TECHNICAL REPORT

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

Part 3: Calibration and validation of interferometric test equipment and measurements

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

Partie 3: Étalonnage et validation des équipements d'essai interférométrique

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Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

International Standards are drafted in accordance with the rules given in the ISO/IEC Directives, Part 2.

The main task of technical committees is to prepare International Standards. Draft International Standards adopted by the technical committees are circulated to the member bodies for voting. Publication as an International Standard requires approval by at least 75 % of the member bodies casting a vote.

In exceptional circumstances, when a technical committee has collected data of a different kind from that which is normally published as an International Standard (“state of the art”, for example), it may decide by a simple majority vote of its participating members to publish a Technical Report. A Technical Report is entirely informative in nature and does not have to be reviewed until the data it provides are considered to be no longer valid or useful.

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. ISO shall not be held responsible for identifying any or all such patent rights.

ISO/TR 14999-3 was prepared by Technical Committee ISO/TC 172, *Optics and photonics*, Subcommittee SC 1, *Fundamental standards*.

ISO 14999 consists of the following parts, under the general title *Optics and photonics — Interferometric measurement of optical elements and optical systems*:

— *Part 1: Terms, definitions and fundamental relationships* (Technical Report)

— *Part 2: Measurement and evaluation techniques* (Technical Report)

— *Part 3: Calibration and validation of interferometric test equipment and measurements* (Technical Report)

— *Part 4: Interpretation and evaluation of tolerances specified in ISO 10110*

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 tolerances,* it became evident to the experts involved that additional complementary documentation is 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 or excluded into 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. that is based more in the field of physical optics than in the field of geometrical optics. As a consequence only 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 there was discussion, 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 order to complement ISO 10110, the guideline adopted was to include what nowadays are common techniques used for the purpose of characterizing the quality of optical parts. Decision was made to complete a first Technical Report, and to then update it by supplementing new parts, as required. It is very likely that more material will be added in the near future as more stringent tolerances (two orders of magnitude) for optical parts and optical systems become mandatory, when dealing with optics for the EUV range (wavelength range 6 nm to 13 nm) for microlithography. Also, testing optics with EUV radiation (the same wavelength as they are later used, e.g. at-wavelength testing) can be a new challenge, and is not covered by any current standards.

This part of ISO 14999 should cover 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 part of ISO 14999 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, infrared radiation from CO_2-lasers in the range of 10,6 µm is used for testing rough surfaces after grinding or ultraviolet radiation from excimer-lasers in the range of 193 nm or 248 nm is used for at-wavelength testing of 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 3: Calibration and validation of interferometric test equipment and measurements

1 Scope

This part of ISO 14999 discusses sources of error and the separation of errors into symmetric and non-symmetric parts. It also describes the reliance of measurements on the quality of a physical reference surface and the development of test procedures capable of achieving absolute calibration.

2 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

2.1
perfect shape
mathematically represented figure of the optical surface

2.2
surface error
deviation from the perfect shape of the surface under test, including the influence of gravity and support

2.3
wavefront error
error of the interferometric wavefront corresponding to the surface error

2.4
absolute test
method, which gives the wavefront error of the test piece with respect to a perfect shape, not to a bodily reference

2.5
quasi-absolute test
method, which gives the wavefront error, limited to special error types, of the test piece with respect to a perfect shape, not a bodily reference

3 Systematical investigation of test equipment, test set-up and test environment for sources of errors

3.1 General

The objective of a measurement is to determine the value of the measurand, that is the specific quantity subject to measurement. In the general context of testing and calibration laboratories, the measurand may cover many different quantities, but in the context of this Technical Report it is an optical parameter, such as wavefront shape, associated with optical elements or optical systems. A measurement begins with an appropriate specification of the measurand, the generic method of measurement and the specific detailed measurement procedure.

No measurement is perfect and the imperfections give rise to error of measurement in the result. Consequently, the result of a measurement can only be an approximation to the value of the measurand and it is only complete when accompanied by a statement of the uncertainty of that approximation. Because of measurement uncertainty the *true value* can never be known.

Uncertainty of measurement comprises many components. Some may be evaluated from the statistical distribution of the results of a series of measurements and can be characterized by experimental standard deviations. The other components are based on experience or other information and are evaluated from assumed probability distributions. They are also characterized by (equivalent) standard deviations.

Random errors arise from random variations of the observations, due to random effects from various sources affecting measurements taken under nominally the same conditions. These produce a scatter around the mean value of a series of measurements. They cannot be eliminated but the uncertainty due to their effect can be reduced by increasing the number of observations and applying statistical analysis.

Systematic errors arise from systematic effects, that is an effect on the measurement result arising from a quantity that is not included in the measurement specification of the measurand but influences the result. These remain unchanged when the measurement is repeated under the same conditions. Examples might be drifts during measurements or since the last calibration of a measuring instrument, zero errors in scales, errors in assumed expansion coefficients, etc. Their effect is to introduce a displacement, or bias, between the value of the measurand and the experimentally determined mean value. They cannot be eliminated but may be reduced by making corrections for the *known extent* of an error due to a recognized systematic effect.

The total uncertainty of measurement is a combination of all identified component uncertainties. Careful consideration of each measurement involved in the test or calibration is required to identify and list all the factors that contribute to the overall uncertainty. This is a very important step that requires a good understanding of the measurement equipment, the process of the test or calibration and the influence of the environment.

Having identified the component uncertainties, the next step is to quantify them by appropriate means. An initial approximate quantification can be valuable in identifying components that are negligible, less than one fifth the largest component, and not worthy of more rigorous evaluation. Uncertainties from random sources, classified as *Type A*, may be quantified by calculation of the standard deviation of repeated measurements. Uncertainties from systematic sources, classified as *Type B*, require an exercise of judgement by the metrologist, using all relevant information on their possible variability, to evaluate effective standard deviations.

Subsequent calculations are made simpler if, wherever possible, all components are expressed in the same way, e.g. as a proportion, or in the same units as used for the reported result.

3.2 Sources of uncertainty

There are many possible sources of uncertainty, which will depend on the technical discipline involved. However, the following general points will apply to many areas of optical testing and calibration:

— incomplete definition of the test; the requirement may not be clearly described in sufficient detail;

- imperfect realization of the test procedure; even when the test conditions are clearly defined, it may not be possible to produce the theoretical conditions in practice due to imperfections in the systems used;
- personal bias in the reading of analogue instruments and scales;
- instrument resolution or discrimination threshold, errors in scales;
- values attributed to measurement standards and reference artifacts;
- changes in characteristics or performance of a measuring instrument or reference artifact since the last calibration;
- approximations and assumptions incorporated in the measurement method and procedure;
- random effects in repeated measurements.

These sources are not necessarily independent and, in addition, unrecognized systematic effects may exist that cannot be taken into account but contribute to the error. It is for this reason that interlaboratory comparisons, measurement audits and internal cross-checking of results by different means are undertaken.

NOTE Sources of uncertainty specific to the interferometric evaluation of optical elements and optical devices will be included as they become identified.

3.3 Combination of uncertainties

Once the uncertainty contributions associated with a measurement process have been identified and quantified, it is necessary to combine them in some manner in order to provide a single value of uncertainty that can be associated with the measurement result.

There is no *correct way* of combining uncertainties. The ISO *Guide to the expression of uncertainty of measurement,* known as the *GUM*, is the accepted method for most laboratories and accreditation bodies, but it is only a guide, a set of conventions.

By using a predetermined set of conventions, such as presented in *the GUM*, laboratories and their clients are able to compare results from different sources in a meaningful manner. This is also true of uncertainties passed down from national standards institutions and secondary standards laboratories.

The combination process may be summarized as follows:

a) individual uncertainties are evaluated by the appropriate method and each is expressed as a standard deviation, referred to as a standard uncertainty;

b) the individual standard uncertainties are combined, by the root of the sum of squares method, to produce an overall value of uncertainty, known as the combined standard uncertainty;

c) an expanded uncertainty is obtained by multiplying the combined standard uncertainty by a coverage factor, k. The choice of factor is based on the level of confidence required. A value of $k = 2$ is usually chosen, corresponding to a confidence level of approximately 95 %.

There are some exceptions to this general guidance. Reference should be made to the *GUM* for further information.

4 Separation of errors into rotationally symmetric and non-rotationally symmetric terms

4.1 General

The separation of errors into rotationally symmetric and non-rotationally symmetric terms is a powerful tool in practice as it makes possible the collection of a lot of information by simple means. It should be used with care because it does not determine the rotationally symmetric errors of the test piece. Nevertheless in practice very often rotationally symmetric error terms do not influence the results as much as non-rotationally terms does.

Subclauses 4.2 to 4.4 establish the procedure to separate measured wavefront errors of optical components into rotationally symmetric and non-rotationally symmetric terms to determine the non-rotationally symmetric surface errors of the test piece in an absolute sense.

The method is applicable to all optical surfaces with rotationally symmetric shape, including flats, spheres, and aspheres. It is also applicable to test optical components or systems in transmission.

The method is not applicable to optical surfaces without rotationally symmetric shape, e.g. off-axis aspheres. It is not applicable to determine the rotationally symmetric errors of the test piece in an absolute sense.

4.2 Principle

Two beam interferometers used for wavefront testing always measure the difference between the wavefront errors of the test piece and the wavefront errors of the interferometer which can not be separated by a single measurement. The interferometer errors include for example errors of the reference surface, errors of the transmission spheres or compensation optics. To determine the errors of the test piece, reference standards or so-called absolute tests shall be used. But there are a few well known procedures available for practical usage. The best known of the absolute tests, which do not need any auxiliary optics, is the three-position test [1] for spheres with accessible focus. But there are no easy and cheap solutions for absolute tests of flats, convex spheres, aspheres or optical components in transmission.

A quasi-absolute test of the non-rotationally symmetric wavefront errors can be based on the measurements of the test piece under different angles of rotation (θ, Figure 1) and on the error

$$P(r,\theta) = P_{\mathrm{R}}(r) + P_{\mathrm{NR}}(r,\theta) \quad (1)$$

where

$P_{\mathrm{R}}(r)$ is the rotationally symmetric term;

$P_{\mathrm{NR}}(r,\theta)$ is the non-rotationally symmetric term.

If the interferometer error is also split into a rotationally symmetric term $T_{\mathrm{R}}(r)$ and a non-rotationally symmetric term $T_{\mathrm{NR}}(r,\theta)$, the measured wavefront error can be expressed as

$$W = T_{\mathrm{R}} + P_{\mathrm{R}} + P_{\mathrm{NR}} \quad (2)$$

as sum of all the rotationally and non-rotationally symmetric terms.

It can be shown [2] [3] [4], that rotating a wavefront to N (where N = 2,3,...) equally spaced positions at $2\pi / N$ intervals and then averaging the data reduces to zero all non-rotationally symmetric terms except those of order $kN\theta$, where k = 1,2,...

This can be used to separate the non-rotationally symmetric errors of the test piece by measuring N rotational positions and averaging the results. Explicitly, the procedure can be written as a series of measurements W_i, i = 1,..,N:

$$W_1 = T_R + T_{NR} + P_R + P_{NR}^1 \quad (3)$$

$$W_2 = T_R + T_{NR} + P_R + P_{NR}^2$$

etc.

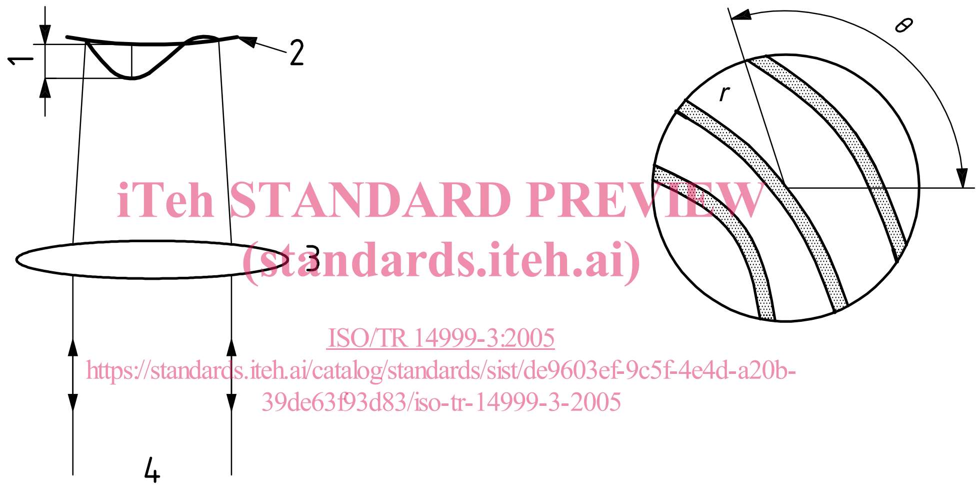
By averaging these measurements to reduce the non-rotationally symmetric terms of the test part to zero except those of order $kN\theta$, the following is obtained:

$$W_A = T_R + T_{NR} + P_R + P_{NR}^{kN\theta} \quad (4)$$

Thus,

$$W_1 - W_A = P_{NR} - P_{NR}^{kN\theta} \quad (5)$$

which may be subtracted from any of the measurements W_i, appropriately orientated, to give the non-rotationally symmetric terms of the test piece except those of order $kN\theta$.



a) Test set-up

b) Interferogram

Key

1 surface error $S(r,\theta)$

2 perfect shape

3 lens

4 plane wave from interferometer

The relation between the surface error S and the measured wavefront error P is $P = 2\,S$.

Figure 1 — Schematic diagram of an interferometric test set-up for testing a convex surface in reflection

If the data of the single measurements are rotated back before averaging, then the following are obtained:

$$W_B = T_R + T_{NR}^{kN\theta} + P_R + P_{NR} \quad (6)$$

and

$$W_1 - W_B = T_{NR} - T_{NR}^{kN\theta} \quad (7)$$

which is the non-rotationally symmetric term of the interferometer errors except those of order $kN\theta$.

4.3 Apparatus

The minimum test apparatus required to perform the specified test procedure is listed below.

4.3.1 Interferometer, with digital data readout.

4.3.2 Qualified test set-up.

4.3.3 Rotation stage, for the test piece.

4.3.4 Evaluation software, with the ability to average and difference (rotate) wave front data.

4.4 Procedure

The test piece shall be measured in $N \geqslant 4$ equally spaced rotational positions. Proceed as follows.

a) Measure the test piece in the first rotational position and store the wavefront data, piston and tilt may be subtracted.

b) Rotate the test piece about $2\pi / N$, $N \geqslant 4$, and repeat the measurement. Store the wavefront data.

c) Repeat step b) measuring N rotational positions in total.

d) Calculate the average of the N measurements and store the averaged wavefront data.

e) Subtract the result from the measurement obtained in a) and store the final result.

5 Measurement relying on the quality of a physical reference surface

5.1 Planes

5.1.1 General

In this case, there are

a) a plane master as reference mirror, and

b) a roughly plane sample, or optical system emitting a plane wavefront, to be measured.

Incidence beams are propagated as plane wavefronts under quasi normal incidence onto the master and the sample. Both surfaces reflect the wavefront modified by their surface defaults. The interferogram is generated by the distorted emergent wavefronts and contains the required information.

As described, adjustment of the relative position of the master surface and the sample allow the user to modify the interference pattern.

— By tilting, the inter-fringe spacing, i.e. the sensitivity of the measurement, can be enhanced or reduced (interval between two fringes represents a mechanical gradient of $\lambda/4$ on the sample).

— By translation (translation parallel to the optical axis), one can enhance a small and local default, by placing a fringe ramp on it.

Because the beams reflect only once from the reference mirror and from the measured object, the interference pattern cannot emphasize a small defect. The user should note that the Michelson interferometer is not able to provide information about surface errors to much better than $\lambda/10$.

5.1.2 Measurement relying on a plane master

5.1.2.1 Perfect plane master

For some applications, the plane master may be considered perfect, or assumed to be of a quality at least ten times better than the sample.

The user may then consider the interferogram as generated by a perfect wavefront (returning from the master) and an aberrated one, coming back from the sample. The aberrations of this wavefront, made visual by the interferogram, can qualify the sample.

5.1.2.2 Imperfect plane master

In many applications, the plane master cannot be considered perfect in comparison to the sample. The user shall then consider the interferogram as being the summation of the defaults of both surfaces.

In order to determine amplitudes and positions of the defaults on the sample and on the master, the user can compare to the first measurement one or more measurements generated by

— a translation of the master (with respect to the sample) in its surface plane;

— a rotation of the master (with respect to the sample) around the optical axis.

The user

— can create more than one translation, in more than one direction;

— can generate more than one rotation; and

— can combine translation(s) and rotation(s).

See Figures 2 and 3.

By comparing the different interference patterns issuing from the different relative positions, the user may determine the localization and amplitude of the defects (remembering that an interferogram represents the algebraic addition of aberrations).

5.1.2.3 Determination of plane master quality

The plane master to be used as a reference shall be qualified. This may be made with a second plane mirror (or better with two additional plane mirrors) of the same quality.

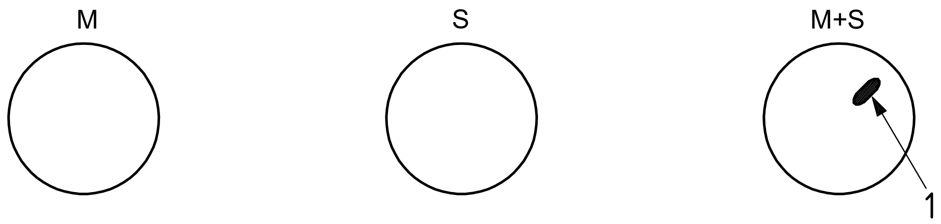
The quality determination is achieved using the procedure described in 5.1.2.2, by carrying out measurements with different combinations.

EXAMPLE With three-plane mirrors available, the user tests No. 1 against No. 2, No. 1 against No. 3, No. 2 against No. 3, and extracts the mapping of the objects No. 1, No. 2, No. 3. This is referred to as the “three-planes method” (see 6.2).

5.1.3 Calibration certificate

Commercially made interferometers and ancillary reference plane surfaces should come with fully authenticated calibration documents.

A calibration certificate for a reference surface should indicate the departure from flatness, and should also contain detailed mapping of the position and size of defects.



Key

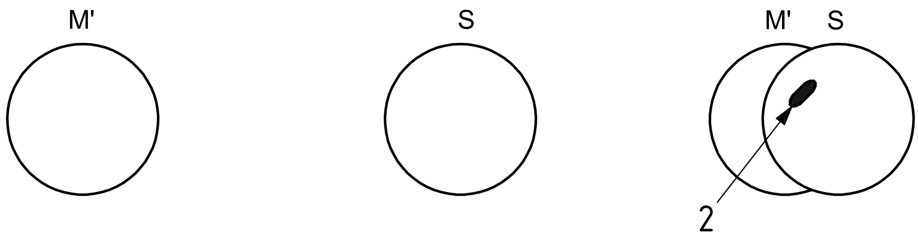
1 information 1

M master in initial position

S sample in initial position

M+S initial interference pattern

a) Observations at initial positions



Key

2 information 2

M' master after translation

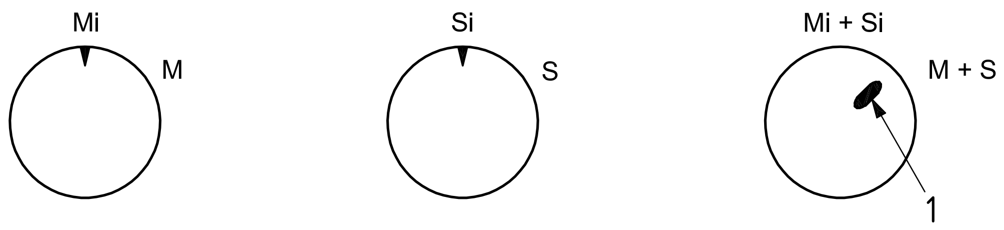
S sample

M', S second interference pattern

b) Observations after a translation of master

The master and sample can be individually observed by the introduction of an opaque screen in the interferometer arms. Translation vectors can be carried by the master and/or the sample. Direction and length of the vectors are chosen by the user. The user can execute one or more translations. Interference patterns are generated by the algebraic summation of the defects present on both surfaces. The interference pattern gives information about both surfaces. The user can mix effects from translation(s) and rotation(s); see Figure 3.

Figure 2 — Examples of interference patterns and translation effects



Key

1 information 1

M master in initial position

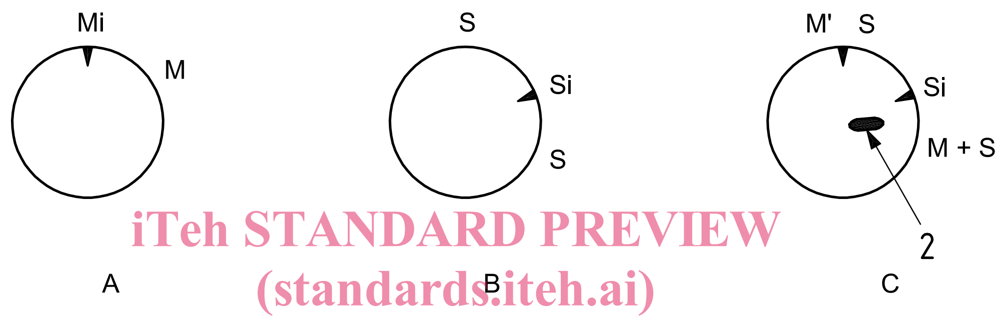
Mi master index

S sample in initial position

Si sample index

M+S, Mi+Si initial interference pattern

a) Observations at initial positions



Key

2 information 2

A master

B sample after rotation

C second interference pattern

b) Observations after a rotation of sample

The master and sample can be individually observed by the introduction of an opaque screen in the interferometer arms. Rotations can be carried out on either the master and/or the sample. Rotation angles are chosen by the user. The user can execute one or more rotations. Interference patterns are generated by the algebraic summation of defects present on both surfaces. The interference pattern gives information about both surfaces. The user can mix effects from rotation(s) and translation(s); see Figure 2.

Figure 3 — Examples of interference patterns and rotation effects

5.2 Spheres

5.2.1 General

The optical quality of concave and convex wavefronts can be analysed relative to a physical spherical surface of known (calibrated) quality, with the usual reservations in relation to the source coherence.

Both a spherical wavefront and spherical reference surface have a centre of curvature.