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Digital Wavefront Sensors Measure Aberrations in Eyes

Figures:

1 Wavefront Sensors in Ophthalmology

The wavefront is the change in shape of the front of the light waves that hit the eye as they exit the cornea. Ophthalmologists can measure the wavefronts using devices called aberrometers, which pass eye-safe light through the eye and monitor as the light exits the eye. Ophthalmic aberrometry relies on wavefront sensing technologies to determine the way the human eye is able to distinguish outside objects, prescribe correction lenses or surgical treatment such as LASIK to improve on the visual acuity. Also, aberrometry helps improve on 3D retina imaging techniques such as Optical Coherence Tomography (OCT) to detect early signs of severe retina diseases like glaucoma or age-related macular degeneration.

Aberrometers have been used in astronomy for years but only recently have been applied to ophthalmology. In eye surgery for example, the aberrometer programs how the laser will perform LASIK: the variables are custom-tailored to the wavefront of a patient's eyes. Wavefront guidance and the femto - second laser for precisely cutting the outer layer of the cornea have improved the safety and efficacy of LASIK. In conventional as opposed to wavefront-guided LASIK, the laser settings, rather than custom – tailored, are preprogrammed to suit all patients.

Combined with wavefront correction elements and command-and-control system in an integrated adaptive optics setup, aberrometers can help improve on the laser spot quality, thus improving the 3D retina imaging by such technologies as Optical Coherence Tomography (OCT). The primary applications of OCT have involved scanning the retina to detect the presence of, or any change in, retinal disease, or to diagnose glaucoma.

OCT has proven extremely useful in ophthalmic imaging: however, the eye's optics have limited its ability to deliver images with high lateral resolution. These problems are almost entirely the result of natural imperfections that occur in the eye's refractive interfaces. These imperfections create high-order aberrations as well as low-order ones such as defocus and astigmatism. All these reduce the quality of OCT images. Being able to handle higher-order aberrations by using aberrometers could be important in elderly patients because their eyes are more likely to exhibit such characteristics. The capability also means better imaging spot size and contrast.

As more therapies become available for age-related macular degeneration, doctors are increasingly interested in identifying and monitoring the earliest stages of the disease so that they can address it appropriately, and they want to watch the retina so that they can time the treatment properly. This requires the highest resolution of the retina imaging – the resolution limited only by diffraction caused by the finite diameter of the iris. To achieve this – diffraction-limited – resolution at iris diameters >3mm requires that the aberrometers produce highly resolved 3D images of both wavefront and intensity of light coming out of the eye, with highest possible dynamic range and in real time.

Nowadays aberrometers feature good wavefront resolution, allow good treatment planning and integrate iris registration. The aberrometers are mostly based on the Shack-Hartmann wavefront sensors, which transform the light coming out of the aye into a set of spots ("data points") on the digital camera. The spots are obtained by focusing the light by tiny micro-lenses onto the camera placed in the lenses' focal plane. The local slope of the wavefront is then proportional to the deviation of a spot from its pre-calibrated position. Current standard is 400 μm resolution providing 241 data points over a 7 mm pupil. This corresponds to 123 measurement points over a 5 mm – diameter pupil. Newer systems boast 177 μm resolution providing 1257 points for a 7 mm – diameter pupil, or 641 measurement points for a 5 mm – diameter pupils. Still, "ideal" aberrometer would feature higher resolution, higher dynamic range allowing to measure a wide range of prescriptions in a wide fields of view (including 8.5 mm dilated pupils), auto centering, combining several or any of the instruments in a doctor's office: aberrometer, auto refractor, keratometer, pupilometer and topographer. The greater resolution would transform the spot of the conventional systems based on the standard Shack-Hartmann wavefront sensors into, ideally, a pixel on the CCD camera. Dealing with images on the CCD or CMOS cameras rather than with Shack-Hartmann spots that are subjected to image processing (like spot center detection) results in higher resolution, that means more data points leading to higher dynamic ranges capturing difficult eyes (e.g. with keratoconus).

The wavefront analyzers currently available on the marketplace can only provide for low resolution wavefront data and, in the best case, low resolution intensity distributions. Therefore, for a comprehensive ophthalmic system, both a digital camera and a wavefront sensor would usually be needed as separate instruments. In these "analogue" wavefront sensors, special hardware components transform the light intensity into interferometric fringes (as in shearing interferometers) or in a series of spots (as in Shack-Hartmann sensors), so that the original high-resolution intensity data are lost and can only be captured by an independent camera.

As technology advances towards higher-resolution wavefront sensors, it is advantageous to remove the maximum of the hardware elements – such as micro-lenses and any diffractive elements used in Shack-Hartmann or similar sensors – since they limit the resolution and dynamic range of the aberrometers. Also, the hardware renders results highly dependent on the skills of a technician for operations such as pupil location and centering the device. Instead, more emphasis is being given to software that processes digital images of human eye's retina.

The new Digital Wavefront Camera (DWC®) allows building a high-resolution digital aberrometer system having the high resolution (600 x 600 points for 6 mm pupil) limited only by the size of one CCD pixel, while measuring both high-resolution wavefront and high-resolution intensity, making it an "all-in-one" instrument (retina imager plus aberrometer). The DWC is capable of measuring from -16D to 12D sphere, and perform up to 8 μm RMS measurement of higher-order aberrations compared to current 1.6μm. This provides a more accurate representation of the wavefront, excellent for examination of unusual eyes (scars, keratoconus, injury) and allows to increase capture rate thus increasing both the quantity of eyes captured and the quality of prescriptions. DWC software performs automatic pupil location, auto-centering and auto-focusing, therefore the aberrometer is technician – independent and more forgiving with respect to human factor.

2 Analogue Wavefront Sensors

Industrial wavefront sensing has its roots in astronomy when in 1980 an array of micro lenses was used to improve on the transmission efficiency of the wavefront sensing for low-light situations. This new Shack-Hartmann technology achieved its maturity in 1990 when first wavefront sensors became commercially available. The race for a higher resolution of wavefront sensing has resulted in development of wavefront sensors based on the multilateral shearing interferometry introduced in 1995 and in wavefront curvature sensors in 2000, both systems using two-dimensional diffraction gratings. These instruments are "analogue", as to achieve better parameters such as dynamic range, sensitivity and resolution, they resort to a mix of more or less complex optical hardware components and electronics.

Commercially available wavefront sensors

Sensor Technology	Sensor Type	Pluses	Minuses
Analogue	Shack-Hartmann (SH)	Wide wavelength range High sensitivity Insensitive to vibration	Low resolution Limited dynamic range Needs Careful Calibration No flexibility in sensitivity vs. dynamic range
	Lateral shearing interferometry (LSI)	Higher resolution than Shack-Hartmann Flexibility in sensitivity vs. dynamic range Wavefront error control	Hardware more complex than SH
	Curvature Sensor (CS)	Higher resolution than SH or LSI	The most complex hardware than for SH and LSI Wavelength dependent Broadband limited
Digital	Digital Wavefront Sensor (DWS)	Highest resolution No special hardware Unlimited wavelength range Best Cost/Performance ratio	High Computational Burden

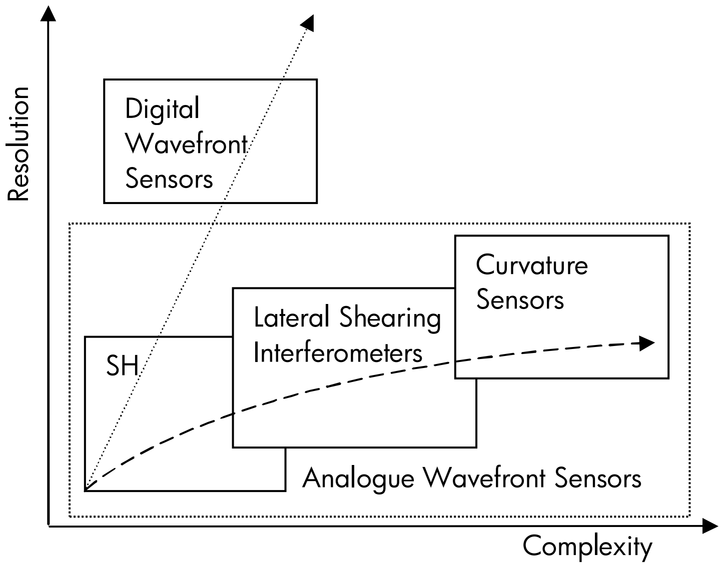


Figure 1. Major technology nodes in industrial wavefront sensors.

In *Shack-Hartmann sensors*, the surface of a wavefront is decomposed into elementary sub-wavefronts by a grid of micro lenses placed at the plane of wave front analysis. Each of the micro-lenses creates a beam focused into a spot on a focal plane where a CCD camera is placed. The displacement of the spot with respect to a pre-calibrated position (corresponding to an undisturbed wavefront) is proportional to the local slope of the wavefront. Detecting the spots and integrating their displacements all over the focal plane in a very short time results in an instantaneous estimate of the wavefront.

A disadvantage of the Shack-Hartmann sensors is their limited resolution, particularly in detecting higher order aberrations: to obtain a measurement of a wavefront at one point in the analysis plane, several square pixels are required. First Shack-Hartmann sensors were used closed-loop adaptive optics systems in astronomic telescopes, where the speed of the measurement and its convergence to a perfect measurement over several iterations is of prime concern. Improving the resolution by reducing the area allocated to one spot leads to reducing the dynamic range of the sensor. Moreover, reducing the size of a micro lens leads to increased crosstalk between the micro lenses as each micro-lens creates several diffraction orders with elevated side lobes. This leads to difficulties with identifying the centers of each spot. Placing a high-frequency signature on each micro-lens so that each spot could be recognizable increases the manufacturing cost of the micro lenses.

To improve on resolution, the *Lateral Shearing interferometers* feature a two-dimensional diffraction grating, whereby the incident beam is split into several sub-beams that interfere in the plane of the camera. The interference pattern so created is processed and the local slope of the wavefront at the analysis plane is measured. The resolution of the lateral shearing interferometer is several times finer than that for Shack-Hartmann sensors: historically, the lateral shearing interferometers were first used in off-line deconvolution of images, where the quality of measurement was important. In the lateral shearing interferometers, the distance between the analysis plane and the detector plane can be modified to optimize the ratio between the dynamic range and the resolution for a given application. As a natural generalization of the Shack-Hartmann sensors, the Lateral Shearing Interferometers share the same disadvantages as the former, however in a lesser extent, at the cost of increased complexity of micro lens manufacture and processing of individual interferograms.

In further drive to improve on resolution of the wavefront sensing, in *Curvature Sensors*, the second-order derivative of the wavefront is estimated, by measuring the longitudinal variation of the wave's intensity. Real – time sensing of the two or more intensity profiles requires introduction of a parabolic-shaped diffraction grating with spatially varying period and pitch of the diffraction grating, with images recorded on a CCD behind the grating. Instead of using a periodic two-dimensional grating as in Lateral Shearing Interferometers, a specially designed diffraction grating of curvature sensors serves to spatially separate two images of the beam as it propagates along the optical axis. The resolution of the Curvature Sensors is the highest among the three major analogue wavefront sensors, as roughly two neighboring pixels yield one measured value of the wavefront, whereas several pixels are required to yield one measurement point on the other two sensors. This resolution, however, comes at the expense of decreased allowed bandwidth of the wavefront as the grating is designed for a specific central wavelength, increased light energy required to measure the wavefront as the division in diffraction order splits the light energy, increased complexity of the grating and therefore, higher cost of manufacturing special diffracting elements.

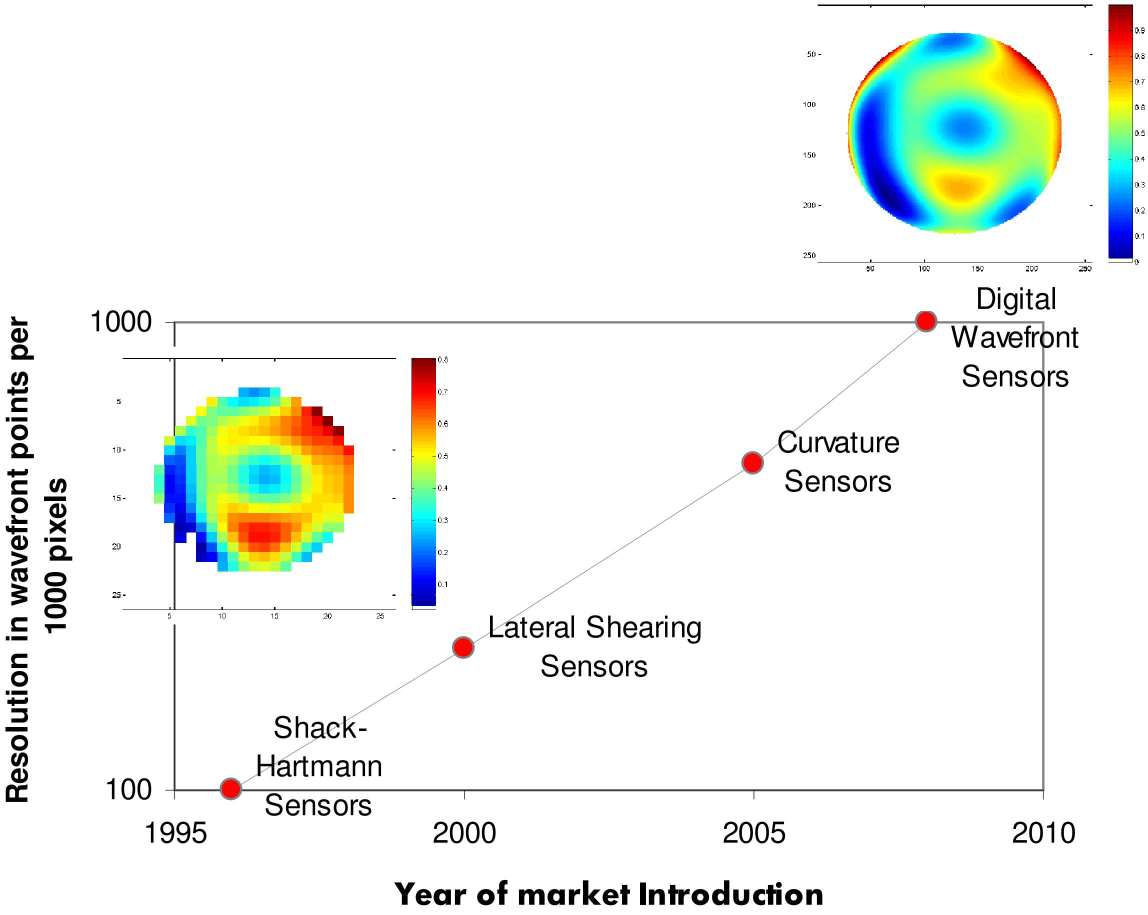


Figure 2. Wavefront sensing technology nodes: history and current trends.

Today, the conventional wavefront sensors are handicapped by use of complex hardware elements. To achieve the better resolution required by advances in the industries where wavefront sensors are used as quality control tools, they need be equipped with still more complex hardware components such as special micro lenses containing high-frequency signatures or rotations for better localization of spots and for reducing the cross-talk between lenses, complex multiple-order two-dimensional tri- or tetrahedral diffraction lens arrays. Despite their use in a relatively broad range of optical frequencies, the use of the sensors in a UV, IR or X-ray radiation spectra rely upon hardware components specially designed for the given application or wavelength.

Moreover, these sensors do not allow simultaneous measurement of high-resolution intensity and wavefront of a laser beam, since they transform the original intensity data in intermediary data (like interferometric fringes or spots), from which low-resolution wavefronts are computed. Thus, for a complete characterization of a laser beam, they require additional digital cameras to capture intensity information. Digital Wavefront Sensors enable to measure the high-resolution intensity and wavefront simultaneously in one plane and predict the propagation of the laser beam through the focal plane and beyond.

3 Digital Wavefront Sensors

The term "digital" associated with PhaseView digital wavefront sensing technology means the minimum use of hardware components and the intensive use of specialized algorithms. As technological innovation, the digital wavefront sensing technology is based on the prevalence of software as compared to conventional use of hardware elements to achieve highest wavefront sensing performances.

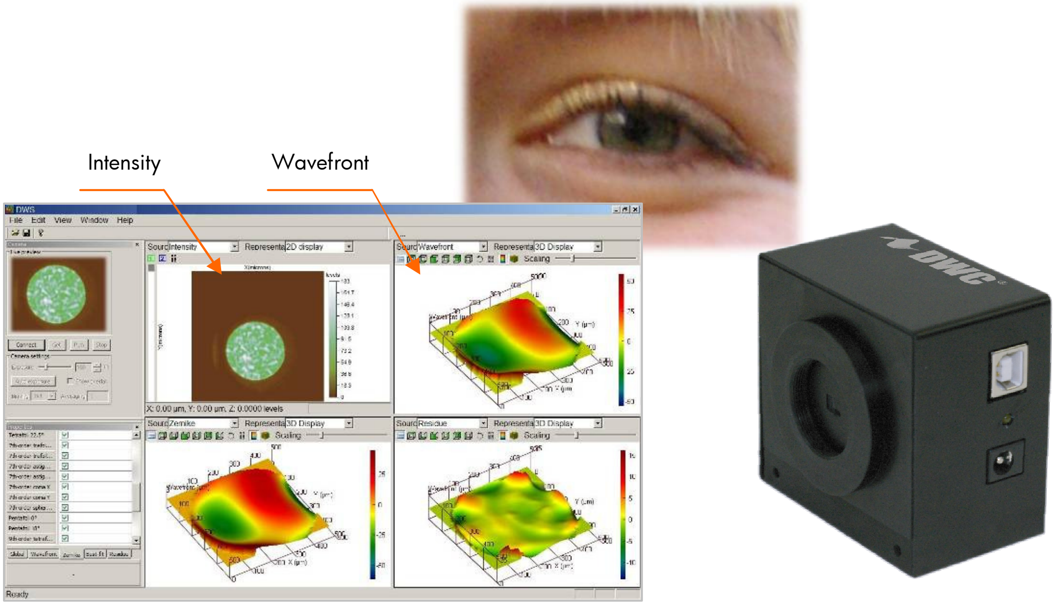


Figure 3. Digital Wavefront Cameras are used in measuring aberrations in wavefronts of beams reflected from eye's retinas to provide critical vision acuity parameters from simultaneous measurement of high-resolution wavefront and intensity.

The digital wavefront sensors rely upon measurements of the energy redistribution in the 3D space: as curvature sensors, they measure the variation of the wave's intensity in the optical – axis direction, while as Shack-Hartmann and Lateral Shearing interferometers, digital wavefront sensors measure the redistribution of the wave's intensity in the transversal direction. The measurement of the intensity in three dimensions in real time leads to the high resolution measurement of the wavefront with no use of the hardware diffracting elements or micro-lenses, at the cost of increased computational effort. The evolution of the beam through space is sensed by projecting the beam corresponding to different planes transversal to the optic axis, onto a digital camera, de-multiplexing the images and applying complex fast mathematical differential equation solvers to obtain the beam's wavefront (Figure 4).

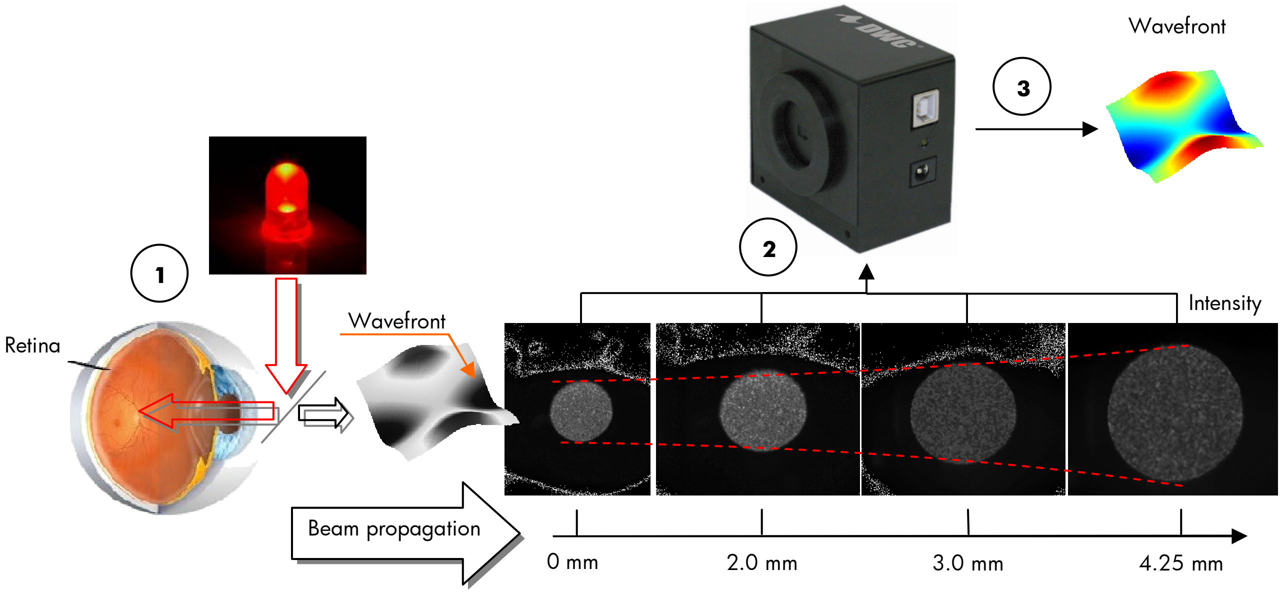


Figure 4. Measurement of aberrations in human eyes by Digital Wavefront Camera: 1) a collimated beam of IR light is projected onto the retina; 2) the reflected light (1/1000th of the incident light is recorded in several positions along the optical axis by the DWC®); 3) DWC® software computes the high resolution wavefront (here: a highly astigmatic beam featuring gradually expanding beam waist in y-axis direction as the beam propagates). The real-time processing results in one-shot measurement of both high-resolution images of intensity and wavefront for subsequent analysis by DWC® software, GetWave®.

Today's Digital Sensors typically feature sensitivity of λ/100 over entire dynamic range of several hundreds of wavelengths. The resolution of about 360 000 measurement points per aperture diameter of 6 mm is achievable. With no use of hardware elements, digital wavefront sensors suit for measurements in a broad illumination frequency spectrum, including infrared frequency band, and perform very well given low-light conditions of image acquisition in ophthalmic settings, due to power delivery requirements set forth by the Maximum Permissible Exposure regulations. Although these performances come at the cost of increased computational burden, the measurement frequency of 15 Hz or higher is achieved. Digital wavefront sensors can measure tilts, divergence and convergence of the wave fronts, thereby reducing the burden onto the adaptive optics and thus the capability of measuring aberrations even faced with patient's eye instability. Digital sensors boast considerably relaxed "resolution versus dynamic range" trade-off since they feature tunable inter-image distance setting.

The DWC® has been thoroughly tested by using the compact aberrometry setup (Figure 5), consisting of:

- Superluminescent diode emitting infrared light at 880 nm less than 2mW peak power;
- Optical fiber delivering the light in the optical assembly;
- Simulated eye (Heine GmBH, sphere ranges from -7D to +6D, iris diameter ranges from 2 mm to 8 mm, with achromatic lens of 32 mm focal distance);
- Artificial eye, as a custom-made plano-convex BK7 lens, used at 880 nm, with focal length of 18.48 mm and diameter approximately 7mm;
- Achromatic lens with focus at 32 mm;
- Optical assembly delivering the light from the SLED to the eye;
- Digital Wavefront Camera connected to a PC via a standard USB 2.0 interface.

This setup is ideally suited for measuring close-to-real human eyes in situations where reflectivity is very low and the illumination power density is limited to be well below the Maximum Permissible Exposure.

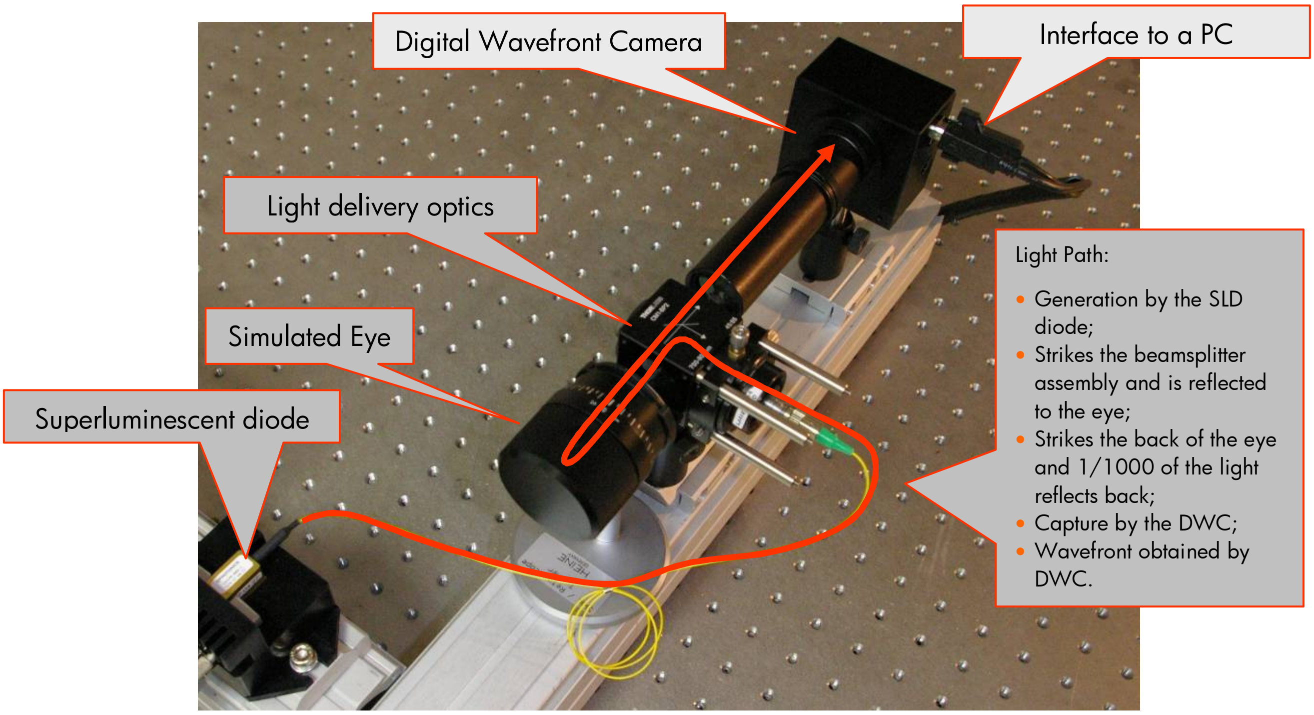
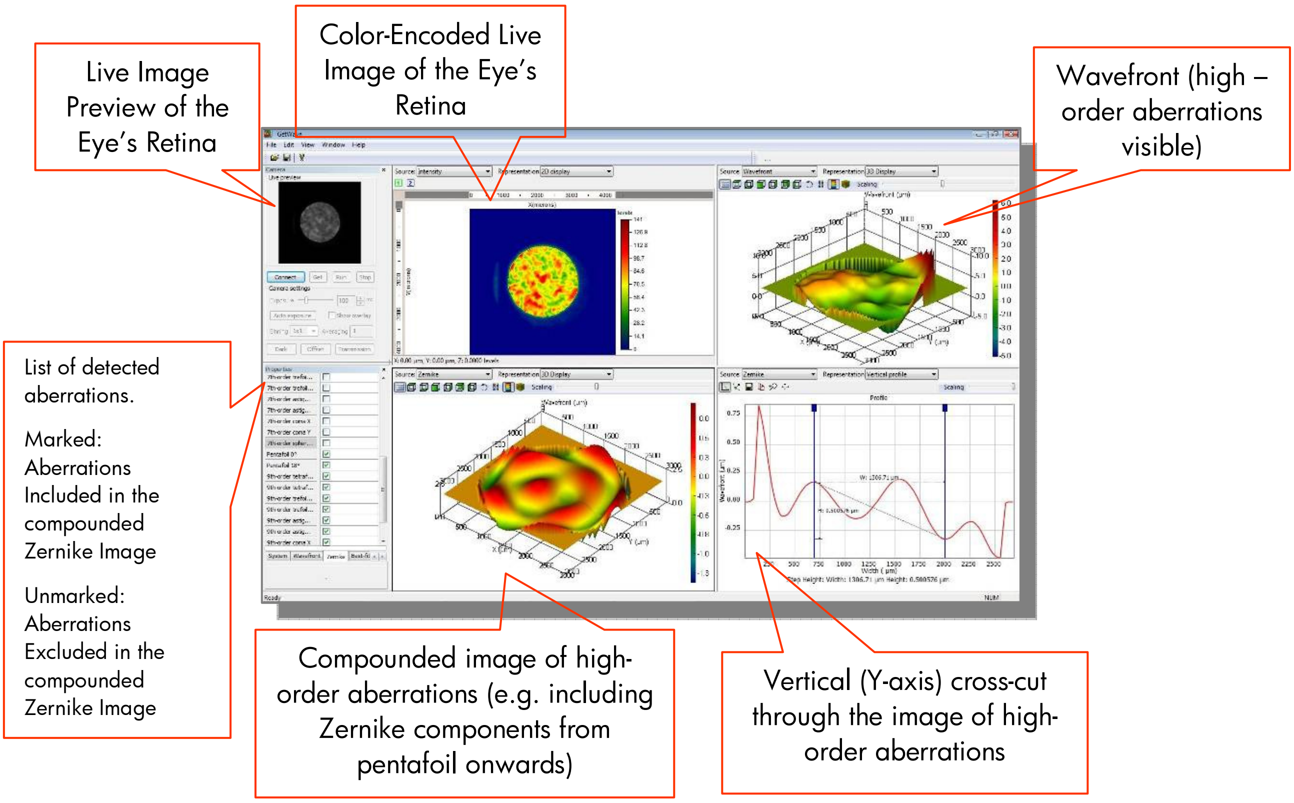


Figure 5. Aberrometry setup for eye testing with DWC®.

The data from DWC are transferred to PhaseView's GetWave® software that outputs the results of wavefront analysis in several windows including (Figure 6):

- List of detected aberrations classified in conventional Zernike basis;
- Live (25Hz) output of high resolution images of the intensity and wavefront, in 2D and 3D formats;
- 3D graphs of the residual images, after subtraction of user – defined aberrations, allowing to visualize higher-order aberrations;
- 2D graphs of the vertical and horizontal cross-cuts through any of the above 3D representations;

MTF and OTF measurements.



Live Image Preview of the Eye's Retina

Color-Encoded Live Image of the Eye's Retina

Wavefront (high – order aberrations visible)

List of detected aberrations.

Marked: Aberrations Included in the compounded Zernike Image

Unmarked: Aberrations Excluded in the compounded Zernike Image

Compounded image of high-order aberrations (e.g. including Zernike components from pentafoil onwards)

Vertical (Y-axis) cross-cut through the image of high-order aberrations

Figure 6. Typical results of the wavefront analysis of an artificial eye.

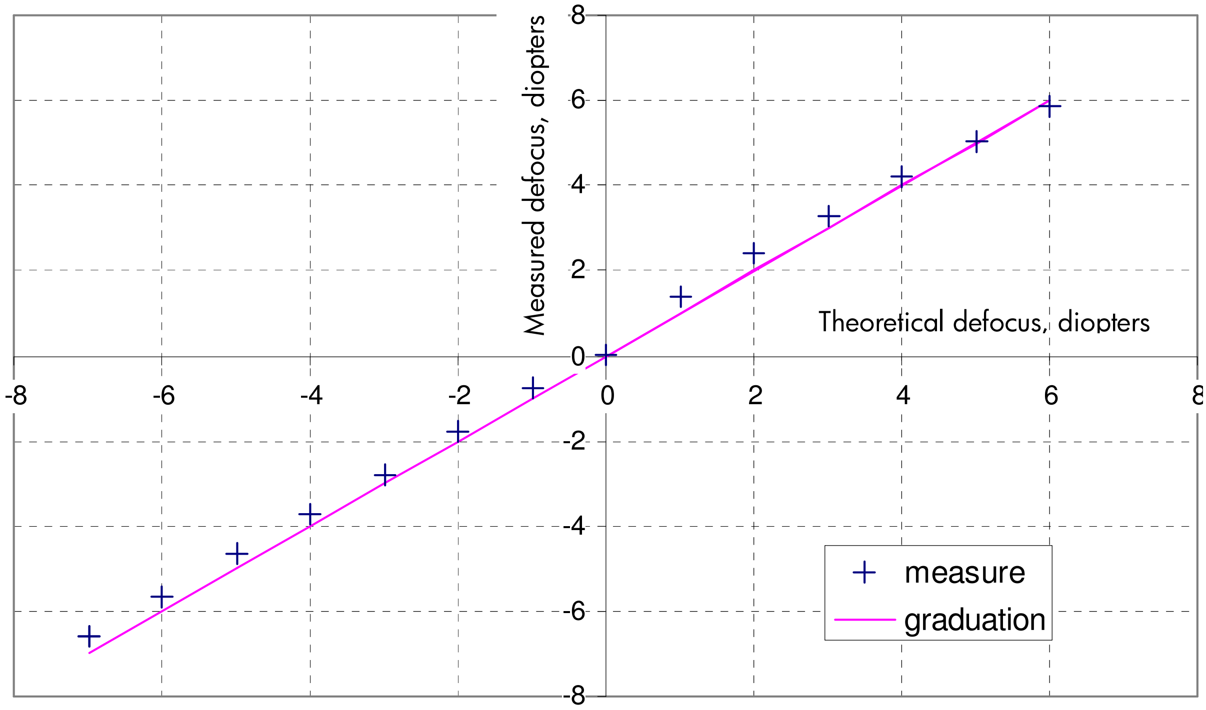


Figure 7. Comparison between defocus (or sphere) at the output of a simulated eye and its calibrated graduations to evaluate accuracy of DWC® in the -7D to +6D range in defocus (sphere) for a pupil of 6 mm.

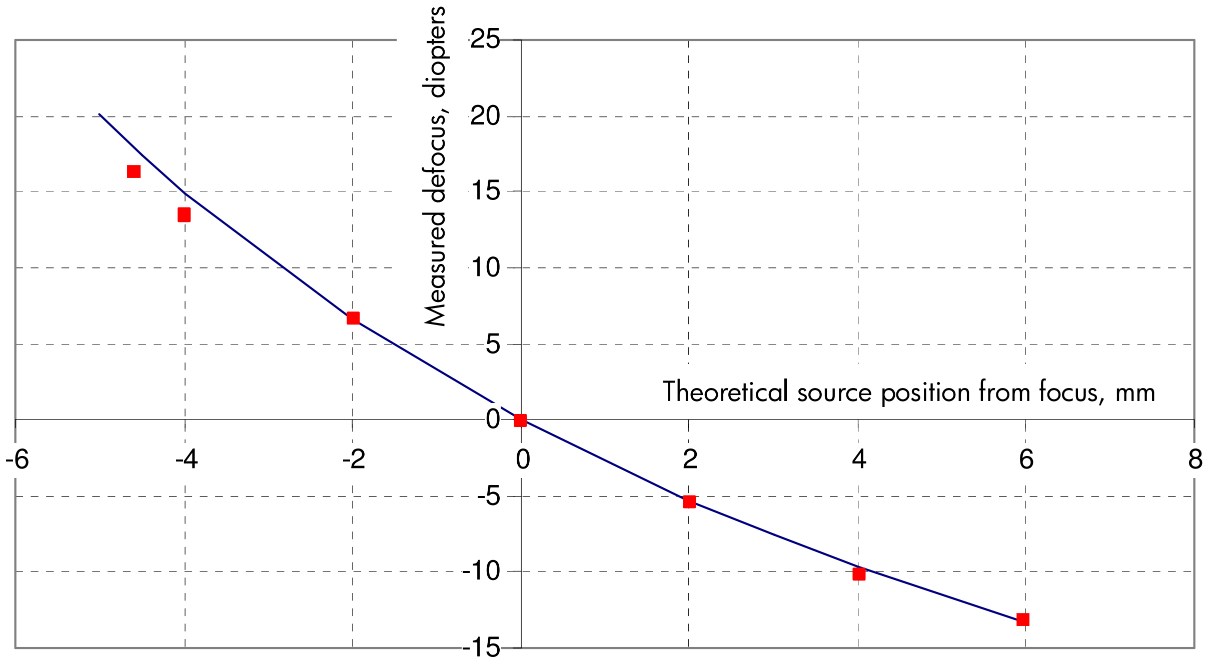


Figure 8. Comparison between the measured sphere to its theoretical value to estimate dynamic range of defocus (or sphere) measurement by DWC®, for a pupil of approximately 6 mm. Deviation from this curve from a given value (linked to accuracy) limits the useful domain of the measurement. Blue line is the calculated sphere value. Red dots are some of the measured points.

To test the accuracy of DWC® in the -7D to +6D range in defocus (sphere) for a pupil of 6 mm, the defocus is measured in the output of a simulated eye. Measurement is then compared to calibrated graduations on the simulated eye to evaluate accuracy in the range between -6D and +6D (Figure 7). To estimate dynamic range of defocus (or sphere) measurable by DWC® for a pupil of approximately 6 mm, defocus is measured in the output of the artificial eye, whose object space is moved to produce sphere in its image space where measurement took place. The measured defocus is then compared to its theoretical value to evaluate accuracy over the range of input values. Deviation from this curve from a given value (linked to accuracy) limits the useful dynamic range of the measurement, which for DWC® is from -16D to +12D (Figure 8).

Digital wavefront sensors open up new opportunities for characterization of human's visual acuity. When used in measuring aberrations (wavefront deformations) in aberrometers, the high resolution in wavefront reconstruction coupled with simultaneous measurement of high-resolution light intensity allows delivering quality prescriptions to correct vision and to cornea laser ablation wavefront-guided eye surgery procedures and thus assure their better outcomes. The higher resolution of 360 000 measurement points per 6 mm diameter pupil transforms the spots of the conventional aberrometers based on Shack-Hartmann systems into a pixel on the digital camera. Dealing with images on the CCD or CMOS cameras rather than with spots that are subjected to image processing (like spot center detection) results in higher resolution, that means more data points leading to higher dynamic ranges capturing difficult eyes (e.g. with keratoconus). The new Digital Wavefront Camera® sensor allows building a system which is auto-centering and auto-focusing, therefore the aberrometer is less technician – dependent and more forgiving with respect to human factor. GetWave® software that pilots DWC® computes the pupil location and automatically centers the device, at the same time allowing for more tolerance for centering. High resolution (600 x 600 points for 6 mm pupil) DWC® is capable of measuring of -16D to 12D sphere and perform up to 8 μm RMS for higher order aberrations, compared to currently achieved 1.6 μm. Being able to handle higher-order aberrations could be important in elderly patients because their eyes are more likely to exhibit such characteristics. The capability also means better imaging and contrast. This provides a more accurate representation of the wavefront, excellent for examination of unusual eyes (scars, keratoconus or injury) and helps increase capture rate thus increasing both the quantity of eyes captured and the quality of prescriptions. This will result in the ability to capture a wider range of patients, provide more accurate wavefront representations, and ultimately improve treatment planning and outcomes.

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