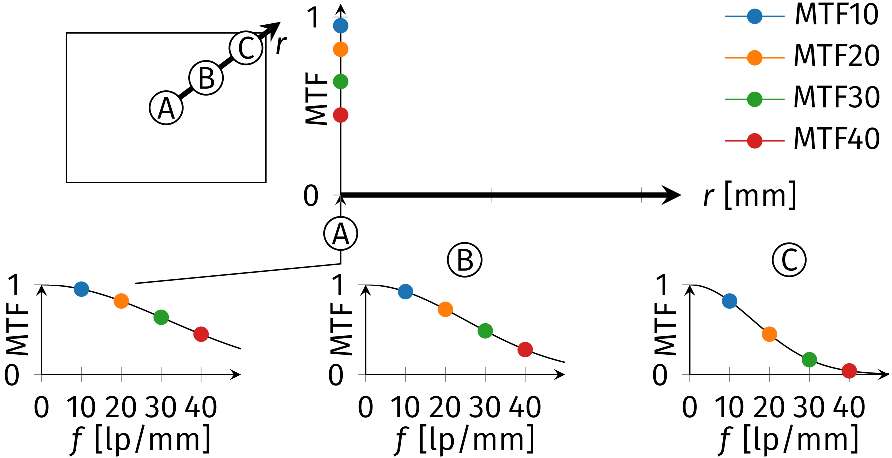




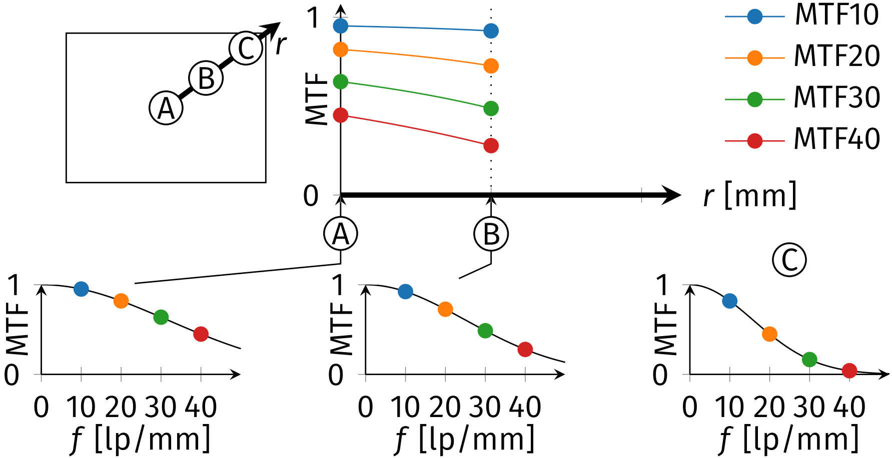
Aggregate local MTF curves into global MTF charts



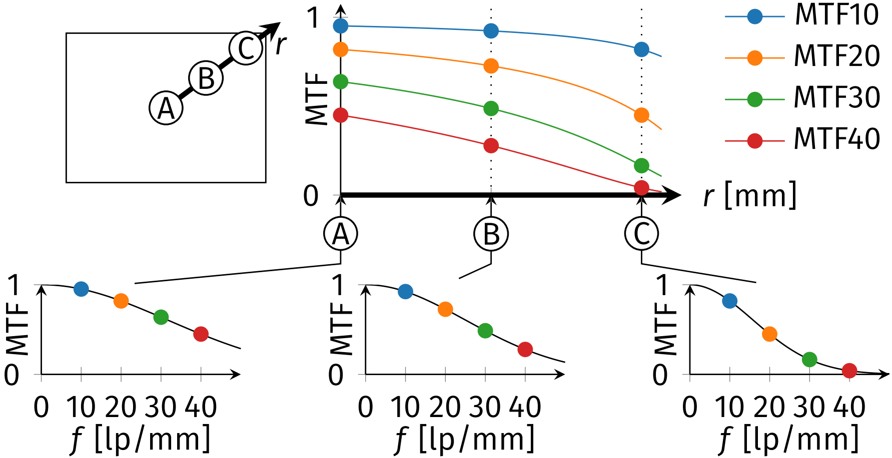
Aggregate local MTF curves into global MTF charts



Aggregate local MTF curves into global MTF charts



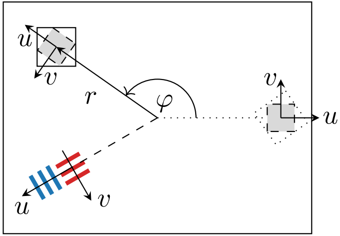
Aggregate local MTF curves into global MTF charts

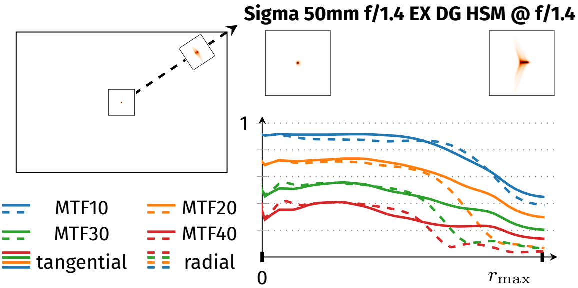


Global MTF Charts: Radial and Tangential MTF

measure the ***radial MTF*** (

measure the ***tangential MTF*** (





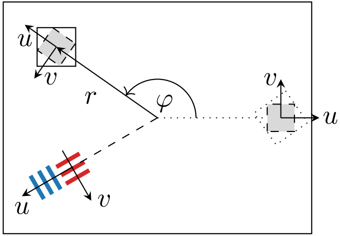
Global MTF Charts: Radial and Tangential MTF

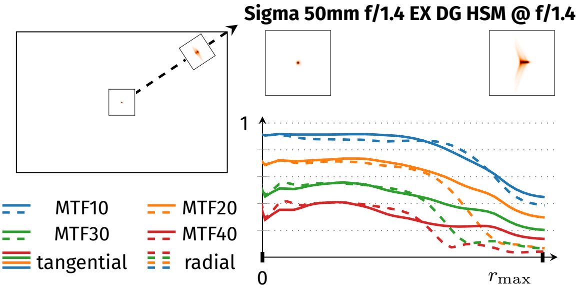
measure the *radial MTF* (

)

measure the *tangential MTF* (

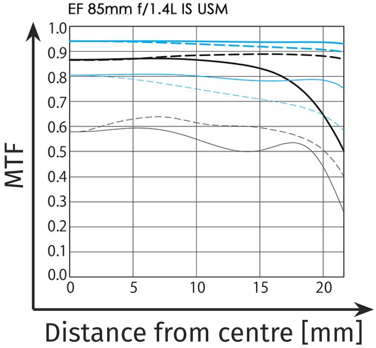
)



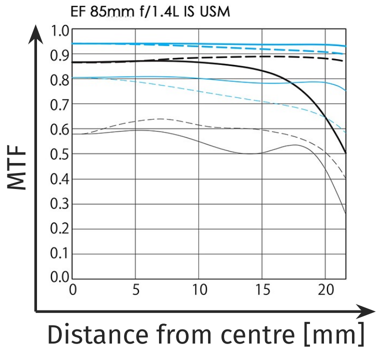


Lens manufacturers provide MTF charts

How good is this lens?



How good is this lens?



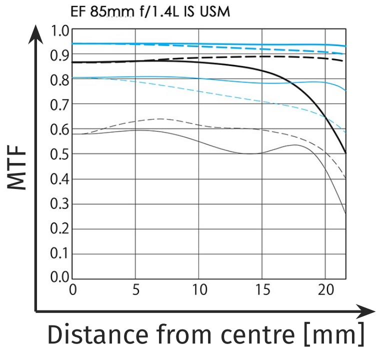
How good is your lens? Assessing performance with MTF full-field displays

BRANDON DUBE,[1,2,*] ROGER CICALA,[1] AARON CLOSZ,[1] AND JANNICK P. ROLLAND[2]

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

Image Source: Canon

How good is this lens?



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

BRANDON DUBE,[1,2,*] ROGER CICALA,[1] AARON CLOSZ,[1] AND JANNICK P. ROLLAND[2]

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

Want the MTF curve for a specific specimen of a lens

Image [redacted]

Photometric MTF measurements

Typical techniques used for lens quality assessment

simple/cheap		**complex/expensive**
▸ visual inspection of images	▸ ***MTF test charts***	▸ 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, ...

Photometric MTF measurements

Typical techniques used for lens quality assessment

simple/cheap ⟷ **complex/expensive**

- visual inspection of images
- ***MTF test charts***
- wavefront sensor
- professional MTF testing station

qualitative ⟷ **quantitative**

MTF test charts

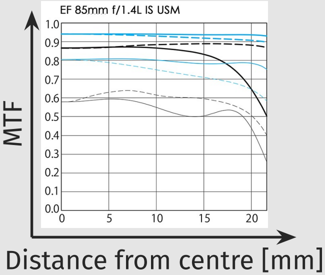
- Several methods:
  - Slanted edge [Burns2000]
  - Dead leaves
  - Siemens stars [Loebich2007]
- DxO, imatest, Image Engineering, ...

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

Learning system



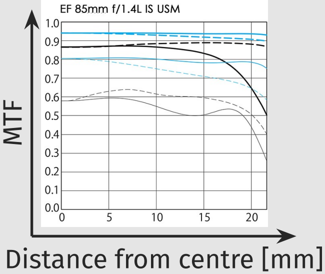
unprocessed photographs

global MTF chart

Our approach: Estimate MTF blindly from photographs

This work: A learning system for MTF estimation from photographs

Learning system

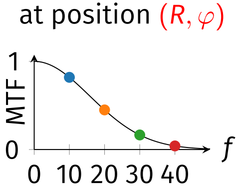


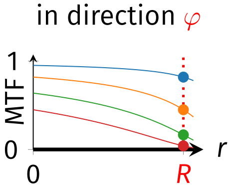
unprocessed photographs

global MTF chart

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

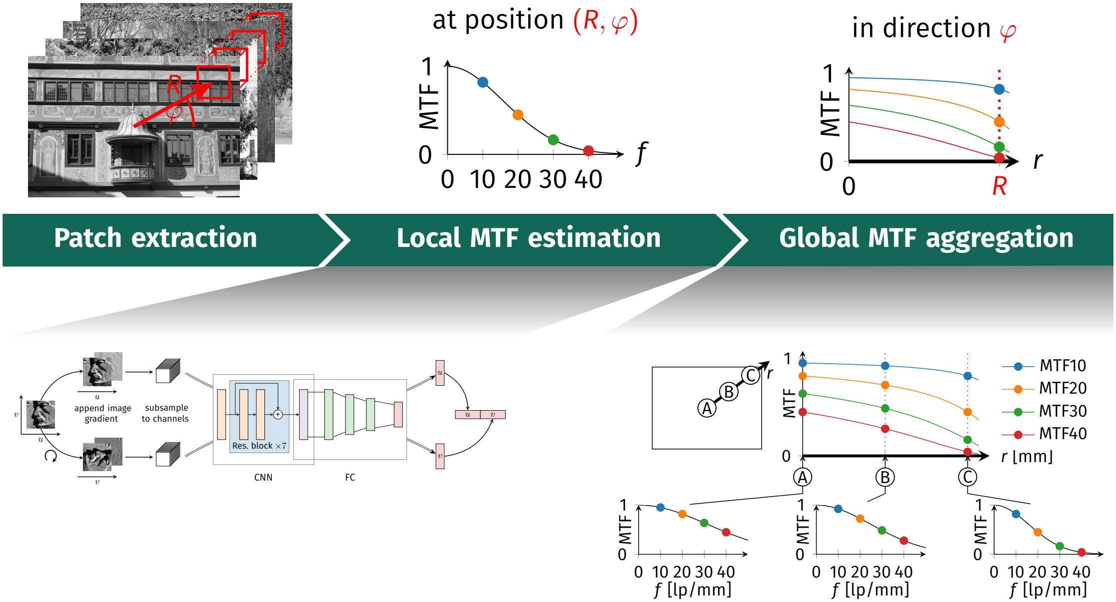
Overview of our learning system



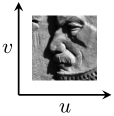


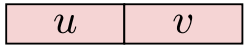
Patch extraction → **Local MTF estimation** → **Global MTF aggregation**

Overview of our learning system



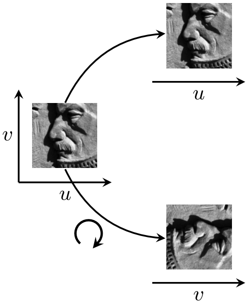
Local MTF Estimation: Network Architecture

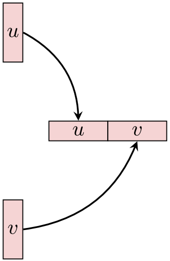




- **Inputs**: $192 \times 192 \times 1$ image patches
- **Outputs**: MTF10, MTF20, MTF30, MTF40 (tangential and radial)

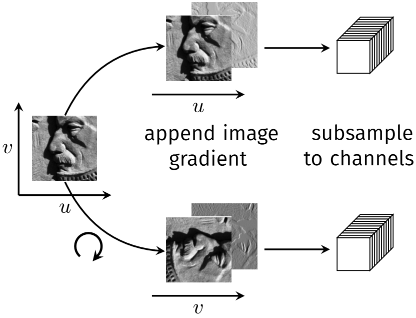
Local MTF Estimation: Network Architecture

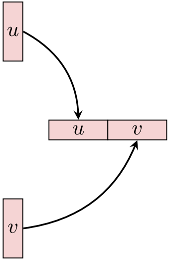




- **Inputs**: $192 \times 192 \times 1$ image patches
- **Outputs**: MTF10, MTF20, MTF30, MTF40 (tangential and radial)

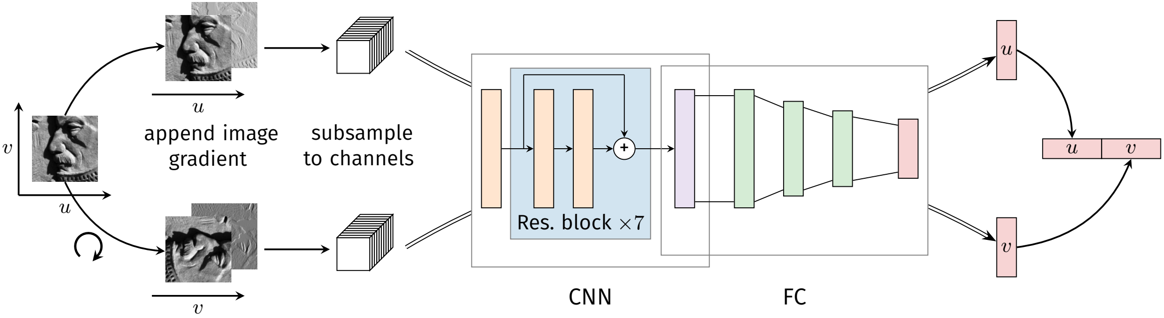
Local MTF Estimation: Network Architecture





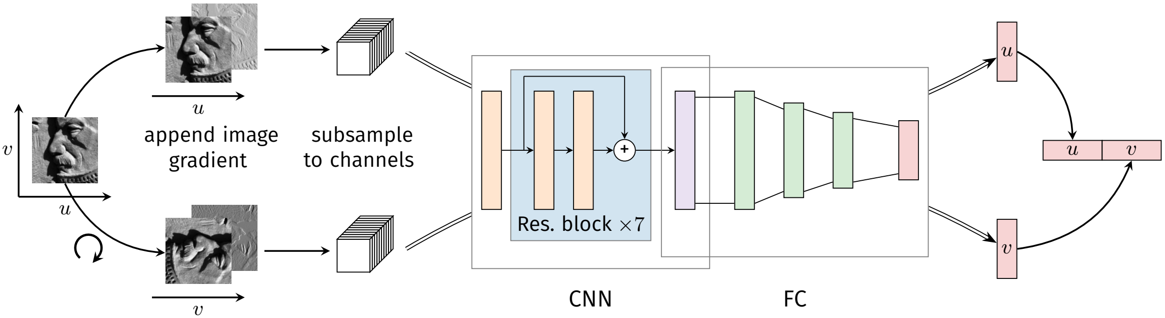
- **Inputs**: $192 \times 192 \times 1$ image patches
- **Outputs**: MTF10, MTF20, MTF30, MTF40 (tangential and radial)
- **Initial data processing**: Rotation, image gradient, subsampling into channels

Local MTF Estimation: Network Architecture



- **Inputs**: 192 $\times$ 192 $\times$ 1 image patches
- **Outputs**: MTF10, MTF20, MTF30, MTF40 (tangential and radial)
- **Initial data processing**: Rotation, image gradient, subsampling into channels
- **DNN** with convolutional residual blocks and fully connected layers

Local MTF Estimation: Network Architecture



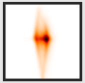
- **Inputs**: 192 × 192 × 1 image patches
- **Outputs**: MTF10, MTF20, MTF30, MTF40 (tangential and radial)
- **Initial data processing**: Rotation, image gradient, subsampling into channels
- **DNN** with convolutional residual blocks and fully connected layers
- **Treat multiple input patches**
  Compute 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

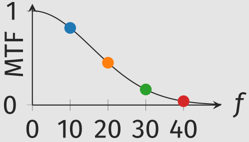
Set up a supervised training task

Input: Synthetically blurred patches

$*$



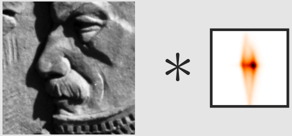
Output: MTF values of the blur



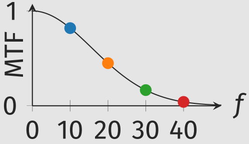
Train the Local Estimation Network on synthetically blurred patches

Set up a supervised training task

Input: Synthetically blurred patches

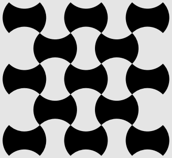


Output: MTF values of the blur



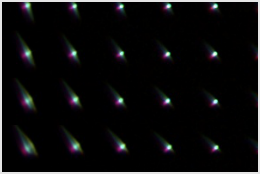
Required training and validation data

Sharp image patches



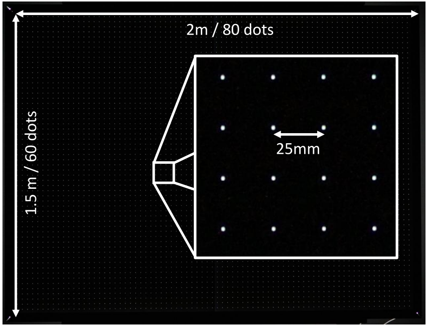
- regular patterns [Joshi 2008]
- patches from photos in the wild

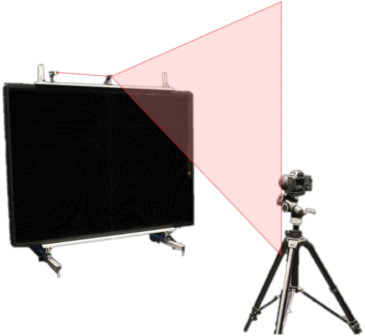
Lens blurs and their MTFs



- Record lens blurs with custom pinhole array

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



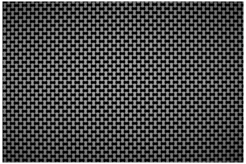


- Custom-built pinhole array to efficiently and accurately record PSFs
- Image of a point light source is the PSF
- Record $80 \times 60 = 4800$ PSFs per lens and setting over the entire field of view

New dataset of real PSFs for aberrated lenses

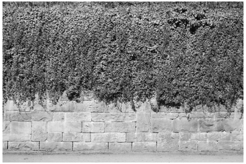
Experiments: Estimate MTF charts from three types of images

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



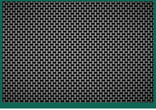

3. **Photographs of natural scenes** in the wild

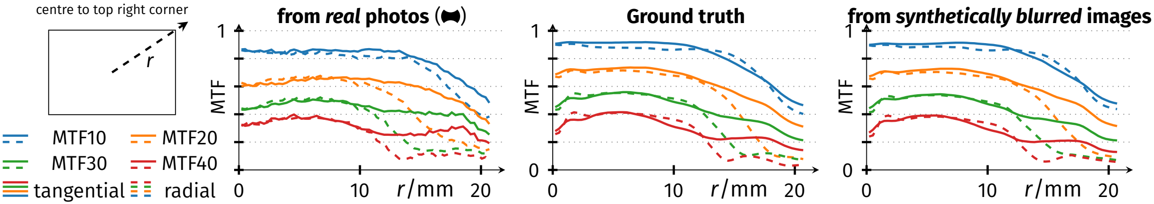




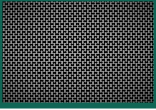

All results for the same lens (Sigma 50mm f/1.4 EX DG HSM @ f/1.4)

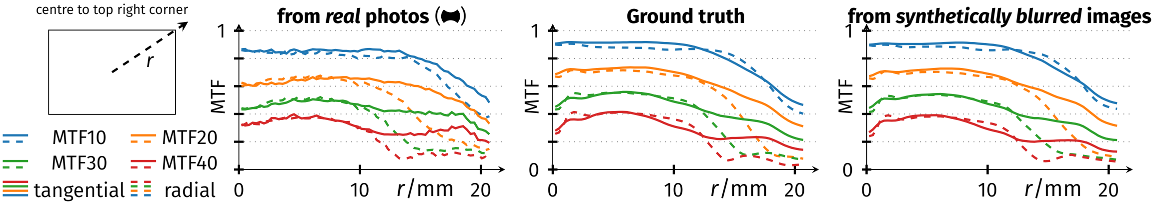
① + ② Results on the test pattern

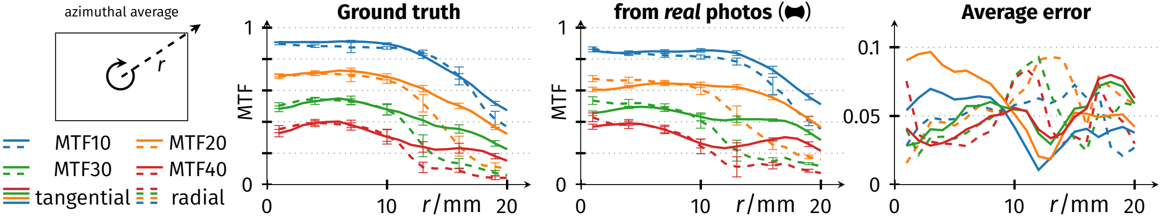




① + ② Results on the test pattern

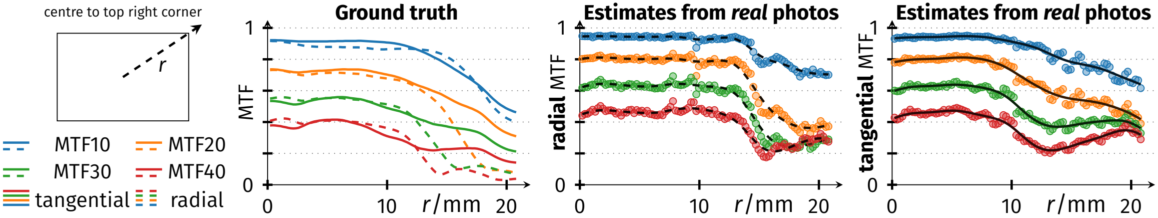




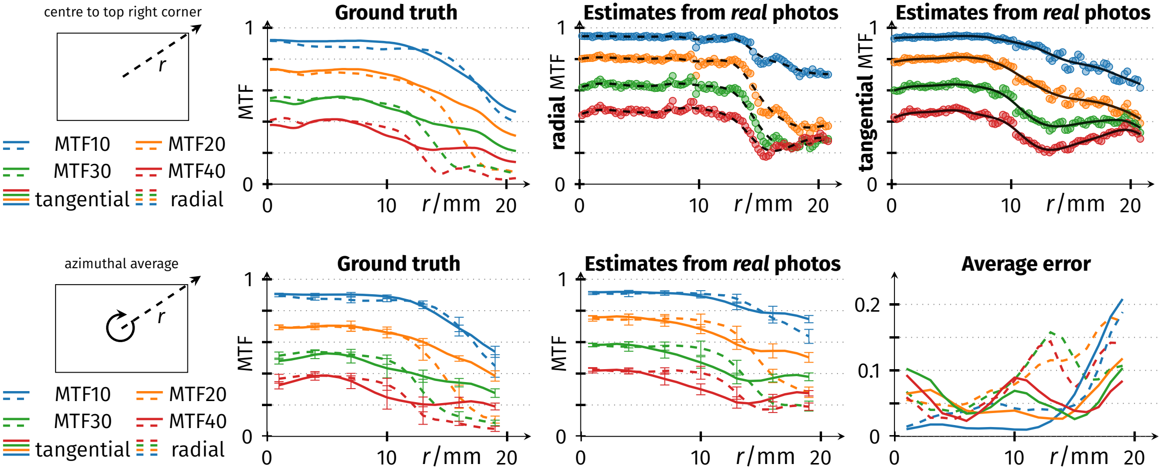


- Estimation from synthetically blurred patches almost perfect (for all lenses)
- Very good quantitative and qualitative agreement
- Estimation errors for other lenses typically similar

③ Results on natural scenes



③ Results on natural scenes



- 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

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
- **Not all patches suitable**
  - 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

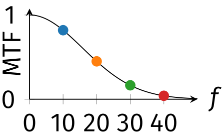
- **Curvature of the focal plane**
  the PSF panel is completely flat while real objects have depth variations
- **Not all patches suitable**
  - Objects not in focus
  - homogeneous/texture less areas (e.g. sky)
  - edges in only one direction

Mitigation strategies

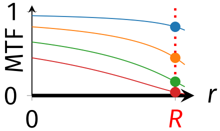
- *So far*: Select suitable photographs
- *Future work/Production system*: Automatic patch selection from photographs, similar to "*Finding good regions to deblur images*" [Hu 2012]

We present a system for MTF estimation from real photographs

at position (R, φ)



in direction φ



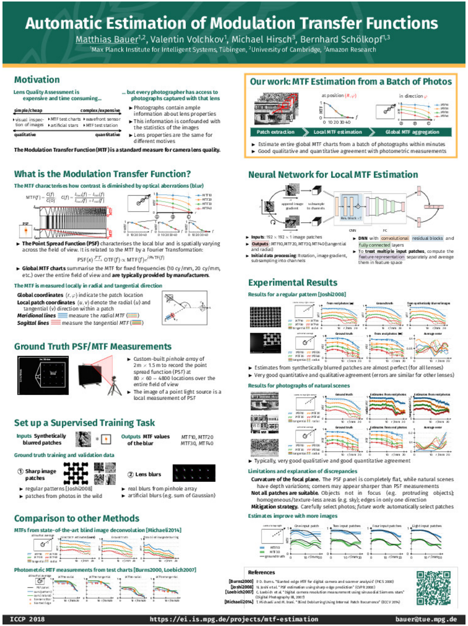
Patch extraction → **Local MTF estimation** → **Global MTF aggregation**

- 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?

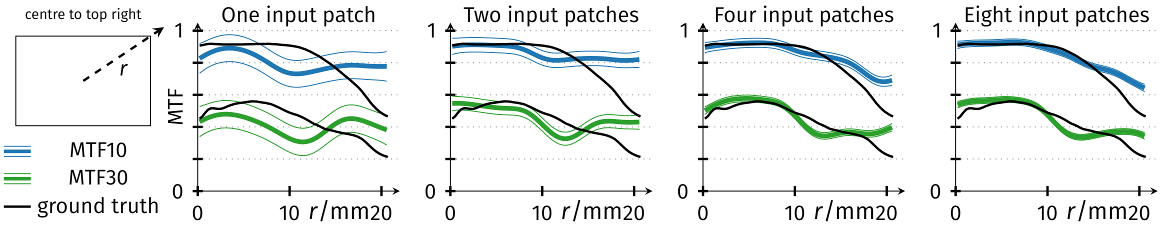
Questions? See you at the poster session!



Poster P46

Appendix/Backup

Results improve with more data

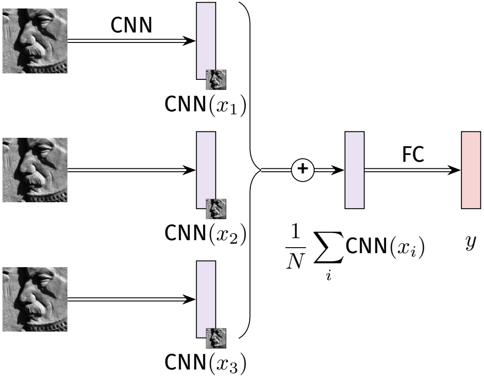


- Increase the number of input patches from the same location but different images
- Patches are averaged in feature space

Treat multiple input patches

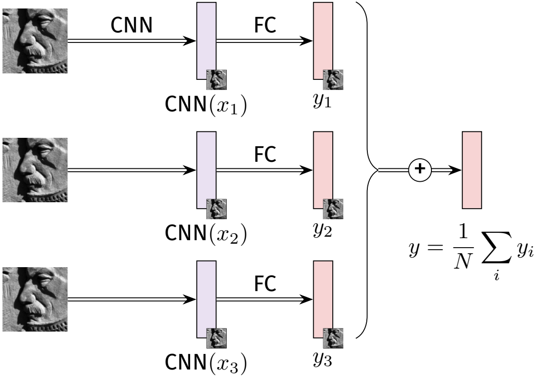
Average in feature space

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



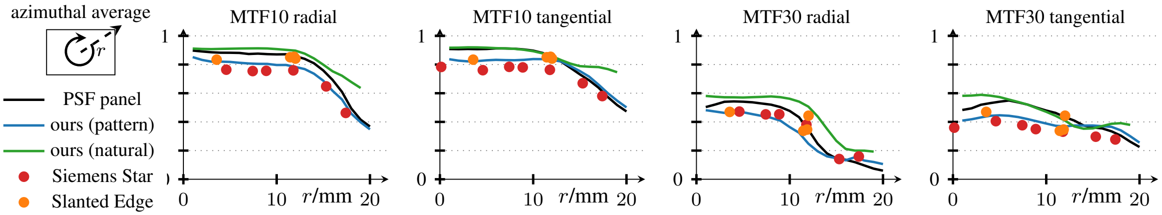
Average in output space

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

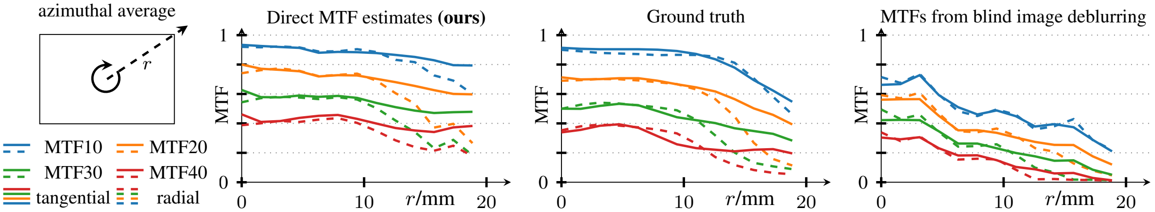


Comparison to other methods

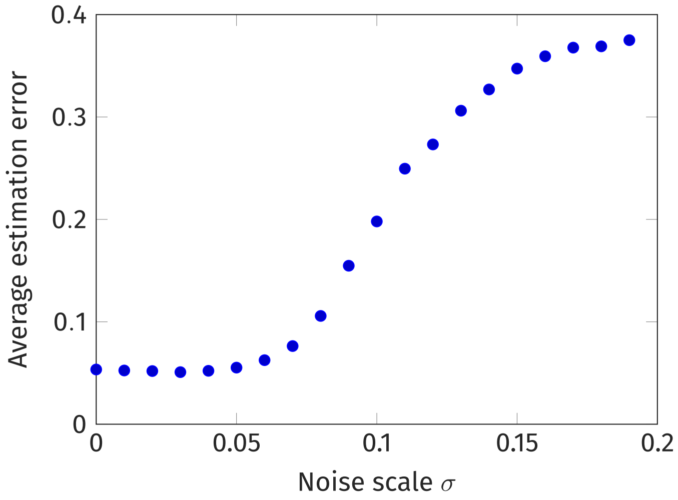
Photometric measurements



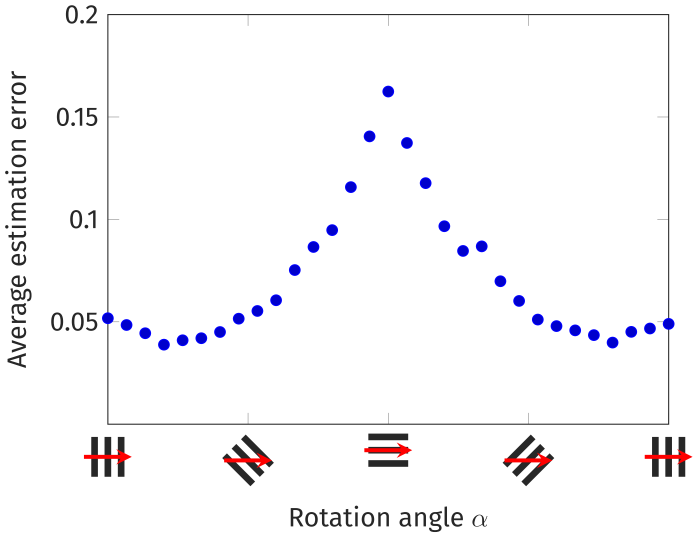
State-of-the-art deblurring algorithm



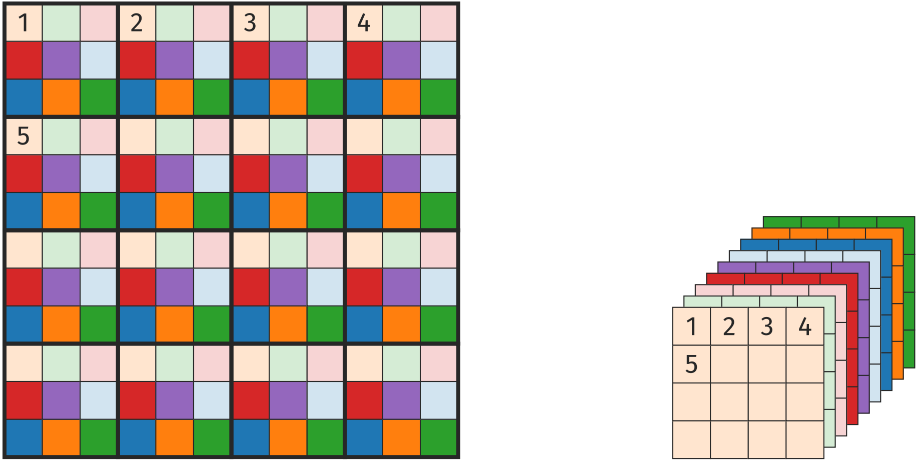
Robustness to noise



Orientation of edges



Subsampling into channels



Before subsampling: $12 \times 12 \times 1$ After subsampling: $4 \times 4 \times 9$