Ophthalmic Shack-Hartmann wavefront sensor applications

Eye aberration measurements can be used in wavefront-guided laser ablation and clinical research applications.

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Shack-Hartmann wavefront sensors (SHWFSs) have been used for a wide variety of applications over a period spanning more than 35 years, with human-eye measurements being by far the most common in terms of the number of sensors in routine use. For instance, these sensors have become the norm for supporting laser refractive surgery, while being increasingly used in various ophthalmology and optometry applications.

The architecture of a Shack-Hartmann aberrometer is similar to that of a laser guide star arrangement. Light is projected into the eye and scattered from the retina. It is then collected by the SHWFS to analyze eye aberrations (see Figure 1). The aberrations are readily categorized as either lower or higher order effects, with defocus and astigmatism being the primary lower orders, and coma, trefoil, spherical and other aberrations being the higher orders. A convenient measure of eye aberration is the diopter value, a unit of measurement of the refractive power of a lens, equal to the reciprocal of the focal length: the higher the number, the higher the eye aberration. The eye can be extremely aberrated, with defocus ranging from −16 to +8 diopters, and cylinder ranging up to 5–6 diopters.

It is common practice to use a Keplerian telescope with adjustable focus to optically correct the defocus term (spherical equivalent). This is done using a one degree of freedom closed-loop adaptive optics system to minimize the SHWFS error. In a few seconds, the instrument can find the appropriate defocus condition and neutralize it optically, so that the sensor only measures the cylinder and higher order aberrations. Some commercially available systems use a fixed optometer, and others also correct for the astigmatism terms.[1]

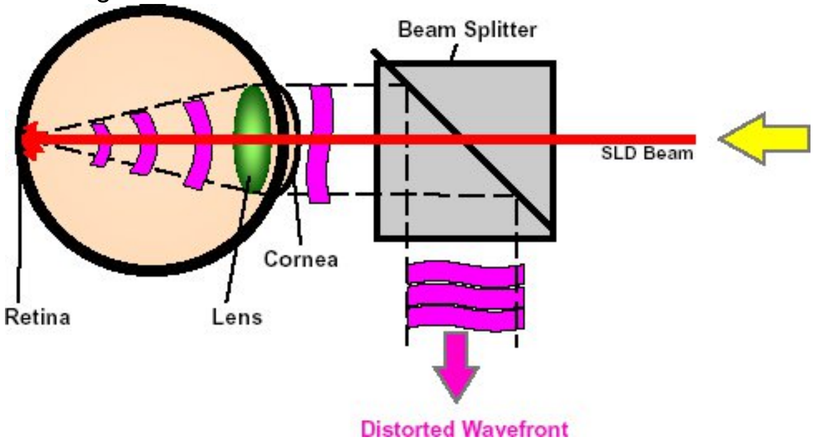


Figure 1. *Arrangement for guide star measurement of the eye. SLD: superluminescent diode.*

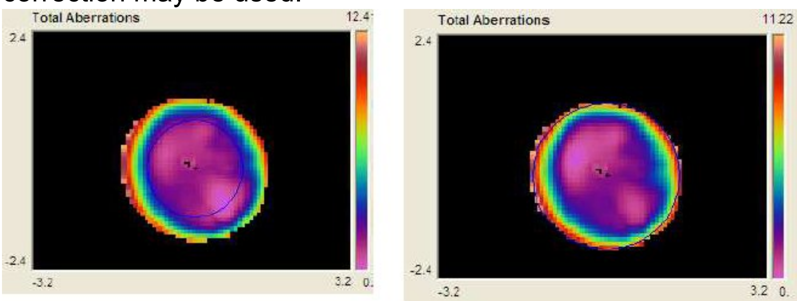
The instruments are accurate to a fraction of a wave, have a dynamic range of 50–70μm, and can measure an eye in a few seconds. To date, there are approximately ten different companies manufacturing such instruments for various markets.

There are currently four basic clinical applications using ocular measurement systems: wavefront guided ablation in laser refractive surgery; auto-refraction for spectacle and contact lens fitting; diagnostics of kerataconus, ectasia or other aberrated conditions; and research in accommodation, scattering, tear-film, customized contacts, and other applications.

Wavefront-guided ablation has now become the standard technique for nearly all forms of laser refractive surgery. Prior to the introduction of the wavefront instruments, laser

laser refractive surgery. Prior to the introduction of the wavefront instruments, laser assisted in situ keratomileusis (LASIK) and photorefractive keratectomy (PRK) procedures had the drawback of inducing a significant amount of (mostly spherical) higher order aberrations that went undetected, except through variations in manifest refraction as a function of pupil size. With the wavefront-guided treatment, aberrations are now measured directly and can provide the information needed to adjust the nomograms for optimizing the surgery. This approach has been very successful over the last 6–7 years with the result that the majority of procedures are now fully customized.

Figure 2 shows an example of the same wavefront measurement analyzed for two different pupil sizes. Results are indicative of significantly different refractions with a sphere value of +0.28D for the 4mm pupil and of −1.31D for the 5mm pupil. These values point to a large spherical aberration component and the patient in this case may be best served by prescribing two pairs of spectacles: one for normal daytime vision and the other for night-time use, particularly for driving. Alternatively, some form of customized correction may be used.



quantity		value
sphere(0)	X	+0.28 D
cylinder(0)	X	-1.06 D
axis		127°

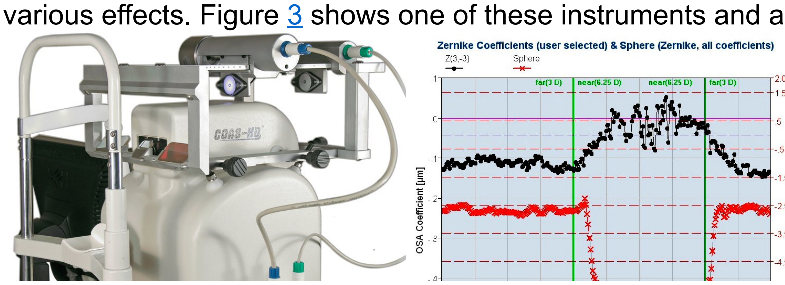
quantity		value
sphere(0)	X	-1.31 D
cylinder(0)	X	-0.89 D
axis		121°

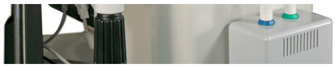
Figure 2. *Variation in-eye refraction as a function of pupil size. Left: 4mm-pupil. Right: 5mm-pupil.*

One major application of this technology is the identification and tracking of unusual pathologies, including common conditions such as kerataconus, ectasia, corneal scars, dry-eye and damage resulting from injury. Some of these, notably kerataconus, can be detected earlier in a wavefront measurement than when using other techniques such as corneal topography.

The ocular wavefront measurement instrument also represents a key element in understanding human eye function. It can provide insights in how the perceptions of a subject change with aberrations, in eye accommodation processes, and in the dynamics of eye-movement-induced aberrations. Furthermore, it can also quantify many of these effects, all of which are critical to advancing human vision knowledge. For example, instruments for measuring accommodation are starting to provide quantitative feedback on the effectiveness of some newly emerging surgical techniques.

As the general population ages, understanding and correcting for presbyopia is also becoming an increasingly important issue. Numerous corrective techniques are available, with the more common being multi-focal contact lenses, intraocular lenses, laser refractive surgery, and scleral surgery. To assess their respective efficiency, it becomes crucial to use a technique that can measure objective changes in the lens, and to distinguish this effect from multi-focal, depth-of-field, and neurological contributions. To this end, we have developed a sequence of instruments dedicated to accommodation measurements. Using the wavefront sensor in this context involves the careful presentation of targets to the subject while simultaneously recording the full dynamic ocular response. The sensor has proven ideal since it provides a means, inherent in the data, for distinguishing between the various effects. Figure 3 shows one of these instruments and an example measurement.





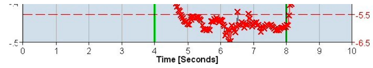


Figure 3. *Accommodation measurement with an objective aberrometer. Left: Aberrometer with external dynamic binocular target. Right: Example data showing both defocus response along with change in coma.*

The development of ocular Shack-Hartmann measurement systems has improved our ability to make detailed measurements of the eye. These advances have also improved techniques used for correcting the optical errors of the eye, including laser refractive surgery, contact lenses, spectacles, and contact lens fittings.

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Daniel Neal has developed many applications of wavefront sensing technology. These include astronomical applications, super-Mach wind tunnel testing, and silicon wafer metrology. He is a co-founder of WaveFront Sciences, a leader in wavefront technology.WaveFront was recently acquired by Advanced Medical Optics.

References:

1. D. R. Neal, Shack-Hartmann sensor engineered for commercial measurement applications, James Harvey and R. Brian Hooker (eds.), *Robert Shannon and Roland Shack: Legends of Applied Optics*, SPIE Press, 2005. ISBN: 9780819458445