

Measurement of Contact Lenses Using Wavefront Aberrometry

Daniel R. Neal
James Copland
WaveFront Sciences, Inc.
14810 Central S.E.
Albuquerque, NM 87123
www.wavefrontsciences.com

Introduction

In the last ten years, we have seen tremendous advances in the science of vision care. The growth in laser refractive surgery has been due, in part, to the application of high tech solutions first developed for defense and astronomical applications^{1,2}. Today, it is imperative that the laser system incorporates the latest technology for tracking, control, and guidance. The eye to be treated will be first measured with an aberrometer to provide for a precise, customized correction of an individual patient's vision. While there are variations among laser manufacturers, all have benefited greatly from the development of commercial aberrometers³.

The aberrometer used to make the measurement for laser refractive surgery is most likely a derivative of a measurement system that was originally developed for High Energy Lasers and astronomical imaging. The same sensor, the Shack-Hartmann wavefront sensor, is now used to measure the eye.

This technology applies not only to Lasik and PRK, but also to contact lenses and other means for vision care.

Principles of Shack-Hartmann Wavefront Sensing

The most commonly used aberrometer is based on the Shack-Hartmann principle. This instrument is beautiful in its simplicity while being scalable to many different types of measurement and control problems. It can be scaled to vastly different regions of dynamic range and accuracy.

The Shack-Hartmann sensor is based on the principle that light travels in a straight line. It uses this simple fact to construct straight lines from the center of a measurement element (lenslet) to the center of a spot of light imaged on a detector (focal spots on CCD). With



Figure 1 ClearWave™ contact lens metrology instrument.

a little computer processing and some very clever analysis routines, this map of the direction of travel is soon converted to a detailed, highly accurate map of the surface shape or index variation of the system being measured.

The sensor constructs a function called the “wavefront.” This is a map of the optical thickness of an optical system. The “wavefront” is used to infer the thickness variation for a system with uniform index or refraction. Conversely, it may be used to infer the index of refraction variations if the thickness is known.

The Shack-Hartmann sensor can be made extremely robustly with the lenslet array rigidly fixed in front of the detector in a small package with minimum. For practical use, it is generally part of a larger optical system so that the appropriate light can be directed through the object that is being measured. The light is then collected and imaged onto the lenslet and analyzed. For an eye measurement instrument, there are also systems for injecting a spot of light onto the retina, collecting this light onto the wavefront sensor, aligning the eye with the instrument, providing the patient with fixation so that the measurement axis is correct, etc.

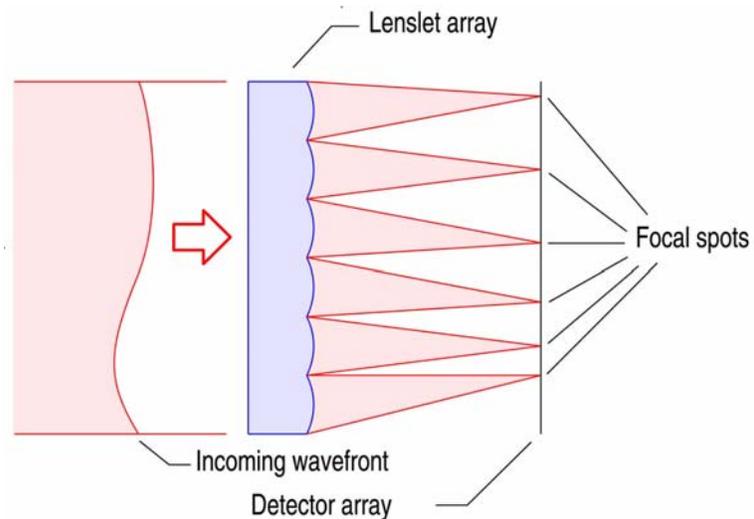


Figure 2 – Basic arrangement of a Shack-Hartmann wavefront sensor. Incident light is collected by a lenslet array that dissects the incoming light into a large number of small samples. Each sample is focused by the lenslet onto a detector (usually a CCD). The light is traveling along a line between the center of the lenslet and the center of the focal spot. Thus by knowing the lenslet spacing and position, the CCD image can be used to completely determine the position and direction of each sample of incoming beam. This map of ray angles can then be converted to a map of the incident wavefront (since the wavefront is, by definition, the surface normal to the direction of propagation at every point).

Applications for Contact Lenses

The manufacturer of contact lenses benefits from accurate metrology in a number of ways. Contact lenses can be manufactured in either wet or dry states and come in a variety of sizes, shapes, and descriptions. Metrology is needed for lens power and astigmatism in addition to identification of defects and other manufacturing errors. The lens geometry parameters (radius of curvature, toricity, material thickness) are important metrics at various stages of the manufacturing process. A list of typical requirements is shown in . The contact lens must also be fixtured, held precisely without distorting it, aligned to the instrument, and otherwise processed.

CL measurement

- Power
 - Sphere ± 20 D
 - Cylinder 10D
 - Axis relative to alignment marks
- Dimensions
 - Edge diameter
 - Other geometry features desired
- Other aberrations
 - Spherical aberration
 - Coma
 - Trefoil
 - Other higher orders
- Defects
- Prism
- Point spread function
- Modulation transfer function
- Quality factor
- Roughness (scattering)
- Cloudiness

Table 1 **ClearWave™ basic specifications**

In order to address these metrology issues, we have applied the same techniques that are used for astronomy, laser beam characterization, and measurement of the eye to the metrology of contact lenses. In many ways, the contact lens measurement is very similar to the measurement of the human eye. The range of power and cylinder, optical zone diameter, and curvature of the contact lens are all naturally similar to those of the human eye. Hence we can borrow from the principles that are used to measure the eye to measure the contacts that are fitted to correct vision.

The wavefront technology is ideally suited for measuring optical power and variations in power that would be present in a contact lens (as it is ideal for measuring visual quality). In the eye, we measure the sphere, cylinder, and axis, along with higher order aberrations and pupil size. From these measurements we derive the point spread function, the modulation transfer function, and even simulated visual performance. These same parameters can be determined for the contact lens.

The contact lens, however, poses special problems. Soft contacts in particular are extremely flexible. They may take their shape from whatever they are resting on. They can be quite buoyant and yet must be aligned precisely in order to get a good measurement.

The ClearWave™ Contact Lens Precision Aberrometer™ has been under development at WaveFront Sciences for about three years. During this time, we have seen the requirements continue to evolve to support a wider variety of contact lenses, stabilization schemes, and manufacturing methods. The ClearWave™ instrument has been redesigned in response to these changing requirements in order to make an extremely wide variety of measurements.

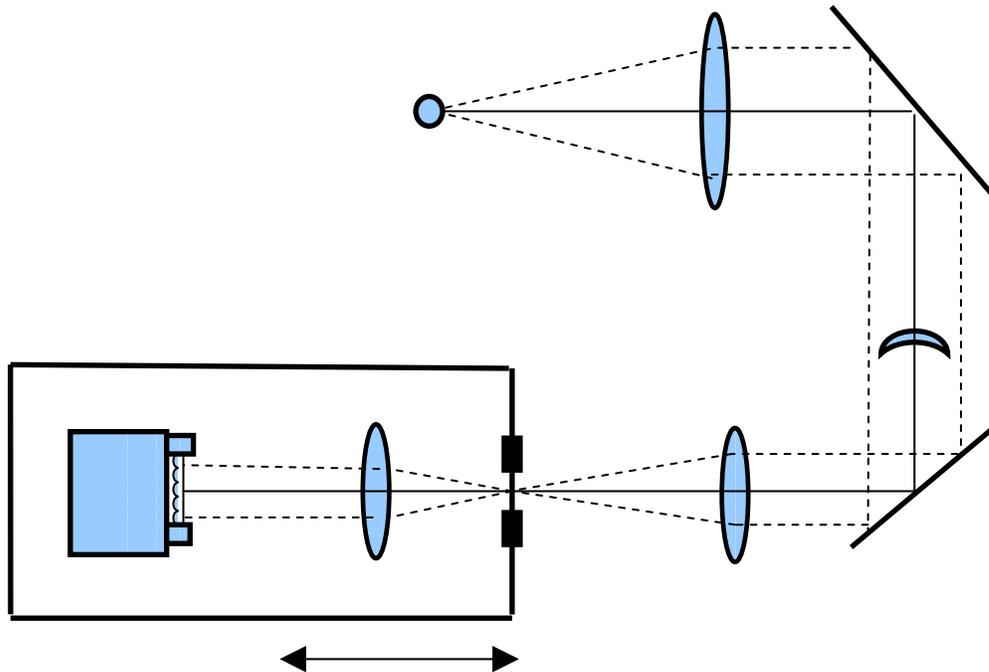


Figure 3 ClearWave™ basic optical layout. Additional paths are also needed for contact alignment, prism adjustment, and other features necessary to make a practical instrument.

ClearWave™ is conceptually a very simple instrument (see Figure 3). The contact lens is illuminated in transmission with collimated light which is then collected through an optical imaging system onto the wavefront sensor. The sensor is then used to derive all the important imaging parameters. In practice, however, there are a number of technical difficulties. The power of the contact (RGP or dry state) may exceed the dynamic range of the instrument or the prism may be so strong that the light does not properly traverse the optical system. To deal with these various problems, we designed an adjustable optical system. In doing so, we borrowed heavily from the COAS instrument which is designed to measure the eye itself.

Figure 1 is a photograph of the resulting instrument and gives the basic specifications. The instrument measures a contact lens in either wet or dry state and accurately determines the contact power (sphere, cylinder, and toric axis). It measures overall quality factor, asphericity, and even higher order aberrations. The data is used to produce a point spread function or modulation transfer function. The user interface allows for both production mode and research measurements.

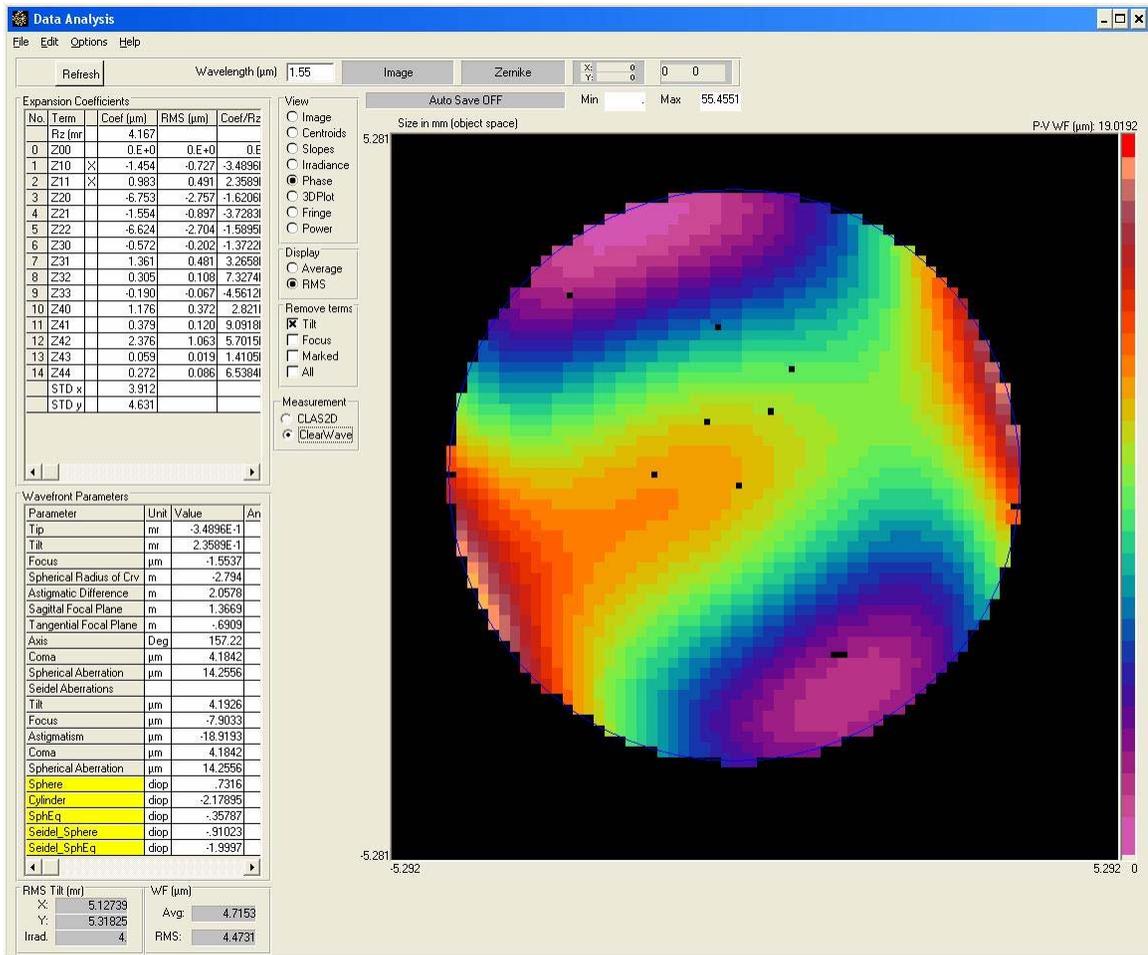


Figure 4 Measurement of an RGP contact lens. Note that a number of optical parameters can be calculated from this measurement, including the sphere, cylinder, and axis (yellow numbers). The higher order aberrations are also presented in terms of Zernike polynomial coefficients now standard in ocular aberrometry.

One key application of this technology is metrology for customized contacts. With the advent of fast-axis lathes (now available from DAC), it is possible to make a measurement of the subject eye with an ocular aberrometer and then build a customized contact lens to correct the full optical errors. It is extremely desirable to know if the contact lens has been manufactured according to the full specifications. Thus a means is needed to measure the (potentially highly aberrated) contact lens and then compare it to ocular aberrometer measurements. ClearWave™ is ideally suited to this role and is designed to be able to directly read in the ocular aberrometer files to allow for a direct comparison.

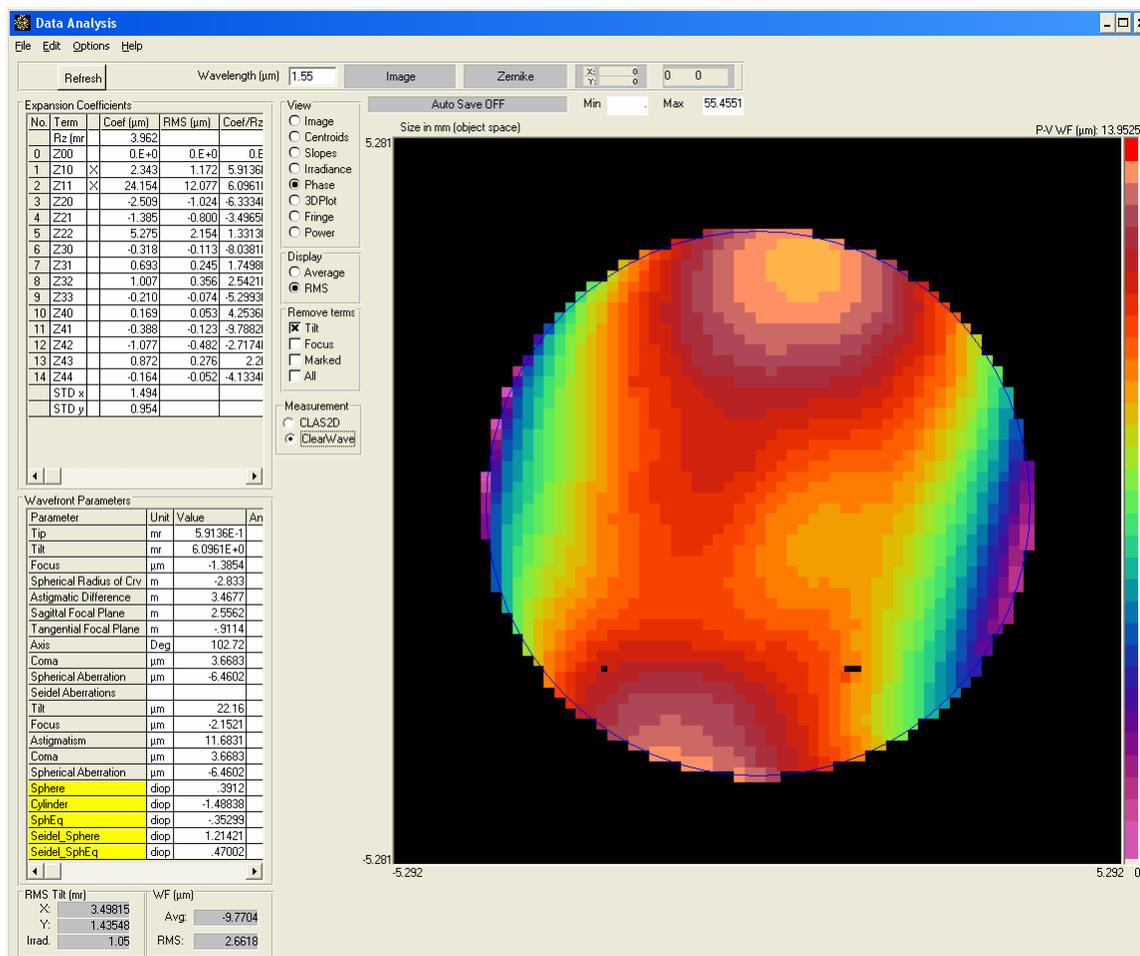


Figure 5 Measurement of the optical zone of a soft contact in solution. In this case the measurement is scaled by a factor of 4.8 to compensate for the low contrast index of refraction between saline and the CL material. The measurement data is trimmed to the optical zone, but the CL could be measured over a much larger region if desired.

Examples of measurements of contact lenses are shown in Figure 4 and Figure 5. Figure 4 is a measurement of an RGP lens measured in the dry state. This measurement takes about three seconds to complete with minimal fixturing (the CL was placed on a glass slide at the appropriate location and then adjusted for centering).

Figure 5 is an example of a soft contact lens measured in solution. In this case, the fixturing included a small wet cell that could be filled with saline and only the central 5-mm optical zone was analyzed to calculate the appropriate optical parameters. Note that this lens has a significant amount of aberration that is not spherical or cylindrical in nature. If this was a typical measurement of sphero-cylindrical lenses in manufacturing, then the instrument would have flagged this lens (or lens lot) for rejection.

Often the next generation of technology is limited by the instruments that are available for diagnosis and metrology. ClearWave™ is the next step for enabling the development of full wavefront corrected contacts. It provides useful information both in the development phases of new contact lens products and in manufacturing for all types of

contacts. The availability of this type of instrument is a critical step for the development of individually customized contact lenses.

References

¹ Neal, Daniel R., and Jim Schwiegerling. "Historical Development of the Shack-Hartmann Wavefront Sensor." Legends in Applied Optics. Ed. James E. Harvey and R. Brian Hooker. Bellingham, WA: SPIE, 2005. 132-139.

² Neal, Daniel R. "Shack-Hartmann Sensor Engineered for Commercial Measurement Applications." Legends in Applied Optics. Ed. James E. Harvey and R. Brian Hooker. Bellingham, WA: SPIE, 2005. 140-160.

³ "Proceedings of the 6th International Congress on Wavefront Sensing and Optimized Refractive Corrections" Journal of Refractive Surgery 21 (2005): 506-575.