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# Use of experimental ray tracing for locally resolved characterization of progressive addition and contact lenses

https://doi.org/10.1515/cdbme-2025-0105

**Abstract:** Progressive Addition Lens (PAL) exhibits complex freeform surfaces. More and more user specific optimization is designed into modern PAL, increasing the complexity of its characterization. Also, modern additive manufacturing methods implement not only ways to create individual freeform shape, but to vary locally refractive index, too. Improvements demand complementary methods to topography measurement and traditional powermapping to characterize the optical performance, especially in a user-centric way taking into account individual direction of sight. We present an overview of different implementations of experimental raytracing (ERT) for measurement of relevant functional parameters of PAL and contact lenses (CL), locally resolved, and taking into account different illumination scenarios, simulating real life use cases.

**Keywords:** Experimental raytracing, PAL, freeform measurement, GRIN lens, optical performance analysis

## 1 Introduction

Modern PAL exhibit individualized freeform surfaces to meet demand of customers for optimized view. More and more user specific optimization is designed into modern PAL, increasing the complexity of its characterization. Traditional characterization techniques in manufacturing rely on measurement of surface shape, using interferometers and tactile profilometers. Optical function often is measured by Moire deflectometry or Shack-Hartmann sensors. Also, modern additive manufacturing methods implement not only ways to create individual freeform shape, but to vary locally refractive index, too. Improvements demand complementary methods to traditional powermapping to characterize the optical performance, especially in a user-centric way taking into account individual direction of sight. It is known that user's visual performance is highly sensitive to the optics of PAL, so new metrices are required to quantify the optical performance adequately [1-4].

For this purpose, we present different implementations of experimental raytracing (ERT) for measurement of relevant functional parameters of PAL and contact lenses (CL), locally resolved, and taking into account different illumination scenarios, simulating real life use cases.

## 2 Method

### 2.1 Principle of ERT

Experimental ray tracing (ERT) was introduced by Häusler et al. already in 1988 [5] and has been used successfully for high precision measurement of optical elements [6,7]. In ERT, the device under test (DUT) is scanned by a narrow beam of light, named test beam in figure 1. The direction of the refracted beam is detected from its intersection with two parallel imaging planes yielding a beam gradient. In both planes, separated by a distance Δz, centroid positions $S^1_{i,j}$ and $S^2_{i,j}$ are calculated from intensity distributions acquired by a CMOS sensor. The gradient is defined as the slopes $T_x$ and $T_y$ of the beam in $x$- and $y$-direction. Naming the beam centroid position for each test beam position (i,j) at camera position on the camera chip in $z_1$ ($x_1$, $y_1$) and in $z_2$ ($x_2$, $y_2$), respectively, the slopes are derived by eq 1.

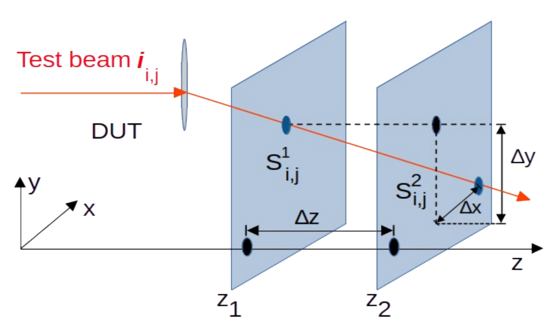


**Figure 1:** ERT principle. For each measurement point ($x_i$, $y_j$) refracted test beam is detected in 2 planes and the ray slopes are derived from centroid positions $S_{i,j}$.

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$$T_x = \frac{x_1 - x_2}{z_1 - z_2} = \frac{\Delta x}{\Delta z}; T_y = \frac{y_1 - y_2}{z_1 - z_2} = \frac{\Delta y}{\Delta z} \quad (1)$$

This is done for a series of test positions (i,j) to scan the DUT. From gradients, the wavefront aberration function W is determined. [8] For evaluation of a PAL, test rays can be distributed across the complete lens, or across subapertures of it to evaluate performance locally resolved within a region of interest. In a user centric approach, subapertures should reflect the projected pupil of the eye, depending on physiology of wearer and illumination condition.

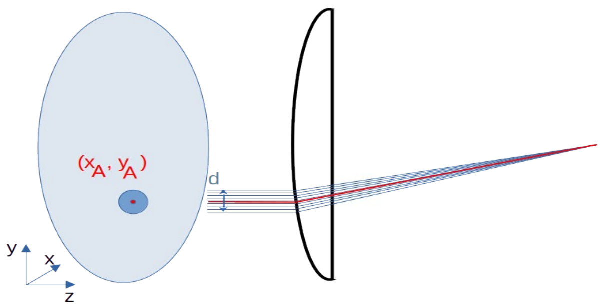


**Figure 2:** Locally resolved evaluation of optical performance within a subaperture of lens. Around each center ($x_A$,$y_A$) of pupil (left, front view), test beams are used to determine wavefront aberration in a circle with diameter d representing projected pupil of eye (right, cross-section).

## 2.2 Wavefront reconstruction

The gradient of the wavefront is related to ray slopes by

$$\nabla W = \begin{pmatrix} \frac{\partial W(x,y)}{\partial x} \\ \frac{\partial W(x,y)}{\partial y} \end{pmatrix} = \begin{pmatrix} T_x \\ T_y \end{pmatrix}. \quad (2)$$

By minimizing the difference between measurement from eq. 2 [6, 8] and the gradient of the waveform representation by a polynomial series like Zernike polynomials, the wavefront is reconstructed by modal integration and parameters like optical power, point spread function (PSF), modulation transfer function (MTF) and strehl ratio are derived. [10]

## 2.3 Parameters

### 2.3.1 Local powermap

The local powermap is a map visualizing the optical power of a DUT in very small local areas. The DUT is investigated at discrete positions ($x_A$, $y_A$) as indicated in figure 2. As described, power map can be constructed from subaperture wavefronts. In a simplified version, each subaperture may include only four measured positions, and local optical power in center of such subaperture is directly calculated from measured ray slopes $T_x$ and $T_y$ at each of that four positions. [9]

### 2.3.2 MTF

While optical power plots are well known to characterize PAL, visualizing MTF is more complex. Gutierrez has introduced a method to represent it in a similar convenient way by plotting $MTF_{50}$ or any appropriate value of criterion. [10]

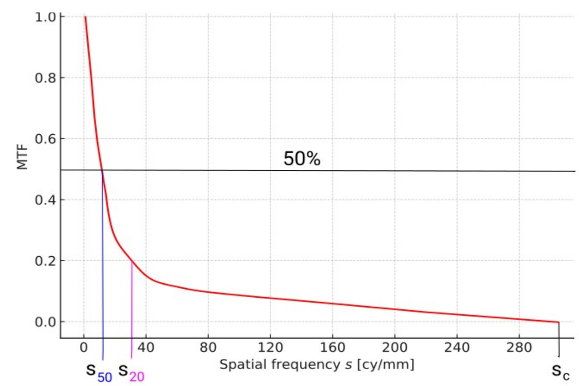


**Figure 3:** Definition of MFT 50 criterion as the value MTF has dropped to 50% of cutoff $S_c$.

## 2.4 Setup

For measurement of optical properties in use case condition, a specialized setup to realize ERT was developed, see fig. 4. DUT is mounted in lens holder on rotary stage labeled “φ”.

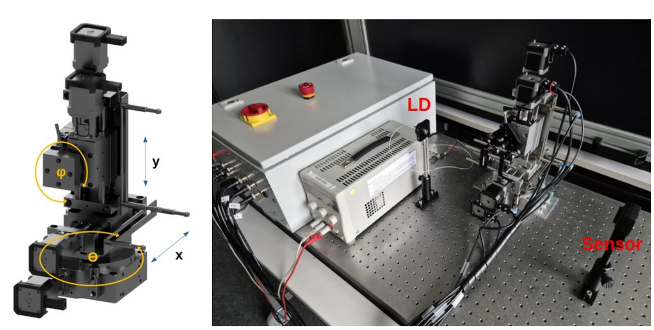


**Figure 4:** Positioning system for rotary (Θ, φ) and lateral movement (x,y) of lens (left) and realized measurement setup (right). Test beam emerges from laserdiode LD to sensor.

By rotating lens in direction of ϴ and φ, the viewing angle according to user's view in direction of the center of subaperture of interest is adjusted, so test beam follows the line of sight. For measurement of beam gradients in a given subaperture, lens is scanned via x- and y-axes, so while scanning each subaperture, the test beam hits lens in a fixed angle.

# 3 Results

From MTF measurement, the resultant two-dimensional maps in sagittal and tangential directions are depicted as in figure 5. As expected, the map shows that the highest values are in near vision zone and the lowest values are obtained in the blending regions.

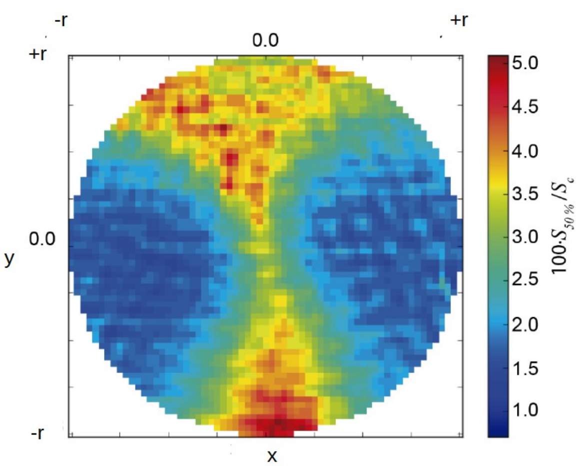


**Figure 5:** 2-dimensional plot of MTF $_{50}$ plot of a PAL.[10]

Also, the small corridor clearly is visible, showing a mediocre resolution.

# 4 Conclusion

Methods for measurement of optical properties of lenses by experimental ray tracing (ERT) have been presented, especially for, but not limited to progressive addition lenses (PAL). The proposed method allows to evaluate performance in subapertures of lens, and size of subaperture also can be adjusted to the size of projected pupil of eye. This allows not only to map optical parameters to regions of DUT, but to evaluate the influence of illumination (and therefore pupil size of eye) to parameters like MTF. A setup for realization of ERT for PAL measurement simulating user view conditions is presented. Ongoing work will compare parameters obtained by classical approach of measurement using orthogonal ray orientation versus those obtained in user view condition.


**Author Statement**

Research funding: The author state no funding involved. Conflict of interest: Authors state no conflict of interest. Informed consent: Informed consent has been obtained from all individuals included in this study. Ethical approval: The research related to human use complies with all the relevant national regulations, institutional policies and was performed in accordance with the tenets of the Helsinki Declaration, and has been approved by the authors' institutional review board or equivalent committee.


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