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Optics and photonics — Wavefront sensors for characterising optical systems and optical components

Optique et photonique — Capteurs de front d'onde pour caractérisation des systèmes optiques et des composants optiques

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Foreword

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Optics and photonics — Wavefront sensors for characterising optical systems and optical components

1 Scope

This Technical Report gives terms and definitions and describes techniques for the characterization of wavefronts influenced by optical systems and optical components. It describes basic configurations for a variety of wavefront sensing systems and discusses the usefulness of tests in different situations.

The aim is to cover practical instruments and techniques for measuring the wavefronts produced by optical systems and optical components. This Technical Report includes various implementations of the Hartmann method, the curvature sensor and applications of the knife-edge method. The use of interferometers is discussed. This Technical Report also includes techniques such as phase diversity and pyramid sensors, currently used in astronomy and being developed for other areas.

NOTE More information on interferometry can be found in ISO/TR 14999-1, ISO/TR 14999–2 and ISO/TR 14999–3.

This Technical Report explains briefly how these techniques work and includes diagrams illustrating the use of this type of equipment for making the measurements required for ISO 10110-5, ISO 10110-8, ISO 10110-12 (slope requirements) and ISO 10110-14.

2 Introduction to wavefront sensing techniques

Interferometry is a well-established technique for comparing a test wavefront with a reference wavefront, usually spherical or planar, and requires a degree of coherence between the two wavefronts to produce an interference pattern. Some interferometers for wavefront characterization are self-referencing, such as shearing interferometers. These reveal the slope of the wavefront at various points with values deduced from the interferogram and integrated to calculate the phase profile.

More recently non-interferometric techniques have been developed, partly driven by the needs of adaptive optics, and it is possible to apply these to wavefronts with limited coherence. The majority of these techniques are based on measuring the wavefront slope values.

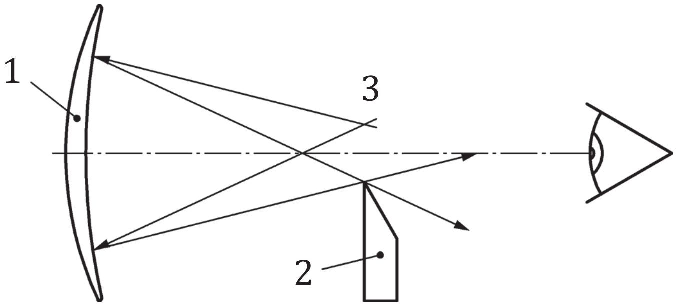
Many of the non-interferometric techniques can be categorized as screen tests. A screen test is a general term for the test of a beam with an opaque plate placed or moved in the focusing beam and the irradiance pattern transmitted by the opaque plate analysed. The screen may have one or more holes, slits or edges to transmit part of the beam while blocking with the opaque part.

Non-interferometric techniques include focused waist (image of source) measurements and wavefront sampling which gives slope measurements. The knife-edge is a simple test that isolates regions of the wavefront to reveal aberrations. The Hartmann test uses a perforated screen to isolate bundles of rays and the direction of these bundles is measured to calculate the wavefront slopes. The Shack-Hartmann test uses an array of small lenses to sample the wavefront. The wavefront slopes are deduced from the positions of the focal spots generated by the lens array and the slope values are integrated to calculate the phase profile.

Wavefront curvature sensing and phase diversity techniques are a class of wavefront retrieval mechanisms that infer the wavefront from measurements of the intensity of the light as the beam propagates. Typically this involves the measurement of two images along the beam path, from which the intensity gradient is derived. Two standard approaches are to measure the intensity either side of a focus or either side of a pupil plane in an optical system. Phase diversity techniques use calculation algorithms for the retrieval of wavefront phase. Once the intensity data are collected, a processing step is required to calculate the wavefront. This can be achieved using the intensity transport equation, and solved by direct integration or iteratively using Fourier transform techniques.[11] Phase diversity methods are finding more use with faster phase retrieval methods as computation speeds increase.

3 Foucault knife-edge test

3.1 The knife-edge test



a) Test set-up

b) typical intensity pattern seen by observer

Key

1 mirror
2 knife-edge
3 source

Figure 1 — Knife-edge test for wavefront from a concave mirror

The knife-edge test is one of a family of techniques in which elements of a deformed wavefront are detected by blocking with an opaque mask that has an edge that clearly defines the boundary between the opaque and transmitting regions of the mask. The mask is placed in the plane of best focus of the wavefront.

The knife-edge test was reported by Foucault in 1858 as a method for examining the form of a concave mirror surface.[12] The mirror is used to form an off-axis image of a pinhole source placed in a plane containing the centre of curvature of the mirror and a blade with a knife-edge as shown in Figure 1a). The mirror is observed from the vicinity of the image and the knife-edge is moved across the line of sight until a shadow is seen to cross the mirror. The direction of movement of the shadow will depend on whether the image is formed in front of or behind the knife-edge. If the centre of curvature lies exactly in the plane of the pinhole and the knife-edge, the whole aperture of the mirror will darken simultaneously revealing imperfections in the image. When the knife-edge is scanned across, imperfections in the image will be revealed as dark and bright regions, simulated in Figure 1b).

Knife-edge scanning is a relatively simple method for measuring spot sizes but inaccuracies can occur due to uncertainties in the location of the knife-edge. The method has been applied to the measurement of spot diameters to a precision of better than 50 nm using interferometry to monitor the knife-edge position.[13] In applications such as optical data recording, the size and structure of the smallest possible focused spot is important. These parameters are described by the point-spread function, a measure of the quality of the optical system.[14-16]

3.2 Variations on the knife-edge test

The Foucault knife-edge test can be used to make precise measurements of zonal errors in near-spherical wavefronts and is useful as a null test.[17] It is not, however, so useful for testing aspherical wavefronts.

The asymmetry of the single knife-edge allows systematic errors to accrue. A better arrangement is to use two knife-edges that block the light simultaneously in opposite directions. Either a thin wire or a thin slit will achieve this. A thin wire blocks out a very narrow region of the wavefront and the shadow patterns consist of thin dark contours. Platzeck and Gaviola applied the thin-wire method to the testing of parabolic mirrors.[18] They measured the caustic, which is the line of centres of curvature of the surface elements.

3.3 Application of knife-edge test to diode lasers

The characteristics of diode laser sources are dependent on the choice of semiconductor materials and the geometry of the junction structure. The active layer of a typical laser is about one tenth of a wavelength thick while the waveguide dimensions are typically 1 µm by 3 µm in the planes perpendicular and parallel to the junction respectively. Mode confinement is achieved either by gain guiding or by index guiding. A laser beam is emitted from the facet and diverges strongly due to the small size of the source.

Diffraction causes the beam to spread over large angles, typically ranging from 25° to 60° in the perpendicular direction and 7° to 35° in the junction plane. The radiation pattern is asymmetrical. Depending on the type of diode the mechanisms of constraining the beam in the plane of the active laser and in the plane normal to it are quite different and the wavefront becomes strongly astigmatic. The window in the canister containing the diode source is usually a thin plate and this can introduce spherical aberration. Anamorphic lenses are sometimes used to collimate the elliptical beam.[19,20] Near-field and far-field measurements are often required to fully characterize a laser diode.[21]

Knife-edge scanning is often recommended for the measurement of the astigmatic distance of wavefronts from diode lasers. The diode source is imaged at the plane of the knife edge with a relay lens such as a microscope objective. The total optical power passing the knife edge is measured with a photodiode and meter. This is plotted against knife edge position and an integrated power profile drawn. Differentiation of this curve gives the actual power profile from which the beam diameter, defined as full width at half maximum height, can be determined.

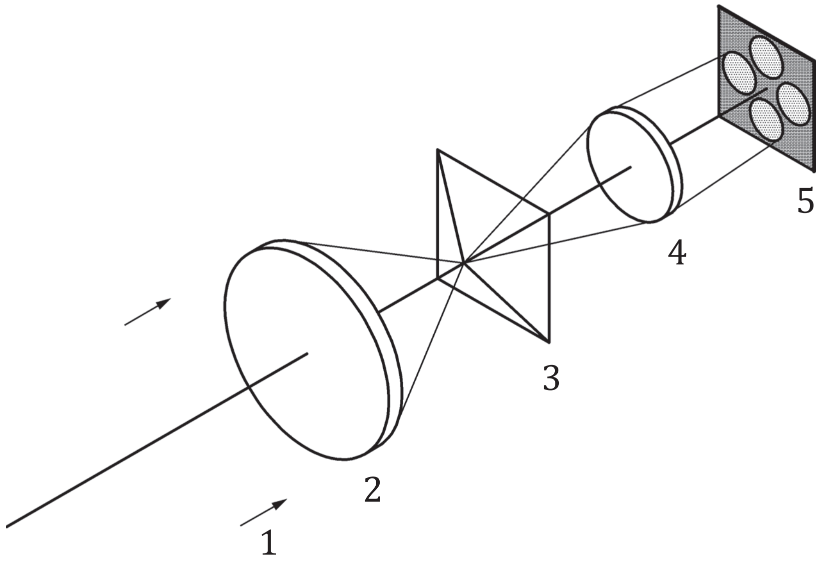
A beam diameter profile is produced by measuring the beam diameter at different points along the axis, achieved by displacing the source. The beam diameter profile is produced for movement of the knife edge in the direction perpendicular to the junction plane of the laser diode and the other for travel parallel to the junction plane. The astigmatic distance is defined as the displacement of the source between the minima of these plots.

An advantage is that it is a simple test with no demands on coherence properties of source. It is sensitive to small deviations in slope of the sampled wavefront or to slope deviations that are changing slightly in magnitude or direction.

3.4 The pyramid sensor

The pyramid sensor may be considered as an extension of the knife-edge test and was primarily developed as a wavefront gradient sensor for astronomy.[22] In that application it uses a shallow glass pyramid with four faces, placed in the focal plane of a telescope and with the tip in line with the optical axis. An incident wavefront is collected by the telescope and focused to the pyramid which generates four beams, as shown in Figure 2. Another lens collects this light to reimage the telescope aperture and form four images on a detector array. The relative intensities of the light in these four images are compared and the wavefront gradients in two orthogonal directions are calculated. By modulating the position of the pyramid a linear gradient signal may be obtained. The accuracy of the pyramid sensor has been investigated and the linearity considered from both the geometrical optical model and diffraction calculations.[23,24]

The test makes efficient use of the light and is able to sense two orthogonal directions. The main use of the pyramid sensor is with adaptive optics in astronomical and ophthalmic applications but its use is gradually being extended to more general wavefront sensing.



Key

1	wavefront
2	lens
3	pyramid prism
4	field lens
5	four images of entrance pupil on detector array

Figure 2 — Pyramid prism sensor

4 Screen testing

4.1 General

The Hartmann principle is based on a subdivision of the beam into a number of beamlets. This is either accomplished by an opaque screen with pinholes placed on a regular grid as in the Hartmann sensor or by a lenslet or microlens array as in the Shack-Hartmann sensor. The use of these techniques to determine the shape of a laser beam wavefront is described in ISO 15367-2. The techniques are also suitable for the measurement of non-laser wavefronts with reduced spatial coherence.

4.2 Hartmann test

The Hartmann test is based on a geometrical optics approach and uses a perforated screen or mask with multiple holes to sample the wavefront at a number of locations in a predetermined fashion.[25] The Hartmann test is often used for testing optical components such as telescope mirrors.[26]

The principle is that a portion of the wavefront, when tilted relative to an ideal wavefront in that region, causes light to come to a focus at a place other than the intended focus, or to intercept a chosen plane at a location other than the one which would be obtained with light coming from the ideal wavefront and from that region.

The converse can be used to determine the tilt error in a portion of a wavefront, by determining where the light from that region intercepts a chosen plane, and what difference there is between that intersection and the one to be expected from a perfect wavefront.

With interferometry, deviations of the wavefront are found using the interference of light from two different regions. With screen testing, the light from each of the various regions of the wavefront is recorded on a photosensitive material, such as a photographic plate, which is measured after processing. The beam deviations are measured to obtain a surface slope error at the sampled points.

One of the major difficulties in screen testing is the introduction of errors through the method used to reduce the data in order to obtain the surface deviations. The main assumption is that the wavefront changes between samples are gradual rather than abrupt. Abrupt changes can be readily detected by other means such as the Foucault knife-edge test. The screen test is better suited for smooth wavefronts.

Several screens have been designed for testing including the Hartmann radial pattern. The holes in the screen have to be accurately placed and small but not so small that their diffraction images overlap at the recording stage.

The advantages of this test include the low number of components and low requirements for source coherence.

Disadvantages include:

a) the Hartmann test samples the wavefront at a discrete number of points;

b) the highest accuracy is achieved for the smoothest wavefronts;

c) considerable time is required to record, process and measure the images on the photographic plate.

The main advantages of the Hartmann technique are:

1) wide dynamic range;

2) high optical efficiency;

3) suitability for partially coherent beams;

4) no requirement of spectral purity;

5) no ambiguity with respect to increment in phase angle.

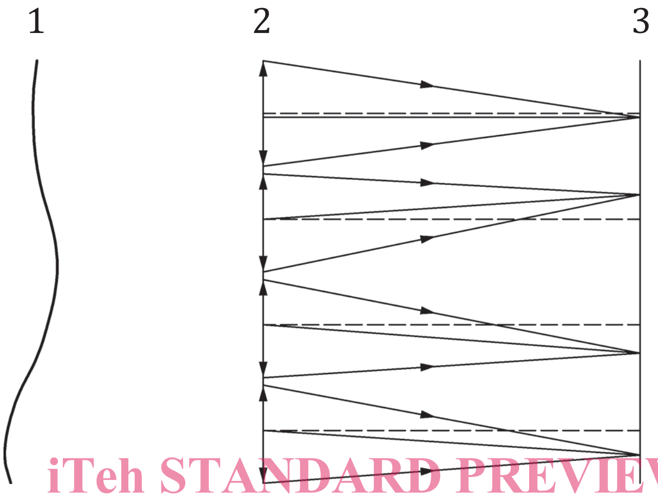
Kingslake considered using the Hartmann test to measure spherical aberration in microscope objectives. A relatively small screen was needed and he realized that interference effects between the light transmitted by adjacent holes in the screen would be a problem. He therefore devised a method that used a single hole, traversed across the aperture to isolate a series of light beams in succession.[27]

4.3 The development of automated wavefront sensing

In the Hartmann test a spot diagram is generated by the intersection of a defined plane and the ray bundles generated by a mask with an array of apertures. An automated device for achieving this was described by Baker and Whyte in 1964.[28] They used a rotating polygon mirror to scan the pupil of the optical element under test. In a modified version a spiral disc scanner was used instead of the polygon mirror.[29] The position at which each ray intersected the image plane was measured with a position-sensitive photodiode and the results displayed in real time on a cathode ray tube. A silicon quadrant detector was also used to measure the ray intersection coordinates. In a further development the system was able to measure wavefront aberration.[30] In 1972 Williams described a system that measured both spot diagrams and wavefront aberrations using an image dissector tube as detector.[31] The subsequent availability of large detector arrays and powerful portable computers has led to the development of equipment that operates on these principles and offers a serious alternative to the interferometers more commonly found in optical workshops. One particularly successful configuration has been that due to Shack and Platt and described below.[32]

4.4 Shack-Hartmann test

The Shack-Hartmann sensor uses an array of lenslets or microlenses to sample the wavefront.[33] Compared with the Hartmann screen test this gives a better optical efficiency and in comparison with the automated system described above, the static lenslet array obviates the need to scan a pencil of light over the pupil of the test piece to sample the wavefront.



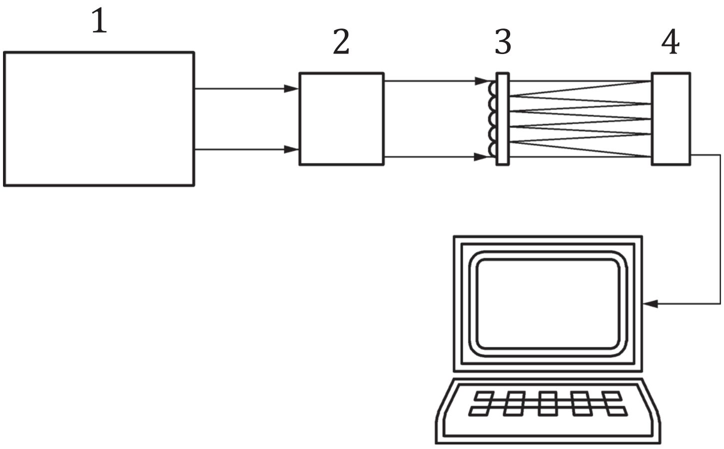
Key

1 wavefront

2 lenslet array

3 detector array

Figure 3 — Array of lenslets (microlenses) used to sample an incident wavefront



Key

1 source of wavefront

2 beam expansion or compression optics

3 lenslet array

4 detector array

Figure 4 — Experimental arrangement for wavefront measurement using Shack-Hartmann technique

The lenslet array divides the incident wavefront into a number of small areas, each of which is focused to a spot as in Figure 3. If a plane reference wavefront is used at normal incidence the spots are formed on the lens axes. If the test wavefront is non-planar the spots are formed away from the axes. A charge-coupled device (CCD) is commonly used to capture the images of the multiple spots allowing the positions of the centroids of the spots to be determined. The transverse positions of the spots are related to the local slopes of the wavefront in the regions of the lens apertures and the form of the wavefront can be calculated using a small computer and dedicated software. In practice it is usually necessary to expand or contract the dimensions of the wavefront to match the dimensions of the lenslet and CCD arrays, as shown in the schematic layout in Figure 4.

The average slope of each area of the wavefront that is sampled is determined from the focal length of each lens and the displacement of each image on the array relative to its position when a perfect test wavefront is used. The wavefront is computed from the slope data.

The method yields values for the local wavefront slopes. Two approaches, the zonal method and the modal method, can be used to fit the data to compute the wavefront. The choice depends on whether the estimate is a phase value in a local zone or a coefficient of an aperture function. In either case, the least squares method may be used for the phase reconstruction.[34]

The Shack-Hartmann test can achieve a high sensitivity and is commonly used with adaptive optic systems where a deformable mirror is adjusted to give an optimum shape wavefront.[35] The test has been applied to the measurement of wavefronts from diode lasers and to industrial infrared lasers. Michau et al. describe testing a collimated beam from a laser diode for space communication.[36] One advantage of the Shack-Hartmann test is that the system is relatively simple with few components and can be used with low coherence wavefronts. Another advantage is the speed of the measurement. By use of the CCD and software to analyse the spot positions, the wavefront error is determined immediately. This measurement can then be used in the feedback controls of adaptive optics.

Disadvantages include the fact that the local wavefront is determined from the slope averaged over the lenslet aperture. The lateral resolution of the wavefront is limited by the pitch of the lenslets in the array. Wavefront measurement accuracy is limited by the accuracy with which the centroids of the focused spots can be determined.

4.5 Measurements with a Shack-Hartmann sensor

4.5.1 General

There are several Shack-Hartmann systems that are commercially available and each will come with its own instructions for use. Some common aspects include those described in 4.5.2 to 4.5.5.

4.5.2 Wavefront dynamic range

The wavefront shape must lie within the dynamic range of the sensor. The dynamic range depends primarily on the geometry of the lens array, for example lenses of longer focal length produce greater lateral displacement of the spots for a given angular tilt of wavefront. This limits the angular range that can be detected because the spot from one lens translates to a region of the detector assigned to an adjacent lens. However manufacturers have evolved different techniques for identifying and tracking the spots and thus extending the dynamic range.

4.5.3 Alignment

To make the most of the dynamic range the sensor must be carefully aligned. It is usually best to fit the sensor head to a precision adjustable tip/tilt table. The sensor should be aligned to be normal to the incident beam. One manufacturer recommends placing an adjustable aperture in the beam to define a small area and placing a small plane mirror on the sensor. The sensor is then tilted until the spot transmitted by the aperture is reflected back on itself. If this procedure is not possible and it is necessary to use the sensor in an off-normal position then the normal incidence calibration may not apply and a new reference measurement should be taken.

4.5.4 Illumination levels

The level of illumination reaching the sensor must be adjusted to within the limits of the sensor. Modern sensors have software that shows the signal levels along with minimum, maximum and average values.

The irradiance level can be adjusted by inserting neutral density filters in front of the camera but if the filters are not of high quality they may introduce additional aberrations to the wavefront. In that case a reference measurement should be made with the filter in place and the measured aberrations subtracted from the test wavefront results.

Another way of ensuring the light levels are within limits is to adjust the camera gain and exposure time. Typically, a value of 80 % of the maximum enables accurate measurements to be made without the danger of saturating the sensor. Changing the camera gain may change the signal to noise ratio.

4.5.5 Calibration

4.5.5.1 General

The calibration of the system should be checked before making a measurement. Some manufacturers will supply a data file from a calibration check made beforehand. Alternatively a live check may be performed by illuminating with a wavefront of known form such as a spherical or plane wavefront to provide an absolute calibration. Where it is only required to monitor the change in a wavefront, a measurement may be made before and after the change without necessarily carrying out an absolute calibration.

4.5.5.2 Calibrating sphericity component

The performance of the sensor in measuring spherical wavefronts of different radii can be assessed by monitoring a wavefront emitted by a point source such as an optical fibre and making measurements at different distances from the source. It is desirable to use a very long precision slideway for this.[37]

5 Wavefront curvature sensors

5.1 General

Wavefront curvature sensing is a technique which uses local tilt values to calculate wavefront curvature and commonly finds applications with adaptive optics. It measures the local wavefront curvature, together with the wavefront tilts at the aperture edge in a direction perpendicular to the edge. A curvature sensor shown in Figure 5 consists of two image detectors which detect the irradiance distributions either side of the wavefront focus produced by the action of lens L on the wavefront W.[38]

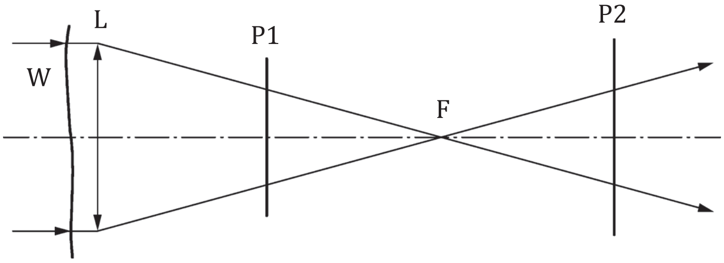


Figure 5 — Curvature sensing by measuring irradiance distributions either side of the focus

5.2 Wavefront curvature sensing and phase diversity techniques

Phase diversity techniques are a class of wavefront retrieval mechanisms that infer the wavefront from measurements of the intensity of the light as the beam propagates. Typically this involves the measurement of two images along the beam path, from which the intensity gradient is derived. Two