imagine optic™

Shack-Hartmann wavefront analysis

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APPLICATION NOTE

Introduction

Imagine Optic™ HASO™ wavefront sensor hardware and software technologies are based on the Shack-Hartmann principal. HASO is optimized at every stage of production from design and manufacturing through to calibration and meticulous quality control.

Overview

Shack-Hartmann wavefront sensors are based upon the principals proposed late in the 19^{th} century by a German physicist named Hartmann. At that time, the instruments needed to bring that idea to life had not yet been conceived. In 1971, when technology had matured to a point where putting Hartmann's idea into action became possible, two American scientists named Shack and Platt improved on Hartmann's idea and built the first wavefront sensor of this type, calling it a Hartmann-screen. Since then, it has become commonly known as Shack-Hartmann and is considered around the world to be the technique of choice for precision wavefront metrology. Imagine Optic has further improved on this technique by incorporating several proprietary technologies, including Dynamic Spot Tracking™ and Auto Spot Finder™, to increase the HASO family of wavefront sensors' dynamic range.

Hartmann's idea was to measure the aberrations (imperfections) present in a luminous source by passing it through a screen of apertures that would spatially decompose it into the equivalent number of points, each point being relative to a specific zone of the incoming source. To do this, he would have to measure the light at a given moment in time and, today, we call this the source's wavefront.

Because he knew that the light coming through the screen from a perfect source would intersect the measurement grid at a specific point, he knew that the aberrations could be measured by calculating the difference between where a plane (perfect) wavefront would appear on the grid versus that of the one to be measured. This calculation would also provide the local slopes, or first derivative (angle), at which the wavefront intersected the surface behind each aperture of the grid.

Shack and Pratt improved on Hartmann's idea by using microlenses to focus the incident wavefront onto the grid of a CCD camera. These subdivisions of the original source created what are called "multiple elementary beams." These two improvements on Hartmann's original idea gave birth to what have come to be known as Shack-Hartmann wavefront sensors. Devises based on this technology, including Imagine Optic's HASO family of products, are the industry standard for precision wavefront metrology.

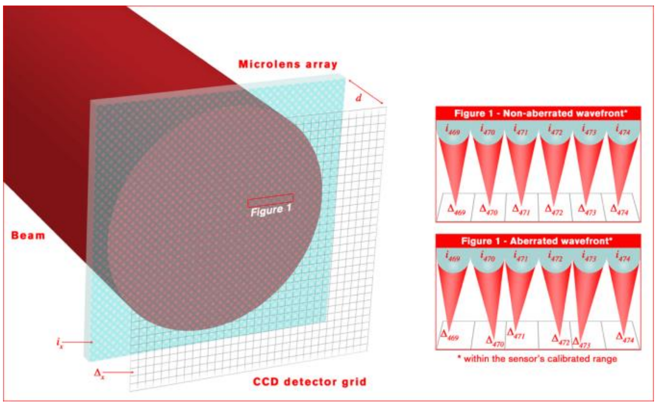

Figure 1. Working principal of Shack-Hartmann wavefront sensor.

Figure 1 illustrates how HASO Shack-Hartmann wavefront sensors function. In this diagram, d is the distance between the microlens array (principal image plane) and the CCD detector grid, i is the number of the microlens in the array, and Δx is the intersection point of the elementary beam on the CCD detector grid. By using the using the simple formula below, the wavefront's local slopes are calculated and the phase map is displayed.

$$\tan_i = \frac{\Delta x_i}{d}$$

Figure 2 illustrates how HASO uses the information to construct both 2D and 3D images of the wavefront. Whereas some wavefront sensor providers' software interface may present a wavefront image with smooth edges, this is not a true representation of your wavefront. Because, to do this, they must perform what is called circular truncation of the wavefront data. This entails either the removal of data from the outside edge or the supposition of that data to smooth the edge. Imagine Optic provides you with a true image of your wavefront from each and every measured point.

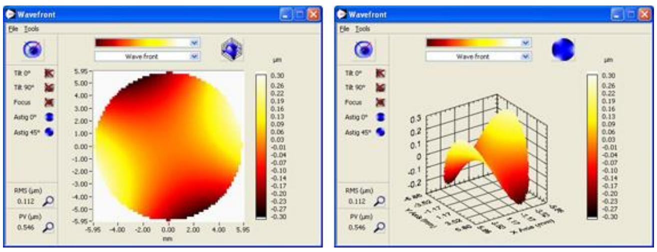

Figure 2. Reconstruction of 2D (left) and 3D (right) images of the wavefront from HASO wavefront sensor measurement.

Some facts about precision in well-built Shack-Hartmann wavefront sensors

We would like to take this opportunity to dispel two widespread myths about Shack-Hartmann technology. The first being "crossing spots," or the claim that these wavefront sensors can be misled when measuring highly aberrated wavefronts.

This first erroneous claim purports that large aberrations in the source would be misinterpreted by the device as light from a different microlens and therefore cause the sensor to provide a false measurement. Not only is this myth unfounded but the simple truth is that it's impossible in wavefronts with a continuous derivate.

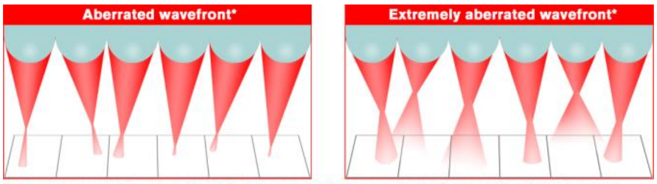

Figure 3. Examples of wavefront aberrations.

In the case where a wavefront were to be so aberrated that it could cause the light from one microlens to stray into an adjacent measurement zone on the CCD camera's detection grid, the wavefront's local radius of curvature would render it undetectable due to a simple lack of contrast (see Figure 3). Theoretically, for two spots to cross or to superimpose on the detection grid, the wavefront's local radius of curvature would have to be such that it would be exactly equal to the microlens' focal distance. In this case, the microlens' focal point would not be on the detection grid but far in advance, creating an image on the detection grid equal to or superior to the size of the microlens. This complete defocalization of the light from that microlens would be considered by the HASO wavefront sensor as non-measurable and no data would be provided for that point.

Although HASO wavefront sensors have an exceptional dynamic range, no sensor can claim to measure any and all aberrations regardless of their magnitude. When a HASO device encounters this type of situation, the data is discarded and no measurement is provided for that measurement point. In contrast, inferior devices may provide erroneous data based on false "assumed" data.

The second erroneous claim is based on the supposition that devices of this type are subjects to provide erroneous data due the chromatic effects introduced by the microlens array. Yes, it is true that any optical medium induces chromatic effects. What really matters is the understanding of these effects on measurement and working around them. Imagine Optic's HASO wavefront sensors are built using patented fabrication techniques to ensure precision measurement, no matter what wavelength you work with.

First, HASO wavefront sensors are precision built devices with a fixed and known distance between the principal image plane (microlens array) and the CCD detection plate ("d" in Figure 1). Using the distance between those two elements is the only sure way to correctly calculate the wavefront's local slope. Second, the optical geometry chosen by Imagine Optic employs a microlens array that places the microlens' convex face towards the CCD detection plate. This enables HASO wavefront sensors to calculate by means of a fixed parameter where the distance between the principal image plane and the detection grid never changes, making them achromatic.

By means of these two constants, HASO wavefront sensors measure correctly no matter the chromatic properties of your source.

In short, HASO Shack-Hartmann wavefront sensors are the most reliable means of using wavefront sensing and analysis to achieve precision results every time you use them – even on the most highly aberrated, convergent or divergent beams.

Key HASO technology features

- Design optimization using wave propagation and signal detection modeling
- High-quality microlens array
- Ultra-precise coupling between camera and microlens array
- Robust bulk mechanical assembly
- Wide-range spot detection algorithms
- Rigorous calibration and test procedure

For more information, and to find the Imagine Optic office or distributor nearest you, please visit www.imagine-optic.com