Light Field Methods for the Visual Inspection of Transparent Objects

UC Louvain, Image and Signal Processing Seminars - 2017

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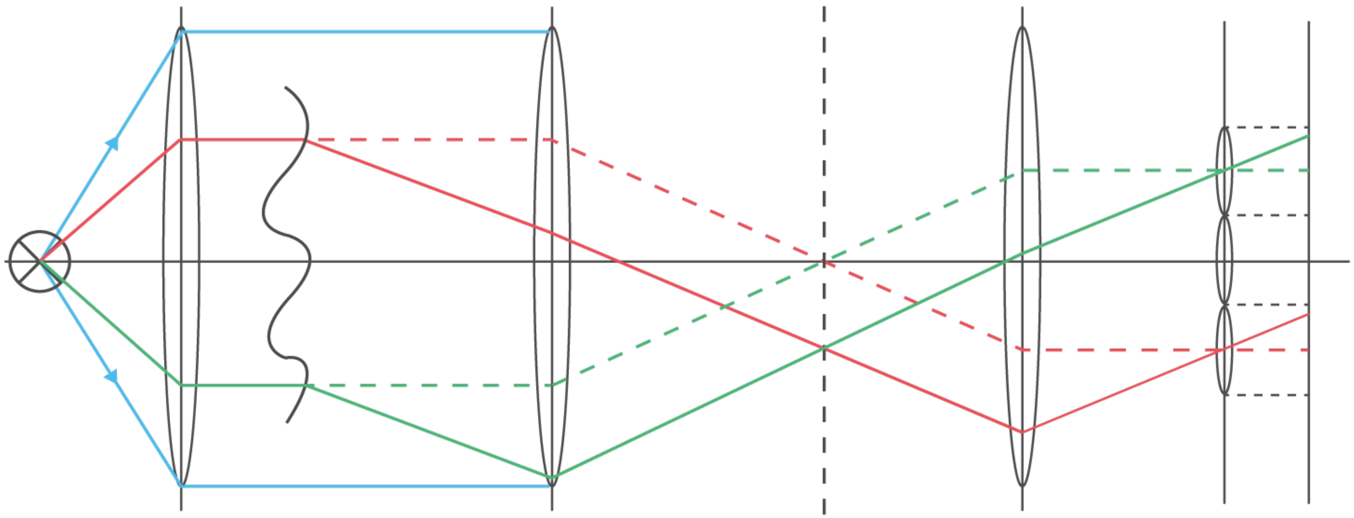
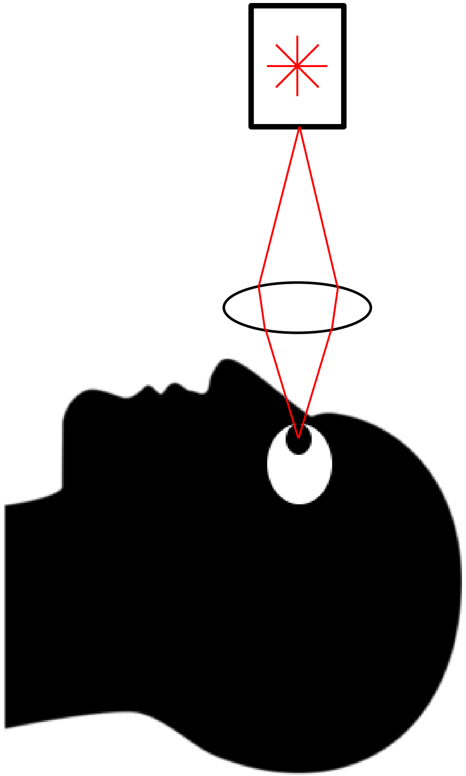
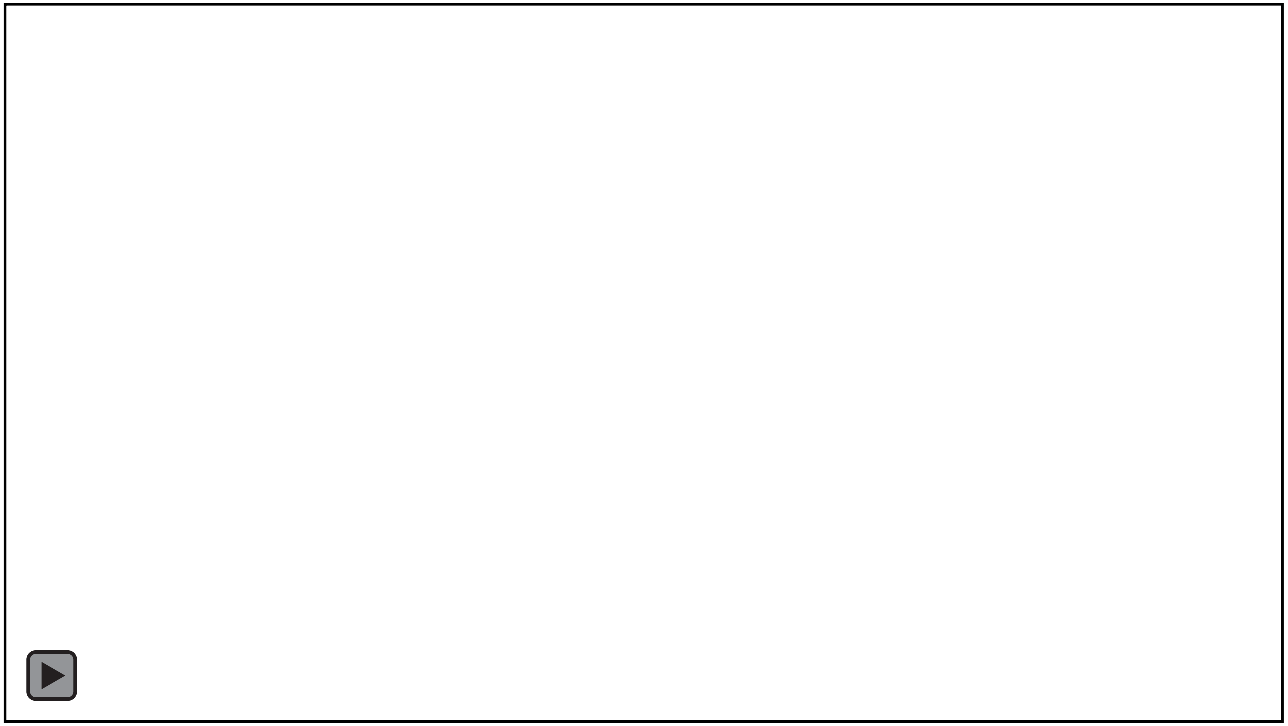


Motivation and Introduction

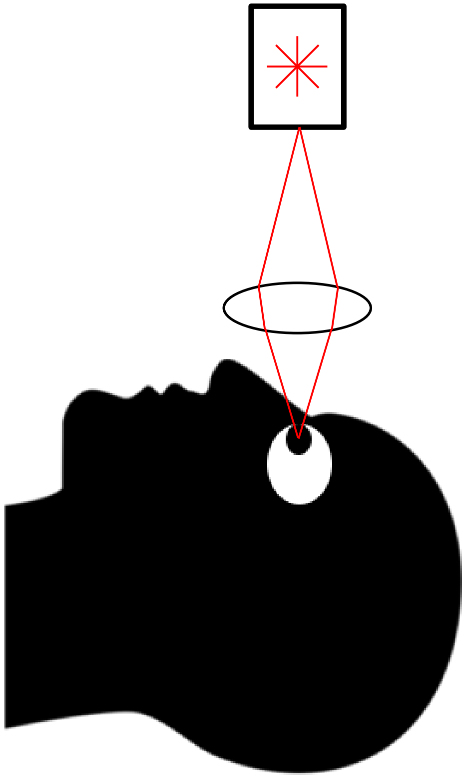
- Why bother about transparent object inspection?
  - Transparent objects are massively used in diverse industries and need to meet highest quality requirements.

Motivation and Introduction





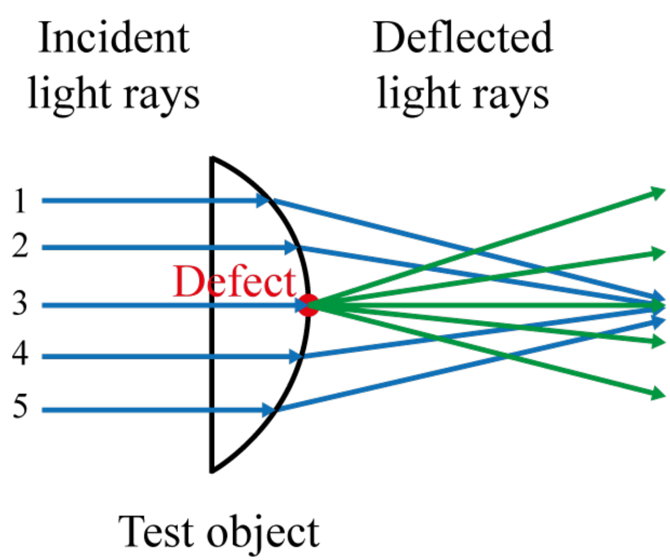
Motivation and Introduction



- Quality control indispensable
  - Human inspectors
  - Automated visual inspection system
- Important types of defects:
  - Opaque inclusions
  - Transparent, scattering inclusions

Motivation and Introduction

- Why use light fields?



- Because for some important kinds of material defects, the information about their presence is conveyed by the light's propagation direction.

Motivation and Introduction

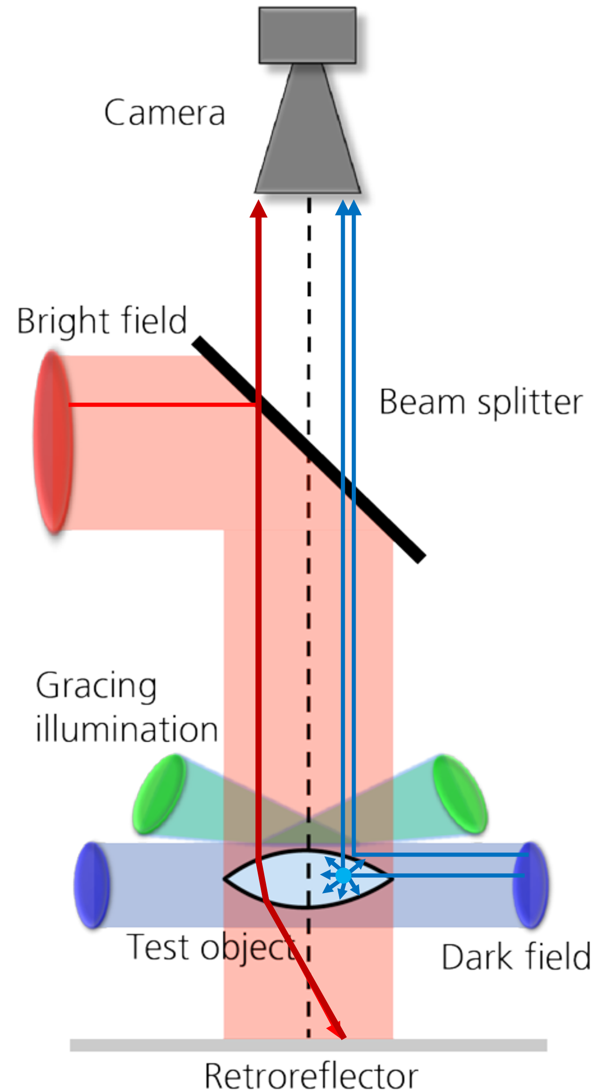
- Why am I here?
  - We will come to that … ☺

Outline

- State of the Art
- Light Field Methods
  - Basic Idea
  - Deflection Maps
    - Acquisition
    - Processing
  - Inverse Light Field Illumination
- Summary & Outlook

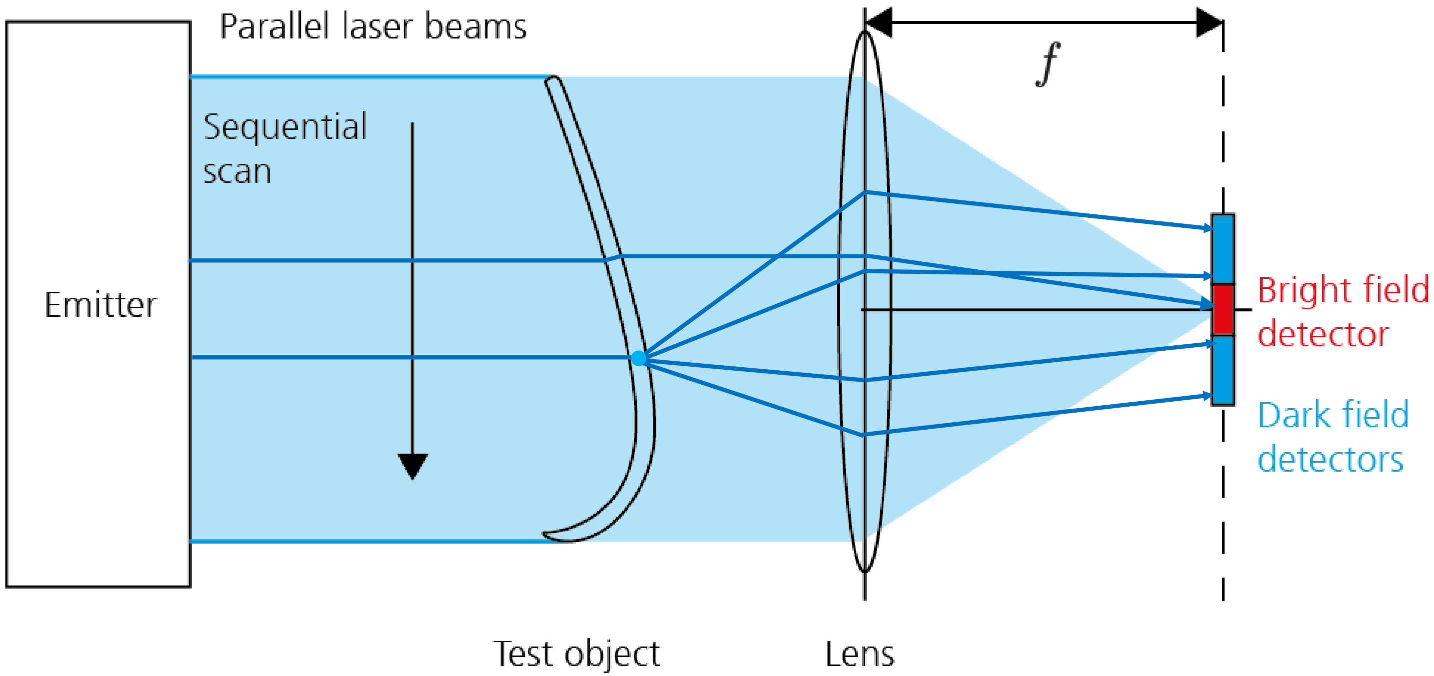
State of the Art

- Purity
  a multi channel inspection system
  - Bright field (red channel)
    Opaque contaminants ✓
  - Dark field
    (blue & green channels):
    Transparent, scattering
    inclusions & scattering surface defects ✓
    - Problem:
      – Requires well-designed arrangement and placement of light sources in order to avoid reflections.



State of the Art

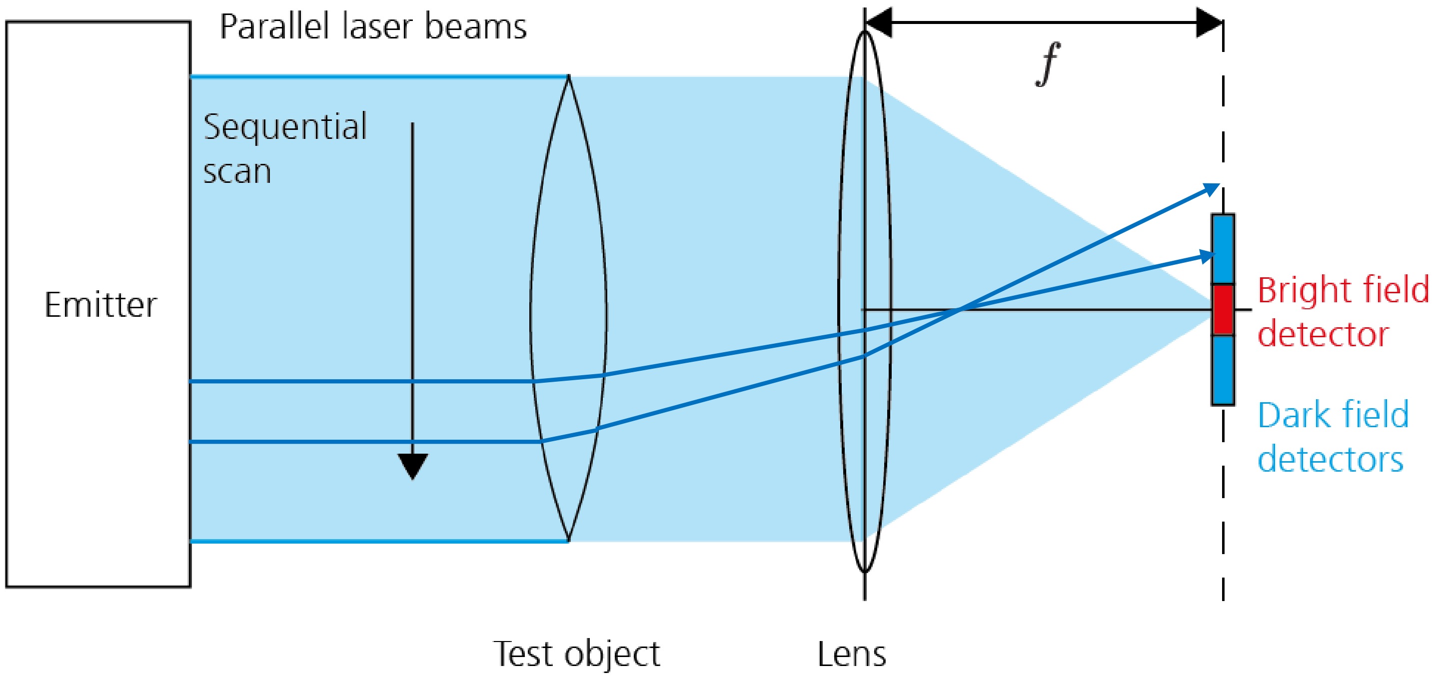
- Laser scanner system Purity



- Bright field channel: opaque inclusions ✓
- Dark field channel: transparent, scattering inclusions ✓

State of the Art

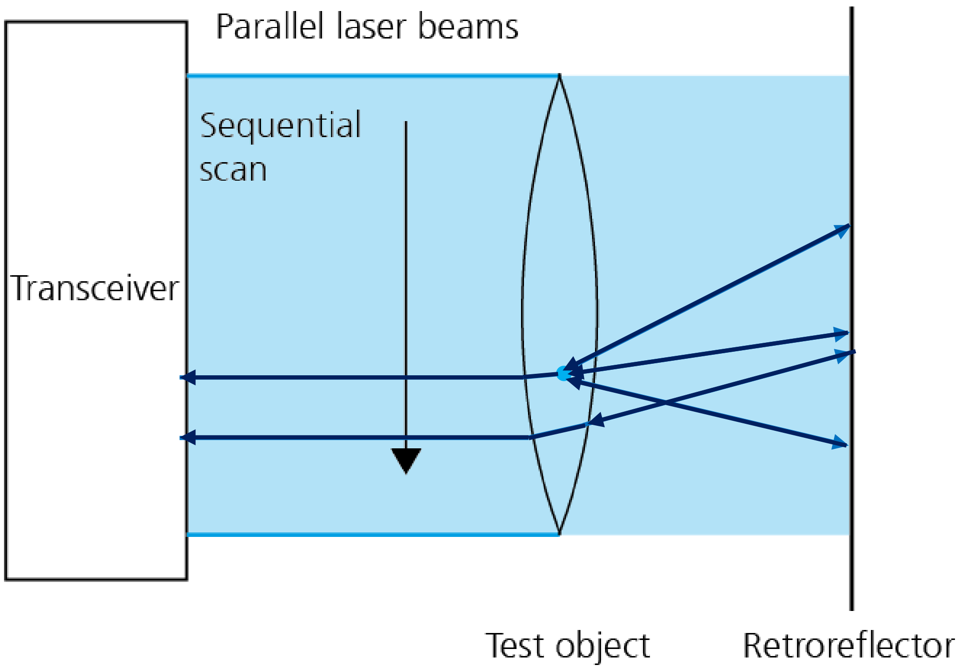
- Laser scanner system Purity – uncooperative test object



  – Ray deflections caused by the test object's more complex geometry
    ➔ False signals captured by the dark field detectors
    ➔ Dark field detectors missed at all

State of the Art

- Laser scanner system Purity with retroreflector



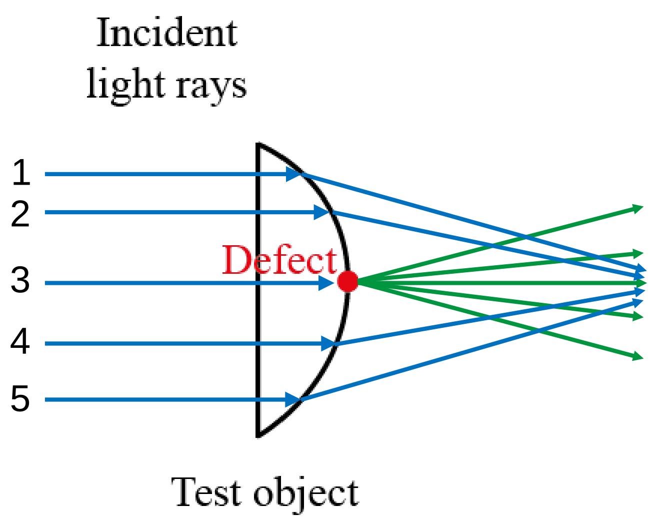
- Retroreflector

\+ mitigates influence of the test object's geometry
➔ visualization of opaque defects ✓

– compensates deflections caused by scattering defects
➔ scattering defects are **not** visualized ✗

Light Field Methods

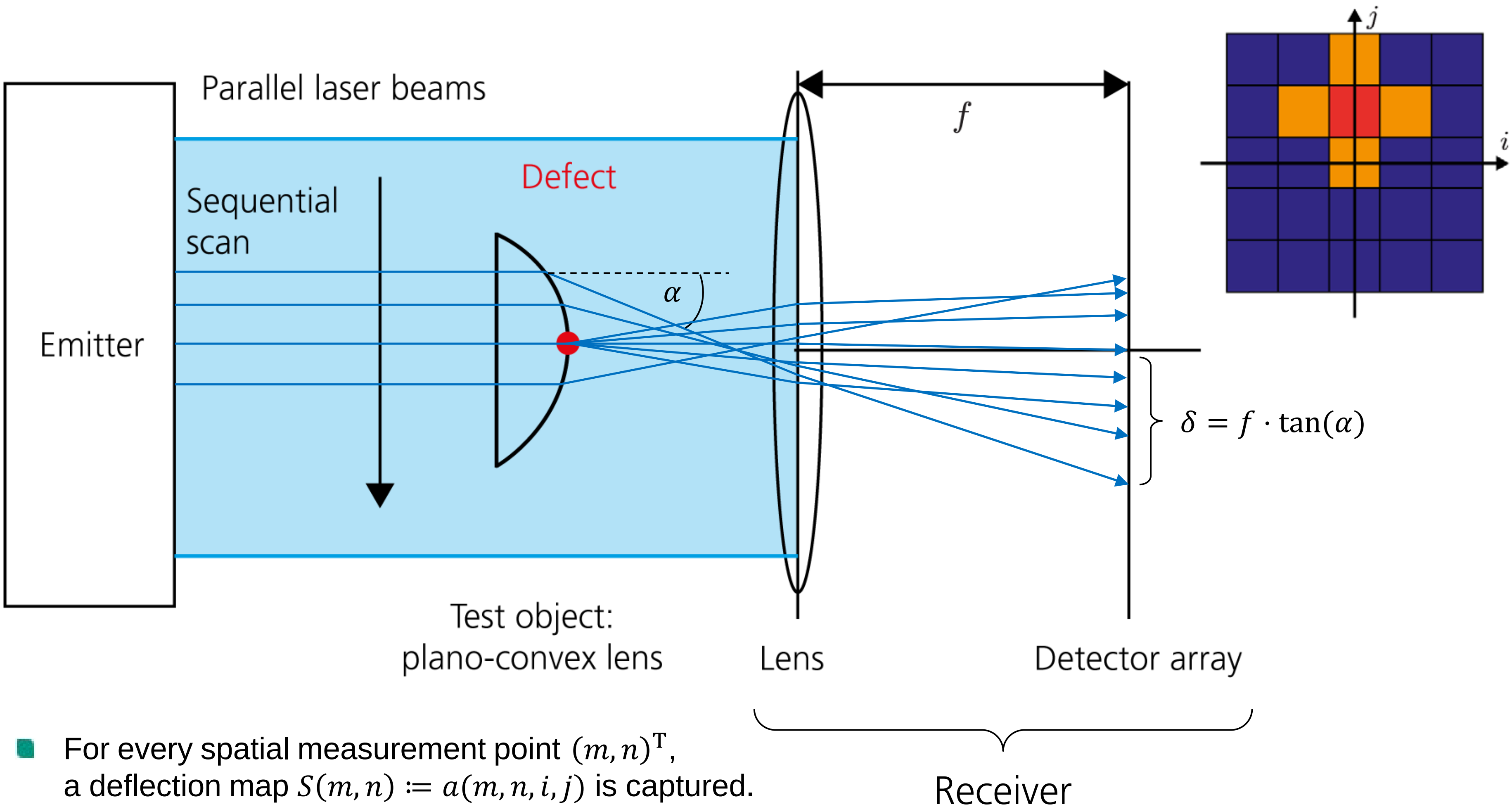
- Basic ideas – consider a test object with a scattering defect



- 4D-Light field $\mathcal{L}(x, y, \theta, \varphi)$ contains the information for defect detection.

Light Field Methods – Deflection Map Acquisition

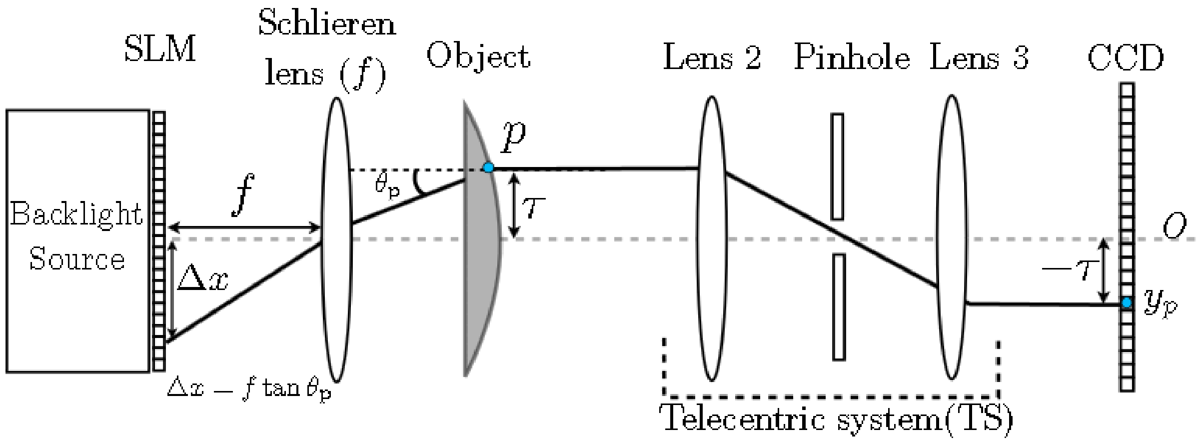
- Acquisition of deflection maps using a laser deflection scanner

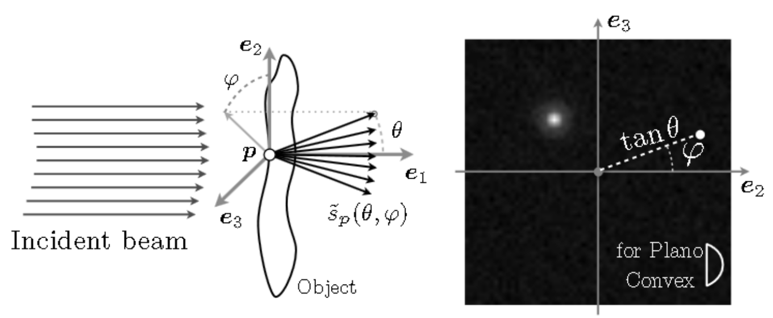


- For every spatial measurement point $(m, n)^{\mathrm{T}}$, a deflection map $S(m, n) \coloneqq a(m, n, i, j)$ is captured.

Light Field Methods – Deflection Map Acquisition

- Deflection maps… sounds familiar?

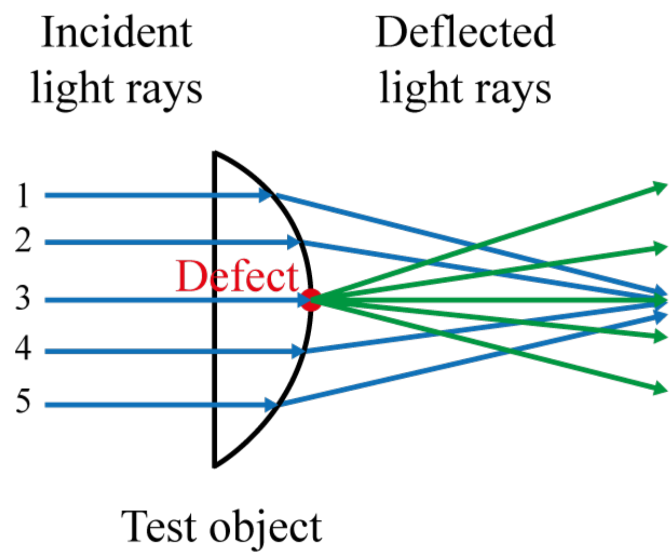


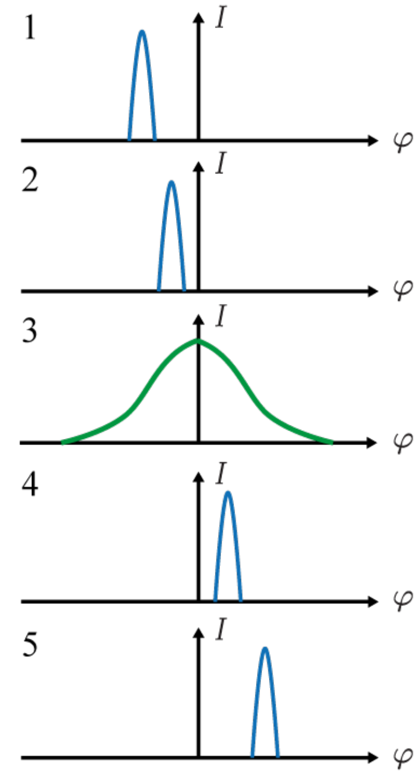


- Sudhakar, P., Jacques, L., Dubois, X., Antoine, P., & Joannes, L. (2015). Compressive imaging and characterization of sparse light deflection maps. SIAM Journal on Imaging Sciences, 8(3), 1824-1856.

Light Field Methods – Deflection Maps

- Processing:
  Scattering defects ➔ Discontinuities between spatially adjacent deflection maps





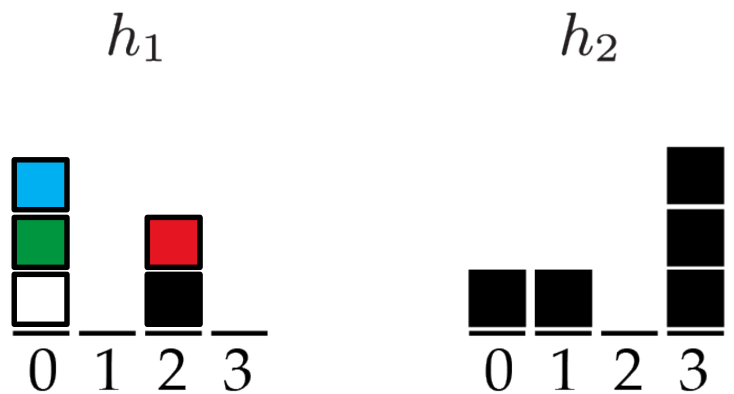
  - Gradient $\mathbf{\Delta}_S$ of S:

$$\mathbf{\Delta}_S(m,n) = \begin{pmatrix} d\big(S(m-1,n), S(m+1,n)\big) \\ d\big(S(m,n-1), S(m,n+1)\big) \end{pmatrix}$$

  - Search for defects in $||\mathbf{\Delta}_S||$ using common image processing methods.
  - Which distance $d(\cdot,\cdot)$ to choose? ➔ Histogram distances!

Light Field Methods – Deflection Map Processing

- Possible choice for $d(\cdot,\cdot)$: Earth Mover's Distance $EMD(\cdot,\cdot)$
  - Distance measure between two histograms h_1, h_2.
    - $EMD(h_1, h_2) \approx$ minimal transformation costs between h_1 and h_2 .
  - Example for 1D-EMD:



$$EMD(h_1, h_2) = 1 + 1 + 3 + 1 = 6$$

Light Field Methods – Deflection Map Processing

- Generalized Cramér-von Mises Distance
  - Main ingredient: Localized Cumulative Distribution (LCD)
  - Random vector $\tilde{\mathbf{x}} \in \mathbb{R}^N, N \in \mathbb{N}$ with probability density function $f: \mathbb{R}^N \rightarrow \mathbb{R}_+$
    ➔ cumulative distribution not well-defined
  - Hanebeck et al. introduced well-defined LCD $F(\mathbf{x}, \mathbf{b})$:

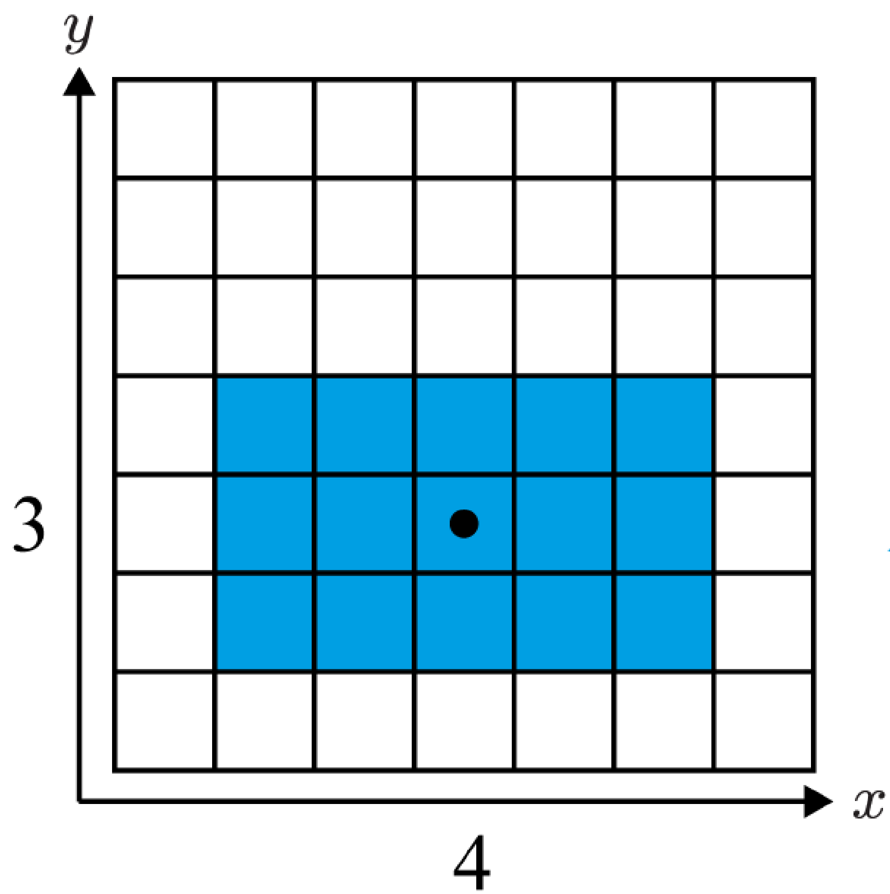
$$F(\mathbf{x}, \mathbf{b}) = \int_{\mathbf{x}-\mathbf{b}}^{\mathbf{x}+\mathbf{b}} f(\mathbf{t}) d\mathbf{t}$$

  - LCD is kind of an integral transform with kernel $\mathbf{b}$.

Hanebeck, Uwe D., and Vesa Klumpp. "Localized cumulative distributions and a multivariate generalization of the cramér-von mises distance." *Multisensor Fusion and Integration for Intelligent Systems, 2008. MFI 2008. IEEE International Conference on*. IEEE, 2008.

Light Field Methods – Deflection Map Processing

- Generalized Cramér-von Mises Distance
  - Main ingredient: Localized Cumulative Distribution (LCD)



$$F\left((4,3)^{\mathrm{T}},(2,1)^{\mathrm{T}}\right)$$

Hanebecl
cramér-v
MFI 2008. IEEE International Conference on. IEEE, 2008.

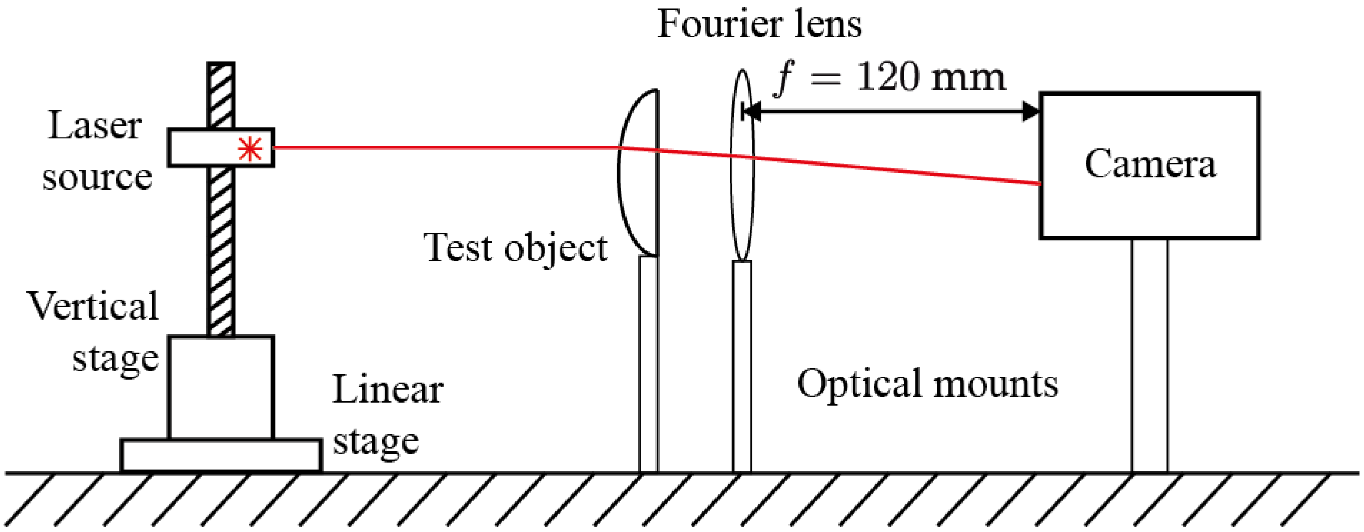
Light Field Methods – Deflection Map Processing

- For two random vectors $\tilde{\mathbf{x}}, \tilde{\mathbf{y}} \in \mathbb{R}^N, N \in \mathbb{N}$
  with probability density functions $f(\mathbf{x}), g(\mathbf{x})$
  and their LCDs $F(\mathbf{x}, \mathbf{b}), G(\mathbf{x}, \mathbf{b})$,
  the generalized Cramér-von Mises distance is defined as:

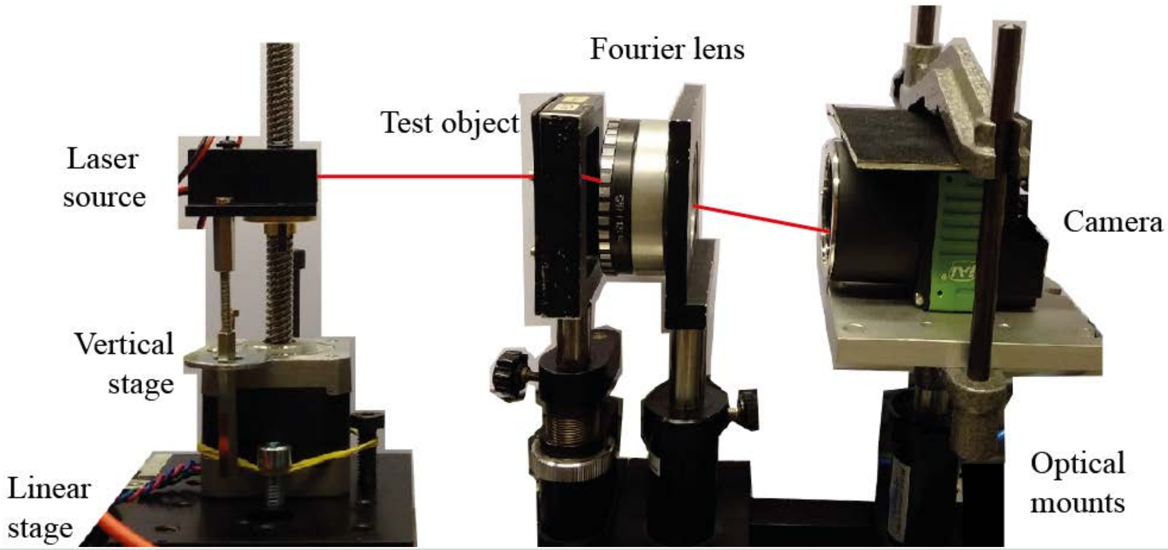
$$D(f,g) = \int_{\mathbb{R}^N} \int_{\mathbb{R}_+^N} \left(F(\mathbf{x},\mathbf{b}) - G(\mathbf{x},\mathbf{b})\right)^2 d\mathbf{b}\, d\mathbf{x}$$

Light Field Methods – Deflection Map Processing

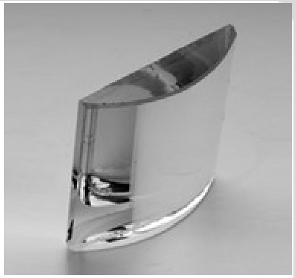
- Design of a first prototype:



- Realization:

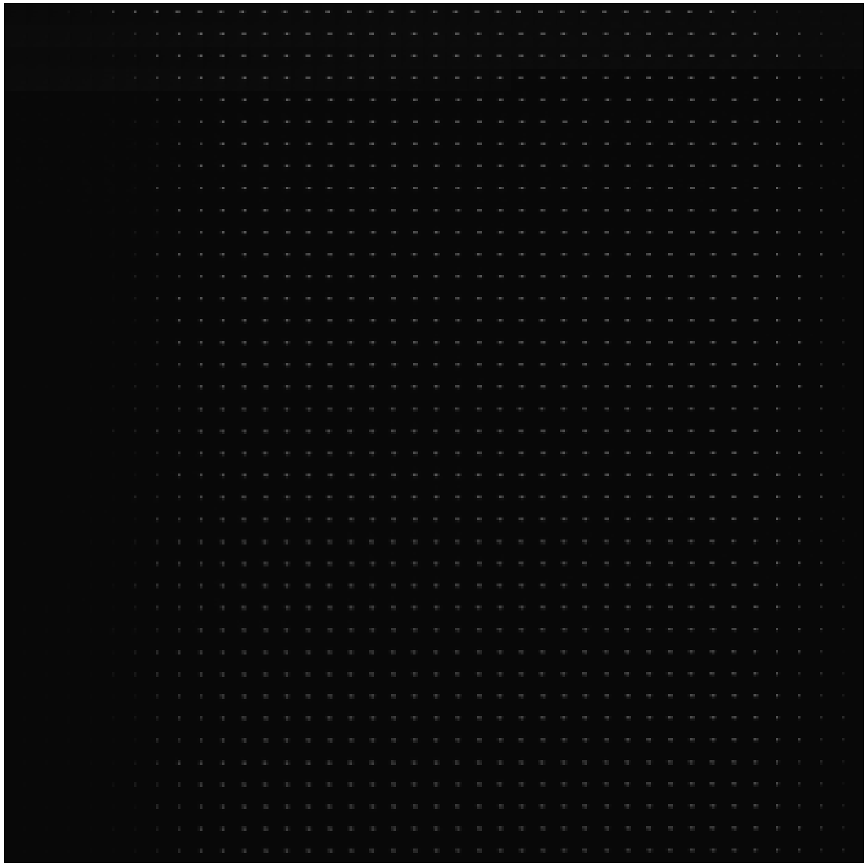


Light Field Methods – Deflection Map Processing

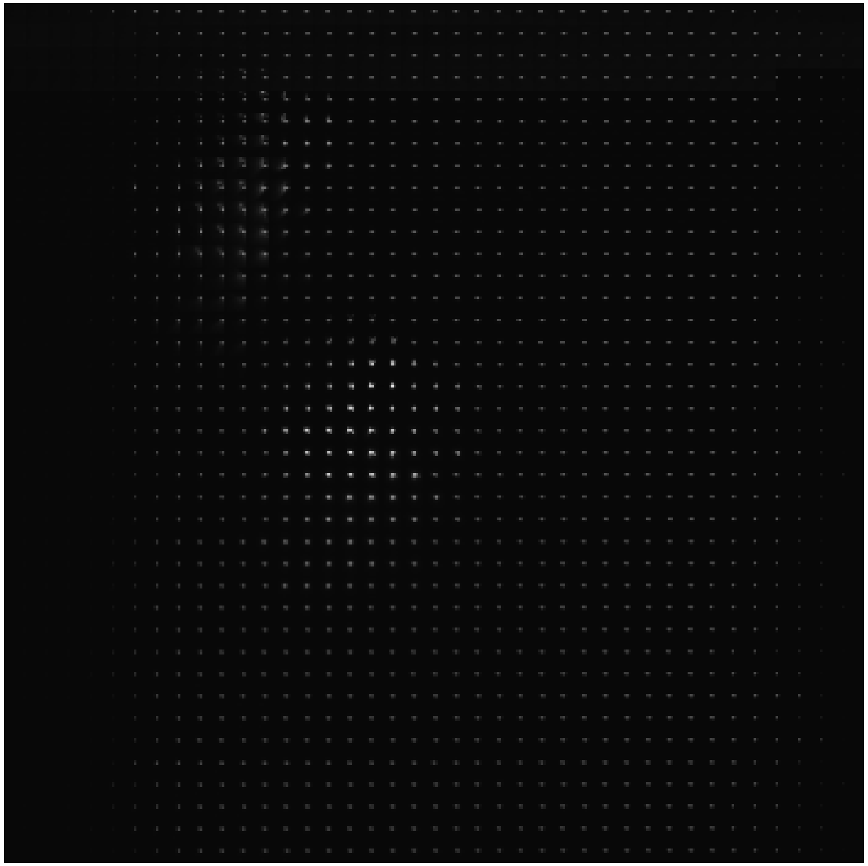


- Experiments with the first prototype

No defects

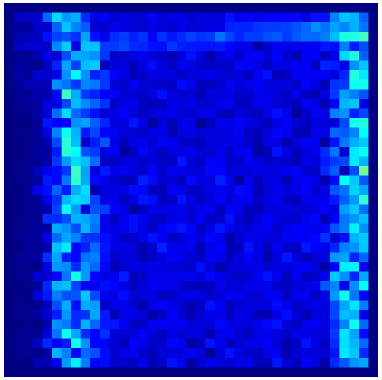
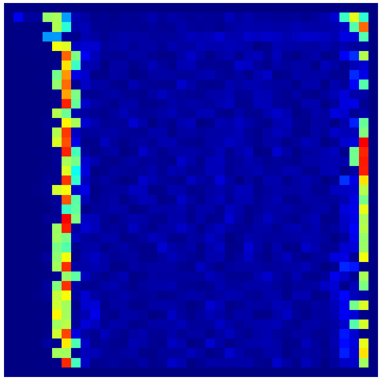
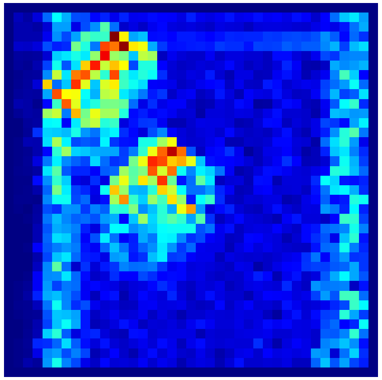
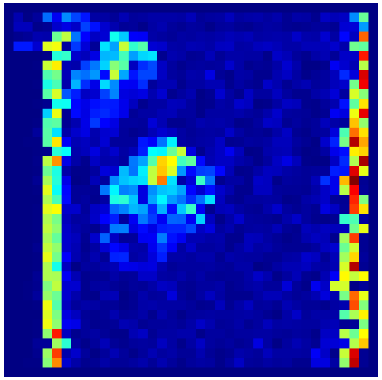


Two scattering defects



Light Field Methods – Deflection Map Processing

- Experiments:
  Test object: cylindrical plano-convex lens
  Acquisition setup: early prototype of the laser deflection scanner

	Earth mover‘s distance	Generalized Cramér-von Mises distance
Defect-free		
Two scattering defects		

Light Field Methods – Deflection Map Processing

- Experiments:
  - Inferred defect size

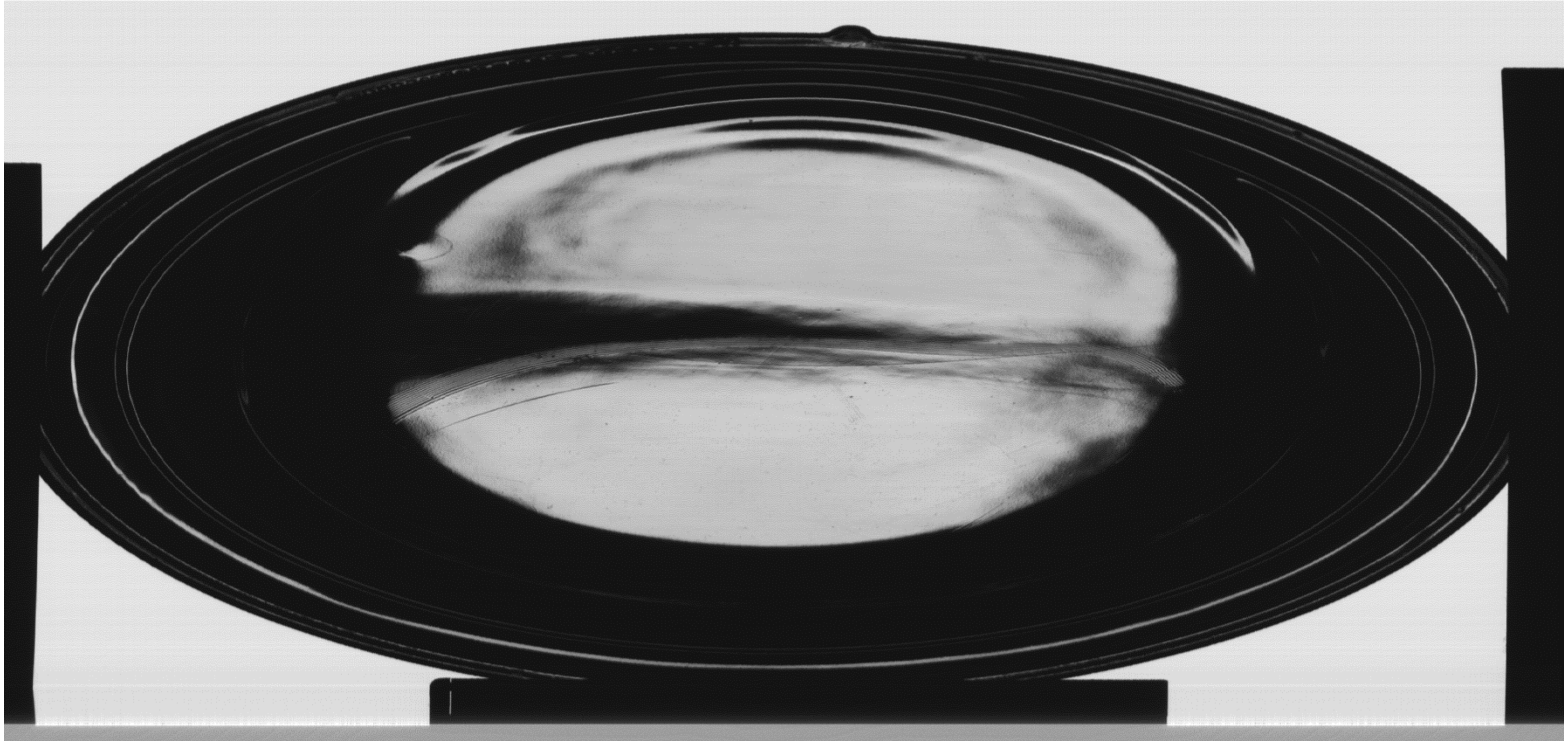
Defect	Upper left	Lower right
Manually measured size	2.8 mm x 2.8 mm	4 mm x 4 mm
EM-distance based estimation	4 mm x 4 mm	4.68 mm x 4.68 mm
CVM-distance based estimation	3 mm x 3 mm	4.34 mm x 4.34 mm

  - Signal-to-noise ratio and peak signal-to-noise ratio

	SNR	PSNR
EM-distance	15.3	28.3
CVM-distance	18.1	39.8

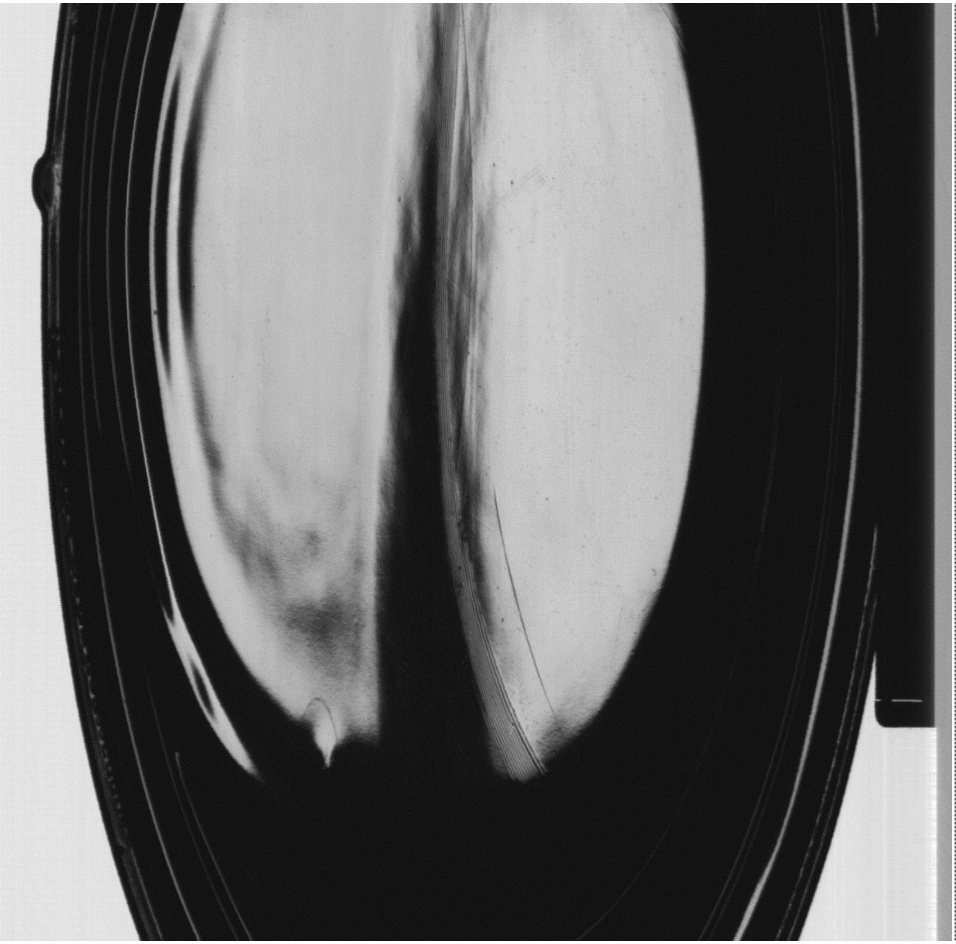
Light Field Methods – Deflection Map Processing

- Experiments with another prototype
  - Test object: Cover glass of a washing machine
    - Image obtained using conventional scanner:

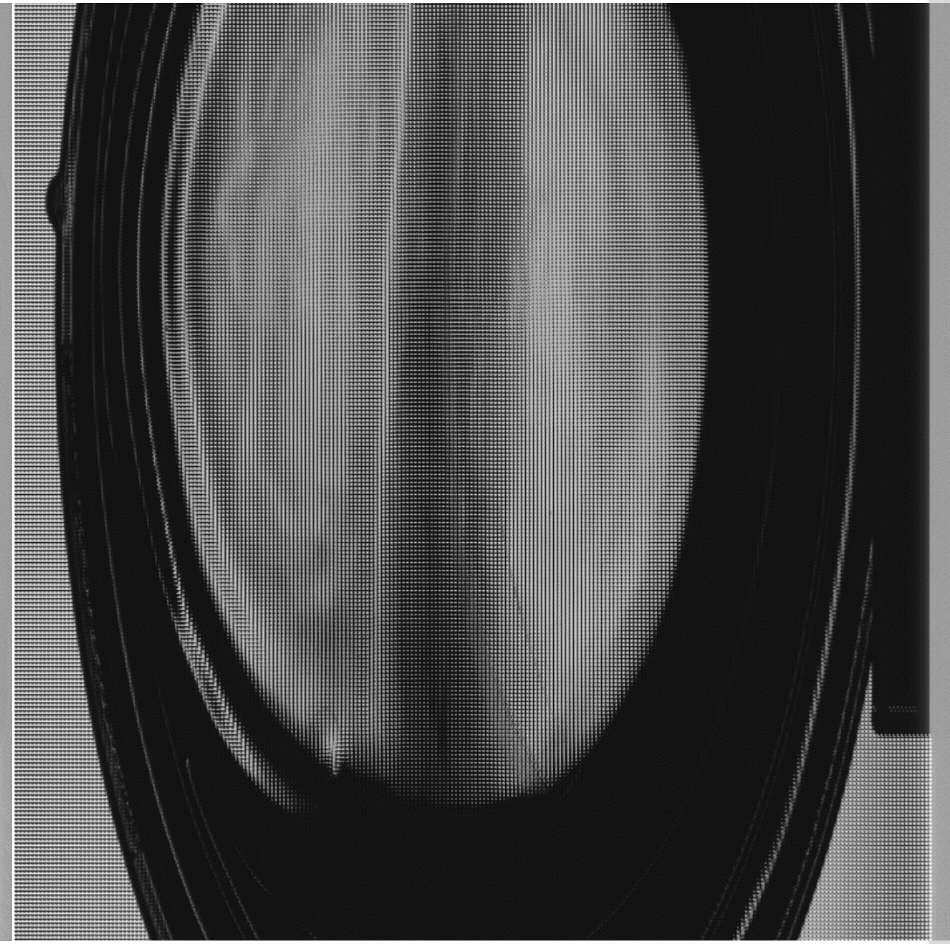


Light Field Methods – Deflection Map Processing

- Image from conventional scanner:



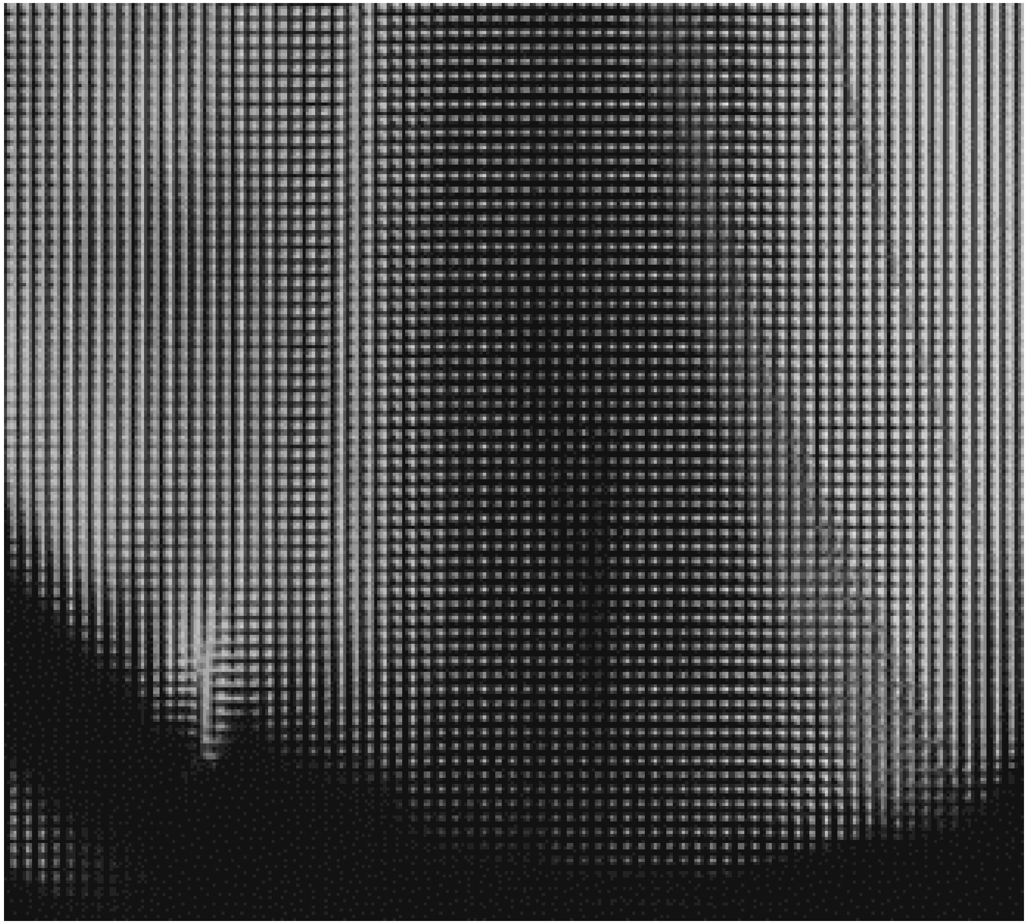
- Light field from laser deflection scanner:



Light Field Methods – Deflection Map Processing

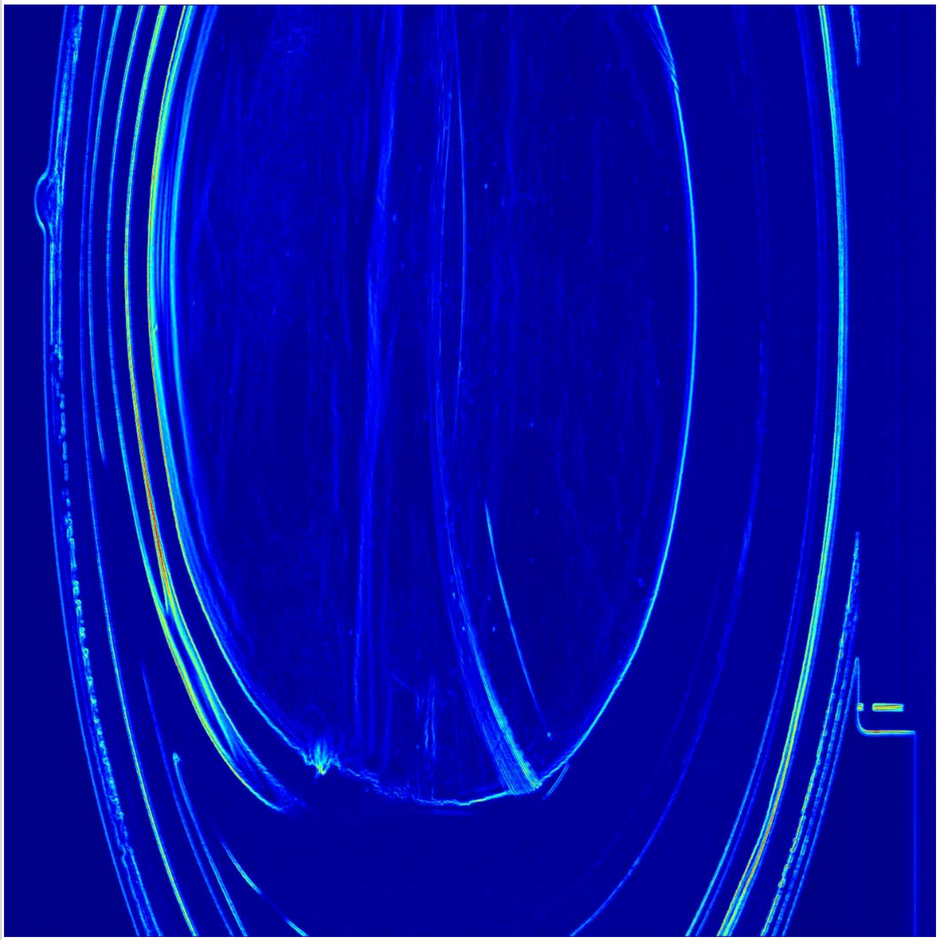
- Image from conventional scanner:

- Light field from laser deflection scanner:

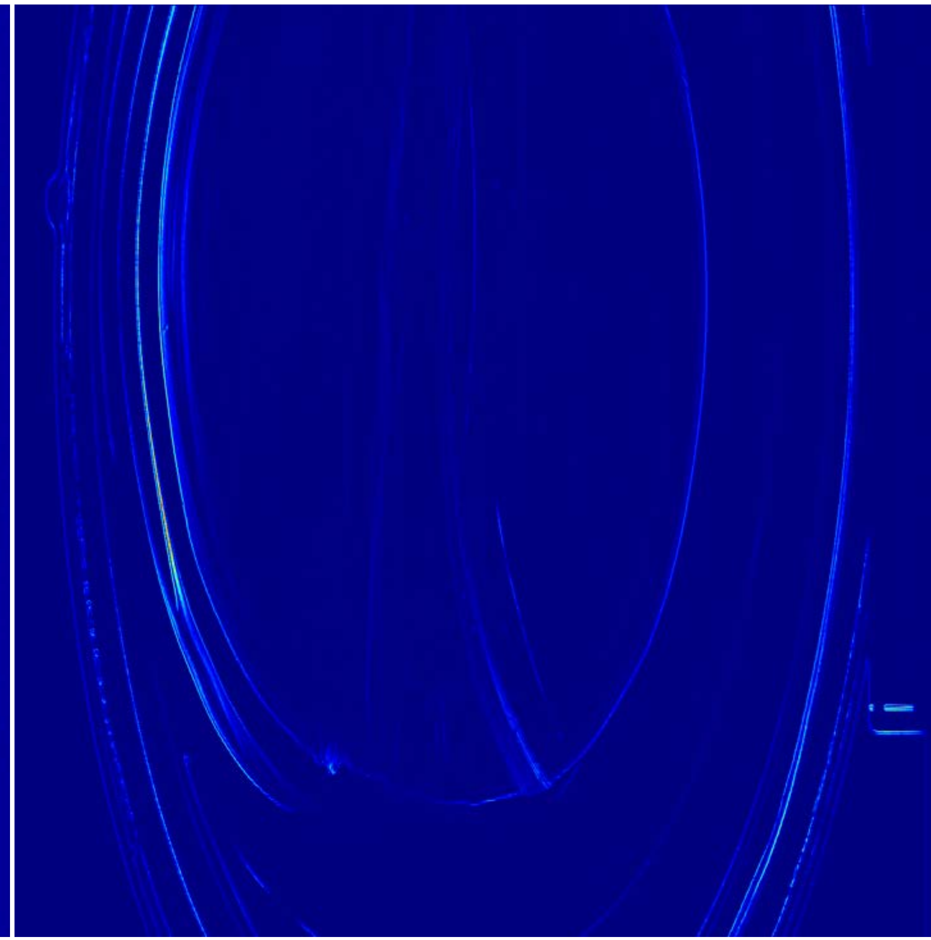


Light Field Methods – Deflection Map Processing

- EM distance

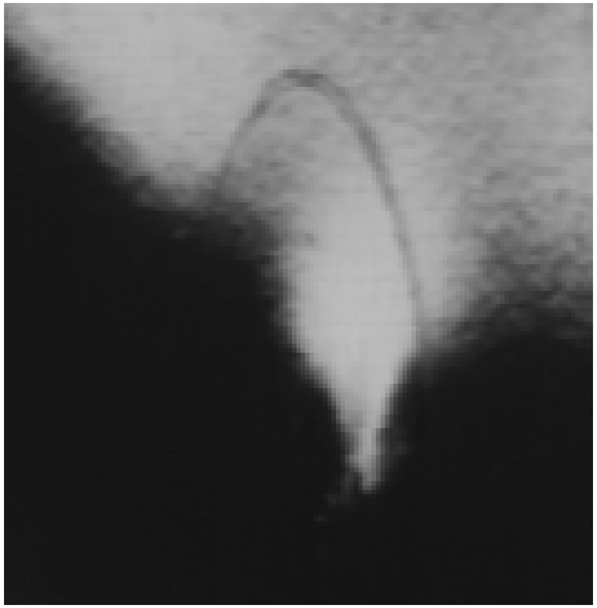


- GCVM distance

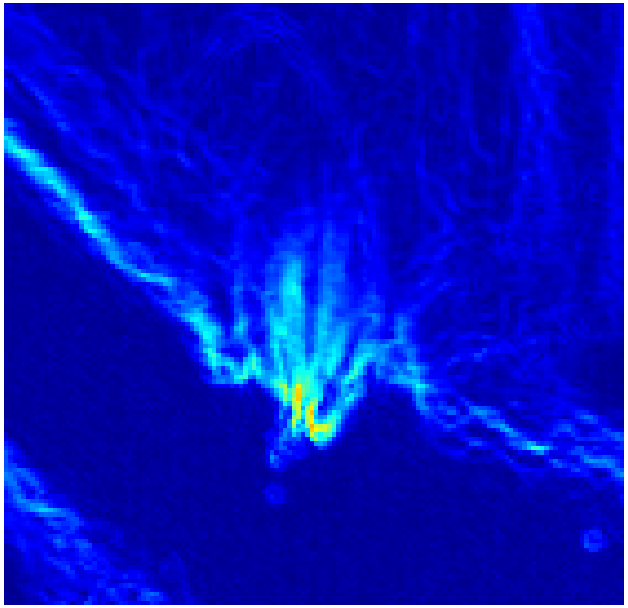


Light Field Methods – Deflection Map Processing

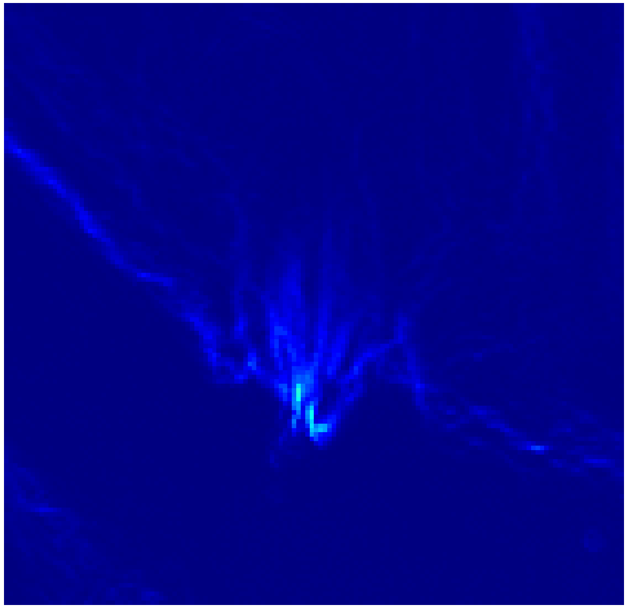
- Image from conventional scanner



- EM distance

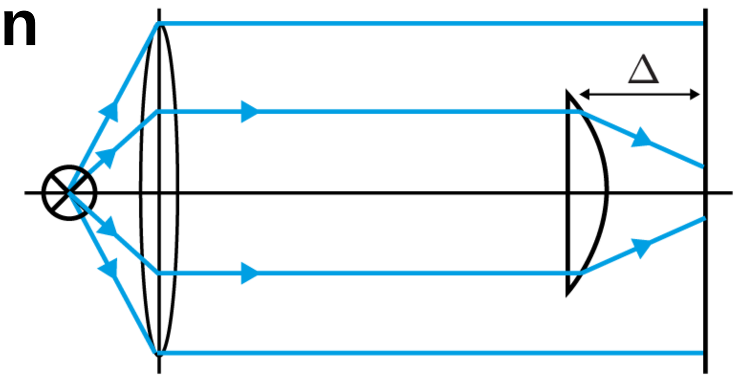


- GCVM distance

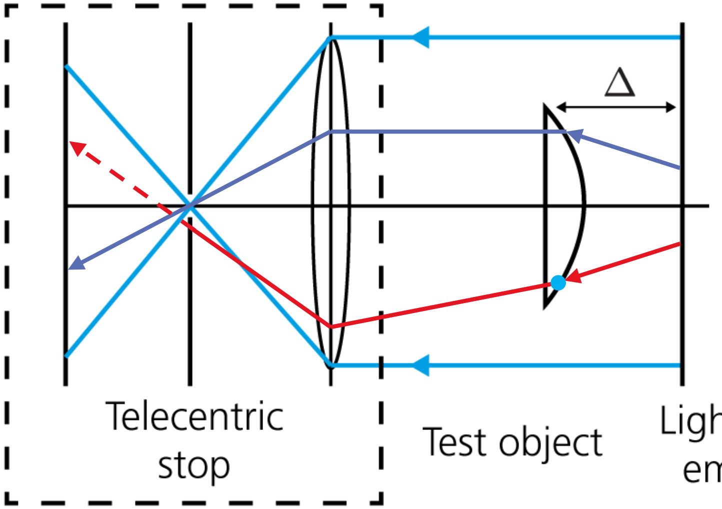


Light Field Methods - Inverse Light Field illumination

- Acquisition of a reference light field $\mathcal{L}$ of a defect-free test object instance.

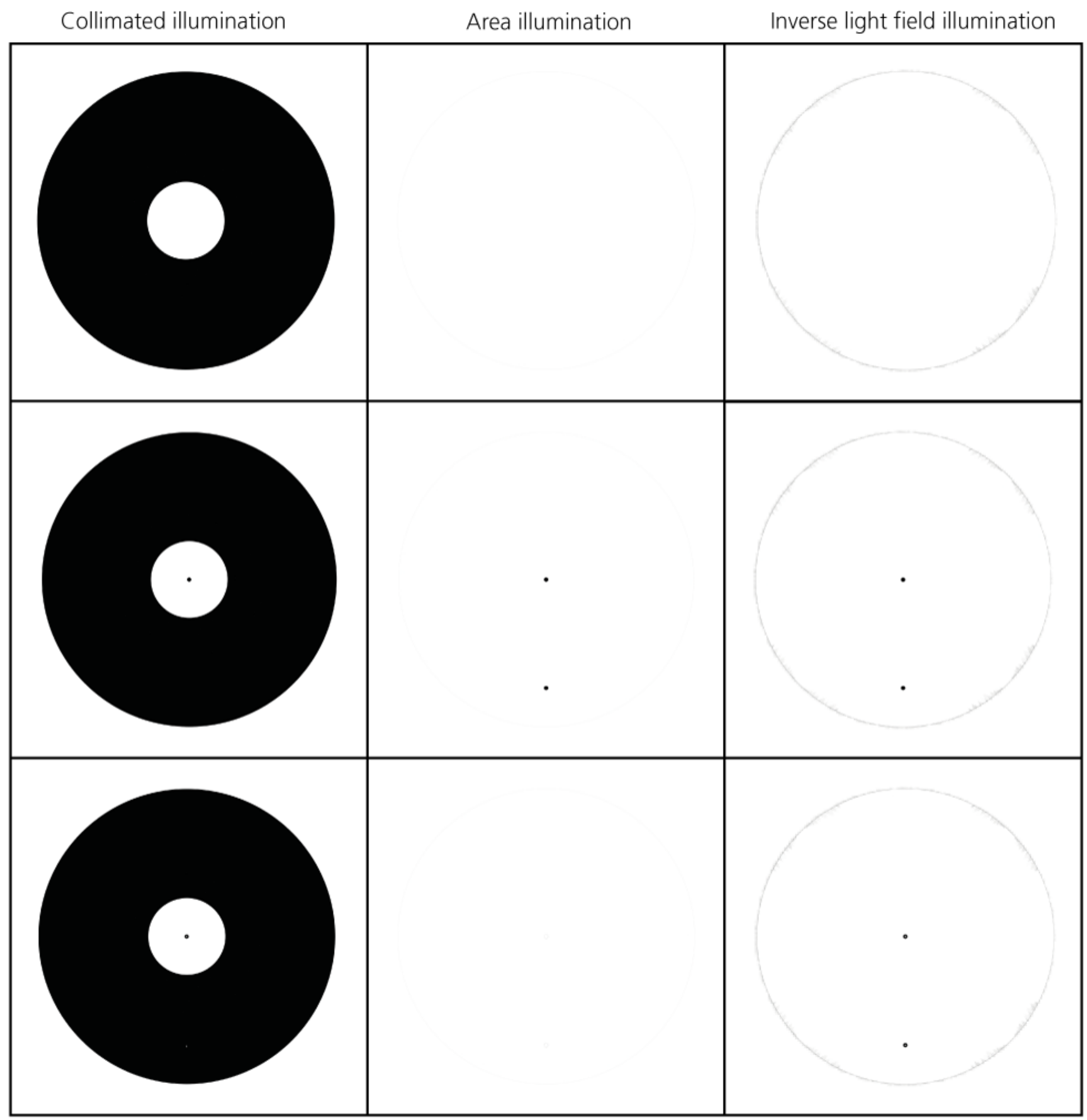


- Inspection of other test objects via illumination with $\mathcal{L}$ and image acquisition using a telecentric camera.



Simulation results

- Defect-free test object
- Test object with opaque inclusions
- Test object with enclosed air bubbles



Summary & Outlook

- Automated visual inspection of transparent objects
  - High relevance for industry and academia
  - Consideration of the light‘s propagation direction leads to promising results

- Light field methods
  - Acquisition and processing of deflection maps
    - Laser deflection scanner
      - Proof of concept done with first prototypes
      - ➔ **Industrial sensor currently under construction**
    - Processing methods and distance measures
      - 2D-Earth mover‘s distance, vector analysis, statistical methods
      - ➔ **More experiments and comparison**
  - Inverse light field illumination
    - Successfully evaluated by simulation
    - **Practical evaluation**
      ➔ Prototype built (is currently being calibrated)

Thank You for Your Attention!
Questions & Comments are Welcome!

Contact: johannes.meyer@kit.edu

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