This international standard was developed in accordance with internationally recognized principles on standardization established in the Decision on Principles for the Development of International Standards, Guides and Recommendations issued by the World Trade Organization Technical Barriers to Trade (TBT) Committee.

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Standard Test Method for Evaluating the Point-to-Point Distance Measurement Performance of Spherical Coordinate 3D Imaging Systems in the Medium Range[1]

This standard is issued under the fixed designation E3125; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 This test method covers the performance evaluation of laser-based, scanning, time-of-flight, single-detector 3D imaging systems in the medium-range and provides a basis for comparisons among such systems. This standard best applies to spherical coordinate 3D imaging systems that are capable of producing a point cloud representation of an object of interest. In particular, this standard establishes requirements and test procedures for evaluating the derived-point to derived-point distance measurement performance throughout the work volume of these systems. Although the tests described in this standard may be used for non-spherical coordinate 3D imaging systems, the test method may not necessarily be sensitive to the error sources within those instruments.

1.2 System performance is evaluated by comparing measured distance errors between pairs of derived-points to the manufacturer-specified, maximum permissible errors (MPEs). In this standard, a derived-point is a point computed using multiple measured points on the target surface (such as the center of a sphere). In the remainder of this standard, the term point-to-point distance refers to the distance between two derived-points.

1.3 The term "medium-range" refers to systems that are capable of operating within at least a portion of the ranges from 2 m to 150 m. The term "time-of-flight systems" includes phase-based, pulsed, and chirped systems. The word "standard" in this document refers to a documentary standard in accordance with Terminology E284.

1.4 This test method may be used once to evaluate the Instrument Under Test (IUT) for a given set of conditions or it may be used multiple times to assess the performance of the IUT for various conditions (for example, surface reflectance factors, environmental conditions).

1.5 SI units are used for all calculations and results in this standard.

1.6 This test method is not intended to replace more in-depth methods used for instrument calibration or compensation, and specific measurement applications may require other tests and analyses.

1.7 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety, health, and environmental practices and determine the applicability of regulatory limitations prior to use.* Some aspects of the safe use of 3D imaging systems are discussed in Practice E2641.

1.8 *This international standard was developed in accordance with internationally recognized principles on standardization established in the Decision on Principles for the Development of International Standards, Guides and Recommendations issued by the World Trade Organization Technical Barriers to Trade (TBT) Committee.*

2. Referenced Documents

2.1 *ASTM Standards:*[2]

E284 Terminology of Appearance
E1164 Practice for Obtaining Spectrometric Data for Object-Color Evaluation
E1331 Test Method for Reflectance Factor and Color by Spectrophotometry Using Hemispherical Geometry
E2544 Terminology for Three-Dimensional (3D) Imaging Systems
E2641 Practice for Best Practices for Safe Application of 3D Imaging Technology
E2919 Test Method for Evaluating the Performance of Systems that Measure Static, Six Degrees of Freedom (6DOF), Pose

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[1] This test method is under the jurisdiction of ASTM Committee E57 on 3D Imaging Systems and is the direct responsibility of Subcommittee E57.20 on Terrestrial Stationary Systems.

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[2] For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

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2.2 *ASME Standards:*[3]

ASME B89.4.19-2006 Performance Evaluation of Laser-Based Spherical Coordinate Measurement Systems

ASME B89.7.3.1-2001 Guidelines for Decision Rules: Considering Measurement Uncertainty in Determining Conformance to Specifications

ASME Y14.5-2009 Dimensioning and Tolerancing

2.3 *ISO Standards:*[4]

ISO 1:2016 Geometrical product specifications (GPS)—Standard reference temperature for the specification of geometrical and dimensional properties

ISO 10360-10:2016 Geometrical product specifications (GPS)—Acceptance and reverification tests for coordinate measuring systems (CMS)—Part 10: Laser trackers for measuring point-to-point distances

2.4 *JCGM Standards:*

JCGM 100:2008 Evaluation of measurement data—Guide to the expression of uncertainty in measurement (GUM), 1st edition

JCGM 200:2012 International vocabulary of metrology—Basic and general concepts and associated terms (VIM), 3rd edition

3. Terminology

3.1 *Definitions:*

3.1.1 *3D imaging system, n*—a non-contact measurement instrument used to produce a 3D representation (for example, a point cloud) of an object or a site. **E2544-11a – 3.2**

3.1.1.1 *Discussion*—Some examples of a 3D imaging system are laser scanners (also known as LADARs or LIDARs or laser radars), optical range cameras (also known as flash LIDARs or 3D range cameras), triangulation-based systems such as those using pattern projectors or lasers, and other systems based on interferometry.

3.1.1.2 *Discussion*—In general, the information gathered by a 3D imaging system is a collection of *n*-tuples, where each *n*-tuple can include but is not limited to spherical or Cartesian coordinates, return signal strength, color, time stamp, identifier, polarization, and multiple range returns.

3.1.1.3 *Discussion*—3D imaging systems are used to measure from relatively small scale objects (for example, coin, statue, manufactured part, human body) to larger scale objects or sites (for example, terrain features, buildings, bridges, dams, towns, archeological sites).

3.1.2 *beam width, n*—the extent of the irradiance distribution in a cross section of a laser beam (in a direction orthogonal to its propagation path). **E2544-11a – 3.2**

3.1.3 *calibration, n*—operation that, under specified conditions, in a first step, establishes a relation between the quantity values with measurement uncertainties provided by measurement standards and corresponding indications with associated measurement uncertainties and, in a second step, uses this information to establish a relation for obtaining a measurement result from an indication. **JCGM 200:2012 (VIM) – 2.39**

3.1.4 *combined standard uncertainty, n*—standard uncertainty of the result of a measurement when that result is obtained from the values of a number of other quantities, equal to the positive square root of a sum of terms, the terms being the variances or covariances of these other quantities weighted according to how the measurement result varies with changes in these quantities. **JCGM 100:2008 (GUM) – 2.3.4**

3.1.5 *coverage factor, n*—numerical factor used as a multiplier of the combined standard uncertainty in order to obtain an expanded uncertainty. **JCGM 100:2008 (GUM) – 2.3.6**

3.1.5.1 *Discussion*—A coverage factor, *k*, is typically in the range 2 to 3.

3.1.6 *diffuse reflectance factor, n*—the ratio of the flux reflected at all angles within the hemisphere bounded by the plane of measurement except in the direction of the specular reflection angle, to the flux reflected from the perfect reflecting diffuser under the same geometric and spectral conditions of measurement. **E284-13b – 4.1**

3.1.6.1 *Discussion*—The size of the specular reflection angle depends on the instrument and the measurement conditions used. For its precise definition the make and model of the instrument or the aperture angle or aperture solid angle of the specularly reflected beam should be specified.

3.1.7 *documentary standard, n*—document, arrived at by open consensus procedures, specifying necessary details of a method of measurement, definitions of terms, or other practical matters to be standardized. **E284-13b – 4.1**

3.1.8 *expanded measurement uncertainty (expanded uncertainty), n*—product of a combined standard measurement uncertainty and a factor larger than the number one. **JCGM 200:2012 (VIM) – 2.35**

3.1.9 *limiting conditions, n*—manufacturer's specified limits on the environmental, utility, and other conditions within which an instrument may be operated safely and without damage. **ASME B89.4.19-2006 – 4**

3.1.9.1 *Discussion*—Manufacturer's performance specifications are not assured over the limiting conditions.

3.1.10 *maximum permissible measurement error (maximum permissible error), n*—extreme value of measurement error, with respect to a known reference quantity value, permitted by specifications or regulations for a given measurement, measuring instrument, or measuring system. **JCGM 200:2012 (VIM) – 4.26**

3.1.10.1 *Discussion*—Usually, the term "maximum permissible errors" or "limits of error" is used where there are two extreme values.

3.1.10.2 *Discussion*—The term "tolerance" should not be used to designate 'maximum permissible error'.

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[3] Available from American Society of Mechanical Engineers (ASME), ASME International Headquarters, Two Park Ave., New York, NY 10016-5990, http://www.asme.org.

[4] Available from American National Standards Institute (ANSI), 25 W. 43rd St., 4th Floor, New York, NY 10036, http://www.ansi.org.

3.1.11 *measurand, n*—quantity intended to be measured. **JCGM 200:2012 (VIM) – 2.3**

3.1.11.1 *Discussion*—The specification of a measurand requires knowledge of the kind of quantity, description of the state of the phenomenon, body, or substance carrying the quantity, including any relevant component, and the chemical entities involved.

3.1.11.2 *Discussion*—In the second edition of the VIM and in IEC 60050-300:2001, the measurand is defined as the 'particular quantity subject to measurement'.

3.1.11.3 *Discussion*—The measurement, including the measuring system and the conditions under which the measurement is carried out, might change the phenomenon, body, or substance such that the quantity being measured may differ from the measurand as defined. In this case, adequate correction is necessary.

Example 1: The length of a steel rod in equilibrium with the ambient Celsius temperature of 23 °C will be different from the length at the specified temperature of 20 °C, which is the measurand. In this case, a correction is necessary.

3.1.12 *measurement error, n*—measured quantity value minus a reference quantity value. **JCGM 200:2012 (VIM) – 2.16**

3.1.12.1 *Discussion*—The concept of 'measurement error' can be used both a) when there is a single reference quantity value to refer to, which occurs if a calibration is made by means of a measurement standard with a measured quantity value having a negligible measurement uncertainty or if a conventional quantity value is given, in which case the measurement error is known, and b) if a measurand is supposed to be represented by a unique true quantity value or a set of true quantity values of negligible range, in which case the measurement error is not known.

3.1.12.2 *Discussion*—Measurement error should not be confused with production error or mistake.

3.1.13 *measurement precision, n*—closeness of agreement between indications or measured quantity values obtained by replicate measurements on the same or similar objects under specified conditions. **JCGM 200:2012 (VIM) – 2.15**

3.1.14 *measurement repeatability, n*—measurement precision under a set of repeatability conditions of measurement. **JCGM 200:2012 (VIM) – 2.21**

3.1.14.1 *Discussion*—See also 3.1.13, *measurement precision*, and 3.1.21, *repeatability condition of measurement*.

3.1.15 *measurement uncertainty, n*—non-negative parameter characterizing the dispersion of the quantity values being attributed to a measurand, based on the information used. **JCGM 200:2012 (VIM) – 2.26**

3.1.15.1 *Discussion*—Measurement uncertainty includes components arising from systematic effects, such as components associated with corrections and the assigned quantity values of measurement standards, as well as the definitional uncertainty. Sometimes estimated systematic effects are not corrected for but, instead, associated measurement uncertainty components are incorporated.

3.1.15.2 *Discussion*—The parameter may be, for example, a standard deviation called standard measurement uncertainty (or a specified multiple of it), or the half-width of an interval, having a stated coverage probability.

3.1.15.3 *Discussion*—Measurement uncertainty comprises, in general, many components. Some of these may be evaluated by Type A evaluation of measurement uncertainty from the statistical distribution of the quantity values from series of measurements and can be characterized by standard deviations. The other components, which may be evaluated by Type B evaluation of measurement uncertainty, can also be characterized by standard deviations, evaluated from probability density functions based on experience or other information.

3.1.15.4 *Discussion*—In general, for a given set of information, it is understood that the measurement uncertainty is associated with a stated quantity value attributed to the measurand. A modification of this value results in a modification of the associated uncertainty.

3.1.16 *point cloud, n*—a collection of data points in 3D space (frequently in the hundreds of thousands), for example as obtained using a 3D imaging system. **E2544-11a – 3.2**

3.1.16.1 *Discussion*—The distance between points is generally non-uniform and hence all three coordinates (Cartesian or spherical) for each point must be specifically encoded.

3.1.17 *rated conditions, n*—manufacturer-specified limits on the environmental, utility, and other conditions within which the manufacturer's performance specifications are guaranteed at the time of installation of the instrument. **ASME B89.4.19-2006 - 4**

3.1.18 *reference length, n*—calibrated value of the distance between two points in space at the time and conditions when a test is performed. **ASME B89.4.19-2006 – 4**

3.1.19 *reflectance, n*—ratio of the reflected radiant or luminous flux to the incident flux in the given conditions. **E284-13b – 4.1**

3.1.19.1 *Discussion*—The term reflectance is often used in a general sense or as an abbreviation for reflectance factor. Such usage may be assumed unless the above definition is specifically required by context.

3.1.20 *reflectance factor, n*—ratio of the flux reflected from the specimen to the flux reflected from the perfect reflecting diffuser under the same geometric and spectral conditions of measurement. **E284-13b – 4.1**

3.1.21 *repeatability condition of measurement, n*—condition of measurement, out of a set of conditions that includes the same measurement procedure, same operators, same measuring system, same operating conditions and same location, and replicate measurements on the same or similar objects over a short period of time. **JCGM 200:2012 (VIM) – 2.20**

3.1.22 *retroreflector, n*—passive device that reflects light back parallel to the incident direction over a range of incident angles. **ASME B89.4.19-2006 – 4**

3.1.22.1 *Discussion*—Typical retroreflectors are the cat's-eye and the cube corner.

3.1.23 *spherically mounted retroreflector (SMR), n*—retroreflector that is mounted in a spherical housing. **ASME B89.4.19-2006 – 4**

3.1.23.1 *Discussion*—In the case of an open-air cube corner, the vertex is typically adjusted to be coincident with the sphere center.

3.1.24 *standard uncertainty, n*—uncertainty of the result of a measurement expressed as a standard deviation. **JCGM 100:2008 (GUM) – 2.3.1**

3.1.25 *systematic measurement error (systematic error), n*—component of measurement error that in replicate measurements remains constant or varies in a predictable manner. **JCGM 200:2012 (VIM) – 2.17**

3.1.25.1 *Discussion*—A reference quantity value for a systematic measurement error is a true quantity value, or a measured quantity value of a measurement standard of negligible measurement uncertainty, or a conventional quantity value.

3.1.25.2 *Discussion*—Systematic measurement error, and its causes, can be known or unknown. A correction can be applied to compensate for a known systematic measurement error.

3.1.25.3 *Discussion*—Systematic measurement error equals measurement error minus random measurement error.

3.1.26 *uncertainty budget, n*—statement of a measurement uncertainty, of the components of that measurement uncertainty, and of their calculation and combination. **JCGM 200:2012 (VIM) – 2.33**

3.1.26.1 *Discussion*—An uncertainty budget should include the measurement model, estimates, and measurement uncertainties associated with the quantities in the measurement model, covariances, type of applied probability density functions, degrees of freedom, type of evaluation of measurement uncertainty, and any coverage factor.

3.1.27 *work volume, n*—physical space, or region within a physical space, that defines the bounds within which a pose measurement system is acquiring data. **E2919-14 – 3.2.8**

3.2 *Definitions of Terms Specific to This Standard:*

3.2.1 *azimuth angle, n*—the angle between the orthogonal projection of the laser beam on a plane perpendicular to the vertical (standing) axis of the instrument and a fixed (reference) axis in that plane.

3.2.2 *backsight, n*—measurement mode, where the target is measured with the laser beam emerging from the back-face of the instrument.

3.2.2.1 *Discussion*—The back-face may be arbitrarily chosen or may be defined in terms of the zenith angle of the spinning prism mirror that directs the laser beam. For example, the face of the instrument from which the laser beam emerges that corresponds to a zenith angle between 180° and 360° may be defined as the back-face.

3.2.2.2 *Discussion*—See also *frontsight* (3.2.6).

3.2.3 *derived-point, n*—a point (such as the center of a sphere) that is not measured directly but computed using multiple measured points on a target surface.

3.2.4 *derived-point to derived-point distance, n*—the distance between two derived-points.

3.2.4.1 *Discussion*—The derived-point to derived-point distance is also referred to as point-to-point distance in this standard.

3.2.5 *elevation angle, n*—the angle between the laser beam and the orthogonal projection of the laser beam on a plane perpendicular to the vertical (standing) axis of the instrument, measured from that plane.

3.2.5.1 *Discussion*—Some systems report the zenith angle instead of the elevation angle. The sum of the elevation and zenith angle is equal to 90°, therefore elevation angle can be determined if the zenith angle is known.

3.2.6 *frontsight, n*—measurement mode, where the target is measured with the laser beam emerging from the front-face of the instrument.

3.2.6.1 *Discussion*—The front-face may be arbitrarily chosen or may be defined in terms of the zenith angle of the spinning prism mirror that directs the laser beam. For example, the face of the instrument from which the laser beam emerges that corresponds to a zenith angle between 0° and 180° may be defined as the front-face.

3.2.6.2 *Discussion*—See also *backsight* (3.2.2).

3.2.7 *instrument settings, n*—parameters that a user is allowed to select prior to performing a measurement, such as point spacing, filtering options, valid intensity range.

3.2.8 *IUT, n*—instrument under test.

3.2.9 *measurement axis, n*—a radial line, passing through the origin of the IUT, along which a relative-range test is performed.

3.2.9.1 *Discussion*—The derived-points of the target at the reference position and the test position also lie on this axis.

3.2.10 *operating mode, n*—a collection of instrument settings pre-selected by the manufacturer for a particular type of measurement.

3.2.10.1 *Discussion*—For example, operating mode A might include a pre-defined scanning acquisition rate and spatial averaging. A user might select this operating mode in conjunction with other instrument settings for a particular measurement task.

3.2.10.2 *Discussion*—Because some systems can measure a target in frontsight and in backsight, these are also considered to be operating modes.

3.2.11 *origin of the IUT, n*—the point in space that corresponds to a range value of zero.

3.2.11.1 *Discussion*—Ideally, the intersection of the horizontal and vertical axes of the IUT lies on the face of the spinning mirror and is also the point of zero range.

3.2.12 *RI, n*—reference instrument.

3.2.13 *SMR-integrated sphere target, n*—a special artifact consisting of a hollow partial sphere with a kinematic nest located inside so that an SMR mounted on this nest is concentric with the outer spherical surface of the hollow sphere.

3.2.14 *two-face test, n*—a test to characterize certain geometric errors of the instrument by measuring a target in the frontsight mode followed immediately by a measurement of the same target in the backsight mode.

3.2.14.1 *Discussion*—The apparent distance, perpendicular to the laser beam, between the measurement results from each of the measurement modes yields the test result.

3.2.15 *zenith angle, n*—the angle between the laser beam and the vertical axis of the instrument, measured from the pole (point directly above the instrument when the instrument is mounted right-side up).

3.3 *Symbols:*

3.3.1 The following symbols are used in this standard.

TABLE 1 Symbols

Symbol	Meaning
(r, θ, ϕ)	Range, azimuth angle, and elevation angle, respectively, of a single point measured by the IUT or of the derived-point obtained from the IUT point set
(x, y, z)	Cartesian coordinates of a single point measured by the IUT or of the derived-point obtained from the IUT point set
(X, Y, Z)	Cartesian coordinates of a single point measured by the RI or of the derived-point obtained from the RI point set
$E_{two\text{-}face}$	Two-face error
$E_{distance}$	Derived-point to derived-point distance error
$E_{two\text{-}face,MPE}$	MPE specification for two-face error
$E_{distance,\ MPE}$	MPE specification for derived-point to derived-point distance error
R	Calibrated radius of a sphere target
D_{meas}	Distance between two derived-points as obtained by the IUT
D_{ref}	Distance between two derived-points as obtained by the RI
U	Expanded test uncertainty (k = 2)
α	The angle as shown in Figs. 2 and 3. In general, α is the angular sweep between two targets measured by the IUT in the plane containing the origin of the IUT and the derived-points of the two targets, except in Fig. 3(e) and (f).
$e_{r,MPE}$	MPE specification for range measurement error of the IUT
$e_{t,MPE}$	MPE specification for transverse measurement error of the IUT
d	Distance of the target from the IUT in the horizontal plane
S	Sphere point set
P	Plane point set
s	Standard deviation of residuals

4. Significance and Use

4.1 This standard provides a test method for obtaining the point-to-point distance measurement errors for medium-range 3D imaging systems. The results from this test method may be used to evaluate or to verify the point-to-point distance measurement performance of medium-range 3D imaging systems. The results from this test method may also be used to compare performance among different instruments.

4.2 The purpose of this document is to provide test procedures that are sensitive to instrument error sources. The point-to-point distance measurement performance of the IUT obtained by the application of this test method may be different from the point-to-point distance measurement performance of the IUT under some real-world conditions. For example, object geometry, texture, surface reflectance factor, and temperature, as well as particulate matter, thermal gradients, atmospheric pressure, humidity, ambient lighting in the environment, mechanical vibrations, and wind induced test setup instability will affect the point-to-point distance measurement performance (see Appendix X10 for a discussion on thermal effects). A derived-point such as the center of a suitable sphere or plate target that meets the requirements described in Section 7 provides a reliable point in space that is minimally impacted by target-related properties such as geometry, surface texture, color, and reflectivity. Additional tests not described in this standard may be required to assess the contribution of these influence factors on point-to-point distance measurements.

4.3 The test may be carried out for instrument acceptance, warranty or contractual purposes by mutual agreement between the manufacturer and the user. The IUT is tested in accordance with manufacturer-supplied specifications, rated conditions, and technical documentation.

4.4 For the purposes of understanding the behavior of the IUT and without warranty implications, this test may be modified as necessary to evaluate the point-to-point distance measurement performance of the IUT outside the manufacturer's rated conditions, but within the manufacturer's limiting conditions.

4.5 The manufacturer may provide different performance specification values for different sets of rated conditions, for example, better point-to-point distance measurement performance might be specified under a set of more restrictive environmental conditions. The user is advised that the IUT's performance may differ significantly in other modes of operation, with other instrument settings, or outside the rated conditions, and should consult the manufacturer for performance specifications of the operating mode and instrument settings that best represent the planned usage.

4.6 This standard is intended to expand and complement the ranging tests described in Test Method E2938. While Test Method E2938 specifically describes the evaluation of the ranging capability of any medium-range 3D imaging system, this standard provides test procedures to evaluate the point-to-point distance error due to the combined effect from angular and ranging errors of a particular type of these systems, that is, spherical coordinate 3D imaging systems.

5. Introduction

5.1 *Overview:*

5.1.1 This standard consists of two types of test procedures to evaluate the point-to-point distance performance of 3D imaging systems – two-face tests and point-to-point distance tests.

5.1.2 Two-face tests can be regarded as a special case of a point-to-point distance test, with zero reference length. These tests are quick and easy to perform, and are sensitive to many sources of mechanical and optical misalignments within the IUT. Similar two-face tests are used to evaluate the performance of laser trackers which are also spherical coordinate measurement systems (see ASME B89.4.19-2006 or ISO 10360-10:2016).

5.1.3 The point-to-point distance tests involve measuring a reference length in many positions and orientations within the IUT work volume. These tests are not only sensitive to all known mechanical and optical misalignments in the IUT, but also provide the connection to the SI unit of length, the meter. Point-to-point distance tests are further categorized as symmetric tests, asymmetric tests, inside test, relative-range tests, and user-selected tests.

5.1.4 The two-face tests, symmetric tests, asymmetric tests, and the inside test are performed using sphere targets. In some cases, especially when the sphere target is far away from the IUT, the sphere center appears closer to or farther away from the IUT due to sphere target geometry induced error. This is described in Appendix X9. Since the relative-range tests may involve longer distances, these tests are performed using plate targets to eliminate this target-induced error. If the user chooses to perform additional relative-range tests as the user-selected tests, they are performed using plate targets; otherwise, the user selected tests are performed using sphere targets.

5.1.5 See Appendix X3 for a discussion on the rationale for the selection of test positions and orientations required in this standard.

5.2 *Two-face Tests:*

5.2.1 The objective of the two-face tests is to quantify the errors in measured coordinates generated by the IUT due to mechanical and optical misalignments within the IUT. This is achieved by first measuring the derived-point of a stationary sphere target in the IUT's frontsight mode and immediately repeating the measurement in the IUT's backsight mode. The difference in distance between the two derived-points, perpendicular to the laser beam, from each of the measurement modes yields the test result. This test result depends on the range, the azimuth, and the elevation of the sphere target with respect to the IUT. Therefore, the two-face tests are performed at different positions in the work volume of the instrument.

5.2.2 Some 3D imaging systems may not be designed to measure any part of the work volume in the backsight mode. The two-face tests cannot be performed on those systems. For all other 3D imaging systems where at least some portion of the work volume can be measured in both faces, two-face tests are mandatory.

5.2.3 Two-face tests can be performed quicker than the point-to-point distance tests described in this standard and will immediately reveal problems with the IUT. It is therefore recommended that these tests be performed first to verify if the IUT meets the two-face MPE specifications before proceeding with the point-to-point distance tests.

5.3 *Point-to-point Distance Tests:*

5.3.1 The objective of the point-to-point distance tests is to evaluate the point-to-point distance measurement performance of the IUT by comparing the point-to-point distance between two targets as measured by the IUT against the calibrated distance obtained by a reference instrument (RI).

5.3.2 Such comparison against a calibrated reference length is performed for all point-to-point distance tests, that is, symmetric tests, asymmetric tests, inside test, relative-range tests, and user-selected tests.

5.3.3 Mechanical and optical misalignments within the IUT introduce systematic errors in the measured point coordinates (range, azimuth angle, and elevation angle), see Ref (**1**).[5] In order to adequately capture known sources of systematic errors within the IUT, reference lengths (realized as the distance between two sphere targets or two plate targets) are positioned at different distances and orientations within the work volume.

6. Test Conditions and Requirements

6.1 *Rated Conditions:*

6.1.1 The rated conditions are manufacturer-specified limits on environmental, utility, and other conditions within which the manufacturer-specified MPEs are guaranteed. Rated conditions may include minimum and maximum measurement ranges, target characteristics (Section 7), minimum and maximum temperatures of operation, maximum thermal gradient (°C/m and °C/h). If limits are not specified for a condition, then it is assumed that the manufacturer's specifications will be valid for any range of that condition.

6.1.2 The rated conditions also include manufacturer-specified limits on instrument settings such as point density or point-to-point spacing, and scanning acquisition rate. The manufacturer must state the limits for the instrument settings under which the specified MPEs are valid.

6.1.3 Some instruments do not allow the user to select individual settings and only allow certain pre-set operating modes. The rated conditions therefore also include manufacturer-specified operating modes. The manufacturer must state the operating modes for which the specified MPEs are valid.

6.1.4 Operating modes and instrument settings must be clearly described and reproducible by any qualified user (see Note 1). If no limits are specified for a specific instrument setting (for example, point density), then it is assumed that the MPE will be valid for any value of that setting. If no operating modes are specified, it is assumed that the MPE is valid for all operating modes available to the user (see Note 2).

NOTE 1—A qualified user is a person who has been trained in the proper operation of the IUT.

NOTE 2—As an example, the manufacturer may specify the MPE to be valid for the following rated conditions: target range between 2 m and 100 m; point density from 30 points/degree to 90 points/degree along azimuth and elevation angle directions; operating mode A (which includes a certain pre-set scanning acquisition rate and spatial averaging), and indoor measurements only with temperature in the range 20 °C ± 5 °C. Because the manufacturer does not specify other factors such as target reflectivity, temperature gradient limits, bounds on atmospheric pressure, etc., the MPE is assumed to be valid for any value of those settings/conditions.

6.1.5 When the test is carried out for verifying manufacturer's specifications, the conditions of the test environment, instrument settings and operating modes shall remain within the bounds of the manufacturer's rated conditions throughout the test.

6.1.6 The IUT shall be operated in accordance with the procedures given in the manufacturer's User Manual. All applicable procedures described in the manufacturer's User Manual for the proper use of the instrument, such as machine start-up/warm-up time, compensation procedures and manufacturer maintenance requirements, shall be adhered to.

6.2 *Test Uncertainty:*

6.2.1 A test value is an estimate of the IUT error under a certain set of conditions and at a certain instant in time. Test value uncertainty (or test uncertainty) is the uncertainty of the test value and is a quantitative measure of the dispersion of values that could reasonably be attributed to the (true) error. Examples of test values in this document are *(1)* the IUT error in a particular instance of determining a point-to-point distance, and *(2)* the IUT error in a particular instance of

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[5] The boldface numbers in parentheses refer to the list of references at the end of this standard.

measuring the same derived-point using frontsight and backsight measurements of a sphere target (the error being represented by the distance between the two derived-points perpendicular to the laser beam).

6.2.2 In the case of a point-to-point distance test described in this standard, the test value uncertainty is determined by the uncertainty in the reference length.

6.2.3 In the case of the two-face tests, the test value uncertainty is determined by the possible displacement of the target between frontsight and backsight measurements. For a rigidly-mounted target and a short period of time (a few minutes) between measurements that minimizes thermal drift, the test value uncertainty should be a negligibly small quantity and can be considered zero.

6.2.4 In this standard, the expanded test value uncertainty, U, is equal to two times the combined standard uncertainty (that is, a coverage factor of $k = 2$). This standard follows the 4:1 simple acceptance/simple rejection decision rule described in ASME B89.7.3.1-2001 to make conformance decisions (pass/fail). For this purpose, the expanded test value uncertainty U shall be less than or equal to ¼ of the MPE ($E_{distance,MPE}$ for point-to-point distance tests and $E_{two\text{-}face,MPE}$ for two-face tests). The MPE values shall be specified by the manufacturer of the IUT.

7. Apparatus

7.1 *Target Geometry:*

7.1.1 Two target geometries are specified in this standard: a sphere target and a plate target. The plate target may be square, rectangular, circular or any other planar shape for which a boundary is easily defined; however, for illustration purposes, a square- or rectangular-shaped target is assumed throughout this document. The sphere target shall be at least a hemisphere, oriented in such a way that the hemispherical surface is fully visible to the IUT.

7.2 *Target Material and Optical Requirements:*

7.2.1 Different materials have different optical characteristics such as surface reflectance factor at the IUT's operating wavelength, optical penetration depth (volumetric scattering), and surface scattering characteristics, which means that the values of the errors may differ for different materials.

7.2.2 The types of target materials, and their optical characteristics (for example, surface diffuse reflectance factor), used in the tests should be specified by the manufacturer. If a material other than that specified by the manufacturer is used for the tests, the performance of the IUT using this material may not meet the manufacturer's specifications. If the target material or material characteristics are not specified by the manufacturer, the user is free to use any material for the tests. It is recommended that the manufacturer specify target materials for the tests that may be obtained at a reasonable cost to the user. Suggested materials that may be used for the target include, but are not limited to, steel and aluminum.

7.2.3 The reflectance factor of the target surface, as measured in accordance with Practice E1164 and Test Method E1331, must be within the manufacturer's specifications. It is strongly recommended that the reflectance factor (measured at the IUT's operating wavelength) with and without the specular component be reported if possible (see Note 3). If the reflectance factor is not specified by the manufacturer, the user is free to use target material with any reflectance factor for the tests.

NOTE 3—The reflectance factor consists of both diffuse and specular components, while the diffuse reflectance factor excludes the specular component.

7.3 *Target Mechanical Requirements:*

7.3.1 The minimum plate target size should be specified by the manufacturer, and shall be sufficient to yield a minimum of 100 points after point selection as described in Section 10. The front-side of the plate target shall consist of a single planar surface made of a single material. The edges of the target shall have a radius of less than or equal to one quarter of the smallest beam width of the IUT (see Fig. 2 in Test Method E2938).

7.3.2 In the case of point-to-point distance tests that require the use of plate targets (for example, relative-range tests), the flatness of the plate target shall not exceed 20 % of the smallest relative-range *MPE* (that is, the smallest *MPE* from tests PP16 through PP18 in Table 6). The flatness should be measured in accordance with the procedures in Section 5.4.2 of ASME Y14.5-2009.

7.3.3 The minimum sphere target size should be specified by the manufacturer, and shall be sufficient to yield a minimum of 300 points after point selection as described in Section 9. The sphere target may be hollow or solid and the front (measurement) surface shall consist of a single surface made of a single material.

7.3.4 The radius of the sphere target along with its uncertainty shall be determined through a calibration procedure. Typically, such calibration is performed using a contact probe coordinate measuring machine (CMM), but other methods may be used. The uncertainty in radius shall be accounted for in the determination of the test value uncertainty (see X5.2.7, X6.2.8, and X7.2.5 for examples).

7.3.5 In the case of point-to-point distance tests that require the use of sphere targets, the circularity of the sphere target shall not exceed 20 % of the smallest point-to-point distance *MPE* excluding the relative-range tests and the user-selected tests (that is, the smallest *MPE* from tests PP1 through PP15 in Tables 3-5). The circularity should be measured in accordance with the procedures in Section 5.4.3 of ASME Y14.5-2009.

7.3.6 In the case of two-face tests, the circularity of the sphere target shall not exceed 20 % of the smallest two-face *MPE* (that is, the smallest *MPE* from tests TF1 through TF12 in Table 2). The circularity should be measured in accordance with the procedures in Section 5.4.3 of ASME Y14.5-2009.

7.4 *Practical Realization of the Target:*

7.4.1 The relative-range portion of the point-to-point distance tests shall be performed with a plate target as described in 7.2 and 7.3. If there are no fiducials attached to the plate to facilitate identification of the derived-point, the plate shall be carefully aligned with the measurement axis. That is, the plate shall be perpendicular to the measurement axis (see 7.5.1 for alignment tolerance requirements) and the derived-point shall lie on that axis. It is also permissible to add fiducials to the plate to facilitate identification of the derived-point. If fiducials are used, they shall be mounted on the sides or back of the plate

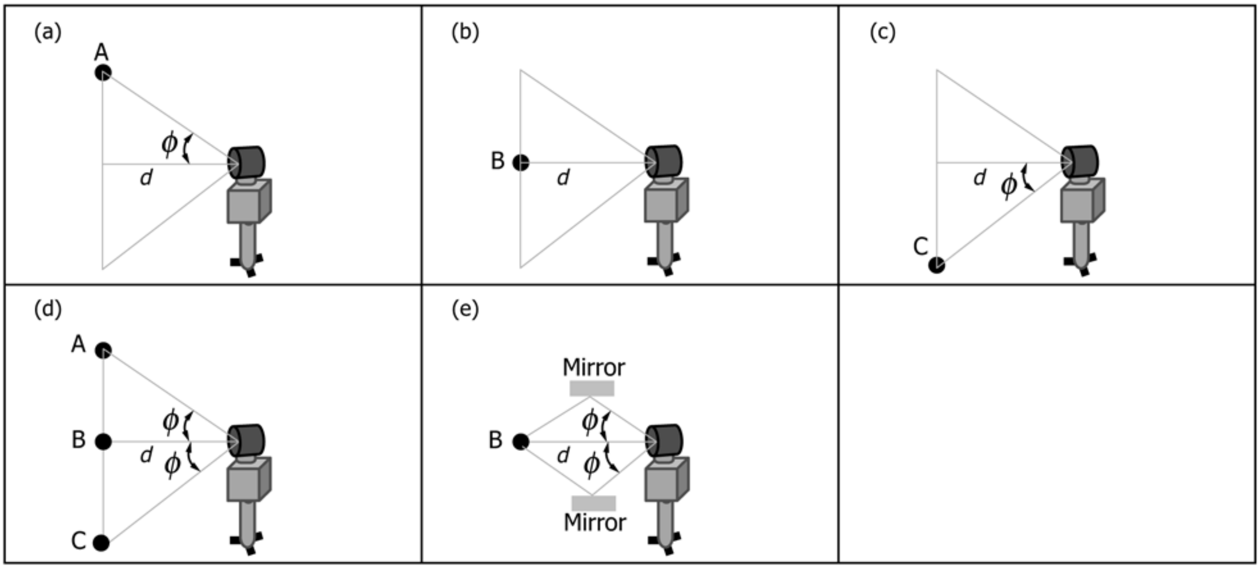

FIG. 1 Two-Face Test (a) on sphere target A that is at an elevation angle ϕ of 45° ± 10° (b) on sphere target B that is at IUT height (elevation angle ϕ of 0° ± 10°), (c) on sphere target C that is at an elevation angle ϕ of -45° ± 10°, (d) using three sphere targets mounted on a column, (e) using a single sphere target and two mirrors

in such a manner that they do not occlude or generate multi-path measurement signals from the central region of the plate that is used to determine the derived-point for the IUT. Examples of plate target designs are described in Appendix X8.

7.4.2 All point-to-point distance tests except the relative-range tests shall be realized using sphere targets that meet the requirements described in 7.2 and 7.3. If a laser tracker is used to obtain reference measurements, the derived-point of the sphere may be obtained by manually probing a spherically mounted retro-reflector (SMR) on the surface of the sphere target (Ref (**2**)). It is also permissible to use SMR-integrated sphere targets that contain a kinematic nest to mount an SMR inside the sphere, accessible from the back, and for which the center of the SMR coincides with the center of the outer surface of the sphere target. In this case, the reference measurements are obtained using a laser tracker and the SMR located inside the sphere target. If this type of target is used, the concentricity between the outer surface of the sphere target and the SMR center shall be accounted for in the determination of the test value uncertainty. Various methods to realize point-to-point distance tests using sphere targets are described in Appendix X4.

7.5 *Alignment of the Plate Target:*

7.5.1 The required alignment of the plate target (position and orientation with respect to the measurement axis) is primarily determined by the specifications of the IUT. Acceptable alignment criteria shall be determined by conducting an uncertainty analysis for the specific test setup and IUT utilized. An example of the procedure to determine the uncertainty budget for a specific test setup is given in Appendix X2 of Test Method E2938.

7.6 *Mounting:*

7.6.1 The targets (both sphere and plate) shall be rigidly mounted on stable supports and the supports shall not obstruct the front (measurement) surface of the targets. In addition, any part of the target support that is visible to the IUT should be sufficiently separated from the target so that any measured points on the support can be easily removed in the data segmentation described in Sections 9 and 10.

7.7 *Reference Instrument:*

7.7.1 The RI shall measure the point-to-point distance with an expanded uncertainty *U* that is in conformance with 6.2. The RI shall be calibrated, maintained, and operated in accordance with the manufacturer's instructions.

8. Test Procedure

8.1 *Overview:*

8.1.1 The test procedure described in this section may take several hours to execute depending on the procedure to realize the reference lengths. It is recommended that the user assess the stability of the IUT and the targets by performing simple repeatability tests, such as those suggested in Appendix X1, prior to commencing the test procedures described in this section.

8.1.2 The rationale for selection of the test positions and orientations is given in Appendix X3.

8.1.3 The instrument settings and operating modes for the test procedure shall be chosen, within rated conditions, to yield a minimum of 300 measured points on the sphere target after point selection as described in Section 9, or 100 measured points on the plate target after point selection as described in Section 10.

8.1.4 IUT data is acquired in the instrument coordinate frame, that is, the origin and orientation of the coordinate system of the data shall also be the origin and orientation of the IUT coordinate frame.

8.1.5 It is permissible to unmount the IUT from its stand and remount it on a different stand between tests.

TABLE 2 Two-Face Test Positions (see Fig. 1)

Test number	Distance of target from IUT, *d*	Elevation angle ϕ of target	Azimuth angle θ, see 8.2.7	Description	Fig. 1, subfigure
TF1	Not more than 10 m	45° ± 10°	0°	Measurements on sphere target A located at an elevation angle ϕ = 45° ± 10°, with the IUT not more than 10 m away and nominally at azimuth angle θ = 0° when facing the sphere target.	a
TF2	Not more than 10 m	0° ± 10°	0°	Measurements on sphere target B located at IUT height (ϕ = 0° ± 10°), with the IUT not more than 10 m away and nominally at azimuth angle θ = 0° when facing the sphere target.	b
TF3	Not more than 10 m	-45° ± 10°	0°	Measurements on sphere target C located at an elevation angle ϕ = -45° ± 10°, with the IUT not more than 10 m away and nominally at azimuth angle θ = 0° when facing the sphere target.	c
TF4	Not more than 10 m	45° ± 10°	90°	Measurements on sphere target A located at an elevation angle ϕ = 45° ± 10°, with the IUT not more than 10 m away and nominally at azimuth angle θ = 90° when facing the sphere target.	a
TF5	Not more than 10 m	0° ± 10°	90°	Measurements on sphere target B located at IUT height (ϕ = 0° ± 10°), with the IUT not more than 10 m away and nominally at azimuth angle θ = 90° when facing the sphere target.	b
TF6	Not more than 10 m	-45° ± 10°	90°	Measurements on sphere target C located at an elevation angle ϕ = -45° ± 10°, with the IUT not more than 10 m away and nominally at azimuth angle θ = 90° when facing the sphere target.	c
TF7	At least 20 m	45° ± 10°	0°	Measurements on sphere target A located at an elevation angle ϕ = 45° ± 10°, with the IUT at least 20 m away and nominally at azimuth angle θ = 0° when facing the sphere target.	a
TF8	At least 20 m	0° ± 10°	0°	Measurements on sphere target B located at IUT height (ϕ = 0° ± 10°), with the IUT at least 20 m away and nominally at azimuth angle θ = 0° when facing the sphere target.	b
TF9	At least 20 m	-45° ± 10°	0°	Measurements on sphere target C located at an elevation angle ϕ = -45° ± 10°, with the IUT at least 20 m away and nominally at azimuth angle θ = 0° when facing the sphere target.	c
TF10	At least 20 m	45° ± 10°	90°	Measurements on sphere target A located at an elevation angle ϕ = 45° ± 10°, with the IUT at least 20 m away and nominally at azimuth angle θ = 90° when facing the sphere target.	a
TF11	At least 20 m	0° ± 10°	90°	Measurements on sphere target B located at IUT height (ϕ = 0° ± 10°), with the IUT at least 20 m away and nominally at azimuth angle θ = 90° when facing the sphere target.	b
TF12	At least 20 m	-45° ± 10°	90°	Measurements on sphere target C located at an elevation angle ϕ = -45° ± 10°, with the IUT at least 20 m away and nominally at azimuth angle θ = 90° when facing the sphere target.	c

8.1.6 The tests shall be performed with the IUT mounted either right-side up or upside down. However, all tests shall be performed with the IUT in the same orientation (that is, right-side up or upside down). The IUT shall not be mounted sideways, or in a tilted (inclined) orientation for any of the tests described in this standard (see Note 4).

NOTE 4—Figs. 1-5 show the position of the targets and reference lengths for the right-side up orientation of the IUT. The same position of the targets and reference lengths is also valid for the upside down orientation of the IUT, that is, even when the IUT is flipped upside down, the targets and reference lengths remain as shown in Figs. 1-5. In the case of Fig. 3(e) and Fig. 3(f), the IUT measures one of the targets at a negative elevation angle (with respect to the IUT) if the test is performed with the IUT mounted upside down.

8.2 *Two-face Test Procedure:*

8.2.1 The two-face test procedure involves measurement of a sphere target in frontsight mode followed immediately by measurement of the same target in backsight mode. This procedure is performed for the 12 tests (TF1 through TF12) described in Table 2.

8.2.2 It is permissible to use different instrument settings and operating modes, within rated conditions, for the different tests described in Table 2 provided the condition in 8.1.3 is satisfied.

8.2.3 It is permissible to use different instrument settings and operating modes, within rated conditions, for the frontsight and backsight measurements of any given two-face test in Table 2 provided the condition in 8.1.3 is satisfied (see Note 5).

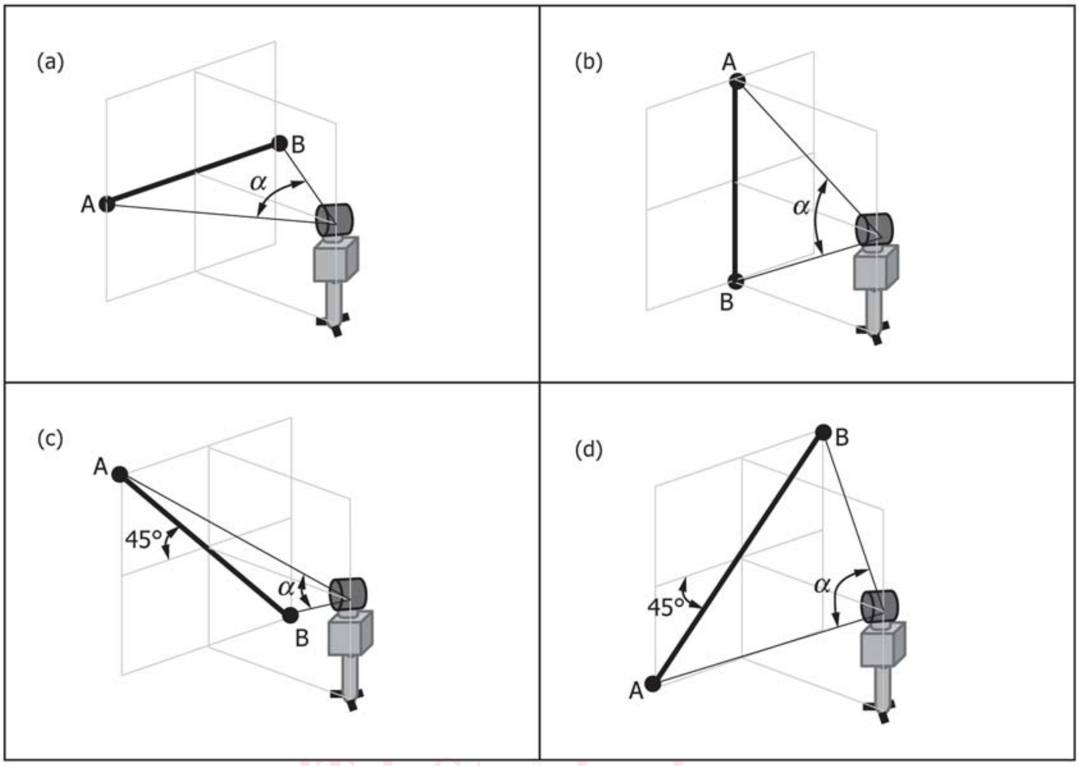

FIG. 2 Symmetric Tests (a) symmetric horizontal (b) symmetric vertical (c) symmetric left diagonal (d) symmetric right diagonal

NOTE 5—It is recommended that the frontsight and backsight measurements be performed with the same instrument settings and operating modes.

8.2.4 It is permissible to use targets of different sizes and characteristics, within rated conditions, for the different test positions described in Table 2 provided the condition in 8.1.3 is satisfied.

8.2.5 The same target shall be used for both the frontsight and backsight measurements of any given test in Table 2.

8.2.6 The first set of six two-face tests (TF1 through TF6) in Table 2 are realized with the IUT placed at any distance *d* not exceeding 10 m, provided the distance *d* is within the rated conditions of the IUT. The next six two-face tests (TF7 through TF12) in Table 2 are realized with the IUT placed at any distance *d* that is at least 20 m from the target provided that the distance *d* is within the rated conditions of the IUT. The distance *d* may be different for each of the tests in Table 2 provided that *d* meets the requirement of that test as specified in Table 2, Column 2.

8.2.7 Six of the two-face tests (TF1 through TF3 and TF7 through TF9) in Table 2 are realized with the IUT set at an arbitrary azimuth angle ($\theta = \theta_i$) to the target. The remaining six two-face tests (TF4 through TF6 and TF10 through TF12) are realized with the IUT set at an angle that is either $\theta_i + 90° \pm 10°$ or $\theta_i - 90° \pm 10°$. While the azimuth angles listed in Table 2 are nominally 0° and 90°, they can be any pair of angles that are 90° apart to within ±10°.

8.2.8 The two-face tests may be realized by using a single sphere target placed at appropriate positions listed in Table 2 (as shown in Fig. 1(a), (b), and (c)). The tests may also be realized in other ways. Fig. 1(d) shows a setup with three sphere targets mounted on a vertical column to realize the different elevation angles. Fig. 1(e) shows a setup with a single sphere that is measured directly as well as through reflections from two high-quality mirrors to realize the different elevation angles. If using multiple spheres or mirrors, or both, it is permissible to acquire sphere point-cloud data corresponding to the different sphere target locations in a single scan in frontsight mode and then acquire data corresponding to those locations in backsight mode. If using a mirror to realize different elevation angles, the effect of mirror characteristics such as flatness and optical properties on the two-face error shall be considered in the determination of the test value uncertainty.

8.3 *Point-to-point Distance Test Procedure:*

8.3.1 The point-to-point distance test procedure consists of 20 point-to-point distance tests. The tests are described in Tables 3-7. They are broadly classified as symmetric tests, asymmetric tests, inside test, relative-range tests, and user-selected tests. The symmetric tests, asymmetric tests, and the inside test are performed using sphere targets. The relative-range tests are performed using plate targets. If the user chooses to perform additional relative-range tests as the user-selected tests, they are performed using plate targets; otherwise, the user selected tests are performed using sphere targets.

8.3.2 It is permissible to use different instrument settings and operating modes, within rated conditions, for the different test positions described in Tables 3-7 provided the condition in 8.1.3 is satisfied.

TABLE 3 Symmetric Tests (see Fig. 2)

Test number	Angular sweep α between A and B	Azimuth angle θ, see 8.3.6.3	Description	Fig. 2, subfigure
PP1	At least 80°	0°	The center of the horizontal reference length realized using sphere targets A and B is at the same height as the IUT, with the IUT nominally at azimuth angle θ = 0° when facing the center of line AB.	a
PP2	At least 80°	90°	The center of the horizontal reference length realized using sphere targets A and B is at the same height as the IUT, with the IUT nominally at azimuth angle θ = 90° when facing the center of line AB.	a
PP3	At least 80°	0°	The center of the vertical reference length realized using sphere targets A and B is at the same height as the IUT, with the IUT nominally at azimuth angle θ = 0° when facing the center of line AB.	b
PP4	At least 80°	90°	The center of the vertical reference length realized using sphere targets A and B is at the same height as the IUT, with the IUT nominally at azimuth angle θ = 90° when facing the center of line AB.	b
PP5	At least 80°	0°	The center of the left-diagonal reference length realized using sphere targets A and B is at the same height as the IUT, with the IUT nominally at azimuth angle θ = 0° when facing the center of line AB, and sphere target at the left end of the reference length (target A in Fig. 2(c)) is above the IUT. The line AB makes an angle of 45° with its projection in the horizontal plane.	c
PP6	At least 80°	90°	The center of the left-diagonal reference length realized using sphere targets A and B is at the same height as the IUT, with the IUT nominally at azimuth angle θ = 90° when facing the center of line AB, and sphere target at the left end of the reference length (target A in Fig. 2(c)) is above the IUT. The line AB makes an angle of 45° with its projection in the horizontal plane.	c
PP7	At least 80°	0°	The center of the right-diagonal reference length realized using sphere targets A and B is at the same height as the IUT, with the IUT nominally at azimuth angle θ = 0° when facing the center of line AB, and sphere target at the left end of the reference length (target A in Fig. 2(d)) is below the IUT. The line AB makes an angle of 45° with its projection in the horizontal plane.	d
PP8	At least 80°	90°	The center of the right-diagonal reference length realized using sphere targets A and B is at the same height as the IUT, with the IUT nominally at azimuth angle θ = 90° when facing the center of line AB, and sphere target at the left end of the reference length (target A in Fig. 2(d)) is below the IUT. The line AB makes an angle of 45° with its projection in the horizontal plane.	d

8.3.3 It is permissible to use different instrument settings and operating modes, within rated conditions, for the two targets measured in any given test in Tables 3-7 provided the condition in 8.1.3 is satisfied.

8.3.4 It is permissible to use targets of different sizes and characteristics, within rated conditions, for the different test positions described in Tables 3-7 provided the condition in 8.1.3 is satisfied.

8.3.5 It is permissible to use targets of different sizes and characteristics, within rated conditions, for the two targets in any given test in Tables 3-7 provided the condition in 8.1.3 is satisfied.

8.3.6 *Symmetric Tests:*

8.3.6.1 The symmetric tests involve measuring the point-to-point distance between pairs of sphere targets symmetrically placed with respect to the IUT as shown in Fig. 2. The sphere-target pair is measured in eight positions and orientations within the work volume of the IUT, as listed in Table 3.

8.3.6.2 The angular sweep α between the two targets A and B shall be at least 80° in the plane containing the two target centers and the origin of the IUT. The user is free to select any combination of distance between targets and distance from the IUT that meets the angular sweep requirement provided the range distances to the sphere targets are within the rated conditions of the IUT.

8.3.6.3 Four of the symmetric test positions (PP1, PP3, PP5, PP7) in Table 3 are realized with the IUT set at an arbitrary azimuth angle ($\theta = \theta_i$) to the center of the line AB. The remaining four symmetric positions (PP2, PP4, PP6, PP8) are realized with the IUT set at an azimuth angle that is either $\theta_i + 90° \pm 10°$ or $\theta_i - 90° \pm 10°$. While the azimuth angles listed in Table 3 are nominally 0° and 90°, they can be any pair of angles that are 90° apart to within ±10°.

8.3.7 *Asymmetric Tests:*

8.3.7.1 The asymmetric tests involve measuring the point-to-point distance between two sphere targets asymmetrically placed with respect to the IUT. The sphere-target pair is measured at six different positions and orientations within the work volume of the IUT, as listed in Table 4.

8.3.7.2 For tests PP9 through PP12, the angular sweep α between the two targets shall be at least 40°. For tests PP13 and PP14, the angular sweep α between the two targets shall be at