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Optics and photonics — Interferometric measurement of optical elements and optical systems —

Part 2:
Measurement and evaluation techniques

Optique et photonique — Mesurage interférométrique de composants et systèmes optiques —

Partie 2: Mesurage et techniques d'évaluation

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Foreword

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The procedures used to develop this document and those intended for its further maintenance are described in the ISO/IEC Directives, Part 1. In particular, the different approval criteria needed for the different types of ISO documents should be noted. This document was drafted in accordance with the editorial rules of the ISO/IEC Directives, Part 2 (see www.iso.org/directives).

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For an explanation of the voluntary nature of standards, the meaning of ISO specific terms and expressions related to conformity assessment, as well as information about ISO's adherence to the World Trade Organization (WTO) principles in the Technical Barriers to Trade (TBT) see www.iso.org/iso/foreword.html.

This document was prepared by Technical Committee ISO/TC 172, *Optics and Photonics*, Subcommittee SC 1, *Fundamental standards*.

This second edition cancels and replaces the first edition (ISO/TR 14999-2:2005) which has been technically revised. The main changes are:

a) Figure 1 has been updated.

b) A.1 has been aligned with the notation of ISO 14999-4.

c) Updated text referring to technologies that have evolved over the last 10+ years, such as lasers and detectors.

d) Improved clarity of the overall document (many minor edits made throughout the text).

A list of all parts in the ISO 14999 series can be found on the ISO website.

Any feedback or questions on this document should be directed to the user's national standards body. A complete listing of these bodies can be found at www.iso.org/members.html.

Introduction

A series of International Standards on Indications in technical drawings for the representation of optical elements and optical systems has been prepared by ISO/TC 172/SC 1, and published as ISO 10110 under the title *Optics and photonics — Preparation of drawings for optical elements and systems*. When drafting this standards series and especially its Part 5, *Surface form tolerances* and Part 14, *Wavefront deformation tolerance*, it became evident to the experts involved that additional complementary documentation was required to describe how the necessary information on the conformance of the fabricated parts with the stated tolerances can be demonstrated. Therefore, the responsible ISO Committee ISO/TC 172/SC 1 decided to prepare an ISO Technical Report on Interferometric measurement of optical wavefronts and surface form of optical elements.

When discussing the topics which had to be included into or excluded from such a Technical Report, it was envisaged that it might be the first time, where an ISO Technical Report or Standard is prepared which deals with wave-optics, i.e., in which the ray approximation of geometrical optics is no longer valid. As a consequence, fewer references than usual were available, which made the task more difficult.

Envisaging the situation, that the topic of interferometry has so far been left blank in ISO, it was the natural wish to now be as comprehensive as possible. Therefore, the committee held discussions, whether important techniques such as interference microscopy (for characterizing the micro-roughness of optical parts), shearing interferometry (e.g. for characterizing corrected optical systems), multiple beam interferometry, coherence sensing techniques or phase conjugation techniques should be included or not. Other techniques, which are related to the classical two beam interferometry, like holographic interferometry, Moiré techniques and profilometry were also mentioned as well as Fourier transform spectroscopy or the polarization techniques, which are mainly for microscopic interferometry.

In the end, the committee adopted the guideline to include what presently are common techniques used for the purpose of characterizing the quality of optical parts as described in the ISO 10110 series. The decision was made to complete a first Technical Report, and to then update it by supplementing new parts, as required.

The committee intends that this document covers the need for qualifying optical parts and complete systems regarding the wavefront error produced by them. Such errors have a distribution over the spatial frequency scale; in this document only the low- and mid-frequency parts of this error-spectrum are covered, not the very high end of the spectrum. These high-frequency errors can be measured only by microscopy, measurement of the scattered light or by non-optical probing of the surface.

A similar statement can be made regarding the wavelength range of the radiation used for testing. ISO 14999 considers test methods with visible light as the typical case. In some cases, longer wavelength infrared radiation (e.g. 10,6 µm CO_2 lasers) is used for testing rough surfaces after grinding. A variety of laser wavelengths might be used for transmitted wavefront testing of optical systems at the application wavelength (e.g. near infrared 1,55 µm or 1,06 µm, or ultraviolet 193 nm or 248 nm excimer lasers for microlithography optics). However, these are still rare cases, which are included in standards, that will not be dealt with in detail. The wavelength range outside these borders is not covered.

Optics and photonics — Interferometric measurement of optical elements and optical systems —

Part 2:
Measurement and evaluation techniques

1 Scope

This document gives fundamental explanations to interferometric measurement objects, describes hardware aspects of interferometers and evaluation methods, and gives recommendations for test reports and calibration certificates.

2 Normative references

There are no normative references in this document.

3 Terms and definitions

No terms and definitions are listed in this document.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

— ISO Online browsing platform: available at https://www.iso.org/obp

— IEC Electropedia: available at http://www.electropedia.org/

4 Measurement objects

4.1 Surfaces

4.1.1 Boundary surfaces of optical components

A common task in interferometry is measurement of the shape of a surface. This can be accomplished in two different ways. Either reflected light or the light transmitted through the surface could be used for the measurement.

Interferometric measurement is achieved by comparing the difference of two optical path lengths $\int nd$. Usually one path is called the reference path, the other the measurement path.

The resulting wave aberration, ΔW, for a displacement d of the surface, if measured in reflection, is $\Delta W = 2nd$. The same displacement measured in transmission results in the wave aberration $\Delta W = (n_2 - n_1)d$.

4.1.2 Reflection degree

The Fresnel reflection from the boundary between two different media, R, can be calculated from the refractive index n_1 and n_2 at the boundary surface.

$$R = \left(\frac{n_2 - n_1}{n_2 + n_1} \right) \tag{1}$$

For most optical glasses this value is between 4 % and 6 %, so an average of 5 % is usually a good estimate.

This reflection causes a loss of light from the transmitted wavefront at every surface. On the other hand, this reflection is often used for the measurement itself. To obtain maximum fringe visibility, or contrast, the two interfering beams should have approximately the same intensity. Changing the reflectivity of the beam splitter within an interferometer only changes the amount of light in the interference pattern and does not change the beam intensity ratio of the two beams because the light in both arms is transmitted through and reflected by the beam splitter once. If the measurement path and reference path are separated, as in a Mach-Zehnder or Twyman-Green set-up, it is usually possible to adjust the intensities of the light in both arms.

A major problem arises in a Fizeau interferometer if the reference surface has high reflectance, the result will be multiple beam interference fringes resulting in narrow fringes as in a Fabry-Perot interferometer. If sinusoidal fringes are required as for the evaluation by phase shifting interferometry, the reference surface should have low reflection and an element needs to be introduced between the reference and the measurement surface that will absorb light without distorting the wave aberration.

The issue is solvable, when using a wavelength shifting interferometer or short coherence interferometer.

4.1.3 Roughness

For interferometric measurement the roughness of the measured surface should not exceed a certain limit that is a fraction of the wavelength and of the difference of indices of refraction, if used in transmission.

4.1.4 Topology of the regions (discontinuous regions)

Difficulties may arise with interferometer software when the wavefront area has breaks in it (e.g. because it is split into segments by the mechanical supports of the secondary mirror of a mirror telescope). Problems are most severe with static fringe analysis software that depends strongly on using neighbouring points to determine the position and continuity of fringes. Software analysis of phase differences is not affected to the same extent as it is a point-by-point evaluation of wave aberrations.

Similar problems may occur if the wavefront area has a complicated outline.

4.1.5 Continuity of the surface; gradient of the surface

Due to the inherent ambiguity of $\pm n2\pi$ phase difference, it is not possible to measure any arbitrary surface shape uniquely. The evaluation of a smooth surface is usually correct, if the wave aberration between two resolvable points is less than π. This effectively limits the largest slopes (or highest step discontinuities) that can unambiguously be measured with the interferometer.

The gradient of the surface under test relative to the reference surface results in a gradient of the measured wave aberration and in high-density or closely spaced fringes. Interferograms cannot be evaluated, if the fringe separation is less than twice the distance of two resolvable points. Thus the local gradient of the imaged wavefront needs to be less than (0,5 λ)/(detector element spacing) for unambiguous phase recovery. If this condition is not possible by adjustment, or by changing the measurement set-up, compensating optics may be required in some cases.

Some of the problems caused by phase difference ambiguity can be solved by multiple wavelength interferometry.

4.1.6 Stiffness of mirrors; finite-element-calculations

An optic under test should not be deformed in a manner other than it would be deformed under its intended application. It can be difficult to notice whether an optic is deformed during the measurement by the test fixture, which holds the optic in place during the measurement. As a first indication of the influence of the test fixture, the object can be measured by using two or more different test fixtures to hold the optic in different ways. In case of any doubt, a finite-element calculation is recommended to evaluate the effect of deformation on the optic.

4.1.7 Temperature homogeneity of mirrors

During measurement the object should have a homogeneous temperature. Inhomogeneous temperatures can cause deformations. The thermal expansion coefficient of optical materials is rather high and the thermal conductivity of optical materials is very low. Sufficient time should be allowed for optics under test to reach thermal equilibrium. In some cases, this can take minutes, but in others it might require several hours to reach thermal equilibrium.

4.1.8 Examples of measurement objects

Items that can be measured by interferometry include optical flats, windows, raw glass, convex and concave mirrors, lenses, prisms, and optical systems.

4.2 Optical components in transmission

4.2.1 Single-pass versus double-pass testing

Transmitting optical components can be measured in single-pass or double-pass, depending on the interferometric set-up. Double-pass measurement increases the sensitivity by a factor of two but may also include the effect of the reflecting surface. In double-pass measurements consideration should also be given to the possibility that the returning light passes back through the component at different locations.

4.2.2 Windows (wavefront aberrations in transmission)

For windows the shape error of the surfaces is usually not important. Also, the measured transmitted wavefront will include the homogeneity of the material. Depending on the application, a certain amount of power may be tolerated separate from the other wave aberrations. Also, a tolerated wedge can be measured by interferometry. However, it can be more convenient to measure angular errors by different equipment.

4.2.3 Prisms (wavefront aberrations and angle error)

As in the case for windows, the wavefront aberrations and angular errors of prisms can be measured by different equipment. However, if the angular tolerances are in the interferometric region, and many parts are to be measured, it can be more convenient to measure both features by interferometry. In this case a fixed set-up, or a master specimen, is used as a reference.

4.2.4 Influence of temperature on the refractive index

For measurement of an optical component in transmission, it should be noted that not only the objects might be deformed by the thermal expansion but, also, that the refractive index of the material changes with temperature. Therefore, thermal settling of the test piece before testing is even more important.

4.3 Optical systems

4.3.1 Single-pass versus double-pass testing

Complete optical systems can be measured by interferometry in a manner similar to the testing of single components. It is, however, important that systems be measured in the same geometry as they were designed to be used. This can lead to a complicated set-up in single or double pass. For long systems tested in double pass and in the presence of severe aberrations, it is necessary to consider that the return light path can be considerably different from the incident light path.

4.3.2 Examination in the pupil

Interferometric measurements should be made in the exit pupil of the optical system.

4.3.3 Chromatic aberrations

If systems are measured at wavelengths different than those they are designed for, the effects caused by chromatic aberrations should be computed. There will be some systems, where the wave aberrations can be simply scaled by the ratio of the test and design wavelengths, whereas other systems are so different that a measurement is not possible.

For transmitted wavefront measurements with a wavelength-shifting interferometer, consider whether the classical refractive index or the group refractive index should be used to describe the medium.

4.4 Indirect examination of the function of optical elements

4.4.1 Examination with different wavelengths

In some cases, examination of flat optical elements is possible at wavelengths other than the application wavelength. In these cases, corrections can be scaled to the application wavelength. It should be noted, however, that inhomogeneities of optical materials may to some degree depend on the wavelength range. Because of the presence of chromatic aberrations no universal recommendation is possible.

4.4.2 Examination with different beam paths

It is preferred that the measurement set-up should be as similar as possible to the application. However, in some cases it may be more convenient to measure optical elements in a way that is different from their use. In this case, it may be difficult to find a correlation between the measured wave aberration and how the application is affected by these aberrations.

4.4.3 Tolerance range

Sometimes the relationship between the interferometric measurement and the tolerances of the measured objects is not clear. Usually the complete test set-up should be considered and, if possible, the sensitivity to measurement tolerances analyzed with finite-element calculations. Optical design calculations may also be used as an evaluation method.

5 Hardware aspects of an interferometer and test environment

5.1 General

The purpose of this clause is to acquaint the user with common issues associated with interferometric measurements that can affect the accuracy of measurements. It is a matter of fact that two different persons using the same hardware and doing their measurements in the same laboratory, will not necessarily achieve identical results with their measurements. The skilled user might achieve a highly accurate result, whereas the unskilled user might have severe errors in his result that he might not be aware of. It is important to keep in mind that good reproducibility of measurement is no guarantee for a correct result, because systematic sources of errors might have influenced the measured results. Knowledge about such possible influences, and how to avoid them, is what experimental skill is about.

Sources of errors in interferometric measurements include, for example:

- improper use of the measuring instrument, because the optical principles are not well understood, e.g. failure to image the surface under test onto the CCD camera of the interferometer;
- use of unsuitable fixtures to hold the test piece, inducing stress which causes bending;
- influence of gravity on the test piece;
- vibrations of the test set-up, which might induce phase-measuring errors;
- unsuitable use of polynomial fits with respect to the given shape of the aperture (for example due to some obscured parts of the circular shape) and adjacent subtraction of error terms like tilt and focus terms, due to a violation of the orthogonality assumption;
- presence of stable layers of air with different temperatures in the interferometer cavity, causing systematic low-order aberration;
- flipping (mirroring), or some other mismatch, of a calibration error map with respect to the actual orientation, shape or magnification of the measured field;
- influence of different temperature or different focus settings between calibration and measurement;
- use of test pieces that are not homogeneous in temperature and have a considerable coefficient of temperature expansion;
- adjustments with tilt or focus subtraction can lead to unnoticed misalignments.

These are only examples; although there are a much greater number of “typical” sources of error. The only way to overcome such types of error, which depend very much on the actual test situation and the demands for the final accuracy, is that the operator planning and assembling the test should be aware of possible influences on the accuracy of the measurement, which might be of an optical or mechanical nature.

Conceptually, it is very important not to believe blindly the results which the instrument shows. At the same time, it is equally important not to blame the instrument, or the principle of the interferometric measurement, if there are inexplicable results. Note that in the majority of cases the instrument shows the “correct” readings from what is presented to it, even if that is not the measurement task in question. If, for example, the measured error map does not rotate by 72° when the test piece is rotated physically by 72°, this might indicate that the reference surface may contribute a considerable amount to the total error. The support of the test piece can also influence the measurement, etc.

Another test might be to repeat the measurement after 1 h without touching anything in the meantime. If the results deviate from each other, the temperature of the surface under test or its support structure may have had an uneven temperature distribution in the first test. The time needed to achieve thermal stability adequate for the measurement can vary significantly, based on the part and fixture dimensions, coefficient of thermal expansion, dn/dT, thermal conductivity, heat capacity, initial temperature distribution, and the desired measurement accuracy. Also, the temperature in the laboratory might have changed, the instrument might have warmed up, etc.

Such tests are imperative in order to exclude at least the most common sources of error. It is strongly recommended to repeat a measurement at least three times and compare the results; this repetition should include the demounting and remounting of the part in the test set-up, as well as all the adjustments of the set-up and the settings of the interferometer. It is even better to repeat the whole test procedure on another day, and even by another operator.

All measurement conditions and settings should be documented and the final data sets should be stored in the computer in an organized way. Ideally, the documentation should be stored together with the measured data sets. Any further treatment like subtraction of tilt or even higher order (Zernike) functions, number of averages, any filtering like smoothing with a spatial low pass or median filter to remove “spikes”, should be documented and stored together with the data set. Such information is part of the result and when not given together with the measured surface map, the result is useless and cannot be used for proof of quality for the part under test.

5.2 Construction principles and influences on the quality of measurements

5.2.1 General

When the wavefront deviation of a test piece is measured by an interferometer, the test piece becomes part of the optics of the instrument. The auto-collimation condition should be met, as well as the condition to image the surface under test onto the detector. In order to achieve high flexibility of possible locations for the surface under test and for different test configurations, there will be stringent requirements on the spatial and temporal coherence of the light source that need to be fulfilled. These can easily be attained by use of a laser and, together with a very high intensity compared to other light sources, are the reason that the laser is the typical light source for interferometers.

One of the consequences of the very high coherence of lasers is that all kinds of imperfections, such as impurities of substrates, optical cements and coatings, tiny scratches, bubbles, holes, dust particles, micro-roughness of surfaces, which can occur at any part of the light path through the interferometer, are “collected” and are superimposed as an uncleanliness, i.e., unwanted amplitude and phase modulations of the wavefronts. The further away the disturbing defects are from an image plane of the detector, the more the defects are altered in their phase distributions due to Fresnel diffraction and in spatial frequency. A very narrow defect located on a surface near an image of the light source might spread out to a big size in the detector plane. The specification of optical parts used in an interferometer set-up therefore have to be much more stringent than in conventional optical instruments and depend on the position of the part in the ray path. For surfaces near the image of the light source (where the diameters of the ray bundles are small) ultra-high surface quality requirements should be maintained. Generally speaking, the higher the test accuracy needs to be, the more severe are the demands for the quality of all interferometer parts.

As discussed in ISO/TR 14999-1, it is very important to image the wavefront under test onto the detector plane. If the location of this wavefront relative to the instrument changes from one test set-up to another, a possibility of refocusing the detector to this new location should be provided. In some instruments, provision is made to alter the magnification with which the wavefront under test is imaged onto the detector. In some cases, this is done in fixed steps, in other cases this is done continuously over a certain range. On the other hand, it is necessary to attain a good optical wavefront-correction when “tailoring” the wavefronts in the instrument to the desired shape and at the same time realizing a good optical transfer function for the amplitude and phase when imaging the wavefront under test at the detector plane. An interferometer’s ability to transfer different spatial frequency features (with amplitudes a small fraction of a wavelength) to the detector is quantified with an instrument transfer function (ITF). This is also sometimes termed system transfer function (STF) or height transfer function (HTF). Definitions and methods for quantifying the ITF can be found in References [5], [6] and [7] and elsewhere in the literature.

All such possibilities and demands cause a certain amount of complexity of the optical layout of such an instrument, leading to optical systems with multiple surfaces. It is obvious that it is more difficult to keep the unwanted additional disturbances by the optical parts small when more optical parts are necessary to achieve the desired functionality. The skill of the designer of an instrument lies in finding the best compromise between the degree of aberration correction (keeping the wavefront errors with low spatial frequency small) and the degree of noise (i.e., high spatial frequency errors). The noise increases with every additional surface which might be necessary for aberration correction. Since the complexity of the optical layout grows with the universality of the use of the instrument, it is much easier to construct a high-quality single-purpose instrument.

Due to higher cost of production, and the deterioration in the appearance of the interferograms obvious to any customer, companies tend to minimize the number of optical elements and seek to achieve the best correction for wavefront aberrations. This might have consequences for the handling of the instrument. If, for example, the transmission sphere, used for spherical testing, is not aligned properly when attached to the instrument, coma and astigmatism might be introduced into the measured wavefront. If deviations in the alignment of the focus setting between calibration measurements and final measurements for the parts under test exist, this again might cause wavefront errors in the final results. While an instrument that incorporates more wavefront corrective components may be “robust” against higher order aberration errors, it may lead to measurement results with a higher amount of coherent noise due to the increased number of surfaces.

The opposing criteria for the way to design a laser interferometer require a compromise between wavefront quality, field correction, versatility on the one hand and number and location of surfaces on the other hand.

5.2.2 Intrinsic instrument errors and the principle of common path

The task gets more and more difficult when the errors, which have to be measured accurately, become smaller and smaller. It might be concluded from this that it would be nearly impossible to get reliable measuring results. Needless to say, it is necessary that the “intrinsic errors” caused by the instrument itself should be at least not higher than the errors caused by the test piece. Example: suppose the test piece is a well-polished spherical surface of a lens. The interferometer itself might include in total 12 lens surfaces and another 10 surfaces of plane plates. Therefore, it would be necessary to fabricate the 22 surfaces within the instrument to a degree of perfection that is at least 22 times better than that of the test piece in order to attain the same disturbance from the instrument (i.e. “intrinsic errors”) and from the test piece. Or, it might be concluded that a factor 4 to 5 would be sufficient for randomly distributed errors. Even in the latter case, it would be nearly impossible to fabricate and maintain an instrument with such a degree of perfection.

This argument is both right and wrong. It is the principle of interference that errors common to both waves, i.e., the test wave and the reference wave, cancel out. The ultimate use of this principle is apparent in the Fizeau-type interferometer, where all but the last surface before the surface to be tested and the air between these two surfaces are common to both waves. The quantity that is measured by a Fizeau interferometer is the optical path difference between the two surfaces facing each other (the “optical thickness distribution” of the air gap; this includes the distribution of the refractive index of the air). So far the argument is wrong; but it is right for very small-scale errors. It is never possible for the rays to travel exactly the same path, so the principle of “common path” with cancellation of common errors is always violated, if high spatial frequency noise is in demand. So, even if Fizeau interferometers are more robust for errors with low spatial frequencies, this is not the case for coherent noise.

In order to check the sensitivity of an instrument to alignment errors as well as for intrinsic high frequency noise, the following two procedures can be useful.

a) The following procedure should be repeated with different orientations of the fringes and also with the highest number of fringes the instrument is capable of measuring. This test is one measure for the robustness of the instrument against misalignments of all kinds. Proceed as follows.

    1) Place a reference flat in front of the transmission flat of the instrument and adjust for about 25 fringes of tilt.

    2) Perform a measurement and store the result.

    3) Adjust for zero-fringes and perform another measurement.

    4) Subtract the step 3 measurement data from the step 2 data and compute the Zernike terms for the resulting difference-data set; besides other errors, the induced wavefront tilt with respect

to the optical axis make visible the optical wavefront aberrations which go along with the small angle of the test wave.

b) The second procedure checks the intrinsic high frequency noise and therefore the ability to detect small-scale errors which normally go along with very small amplitudes. Proceed as follows.

   1) Take the data of the difference from the measurement on-axis and the measurement with the 25 fringes of tilt.

   2) Subtract the first 36 Zernike terms. The remaining surface map shows mainly the intrinsic coherent noise of the instrument.

   3) When “spikes”, which occur at the boundary of the measured part, are removed, the rms value is a quality number for the intrinsic noise. This noise should be uncorrelated when the experiment is repeated with different orientations of the fringes and therefore reduce with the square root law, if measurements with different fringe orientations are averaged and the difference of those averages are calculated instead of the difference of only two measurements.

Together with these tests, it is recommended that two other simple checks be performed to assess the proper alignment of the instrument:

The collimation of the plane-wave leaving the system can be checked with the help of a thick (>30 mm) plane-parallel plate of known good optical quality by inserting the plane parallel plate with an incident angle of 45° into the beam and projecting the lateral shearing interferogram onto a screen. If the plate has no wedge-angle, no fringes should be visible, but they will be present if the wavefront from the interferometer converges or diverges.

The adjustment for the alignment reticle, or other means for the alignment of the beam, can also be checked using a corner-cube mirror or prism of known good quality. The returning beam should be incident precisely at the centre of the alignment device. This is also a method for adjusting the reference surface perpendicular to the beam. By tilting the reference surface, the interference fringes formed by the reference wave and a wave reflected by the triple-mirror (having three surfaces with angles of 90° between them) should be made as broad as possible.

5.2.3 Optical compensation of errors

It is a very useful property of two-beam interference that the physical principle can help to suppress the errors caused by component parts of the interferometer. If the two interfering beams experience the same disturbances when passing through the optical parts, the wavefront errors impressed on them are identical and cancel out in the final wavefront difference. Therefore, the two wavefronts should travel almost the same path through the instrument so ensuring that “optical compensation” of errors takes place. This is achieved best by the arrangement of a Fizeau test set-up, where the test surface and the reference surface face each other without any component in between. This cancellation is not necessarily perfect, if there are deviations in the optical path when the beams are tilted with respect to each other.

Another deviation from perfect symmetry of the interfering waves is due to the imaging conditions of the two surfaces in question onto the detector. The two surfaces in a Fizeau configuration, the test surface and the reference surface, cannot both be imaged exactly onto the detector surface at the same time. Normally, the reference surface is larger than necessary, so that the surface under test defines the final aperture for the size of the interferogram. In this case, no errors are introduced to a first order by Fresnel diffraction at the boundary of the reference surface, when this boundary is larger than the diameter used. Nevertheless, there is another higher-order error, which will be explained in conjunction with the testing of spherical surfaces with a so-called “Fizeau transmission sphere”.

Figure 1 shows the optical conditions when testing a spherical surface B with respect to a reference surface A. In this example, it is assumed that the reference surface A (this is the last surface of the transmission sphere) as well as the test-surface B are both concave. The apexes of the surfaces are called S_A and S_B. The Fizeau cavity is set up correctly when both surfaces are arranged so that they