Applications of Non-sequential Ray Tracing to Investigate Lenslet Image Point Spread Function Uniformity Under Geometrical & Physical Optical Coherent & Incoherent Source Modeling

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Overview

- Past work using Shack-Hartmann Wavefront Sensors (SHWS) to quantify intraocular scatter
- Wavefront & scatter simulation through a Shack-Hartmann (S/H) lenslet array
- Techniques for identifying scatter sources
- Visual comparison to real S/H imaging
Introduction

• Aberrations, diffraction, & scatter in the eye decrease retinal image quality
• Although used mainly for aberrations, SHWS contain all this information
  • Previous work: Optimizing SHWS for sensing scatter
    • Univ. of Houston Col. Of Optometry (UHCO)
    • Wavefront Sciences, Inc.
Background

Using the SHWS to assess forward scatter
S/H derived forward scatter is correlated to vision by optics reversibility.

Vision with forward scatter from nuclear cataract.

SHWS to assess forward light scatter.

Forward scatter from the lens is correlated.
What can be done w/ scatter information from a SH image?

• Clinical assessment of intraocular scatter associated w/ wavefront data
• Create improved visual performance predictions & PSF reconstruction
• Assist development of IOLs, spectacles, lenses, & ocular instrumentation to reduce stray light
• Predict
  • refractive surgery outcomes, i.e. halos
  • scatter from trauma or disease
SHWS has 2 primary optical channels

1) Wavefront channel
2) Forward scatter channel
SHWS layout: 2 channels

Wavefront channel

Forward scatter channel
Previous UHCO TINCO study showed that with advancing nuclear cataract there was...

- **Transmission loss in the wavefront channel**
  - Lenslet image PSFs were attenuated in the CCD plane (conjugate to the retina)
    - PSF height had best correlation with nuclear cataract
    - We learned to assess cataract progression, we must optimize & fix exposure

- **Veiling luminance in the forward scatter channel**
  - Local areas at the CCD plane
    - Could contain both forward scatter & backscatter from surfaces
    - Mild correlation with nuclear cataract using 2nd moment techniques
Height fields from 2 patient SH images (lenslet image PSFs)

Age 25, NO = 0.8
Clear Eye
(PSFs are pointy and steep)

Age 71, NO = 5.6
Dense Nuclear Cataract
(PSFs attenuate, veiling luminance increases)
2 types of intraocular scatter

- **Volumetric (bulk) scatter**
  - Attenuates retinal & lenslet image PSFs
  - Caused by small particles in the lens volume
  - Increases with age & nuclear cataract
  - Can be characterized by Rayleigh & Mie scatter models

- **Surface scatter**
  - Creates areas of localized veiling luminance
  - Increases with lens & corneal surface roughness
  - Probe beam & tear film surface can contribute
  - Refractive surgery or IOLs can contribute
  - Characterized by Harvey scatter models
We can predict PSF attenuation from Mie volumetric scatter via microspheres in solution & computer modeling. TINCO linked Mie scatter to nuclear opalescence.

Physical model: Cox et al 2001

Computer Model & confirmed physical model: Donnelly, et al 2005
Harvey surface scatter

- Harvey scatter can be predicted using the Bi-Directional Scatter Distribution Function (BSDF)
- The Bi-Directional Reflectance Distribution (BRDF) & Bi-Directional Transmittance Distribution (BTDF) are derived from the BSDF
Harvey surface scatter model
BSDF as a function of angle
Volumetric (bulk) & Surface scatter
General Research Question

- Can we separate & quantify aberrations and volumetric and surface scatter in a Shack-Hartmann image?
Specific Research Question

• What uniformity exists in lenslet image PSFs when we use non-sequential ray tracing to model
  • Lenslet arrays & Sources
    • Incoherent & coherent
  • Wavefront propagation
  • Volumetric & surface scatter
Methods

- We used the Advanced Systems & Analysis Program (ASAP) by Breault Research Organization
  - Time tested optical systems engineering & analysis program
  - In use & continuous development since 1978
- Visually compare results w/ TINCO data
Methods

• The end system of a SHWS was modeled
  • Used a coherent source to illustrate diffraction patterns & cross-talk
  • Produced lenslet image PSFs at the detector w/ and w/out aberrations
  • Used incoherent volumetric & surface scatter
Lenslet array modeling

Pillow lenslet array
Typical pillow rectangular lenslet array
To illustrate lenslet PSFs in detail...

- We will look at smaller 4x4 section of a larger 30x30 lenslet array
4x4 rectangular array: Lenslet image PSFs
No aberrations
Notice diffraction pattern
4x4 rectangular array: Lenslet image PSFs
Aberrations: 3um defocus & 2um sphere
Notice PSF blur & displacement
Aberrations (only) modeling shows...

• Aberrations cause some lenslet image PSF displacement & blur
• Next step: Add scattering
Attenuation from scatter

• From TINCO we learned
  • volumetric scatter from nuclear cataract or blockage (such as floaters or cortical cataract) can cause transmission loss (attenuation) over local lenslet image PSFs

• So, let’s insert a local attenuator in the wavefront
Local attenuator from nuclear cataract volumetric scatter or blockage

Lenslet array

Detector
Profile trace through the 2nd row.

Attenuated lenslet image PSF.
And now for surface scatter..

- Insert a localized Harvey model in the forward scatter channel
- Surface scatter is conjugate to the lenslet array, not the CCD
Log scaling

- Log scaling can enhance observable scatter in a SH image
- Next slides show & surface scatter combined in log scale
Crosshairs on Attenuated PSF.
Crosshairs on Surface scatter. Clamping shows angular extent of scattering.
SH images & scatter maps of real eyes
Results

- We have demonstrated methods to model aberrations & scatter separately & simultaneously
- Modeling shows similarities to real S/H images inclusive of scatter
- With scatter model parameters derived from the image, we could reverse calculate the extent of local volumetric & surface scattering in the eye
Conclusions

• With wavefront & quantifiable scatter data
  • We can develop a more complete description of the retinal image
  • We can also use this data to develop custom eye models
    • Such as aberrant or diseased eyes
    • To assist intraocular, spectacle, & contact lens design
  • Estimate refractive surgery outcomes
  • To provide a modular Interface w/ ocular instrumentation designs
  • For ‘What if?’ scenarios for vision research
At Breault Research, we are incorporating these techniques into advanced eye models inclusive of intraocular scatter.

Advanced Human Eye Model (AHEM)
Refraction & scatter through spectacles & into eyes
Thank you for your attention
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