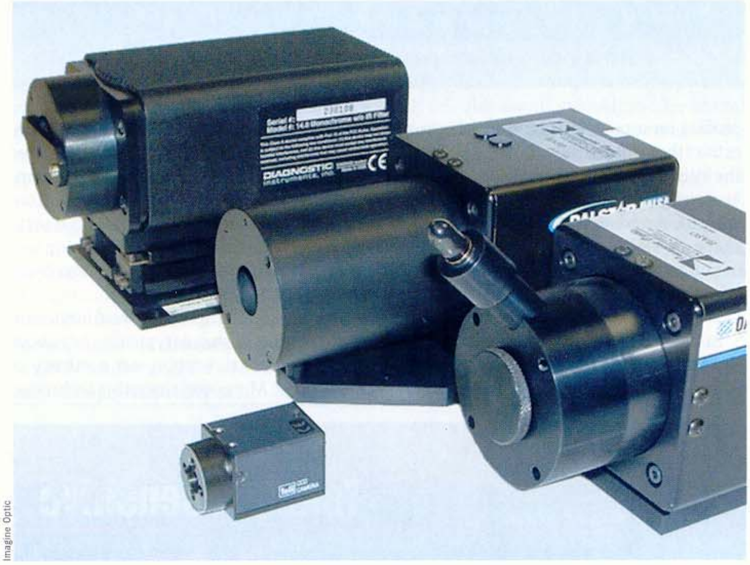
Wavefront sensors show up problems with beams

Whether it's adjusting a telescope or focusing a laser beam to a small spot, wavefront sensing can help. **Xavier Levecq** explains the technique and the options available.

Measuring the wavefront (optical phase) of a light beam is critical for assessing the quality of an optical system and optimizing its performance. When light passes through an imperfect optical component, aberrations – or wavefront errors – are generated. By measuring these errors with a wavefront sensor, they can be either corrected or minimized.

Today, several types of wavefront sensor are commercially available: the most popular being the Shack-Hartmann; curvature sensors; and multilateral shearing interferometers. Such sensors can be found in a variety of applications, including telescope adjustment, performance assessment of aspheric lenses, characterization of DVD pick-up heads and the development of femtosecond lasers.

The reason why wavefront analysis is so important is that the shape of a wavefront strongly influences how a light beam propagates through a medium. For example, to focus a beam to a tight spot requires that the incident beam has a perfect Gaussian intensity profile and an undistorted phase profile.

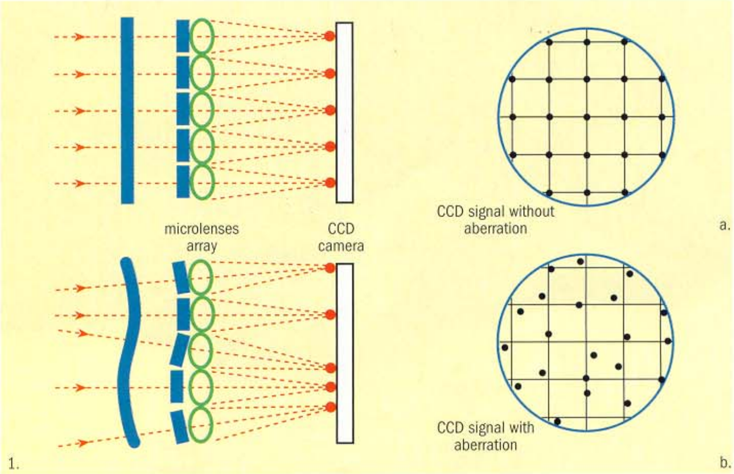

Imagine Optic

Origins of wavefront sensing

The origins of wavefront sensing lie in astronomy, where Shack-Hartmann sensors and adaptive optics were first used to increase the imaging resolution of telescopes in the 1980s and 1990s. Since then, several companies, like Wavefront Sciences, in the US, and Imagine Optic, in Europe, have developed a new generation of sensors that are dedicated to the needs of industrial metrology.

Today's wavefront sensors are able to provide fast, accurate and absolute measurements that do not need a reference beam.

Here is a brief description of the different types of wavefront sensor, complete with their principle of operation and strengths and weaknesses. Each is capable of "single-shot" wavefront measurement and is insensitive to vibration.



Beam diagnostics: a selection of commercially available Shack-Hartmann wavefront sensors (top). The instruments use the principles described below to measure the wavefront of a light beam and are useful for characterizing and optimizing the performance of a wide variety of optical systems. Fig. 1: a Shack-Hartmann sensor analysing the wavefront from a perfect beam (a) and a beam with aberrations (b) (bottom). The deviations of the focal points from the grid relate to the local gradient of the wavefront.

Curvature sensors

Curvature sensors rely on measuring the intensity profile of a light beam of interest in two different planes along the optical axis. By comparing the two recorded intensity ▷

Wavefront sensors at a glance

Sensor type	Strengths	Weaknesses
Curvature	single shot high lateral resolution insensitive to vibration speed	only measures collimated beams limited wavelength range limited dynamic range not suitable for low light levels
Multiwave lateral shearing interferometry	single shot tunable sensitivity, dynamic range and lateral resolution	limited wavelength range low dynamic range not suitable for low light levels
Shack-Hartmann	collects phase and intensity information wide wavelength range high sensitivity and dynamic range	high number of pixels needed to create a data point needs high-resolution CCD camera

profiles on a point-by-point basis, one can extract the axial derivative (along the z-axis) of the intensity over the image plane. With this knowledge it is possible to calculate the curvature (second derivative) of the wavefront shape via the Poisson propagation equation.

This is in contrast with Hartmann or multilateral interferometry techniques, which provide a first derivative measurement of phase.

In the original technique, the two intensity profiles were recorded by moving either collection optics or the detector to two distinct positions along the optical axis. Recently, this technique has been improved by adding a diffraction grating so that a single CCD detector can record the two intensity profiles simultaneously.

The key strength of curvature sensing is its unique high lateral resolution, in which one pixel gives one phase data point.

The dynamic range is a critical limitation of curvature sensing as typically only about 3μm is achieved, keeping an accuracy of λ/100 rms. Moreover, since this technique gives information about the curvature (second derivative) of the phase, the measurement of wavefront tilt (the gradient of the wavefront) is not possible.

Another limitation is that this technique requires a collimated beam and cannot measure diverging or converging beams. For low-light-level applications, such as ophthalmology or astronomy, the optical loss associated with splitting the beam by a grating can be a limitation.

Multiwave lateral shearing interferometry

In this technique, a 2D diffraction grating splits the incident beam into four identical waves, which propagate along slightly different directions. An interference pattern is generated a short distance behind the grating. Where aberrations are present in the beam, the interference grid is distorted. The grid deformations directly relate to the gradient of the phase at each point of the optical beam. The phase map is obtained by integration of these gradients.

What's more, the sensor's sensitivity, dynamic range and lateral resolution can be tuned by adjusting the distance between the diffractive element and the CCD detector with a translation stage. The required number of CCD pixels to obtain one phase data point is lower than that of the Hartmann technique, but higher than curvature sensors.

For shearing interferometers, the transverse resolution of a measurement is equal to the spatial shift between the interfering wavefronts. When a higher sensitivity (smaller phase error) measurement is required, this shift needs to be increased by moving the analysis plane away from the diffractive element. However, this causes the transverse resolution to drop significantly.

To achieve a sensitivity of λ/100, the transverse resolution of a commercially available shearing interferometer approaches that of a standard Shack-Hartmann wavefront sensor. Moreover, the intrinsic dynamic range of such devices is low and the largest phase measurement cannot exceed about 100 times the sensitivity. So, it is not possible to characterize a high-aberration optic, such as an asphere, with good accuracy.

Another limitation is that the shearing principle makes it impossible to measure the defects around the edge of the pupil. This kind of sensor is not well adapted to low-light-level applications because the diffractive element significantly decreases the incident optical power to the detector.

Shack-Hartmann sensor

Shack-Hartmann sensors are widely manufactured and sold by more than 10 companies worldwide. These wavefront sensors measure the gradient (first derivate) of the wavefront at a series of points across the beam.

The incident wavefront illuminates a microlens array and a CCD detector is located in the focal plane of the lenses (see figure 1, p33). Each microlens focuses the local wavefront onto the CCD. Without aberration, the CCD signal is a perfect array of regular spots. However, where the wavefront is distorted, each spot moves away from its ideal position, with the size of the deviation being proportional to the local slope of the wavefront. By measuring the size of each local wavefront deviation, the entire wavefront can be reconstructed. They are very easy to use and set up.

A benefit of Shack-Hartmann wavefront sensors is that they provide both intensity and phase information about the beam. The measurement of these two parameters is independent: the local intensity is given by the amplitude of each spot and the local slopes and wavefront phase is given by the position of the spots. The intrinsic dynamic range of these sensors is huge (many hundreds of lambdas), and the sensitivity and the accuracy remains excellent ($\lambda/100$) over the entire dynamic range.

The useful wavelength range and optical transmission of Shack-Hartmann sensors is also far better than other techniques as they do not contain diffraction gratings, only microlenses. As a result, these sensors are very convenient for low-light applications.

> **“The intrinsic dynamic range of Shack-Hartmann sensors is huge.”**

The main drawback of these wavefront sensors is the number of pixels required to create one phase data point. It is much higher than curvature sensors, and high-spatial-resolution Shack-Hartmann sensors require at least 1000 × 1000 pixel CCD cameras.

Strengths and weaknesses

As one would expect, these different sensor techniques each have their own set of strengths and weakness. The curvature sensors offer the best lateral resolution, but the inconvenience of their alignment and their small dynamic range for a $\lambda/100$ rms accuracy strongly limits their use.

Multiwave lateral shearing interferometers are quite new to the market and currently suffer from two chief limitations: a very small dynamic range and a low optical transmission. Their greatest attraction is the ability to tune their sensitivity, dynamic range and lateral resolution.

However, a common limitation of both sensor technologies is their narrow wavelength range of operation. Their spectral bandwidth is limited due to the fact that they contain diffraction gratings.

In contrast, the achievable wavelength range for a Shack-Hartmann sensor can be a factor of two (spanning 532–1064 nm, for example). Furthermore, in terms of dynamic range, Shack-Hartmann technology is the only one able simultaneously to offer several hundred microns of dynamic range while maintaining $\lambda/100$ precision.

Until now, the only technology widely and commonly in use all over the world in both the research and industrial applications is the Shack-Hartmann sensor. Its precision, ease of use and robustness make it suitable for all fields of the optical industry. □

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