ASME B89.1.8-2011

Performance Evaluation of Displacement-Measuring Laser Interferometers

AN AMERICAN NATIONAL STANDARD

The American Society of Mechanical Engineers

INTENTIONALLY LEFT BLANK

ASME B89.1.8-2011

Performance Evaluation of Displacement-Measuring Laser Interferometers

AN AMERICAN NATIONAL STANDARD

The American Society of Mechanical Engineers

Three Park Avenue • New York, NY • 10016 USA

Date of Issuance: March 30, 2012

This Standard will be revised when the Society approves the issuance of a new edition.

ASME issues written replies to inquiries concerning interpretations of technical aspects of this Standard. Periodically certain actions of the ASME B89 Committee may be published as Cases. Cases and interpretations are published on the ASME Web site under the Committee Pages at http://cstools.asme.org/ as they are issued.

Errata to codes and standards may be posted on the ASME Web site under the Committee Pages to provide corrections to incorrectly published items, or to correct typographical or grammatical errors in codes and standards. Such errata shall be used on the date posted.

The Committee Pages can be found at http://cstools.asme.org/. There is an option available to automatically receive an e-mail notification when errata are posted to a particular code or standard. This option can be found on the appropriate Committee Page after selecting "Errata" in the "Publication Information" section.

The American Society of Mechanical Engineers
Three Park Avenue, New York, NY 10016-5990

CONTENTS

FOREWORD

Laser interferometry has become the preferred way to measure machine tool and coordinate measuring machine (CMM) linear displacement accuracy. Laser interferometers are also used as the main incremental radius-measuring devices in other dimensional measuring systems, such as laser trackers. The laser interferometer is preferred because of its versatility, portability, robustness, high bandwidth, and high accuracy, and because the laser frequency can be measured with a high degree of accuracy relative to a He–Ne iodine stabilized laser, which, for all practical purposes, may be considered to be an intrinsic length standard. The vacuum laser wavelength, the basic unit of measure, is a direct function of this frequency. Commercial instruments based on laser interferometry offer an extremely high degree of measurement accuracy to the user.

This Standard is written to help users evaluate the accuracy of laser interferometer systems. A folded common path test is included to permit users to functionally compare systems for accuracy, even if the laser systems use different wavelengths or measurement techniques. A measurement uncertainty table is included to allow users to evaluate a measurement or compare competing laser systems. A Nonmandatory Appendix covering best practices gives the user guidance in the proper application of laser systems to practical incremental distance measurement.

This Standard was approved by the American National Standards Institute on July 15, 2011.

ASME B89 COMMITTEE
Dimensional Metrology

(The following is the roster of the Committee at the time of approval of this Standard.)

CORRESPONDENCE WITH THE B89 COMMITTEE

General. ASME Standards are developed and maintained with the intent to represent the consensus of concerned interests. As such, users of this Standard may interact with the Committee by requesting interpretations, proposing revisions, and attending Committee meetings. Correspondence should be addressed to:

Secretary, B89 Standards Committee
The American Society of Mechanical Engineers
Three Park Avenue
New York, NY 10016-5990
http://go.asme.org/Inquiry

Proposing Revisions. Revisions are made periodically to the Standard to incorporate changes that appear necessary or desirable, as demonstrated by the experience gained from the application of the Standard. Approved revisions will be published periodically.

The Committee welcomes proposals for revisions to this Standard. Such proposals should be as specific as possible, citing the paragraph number(s), the proposed wording, and a detailed description of the reasons for the proposal, including any pertinent documentation.

When appropriate, proposals should be submitted using the B89 Project Initiation Request Form.

Proposing a Case. Cases may be issued for the purpose of providing alternative rules when justified, to permit early implementation of an approved revision when the need is urgent, or to provide rules not covered by existing provisions. Cases are effective immediately upon ASME approval and shall be posted on the ASME Committee Web page.

Requests for Cases shall provide a Statement of Need and Background Information. The request should identify the Standard, the paragraph, figure or table number(s), and be written as a Question and Reply in the same format as existing Cases. Requests for Cases should also indicate the applicable edition(s) of the Standard to which the proposed Case applies.

Interpretations. Upon request, the B89 Committee will render an interpretation of any requirement of the Standard. Interpretations can only be rendered in response to a written request sent to the Secretary of the B89 Standards Committee.

The request for interpretation should be clear and unambiguous. It is further recommended that the inquirer submit his/her request in the following format:

Subject: Cite the applicable paragraph number(s) and the topic of the inquiry.

Edition: Cite the applicable edition of the Standard for which the interpretation is being requested.

Question: Phrase the question as a request for an interpretation of a specific requirement suitable for general understanding and use, not as a request for an approval of a proprietary design or situation. The inquirer may also include any plans or drawings, that are necessary to explain the question; however, they should not contain proprietary names or information.

Requests that are not in this format may be rewritten in the appropriate format by the Committee prior to being answered, which may inadvertently change the intent of the original request.

ASME procedures provide for reconsideration of any interpretation when or if additional information that might affect an interpretation is available. Further, persons aggrieved by an interpretation may appeal to the cognizant ASME Committee or Subcommittee. ASME does not "approve," "certify," "rate," or "endorse" any item, construction, proprietary device, or activity.

Attending Committee Meetings. The B89 Standards Committee regularly holds meetings that are open to the public. Persons wishing to attend any meeting should contact the Secretary of the B89 Standards Committee.

PERFORMANCE EVALUATION OF DISPLACEMENT-MEASURING LASER INTERFEROMETERS

1 SCOPE

This Standard establishes requirements and methods for the specification, evaluation, setup, and use of laser interferometers. This Standard will explicitly discuss only single-pass optics and a single axis of linear displacement measurement.

The Standard is currently limited to ionized gas laser interferometer systems. Only single-color lasers will be considered in this edition of the Standard. Single color will include both homodyne systems and heterodyne systems (see Nonmandatory Appendix E) where all operating frequencies lie within a Doppler-broadened frequency band associated with one specific atomic transition or Zeeman multiplet. Diode laser systems, chirp systems, and two-color interferometers may be included in future editions of this Standard. It should be noted that the folded common path comparison technique of this Standard could be used to compare any of the above systems to a standard He–Ne laser interferometer.

Testing of laser interferometers as described in this Standard has bearing on a number of other standards, such as ASME B89.4.19, ASME B5.54, ASME B5.57, ISO 230-1, ISO 230-2, ISO 230-3, and ISO 230-6 (see references [1–7] in section 7).

2 DEFINITIONS

This section contains brief definitions of the majority of technical terms used in this Standard. Omissions should be reported to ASME. In this section, some definitions have been taken from the International Vocabulary of Metrology (VIM) [8], others are taken from the Guide to the Expression of Uncertainty in Measurement (GUM) [9], and some are taken from ASME B89 or ASME B5 standards as indicated. References to all of these standards are given in section 7.

Abbe offset: the instantaneous value of the perpendicular distance between the displacement-measuring system of a machine (scales) and the measurement line where the displacement in that coordinate is being measured. A schematic illustration of this concept is shown in Fig. 2-1.

Abbe offset error: the measurement error resulting from angular motion of a movable component and an Abbe offset between the scales measuring the motion of that component and the measurement line (see Fig. 2-1).

accuracy [8]: the closeness of agreement between a measured quantity value and a true quantity value of a measurand. See reference [8] for a detailed discussion.

air dead path: distance imbalance between the interferometer reference and measurement arms when the laser system readout is set to zero. If the refractive index of the air within the interferometer changes during the measurement, there will be a measurement error unless the laser system includes a dead path correction capability.

air turbulence: regions of varying refraction in air, usually caused by thermal gradients. Air turbulence is a common source of fluctuations in the reading of an interferometer. This weakens the signal and, if severe enough, interrupts the measurement.

back-to-back test: a test for comparing the performance of two laser systems arranged in a back-to-back configuration, as defined in Nonmandatory Appendix B.

beamsplitter: optical component in an interferometer that divides the light beam into reference and measurement beams. In most interferometer designs, the beamsplitter is also used to recombine the reference and measurement beams on their return so that interference fringes may be detected or observed.

calibration [8]: an operation that, under specified conditions, first establishes a relationship between the quantity values with measurement uncertainties provided by measurement standards and corresponding indications with associated measurement uncertainties, then uses this information to establish a relation for obtaining a measurement result from an indication. See reference [8] for a detailed discussion.

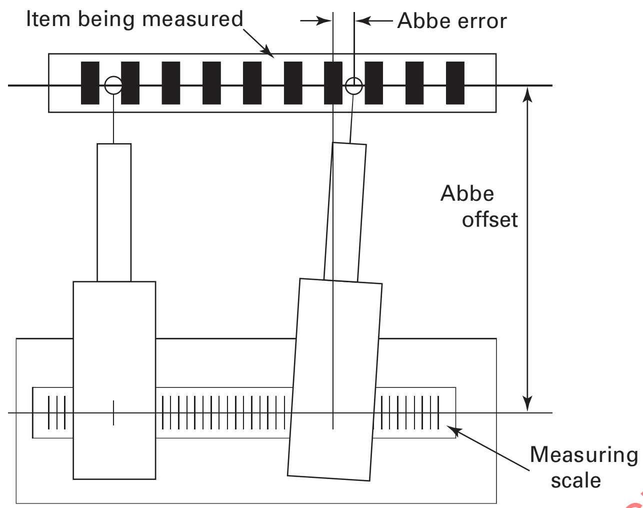
chirp system: a laser system employing a swept laser frequency to determine absolute distance.

coefficient of thermal expansion [10]: the rate of change of length of a body with respect to temperature.

common optics test: a test for comparing the performance of two laser systems where both lasers share a single set of external optics, as defined in Nonmandatory Appendix B.

compensated back-to-back test: a test for comparing the performance of two laser systems arranged in a special back-to-back configuration that compensates for

Fig. 2-1 Schematic Illustration of the Abbe Offset



changes in air refractive index, as defined in Nonmandatory Appendix B.

control artifact: an artifact that is measured periodically to establish process control. (See also *process control*.)

corner cube: see *cube corner*.

cosine error: a measurement error due to a small misalignment between two axes. Within the context of this Standard, cosine error primarily refers to the error, when measuring a displacement with an interferometer, that arises from misalignment between the direction of the laser beam and the direction of displacement of the retroreflector. It is defined as $L[\cos(\theta) - 1] \approx -L\theta^2/2$, where θ is the misalignment angle, L is the true displacement, and the angle θ is assumed to be small. The term "cosine error" is also used when a part is misaligned with the axis of measurement, and in this situation the error has the opposite sign.

coverage factor [9]: numerical factor used as a multiplier of the combined standard uncertainty to obtain an expanded uncertainty.

NOTE: A coverage factor, *k*, is typically two or three.

cube corner [1]: also known as a corner cube, a type of retroreflector constructed from three mutually orthogonal reflective surfaces that form an internal corner. Cube corners may be constructed of three plane mirrors or a trihedral prism. (See also *retroreflector*.)

dead path: see *air dead path*.

dead path error: measurement error that arises from uncompensated changes in the optical length of the dead path in the interferometer setup. It appears as a shift in the measurement zero point. This error is best eliminated by an optical setup that has zero dead path.

deviation: the difference between a specified quantity and the measured value of that quantity that represents a departure from a stated norm.

displacement in air: displacement measured by an interferometer in air. The uncertainty reported for displacement in air does not include any uncertainty associated with material thermal expansion compensation.

displacement in vacuum: displacement measured by an interferometer in vacuum that does not require compensation for the refractive index of air or material thermal expansion compensation. The uncertainty reported for this quantity does not include uncertainties from any environmental sensors.

Edlén equation: an equation originally developed by B. Edlén and subsequently modified by others (see references [27–29]) for calculating the index of refraction of air when the air pressure, temperature, and atmospheric composition are known. (Atmospheric composition varies primarily as a consequence of variations in humidity.)

error: conceptually, the result of a measurement minus the true value, or, more precisely, a measured quantity value minus a reference quantity value. See reference [8] for details of the formal definition.

expanded uncertainty [9]: the quantity defining an interval about the result of a measurement that may be expected to encompass a large fraction of the distribution of values that could reasonably be attributed to the measurand.

folded common path test: a test for comparing the performance of two laser systems measuring over a folded common path, as defined in Nonmandatory Appendix B.

fringe: see *interference fringe*.

fringe-counting displacement interferometry: a method of measuring changes in displacement by counting the optical fringes generated as laser light from the reference and measurement beams of the interferometer system interfere with each other. In typical systems, a change in distance between the beamsplitter and retroreflector of one-half of the laser wavelength generates a count of one fringe. (This is true for single-pass systems where the beam travels only once to the moving retroreflector. See also *single-pass interferometer.*)

fringe interpolation:

(a) the subdividing of an interference fringe to increase the measurement resolution of an interferometer by optically folding the measurement arm of the interferometer and/or by electronic or digital phase interpolation of the electrical signals from the photodetector circuitry.

(b) a method used to increase the resolution of measurement. Whole fringe counting alone gives a linear measurement resolution equal to one-half the laser wavelength in single-pass systems. However, using either phase- or intensity-sensitive detection techniques, it is possible to interpolate to higher resolutions by subdividing each fringe into a number of equal smaller steps.

He–Ne laser: helium neon laser.

index of refraction: the ratio between the velocity of light in a vacuum to that within the medium. More precisely, this ratio is the phase index of refraction, as opposed to the group index of refraction used for time-of-flight or certain multiwavelength measurements. The refractive index of a vacuum is exactly one. The refractive index of air is slightly greater than one and varies depending on the air temperature, pressure, humidity, and composition (and varies slightly with changing laser wavelength).

interference fringe: the bright/dark/bright transition that is observed when the phase difference of two combined light waves is varied from 0 deg/180 deg/360 deg. In-phase waves are said to constructively interfere (amplitudes add). Out-of-phase waves are said to destructively interfere (amplitudes subtract).

interferometer:

(a) any of several optical, acoustic, or radio frequency instruments that use interference phenomena between a reference wave and an experimental wave, or between two parts of an experimental wave, to determine wavelengths and wave velocities, measure very small distances and thicknesses, or measure indices of refraction.

(b) an instrument that measures changes in mechanical size, shape, or position in terms of changes in optical path length by counting or displaying interference fringes created by a light source of known wavelength (see Nonmandatory Appendix E for a comparison of AC interferometers and DC interferometers).

interpolation error: a very small measurement error that can occur if fringe interpolation does not produce subdivided steps of exactly equal size.

iodine-stabilized laser: a laser that employs an iodine absorption cell to produce a single frequency of light to an extraordinarily high degree of accuracy.

ionized gas laser: a laser that uses an ionized gas to generate the laser discharge. Examples include helium neon (He–Ne) and argon ion laser systems.

laser interferometer: an interferometer for displacement measurement that uses a laser as a light source.

length-dependent error (LDE): the measurement error of a laser system that varies in proportion to the length being measured. *LDE* is typically expressed in micrometers/meter (μm/m) or parts in 10^6 (parts per million).

length-independent error (LIE): the measurement error of a laser system that does not vary in proportion to the length being measured. Examples of length-independent errors include interpolation errors and noise. *LIE* is typically expressed in micrometers (μm) or nanometers (nm).

master: an object used as a standard for a comparison test.

material sensor or *material temperature sensor:* a device that measures the temperature of the object being measured or a feedback mechanism (as described in Nonmandatory Appendix C) so that thermal expansion can be taken into account.

material thermal expansion compensation: a mathematical procedure (implemented in the software of many interferometer systems) for taking into account thermal expansion of the object being measured. Based on the temperature measured by the material temperature sensor and a thermal expansion coefficient appropriate for the material of the object being measured, the software corrects the measured displacement to an equivalent displacement that would have been measured at 20°C. (See reference [11].)

metrological traceability [8]: the property of a measurement result whereby the result can be related to a reference through a documented unbroken chain of calibrations, each contributing to the measurement uncertainty.

multicolor interferometry: interferometry that uses two or more laser beams of significantly differing wavelengths. This specialized technique can be used to measure absolute distance and is not covered in this Standard.

nodal point: the location within a retroreflector optic about which small pitch, roll, and yaw movements of the optic relative to an incident light beam will produce no change in the optical path of the beam. The nodal point (or optical center) of a cube corner is located at a distance H/n' from the face of the prism (where H is the height of the cube corner and n' is the refractive index of its material), along a line from the apex of the prism and perpendicular to the face of the prism.

optical path length: the product of the physical path length and refractive index of the optical medium.

optics thermal drift: variations in the optical path length due to temperature variations of optical components.

performance test: any of a number of test procedures that are used to measure machine performance.

positioning error [12]: the difference between the true displacement of a defined point on a movable component along a machine axis and that indicated by the machine-measuring system.

process control: in the context of this Standard, "process control" is used in a broad sense to denote some form of internal consistency checks periodically employed to verify that the measurement process has not changed. For example, this could take the form of periodic measurements of a control artifact, where a change in the measurement result will be indicative of problems with the measurement process if the change is larger than what would be expected from normal day-to-day variations.

quadrature: the quadrature sum or quadrature combination is equivalent to the root sum square. The term "quadrature" is also commonly used in describing signals differing in phase by 90 deg, but this usage does not appear in this Standard. (See also *root sum square*.)

refractive index of air: see *index of refraction*.

refractometer: a device for directly measuring the index of refraction of air (or other gaseous medium). A refractometer is often based on an extremely stable hollow reference cavity and a laser interferometer system. The cavity is filled with the air (or gas) to be measured, and the laser system measures apparent changes in the internal cavity length caused by variations in the refractive index of the air inside it.

remote interferometer: an assembly consisting of a beamsplitter with a retroreflector attached. The attached retroreflector provides a fixed reference path length. The assembly can be mounted separately from the laser head. "Remote" is used to distinguish this configuration from other systems where the beamsplitter and reference beam path are mounted inside the laser housing.

resolution [8]: the smallest change in a quantity being measured that causes a perceptible change in the corresponding indication.

retroreflector [1]: a passive device that reflects light back parallel to the incident direction over a range of incident angles.

NOTE: Typical retroreflectors are a corner cube, which has three internal perpendicular reflecting surfaces, or a cat's eye, which uses spherical refracting and reflecting surfaces. Retroreflectors are used to return the reference and measurement laser beams to the beamsplitter, where they interfere to produce fringes.

roll: the angular motion of a carriage designed for linear motion about the linear motion axis.

root mean square (RMS): the root mean square (RMS) of a set of n numbers is RSS/$\sqrt{n}$, where RSS is the root sum of squares as given in the following definition. Equivalently, for n numbers x_i, RMS is given by

$$RMS = \sqrt{\left(\sum_{i=1}^{n} x_i^2\right)/n} \tag{1}$$

root sum square (RSS): the square root of the sum of the squares of a set of numbers; that is, the root sum of squares of a set of n numbers x_i given by

$$RSS = \sqrt{\left(\sum_{i=1}^{n} x_i^2\right)} \tag{2}$$

single-pass interferometer: an interferometer in which light travels once from the beamsplitter to the retroreflector in the measurement arm of the interferometer (and is then reflected back).

slope: a gradient or progressive trend within a set of data. The slope is typically calculated by linear regression or least squares best fit, or by estimating the angle of the line passing through the data when plotted graphically. The slope is expressed as a rate of change in one item with respect to another (for example, micrometers of positioning error per meter of axis travel).

soak: to bring a body to a stage of thermal equilibrium. The term "soak out" is also used.

standard:

(a) the representation in matter or energy of a physical quantity.

(b) that which is established by authority or mutual consent as a model to be followed.

(c) an authoritative written specification covering methods, materials, or practices.

standard atmospheric conditions: by a widely accepted industry convention, standard atmospheric conditions correspond to air pressure, $P = 101\,325$ Pa (760 mm Hg); air temperature, $T = 20°C$; and relative humidity, $H = 50\%$.

standard conditions: see *standard atmospheric conditions*.

standard uncertainty [9]: uncertainty of the result of a measurement expressed as a standard deviation.

thermal drift [13]: a changing distance or angle between two objects, associated with a changing temperature distribution within the structural loop.

thermal equilibrium: a state of a body in which all its elements are at the same temperature.

thermal expansion: increase in linear dimensions of a solid because of a temperature rise.

traceability: see *metrological traceability.*

traceable: see *metrological traceability.*

uncertainty budget: a method of combining uncertainties in each of the variables that affect a measurement.

uncertainty (of a measurement result) [9]: the parameter associated with the results of a measurement that characterizes the dispersion of the values that could reasonably be expected from the measurement process.

vacuum wavelength: because the refractive index of air varies with temperature, pressure, and humidity, the wavelength of a laser is usually specified in a vacuum. The wavelength in air depends on the vacuum wavelength and on the air refractive index. The refractive index may be calculated using the Edlén equation and the current air temperature, pressure, and humidity.

variance: the variance, s^2, of n numbers x_i is defined as

$$s^2 = \sum_{i=1}^{n} (x_i - \overline{X})^2/(n-1) \qquad (3)$$

where

$\overline{X}$ = the mean of the data

wavefront: the imaginary surface on which the crests (or troughs) of a propagating lightwave lie. All points on this surface have the same phase.

wavefront aberration: departure of the wavefront from its ideal shape. (For a displacement-measuring interferometer, the ideal shape is a plane wave.)

wavelength errors: errors in the assumed wavelength of the laser radiation. The wavelength error in air depends on the wavelength error of the laser in vacuum and the error in the determination of the refractive index of the air.

wave plate: an optical element that changes the polarization state of light by delaying one polarization component relative to another.

yaw [12]: the angular motion of a movable component designed for linear motion about a specified axis perpendicular to the motion direction. In the case of a movable component with horizontal motion, the specified axis shall be vertical unless explicitly specified. For a movable component that does not have horizontal motion, the axis must be explicitly specified.

Zeeman multiplet: a set of spectral lines that are degenerate (that is, they all have the same frequency) in the absence of an external magnetic field but are split into a set of closely spaced lines when a magnetic field is applied.

zero drift, D: a parameter that quantifies the drift in the interferometer system's zero point measurement recorded over the duration of a test.

3 SYSTEM PERFORMANCE EVALUATION: GENERAL CONSIDERATIONS

An interferometer system designed to measure displacements is a complex instrument that may include a number of subsystems, such as a frequency-stabilized laser, optical components (including polarizing beamsplitters, retroreflectors, and possibly wave plates), electronics for fringe counting and interpolation, environmental sensors to measure atmospheric parameters or part temperature, and software to perform appropriate computations. Evaluating the performance of an interferometer, therefore, requires some care.

There are two basic techniques required to determine the accuracy of a laser interferometer system. The first is performance testing of the overall system, using the interferometer to measure one or more known displacements. The second is uncertainty analysis, combining estimated errors of all subsystems to obtain the overall interferometer system uncertainty.

It is recommended that the accuracy of a laser interferometer system can best be documented by combining these two methods. A performance test gives direct evidence that an interferometer can achieve the accuracy specified. The uncertainty budget can be used to combine results from a performance test at ambient conditions with additional uncertainty attributed to environmental sensors. The additional uncertainty would account for uncertainty in environmental sensors throughout the operating range specified by the manufacturer of the interferometer, or uncertainty that might be expected as a consequence of drift in the calibration of the sensors.

NOTES:

(1) The laser uncertainty budget and the application uncertainty budget (see section 6) can also be used to evaluate performance of an interferometer in use.

(2) The ambient conditions of the performance test should be well within the environmental operating range specified by the manufacturer of the interferometer system.

As indicated above, calibration of an interferometer system will typically require two distinct types of tests, and results of the tests can be combined using an uncertainty analysis. The two tests are

(a) verification of the overall performance of the interferometer as a system by measuring known displacements at ambient laboratory conditions. Only by testing the interferometer as a complete system, as opposed to testing individual subsystems, is it possible to verify that there are no hidden problems associated with integrating all parts of the system together.

(b) separate calibration of individual environmental sensors to assess their accuracy over the range specified by the manufacturer of the interferometer. Results of this test can be combined with the results of the test at ambient conditions [see (a) above] to obtain overall

system accuracy throughout the range of possible operating conditions.

An alternative procedure, more difficult to implement but giving a more direct measure of accuracy, would be to verify performance of the interferometer directly over a wide range of atmospheric conditions. This second procedure is also applicable to interferometer systems that do not have separate environmental sensors, such as those that directly stabilize laser wavelength in air (as opposed to stabilizing frequency or vacuum wavelength) and systems that use a refractometer in place of environmental sensors. It is also appropriate for verifying performance of a wavelength tracker used in conjunction with an interferometer. (A wavelength tracker is a device that measures and compensates changes in the laser wavelength in air due to changing atmospheric conditions.)

3.1 Performance Test: Measurement of Known Displacements

The primary performance test consists of using the laser measurement system to measure one or more known displacements. The following are ways in which this procedure might be carried out:

(a) Method (a). Displacements measured by the interferometer may be compared with the same displacements as measured simultaneously by a second interferometer of known accuracy and under process control (periodically verified against a check standard).

(b) Method (b). The interferometer can be integrated into a measurement machine under process control and used to measure known lengths of physical artifacts.

Method (b) is generally more difficult to implement than method (a). As such, it is not recommended for routine use, but it may represent a viable alternative when well characterized equipment is available. This Standard will not discuss method (b) further because details of the implementation can vary greatly from one facility to the next. However, much of the discussion of method (a) is also applicable to method (b).

3.2 Requirements for Comparing Interferometers

Four methods for implementing a comparison between interferometers are described in references [18–26] and are discussed in Nonmandatory Appendix B. The first of these methods, the folded common path method, is preferred under most circumstances, but the other methods may be used if they better meet particular needs.

All methods of interferometer testing discussed here require the comparison of a linear displacement as measured by the interferometer under test to the displacement as measured by a master interferometer. The following conditions must be fulfilled to ensure the validity of the test:

(a) The overall length scale accuracy and uncertainty of the master interferometer must be known. This could be accomplished, for example, through the use of a traceable master interferometer and traceable instrumentation for measuring atmospheric parameters, or through a traceable artifact that can be measured with the master interferometer to demonstrate that it is working properly.

(b) An uncertainty budget for the comparison process with well documented justification is needed. The uncertainty budget should be backed up by demonstrated ability to compare master and test interferometers. Accuracy can be demonstrated, for example, by comparing the master interferometer to a second interferometer system of known accuracy and verifying that the difference in readings of the two systems is as expected. Guidelines for estimating uncertainty are provided in section 5 and Nonmandatory Appendix F.

(c) Procedures must be in place to ensure that reliable answers are obtained over time. Periodic recalibration of all equipment may be needed to ensure accuracy. Some form of process control is desirable. This might be provided by redundant instrumentation (two complete interferometer systems that can be compared periodically) or by measurement of a control artifact.

3.3 Recommended Good Practices for Comparing Interferometers

The following are some general considerations that apply to all methods for interferometer comparisons:

(a) All methods of interferometer comparison will benefit from conditions universally recognized as desirable for dimensional measurement. Good environmental control is important to all methods of comparison, although some methods are much more subject to the environment than others. Method 3 of Nonmandatory Appendix B, the common optics comparison, is least sensitive to the environment, while Method 4, back-to-back comparison, is most sensitive. A good temperature-controlled room may not be essential when using the folded path or compensated back-to-back methods, but it will make the measurement easier and improve accuracy by avoiding problems arising from thermal drift in mounting for optical elements or varying thermal gradients in the air path. Very high accuracy measurements will benefit from careful thermal management, with attention to details such as local heating by people present in the room or heat exhaust from equipment. A low level of mechanical vibration is also desirable to obtain reliable results.

(b) Optical elements should be mounted rigidly in such a way as to minimize the effects of temperature changes. Mechanical stability of the mounting might be tested as described in Nonmandatory Appendix C (para. C-2.2), or by using the setup hysteresis and setup stability tests of references [2] and [3].

(c) Care must be taken to avoid alignment errors.

(d) The linear displacement mechanism must be reasonably straight and, except in the case of the folded path or common optics methods, pitch and yaw errors should be as small as possible. A minimum displacement of 1 m is desirable to aid in alignment and in distinguishing sources of error proportional to length from length-independent errors. A shorter length is appropriate for testing interferometers with a very short specified operating range. It is recommended that straightness of travel of the moving reflector should be better than 20 μm per meter of travel to ensure that there will be little change in overlap of the return beams as the carriage moves, even if the interferometer employs a 1-mm diameter beam. It is desirable to perform additional tests as needed to confirm proper operation of the interferometer at very long range if the interferometer is to be used to measure at such long distances that beam divergence is appreciable.

4 TEST PROCEDURE — LASER INTERFEROMETER COMPARISON TEST

The objective of the comparison test is to evaluate two critical performance parameters of the interferometer system. In some circumstances, it might be of interest to quote a value for an optional third parameter. These parameters are as follows:

(a) Length-Dependent Error (LDE). This parameter quantifies the component of the interferometer system's measurement error that rises in proportion with measurement distance. It is usually expressed as a fraction of the measurement distance, in parts in 10^6. The actual magnitude of this error, at a measurement distance of L, is given by $LDE \times L$. This parameter is primarily influenced by inaccuracies in the interferometer system's environmental compensation system and, to a lesser degree, by inaccuracies in the laser's vacuum wavelength.

(b) Zero Drift, D. This parameter quantifies the drift in the interferometer system's zero point measurement, recorded over the duration of the test (1 h). It is usually expressed in nanometers, micrometers, or microinches of drift over the test duration. Zero drift is primarily influenced by changes in the temperature of the interferometer optics or their mounts over the duration of the test (especially if these are subject to heat from the laser) or by incorrect dead path correction combined with a change in atmospheric conditions.

(c) Length-Independent Error (LIE). This optional parameter quantifies the component of the interferometer system's measurement uncertainty that does not rise in proportion with measurement distance. It would normally be expressed in nanometers, micrometers, or microinches. The laser system's measurement resolution, electrical noise, and fringe interpolation errors primarily influence this parameter. The *LIE* can be measured, or the length-independent uncertainty, U_{LIE}, can be estimated, by carrying out appropriate tests or by using an uncertainty-budget approach. A specific procedure to quantify *LIE* is not included in this Standard; however, see Note (3) of this paragraph for further discussion. Specifying *LIE* and U_{LIE} is optional.

Evaluation of these three parameters then allows the performance of the test interferometer system to be summarized by simply quoting a value for each, as shown in Forms 4.10-1, 4.10-2, and 4.10-3.

It is also a requirement of this Standard to quantify the measurement uncertainty associated with the evaluation of the *LDE* and drift. These uncertainties are

U_D = the estimated expanded uncertainty of measurement of D with a coverage factor of $k = 2$

U_{LDE} = the estimated expanded uncertainty of measurement of *LDE* with a coverage factor of $k = 2$

NOTES:

(1) In the case of a calibration that includes adjustment of the system under test, such as that which may be performed by the manufacturer, *LDE*, and possibly other errors may be reduced to zero by adjustment. In that case, the system's resultant accuracy may be specified by the uncertainties in the calibration process, U_{LDE}, U_{LIE}, and U_D, with no additional error. However, reducing the system uncertainty to this value should be done only if it can be reasonably expected that the cause of the original *LDE* will not recur. For example, it is not realistic to reduce the uncertainty to U_{LDE} if the original *LDE* arises from drifting calibration of environmental sensors; it is likely that the sensors will continue to drift in the future, and reducing the uncertainty to U_{LDE} would not give a realistic estimate of the actual uncertainty of the system at intervals between sensor recalibration.

(2) In the case of product performance specifications (given in sales literature, etc.), the equipment manufacturer can add the contribution from U_{LDE}, U_{LIE}, and U_D into *LIE*, *LDE*, and *D*, respectively. This allows the product performance to be summarized in just three terms (or two terms if *LIE* is not included) that already include the manufacturer's measurement uncertainty with a coverage factor of $k = 2$.

(3) In principle, the *LIE* can be evaluated using the tests described in this Standard that evaluate error as a function of measured distance. After subtracting a best-fit linear error from the data, the root mean square (RMS) of residuals at short measurement distances provides a measure of the *LIE*. In practice, it is difficult to implement a good-quality *LIE* test using this method when the test apparatus is optimized to test interferometers of arbitrary design over longer distances. Consequently, a specific testing method is not recommended in this Standard. The primary contributors to the *LIE* are noise (easily measured), resolution (well known), and periodic interpolation errors. Combining these three sources of error would give a good estimate of length-independent uncertainties. Methods for measuring the periodic errors are described in references [14–17].

(4) Except where explicitly stated otherwise, normal distributions will be assumed throughout this Standard, and consequently, the coverage factor of $k = 2$ corresponds to a 95% confidence interval.

Table 4.2-1 Recommended Target Positions

Target Number, *t*	Target Positions for ½ m (20 in.) Test		Target Positions for 1 m (40 in.) Test		Target Positions for 2 m (80 in.) Test	
	mm	in.	mm	in.	mm	in.
1	0	0	0	0	0	0
2	50	2	100	4	200	8
3	100	4	200	8	400	16
4	150	6	300	12	600	24
5	200	8	400	16	800	32
6	250	10	500	20	1 000	40
7	300	12	600	24	1 200	48
8	350	14	700	28	1 400	56
9	400	16	800	32	1 600	64
10	450	18	900	36	1 800	72
11	500	20	1 000	40	2 000	80

4.1 Test Procedure Overview

The procedure is based on the simple comparison of the readings from the master and test interferometers at a series of displacements (target positions), under quasistatic (nominally zero velocity) conditions. The comparison is performed with both interferometer systems performing their own automatic air refraction compensation, and with both sets of environmental sensors arranged so that they are measuring identical atmospheric environments. The comparison is repeated a number of times in a bidirectional manner, with a target position sequence (run) that is designed to allow evaluation of length-dependent and drift error parameters from a single test. The procedure evaluates the performance of the complete interferometer system (*with the exception of the material thermal expansion compensation, which should be turned off or set to use a zero expansion coefficient*).

NOTE: For diagnostic purposes or for systems that do not have automatic environmental compensation, this procedure may alternatively be used with the environmental compensation systems of both interferometers manually set to the same conditions.

4.2 Target Positions

Target positions are the linear displacements at which the readings from the two laser interferometer systems are compared. Target positions are chosen to be equally spaced over the measurement range of the test. The measurement range selected will depend on the carriage and slideway design, the measurement range of the laser under test, and the test method selected. Measurement ranges of less than 0.5 m are not recommended except when testing specialized systems intended only for shorter measurements. The recommended target positions for three representative carriage lengths are shown in Table 4.2-1.

NOTE: The interferometer reading will show double the carriage movement when using the folded path method.

4.3 Runs

The two laser interferometer readouts are compared at each of the target positions in turn, starting with target 1, and finishing with target 11. This sequence of comparisons is called a run. The first run visits the targets in the forward direction and is called run 1. The laser interferometer readouts are then compared again at each target position, but this time in the reverse direction, starting with target 11, and finishing with target 1. This sequence of comparisons is called run 2. The overall sequence is repeated five times to give data for runs 1 through 10, with the five odd-numbered runs being in the forward direction, and the five even-numbered runs being in the reverse direction.

4.4 Initialization

Follow the steps below in setting up a comparison.

Step 1: Set up the test laser and master as prescribed in para. 3.3 and taking into account the recommendations of Nonmandatory Appendix B. Take particular care in aligning the laser systems on the test equipment.

Step 2: When testing systems employing a beamsplitter and reference path built into the laser head, it is important to mount the laser head in a manner that controls thermal drift in accordance with the manufacturer's or customer's recommendations. The customer requesting a test of this type of interferometer should provide mounting hardware, and precisely specify mounting procedures so that all elements likely to be subject to thermal drift are well defined.

Step 3: Place the environmental sensors from both systems so that they are measuring (as nearly as possible) identical environments. If the system under test does not include a humidity sensor, then it will be necessary to arrange the test so that both the master interferometer and the system under test use the same humidity when calculating displacement. For example, if both systems have a provision for manual entry of humidity, then set both to 50% RH.

Step 4: Before beginning the test, warm up the master interferometer for a period of time deemed suitable for it to achieve good stability and for any nearby hardware to come to thermal equilibrium with this heat source.

Step 5: Switch the test interferometer system off, and allow its laser, optics, and environmental sensors to reach ambient temperature. A cooling-off period of 2 h is recommended. (The master laser should remain turned on during this period of time, so that it will be in good thermal equilibrium with its surroundings when the test is begun.)

Step 6: Switch on the test laser interferometer and enable air refraction compensation on both interferometer systems. *Do not enable material thermal expansion compensation.* This may require a zero expansion coefficient to be entered into the system software, or disconnection of the material temperature sensor.

Step 7: If the systems include a readout averaging or filtering option, this should be selected.

NOTE: Selecting similar averaging response times on both master and test interferometer systems is recommended.

Step 8: If the systems include air dead path correction capability, ensure that the appropriate air dead path length has been entered. [Usually the dead path is small but it could be substantial if, for example, the interferometer is zeroed when the moving retroreflector is positioned at its farthest distance from the beamsplitter, as might occur when using the back-to-back method (see Nonmandatory Appendix B). However, note carefully that this dead path correction should not be employed when using the compensated back-to-back method (see Nonmandatory Appendix B), when the imbalances in the two interferometers automatically compensate each other.]

Step 9: Wait for the test laser interferometer system to indicate that it is ready to perform measurements (usually as soon as laser stabilization is complete), or wait for the time specified by the manufacturer's operating instructions.

Step 10: Move the retroreflector optics carriage to target position 1 (0 mm) at the end of the axis of travel closest to the test interferometer. Set the direction sense selector so that the distance readouts of both interferometer systems increase (become more positive) as the carriage is moved away from the end position toward target 2.

4.5 Data Capture

Usually, data capture should start as soon as possible after the test laser is deemed ready for use as specified above. The time elapsed from first turning on the laser to the beginning of measurements should be recorded and will be included in the report of calibration as described in para. 4.10. The procedure for capturing the data is given below.

4.5.1 Forward Run

(a) Zero the distance readouts of both interferometer systems.

(b) Wait for the distance readouts to settle, and then record the readouts from both master and test interferometers [see para. 4.5.4(a)]. This is the first point of a forward run.

(c) Move the retroreflector carriage to the next target position in the forward direction [see paras. 4.5.4(b) and (c)].

(d) Wait for the distance readouts to settle, and then record the readouts from both master and test interferometers [see para. 4.5.4(a)].

(e) Repeat steps (c) and (d) an additional nine times [see para. 4.5.4(d)], whereby the retroreflector carriage will have reached the last target position, at the far end of the axis.

4.5.2 Reverse Run. Record the readouts from both master and test interferometers again [see para. 4.5.4(a)]. This is the first point (target 11) of a reverse run.

(a) Move the retroreflector carriage to the next target position in the reverse direction [see paras. 4.5.4(b) and (c)].

(b) Wait for the distance readouts to settle, and then record the readouts from both master and test interferometers [see para. 4.5.4(a)].

(c) Repeat steps (a) and (b) an additional nine times, whereby the retroreflector carriage will have returned to the starting position.

4.5.3 Repeat Runs. Repeat the steps given in paras. 4.5.1(b) through (e) and 4.5.2(a) through (c) an additional four times, recording data at approximately the same target positions along the axis, to give five sets of bidirectional data [see para. 4.5.4(d)]. Do not re-zero the laser readouts between runs.

4.5.4 Notes Regarding Data Capture

(a) It is important to synchronize the recording of the readouts of both laser systems as closely as possible. If an electronic trigger or software command is available, it should be used. If synchronization is difficult, the uncertainty of measurement may be degraded and it may be necessary to pay extra attention to reducing vibration, thermal drift, and air turbulence noise.

(b) Because the analysis will compare the two interferometer readings directly, it is not necessary to position the carriage very accurately along the axis at each target position. It is suggested that the laser readings be recorded at positions that are within a tolerance of a few millimeters from the target position. This means that the test can easily be performed using a manually operated carriage.

(c) Because this test is also designed to detect any drift in the readings from the test laser under conditions that are close to those in actual use, it is important that the test time be controlled. The test should therefore be arranged so that the readings from both lasers are recorded at nominally 33-s intervals, and the total time from recording the first pair to the last pair of readings will then be just over 1 h. It is suggested that the elapsed test time be recorded every time the laser readings are recorded. The ambient temperature variation during the test should also be recorded since this may influence the drift result. In some interferometer systems, the zero drift is likely to be correlated with thermal variations in mounting hardware, such as the mounting of the remote interferometer or of optical components within the remote interferometer. It is therefore desirable (but not required) to record relevant temperatures that might show a time correlation with the zero drift from one run to the next. For a system that employs a remote interferometer, the temperature of the remote interferometer could be monitored as a function of time, and for a system where the reference path is built into the laser head, the temperature of the laser housing could be monitored as a function of time.

(d) The number of runs and target positions specified above should be regarded as the minimum required. Additional target positions or runs may be performed, but the total test time should be maintained at 1 h.

4.6 Data Analysis

This section describes the data analysis calculations required to evaluate *LDE*, drift, and uncertainty terms.

If the master laser interferometer system contains a known and well characterized *LDE*, then the master interferometer readings should be corrected accordingly so that there is no known bias (error) in the readings of the master.

Calculate the difference between each pair of master and test interferometer readings to give a set of 110 difference values [110 = 11 targets × (5 forward runs + 5 reverse runs)].

$$D_{r,t} = T_{r,t} - M_{r,t} \qquad (4)$$

where

$D_{r,t}$ = difference between master and test laser interferometer system readings at target t, on run r

$M_{r,t}$ = master laser interferometer system reading at target t, on run r

r = run number

t = target number

$T_{r,t}$ = test laser interferometer system reading at target t, on run r

It is suggested that these data be represented graphically, with the x-axis of the graph being the target position (in millimeters or inches), and the y-axis of the graph being the difference between the two laser readings (in micrometers or microinches).

The second step is to calculate the best-fit straight line through each run of data independently. Standard linear regression, or least-squares fitting, should be used for this process. Note that the best-fit lines must be fitted to each run of data independently and must not be constrained to pass through the graph origin. The calculation will give 10 slopes, and 10 y-axis intercept values. The slope of run number r is denoted as S_r, and the intercept as Z_r. These quantities can be found using fitting routines in standard spreadsheets or other analysis packages, or they can be calculated from the formulae given in eqs. (5) through (11). The error and uncertainty parameters are then calculated as shown in paras. 4.6.1 through 4.6.5. If a standard fitting routine is not available, S_r and Z_r can be determined as follows:

Let n = the number of points in each run ($n = 11$ is recommended). Define

$$\alpha_r = \sum_{t=1}^{n} D_{r,t} \qquad (5)$$

$$\beta_r = \sum_{t=1}^{n} M_{r,t} \qquad (6)$$

$$\gamma_r = \sum_{t=1}^{n} M_{r,t}^2 \qquad (7)$$

$$\delta_r = \sum_{t=1}^{n} D_{r,t}\, M_{r,t} \qquad (8)$$

$$\eta_r = n\gamma_r - \beta_r^2 \qquad (9)$$

Then

$$S_r = (n\delta_r - \alpha_r\beta_r)/\eta_r \qquad (10)$$

and

$$Z_r = (\alpha_r\gamma_r - \beta_r\delta_r)/\eta_r \qquad (11)$$

4.6.1 Calculation of Length-Dependent Error, LDE_C. The comparison procedure gives us an estimate for the *LDE*. The *LDE* determined by the comparison test is denoted as LDE_C. The total *LDE* will be determined as a combination of this value with additional errors associated with the environmental sensors. LDE_C is equal to the mean slope of the ten best-fitted lines (the average of the ten values S_1 through S_{10} from para. 4.6).

$$LDE_c = \frac{1}{m}\sum_{r=1}^{m} S_r \tag{12}$$

where m is the number of runs ($m = 10$ is recommended here).

4.6.2 Calculation of Length-Dependent Uncertainty, $U_{LDE,C}$. The expanded uncertainty in the *LDE*, $U_{LDE,C}$, is calculated by adding the standard deviation of the ten slope values to the other estimates of measurement length-dependent uncertainties using root sum square (RSS) addition.

If σ_L is the standard deviation of the ten values S_1 through S_{10}, then

$$U_{LDE,C} = 2\sqrt{\sigma_L^2 + u_m^2 + u_c^2} \tag{13}$$

where u_m and u_c are length-dependent uncertainties of the master interferometer and of the comparison procedure as described in section 5. Note that $U_{LDE,C}$ includes a contribution from run-to-run variability of the test laser, as quantified by σ_L. When the test laser is intended to be used as a master laser for secondary calibrations, it may also be desirable to know the uncertainty in the average value obtained for LDE_C, exclusive of run-to-run variations. This is discussed in Nonmandatory Appendix F.

4.6.3 Calculation of Zero Drift, *D*. The zero drift, *D*, is simply given by calculating the unsigned range of the *y*-axis intercept values of the best-fit lines from all *m* runs

$$D = \mathrm{MAX}(Z_1 \ldots Z_m) - \mathrm{MIN}(Z_1 \ldots Z_m) \tag{14}$$

This is equivalent to the worst-case zero point drift recorded during the test, calculated in a manner that minimizes the influence of any variations associated with short-distance random variations (that is, the errors measured by *LIE*).

4.6.4 Calculation of Uncertainty in the Zero Drift, U_D. U_D, the expanded uncertainty in the zero drift, *D*, is estimated as described in para. 5.2.

4.6.5 Simple Test of Sensor Response. If the comparison test is performed with any of the environmental sensors close to standard or default conditions, then it is recommended to confirm that, if the sensor's environment is changed, the laser position and sensor readout change accordingly. This test ensures that the laser system is responding to the changes in the sensor readings, both in magnitude and in direction.

NOTE: The primary concern is with the temperature sensor. If the interferometer is indicating +1 m and the air temperature sensor is heated by 5°C, then the indicated distance should increase by approximately 5 μm.

Note that the same type of test can be done with the material temperature sensor if one is used. For example, if the reading of the interferometer is +1 m and the sensor is heated by 5°C, and if the thermal expansion coefficient is set to 10 parts in 10^6/°C, then the length should decrease by 50 μm.

4.7 Incorporation of Environmental Sensor Uncertainties

The test procedure described earlier compares the performance of the test interferometer with a master interferometer under a single set of environmental conditions to give a length-dependent error, LDE_C, and a zero drift, *D*.

However, laser interferometers are typically used over a wider range of environmental conditions, and this can have a significant effect on *LDE*. To assess the *LDE* of the test interferometer over a wider range of environmental conditions, there are two options, as follows:

(a) Repeat the comparison test at a number of different environmental temperatures, pressures, and humidities to obtain the worst-case LDE_C, which is then taken as the value for *LDE*.

(b) Evaluate the measurement error from each of the environmental sensors individually over the desired environmental range, then combine with the LDE_C results from the comparison test to calculate *LDE* that applies over the wider environmental range.

The first option is very time consuming and impractical without highly specialized equipment. Therefore, the second option is the method that is normally used.

Below are the procedures that can be used to combine the LDE_C obtained earlier under a single set of environmental conditions with sensor measurement error results over a wider range of conditions, to give an *LDE* value that applies over this wider range.

4.7.1 Calibration of Sensor Errors. The errors in the system's air temperature, pressure, and humidity and material temperature sensors should be calibrated over the operating temperature, pressure, and humidity ranges required.

NOTES:
(1) Ideally, the air pressure sensor should be calibrated over a range of pressures and temperatures. This is because many air pressure sensors are also temperature sensitive.
(2) If desired, the various components can be tested at different laboratories and combined via the methods shown here to obtain a valid B89 test of interferometer performance.

Table 4.7.2-1 Sensitivity Coefficients Associated With *LDE*

Length-Dependent Errors	Length-Dependent Uncertainties	Notes
$LDE_{ATE} = 0.93 \times ATE$	$U_{LDE,ATE} = 0.93 \times U_{ATE}$	[Notes (1) and (2)]
$LDE_{APE} = 0.027 \times APE$	$U_{LDE,APE} = 0.027 \times U_{APE}$	[Notes (1) and (2)]
$LDE_{AHE} = 0.012 \times AHE$	$U_{LDE,AHE} = 0.012 \times U_{AHE}$	[Notes (1) and (2)]
$LDE_{MTE} = 12 \times MTE$	$U_{LDE,MTE} = 12 \times U_{MTE}$	[Notes (2) and (3)]

NOTES:
(1) The sensitivity coefficients used here relate the effects of air temperature, pressure, and humidity on the refractive index of air and have been calculated from the Edlén equation at nominal conditions of $T = 25°C$, $P = 101\ 325$ Pa, and $H = 50\%$ RH. Sensitivity to the relative humidity varies as a function of temperature, and is significantly larger at 25°C than at 20°C.
(2) The results of these calculations are all expressed as parts in 10^6.
(3) The sensitivity coefficient used here assumes material normalization is being applied for a typical steel with an expansion coefficient of 12 parts in 10^6/°C. Different values may be used here, depending on the application.

The calibration methods for these sensors are outside the scope of this Standard. The results from each sensor calibration should provide a maximum sensor error over the environmental range tested, together with a calibration measurement uncertainty as follows:

AHE = maximum air humidity sensor error, %RH, over the range tested
APE = maximum air pressure sensor error, Pa, over the range tested

NOTE: 1 mm Hg = 133.322 Pa

ATE = maximum air temperature sensor error, °C, over the range tested
MTE = maximum material temperature sensor error, °C, over the range tested
U_{AHE} = air humidity sensor calibration expanded uncertainty, %RH
U_{APE} = air pressure sensor calibration expanded uncertainty, Pa
U_{ATE} = air temperature sensor calibration expanded uncertainty, °C
U_{MTE} = material temperature sensor calibration expanded uncertainty, °C

The expanded uncertainties have a coverage factor of $k = 2$.

If some of these sensors are not included in the laser interferometer system, then set the corresponding *LDE*s and U_{LDE}s to zero and include an appropriate note when reporting results as shown in Forms 4.10-1, 4.10-2, and 4.10-3.

4.7.2 Calculation of Effect on *LDE*. Each of these errors and uncertainties needs to be multiplied by the appropriate sensitivity coefficients to estimate their additional contribution (parts in 10^6) to the system's *LDE* and U_{LDE}. When using units of pascal, degrees Celsius, and percent relative humidity, the coefficients are as shown in Table 4.7.2-1.

4.8 Incorporation of Air Refraction Calculation Errors

Most laser interferometer systems use an equation (such as the Edlén or Ciddor equation) to calculate the current refractive index of air from the air temperature, pressure, and humidity measured by the sensors [27–32]. This allows the current laser wavelength to be calculated from the vacuum wavelength. This then allows the interferometer readings to be corrected to largely eliminate the effects of any variation in the air refractive index. However, this process will not provide a perfect correction and some small residual errors may remain due to small inaccuracies in the equation used, programming errors, and lack of numerical precision.

This section provides a way of estimating the size of this length-dependent calculation error, LDE_{ARC}, and the expanded uncertainty in it, $U_{LDE,ARC}$, so that these can be included in the overall system *LDE*.

To carry out this test, it is important that the test interferometer system documentation specify the vacuum wavelength of the laser, λ_V, and that the system software can display the current compensated laser wavelength in air, λ_A. These two values will be used to assess the amount of correction, C_S, measured in parts in 10^6, that the test interferometer system is applying to the laser wavelength, where

$$C_S = (\lambda_V/\lambda_A - 1) \times 10^6 \quad (15)$$

This correction is then compared, under a variety of environmental conditions, to the values in or to values computed using modern versions of the Edlén or Ciddor equations [27–32].

NOTE: As an alternative, if the software provides C_S directly, then its value can be compared directly to values in Tables 4.8-1, 4.8-2, and 4.8-3.

If the test interferometer system allows manual entry of environmental conditions, proceed as follows:

Table 4.8-1 Wavelength Corrections (Parts in 10^6) for Low Humidity Air (25% RH)

Air Pressure, Pa	Air Temperature, °C								
	0	5	10	15	20	25	30	35	40
65 000	187.07	183.67	180.39	177.21	174.12	171.12	168.20	165.35	162.55
70 000	201.47	197.81	194.28	190.86	187.54	184.31	181.17	178.10	175.11
75 000	215.87	211.95	208.17	204.50	200.95	197.50	194.14	190.86	187.66
80 000	230.27	226.10	222.06	218.15	214.37	210.69	207.11	203.62	200.22
85 000	244.68	240.24	235.95	231.80	227.78	223.88	220.08	216.38	212.77
90 000	259.08	254.38	249.84	245.45	241.20	237.07	233.05	229.14	225.33
95 000	273.48	268.53	263.74	259.10	254.61	250.26	246.03	241.90	237.88
100 000	287.89	282.67	277.63	272.75	268.03	263.45	259.00	254.66	250.44
101 325	291.71	286.42	281.31	276.37	271.59	266.94	262.43	258.05	253.77
105 000	302.30	296.82	291.52	286.40	281.45	276.64	271.97	267.42	262.99
110 000	316.70	310.96	305.42	300.06	294.87	289.83	284.94	280.19	275.55
115 000	331.11	325.11	319.32	313.71	308.28	303.02	297.91	292.95	288.11

GENERAL NOTE: The values above were calculated using the Ciddor equation, assuming a CO_2 concentration of 450 parts in 10^6 (slightly higher than outdoors concentration but representative of what might be encountered in a room). The modified Edlén equation of reference [29] gives these same values within about 1 part in 10^8. The equation of reference [27] will deviate somewhat from these values at high temperature, humidity, and pressure.

Table 4.8-2 Wavelength Corrections (Parts in 10^6) for Medium Humidity Air (50% RH)

Air Pressure, Pa	Air Temperature, °C								
	0	5	10	15	20	25	30	35	40
65 000	187.01	183.59	180.27	177.05	173.91	170.84	167.82	164.86	161.92
70 000	201.41	197.73	194.16	190.70	187.32	184.03	180.79	177.62	174.48
75 000	215.81	211.87	208.05	204.35	200.74	197.22	193.77	190.38	187.03
80 000	230.21	226.01	221.94	218.00	214.15	210.40	206.74	203.14	199.59
85 000	244.62	240.16	235.84	231.64	227.57	223.59	219.71	215.90	212.14
90 000	259.02	254.30	249.73	245.29	240.98	236.78	232.68	228.66	224.70
95 000	273.42	268.44	263.62	258.94	254.40	249.97	245.65	241.42	237.26
100 000	287.83	282.59	277.52	272.60	267.82	263.17	258.62	254.18	249.81
101 325	291.65	286.34	281.20	276.21	271.37	266.66	262.06	257.56	253.14
105 000	302.24	296.73	291.41	286.25	281.24	276.36	271.60	266.94	262.37
110 000	316.64	310.88	305.30	299.90	294.65	289.55	284.57	279.70	274.92
115 000	331.05	325.03	319.20	313.55	308.07	302.74	297.54	292.46	287.48

GENERAL NOTE: The values above were calculated using the Ciddor equation, assuming a CO_2 concentration of 450 parts in 10^6 (slightly higher than outdoors concentration but representative of what might be encountered in a room). The modified Edlén equation of reference [29] gives these same values within about 1 part in 10^8. The equation of reference [27] will deviate somewhat from these values at high temperature, humidity, and pressure.

Table 4.8-3 Wavelength Corrections (Parts in 10^6) for High Humidity Air (75% RH)

Air Pressure, Pa	Air Temperature, °C								
	0	5	10	15	20	25	30	35	40
65 000	186.95	183.51	180.16	176.89	173.70	170.55	167.45	164.37	161.30
70 000	201.35	197.65	194.05	190.54	187.11	183.74	180.42	177.13	173.85
75 000	215.75	211.79	207.94	204.19	200.52	196.93	193.39	189.89	186.41
80 000	230.15	225.93	221.83	217.84	213.94	210.12	206.36	202.65	198.97
85 000	244.56	240.07	235.72	231.49	227.36	223.31	219.34	215.41	211.52
90 000	258.96	254.22	249.61	245.14	240.77	236.50	232.31	228.17	224.08
95 000	273.36	268.36	263.50	258.79	254.19	249.69	245.28	240.93	236.63
100 000	287.77	282.50	277.40	272.44	267.60	262.88	258.25	253.70	249.19
101 325	291.59	286.25	281.08	276.06	271.16	266.38	261.69	257.08	252.52
105 000	302.18	296.65	291.29	286.09	281.02	276.07	271.23	266.46	261.75
110 000	316.58	310.80	305.19	299.74	294.44	289.27	284.20	279.22	274.30
115 000	330.99	324.94	319.08	313.39	307.86	302.46	297.17	291.98	286.86

GENERAL NOTE: The values above were calculated using the Ciddor equation, assuming a CO_2 concentration of 450 parts in 10^6 (slightly higher than outdoors concentration but representative of what might be encountered in a room). The modified Edlén equation of reference [29] gives these same values within about 1 part in 10^8. The equation of reference [27] will deviate somewhat from these values at high temperature, humidity, and pressure.

Table 4.8-4 Combinations of Environmental Conditions

Test Combinations	Air Pressure	Air Temperature	Air Humidity
1	Minimum	Minimum	Minimum
2	Minimum	Minimum	Maximum
3	Minimum	Maximum	Minimum
4	Minimum	Maximum	Maximum
5	Mean	Mean	Mean
6	Maximum	Minimum	Minimum
7	Maximum	Minimum	Maximum
8	Maximum	Maximum	Minimum
9	Maximum	Maximum	Maximum

(a) Identify the measuring ranges for the air temperature, air pressure, and air humidity sensors (from the system specifications).

(b) Select nine combinations of environmental conditions in accordance with Table 4.8-4, replacing "minimum," "maximum," and "mean" with the minimum, maximum, and mean of each sensor's measurement range.

(c) Modify the nine combinations so they match the nearest combinations available in Tables 4.8-1 through 4.8-3 (ensure the revised combinations still fall inside the system sensors' measuring ranges).

(d) Manually enter each combination of environmental conditions into the test interferometer system in turn and record the nine corrected laser wavelengths, λ_A, calculated by the system.

(e) Calculate the nine corrections, C_S, being applied by the test interferometer system, using eq. (15).

(f) Calculate the difference between each of these nine values for C_S and the values in Table 4.8-4, identify the largest absolute difference, and record this value as the air refraction calculation length-dependent error, LDE_{ARC}.

(g) The expanded uncertainty of calculation, $U_{LDE,ARC}$, is equal to the estimated expanded uncertainty in the values in Tables 4.8-1 through 4.8-3 that might be conservatively estimated as 5×10^{-8} (0.05 parts in 10^6) for this broad range of conditions. A smaller uncertainty may be appropriate over a narrow range of conditions.

An alternate procedure can be used to evaluate C_S if the software does not provide a readout of either C_S or λ_A. This alternate procedure requires that the laser displays a large, nonfluctuating value that can be achieved as follows: Turn the laser on and manually enter artificial values for environmental conditions. Enter standard environmental conditions (101 325 Pa, 20°C, and 50% RH) into the software. Set the moving retroreflector at least 1 m away from the usual zero position (the further apart the better) and reset the system so that it is reading zero displacement. Do not enter any dead path correction. Displace the retroreflector back to the usual zero position so that the laser indicates a reading with a magnitude of 1 m or more. (The reading will be negative in sign if the system is set to read positive as the retroreflector moves away.) Wait at least ½ h for the system to stabilize before continuing.

There should now be a very stable (no air path) but sizable laser reading, denoted as l_0. Mark this value down, then manually adjust the environmental readings to conditions selected in the manner described previously. If the length reading changes from l_0 to l_1 when the new conditions are entered, then C_S at the new conditions can be calculated using

$$C_S = const \times \frac{l_0}{l_1} - 10^6 \tag{16}$$

where $const$ = 1,000,271.37.

This formula replaces the computation given in (e) above. The steps provided in (f) and (g) now proceed as given.

If the test interferometer system does not allow manual entry of environmental conditions, then the principles are similar, except that it will be necessary to put the sensors into an environmental chamber and physically generate similar combinations of air temperature, pressure, and humidity. The sensor readings indicated by the test interferometer (not the environmental chamber) are then entered into the air refraction equations (Edlén or Ciddor equations), and the results are then compared with the wavelengths, λ_A; hence the corrections, C_S, are applied by the test interferometer system. LDE_{ARC} is then given by the largest absolute difference as before. $U_{LDE,ARC}$ is equal to the estimated uncertainty in the equations for refractive index, as stated in the appropriate reference.

4.9 Calculation of *LDE* Over the Full Environmental Range

The errors and uncertainties of the sensor can now be combined with those of the air refraction calculation, and the values of LDE_C and $U_{LDE,C}$ (obtained under a single set of conditions), by RSS addition. This gives values for LDE and U_{LDE} that apply over the full environmental range, as follows:

$$LDE = \sqrt{(LDE_C)^2 + (LDE_{ATE})^2 + (LDE_{APE})^2 + (LDE_{AHE})^2 + (LDE_{MTE})^2 + (LDE_{ARC})^2} \tag{17}$$

$$U_{LDE} = \sqrt{(U_{LDE,C})^2 + (U_{LDE,ATE})^2 + (U_{LDE,APE})^2 + (U_{LDE,AHE})^2 + (U_{LDE,MTE})^2 + (U_{LDE,ARC})^2} \tag{18}$$

where all of the quantities in the equations above must be expressed in a consistent manner (i.e., all expressed as parts in 10^6). If some sensors are not part of the interferometer system, then the corresponding terms above are set to zero. For example, some interferometer systems do not include a material temperature sensor. In this case, LDE_{MTE} and $U_{LDE,MTE}$ should be set to zero. It will then be necessary to make clear that the LDE is applicable only for measuring displacement in air. In general, it is necessary to specify the applicability of the reported LDE, so as to make clear which sensors are not included in the calculation, as described in para. 4.10.

Although RSS addition of uncertainties is a universally accepted procedure, note that the use of RSS addition for errors is not necessarily the current practice of industry. The internationally recognized Guide to the Expression of Uncertainty in Measurement [9] gives little guidance, assuming that all known errors will most often be corrected to zero. The procedure for taking the root sum of squared errors as given in this Standard is merely a convention, providing a reasonable estimate of errors likely to be encountered by users who are not operating under environmental conditions that happen to simultaneously give the worst performance of all sensors. Note that the resulting estimated error may be significantly less than the maximum error that will be encountered anywhere within the specified envelope of operating conditions for the interferometer system.

RSS addition is plausible when sensor errors are uncorrelated with each other and with the original LDE value from the comparison test. If an air sensor has a large error at the time of the comparison test, this assumption is incorrect and causes some double counting of this sensor's error contribution. Under these conditions, it is recommended that either the comparison test be repeated with the test interferometer's sensor readings manually entered to match those of the master interferometer, or a mathematical correction is made during the error combination. These complications can be avoided, to some extent, if the environmental sensors are calibrated prior to performing the comparison test. Repeat the comparison test if one of the sensors is defective.

4.10 Reporting Results

A summary of performance evaluation should include the information in this paragraph. Expanded uncertainties are quoted with a coverage factor of $k = 2$. Forms 4.10-1, 4.10-2, and 4.10-3 show an example of a suitable presentation format, including typical example results. Note that reporting *LIE* is optional and that in the example shown here, the overall performance evaluation result (Form 4.10-3) gives two values for *LDE* — one for measuring displacement in air, and one for measuring steel. The second of these numbers includes the error in the material temperature sensor, while the first does not. For a system that does not include a material temperature sensor, only the first of these numbers would be given, and the entries in Form 4.10-2 for material temperature would be marked "not applicable." For a system that includes a material temperature sensor, the second *LDE* value is most relevant, but (as shown in the example) the first can also be reported. It would also be permissible to report an *LDE* value for displacement in vacuum (excluding all sensor errors); this is the only number that should be reported if air pressure and temperature sensors are not part of the system. For a system that does not include a humidity sensor, the phrase "displacement in air" should be replaced by "displacement in air at standard humidity."

To satisfy the requirements of reference [1], the length-dependent uncertainty reported should be either displacement in air or, if a humidity sensor is not used in the system, displacement in air at standard humidity.

By convention, the uncertainty for measuring steel is computed assuming an expansion coefficient of 12 parts in $10^6/°C$.

Thus, when reporting one or more *LDE* values in Form 4.10-3, it is always necessary to include a description of *LDE* that is appropriate for the sensors that were tested. This description is one of the following:

(a) "measuring steel" if material temperature sensor, air temperature and pressure sensor, and optionally, a humidity sensor are used. As shown in the example, a note should be included explaining that the material temperature sensor uncertainty is evaluated assuming an expansion coefficient of 12 parts in $10^6/°C$.

(b) "displacement in air" if there is no material temperature sensor but all air sensors present.

(c) "displacement in air at standard humidity" if no material or humidity sensors are included.

(d) "displacement in vacuum" if no environmental sensors are included.

NOTES:

(1) There is no requirement in this Standard that all of the calibrations that go into testing an interferometer system be carried out at the same laboratory. There may arise situations where the performance evaluation test is done at one laboratory and the environmental sensors are calibrated at one or more different laboratories. All of these results can be combined by one of the laboratories or by a third party to calculate the overall *LDE* and thus provide an overall figure of merit for the system (Form 4.10-3), but the report should make clear the origins of all measurements, with references to appropriate calibration reports of individual components. If a laboratory performs a comparison test but does not have access to calibration reports for the sensors, then that laboratory should use only Form 4.10-1 when reporting results.

(2) The quantities measured by this test can be used to verify an uncertainty budget as shown in Nonmandatory Appendix A.

5 VERIFYING TEST PERFORMANCE, ESTIMATING BIAS IN THE TEST, AND UNCERTAINTY OF RESULTS

This section pertains to estimating uncertainties in the testing of a laser interferometer and is only intended for users in calibration laboratories who will be assigning uncertainties for calibrations of laser interferometers; other readers need not be concerned by the details given here. Along with Nonmandatory Appendix F, this section provides guidance in estimating uncertainties for the results of the measurements in section 4, and presents procedures for demonstrating that the assigned uncertainties are reasonable.

NOTE: The procedures described in this section are not part of routine calibration procedures. They are performed once, before establishing a calibration service. It may never be necessary to repeat these procedures if a control interferometer is periodically measured and continues to give results consistent with history, and if recalibration of important subsystems of the master interferometer is carried out on a periodic basis as described in Nonmandatory Appendix D.

It is necessary to estimate the uncertainty of the test results of section 4; that is, it is necessary to assign an uncertainty to the measurements of length-dependent error, LDE_C, and the zero drift, D. The uncertainty in the zero drift may be estimated based on tests described in para. 5.2.

The uncertainty in the length-dependent error, $U_{LDE,C}$, arises from the following three sources:

(a) variations in the interferometer under test

(b) uncertainty in the master interferometer

(c) uncertainty associated with the comparison procedure

Uncertainties in both the master interferometer and in the comparison procedure can be further subdivided into two categories: short-term variations that show up during repeated runs, and additional uncertainty that remains constant through a set of runs. All sources of short-term variability are quantified by the repeatability of the 10 runs that constitute a test, as measured by the standard deviation, σ_L, of para. 4.6.2. Additional measurements, as described here, are needed to quantify errors that do not vary during the 10 runs in a test; these uncertainties are defined as u_c, the uncertainty of the comparison process that does not vary from one run to

Form 4.10-1 Reporting Results for Intercomparison Test

Comparison test method	B89.1.8 — Method 1: Folded Path Method
Test range	0 m to 2 m
Air refraction compensation	Enabled
Material temperature compensation	Disabled (0 parts in 10^6)
Elapsed time prior to starting measurements	20 min
Readout averaging mode	Long term (5 s)
Ambient conditions	23.2°C 101 250 Pa 56% RH
Length-dependent error ($LDE_C \pm U_{LDE,C}$)	+5 parts in 10^6 ± 0.3 parts in 10^6
Zero drift of test laser over first hour ($D \pm U_D$)	100 nm ± 5 nm
Length-independent error ($LIE \pm U_{LIE}$) [Note (1)]	10 nm ± 3 nm
Date of calibration	21-Jan-2001

NOTE:
(1) Optional.

Form 4.10-2 Reporting Results for Sensor Calibration

Air temperature sensor test range	10°C to 30°C
Maximum air temperature sensor error ($ATE \pm U_{ATE}$)	0.5°C ± 0.1°C
Air pressure sensor test range	80 kPa to 110 kPa
Maximum air pressure sensor error ($APE \pm U_{APE}$)	105 Pa ± 5 Pa
Air humidity sensor test range	25% RH to 75% RH
Maximum air humidity sensor error ($AHE \pm U_{AHE}$)	12% RH ± 3% RH
Material temperature sensor test range	10°C to 30°C
Maximum material temperature sensor error ($MTE \pm U_{MTE}$)	0.5°C ± 0.1°C
Date of calibration	21-Jan-1999

GENERAL NOTE: If any sensors are not part of the system, then enter "not applicable" in the right-hand column.

Form 4.10-3 Reporting Overall Result

Length-dependent error ($LDE \pm U_{LDE}$)	+5 parts in 10^6 ± 0.3 parts in 10^6 (displacement in air) +8 parts in 10^6 ± 1 part in 10^6 (measuring steel) [Note (1)]
Zero drift of test laser over first hour ($D \pm U_D$)	100 nm ± 5 nm
Length-independent error ($LIE \pm U_{LIE}$) [Note (2)]	10 nm ± 3 nm

NOTES:
(1) Calculated assuming a thermal expansion coefficient of 12 parts in 10^6/°C.
(2) Optional.

the next, and u_m, the uncertainty of the master interferometer that does not vary from one run to the next. As stated in para. 4.6.2, $U_{LDE,C}$ is found by combining these three sources of uncertainty as follows:

$$U_{LDE,C} = 2 \times \sqrt{\sigma_L^2 + u_m^2 + u_c^2} \qquad (19)$$

where

u_c = an estimated standard uncertainty of the *LDE* that arises from the comparison procedure (primarily from alignment errors). This uncertainty is evaluated as shown in para. 5.2.

u_m = the additional standard uncertainty of the master interferometer. This depends primarily on uncertainties in the atmospheric sensors and vacuum wavelength of the master laser, as discussed in para. 5.1.

σ_L = the uncertainty contribution from run-to-run variations, as discussed in para. 4.6.2.

5.1 Verifying Performance of the Master Interferometer: Estimating u_m

Length-proportional uncertainty of the master interferometer, u_m, can be determined through suitable testing supplemented by an uncertainty budget.

Testing is required to verify the length-dependent uncertainty of the master interferometer. The preferred method for doing this is to calibrate the master interferometer system as a whole against a second interferometer system higher up the traceability chain that is traceable to national or international length standards. Any other method that provides traceability to national standards is also allowed. For example, if the master interferometer is integrated into a system for measuring the length of physical artifacts, its uncertainty could also be established by measuring the known length of a traceable artifact. In either case, the test should provide an estimate of the *LDE* of the master interferometer system and an uncertainty for this value.

Testing determines LDE_C (para. 4.6.1) and $U_{LDE,C}$ (para. 4.6.2) for the master interferometer. The determination of LDE_C and $U_{LDE,C}$ is carried out by comparison of the master to a second interferometer (which might be described as a super-master) that is traceable to national standards. This comparison is essentially the same as any other calibration. However, there are some small operational details that may be different, and if run-to-run variations, σ_L, are large it is permissible to reduce this contribution to the uncertainty (see Nonmandatory Appendix F).

When the measured error of the master interferometer is LDE_C, measured with expanded uncertainty, $U_{LDE,C}$, a reasonable expanded uncertainty to assign to the master interferometer ($U_m = 2u_m$) would be $|LDE_C| + U_{LDE,C}$. Thus the minimum value that should be assigned to U_m is

$$U_m \geq U_{LDE,C} + |LDE_C| \qquad (20)$$

This expanded uncertainty, U_m, is large enough that it plausibly accounts for any possible *LDE*s in the master interferometer at the time when it was calibrated. U_m should be increased from this value using an uncertainty budget-type approach to account for any sources of error that are not tested directly. For example, slow drift in the calibration of the atmospheric sensors will increase the uncertainty over time, and this may be included in U_m by adding an estimate of the drift, X, in quadrature as follows:

$$U_m = \sqrt{(U_{LDE,C} + |LDE_C|)^2 + X^2} \qquad (21)$$

An example showing how U_m might be calculated, including drift of several sensors, is shown in Nonmandatory Appendix F. Note that according to the prescription given here, the length-dependent uncertainty claimed for the master interferometer should never be smaller than the total length-dependent uncertainty with which it is tested.

5.2 Verifying Performance of the Comparison Procedure: Estimating u_c and U_D

Uncertainty of the comparison process can be experimentally established by repeated measurements of a second interferometer system of good quality. The second system is herein referred to as the control interferometer. The testing procedure described below should be carried out to establish that uncertainty estimates for the comparison procedure are realistic.

This test involves performing six or more independent comparisons of the master and control interferometers. The control interferometer should be of a quality at least as good as that of the master. The six comparisons are done according to the prescription of section 4, subject to the following comments and modifications:

(a) The comparison of master and control interferometers should be carried out using whatever procedures are used in a standard comparison of the master to a test interferometer, except where noted otherwise below. If calibrations are normally done under computer control, then this comparison should be done under computer control, but if readings are normally taken manually, the test described here should be done with manual data collection. The master should be operated in the same manner that is normally used when testing interferometer systems. For example, if the master is normally warmed up for a longer period of time than recommended by the manufacturer (to achieve greater stability), it should be tested here in the same manner.

(b) The control interferometer should be operated in a manner that gives the best possible results. For example, it may be warmed up for a longer period of time than suggested by the manufacturer if the additional warm-up improves results.

(c) For a realistic estimate of uncertainty, it is important that the six comparisons sample the full variety of errors that will be encountered during routine testing. The interferometers should be realigned between each of the six tests so as to sample alignment errors. The Abbe offset should be independently readjusted to zero for each comparison when using comparison Methods 2 or 4 in Nonmandatory Appendix B.

(d) The two interferometers should be tested with the atmospheric compensation for both interferometers set to standard conditions. The procedure for this test is as follows:

(1) Six comparisons of the two interferometers must be carried out, where a comparison consists of 10 runs. For each comparison, follow the procedure in paras. 4.1 through 4.5 with the modifications given above.

(2) Every other comparison should be done in a reversed configuration. In a normal comparison, the control interferometer is mounted in the manner normally used for the test interferometer and the master is mounted in its usual location. In a reversed configuration, the control interferometer (all components — laser and optics) is mounted where the master is normally mounted, and the master is mounted in the manner normally used for the test interferometer. Denoting a normal configuration as *N*, and a reversed configuration as *R*, the order of the six comparisons is *N, R, N, R, N, R*.

NOTE: When making a reversed test, the master is still the master, for purposes of analysis, even though it is mounted in the reverse position.

(3) If it is desired, more reliable results can be obtained by carrying out more than six comparisons, continuing to reverse the configuration for every additional comparison as described in (2) above.

(4) Find the standard deviation of the six (or more) values obtained for *LDE*. The result is the minimum value that should be quoted for u_c, the contribution to the uncertainty of *LDE* that arises from the comparison procedure. [See Note (1).] If there is reason to believe that this test might not sample the full range of errors that will be encountered in everyday testing, it may be desirable to quote a larger value of u_c based on an uncertainty budget approach, but a smaller value of u_c should never be quoted.

(5) For each of the six comparisons, calculate the zero drift as in para. 4.6.3. Twice the RMS average of these six results is the minimum value that should be quoted for the expanded uncertainty in the zero drift measurement, U_D.

(6) Although a minimum of six repeated comparisons is recommended to obtain a statistically meaningful result, it may be desirable to perform more runs to improve confidence in the results of this test.

(7) It is not necessary or desirable to do all six tests, one directly after the other. Rather, they should be spread out in time as much as practical, so as to sample the full variety of environmental conditions that might be encountered in the lab.

NOTES:
(1) *LDE*s in the control interferometer system need not be known when determining u_c with this technique; if *LDE*s in the master and control interferometers are repeatable, they do not contribute to the standard deviation. Most repeatable errors that arise in the comparison procedure will switch signs when the master and control interferometers are physically interchanged, and hence will contribute to the standard deviation.
(2) Although the *LDE* of the control interferometer need not be known to carry out this test, if the *LDE* is known from previous measurements, it would be of much interest to compare the *LDE* value measured here with this known value. The two values should agree within their combined uncertainty.

6 MEASUREMENT EVALUATION

To evaluate like systems from competitive vendors or make estimates of measurement uncertainty using a laser interferometer, this section offers a sample uncertainty budget. An uncertainty budget is a method of combining uncertainties in each of the variables that affect a measurement, as shown in the sample spreadsheets of Forms 6-1 and 6-2. For example, in Form 6-1, the values listed under the heading "Lowest Achievable Uncertainties of Measurement" combine all the individual uncertainty components into an overall uncertainty for several different kinds of measurements. The tables include both components of uncertainty that are independent of the measured length and components that are proportional to the length. The length-proportional uncertainties are expressed as parts in 10^6 (equivalently, μm/m).

This section of the Standard contains a fill-in-the-blanks uncertainty budget for users to evaluate their individual system measurement uncertainty or compare potential interferometer systems with each other. The user is expected to fill in appropriate numbers in the spreadsheets, and then the spreadsheet will calculate the overall uncertainty of measurement. (The numbers shown in Forms 6-1 and 6-2 are intended to be realistic, but these numbers can vary widely in actual practice and must be replaced with suitable values by the user.) The evaluation method is broken down into two sections. The first part of the uncertainty budget deals with the sources of error associated with the laser interferometer itself. The second part has to do with application factors, such as environment, laser beam and interferometer alignment, machine temperature, material coefficient of expansion, etc. The first section is used to

Form 6-1 Sample Uncertainty Budget: Errors Predictable by Manufacturer

For:
Laser wavelength: 633 nm
Interferometer: Single pass
Operating range of atmospheric parameters: P = 80 000 Pa to 107 000 Pa (600 to 800 mm Hg), T = 10°C to 30°C
All uncertainties given here are expanded uncertainties with coverage factor k = 2

Uncertainty in Physical Property				Resultant Length Measurement Uncertainty	
1 Laser Wavelength	**Uncertainty**		**Multiplier**	**Length Dependent, µm/m**	**Length Independent, nm**
(a) Vacuum wavelength	0.08	$\times 10^{-6}$	1	0.08	
Air Refraction Compensation					
(b) Air pressure	70	Pa	0.0027	0.19	
(c) Air temperature	0.15	°C	0.93	0.14	
(d) Air humidity (@ 30°C)	15	%RH	0.015	0.23	
(e) Carbon dioxide concentration	460	$\times 10^{-6}$	0.00015	0.07	
(f) Refractive index calculation	0.04	$\times 10^{-6}$	1	0.04	
(g) **Total wavelength uncertainty**				**0.34**	
2 Material Thermal Expansion Compensation	**Uncertainty**			**Length Dependent**	**Length Independent**
(a) Material temperature sensor	0.07	°C			
(b) Steel thermal expansion compensation	@		12.0×10^{-6}/°C	**0.84**	
(c) Aluminum thermal expansion compensation	@		22.0×10^{-6}/°C	**1.54**	
3 Length-Independent Errors	**Uncertainty**		**Multiplier**	**Length Dependent**	**Length Independent**
(a) Optical and electrical nonlinearities	0.02	wavelengths	633		13
(b) Resolution	10	nm	0.577		6
(c) Noise	3	nm	1		3
(d) Zero offset	14	nm	1		14
(e) **Total length-independent uncertainty**					20
4 Zero Drift	**Uncertainty**		**Multiplier**	**Length Dependent**	**Length Independent**
	15	nm	1		15
5 Miscellaneous				**Length Dependent**	**Length Independent**
				0.01	0

Manufacturer's Reported Uncertainty			
Lowest Achievable Uncertainties of Measurement		**Length Dependent, µm/m**	**Length Independent, nm**
6 Linear Displacement Measurement in Vacuum		0.08	25
7 Linear Displacement Measurement in Air		0.34	25
8 Linear Dimensional Measurement of Steel Component in Air		0.91	25
9 Linear Dimensional Measurement of Aluminum Component in Air		1.58	25
10 Optics Thermal Drift	20 nm/°C		
11 Wavefront Aberrations	0.15 wavelengths		

GENERAL NOTE: For a detailed explanation of this spreadsheet, see Nonmandatory Appendix A.

Form 6-2 Sample Uncertainty Budget: Combining Manufacturer's Reported Uncertainty With Additional Sources of Error for a Metrology Laboratory

Manufacturer's Reported Uncertainty				
Lowest Achievable Uncertainties of Measurement			**Length-Dependent Uncertainty, μm/m**	**Length-Independent Uncertainty, nm**
Linear Displacement Measurements				
1 In vacuum			0.08	25
2 In air			0.34	25
Linear Dimensional Measurements of Components in Air				
3 Steel thermal expansion	@	12.0×10^{-6}/°C	0.91	25
4 Aluminum thermal expansion	@	22.0×10^{-6}/°C	1.58	25
5 **Optics Thermal Drift**	20	nm/°C		
6 **Wavefront Aberrations**	0.15	wavelengths		
Additional Sources of Uncertainty				
7 **Possible Misalignment**	0.4	mm/m	**Length-Dependent Uncertainty, μm/m**	**Length-Independent Uncertainty, nm**
(a) Beam diameter	5	mm		
(b) Cosine error			0.08	
(c) Effect of aberrations			0.03	
(d) **Total alignment uncertainty**			0.09	
8 **Air Temperature Effects**				
(a) Uncertainty from gradient	0.3	°C	0.28	
9 **Part Temperature Effects for Steel**	@	**12.0×10^{-6}/°C**		
(a) Uncertainty from gradient	0.05	°C	0.60	
(b) Deviation from 20°C	0.5	°C		
(c) Uncertainty in expansion coefficient	1	$\times 10^{-6}$/°C	0.50	
(d) **Total uncertainty from setup-dependent part temperature effects**			0.78	
10 **Optics Thermal Drift**				
(a) Possible drift in optics temperature	0.3	°C		6
11 **Deadpath**				
(a) Deadpath length	50	mm		
(b) Possible air temperature change	0.1	°C		
(c) Possible air pressure change	100	Pa		
(d) **Possible deadpath error**				18
Summary				
			Length-Dependent Uncertainty, μm/m	**Length-Independent Uncertainty, nm**
12 **Final Interferomtry Uncertainty for Measurement of Steel Part in Air**			1.23	31
13 **Total Uncertainty, When Part Length Is** 0.5 **m, Will Be** 618 **nm**				

GENERAL NOTE: For a detailed explanation of this spreadsheet, see Nonmandatory Appendix A. Also note that, in many environments, factors such as air temperature gradients or deviations of the measurement temperature from 20°C may be much bigger than the values given.

compare interferometer systems from different vendors and relies primarily on data obtained from the manufacturer. The uncertainties given in this form would be expected to be consistent with the results of the testing described in section 4. The second part of the uncertainty budget is filled out, evaluated, and combined with the first part to arrive at a total estimate of the uncertainty in a real-world length measurement. In the second section, estimates of the various sources of error are provided and with proper caution could be used as is or with other values substituted, as experience and circumstance dictate.

Once the blanks have been filled in, each of the quantities is squared. All squared estimates are then summed and the square root of the sum is taken. The result is a final number, usually expressed in parts per million (parts in 10^6), that is the final uncertainty value. To make these calculations easier for the user, an Excel spreadsheet is available from the ASME B89 website (go.asme.org/B89committee) as part of this Standard. Nonmandatory Appendix A will provide detailed information for filling in and evaluating the uncertainty budget.

NOTE: As a practical matter, the various components of an interferometer can be tested at different laboratories and combined via the uncertainty budgets (or equivalently, the procedure described in paras. 4.7 through 4.9) to obtain a valid B89 test of an interferometer system.

7 REFERENCES

The following is a list of publications referenced in this Standard. This selected bibliography is not intended to be comprehensive, but it provides a starting point for background reading related to this Standard. The articles cited here contain numerous additional references that, taken together, should provide a good overview of the field.

[1] ASME B89.4.19-2006, Performance Evaluation of Laser-Based Spherical Coordinate Measurement Systems

[2] ASME B5.54-2005, Methods for Performance Evaluation of Computer Numerically Controlled Machining Centers

[3] ASME B5.57-1998, Methods for Performance Evaluation of Computer Numerically Controlled (CNC) Lathes and Turning Centers

[4] ISO 230-1:1996 Test code for machine tools — Part 1: Geometric accuracy of machines operating under no-load or finishing conditions

[5] ISO 230-2:2006, Test code for machine tools — Part 2: Determination of accuracy and repeatability of positioning numerically controlled axes

[6] ISO 230-3:2007, Test code for machine tools — Part 3: Determination of thermal effects

[7] ISO 230-6:2002, Test code for machine tools — Part 6: Determination of positioning accuracy on body and face diagonals (Diagonal displacement tests)

[8] JCGM 200:2008, International Vocabulary of Metrology — Basic and General Concepts and Associated Terms (VIM), Third Edition [http://www.bipm.org/en/publications/guides/vim.html (accessed January 25, 2012)]

[9] JCGM 100:2008, Evaluation of measurement data — Guide to the expression of uncertainty in measurement (GUM). Available at http://www.bipm.org/en/publications/guides/gum.html (accessed January 25, 2012). (This is the definitive publication on uncertainty.)

[10] ASME B89.1.5-1998, Measurement of Plain External Diameters for Use as Master Discs or Cylindrical Plug Gages

[11] ASME B89.6.2-1973, Temperature and Humidity Environment for Dimensional Measurement

[12] ASME B89TR-1990, Parametric Calibration of Coordinate Measuring Machines (CMM)

[13] ASME B89.3.4-2010, Axes of Rotation: Methods for Specifying and Testing

[14] Norman Bobroff, "Recent advances in displacement measuring interferometry," *Meas. Sci. Tech.* 4, 907–926 (1993). (A comprehensive article including many references to earlier work.)

[15] Norman Bobroff, "Residual errors in laser interferometry from air turbulence and nonlinearity," *Applied Optics* 26, 2676–2682 (1987). (An important early study of fringe interpolation errors.)

[16] C. R. Steinmetz, "Sub-micron position measurement and control on precision machine tools with laser interferometry," *Prec. Eng.* 12, 12–24 (1990). (A seminal study of interferometry in precision engineering applications.)

[17] Jack A. Stone and Lowell Howard, "A simple technique for observing fringe interpolation errors in Michelson interferometers," *Prec. Eng.* 22, 220–232 (1998). (The article contains numerous additional references to methods for measuring fringe interpolation errors.)

[18] H. Kunzmann and K. Herrman, editors, "Calibration and testing of laser interferometers" (collection of papers and printed information of participants in Euromet Conference on Calibration and Testing of Laser Interferometers, 1992, Berlin), PTB report PTB-F-15, Braunschweig, Oct. 1992. (This reference is a conference proceeding that includes many articles on the calibration techniques described in Nonmandatory Appendix B of this Standard.)

[19] M Schröck and H.-H. Schüßler, "Testing of absolute laser interferometers — procedures, results, and experiences," *VDI-Berichte* 1118, VDI-Verlag, Düsseldorf (1994).

[20] G. Sparrer, "Meßanordnungen zur Kalibrierung kompletter Laserinterferometer," *Microtecnic* 3, 27–32, (1994). (The English translation, "Measuring instruments for the calibration of complete laser interferometers," is available from the author.)

[21] G. Sparrer, "Calibration of complete laser interferometers for length measurements," 2002.

[22] H.-H. Schüßler, "Comparison and calibration of laser interferometer systems," *Measurement* 3, 175–183 (1985). (Description of common optics comparison method.)

[23] W. Dutschke, H. Richers, H. Jaklin, and C. Linhart, "Vorrichtung zum Einmessen (Kalibrieren) von Laserinterferometern," OS G01B 9/02 DE 2722887 B1, 20.05.79. (Description of the back-to-back comparison method.)

[24] VDI-Bericht 750 Dokumentation, "Genauigkeit von Laserinterferometersystemen," VDI-Verlag, Düsseldorf, 1989. (Description of the compensated back-to-back method.)

[25] G. Sparrer, "Anordnung zum direkten Vergleich und zur Kalibrierung von Laserinterferometern," OS G01B 9/02 DE 4208189 A1, 08.04.93. (Descriptions of folded-path comparison.)

[26] G. Sparrer, "Anordnung zum direkten Vergleich sowie zur Kalibrierung von Laserinter-ferometern und zur Präzisionsmessung mit einem Laserinterferometer," OS G01B 9/02 DE 4236993 A1, 18.11.93.

[27] K.P. Birch and M.J. Downs, "Correction to the updated Edlén equation for the refractive index of air," *Metrologia* 31, 315–316 (1994).

[28] G. Bonsch and E. Potulski, "Measurement of the refractive index of air and comparison with modified Edlén's formulae," *Metrologia* 35, 133–139 (1998).

[29] Jack A. Stone and Jay H. Zimmerman, "Index of refraction of air," http://emtoolbox.nist.gov/Main/Main.asp (accessed January 25, 2012).

[30] Phillip E. Ciddor, "Refractive index of air: new equations for the visible and near-infrared," *Applied Optics* 35, 1566–1573 (1996).

[31] Jean M. Rüeger, "Refractive Index Formulae for Electro-optical Distance Measurement," Paper TS28/1, XXIst International Congress of Surveyors (FIG'98), July 19–25, 1998, Brighton, UK.

[32] Jean M. Rüeger, "Refractive indices of light, infrared and radio waves in the atmosphere," UNISURV report S-68, University of New South Wales, UNSW Sydney NSW 2052, Australia, 2002.

[33] ASME B89.7.3.2-2007, Guidelines for the Evaluation of Dimensional Measurement Uncertainty

[34] ANSI/NCSL Z540-2-1997, U.S. guide to the expression of uncertainty in measurement. (The U.S. edition of GUM).

INTENTIONALLY LEFT BLANK

NONMANDATORY APPENDIX A
UNCERTAINTY BUDGET FOR INTERFEROMETRIC LENGTH MEASUREMENTS

A-1 INTRODUCTION

This Nonmandatory Appendix covers errors in interferometric length measurements. The purpose of this Nonmandatory Appendix is to alert the reader to significant sources of error and to provide a framework for estimating the uncertainty of a measurement (see also the practical discussion of avoiding errors in Nonmandatory Appendix C). Although most of the errors covered here are common to any interferometric measuring process, the emphasis is directed toward fringe-counting displacement interferometry over distances typically encountered in manufacturing processes, ranging from submillimeter to tens of meters.

Errors particular to other types of systems, such as multicolor interferometry based on the method of exact fractions, are beyond the scope of this Nonmandatory Appendix. In addition, this Nonmandatory Appendix considers only static errors in the interferometer. Dynamic applications require corrections for time delays that might be introduced by electronics or data processing (including analog or digital filtering). Furthermore, it should be emphasized that the errors considered in this Nonmandatory Appendix are primarily those associated with interferometric measurement of the displacement of a moving retroreflector, not the entire range of errors associated with measuring a physical artifact. Any real measuring system that employs interferometry (either directly, to establish the scale, or indirectly, to map certain mechanical errors) will be subject to many sources of error in addition to those discussed here. These include errors arising from Abbe offsets in conjunction with angular imperfections of the measuring machine (pitch, yaw, and roll errors), misalignment of the interferometer measurement axis with the dimension to be measured, and small-scale errors in defining locations of specified features, such as errors in the probing system, errors arising from finite sampling of imperfect feature geometry, or errors due to dirt on the surface of the feature.

This Nonmandatory Appendix only summarizes all the possible error sources that affect interferometric measurements. Numerical values given for uncertainties in this Nonmandatory Appendix are all expanded uncertainties with a coverage factor of $k = 2$ (estimated two-sigma values). Except where explicitly stated otherwise, normal distributions may be assumed and, consequently, $k = 2$ corresponds to a 95% confidence interval.

A-2 SOURCES OF ERROR

Errors may be divided into several general categories, including errors proportional to length, errors independent of length, and errors from miscellaneous sources.

A-2.1 Errors Proportional to Length

Table A-2.1-1 lists some of the larger sources of error that are proportional to the measured length. The table shows the magnitude of the uncertainty in a physical quantity that would produce a 1×10^{-7} (0.1 μm/m) fractional uncertainty in the measured length. Paragraphs A-2.1.1 through A-2.1.3 give a brief description of these errors and some additional, smaller errors.

A-2.1.1 Wavelength Errors. An interferometer measures length in terms of the wavelength of some laser radiation in air. Typically the total uncertainty in wavelength arises from the following two contributions:

(a) a small uncertainty in the vacuum wavelength of the laser

(b) larger uncertainties due to determination of the index of refraction of air (or compensation value) that is required to relate the vacuum wavelength to a wavelength in air

NOTE: This two-step process (stabilizing the vacuum wavelength and determining the wavelength in air from the index of refraction) is not universally employed; it is also possible to determine the wavelength in air directly. This method is not used widely and will not be discussed here, other than to note that the accuracy depends on the mechanical stability of wavelength-sensitive elements, the quality and stability of associated electronics, and possible differences in air temperature (or other atmospheric parameters) between the wavelength-sensing element and beam path.

At present, almost all interferometers employ a red (633 nm) He–Ne laser as a light source. The vacuum wavelength of this laser is easily determined by comparing the laser frequency to the frequency of an iodine-stabilized laser, an internationally recognized frequency/wavelength standard. The intrinsic uncertainty of this calibration is very small (uncertainties smaller than one part in 10^{10} are routinely achievable), so that as a practical matter, the uncertainty in vacuum wavelength is determined by drift of the laser wavelength

Table A-2.1-1 Major Length-Dependent Errors: Uncertainties in Various Physical Parameters That Produce a 0.1 Part in 10^6 Uncertainty in Interferometric Length Measurements

Physical Quantity	Variation Causing a 0.1 Part in 10^6 Change in Measured Length
Vacuum wavelength	0.00006 nm (0.1 parts in 10^6 of 633 nm)
Air pressure	37 Pa (0.28 mm of Hg)
Air temperature	0.11°C (0.20°F)
Humidity	12% RH at 20°C
CO_2 concentration	670 parts in 10^6
Part temperature	0.01°C for steel; 0.005°C for aluminum
Uncertainty in expansion coefficient	1 part in 10^6/°C (if part temperature is 0.1°C away from 20°C)
Alignment	0.45 mm/m (θ = 0.45 mrad)

GENERAL NOTE: Entries in the table have been calculated for visible light and standard conditions (P = 101 325 Pa = 760 mm, T = 20°C, RH = 50%). See the accompanying text for a discussion of additional errors that are not expected to ever be as large as 0.1 parts in 10^6.

between calibrations. In almost all cases, the vacuum wavelength does not drift by more than 0.1 parts in 10^6/yr (unless the stabilization electronics fail or optical components become badly misaligned), and some lasers achieve better than this level of stability over the lifetime of the tube.

For other types of lasers, it may be more difficult to determine the vacuum wavelength. For some types of lasers there is little information available regarding the long-term stability of the vacuum wavelength.

Larger errors are associated with determination of the index of refraction of air. The index of refraction may be determined by one of several methods, such as the use of a refractometer, multicolor interferometry, or calculation of the index of refraction based on measurements of the atmospheric temperature, pressure, and humidity. The last of these methods is most commonly used and is the subject of the following uncertainty analysis. At present, the index of refraction is most commonly calculated using some form of the Edlén equation [27–29] or the Ciddor formulation [29–32].

The Edlén or similar equations provide a method for calculating the index of refraction of air when the pressure, temperature, and atmospheric composition are known. It is usually assumed that the composition of the air varies only due to change in the content of water vapor. This assumption is not always justifiable if accuracies on the order of 0.1 parts in 10^6 are required, because elevated levels of carbon dioxide can cause errors of this magnitude. Other atmospheric contaminants, such as vapor from industrial solvents, might produce similar errors if present in high concentrations.

The expanded uncertainty of updated versions of the Edlén equation is believed to be 0.02 parts in 10^6 when operating near standard conditions, or about 0.04 parts in 10^6 over a range of operating conditions characteristic of commercial interferometers. Uncritical application of Edlén's original version of the equation without the later modifications may give errors in excess of 0.1 parts in 10^6.

Measurements of pressure and temperature are usually the major sources of error in determining the index of refraction. For a red laser and near-standard atmospheric conditions, an error in pressure measurement of 130 Pa (1 mm Hg) will result in an error (proportional to the length measured) of 0.36 parts in 10^6. The same error would occur if air temperature measurement were in error by 0.4°C.

Humidity measurements are much less critical than pressure and temperature measurements; even if humidity is not measured but is simply assumed to be 50%, the maximum measurement error at 20°C is 0.4 parts in 10^6. At 40°C, this maximum error increases to 1.3 parts in 10^6.

Carbon dioxide levels are not usually measured. In a small room with several people present, CO_2 levels will be elevated, but the resulting error is not expected to exceed 0.1 parts in 10^6, even in extreme conditions.

A-2.1.2 Part Temperature. Many commercial interferometers provide part temperature measurement as a component of their overall system. Two sources of error, both associated with part temperature, are often major components of the overall length-dependent measurement error.

(a) An error in temperature measurement of ΔT produces a fractional error in a measured length of $\alpha \times \Delta T$, where α is the coefficient of expansion. For steel, α can range from 10.5 parts in 10^6/°C to 13 parts in 10^6/°C; in this Standard, 12 parts in 10^6/°C is used as a typical value.

(b) An additional error arises from uncertainty of the coefficient of expansion, α, when measurements are not performed exactly at 20°C (68°F). If the uncertainty is $\Delta\alpha$ and measurements are carried out at temperature T, the resulting uncertainty is $\Delta\alpha \times |T - 20|$. For steel, α is often uncertain by about 1 part in 10^6/°C.

A-2.1.3 Alignment Errors. Errors result from misalignment of the laser beam with the direction of the displacement of the retroreflector. If these two directions are misaligned by an angle θ, the resulting error in measuring a length L is equal to

$$(\cos\theta - 1)L \approx -L\theta^2/2$$

where L is the distance measured, and the angle θ is measured in radians. Alignment errors are apparent in that the beam "walks" across the receiver during the displacement. If the return beam moves across the receiver by a distance d when the retroreflector is displaced a distance x, then the misalignment is $\theta = (d/2x)$ for a single-pass interferometer.

This alignment error always makes the measured path look smaller than the actual value of the displacement of the retroreflector. The user of an interferometer should attempt to estimate a typical alignment error and correct his/her measurements accordingly. More precisely, according to Section F.2.4.4 in reference [9], the user should estimate a standard uncertainty for the alignment, $u(\theta)$, and add to the measured length an estimated correction factor, $L[u(\theta)]^2$. Note that there is no factor of ½ here if it is assumed that angular errors can occur in two dimensions. The corresponding expanded uncertainty in the measured length, with a coverage factor of two, is $2L[u(\theta)]^2$. If the estimated alignment error, including the usual coverage factor of two, is denoted as $\Delta\theta$ [so that $\Delta\theta = 2u(\theta)$], then the estimated expanded uncertainty of the measured length is $L(\Delta\theta)^2/2$.

NOTE: In addition to the alignment error described here, which is intimately associated with the interferometry and always makes the measured path look smaller than its actual value, there are often additional alignment errors associated with specific measurement tasks; in some cases these errors may make the measured dimension appear too big while in other cases it will appear too small.

A-2.2 Errors Independent of Length

These errors are typically not as important as the *LDE*s discussed in para. A-2.1, except when measuring small displacements of 100 mm or less.

A-2.2.1 Fringe Interpolation. Interpolation errors may arise from polarization mixing or frequency mixing in two-frequency systems, poor mode purity of the laser, reflections from optical surfaces in the beam path, imperfections in the interpolation electronics, or misalignment of a polarizing beamsplitter relative to the laser head. Methods of detecting such errors are discussed in references [14–17]. The combined effect of these errors is usually less than 10 nm for commercial systems, but some exceptions are noteworthy. The resolution of the interferometer display also sets a limit on the minimum possible interpolation errors. Some interferometer systems have no subfringe resolution and consequently have relatively large interpolation errors.

A-2.2.2 Air Dead Path Error. Some commercial systems can automatically correct for dead path errors. If no such correction is used, then uncorrected dead path errors will give rise to an uncertainty in the measurement. This uncertainty is usually not significant unless the fringe-counting electronics are zeroed at a position where the moving retroreflector is far from the remote interferometer. Dead path errors result when the following two conditions simultaneously occur:

(a) There is a difference in the air paths between the reference arm and measuring arm of the interferometer at the point where the interferometer is zeroed. Typically, the reference arm is very short, and the difference in air paths is of marginal importance if the interferometer can be zeroed when it is located close to the interferometer's beamsplitter. If it is necessary to zero the interferometer when the retroreflector is far from the beamsplitter, care must be taken to account properly for dead path errors.

(b) There is a variation in laser wavelength during a measurement. Most commonly, the wavelength varies in response to variations in pressure or possibly temperature, resulting in variations of the index of refraction. In unusual circumstances, the variations might arise from variations in the vacuum wavelength of the laser, particularly if optical elements in the beam path cause small reflections back into the laser that can result in substantial fluctuations in the laser frequency.

If a displacement is calculated using the compensation value updated at the end of the measurement, then the dead path error can be simply expressed as an error independent of length (a shift in the interferometer zero position). The magnitude of the error for a single-pass interferometer is

$$\text{(air dead path length)} \times (\Delta\lambda/\lambda)$$

where

$(\Delta\lambda/\lambda)$ = the fractional change in wavelength

For example, if the uncompensated distance is 0.5 m and a pressure variation of 133 Pa (1 mm Hg) causes a corresponding change in wavelength $(\Delta\lambda/\lambda) = 0.36$ parts in 10^6, then the dead path error would be 180 nm. Additional errors proportional to length will occur if the displacement is not calculated using the compensation value current at the end of the measurement. Dead path is often misinterpreted; consult a more detailed reference if it is necessary to make significant dead path corrections.

A-2.2.3 Optical Thermal Drift. Variations in the optical path length due to temperature variations of optical components may be a problem in systems not specifically designed to compensate for this effect. Even compensated systems will exhibit drift if heating of all optical components is not uniform, or if the optical components are not mounted well within their metal housings. Many systems exhibit a zero-point drift on the order of 1 μm/°C change in the optics temperature. For some interferometer designs, the zero drift, as described in section 4, may be a consequence of optics thermal drift of components mounted in the interferometer head, subject to heating as the head warms up. However, this is a separate entry in the spreadsheet, to be distinguished from the thermal drift associated with changes in ambient temperature.

A-2.3 Miscellaneous Sources of Error

Other sources of error that might become important in some circumstances are listed below.

(a) Gross errors may occur if the interferometer miscounts fringes or if there are computational errors in the interferometer firmware. Electronic faults or sensitivity of the electronics to electrical interference at any point in the circuit may cause errors of any magnitude. Large errors may occur if the interferometer does not detect beam interruption correctly.

(b) Electronics noise may produce significant random fluctuations in the results. Noise in the fringe interpolation circuitry might generate small errors independent of displacement, and noise in environmental sensors can generate errors that increase with increasing displacement.

(c) Optics flatness and wavefront aberrations or tilt may cause small errors. If the reference and measurement wavefronts are aberrated or if they are tilted relative to each other (a consequence of improperly manufactured corner cubes), then the phase of interference varies across the region of overlap of the two beams. Any variation in the overlap of the measurement and reference beams will then give rise to an error in the measured length. A change in overlap will occur, for example, if the interferometer is misaligned by an angle θ and is displaced by some distance x, so that the return beam shifts in position by $2\theta x$. For plane mirror interferometers, similar errors occur when the angle of the plane mirror rotates as it is displaced.

The magnitude of the resulting errors (usually very small) may be estimated as follows. Suppose that the wavefront tilt or aberration across the reference and measurement beams is a fraction δ of the wavelength λ (typically δ is on the order of $\frac{1}{8}$ wavelength or larger). If misalignment causes the measurement beam to shift relative to the reference beam by an amount equal to its radius, it can be expected that the resulting error will be somewhat smaller than $\delta\lambda$. Because the shift in relative position of the two beams, $2\theta x$, is proportional to displacement, the resulting error can be approximated as an error proportional to the measured displacement, x, as follows:

$$\text{error from wavefront aberrations and misalignment} \approx \delta\lambda(2\theta x/r)$$

where r is the beam radius.

(d) Air turbulence can give rise to significant errors in certain applications. The amplitude of fluctuations due to air turbulence is expected to increase approximately as the square root of distance between the interferometer's beamsplitter and the moving retroreflector. In a quiet laboratory, fluctuations when measuring a 4-m path are on the order of 0.25 μm over a 10-s time interval.

(e) Mechanical vibrations may significantly limit interferometer performance.

(f) Some interferometer systems are subject to a one-count ambiguity following zeroing of the interferometer.

(g) Other small effects should be mentioned, although they are unlikely to cause significant problems. Diffraction of the laser beam, for example, typically does not cause a problem except when working at very high accuracy in the infrared. Pitch or yaw of a solid retroreflector by angles in excess of 1 deg must be avoided or small errors will result. Finally, with an unfavorable setup, small variations in the angle of the laser head relative to the interferometer can generate errors. Although these errors are typically very small in magnitude, under some circumstances they can be much larger than would be calculated based on the previous discussion of alignment errors.

A-2.4 Summary: Error Sources and Methods for Estimating the Corresponding Measurement Uncertainties

Table A-2.4-1 shows a quantitative summary of sources of uncertainty in interferometric length measurements. The table shows how to calculate the contribution to uncertainty of a measured length, L, arising from an uncertainty, Δ, in some physical quantity. (In short, it gives the sensitivity coefficients for uncertainty computation.) For example, if the uncertainty in pressure measurement, ΔP, is 1.5 mm Hg, the corresponding uncertainty, ΔL, in measurement of a length $L = 2$ m can be derived from the third formula in the right-hand column of Table A-2.4-1.

$$\Delta L = (\Delta P)\,(0.36 \times 10^{-6})L = 1.5 \times (0.36 \times 10^{-6}) \times 2 = 1.08 \times 10^{-6}\ \text{m}\ (1.08\ \mu\text{m})$$

Similarly, if the manufacturer states that optics thermal drift $\delta = 1$ μm/°C, and if temperature fluctuations with a 1-sigma distribution of $\Delta T = 0.1$°C are expected during a measurement, then the corresponding 1-sigma uncertainty from Table A-2.4-1 is

$$\delta(\Delta T) = (1\ \mu\text{m/°C}) \times (0.1\text{°C}) = 0.1\ \mu\text{m}$$

and is independent of L.

In Table A-2.4-1, the values given for uncertainties in determining the index of refraction are calculated for visible light and assuming standard conditions (P = 760 mm Hg ≈ 101 325 Pa, T = 20°C, and H = 50%) unless stated otherwise. Values for relative humidity are given at several temperatures because the temperature dependence here is dramatic. (By contrast, results for absolute humidity are nearly independent of temperature.) In the table, a quantity such as ΔP could be interpreted as either the standard uncertainty or an expanded

Table A-2.4-1 Quantitative Effects of Various Sources of Error

Physical Quantity	Units	Uncertainty in Length, L
Vacuum wavelength, λ	. . .	$(\Delta\lambda/\lambda)L$
Air pressure, P	Pa	$(\Delta P)(0.0027 \times 10^{-6})L$
	mm Hg	$(\Delta P)(0.36 \times 10^{-6})L$
Air temperature, T	°C	$(\Delta T)(0.93 \times 10^{-6})L$
	°F	$(\Delta T)(0.51 \times 10^{-6})L$
Humidity, H	Pa	$(\Delta H)(0.00036 \times 10^{-6})L$
	mm Hg	$(\Delta H)(0.048 \times 10^{-6})L$
	%RH at 20°C	$(\Delta H)(0.0085 \times 10^{-6})L$
	%RH at 30°C	$(\Delta H)(0.015 \times 10^{-6})L$
	%RH at 40°C	$(\Delta H)(0.027 \times 10^{-6})L$
Edlén equation (near standard conditions)	. . .	$(0.02 \times 10^{-6})L$
CO_2 concentration, C	parts in 10^6	$(\Delta C)(0.00015 \times 10^{-6})L$
Part temperature, T (with coefficient of expansion, α)	units of α, T, and L must be consistent	$\alpha(\Delta T)L$
Expansion coefficient, α	. . .	$\Delta\alpha \lvert T - T_0 \rvert L$, T_0 = 20°C = 68°F
Interferometer alignment, θ	rad	$(\Delta\theta^2/2) \times L$
Interpolation error, ϵ	fraction of λ	$\epsilon\lambda$
Dead path of length, d	. . .	d(change in λ)/λ
Optics thermal drift, δ	δ and ΔT must have consistent units	$\delta(\Delta T)$, where ΔT = estimated possible change in optics temperature
Optics flatness/wavefront aberration	. . .	See text for possible methods of estimating.

GENERAL NOTE: This table shows how to calculate components of the uncertainty of a length measurement that arise from uncertainties in various relevant quantities (with the uncertainty in some quantity X denoted ΔX). The formulas given in this table were used to calculate the numerical uncertainties in Form 6-2. The sensitivity coefficients given in this table for relating uncertainties in pressure, temperature, humidity, and CO_2 concentration to the uncertainty in length measurement are all calculated for atmospheric conditions near standard conditions (P = 101 325 Pa = 760 mm, T = 20°C, H = 50%), with the exception of the coefficients for relative humidity at 30°C and 40°C.

uncertainty. However, the quantity $\Delta\theta$ must be interpreted as an expanded uncertainty with a coverage factor of $k = 2$, for reasons discussed previously.

The uncertainty budget could be broken down yet further. For example, consider the measurement of air temperature or pressure. Contributions to the uncertainty in the measurement would include

(a) uncertainty in the calibration of the sensors, including uncertainty due to uncalibrated nonlinearities in the sensors

(b) uncertainty due to instrument drift between calibrations

(c) uncertainty due to spatial variations between the point of measurement and the actual air path in the measurement arm

(d) uncertainty due to temporal drifts, if temperature and pressure are not measured at the same time that displacement is computed (e.g., in a system where a compensation value is entered before beginning the measurement)

A-2.5 Finding the Total Uncertainty

The uncertainties above, along with other uncertainties not included in the table, such as air turbulence, should be combined in quadrature to obtain the total estimated uncertainty. (Variances — the squared uncertainties — are added arithmetically to obtain the total variance, and the square root of the total variance gives the total uncertainty.) The resulting uncertainty estimate is applicable to a single measurement. If n measurements are averaged, uncertainties due to errors that are not correlated between one measurement and the next can be reduced by a factor of $1/\sqrt{n}$. For example, air turbulence or electronic noise will be uncorrelated from one run to the next, and the resulting uncertainty in an averaged result will be reduced by $1/\sqrt{n}$ (whereas an error in the vacuum wavelength will usually be the same for all the measurements and therefore will not be reduced in the averaged result). Some errors, such as dead path errors, may be correlated over a period of several hours (as a weather front passes) but uncorrelated over longer periods of time.

A-3 SAMPLE UNCERTAINTY BUDGET

Forms 6-1 and 6-2 show sample uncertainty budgets.

Form 6-1 is an uncertainty budget that might be used by a manufacturer to estimate the accuracy that the system could achieve with a perfect setup under ideal circumstances. It includes a format that the manufacturer might use to report this attainable uncertainty.

Form 6-2 is a user's uncertainty budget; it adds expected setup errors to the manufacturer's specified uncertainty and thus estimates the final uncertainty of a measurement (excluding errors associated with the measuring machine, such as probing errors). This example considers a single-pass system with a 633-nm laser operating over a typical range of conditions. It is assumed that the system includes a complete weather station — even measurement of relative humidity — but does not measure CO_2 concentration.

A-3.1 Manufacturer's Uncertainty Budget

The uncertainties in the two right-hand columns of Form 6-1 are calculated from entries in the first column by using the multiplication factors (sensitivity coefficients) shown. These factors are either explained in this section or are given in Table A-2.4-1. Paragraphs A-3.1(a) through (l) give a line-by-line explanation of the uncertainty budget.

(a) Line 1(a) — Vacuum Wavelength. The expanded uncertainty is estimated at 0.08 parts in 10^6 (0.00008 nm for the 633-nm laser used here).

Up to this point, sensitivity coefficients and methods for combining uncertainty have been discussed, but methods for estimating underlying uncertainties have not been described. Methods of estimating uncertainties based on some underlying assumptions are discussed in detail in references [9], [33], and [34].

For the example given here, the numerical estimate for the uncertainty in vacuum wavelength might be based on expected variations of the laser vacuum wavelength over the lifetime of the laser (a manufacturer's specification) or, if the laser is periodically recalibrated, it might reflect variations expected during the interval between recalibrations. For example, if the largest fractional variation observed between several recalibrations is $\pm 0.07 \times 10^{-6}$, and if the uncertainty distribution is modeled as uniform over this interval, then the corresponding $k = 2$ expanded uncertainty is $0.07 \times 10^{-6} \times 2/\sqrt{3} = 0.08 \times 10^{-6}$. This is a plausible estimate of the uncertainty. This uncertainty makes only a small contribution to the overall uncertainty budget.

(b) Line 1(b) — Air Pressure. The pressure uncertainty might be a combination of two or more factors added in quadrature, as follows:

(1) expanded uncertainty at time of calibration = 25 Pa

(2) expanded uncertainty due to drift between recalibrations = 65 Pa

(3) total pressure expanded uncertainty = 70 Pa

Here the total expanded uncertainty (70 Pa) is found by combining the individual sources of uncertainty in quadrature

$$\sqrt{(25)^2 + (65)^2} = 70$$

The component of expanded uncertainty that accounts for drift between calibrations (65 Pa) might be estimated in a manner similar to the previous discussion of the variations in vacuum wavelength — either on the basis of manufacturer's specification or, preferably, on the basis of repeated calibrations, from which a square uniform distribution can be assigned. The uncertainty at the time of calibration itself might be further broken down into components, such as the uncertainty of the master barometer, hysteresis effects, and possible uncorrected errors due to uncompensated nonlinearities in the instrument. If the pressure sensor is calibrated at a single temperature, it may also be necessary to add additional uncertainty to account for possible variations in the pressure calibration with changing temperature.

(c) Line 1(c) — Air Temperature. Temperature uncertainty might be estimated in a manner analogous to Line 1(b).

(d) Line 1(d) — Uncertainty in Air Humidity. This uncertainty should reflect both the uncertainties in the sensor calibration and expected drifts. The corresponding uncertainty in length measurement has been estimated for worst-case conditions, using the multiplication factor appropriate at 30°C, the upper end of the manufacturer's recommended operating range.

(e) Line 1(e) — CO_2 Concentration. It is assumed that CO_2 is not measured. CO_2 levels can be elevated in poorly ventilated areas. If values for CO_2 concentration characteristic of outside air are used in the compensation calculation (as is commonly done), then the errors due to excess CO_2 indoors will represent a bias rather than a random distribution about the mean, a situation that should ideally be avoided according to reference [9]. This complication will not be covered here. Variations in CO_2 concentrations depend on details such as the number of people in a lab and the rate of air flow from the outside; likely variations can be estimated only crudely from anecdotal reports. It is assumed that CO_2 concentration can vary by at most 400 parts in 10^6 from the value used by the compensation software. Taking this as the half-width of a square distribution, a value for the expanded uncertainty of 460 parts in 10^6 may be assigned. This is expected to be a conservative estimate for almost all cases of practical interest.

(f) Line 1(f) — Refractive Index Calculation. The expanded uncertainty of 0.04 parts in 10^6 is larger than Birch and Downs' estimate [27] because the interferometer operates over a wide range of environmental conditions. If the test of para. 4.8 reveals significant mathematical calculation errors, then it would be necessary to increase this uncertainty to account for these errors.

(g) Line 1(g) — Total Wavelength Uncertainty. Total wavelength uncertainty is the quadrature sum of the entries in Lines 1(a) through 1(f)

$$\sqrt{0.08^2 + 0.19^2 + 0.14^2 + 0.23^2 + 0.07^2 + 0.04^2}$$
$$= 0.34 \text{ parts in } 10^6$$

(h) Lines 2(a) Through 2(c) — Material Thermal Expansion Compensation. The length-dependent uncertainties are calculated assuming an expanded uncertainty of 0.07°C in the material temperature sensor [estimated in a manner analogous to Line 1(b) or 1(c)]

and an expansion coefficient of 12 parts in 10^6 for steel or 22 parts in 10^6 for aluminum.

(i) Lines 3(a) Through 3(e) — Length-Independent Uncertainties. Optical nonlinearity and electronic interpolation errors have been combined and expressed as a fraction of a wavelength interpolation error. The resolution uncertainty is then estimated. It is assumed that the display resolution is 10 nm and that the electronics rounds off to the nearest 10-nm increment. For a square distribution, the expanded uncertainty, $k = 2$, is determined by multiplying by $1/\sqrt{3}$, giving the 6-nm uncertainty shown in the right-hand column. To this uncertainty, additional uncertainty from noise in the fringe interpolation must be added. Also, it must be recognized that the measurement of any length interval includes additional uncertainty in establishing the zero point. This zero point uncertainty is affected by optical and electrical nonlinearities, noise, and resolution, and, in some systems, may also include additional sources of error, depending on details of how the zeroing is implemented. If the zero offset error is assumed to be influenced by the same nonlinearities, resolution, and noise as are other readings, then the uncertainty is 14 nm [the quadrature sum of Lines 3(a), 3(b), and 3(c)].

All of these uncertainties are added in quadrature to give the total length-independent expanded uncertainty in Line 3(e). This number should be consistent with the manufacturer's reported *LIE*.

(j) Line 4 — Zero Drift. If the interferometer is used without any extended warm-up after indicating "ready," then the zero drift, D, as measured in section 4, may contribute to the measurement uncertainty. A reasonable estimate of the uncertainty can be obtained by assuming that errors are uniformly distributed over the range $\pm D$, so that the expanded uncertainty would be $2D/\sqrt{3}$. Thus, if D were 13 nm, the expanded uncertainty entered in Line 4 would be 15 nm, as shown.

(k) Line 5 — Miscellaneous. This category includes other small error sources, such as diffraction.

(l) Manufacturer's Reported Uncertainty. These uncertainty estimates can be combined to estimate the attainable accuracy when measuring displacement in vacuum, displacement in air, or the length of a physical artifact, such as a steel artifact with coefficient of expansion 12 parts in 10^6/°C, a representative choice for high-accuracy manufactured parts.

These results are given in Lines 6 through 9. The uncertainty has two components: one proportional to length, given in the middle column, and one independent of length, given in the right-hand column. The length-independent uncertainty here arises from fringe interpolation errors and zero drift [Lines 3(e) and 4]. The length-dependent error is the quadrature combination of one or more of the following uncertainties:

(1) displacement in vacuum [Lines 1(a) and 5].

(2) displacement in air [Lines 1(g) and 5].

(3) measurement of steel [Lines 2(b) and 7]. This uncertainty should be consistent with the B89 *LDE* test result for steel.

(4) measurement of aluminum [Lines 2(c) and 7].

A manufacturer can give a user sufficient information to assess measurement uncertainty by reporting these numbers and also including specifications for optics thermal drift and wavefront aberrations. These last two specifications are given in Lines 10 and 11.

A-3.2 User's Uncertainty Budget

This manufacturer's information can be combined with additional, user-dependent sources of uncertainty to find the total uncertainty of an interferometric measurement. An example is shown in Form 6-2. This example would likely have to be modified to fit the particular circumstances of an individual user, but it can provide guidance in constructing an uncertainty budget for a measurement. The manufacturer's reported uncertainty from the previous spreadsheet is repeated in Lines 1 through 6. Setup-dependent errors are combined with this uncertainty to assess the overall uncertainty of a measurement. For the example shown, it is assumed that the part is steel (with an expansion coefficient of 12 parts in 10^6/°C). Sensitivity coefficients used by this spreadsheet are either from Table A-2.4-1 or are described in paras. A-3.2(a) through (g).

(a) Misalignment errors are treated in Lines 7 through 7(d). For the example considered here, the user estimates that the laser beam is aligned with an estimated standard uncertainty of 0.2 mm/m (or 0.2 mrad). (This estimate might be based on an expert judgment of how small a misalignment can be seen with confidence. Based on this estimate, a square distribution might be assigned and the standard uncertainty obtained. Other equally valid methods of assigning the standard uncertainty based on expert judgment are discussed in reference [9].) The user corrects the length measurements using this 1-sigma error estimate and then multiplies this uncertainty by the coverage factor of two to give the value of 0.4 mm/m shown in Line 7. The corresponding fractional expanded uncertainty in measuring length, L, due to cosine error is $(0.0004)^2/2 = 0.08$ parts in 10^6 [Line 7(b)].

The 0.15λ specification for wavefront aberration is taken into account by approximating its effect as an error proportional to length and misalignment, as described in para. A-2.3. To calculate the effect, it is necessary to know the laser beam diameter that is entered in Line 7(a). The resulting uncertainty is given in Line 7(c). These two alignment-related errors are combined in quadrature to give the result in Line 7(d).

(b) The user assigns additional uncertainties for temperature effects. Unmeasured air temperature gradients are estimated and increase the air temperature expanded uncertainty by the amount entered in Line 8(a).

(c) Unmeasured temperature gradients can also increase the uncertainty in part temperature. The estimated additional temperature uncertainty is entered into Line 9(a). The length uncertainty in the second column of Line 9(a) is calculated assuming an expansion coefficient of 12 parts in 10^6/°C.

An additional temperature-related uncertainty arises from the uncertainty in the coefficient of expansion [Line 9(c)] and the departure of the part temperature from the reference temperature [Line 9(b)]. The resulting uncertainty [second column of Line 9(c)] is combined in quadrature with the uncertainty in Line 9(a) to give the uncertainty in Line 9(d).

(d) The expanded uncertainty due to optics thermal drift is calculated using the possible drift of optics temperature (estimated 95% level), entered in Line 10(a), and the value from Line 5.

(e) Uncertainty due to possible uncompensated dead path errors [Line 11(d)] is calculated from the dead path length [Line 11(a)] and the estimated possible changes in pressure [Line 11(b)] and temperature [Line 11(c)]. More precisely, the possible changes are $k = 2$ estimates that might be obtained from experimental observations, expert judgment (estimating the likely ranges of variation and distributions), or a combination of such methods.

(f) The final interferometry uncertainty has a length-independent and length-dependent part, given in Line 12. These values are calculated from the quadrature sum of the various components above, including both the manufacturer's reported uncertainty and the additional sources of uncertainty that depend on setup and measurement conditions. Thus, the length-dependent uncertainty in Line 12 is the quadrature sum of the second-column entries in Lines 3, 7(d), 8(a), and 9(d). The length-independent uncertainty is the quadrature sum of the third-column entries in Lines 3, 10(a), and 11(d).

(g) In Line 13, the overall uncertainty for measuring a given length is calculated by taking the combination in quadrature of the length-dependent and length-independent final uncertainties. Note that the combined uncertainty in the last line is calculated using standard GUM procedures and is not a linearized approximation as is common in the U.S.; that is, the uncertainty is calculated as a quadrature sum rather than a linear combination of length-dependent and length-independent terms of the form $a + bL$. However, this is not intended to imply that a linearized approximation to the uncertainty cannot be used if desired.

The uncertainty represents expected interferometry and compensation errors at the two-sigma level for a single measurement of a physical artifact. However, this spreadsheet is not sufficiently complex to capture all possible variations in circumstances that may be encountered in practice. It may be necessary to modify the spreadsheet to give an accurate picture of specific circumstances. For example, the zero drift, D, that is indicative of the performance of the interferometer during the first hour of operation may not be present for measurements taken after the interferometer has been in operation for a few hours. It also may be necessary to include additional terms in the uncertainty budget. For example, uncertainties arising from air turbulence that depend on the measured displacement but do not scale linearly with the displacement have not been included here. Also, when a short displacement is measured at a long standoff from the beamsplitter, uncertainties independent of the length of the displacement will be present due to turbulence and also due to another factor not explicitly discussed in the spreadsheet, noise in the air temperature and pressure sensors. Furthermore, note that the noise in air sensors, turbulence errors, and other contributors to the total uncertainty can be reduced by averaging multiple measurements. It is difficult to capture all such potential complications of a measurement in a short spreadsheet.

NONMANDATORY APPENDIX B
METHODS FOR COMPARING TWO INTERFEROMETER SYSTEMS

B-1 FOUR METHODS FOR COMPARING INTERFEROMETERS

Four different methods for comparing two interferometer systems are described in this Nonmandatory Appendix. Method 1, the folded path method, is most strongly recommended, because it is most likely to yield an accurate comparison of the entire interferometer system. Method 2, the compensated back-to-back method, is also recommended, because it provides some additional flexibility not attainable with the folded path method. Method 3, the common optics method, will probably give the most accurate results when comparing nominally identical systems from the same manufacturer, but the results will require some care in interpretation because the comparison does not include a full check of the test interferometer's external optics. Method 4, the back-to-back comparison, is generally not recommended but can be used if it meets the needs of a laboratory, as long as careful testing supports the estimated uncertainty of the comparison.

B-1.1 Method 1: Folded Path Method

Under most circumstances, the folded path method is the recommended procedure for comparing interferometer systems. Figure B-1.1-1 shows a possible setup for a folded path comparison that uses typical commercial interferometer optics with retroreflectors and beamsplitters enclosed in rectangular metal housings. A retroreflector can be screwed to the top of the beamsplitter housing to form a remote interferometer. The labels "test interferometer" and "master interferometer" in the figure are the remote interferometers for the two systems. The optical parts of the test interferometer are shaded. The laser beam of the test interferometer passes through the shaded remote interferometer and then reflects from the large, common retroreflector and strikes the third shaded element, the second retroreflector of the test interferometer. The beam for the master interferometer follows a similar course through its optics (unshaded elements). Not quite visible behind the master interferometer is a 90-deg turning mirror that directs the beam into the interferometer. The large retroreflector should have silvered faces. It need not be highly accurate in angle. A top view of the same optical setup is shown in Fig. B-1.1-2.

In this comparison scheme, the retroreflectors of the master and test interferometer are stationary, and a common displacement is generated by moving the large retroreflector.

B-1.1.1 Advantages of the Folded Path Method

(*a*) can expect good accuracy of comparison

(*b*) is ideal for systems with detached (remote) interferometers

(*c*) is sufficiently flexible to accommodate most interferometers

(*d*) has no Abbe offset

(*e*) has no dead path difference between the two interferometers

(*f*) measures twice the actual distance traveled for a given carriage displacement

B-1.1.2 Disadvantage of the Folded Path Method

(*a*) cannot superimpose beam paths

B-1.2 Method 2: Compensated Back-to-Back Method

The compensated back-to-back method is shown in Fig. B-1.2-1. This method is more flexible in testing unusual systems than Method 1. Method 2 is similar to Method 4, a straightforward back-to-back comparison described in para. B-1.4, but in Method 2 the reference arm of the master interferometer has been modified by adding a turning mirror and mounting its reference retroreflector close to the beamsplitter/reference reflector of the interferometer under test. This eliminates any dead path differences between the two interferometers.

With this geometry, if the length of the reference arm of the master interferometer is equal to the sum of the lengths of the two measurement arms, any uniform increase in the optical path between the two beamsplitters is automatically compensated by an equal increase in the length of the reference arm of the master interferometer. Thus, there is ideally no change in the sum of the two interferometer readings, even when the air refractive index varies.

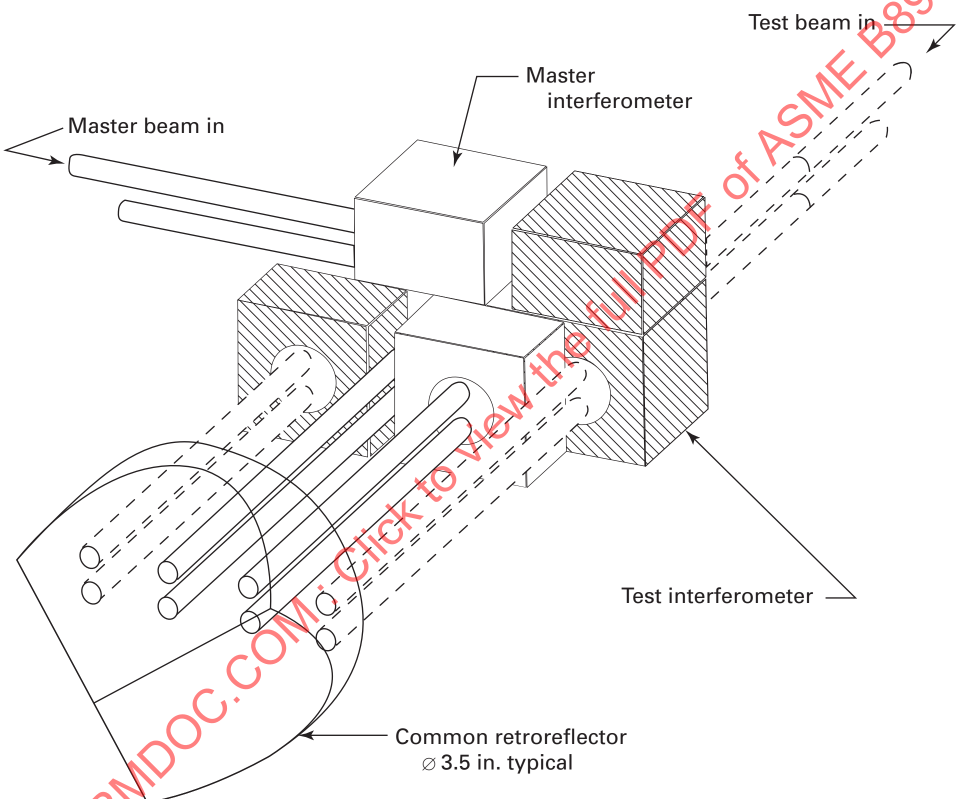
B-1.2.1 Advantages of the Compensated Back-to-Back Method

(*a*) can test any type of interferometer regardless of optical configuration or wavelength because the beam from the test laser only interacts with its own optical components

(*b*) does not need a large retroreflector

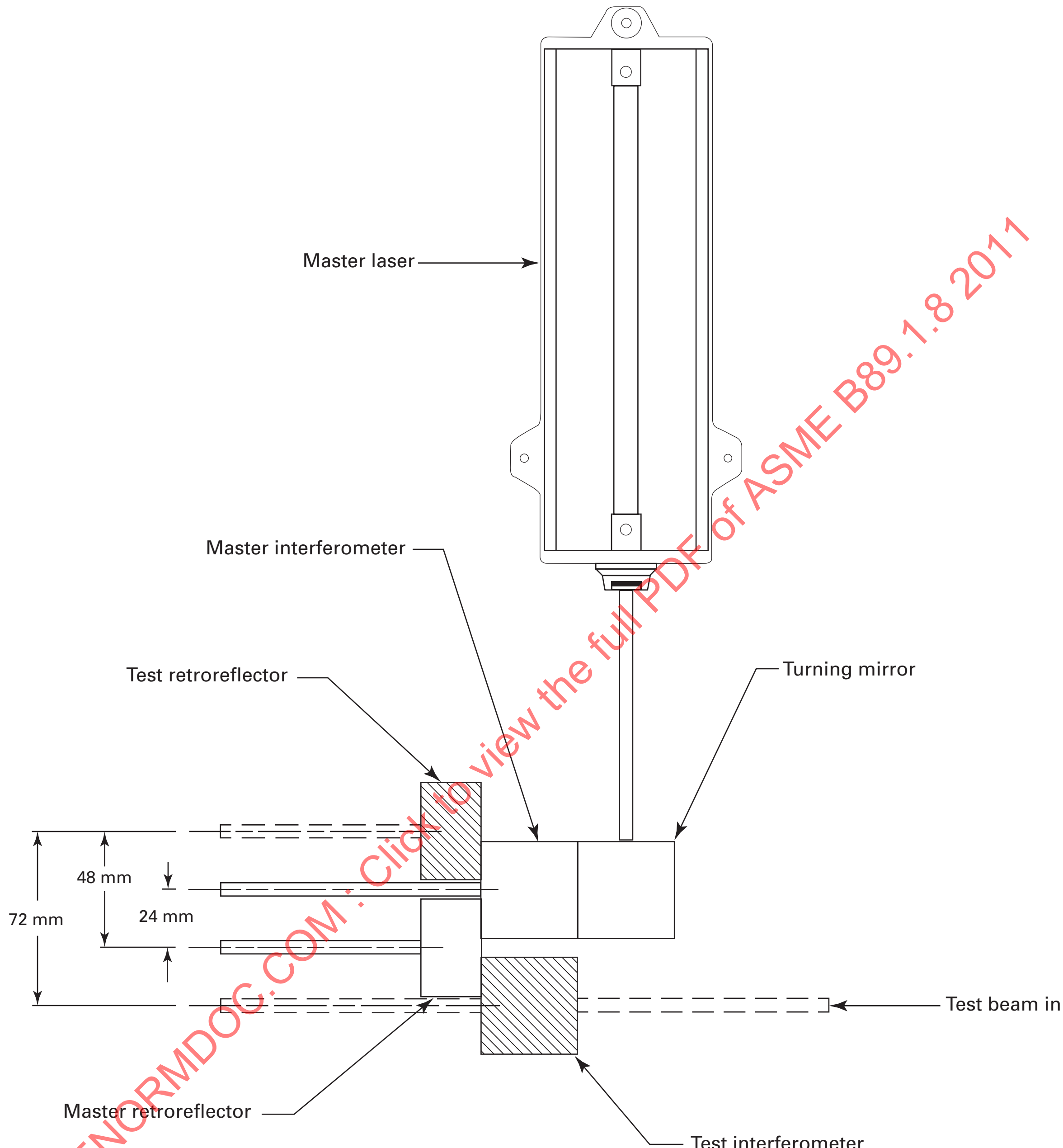
(*c*) does not allow the master interferometer to be influenced by heat from lasers with interferometer optics in laser head

Fig. B-1.1-1 Interferometers Arranged for the Folded Path Method of Comparison



GENERAL NOTE: See para B-1.1 for an explanation of the optics depicted here.

Fig. B-1.1-2 Top View of the Folded Path Method Showing Optics Locations and Suggested Beam Spacing



GENERAL NOTE: The dimensions shown in this figure are appropriate when using typical, commercially available interferometer components.

Fig. B-1.2-1 Compensated Back-to-Back Comparison

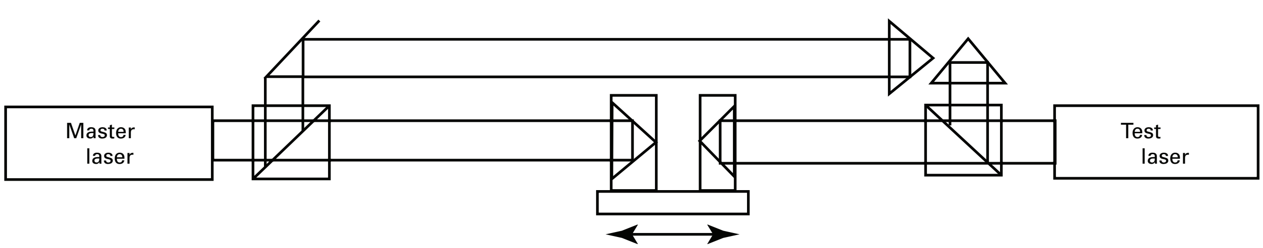
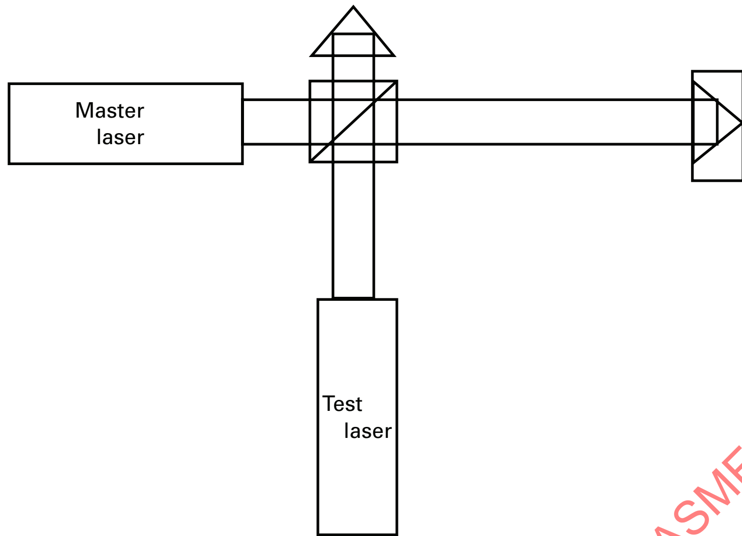


Fig. B-1.3-1 Common Optics Comparison Configuration



B-1.2.2 Disadvantages of the Compensated Back-to-Back Method

(*a*) has a potential for Abbe errors

(*b*) cannot superimpose beam paths

B-1.3 Method 3: Common Optics Method

A system where one set of optics is shared by two interferometers, as shown in Fig. B-1.3-1, can probably yield more accurate comparisons than those obtained with other methods. This method is uniquely immune to external influences because the two laser beams travel through the same optical elements and nearly the same air path. However, a disadvantage of this technique is that it does not test operation of the entire interferometer system; a complete test requires comparing a system using its own optics to a second system with independent optics. Also, the method is not applicable to all interferometer systems currently in use. Several commercial systems have a beamsplitter and reference reflector internal to the laser head.

This test is recommended only for comparisons of systems from the same manufacturer, where the master interferometer is known to give good results employing typical optics from the manufacturer. Furthermore, it may be necessary to assign additional uncertainty to the test interferometer to account for possible errors arising from untested variations in the optics. In spite of these drawbacks, this method is desirable for testing similar interferometer systems, particularly if it is known that the optics are of high quality and unlikely to cause significant problems for the intended application.

The drawbacks of the common optics method must be weighed against the fact that very accurate results can be easily obtained with this technique, even under poor environmental conditions, such as temperature variations and vibration, and even when using a poor translation stage to move the retroreflector.

B-1.3.1 Advantages of the Common Optics Method

(*a*) Common path and shared optics provide highest accuracy and best noise immunity.

(*b*) There is no Abbe offset.

(*c*) Beam paths can be superimposed if care is taken to ensure no cross-influence of lasers.

B-1.3.2 Disadvantages of the Common Optics Method

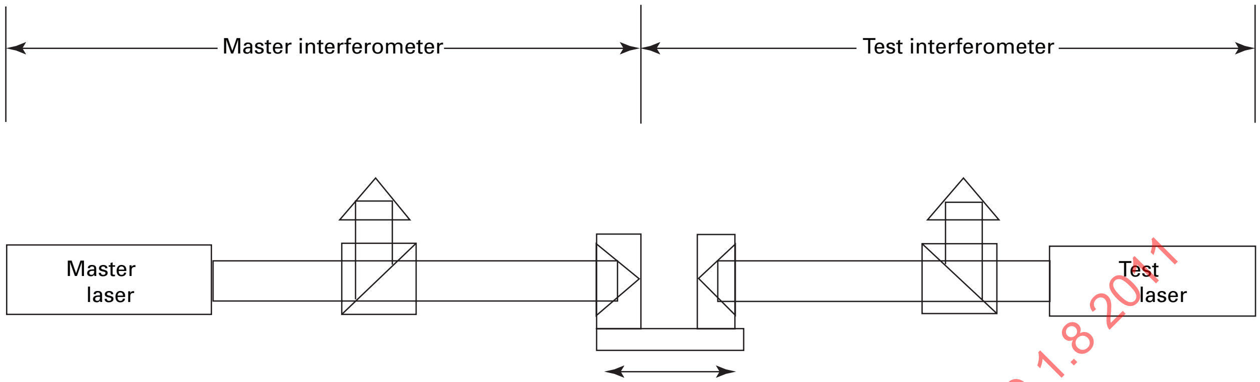
(*a*) cannot be used to test all kinds of systems

(*b*) does not test all optical components of system

B-1.4 Method 4: Back-to-Back Method

The most straightforward method for comparing systems is to arrange two interferometers back-to-back with measuring reflectors mounted on a carriage that moves between two beamsplitters (see Fig. B-1.4-1). If both interferometers are configured to measure positive displacements as the retroreflector measurement arm moves away from the beamsplitter, the sum of the two displacement readings should remain constant as the retroreflectors are moved. An important limitation of this method is that the validity of the measurement depends on maintaining a constant optical length between the beamsplitters of the two interferometers. Thermal expansion of the base upon which the optical components are mounted, mechanical deformations of the base, or changes in the index of refraction of the air path can compromise the validity of the comparison. Although these problems can be overcome, they make it difficult to achieve high accuracy comparisons. Better

Fig. B-1.4-1 Back-to-Back Method for Comparison of Interferometer Systems



results can be obtained using one of the previous methods. Method 4 is not recommended under most circumstances.

B-1.4.1 Advantage of the Back-to-Back Method

(a) great flexibility

B-1.4.2 Disadvantages of the Back-to-Back Method

(a) Abbe offsets must be avoided through careful setup and placement of beams and optics.

(b) Serious errors can be caused by changes in total optical path length between the beamsplitters unless great care is taken.

(c) Beam paths cannot be superimposed.

B-2 COMMENTS AND DETAILED DESCRIPTIONS OF THE FOUR COMPARISON METHODS

B-2.1 Comments on the Folded Path Method (Method 1)

The folded path test is one of the most accurate methods of comparison testing for linear measurements. The measurement paths, while not identical, use the same moving retroreflector and traverse almost the same air path. There are no dead path differences and no Abbe offset errors to contend with. Since the moving retroreflector is common to both master and test interferometers, the linear slide on which it moves need not be particularly good. Any pitch, yaw, roll, or out-of-straightness motion will be common to both measurements.

However, because of the different sizes and shapes of laser heads and interferometer optics, universal mounting hardware may be difficult to achieve. Mounting of the interferometer and fixed retroreflectors becomes easier with a larger aperture measurement cube corner, but only at the expense of larger beam spacing (and hence, greater differences in the atmospheric conditions between the two paths).

NOTE: Figures B-1.1-1 and B-1.1-2 show the optical path of the test interferometer system with dashed lines to better indicate the path of the master beams.

In addition, the folded path method may not work well when comparing a system with its interferometer on board the laser head and a system where the interferometer is the passive, remote type. The heat from the on-board system will cause thermal distortions in the passive remote interferometer. Therefore, it is probably better to use the back-to-back method to compare these differing designs.

B-2.1.1 Equipment

(a) master interferometer system with auto compensation, tripod, input beam bender, and linear interferometer, including two retroreflectors

(b) test interferometer system with auto compensation, tripod, input beam splitter, and linear interferometer, including two retroreflectors

(c) hardware and software for data collection, processing, and plotting

(d) mounting hardware (to assemble fixed optics)

(e) linear motion slide (range 0 m to 0.5 m or more)

(f) large aperture measurement retroreflector with metallic reflective coating, recommended clear aperture of at least 80 mm

(g) plane, front-surface mirror (auto reflection alignment)

B-2.1.2 Setup

NOTE: The more compact the construction, the closer the measurement beams can be and the more common the atmospheric conditions will be in the measurement paths.

(a) If possible, attach the test and master interferometers directly to one another in rigid fashion. The fixed return retroreflectors should likewise be rigidly attached to the interferometer assembly.

(b) Since the lasers are a source of heat, mount them on tripods away from the test interferometers and the measurement path. Depending on the size of the laser heads, it may be necessary to mount a beam bender (or possibly two) to direct the laser beams into the interferometers.

B-2.1.3 Alignment. To eliminate cosine error between the test and master laser systems, their beams must be parallel in the measurement path. This is best achieved by autoreflection.

(a) Establish a front surface using a plane mirror (large enough to receive beams from both interferometers) on the carriage such that its face is perpendicular to the axis of travel. A true square may work well for this.

(b) Select the alignment, small apertures on the laser heads.

(c) Using the tripod adjustments, position the laser beams so they enter the interferometers at the correct height and lateral locations.

(d) Align azimuth and elevation angles so that each beam autoreflects from the carriage mirror back to its source aperture. Since the beams are at normal incidence on the mirror, they are, therefore, parallel to the axis of travel.

(e) When adjusting beam azimuth and elevation angles, the position (height and lateral position) of the beams on the interferometer input ports might have changed. Therefore,

(1) translate the laser(s) with the tripod adjustments to position the beam(s) on the input ports

(2) recheck for good autoreflection alignment

(3) replace the alignment mirror with the large cube corner and verify beam alignment with the full range of travel

(4) power off the test laser and allow it to return to room temperature before beginning the cold-start test

B-2.2 Comments on the Compensated Back-to-Back Method (Method 2)

In addition to the recommended good practices discussed previously, the compensated back-to-back method requires attention to possible Abbe errors. The Abbe offset is the distance between the nodal points of the two cube corner reflectors mounted on the moving carriage, measured along a distance perpendicular to the interferometer beams. If this distance is d and the moving carriage pitches or yaws through a small angle θ, the Abbe error, ε, is $\varepsilon = d\theta$.

B-2.2.1 Recommended Procedures for Setting Up the Compensated Back-to-Back Test

(a) Set up two interferometer systems back-to-back with the measurement arm retroreflectors of the two systems mounted rigidly on a moving carriage. The retroreflectors should be mounted with as small an Abbe offset as can be practically attained. In a system where angular errors are small, it may be possible to estimate by eye where to mount the retroreflectors so as to give a sufficiently small Abbe offset. If angular errors are larger or if very high accuracy is desired, it may be necessary to more carefully adjust the Abbe offset to zero, as described in (d) below.

(b) Mount the retroreflector in the reference arm of the master interferometer as close as possible to the beamsplitter/reference reflector of the interferometer under test.

(c) Align the two interferometers with the direction of motion of the carriage. This can be done using any standard alignment method, such as by adjusting the angle of the laser beam so that the return beam reflected by the retroreflector does not move laterally as the carriage is translated. For highest accuracy, a quad cell might be used to observe this lateral motion.

(d) When minimal Abbe offset is required, small additional adjustments of the position of the retroreflector must be done after an initial alignment. The Abbe error can be measured directly by turning the retroreflectors mounted on the moving carriage through a small, known angle and observing the change in the two interferometer readings. In the absence of Abbe offset, the sum of the two interferometer readings will be constant when the mount for the retroreflectors is turned through a small angle. If a large Abbe offset is evident, it is necessary to adjust the position of the two retroreflectors to reduce the offset.

If the retroreflectors are mounted with a small distance between nodal points, then the Abbe offset will change slightly as the mount is rotated. As a consequence, the error is a quadratic function of angle near zero Abbe offset. The sum of the distances measured by the two interferometers is a minimum at the point where the Abbe offset is zero as shown in Fig. B-2.2.1-1.

(1) By observing the sum of the two interferometer readings while rotating the mount, it is possible to determine where the Abbe offset is zero. This test must be repeated twice: once with rotations to simulate pitch errors, and again with rotations simulating yaw errors. If pitch and yaw errors of the moving carriage have been measured, then the maximum Abbe error can be estimated based on Fig. B-2.2.1-1.

(2) If the retroreflector must be moved significantly to obtain zero Abbe offset, resulting in poor overlap of the reference and measurement beams returning to the interferometer, it may be necessary to slightly readjust the position of the interferometers and recheck alignment.

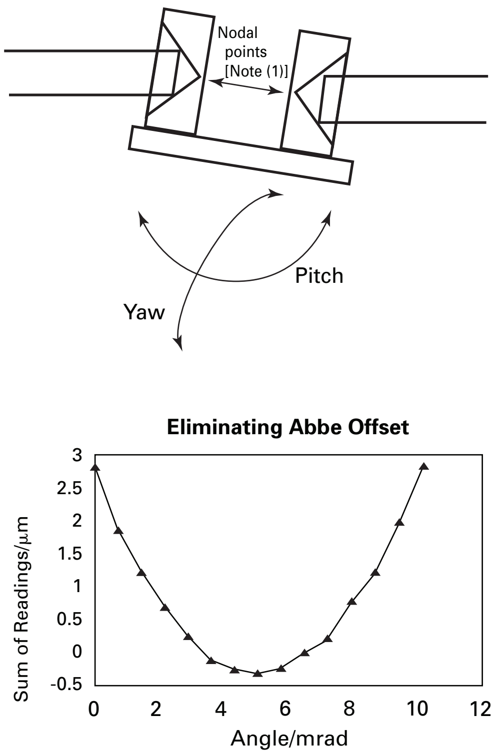
B-2.2.2 Recommended Specifications for Compensated Back-to-Back Comparisons. This paragraph provides suggested specifications for compensated back-to-back interferometer comparison with a target accuracy of a few parts in 10^7. The suggestions here are not meant to be prescriptive, but to provide guidance in design of a system for laser comparisons. The specifications may be relaxed as long as this is reflected appropriately in the uncertainty budget.

The carriage and way bed used to translate retroreflectors are as follows:

(a) length ≥1 m displacement

(b) pitch/yaw errors <30 arcsec

Fig. B-2.2.1-1 Setup for Abbe Offset



NOTE:
(1) Adjust relative position of nodal points.

(c) straighness errors <20 μm/meter of travel

Pitch and yaw errors of 30 arcsec maximum will require modest care in eliminating the Abbe offset if high accuracy is desired. Note that even with a relatively small Abbe offset of 1 mm, a pitch or yaw error of 30 arcsec would give an error 0.15 μm in the comparison. Roll is not an important consideration.

B-2.2.2.1 Environment. As discussed previously, some attention to the environment is necessary when using the compensated back-to-back method, even though most environmental changes are compensated. It is recommended that a temperature-controlled room be used whenever possible.

B-2.3 Comments on the Common Optics Method (Method 3)

The common optics test (see Fig. B-1.3-1) is probably the most accurate method of comparing the performance of the two laser interferometer systems. However, because the test uses just one set of common optics, the performance of any external measurement optics is not compared.

The measurement paths are identical and use the same interferometer and retroreflectors, and the measurement beams pass through the same air path. There are no dead path differences and no Abbe offset errors to contend with. Accurate comparisons are therefore possible, even in environments where there may be some thermal or mechanical movements.

Since the moving retroreflector is common to both master and test interferometers, the linear slide on which it moves need not be particularly good. Any pitch, yaw, roll, or out-of-straightness motion will be common to both measurements.

Because the two lasers are mounted orthogonally, there are rarely any problems with heat, space, or size constraints, so laser mounting is usually straightforward.

However, this comparison test can only be performed if both laser systems use external interferometers and reflectors of substantially the same design (check for any geometric and polarization differences). This test is ideal for comparing two interferometer systems from the same manufacturer and of the same design, but great care is required if comparing systems of different design or from different manufacturers. When doing such a comparison, verify that the common optics used are suitable for use with both laser systems.

B-2.3.1 Equipment

(a) master interferometer system with auto compensation and adjustable laser head tripod or mounting stage.

(b) test interferometer system with auto compensation and adjustable laser head tripod or mounting stage.

(c) common optics set including the linear interferometer and two retroreflectors (of design and performance known to be compatible with both master and test interferometer systems).

(d) hardware and software for data collection, processing, and plotting. For the best accuracy it is recommended that this include hardware/software that takes readings synchronously from both master and test interferometer systems.

(e) linear motion slide (range 0 m to 1 m, or longer) with a straightness of better than 0.25 mm and a pitch/yaw error of less than 0.25 deg.

(f) mounting hardware (to fix optics to linear motion slider).

(g) plane, front-surface mirror (auto reflection alignment and beam deflection).

B-2.3.2 Setup

(a) Rigidly attach the beamsplitter and reference arm retroreflector optics to the stationary part of the linear motion slide. Rigidly attach the measurement arm retroreflector optic to the moving carriage of the linear motion slide.

(b) Since the laser heads are a source of heat, mount them so their heat is isolated from the linear motion slide and the optics and their mounts. This can be achieved either by using separate tripods or appropriately designed laser mounting stages.

(c) Arrange the environmental sensors of master and test systems so they are close and in identical environments.

B-2.3.3 Alignment. To eliminate cosine error between the test and master laser systems (and to minimize lateral traverse of the laser beams across the interferometer optics), their beams must be parallel both to each other and to the motion of the carriage on the linear slide. This is best achieved as follows:

(a) Adjust the in-line laser system so that correct beam alignment is maintained (within 0.5 mm) over the full length of carriage travel. The in-line laser system has the output beam that is parallel to the axis of carriage motion.

(b) Verify that the beamsplitter optic housing is square to the in-line laser beam to minimize any polarization cross-talk between the two systems. This can be checked by putting the plane mirror against the beamsplitter housing and then adjusting the beamsplitter until the laser beam is autoreflected back into the laser output aperture. Recheck laser alignment.

(c) Adjust the perpendicular laser system so that its laser beam is both concentric and parallel to the in-line laser system's beam in the measurement arm, over the full length of carriage travel. The perpendicular laser system has the output beam that is at right angles to the axis of carriage motion.

NOTE: For optimum elimination of cosine error, it is best to check the coincidence of the two laser beams at a much greater distance (e.g., 10 m). This is easily achieved either by temporarily removing the moving retroreflector or by using a plane mirror to deflect both beams onto a distant target.

(d) Verify that there is no significant cross-talk between the two laser systems. Temporarily obscure the output beam from each laser system and confirm that the reading of the other system does not change significantly. Repeat the experiment with the moving reflector at the other end of the linear slide.

(e) Power off the test laser and allow it to return to room temperature before beginning the cold-start test.

B-2.3.4 Reading Drift and Data Recording. Because the measurement laser beams of both systems pass through exactly the same air and optics, the common optics method is less sensitive to environmental and mechanical movements. However, if measurements are taken in such environments, it is essential that the readings from both laser systems are recorded simultaneously and that their measurement response times are identical. To achieve this, it is recommended that all readings are taken in response to an electrical trigger signal and that the same averaging mode is set on both systems.

B-2.4 Comments on the Back-to-Back Method (Method 4)

As stated previously, this method is not generally recommended, but it might be viable if appropriate facilities are already in place. Good results will not be obtained without excellent environmental control and good mechanical design. To keep thermal drifts below 0.1 part in 10^6, it is necessary to maintain air temperatures constant to or better than 0.1°C and the steel way bed temperature constant to 0.01°C.

NONMANDATORY APPENDIX C
PERFORMING ACCURATE LINEAR MEASUREMENTS WITH A LASER INTERFEROMETER SYSTEM — BEST PROCEDURES AND PRACTICES

C-1 INTRODUCTION

The procedures and best practices described here are targeted toward the use of a laser interferometer to calibrate the linear accuracy of machine tools, such as lathes, milling machines, and coordinate-measuring machines. However, the general principles described are universally applicable. The additional techniques associated with laser measurement of angle, flatness, straightness, squareness, and parallelism have been excluded, as have the specialized techniques (such as operation in a vacuum) that are used to achieve short-range accuracies below 0.1 μm (micrometer), or 0.1 parts in 10^6. The procedures described in this Nonmandatory Appendix assume that the interferometer system includes a remote interferometer, an assembly consisting of a beamsplitter and a reference reflector that can be mounted separately from the laser head. Therefore, some of the procedures described here are not applicable for systems where the beamsplitter and reference reflector are built into the laser head.

A micrometer is a very small unit of distance measurement, less than $\frac{1}{25}$ of the thickness of a human hair. It is far too small to see with the naked eye and is close to the limits of a conventional optical microscope. The widespread use of digital readouts that offer resolutions of a micrometer and beyond has generated a degree of complacency about measurement accuracies. Although a measurement display may have many digits after the decimal point, it does not mean they are all accurate. (In many cases the accuracy is 10 to 100 times worse than the display resolution.) It is easy to achieve 1-μm measurement resolution, but achieving a 1-μm measurement accuracy requires considerable attention to detail. This section describes the techniques that can be used to improve measurement accuracy when using a laser interferometer.

C-2 LOCATION OF OPTICS

The optics should be located so that any change in their separation accurately matches the linear motion of the machine components to be calibrated, and is not contaminated by other errors. This can be achieved as described in paras. C-2.1 through C-2.7.

C-2.1 Minimize the Abbe Offset

The laser measurement beam should be coincident (or as close as possible) to the line along which calibration is required. For example, to calibrate the linear positioning accuracy of the *z*-axis of a lathe, the laser measurement beam should be aligned close to the spindle centerline. This will minimize the contamination of the linear accuracy calibration data by any machine pitch or yaw errors.

C-2.2 Fix the Optics Rigidly

To minimize vibration effects and increase measurement stability, the optics should be fixed rigidly to the points between which measurement is required. Mounting pillars should be kept as short as possible, and any additional fixtures should be of substantial cross section. Magnetic bases should be clamped directly to machine castings. Avoid clamping to thinner section machine guards or covers. Ensure the clamping surfaces are flat and free from oil and dirt. To check the rigidity/stability of the fixtures it is suggested that laser readings be taken before, during, and after applying small loads (by hand) to fixtures holding the measurement and reference optics. Quantitative interpretation of these measurements may not be straightforward, but unusually large changes observed in the interferometer readings can serve as a warning of problems, due to loose bolts or other structural deficiencies in test setups, requiring corrective action before data are taken. It might also be helpful to check for vibrations; this can be accomplished, for example, using dynamic data capture software to sample the laser reading at a high sample rate. (Note that the effect of vibrations on actual measurement results will be reduced if filtering is employed.) For further information, refer to the setup hysteresis and setup stability tests in references [2] and [3].

C-2.3 Fix Optics Directly to Points of Interest

Material thermal expansion compensation is normally only applied to a material path length equal to the measured laser distance. If the measurement loop includes additional structures, then any thermal expansion or contraction of this material dead path, or deflection under load, will cause measurement errors. To minimize these errors, it is best to fix the optics directly to the points between which measurement is required. In the case of machine tool calibration, one optic is normally fixed to the work holder and the other optic to the tool holder. Laser measurements will then accurately reflect the errors that will occur between tool and workpiece.

NOTE: Even if machine guards and covers make access difficult, always try to fix both the remote interferometer and the retroreflector to the machine. Do not fix one optic inside the machine and the other outside, for example, on a floor-standing tripod, as movement of the whole machine on its foundation may invalidate the calibration. However, use care if removing way covers, since this can alter machine performance.

C-2.4 Keep the Remote Interferometer Stationary

Try to arrange the laser and optics so that the remote interferometer is the stationary optic. This avoids errors that can occur if there is any beam deflection introduced by the moving remote interferometer.

C-2.5 Bring Optics Together at One End of Axis Travel

Arrange the optics so that the remote interferometer and the moveable retroreflector come close together at one end of the axis travel. This will make alignment easier and minimize the air dead path (see section C-3).

C-2.6 Avoid Localized Heat Sources

Avoid positioning the optics or the laser beam close to any localized heat sources. The heat may cause expansion of the optics or air turbulence in the laser beam.

C-2.7 Use Turning Mirrors

In difficult setups, use turning mirrors to route the laser beam to the desired location. Ensure that any mirrors placed between the laser and the remote interferometer only turn the beam about a horizontal or vertical axis to avoid disturbing the laser beam's polarization states. Also ensure that any mirrors placed in the measurement path are mounted securely to avoid measurement errors.

C-3 BEAM ALIGNMENT

To minimize cosine error, the measurement laser beam must be aligned so that it is parallel to the axis of travel. On axes longer than 1 m, this is relatively easy to achieve by eye. With shorter axes, it becomes increasingly difficult. To reduce cosine error below 0.5 parts in 10^6 requires beam alignment to be better than 1 mm/m. The techniques described in paras. C-3.1 through C-3.9 can be used to optimize alignment and minimize cosine error.

C-3.1 Align With the Remote Interferometer in Position

Perform beam alignment with the remote interferometer in position. This ensures that any beam deflection introduced by the remote interferometer is taken into account. It also has the advantage of allowing the system's signal strength display to assist in the alignment process.

C-3.2 Start With the Optics Close Together

Alignment is easier to achieve if the remote interferometer and retroreflector are first brought close together at one end of the axis. This allows the outside faces of the optics housings to be aligned by eye before accurate laser beam alignment starts. The remainder of alignment can then be achieved by adjusting the laser only.

C-3.3 Do Not Rely Totally on the Signal Strength Readout

Do not assume that because the signal strength is constant all along the axis of travel that alignment is necessarily perfect. Most signal strength meters have insufficient sensitivity and resolution to ensure accurate alignment on short axes.

C-3.4 Recheck Alignment at the Laser Head

After checking alignment at the moving retroreflector, recheck the returned beams at the laser head. The effect of any beam misalignment error is doubled at the laser head and is therefore easier to detect. Also, the coincidence of the returned reference and measurement laser beams can be verified.

C-3.5 Use the Small Diameter Output Beam

If the laser has an output beam shutter that allows selection of a small diameter output beam, then this should be used for alignment on short axes. The smaller diameter beam makes it easier to see any misalignment. It also has the advantage of reducing the signal strength below 100% so that signal strength variations can be seen more easily.

C-3.6 Maximize the Laser Measurement Reading

If there is a cosine error in the laser measurement, the laser reading will be smaller than it should be. Therefore, on short axes it is possible to eliminate cosine error by carefully adjusting the pitch and yaw of the laser head until the largest laser reading is obtained. The procedure is as follows:

(a) Align the beam by eye along the axis of travel.

(b) Move the axis so that the optics are at their closest approach and laser readout is zeroed.

(c) Move the axis so that the optics are at their greatest separation.

(d) Carefully adjust the pitch and yaw of the laser head to give the largest (absolute) laser measurement.

NOTE: This is a delicate but highly effective procedure. If the laser is on a tripod, it may be necessary to make a series of small adjustments and to release the tripod adjustment screws after each one before observing the effect on the laser readout. It may also be necessary to translate the laser head to maintain alignment. The above steps should be repeated to confirm alignment. It may also be necessary to select the maximum resolution setting on the laser readout and to set averaging ON.

C-3.7 Use a Laser Alignment Sensor

A laser alignment sensor can be used to check beam alignment. There are a variety of types of suitable sensors, including four-quadrant photodiode (quad cell), position-sensitive detector (PSD), lateral effect photodiode, or CCD TV camera. Be sure to check for compatibility with beam diameter, wavelength, and power. Also beware of the effects of stray beam reflections from the remote interferometer and of stray ambient light.

C-3.8 The Autoreflection Technique

If the machine axis is very short and there are flat surfaces known to be suitably perpendicular or parallel (within 0.05 deg) to the axis of travel, then the autoreflection technique can be useful. The procedure is as follows:

(a) Check beam alignment by eye along the axis of travel.

(b) Place a steel gage block in the path of the laser beam (after the remote interferometer) and against one or more of the flat surfaces.

(c) Adjust the laser pitch and yaw alignment so that the reflected beam from the gage block surface is returned into the output beam aperture on the laser head.

This technique works particularly well if the laser head is set some distance away from the remote interferometer.

C-3.9 Minimize Remote Interferometer Roll, Pitch, and Yaw

Most remote interferometers contain a polarizing splitting surface that must be correctly aligned with respect to the polarization states of the laser beam. If this alignment is incorrect, there may be mixing between signals. This can lead to degradation in accuracy and possible failure to detect beam obstruction. It is advisable to align the remote interferometer to better than ±2 deg in roll, pitch, and yaw. This is often done by eye; however, it can also be helpful to use the autoreflection technique described above. For further information, consult the laser system handbook. A worthwhile test of satisfactory remote interferometer alignment is to block the laser beam between remote interferometer and retroreflector and confirm that the system flags a beam obstruct error.

C-4 WAVELENGTH COMPENSATION

The velocity and wavelength of the laser beam depends on the refractive index of the air that the laser beam passes through. The refractive index of air varies primarily with air temperature, pressure, and humidity. If the variation in wavelength is not compensated for, linear laser measurement errors can reach 50 parts in 10^6. Compensation is not normally used when measuring pitch, yaw, or straightness.

C-4.1 Using Wavelength Compensation

Interferometric linear distance measurements in free air are inaccurate unless wavelength compensation is used. Even in a temperature-controlled room, the variation in day-to-day atmospheric pressure can cause wavelength changes of over 20 parts in 10^6. Most laser systems include either a manual or automatic compensation function that, depending on the manufacturer, is called environmental, wavelength, or velocity of light (VOL) compensation. To get accurate linear laser measurements in free air, this compensation function must be used.

C-4.2 Automatic Wavelength Compensation

Most laser systems use sensors to measure the air temperature, pressure, and humidity, then calculate the air's refractive index (and hence, the laser wavelength) using the Edlén equation. Some laser systems use an air refractometer to measure the refractive index directly. The laser readout is then automatically adjusted to compensate for any variations in the laser's wavelength. The advantages of an automatic system are that no user intervention is required and compensation is updated frequently.

C-4.3 Manual Wavelength Compensation

In manual compensation, the user reads the air temperature, pressure, and humidity from separate instruments, then manually enters the values into the laser system via keyboard or switch pack. The system then applies the compensation. Because the system is manual, it is usually impractical to update the compensation frequently.

C-4.4 Selection of Manual Sensors

If compensation is performed manually, it is important to select environmental sensors with appropriate measuring accuracies. To ensure that each sensor contributes less than ±0.5 parts in 10^6 of error to the wavelength compensation, the sensor accuracies displayed in Table C-4.4-1 are recommended.

Table C-4.4-1 Sensor Accuracies

Sensor	Recommended Accuracy
Air pressure	±150 Pa (±1 mmHg)
Air temperature	±0.5°C (±1°F)
Air humidity	±20% RH

NOTES:

(1) The atmospheric pressure value needed for compensation is not the sea level pressure quoted by meteorologists, but the actual pressure at the current altitude. If pressures are taken