Adaptive Optics for Vision Science:
Principles, Practices, Design
and Applications

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(Editorial Committee)

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1. Introduction (David Williams)

University of Rochester

1.1 Goals of the AO Manual (This could also be a separate preface written by the editors)

* practical guide for investigators who wish to build an AO system

* summary of vision science results obtained to date with AO

1.2 Brief History of Imaging

1.2.1 The evolution of astronomical AO

The first microscopes and telescopes, Horace Babcock, military applications during Star Wars, ending with examples of the best AO images obtained to date. Requirements for astronomical AO

1.2.2 The evolution of vision science AO

Vision correction before adaptive optics:
- first spectacles, first correction of astigmatism, first contact lenses, Scheiner and the first wavefront sensor.

Retinal imaging before adaptive optics:
- the invention of the ophthalmoscope, SLO, OCT

First AO systems: Dreher et al.; Liang, Williams, and Miller.

Comparison of Vision AO and Astronomical AO: light budget, temporal resolution

Vision correction with AO:
- customized contact lenses, IOLs, and refractive surgery, LLNL AO Phoropter

Retinal Imaging with Adaptive Optics
- Highlighted results from Rochester, Houston, Indiana, UCD etc.

1.3 Future Potential of AO in Vision Science

1.3.1 Post-processing and AO

1.3.2 AO and other imaging technologies (e.g. OCT)

1.3.3 Vision Correction

1.3.4 Retinal Imaging
1.3.5 Retinal Surgery

II. Wavefront Sensing

2. Aberration Structure of the Human Eye (Pablo Artal)
(Murcia Optics Lab; LOUM)

2.1 Aberration structure of the human eye

2.1.1 Monochromatic aberrations in normal eyes

2.1.2 Chromatic aberrations

2.1.3 Location of aberrations

2.1.4 Dynamics (temporal properties) of aberrations

2.1.5 Statistics of aberrations in normal populations (A Fried parameter?)

2.1.6 Off-axis aberrations

2.1.7 Effects of polarization and scattering
3. Wavefront Sensing and Diagnostic Uses (Geunyoung Yoon)
University of Rochester

3.1 Introduction

3.1.1 Why is wavefront sensing technique important for vision science?

3.1.2 Importance of measuring higher order aberrations of the eye

Characterization of optical quality of the eye
Prediction of retinal image quality formed by the eye’s optics
Brief summary of potential applications of wavefront sensing technique

3.1.3 Chapter overview

3.2 Wavefront sensors for the eye

3.2.1 History of ophthalmic wavefront sensing techniques

3.2.2 Different types of wavefront sensors and principle of each wavefront sensor

Subjective vs objective method (SRR vs S-H, LRT and Tcherning)
Measuring light going into vs coming out of the eye (SRR, LRT and Tcherning vs S-H)

3.3 Optimizing Shack-Hartmann wavefront sensor

3.3.1 Design parameters

Wavelength, light source, laser beacon generation, pupil camera, laser safety...

3.3.2 OSA standard (coordinates system, sign convention, order of Zernike polynomials)

3.3.3 Number of sampling points (lenslets) vs wavefront reconstruction performance

3.3.4 Tradeoff between dynamic range and measurement sensitivity

Focal length of a lenslet array and lenslet spacing

3.3.5 Precompensation

Trial lenses, trombone system, bite bar (Badal optometer)

3.3.6 Increasing dynamic range without losing measurement sensitivity

Translational plate with subapertures
Computer algorithms (variable centroiding box position)
3.3.7 Requirement of dynamic range of S-H wavefront sensor based on a large population of the eye’s aberrations

3.4 Calibration of the wavefront sensor

3.4.1 reconstruction algorithm - use of simulated spot array pattern

3.4.2 measurement performance - use of phase plate or deformable mirror

3.5 Applications of wavefront sensing technique to vision science

3.5.1 Laser refractive surgery (conventional and customized ablation)

3.5.2 Vision correction using customized optics (contact lenses and intraocular lenses)

3.5.3 Autorefraction (image metric to predict subjective vision perception)

3.5.4 Objective vision monitoring

3.5.5 Adaptive optics (vision testing, high resolution retinal imaging)

3.6 Summary
III. Wavefront Correction with Adaptive Optics

4. Mirror Selection (Nathan Doble and Don Miller)
   University of Rochester / Indiana University

4.1 Introduction

4.1.1 Describe the DMs used in current systems.
   4.1.1.2 Xinetics type – Williams, Miller, Roorda – (PZT and PMN)
   4.1.1.3 Membrane – Artal, Zhu(Bartsch)
   4.1.1.4 MEMS – LLNL Phoropter, Doble
   4.1.1.5 LC-SLM – Davis System.

4.2 Statistics of the two populations

4.2.1 State of refraction:
   4.2.1.1 All aberrations present
   4.2.1.2 Zeroed Defocus
   4.2.1.3 Same as for 4.2.1.2 but with astigmatism zeroed in addition

4.2.2 For various pupil sizes (7.5 - 2 mm) calculate:
   4.2.2.1 PV Error
   4.2.2.2 MTF
   4.2.2.3 Power Spectra

4.2.3 Required DM stroke given by 95% of the PV error for the various refraction cases and pupil sizes.

4.2.4 Plot of the variance with mode order and / or Zernike mode.

4.3 Simulation of various Mirror Types
   Determine parameters for all mirrors to achieve 80% Strehl.

4.3.1 Continuous Faceplate DMs
   4.3.1.1 Describe mode of operation.
   4.3.1.2 Modeled as a simple Gaussian
   4.3.1.3 Simulations for 7.5mm pupil
   4.3.1.4 Parameters to vary:
      Number of actuators.
      Coupling coefficient.
      Wavelength.
   4.3.1.5 All the above with unlimited stroke.
4.3.2 Piston Only DMs
   4.3.2.1 Describe mode of operation.
   4.3.2.2 Simulations for 7.5mm pupil with either cases
   4.3.2.3 No phase wrapping i.e. unlimited stroke.
   Number of actuators.
   Packing geometry
   Wavelength.
   Need to repeat the above but with gaps.
   4.3.2.4 Effect of phase wrapping
   Two cases:
   Phase wrapping occurs at the segment locations.
   Arbitrary phase wrap.

4.3.3 Segmented Piston / tip / tilt DMs
   4.3.3.1 Describe mode of operation.
   4.3.3.2 Three influence functions per segment, do the SVD fit on a segment by segment basis.
   4.3.3.3 Simulations for 7.5mm pupil.
   4.3.3.4 No phase wrapping unlimited stroke and tip/tilt.
   Number of actuators - square
   Same as above except with hexagonal packing.
   Wavelength.
   Gaps for both square and hexagonal packing.
   4.3.3.5 Effect of phase wrapping
   Phase wrapping occurs at the segment locations.
   Arbitrary phase wrap. Wrap the wavefront and then determine the required number of segments. Everything else as listed in part 1).

4.3.4 Membrane DMs
   4.3.4.1 Describe mode of operation. Bimorphs as well.
   4.3.4.2 Simulations for 7.5mm pupil with either cases.
   4.3.4.3 Parameters to vary:
   Number of actuators.
   Actuator size.
   Membrane stress
   Wavelength.
5. Control Algorithms (Li Chen)  
University of Rochester

5.1 Configuration of lenslets and actuators

5.2 Influence function measurement

5.3 Control command of wavefront corrector
   5.3.1 Wavefront control
   5.3.2 Direct slope control
   5.3.3 Special control for different wavefront correctors

5.4 Transfer function modelization of adaptive optics system
   5.4.1 Transfer function of adaptive optics components
   5.4.2 Overall system transfer function
   5.4.3 Adaptive optics system bandwidth analysis

5.5 Temporal modelization with Transfer function
   5.5.1 Feedback control
   5.5.2 Proportional integral control
   5.5.3 Smith compensate control

5.6 Temporal controller optimization
   5.6.1 Open-loop control
   5.6.2 Closed-loop control
   5.6.2 Time delay effect on the adaptive optics system
   5.6.3 Real time considerations
5.7 Summary
6. Software/User Interface/Operational Requirements (Ben Singer)
University of Rochester

6.1 Introduction

6.2 Hardware setup

6.2.1 Imaging
   6.2.1.1 Hartmann-Shack Spots
   6.2.1.2 Pupil Monitoring
   6.2.1.3 Retinal Imaging

6.2.2 Triggered devices: Shutters, lasers, LEDs

6.2.3 Serial devices: Defocusing slide, custom devices

6.2.4 AO Mirror control

6.3 Image processing setup

6.3.1 Setting regions of interest: search boxes

6.3.2 Preparing the image
   6.3.2.1 Thresholding
   6.3.2.2 Averaging
   6.3.2.3 Background subtraction
   6.3.2.4 Flat-fielding

6.3.3 Centroiding

6.3.4 Bad data

6.4 Wavefront reconstruction and visualization

6.4.1 Zernike mode recovery and RMS
   6.4.1.1 Display of modes and RMS: traces, histograms
   6.4.1.2 Setting modes of interest

6.4.2 Wavefront visualization
   6.4.2.1 Continuous grayscale image
   6.4.2.2 Wrapped grayscale image
   6.4.2.3 Three-D plots

6.5 Adaptive optics
6.5.1 Visualizing and protecting write-only mirrors

6.5.2 Testing, diagnosing, calibrating

6.5.3 Individual actuator control

6.5.4 Update timing

6.5.5 Bad actuators

6.6 Lessons learned, future goals

6.6.1 Case studies from existing systems at CVS and B&L
   6.6.1.1 One-shot wavefront sensing vs realtime AO
   6.6.1.2 Using AO systems in experiments: Step Defocus

6.6.2 Engineering trade-offs
   6.6.2.1 Transparency vs Simplicity
   6.6.2.2 Extensibility vs Stability

6.6.3 How to please everyone
   6.6.3.1 Subject
   6.6.3.2 Operator
   6.6.3.3 Experimenter
   6.6.3.4 Programmer

6.6.4 Software tools

6.7 Summary
7. AO Assembly, Integration and Troubleshooting (Brian Bauman)

Lawrence Livermore

### 7.1 Introduction and Philosophy

### 7.2 Optical alignment

7.2.1 General remarks

7.2.2 Understanding the penalties for misalignments

7.2.3 Having the right knobs: optomechanics

#### 7.2.4 Common alignment practices

- 7.2.4.1 Tools
- 7.2.4.2 Off-line alignment of sub-systems
- 7.2.4.3 Aligning optical components
- 7.2.4.4 Sample procedures (taken from the AO phoropter project)

### 7.3 Wavefront sensor checkout

7.3.1 Wavefront sensor camera checkout

#### 7.3.2 Wavefront sensor checkout

- 7.3.2.1 Proving that centroid measurements are repeatable.
- 7.3.2.2 Proving that the centroid measurements do not depend on where centroids are with respect to pixels
- 7.3.2.3 Measuring plate scale.
- 7.3.2.4 Proving that a known change in the wavefront produces the correct change in centroids.

### 7.4 Wavefront Reconstruction

7.4.1 Testing the reconstruction code: Prove that a known change in the wavefront produces the correct change in reconstructed wavefront.

### 7.5 Aligning the “probe” beam into the eye

### 7.6 Visual stimulus alignment

### 7.7 Flood-illumination alignment

### 7.8 DM-to-WFS Registration
7.8.1 Tolerances & penalties for misregistration

7.8.2 Proving that the wavefront sensor-to-SLM registration is acceptable.

7.9 Generating control matrices

7.9.1 System (“push”) matrix

7.9.2 Obtaining the control matrix

7.9.3 Checking the control matrix

7.9.4 Null spaces

7.10 Closing the loop

7.10.1 Checking the gain parameter

7.10.2 Checking the integration parameter

7.11 Calibration

7.11.1 Obtaining calibrated reference centroids.

7.11.2 Proving that reference centroids are good

7.11.3 Image-sharpening to improve Strehl performance.

7.12 Science procedures

7.13 Trouble-shooting algorithms
8. System Performance: Testing, Procedures, Calibration and Diagnostics 
(Bruce Macintosh, Marcos Van Dam) 
Lawrence Livermore / Keck Telescope 

8.1 Spatial and Temporal characteristics of correction 

8.2 Power Spectra calculations 

8.3 Disturbance rejection curves 

8.4 Strehl ratio/PSF measurements/calculation 

8.5 Performance vs. different parameters (beacon brightness, field angle, …)? 

8.6 Summary Table and Figures of above criteria 

8.6.1 Results from Xinetics, BMC, IrisAO
IV. Retinal Imaging Applications

Schepens Eye Research Institute

9.1 Shape of the retina, geometric optics

9.1.1 Normal fovea, young vs. old
   9.1.1.1 foveal pit
   9.1.1.2 foveal crest

9.1.2 Normal optic nerve head

9.1.3 Periphery and ora serrata

9.2 Two blood supplies, young vs. old

9.2.1 Retinal vessels and arcades

9.2.2 0 – 4 layers retinal capillaries, foveal avascular zone

9.2.3 Choriocapillaris, choroidal vessels, watershed zone

9.3 Layers vs. features, young vs. old, ethnic differences

9.3.1 Schlera

9.3.2 Choroidal vessels, choroidal melanin

9.3.3 Bruch’s membrane

9.3.4 RPE, tight junctions, RPE melanin

9.3.5 Photoreceptors, outer limiting membrane
   9.3.5.1 Outer segment
   9.3.5.2 Inner segment
   9.3.5.3 Stiles-Crawford effect
   9.3.5.4 Macular pigment

9.3.6 Neural retina

9.3.7 Glia, inner limiting membrane, matrix
9.3.8 Inner limiting membrane
9.3.9 Vitreo-retinal interface, vitreous floaters

9.4 Spectra, layers and features
9.4.1 Main absorbers in the retina
9.4.2 Absorbers vs. layers
9.4.3 Features in different wavelengths
9.4.4 Changes with aging

9.5 Light scattering, layers and features
9.5.1 Directly backscattered light
9.5.2 Multiply scattered light
9.5.3 Geometric changes in specular light return
9.5.4 Layers for specular and multiply scattered light
9.5.5 Imaging techniques to benefit from light scattering properties

9.6 Polarization
9.6.1 Polarization properties of the photoreceptors
9.6.2 Polarization properties of the nerve fiber bundles, microtubules
9.6.3 Anterior segment and other polarization artifacts
9.6.4 Techniques to measure polarization properties

9.7 Imaging techniques to produce contrast from specular or multiply scattered light
9.7.1 Confocal imaging
9.7.2 Polarization to narrow the point spread function

9.7.3 Polarization as a means to separate directly backscattered light from multiply scattered light, demonstration using the scattered light

9.7.4 Coherence techniques as a means to separate directly backscattered light from multiply scattered light, with a goal of using the scattered light
10. Strategies for High Resolution Retinal Imaging (Austin Roorda, Remy Tumbar, Julian Christou)
University of Houston / University of Rochester / University of California, Santa Cruz

10.1 Conventional Imaging (Roorda)

10.1.1 Basic principles
This will be a simple optical imaging system

10.1.2 Basic system design
Show a typical AO flood-illuminated imaging system for the eye

10.1.3 Choice of optical components
Discuss the type of optical you would use (eg off axis parabolas)

10.1.4 Choice of light source
How much energy, what bandwidth, flash duration, show typical examples

10.1.5 Controlling the field size
Where to place a field stop and why

10.1.6 Choice of camera
What grade of camera is required? Show properties of typical cameras that are currently used

10.1.7 Implementation of wavefront sensing
Where do you place the wavefront sensor. Using different wavelengths for wfs.

10.2 Scanning Laser Imaging (Roorda)

10.2.1 Basic principles
This will show how a simple scanning imaging system operates

10.2.2 Basic system design
This shows the layout of a simple AOSLO

10.2.3 Choice of optical components
What type of optical components should you use and why (eg mirrors vs lenses). Where do you want to place the components (eg raster scanning, DM etc) and why.

10.2.4 Choice of light source
How to implement different wavelengths. How to control retinal light exposure
10.2.5 Controlling the field size
   Optical methods to increase field size
   Mechanical (scanning mirror) methods to increase field size

10.2.6 Controlling light delivery
   Acousto-optical control of the light source for various applications

10.2.7 Choice of detector
   PMT vs APD what are the design considerations

10.2.8 Choice of frame grabbing and image acquisition hardware
   What are the requirements for a frame grabber. What problems can you expect.

10.2.9 Implementation of wavefront sensing
   Strategies for wavefront sensing in an AOSLO

10.2.10 Other: pupil tracking, retinal tracking, image warping

10.3 OCT systems (Tumbar)
   10.3.1 Flood illuminated vs. Scanning

10.4 Future ideas (Tumbar)
   10.4.1 DIC (Differential Interference Contrast)
   10.4.2 Phase Contrast
   10.4.3 Polarization Techniques
   10.4.4 Two-photon
   10.4.5 Fluorescence/Auto-fluorescence

10.5 Survey of post-processing/image enhancement strategies (Christou)
11. Design Examples

11.1 Design of Houston Adaptive Optics Scanning Laser Ophthalmoscope (AOSLO) (Krishna Venkateswaran)

11.1.1 Basic optical design
   Effect of double pass system on psf, imaging in conjugate planes

11.1.2 Light delivery optics
   Fiber optic source and other optics

11.1.3 Raster scanning
   Scanning speeds etc.,

11.1.4 Physics of confocal imaging

11.1.5 Adaptive optics in SLO
   Wavefront sensing, Zernike polynomials, Deformable mirror, correction time scales

11.1.6 Detailed optical layout of the AOSLO
   Lens, mirrors, beam splitters with specs

11.1.7 Image acquisition
   Back end electronics, frame grabber details

11.1.8 Software interface for the AOSLO
   Wavefront sensing, Image acquisition

11.1.9 Theoretical model of AOSLO:
   Limits on axial and lateral resolution

11.1.10 Image registration

11.1.11 Results

11.1.12 Discussions on improving performance of AOSLO
   Light loss in optics, Deformable mirror, Wavefront sensing,

11.1.13 Next generation AOSLO type systems
11.2 Indiana University AO Coherence Gated System (Don Miller)

11.2.1 Resolution advantages of an AO-OCT retina camera

11.2.2 AO-OCT basic system design concepts

11.2.2.1 Application-specific constraints
   - Sensitivity to weak tissue reflections
   - Tolerance to eye motion artifacts
   - Yoking focal plane to the coherence gate

11.2.2.2 Integration of AO and OCT sub-systems
   - Generic OCT system
   - Specific OCT architectures
   - Preferred AO-OCT embodiments

11.2.3 Description of the Indiana AO-OCT retina camera

   Optical layout of the Indiana AO-OCT retina camera
   11.2.3.1 Adaptive Optics for correction of ocular aberrations
      A. System description
      B. Results
   11.2.3.2 1D OCT axial scanning for retina tracking
      A. System description
      B. Results
   11.2.3.3 High speed 2D incoherent flood illumination for focusing and aligning
      A. System description
      B. Results
   11.2.3.4 CCD-based 2D OCT for en face optical sectioning the retina
      A. System description
      B. Results

11.2.4 Future developments

   11.2.4.1 Smart photodiode array
   11.2.4.2 En face and tomographic scanning
   11.2.4.3 Reduction of image speckle
   11.2.4.4 Detector sensitivity
   11.2.4.5 Faster image acquisition

11.3 Rochester Second Generation AO System (Heidi Hofer)
V. Vision Correction Applications

12. Customized Vision Correction Devices (Ian Cox)
Bausch & Lomb

12.1 Contact Lenses

12.1.1 Rigid or Soft Lenses?

12.1.2 Design Considerations – More Than Just Optics

12.1.3 Measurement – The Eye, the Lens or the System?

12.1.4 Manufacturing Issues – Can The Correct Surfaces Be Made?

12.1.5 Who Will Benefit?

12.1.6 Summary

12.2 Intraocular Lenses

12.2.1 Which Aberrations - The Cornea, The Lens or The Eye?

12.2.2 Surgical Procedures – Induced Aberrations

12.2.3 Design & Manufacturing Considerations

12.2.4 Future Developments & Summary
14. Visual Psychophysics (UC Davis Team, headed by Jack Werner)

UC Davis

14.1 Characterizing visual performance

14.1.1 Acuity

14.1.2 Contrast sensitivity functions (CSFs)

14.1.3 Photopic/scotopic performance (include various ways to define luminance)

14.2 What is psychophysics?

14.2.1 Studying the limits of vision

14.2.2 Differences between detection, discrimination and identification

14.3 Psychophysical methods

14.3.1 Psychometric function

14.3.2 signal detection theory

14.3.3 measuring threshold

14.3.4 Criterion-free methods

14.3.5 Method of constant stimuli, method of adjustment, adaptive methods (e.g. Quest).

14.4 The visual stimulus

14.4.1 Issues in selecting a display system

Temporal resolution
Spatial resolution
Intensity (maximum, bit depth)
Homogeneity
Spectral characteristics

14.4.2 Hardware options
Custom optical systems (LEDs, Maxwellian view)
Displays
CRTs
DLPs
LCDs
Plasma
Projectors
Display generation
custom cards
VSG
Bits++
10-bit cards
Pelli attenuator
Dithering/bit stealing

14.4.3 Software
Off the shelf software is not usually flexible enough. We recommend doing it yourself. This can be done using entirely custom software (e.g. C++) or by using software libraries such as VSG (PC) or PsychToolbox (Mac/PC).

14.4.4 Calibration
Gamma correction
Spatial homogeneity
Temporal and spatial resolution

14.5 Summary
15. Wavefront to Phoropter Refraction (Larry Thibos)
Indiana University

15.1 Basic terminology

15.1.1 Refractive error
15.1.2 Refractive correction
15.1.3 Lens prescriptions

15.2 The goal of subjective refraction

15.2.1 Definition of far point
15.2.2 Elimination of astigmatism
15.2.3 Using depth-of-focus to expand the range of clear vision
15.2.4 Placement of far-point at hyperfocal distance

15.3 Methods for estimating the monochromatic far-point from an aberration map

15.3.1 Estimating center of curvature of an aberrated wavefront
  15.3.1.1 Least-squares fitting
  15.3.1.2 Paraxial curvature matching

15.3.2 Estimating object distance that optimizes focus
  15.3.2.1 Metrics based on point objects
  15.3.2.2 Metrics based on grating objects

15.4 Ocular chromatic aberration and the polychromatic far-point

15.4.1 Polychromatic center of curvature metrics
15.4.2 Polychromatic point image metrics
15.4.3 Polychromatic grating image metrics

15.5 Experimental evaluation of proposed methods

15.5.1 Conditions for subjective refraction
15.5.2. Monochromatic predictions

15.5.3 Polychromatic predictions

16. Design Examples

Detailed Layouts, Numbers, Noise Analysis, Limitations for Visual Psychophysics:

16.1 LLNL/UR/B&L AO Phoroptor (Scot Olivier)

16.2 UC Davis AO Phoropter (Scot Olivier)

16.3 Rochester 2nd Generation AO System (Heidi Hofer)

V. Appendix/Glossary of Terms (Hope Queener, Joseph Carroll)

- Laser safety calculations
- Other ideas?
- Glossary to define frequently used terms