

How Alcon/Summit/Autonomous Answers Six Important Questions About Their Customized Laser Platform

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At the 2nd International Congress on Wavefront Sensing and Aberration-free Correction, each participating company was asked to answer a list of specific questions about their technology. Below is a summary of the presentation I made to address each question.

1A) What wavefront sensor are you using?

Alcon/Summit/Autonomous has been using a prototype wavefront device in clinical trials for the past 2 years. Recently, we began clinical testing of the commercial version of the instrument, which is named "LADARWave." The commercial device was developed in collaboration with Zeiss Humphrey Systems of Dublin, California. Both device configurations operate on the Shack-Hartmann wavefront sensing principle. Specific performance characteristics given below pertain to the commercial device design.

1B) What wavelength of light are you using in your wavefront sensor?

Our commercial instrument operates at 820 nm. We chose this wavelength primarily because it is tolerated easily by the patient. This allows us to obtain multiple wavefront measurements during the clinical examination. The machine uses initial wavefront data to adjust optics in the fixation target pathway automatically so that the eye is properly fogged (ie, not accommodating). Once fogging is complete, the device obtains up to five wavefront measurements, which are then automatically analyzed and combined to generate a representative composite profile. (The five individual measurements are also available for the operator to review.)

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We have done extensive clinical testing to determine whether wavefront measurement at this infrared wavelength is valid for clinical use. This work involved direct comparison to the prototype wavefront sensor (which operates at 670 nm), and to conventional refractive examinations. Results showed that the infrared (IR) probe wavelength had negligible impact on the higher order aberrations measured in an eye. As an example, the higher order aberration profiles for my left eye are shown in Figure 1 for both infrared and visible probes. The IR wavelength of the commercial device does, however, affect the low (second-order) terms, primarily defocus. We have incorporated an algorithm in the device software to compensate for this effect.

1C) How many pupil entry locations do you have for a 7-mm pupil?

Our Shack-Hartmann sensor utilizes a square lenslet array, which samples the pupil every ~430 μm . For a 7-mm circular pupil, this results in 204 to 213 sample points, depending on the precise pupil/array alignment. However, our software automatically rejects peripheral data that is "clipped" by the pupil aperture. After these are removed, approximately 190 samples are used in the wavefront reconstruction.

2) What reference axis do you use for wavefront measurement and treatment?

We reference everything to the patient's natural line of sight. Our wavefront device has a video camera to monitor the patient's eye during the examination. The video image from this camera is displayed to the operator as part of the graphical user interface (GUI). Software reticles projected in this display can be aligned to anatomical features in the image. At the start of the wavefront examination (before any dilation is induced), we use the software to record the geometric relationship between the center of the natural pupil and the limbus.

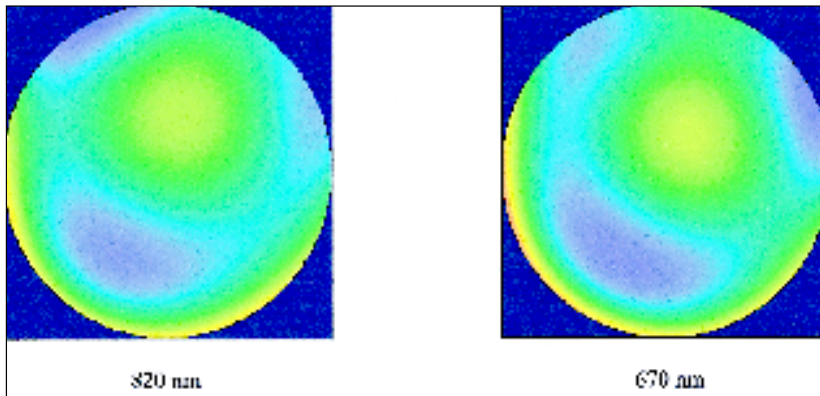


Figure 1. Higher order aberrations for one eye measured at two different wavelengths. The diameter of each measurement is 5 mm. The color scale is the same in both cases, with red indicating the highest portions of the wavefront and blue indicating the lowest parts. Similar agreement has been seen for a large number of eyes in comparative diagnostic work.

3) How do you register and maintain registration of the wavefront ablation shot pattern to the eye?

The wavefront data used for surgery is obtained on the day of treatment. Before the wavefront examination, a number of ink marks are applied to the sclera just outside the limbus. During each of the five wavefront measurements, a frozen video image of the eye is captured. The operator aligns software reticles to the limbal boundary and applied ink marks. This provides translational and rotational information that is saved in the electronic treatment file along with the Zernike polynomial wavefront data.

When the patient subsequently lies down in the LADARVision system, a space-stabilized video image of the eye is displayed to the surgeon as a part of the graphical user interface. Software reticles identical to those used during the wavefront measurement are aligned to the same anatomical landmarks. The ablation profile is then well registered to the true corneal orientation.

4A) How many Zernike coefficients are included in the measurement and treatment?

In our treatment trials to date, we have utilized fourth-order Zernike descriptions of the wavefront profile, which involve 14 individual coefficients. With our commercial instrument, we can go up to eighth-order (44 terms), and further if necessary.

4B) What are the optical and transition zone diameters for a 4-D myope and a 4-D hyperope?

All of our customized surgeries to date (both myopic and hyperopic) have employed a 6.5-mm diameter optical zone, surrounded by a 1.25-mm-wide transition zone, for a total treatment diameter of 9 mm.

5) What are the characteristics of your treatment laser beam?

The LADARVision system employs a 193-nm ArF excimer laser. At the treatment plane the beam has a Gaussian fluence distribution, with a full-width-half-maximum diameter of 0.75 mm, a peak fluence of 400 to 600 mJ/cm², and a total energy per pulse of 2.7 mJ. During surgery the laser fires at a rate of approximately 60 Hz.

6A) What are the characteristics of your eye tracker?

The LADARVision eye tracker is an active closed loop system that measures pupil margin position at 4000 Hz utilizing infrared laser signals. The closed-loop bandwidth of the tracking system is 100 Hz.

6B) What is the mirror adjustment time for a 1-mm distance?

The LADARVision tracking mirrors can adjust for any displacement error in the treatment plane in less than 10 ms (when the tracker is turned on from an off position). However, due to the closed loop nature of the tracker design and the high sampling frequency, the required mirror adjustments during surgery always involve very small distances. These are completed in much less than 10 ms, and on the order of 1 ms or less. This is discussed further in the response to the next question.

6C) What is the corresponding spatial resolution of treatment spot placement during surgery?

As a worst case scenario, we will consider a 1-mm fast saccade. A reasonable peak velocity for such a saccade is about 50 mm/s, with a peak acceleration/deceleration of 5,000 mm/s² (Bahill AT, Stark L. The trajectories of saccadic eye movements. *Scientific American* 1979;240:108-117). This saccade

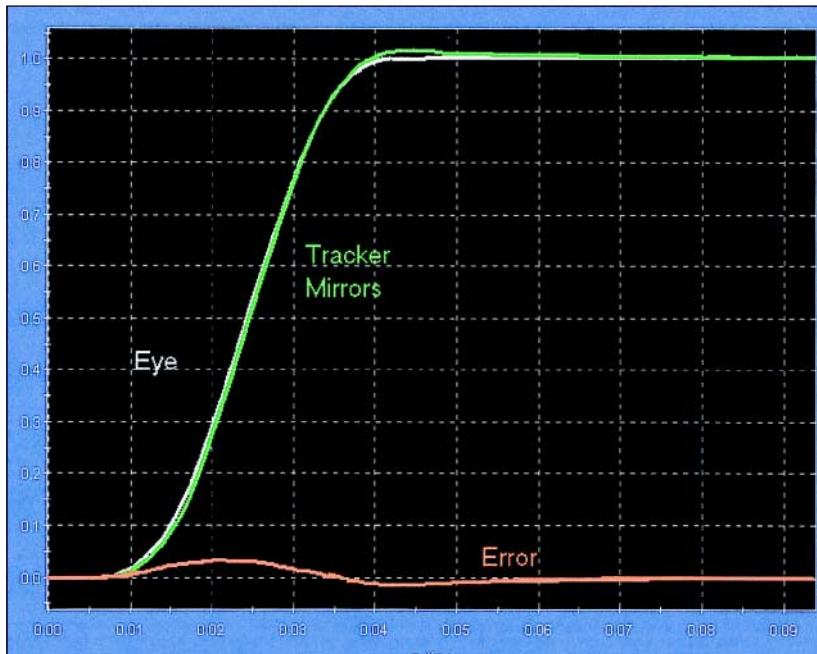


Figure 2. LADARVision tracker response to a fast 1-mm saccade (simulation). Horizontal axis indicates time in fractions of a second. Vertical axis indicates position in millimeters. The white sigmoidal curve is the true eye motion, based on acceleration and velocity data, given by Bahill and Stark (Bahill AT, Stark L. The trajectories of saccadic eye movements. *Scientific American* 1979; 240:108-117). The green trace is the response of the tracker mirrors to the saccade. The difference between these two curves is plotted as the red trace labeled "error." The peak following error of the tracker is approximately 30 μm .

is plotted as the white trace in Figure 2. Because of the 4000-Hz sample rate, the tracker detects the saccade onset almost instantaneously, and begins commanding a series of mirror adjustments to compensate for the motion. The tracker motion is shown by the green curve in Figure 2. The difference

between the eye and tracker positions is indicated by the red trace labeled "error." The tracker lags slightly behind the true eye position at the start of the saccade, and overshoots marginally at the end. The peak position error during this fast saccade is 30 μm .