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Standard Terminology for Three-Dimensional (3D) Imaging Systems[1]

This standard is issued under the fixed designation E2544; 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 terminology contains common terms, definitions of terms, descriptions of terms, nomenclature, and acronyms associated with three-dimensional (3D) imaging systems in an effort to standardize terminology used for 3D imaging systems.

1.2 The definitions of the terms presented in 3.1 are obtained from various standard documents developed by various standards development organizations. The intent is not to change these universally accepted definitions but to gather, in a single document, terms and their definitions that may be used in current or future standards for 3D imaging systems.

1.2.1 In some cases, definitions of the same term from two standards have been presented to provide additional reference. The text in parentheses to the right of each defined term is the name (and, in some cases, the specific section) of the source of the definition associated with that term.

1.3 The definitions in 3.2 are specific terms developed by this committee for 3D imaging systems. Some terms may have generally accepted definitions in a particular community or are defined in existing standards. If there are conflicting definitions, our preference is to adapt (modify) the ISO standard (if available) for this standard.

1.4 A definition in this terminology is a statement of the meaning of a word or word group expressed in a single sentence with additional information included in notes or discussions.

1.5 *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 and health practices and determine the applicability of regulatory limitations prior to use.*

NOTE 1—The subcommittee responsible for this standard will review definitions on a five-year basis to determine if the definition is still appropriate as stated. Revisions will be made when determined necessary.

2. Referenced Documents

2.1 *ASTM Standards:*[2]

E456 Terminology Relating to Quality and Statistics

2.2 *ASME Standard:*[3]

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

2.3 *ISO Standard:*[4]

VIM International vocabulary of metrology -- Basic and general concepts and associated terms

ISO 11146–1 Lasers and laser-related equipment — Test methods for laser beam widths, divergence angles and beam propagation ratios — Part 1: Stigmatic and simple astigmatic beams

2.4 *NIST/SEMATECH Standard:*[5]

NIST/SEMATECH e-Handbook of Statistical Methods

3. Terminology

3.1 *Definitions:*

accuracy of measurement, *n*—closeness of the agreement between the result of a measurement and a true value of the measurand. **(VIM 3.5)**

DISCUSSION—

(1) Accuracy is a qualitative concept.

(2) The term "precision" should not be used for "accuracy."

bias (of a measuring instrument), *n*—systematic error of the indication of a measuring instrument. **(VIM 3.25)**

DISCUSSION—

(1) The bias of a measuring instrument is normally estimated by averaging the error of indication over an appropriate number of repeated measurements.

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[1] This terminology is under the jurisdiction of Committee E57 on 3D Imaging Systems and is the direct responsibility of Subcommittee E57.01 on Terminology.

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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.

[3] Available from American Society of Mechanical Engineers (ASME), ASME International Headquarters, Three 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.

[5] Available from National Institute of Standards and Technology (NIST), 100 Bureau Dr., Stop 1070, Gaithersburg, MD 20899-1070, http://www.nist.gov. e-Handbook available at http://www.itl.nist.gov/div898/handbook/.

bias, *n*—difference between the average or expected value of a distribution and the true value. **(NIST/SEMATECH e-Handbook)**

Discussion—

(1) In metrology, the difference between precision and accuracy is that measures of precision are not affected by bias, whereas accuracy measures degrade as bias increases.

calibration, *n*—set of operations that establish, under specified conditions, the relationship between values of quantities indicated by a measuring instrument or measuring system, or values represented by a material measure or a reference material, and the corresponding values realized by standards. **(VIM 6.11)**

Discussion—

(1) The result of a calibration permits either the assignment of values of measurands to the indications or the determination of corrections with respect to indications.

(2) A calibration may also determine other metrological properties such as the effect of influence quantities.

(3) The result of a calibration may be recorded in a document, sometimes called a calibration certificate or a calibration report.

compensation, *n*—the process of determining systematic errors in an instrument and then applying these values in an error model that seeks to eliminate or minimize measurement errors. **(ASME B89.4.19)**

conventional true value (of a quantity), *n*—value attributed to a particular quantity and accepted, sometimes by convention, as having an uncertainty appropriate for a given purpose. **(VIM 1.20)**

Discussion—

(1) Examples: (*1*) at a given location, the value assigned to the quantity realized by a reference standard may be taken as a conventional true value and (*2*) the CODATA (1986) recommended value for the Avogadro constant, N_A: 6 022 136 7 × 10^{23} mol^{-1}.

(2) Conventional true value is sometimes called assigned value, best estimate of the value, conventional value, or reference value.

(3) Frequently, a number of results of measurements of a quantity is used to establish a conventional true value.

error (of measurement), *n*—result of a measurement minus a true value of the measurand. **(VIM 3.10)**

Discussion—

(1) Since a true value cannot be determined, in practice, a conventional true value is used (see true value and conventional true value).

(2) When it is necessary to distinguish "error" from " relative error," the former is sometimes called "absolute error of measurement." This should not be confused with the " absolute value of error," which is the modulus of error.

indicating (measuring) instrument, *n*—measuring instrument that displays an indication. **(VIM 4.6)**

Discussion—

(1) Examples include analog indicating voltmeter, digital frequency meter, and micrometer.

(2) The display may be analog (continuous or discontinuous) or digital.

(3) Values of more than one quantity may be displayed simultaneously.

(4) A displaying measuring instrument may also provide a record.

limiting conditions, *n*—the 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)**

Discussion—

(1) The manufacturer's performance specifications are not assured over the limiting conditions.

maximum permissible error (MPE), *n*—extreme values of an error permitted by specification, regulations, and so forth for a given measuring instrument. **(VIM 5.21)**

measurand, *n*—particular quantity subject to measurement. **(VIM 2.6)**

Discussion—

(1) Example includes vapor pressure of a given sample of water at 20°C.

(2) The specification of a measurand may require statements about quantities such as time, temperature, and pressure.

precision, *n*—closeness of agreement between independent test results obtained under stipulated conditions. **(ASTM E456)**

Discussion—

(1) Precision depends on random errors and does not relate to the true value or the specified value.

(2) The measure of precision is usually expressed in terms of imprecision and computed as a standard deviation of the test results. Less precision is reflected by a larger standard deviation.

(3) "Independent test results" means results obtained in a manner not influenced by any previous result on the same or similar test object. Quantitative measures of precision depend critically on the stipulated conditions. Repeatability and reproducibility conditions are particular sets of extreme stipulated conditions.

precision, *n—in metrology,* the variability of a measurement process around its average value. **(NIST/SEMATECH e-Handbook)**

Discussion—

(1) Precision is usually distinguished from accuracy, the variability of a measurement process around the true value. Precision, in turn, can be decomposed further into short-term variation or repeatability and long-term variation or reproducibility.

random error, *n*—result of a measurement minus the mean that would result from an infinite number of measurements of the same measurand carried out under repeatability conditions. **(VIM 3.13)**

Discussion—

(1) Random error is equal to error minus systematic error.

(2) Because only a finite number of measurements can be made, it is possible to determine only an estimate of random error.

rated conditions, *n*—manufacturer-specified limits on 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)**

relative error, *n*—error of measurement divided by a true value of the measurand. **(VIM 3.12)**

Discussion—

(1) Since a true value cannot be determined, in practice a conventional true value is used.

repeatability (of results of measurements), *n*—closeness of the agreement between the results of successive measurements of the same measurand carried out under the same conditions of measurement. **(VIM 3.6)**

Discussion—

(1) These conditions are called repeatability conditions.

(2) Repeatability conditions include: the same measurement procedure; the same observer; the same measuring instrument used under the same conditions; the same location; and repetition over a short period of time.

(3) Repeatability may be expressed quantitatively in terms of the dispersion characteristics of the results.

reproducibility (of results of measurements), *n*—closeness of the agreement between the results of measurements of the same measurand carried out under changed conditions of measurement. **(VIM 3.7)**

Discussion—

(1) A value statement of reproducibility requires specification of the conditions changed.

(2) The changed conditions may include: principle of measurement; method of measurement; observer; measuring instrument; reference standard; location; conditions of use; and time.

(3) Reproducibility may be expressed quantitatively in terms of the dispersion characteristics of the results.

(4) Results are usually understood to be corrected results.

systematic error, *n*—mean that would result from an infinite number of measurements of the same measurand carried out under repeatability conditions minus a true value of the measurand. **(VIM 3.14)**

Discussion—

(1) Systematic error is equal to error minus random error.

(2) Like true value, systematic error and its causes cannot be completely known.

(3) For a measuring instrument, see "bias."

true value (of a quantity), *n*—value consistent with the definition of a given particular quantity. **(VIM 1.19)**

Discussion—

(1) This is a value that would be obtained by a perfect measurement.

(2) True values are by nature indeterminate.

(3) The indefinite article "a," rather than the definite article "the," is used in conjunction with "true value" because there may be many values consistent with the definition of a given particular quantity.

uncertainty of measurement, *n*—parameter, associated with the result of a measurement, that characterizes the dispersion of the values that could reasonably be attributed to the measurand. **(VIM 3.9)**

Discussion—

(1) The parameter may be, for example, a standard deviation (or a given multiple of it) or the half width of an interval having a stated level of confidence.

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

(3) It is understood that the result of the measurement is the best estimate of the value of the measurand, and that all components of uncertainty, including those arising from systematic effects, such as components associated with corrections and reference standards, contribute to the dispersion.

3.2 *Definitions of Terms Specific to This Standard:*

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.

Discussion—

(1) 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.

(2) 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) 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).

angular increment, *n*—the angle, $\Delta\alpha$, between reported points, where $\Delta\alpha = \alpha_i - \alpha_{i-1}$, in either the azimuth or elevation directions (or a combination of both) with respect to the instrument's internal frame of reference.

Discussion—

(1) For scanning instruments, the angular increment may also be known as the angle step size.

beam diameter (d_σ), *n*—for a laser beam with a circular irradiance pattern, the beam diameter is the extent of the irradiance distribution in a cross section of the laser beam (in a plane orthogonal to its propagation path) at a distance z and is given by:

$$d_\sigma(z) = 4\sigma(z)$$

where:

$\sigma(z)$ = $\sigma_x(z) = \sigma_y(z)$

$\sigma_x(z), \sigma_y(z)$ = the square roots of the second order moments

Discussion—

(1) Reference ISO 11146–1.

(2) For a laser beam with a Gaussian distribution of irradiance, the beam diameter is often defined as the distance across the center of the beam for which the irradiance, I, equals $1/e^2$ of the maximum irradiance (where e is the base of the natural logarithm). See Fig. 1. The area inside a circle with this diameter and centered at the beam center will contain 86.5 % of the total irradiance of the beam.

(3) The beam diameter may be expressed as X mm measured at Y m. To determine the beam diameter for any other distance, additional parameters are necessary.

(4) The term spot size has been used to mean the radius or the diameter of the laser beam. To avoid confusion, we recommend that spot size not be used.

beam divergence angles ($\theta_{\sigma x}$, $\theta_{\sigma y}$), *n*—measure for the asymptotic increase of the beam widths, $d_{\sigma x}(z)$ and $d_{\sigma y}(z)$, with increasing distance, z, from the beam waist locations, z_{0x} and z_{0y}, given by:

$$\theta_{\sigma x} = \lim_{(z-z_{0x})\to\infty} \frac{d_{\sigma x}(z)}{z - z_{0x}}$$

$$\theta_{\sigma y} = \lim_{(z-z_{0y})\to\infty} \frac{d_{\sigma y}(z)}{z - z_{0y}}$$

Discussion—

(1) Reference ISO 11146–1.

(2) The beam divergence is expressed as a full angle.

(3) For circular laser beams, the beam divergence angle is given by:

$$\theta_{\sigma} = \lim_{(z-z_{0})\to\infty} \frac{d_{\sigma}(z)}{z - z_{0}}$$

(4) For a perfect Gaussian laser beam of wavelength λ, the beam divergence angle is given by:

$$\theta_{\sigma} = 4\frac{\lambda}{\pi d_{\sigma 0}}$$

where:

$d_{\sigma 0}$ = $d_{\sigma}(z_0)$ and is the beam width at the beam waist, z_0. See Fig. 2.

beam propagation ratios (M_x^2, M_y^2), *n*—ratios of the product of the divergence angle, θ, and the beam width, d, at the beam waist location z_0, for a given laser beam to the same product for a perfect Gaussian beam at the same wavelength, and is given by:

$$M_x^2 = \frac{\theta_{\sigma x} d_{\sigma x 0}}{\theta_{G\sigma} d_{G\sigma 0}}$$

$$M_y^2 = \frac{\theta_{\sigma y} d_{\sigma y 0}}{\theta_{G\sigma} d_{G\sigma 0}}$$

where:

$d_{\sigma x0}$, $d_{\sigma y0}$ = beam widths at the beam waist locations, z_{0x} and z_{0y}
= $d_{\sigma x}(z_{0x})$ and $d_{\sigma y}(z_{0y})$, respectively,

$\theta_{G\sigma 0}$ = beam width of a Gaussian beam at the beam waist location, z_0,

$\theta_{G\sigma}$ = beam divergence angle for a Gaussian beam.

Discussion—

(1) For simple astigmatic beams, the beam propagation ratio may also be given by (ISO 11146–1)

$$M_x^2 = \frac{\pi}{\lambda}\frac{\theta_{\sigma x} d_{\sigma x 0}}{4}$$

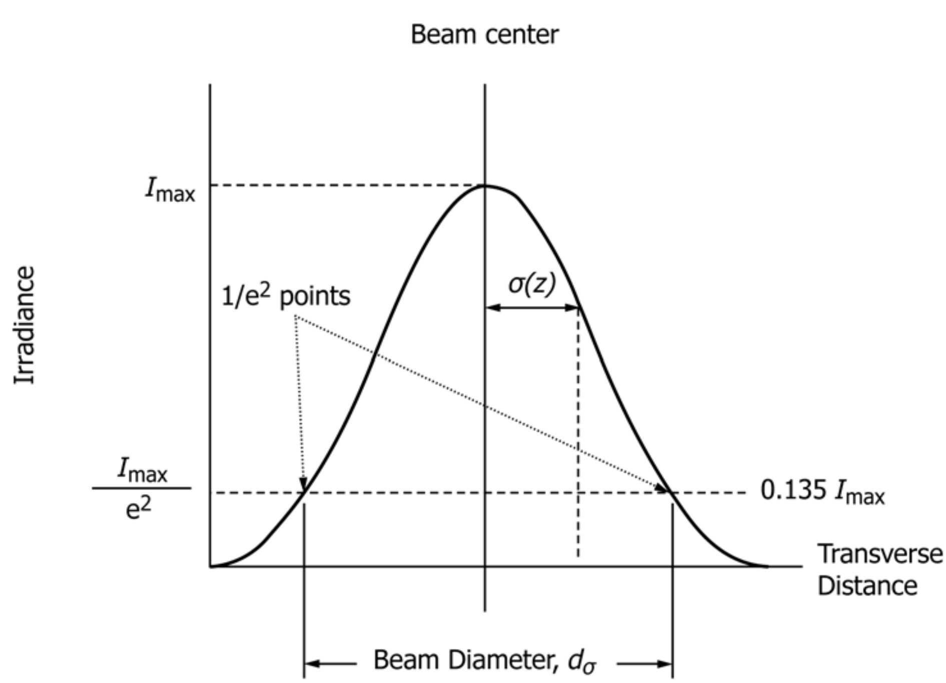

FIG. 1 Gaussian Laser Beam with a Circular Cross Section

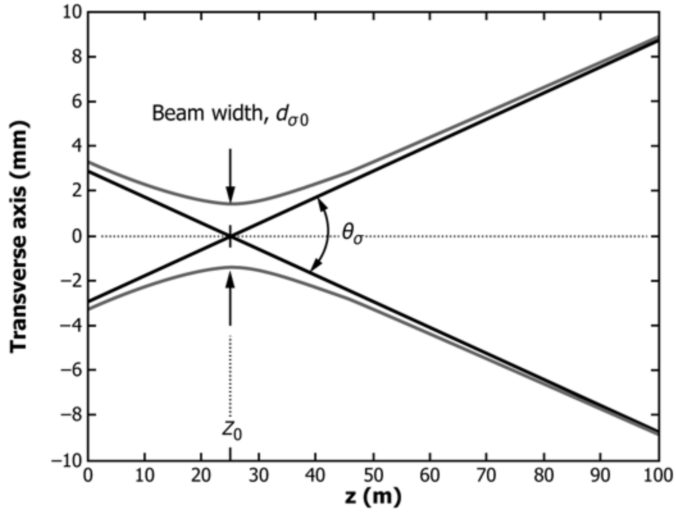

FIG. 2 Perfect Gaussian Beam Profile for a 532 nm beam focused at 25 m

$$M_y^2 = \frac{\pi}{\lambda}\frac{\theta_{\sigma y} d_{\sigma y0}}{4}$$

(2) For a perfect Gaussian beam, $M^2 = 1$. Most laser beams have a beam propagation ratio $M^2>1$, however, some high quality laser beams can have values very close to 1.

(3) The beam propagation ratios are propagation invariants for simple astigmatic beams as long as the optics involved do not change their properties.

beam width ($d_{\sigma x}$, $d_{\sigma y}$), *n*—the extent of the irradiance distribution in a cross section of a laser beam (in a direction orthogonal to its propagation path) at a distance *z* and is given by:

$$d_{\sigma x}(z) = 4\,\sigma_x(z)$$

$$d_{\sigma y}(z) = 4\,\sigma_y(z)$$

where σ_x and σ_y are the square roots of the second order moments along the principal axes, *x* and *y*, respectively. See Fig. 3.

Discussion—

(1) If the ellipticity, ε (the ratio between the minimum and maximum beam widths), of the laser beam is larger than 0.87, the beam profile may be considered to be of circular symmetry and the beam width at a distance *z* is defined as (ISO 11146–1):

$$d_\sigma(z) = 2\sqrt{2}(\sigma_x^2+\sigma_y^2)^{\frac{1}{2}}$$

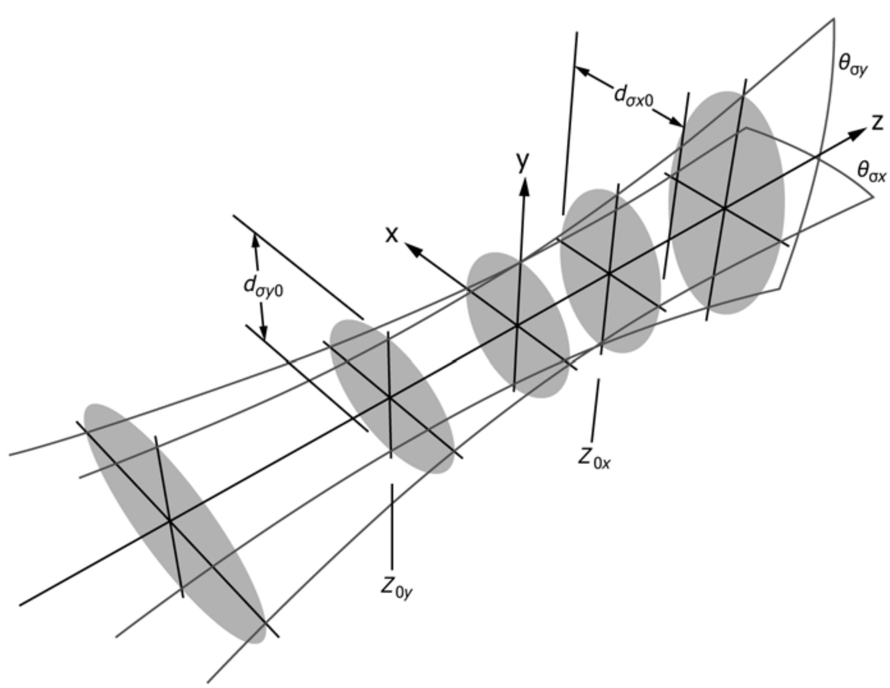

FIG. 3 Schematic Showing Beam Width, Beam Waist, Beam Divergence Angles (Ref ISO 11146)

(2) For a simple astigmatic laser beam with wavelength λ, the beam widths may be expressed as:

$$d_{\sigma x}(z) = d_{\sigma x0}\sqrt{1+\left(\frac{4M_x^2\lambda}{\pi d_{\sigma x0}^2}\right)^2 (z - z_{0x})^2}$$

$$d_{\sigma y}(z) = d_{\sigma y0}\sqrt{1+\left(\frac{4M_y^2\lambda}{\pi d_{\sigma y0}^2}\right)^2 (z - z_{0y})^2}$$

where:

M_x^2, M_y^2 = beam propagation ratios,
$d_{\sigma x0}$, $d_{\sigma y0}$ = beam widths at the beam waist locations z_{0x} and z_{0y},
= $d_{\sigma x}(z_{0x})$ and $d_{\sigma y}(z_{0y})$, respectively.

These equations, $d_{\sigma x}(z)$ and $d_{\sigma y}(z)$, are sometimes referred to as the beam propagation equations and are particularly useful for short range, laser-based 3D imaging systems where the laser beam is focused at z_{0x} and z_{0y}. Using these equations, any missing parameter which defines the laser beam can be derived.

(3) For line scanners or sheet of light profilers, the beam width term is equivalent to the line width orthogonal to the longitudinal axis of the line and to the propagation path.

control network, *n*—a collection of identifiable points (visible or inferable), with stated coordinate uncertainties, in a single coordinate system.

Discussion—

(1) An identifiable point is a point that can be uniquely identified throughout the useful life of the control network.

(2) An example of an inferable point is the center of a sphere, while not visible, can be obtained by processing suitable data.

(3) The purpose of a control network may include:

a. monitoring/controlling data quality (for example, controlling scale error, identifying systematic error),

b. registration,

c. defining the extent of a measuring environment, and

d. verifying the position of an instrument (drift).

(4) A control network should be established by an accepted best practice.

control point, *n*—an identifiable point which is a member of a control network.

Discussion—

(1) An identifiable point is a point that can be uniquely identified throughout the useful life of the control network.

(2) A control point may be derived from an object that is permanent (for example, benchmark) or temporary (for example, target such as a sphere specifically placed in a scene).

field of view (FOV), *n*—the angular extent within which objects are measurable by a device such as an optical instrument without user intervention.

Discussion—

(1) For a scanner that is based on a spherical coordinate system, the FOV can typically be given by two angles: horizontal (azimuth) angle and vertical (elevation) angle.

first return, *n*—for a given emitted pulse, it is the first reflected signal that is detected by a 3D imaging system, time-of-flight (TOF) type, for a given sampling position, that is, azimuth and elevation angle.

flash LADAR, *n*—3D imaging system, comprised of a source of light (commonly a laser, but for close proximity it can be a bank of LEDs) and a focal plane array (FPA) detector, that is designed so that the range (and in some cases intensity) for all the pixels in the frame are acquired nearly simultaneously in a single flash of illumination.

Discussion—

(1) Flash LADAR approaches may allow for the achievement of high frame rates (for example, 30 frames per second or faster) which is critical for real time applications such as collision avoidance and autonomous vehicle navigation.

instrument origin, *n*—point from which all instrument measurements are referenced, that is, origin of the instrument coordinate reference frame (0, 0, 0).

last return, *n*—for a given emitted pulse, it is the last reflected signal that is detected by a 3D imaging system, time-of-flight (TOF) type, for a given sampling position, that is, azimuth and elevation angle.

measurement rate, *n*—reported points per second.

Discussion—

(1) A reported point may be obtained from n samples where $n \geq 1$.

multiple-return range resolution, *n*—the range resolution where the range measurements are obtained from surfaces that produce multiple returns and is determined by a standard or a formal test method.

Discussion—

(1) The multiple-return range resolution is dependent on several factors such as beam width, object reflectivity, distance to the object, angles of incidence and observation with the object, object material/texture, scan speed (for scanning systems), and orientation of the surface with respect to the scan direction.

(2) Fig. 4 shows one example of how the multiple-return range resolution may be obtained. In this example, the multiple-return range resolution is equal to $d_{\min}$ where $d_{\min}$ is the minimum distance for which two returns are reported by the instrument. For distances less than $d_{\min}$, a single return is reported by the instrument

(3) See related terms *multiple returns*, *single-return range resolution*, and *range resolution.*

multiple returns, *n*—the signals returned to a single detector element from simultaneously-illuminated multiple surfaces.

Discussion—

(1) Historically, the word "returns" applies to active systems that illuminate the target. However, the above definition of multiple returns also applies to passive systems that use ambient illumination.

(2) Signals can be electromagnetic or acoustic.

(3) "Multiple surfaces" may be disconnected as in Fig. 5 or connected as in Fig. 6. The distances between these surfaces are defined by the test method for multiple return range resolution. The characteristics of each surface are defined by the test method for single return range resolution.

(4) Returns from multi-path propagation are excluded from this definition.

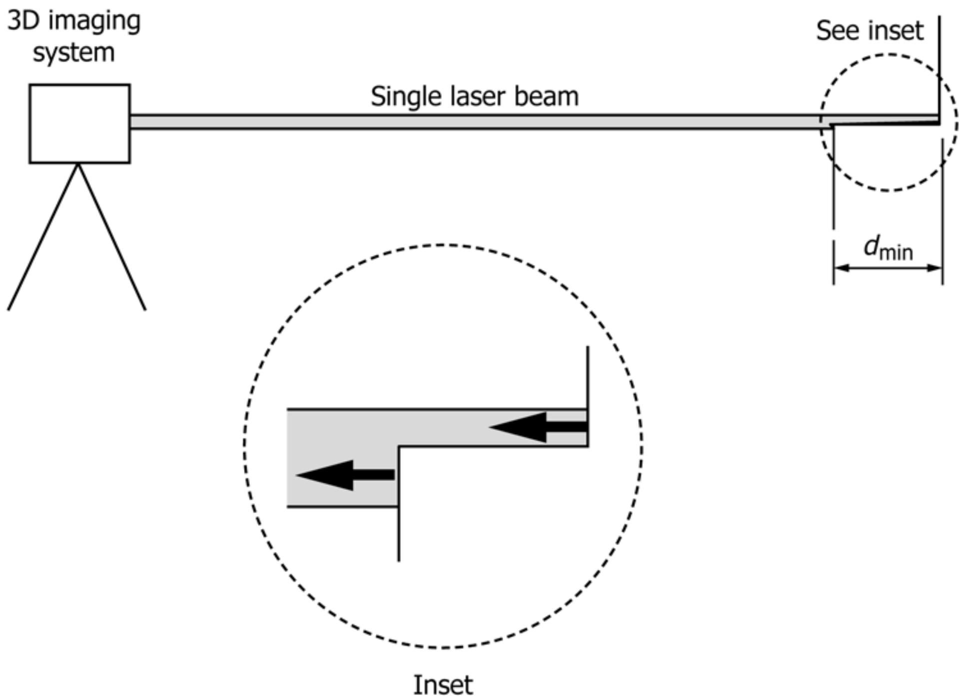

FIG. 4 An Example of How the Multiple-Return Range Resolution may be Obtained

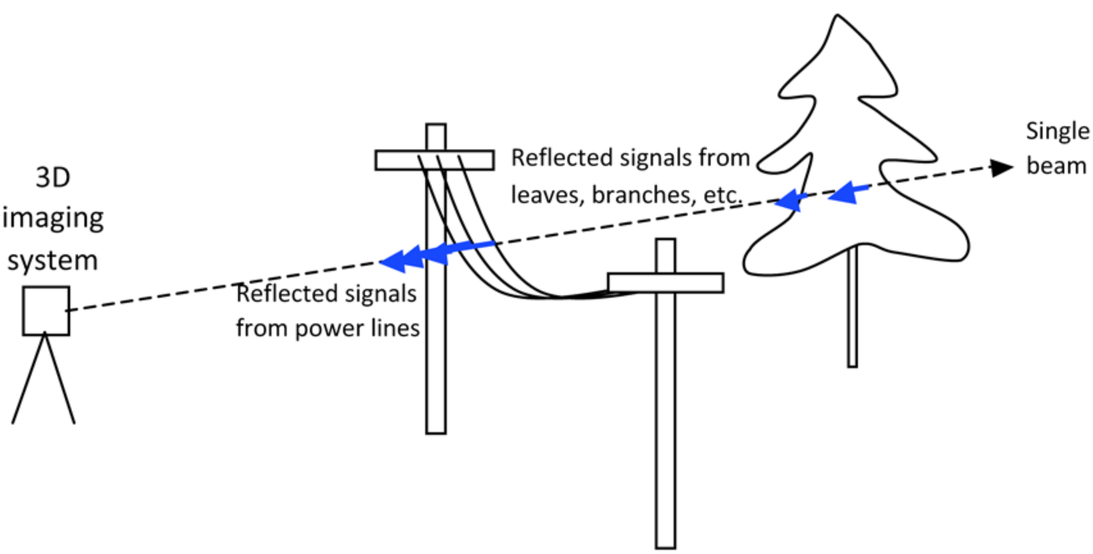

FIG. 5 An Example of Multiple Returns from Multiple Objects

(5) The term simultaneously means during the integration period of the detector.

(6) This definition applies to 3D imaging systems that are capable of distinguishing multiple returns. Many systems do not have this capability and this term would not apply.

(7) See related term *single return*.

pixel, *n*—a single cell in a focal plane array sensor, or a discrete element in a 2D grid representation of data.

Discussion—

(1) The term pixel was originally coined to stand for "picture element" in the image analysis domain.

(2) In computer graphics, a pixel represents the smallest discrete element of an image displayed on a screen. Pixel shape is dependent on the technology used to display it. Pixel size has also been used to describe the resolution of a sensor, but pixel size can also be an arbitrary dimension specified by the user

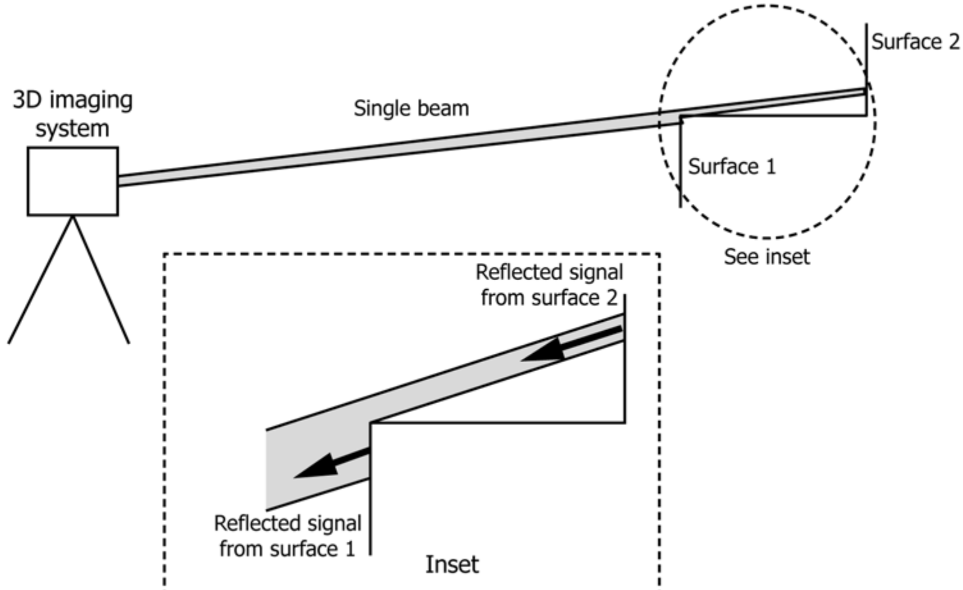

FIG. 6 An Example of Multiple Returns from a Single Object

(for example, it is possible to "pixelate" a digital image so that the smallest pixel size becomes a multiple of the smallest pixel size in the original image).

(3) In 3D imaging applications, 2D projections of point clouds are often displayed on a computer screen (or printed). Hence, although the underlying data may be 3D, it is visualized in terms of pixels projected onto a 2D grid.

point, *n*—an abstract concept describing a location in space which is specified by its coordinates and other attributes.

DISCUSSION—

(1) A point has no dimensions (volume, area, or length).

(2) A point can be derived. For example, a centroid of a group of points or a point representing the corner of an object derived by the intersection of three planes.

(3) Examples of attributes are color, time stamps, point identifier, return pulse intensity, and polarization.

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.

DISCUSSION—

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

range, *n*—the distance, in units of length, between a point in space and an origin fixed to the 3D imaging system that is measuring that point.

DISCUSSION—

(1) In general, the origin corresponds to the instrument origin.

range resolution, *n*—the smallest change in range that causes a perceptible change in the corresponding range measurement indication.

DISCUSSION—

(1) There are two ways to use this term, and to avoid ambiguity it is recommended that the terms *single-return range resolution* or *multiple-return range resolution* be used for quantitative specifications.

(2) The difference in range may be a result of a change between two separate distance measurements or the distance between two static objects separated from each other in range.

(3) A "perceptible change" is a change that is distinguishable by a criterion established in a test method.

(4) The use of "range uncertainty" to mean "range resolution" is incorrect. The terms "resolution" and "uncertainty," as defined by ISO 99:2007 (VIM), have different meanings.

registration, *n*—the process of determining and applying to two or more datasets the transformations that locate each dataset in a common coordinate system so that the datasets are aligned relative to each other.

DISCUSSION—

(1) A 3D imaging system generally collects measurements in its local coordinate system. When the same scene or object is measured from more than one position, it is necessary to transform the data so that the datasets from each position have a common coordinate system.

(2) Sometimes the registration process is performed on two or more datasets which do not have regions in common. For example, when several buildings are measured independently, each dataset may be registered to a global coordinate system instead of to each other.

(3) In the context of this definition, a dataset may be a mathematical representation of surfaces or may consist of a set of coordinates, for example, a point cloud, a 3D image, control points, survey points, or reference points from a CAD model. Additionally, one of the datasets in a registration may be a global coordinate system (as in Discussion Item 2).

(4) The process of determining the transformation often involves the minimization of an error function, such as the sum of the squared distances between features (for example, points, lines, curves, surfaces) in two datasets.

(5) In most cases, the transformations determined from a registration process are rigid body transformations. This means that the distances between points within a dataset do not change after applying the transformations, that is, rotations and translations.

(6) In some cases, the transformations determined from a registration process are non-rigid body transformations. This means that the transformation includes a deformation of the dataset. One purpose of this type of registration is to attempt to compensate for movement of the measured object or deformation of its shape during the measurement.

(7) Registration between two point clouds is sometimes referred to as cloud-to-cloud registration; between two sets of control or survey points as target-to-target; between a point cloud and a surface as cloud-to-surface; and between two surfaces as surface-to-surface.

(8) The word alignment is sometimes used as a synonymous term for registration. However, in the context of this definition, an alignment is the *result* of the registration process.

second order moments (σ_x^2, σ_y^2)**,** *n*—the second order moments of an irradiance distribution of a simple astigmatic laser beam at a give range, *z*, $\sigma_x^2(z)$ and $\sigma_y^2(z)$, along the principal axes, *x* and *y*, are defined as (ISO 11146-1)[6]:

$$\sigma_x^2(z) = \frac{\int\limits_{-\infty}^{o}\int\limits_{-\infty}^{o} I(x,y,z)(x-\bar{x})^2\,dx\,dy}{\int\limits_{-\infty}^{o}\int\limits_{-\infty}^{o} I(x,y,z)dx\,dy}$$

$$\sigma_y^2(z) = \frac{\int\limits_{-\infty}^{o}\int\limits_{-\infty}^{o} I(x,y,z)(y-\bar{y})^2\,dx\,dy}{\int\limits_{-\infty}^{o}\int\limits_{-\infty}^{o} I(x,y,z)dx\,dy}$$

where:

I(x,y,z) = the irradiance or optical power per unit area at point (*x,y,z*),

$\bar{x}$ *and* $\bar{y}$ = the coordinates of the centroid (also referred to as the first order moments) of the beam in the *x-y* plane, respectively.

Discussion—

(1) The coordinates of the centroid (or first order moments of an irradiance distribution) of a laser beam are defined as:

$$\bar{x} = \frac{\int\limits_{-\infty}^{o}\int\limits_{-\infty}^{o} I(x,y,z)x\,dx\,dy}{\int\limits_{-\infty}^{o}\int\limits_{-\infty}^{o} I(x,y)dx\,dy}$$

$$\bar{y} = \frac{\int\limits_{-\infty}^{o}\int\limits_{-\infty}^{o} I(x,y,z)y\,dx\,dy}{\int\limits_{-\infty}^{o}\int\limits_{-\infty}^{o} I(x,y)dx\,dy}$$

simple astigmatic beam, *n*—a beam having non-circular power density distributions and whose principal axes retain constant orientation under free propagation.

Discussion—

(1) This definition is adapted from ISO 11146.

(2) An alternative definition found in the literature: a beam having two principal axes orthogonal to the propagation direction that are defined by non-spherical curvature of the phase front (a surface of constant phase). In particular, the non-spherical curvature will be cylindrical in nature, giving rise to the beam waist for each principal axis occuring at different propagation planes. The distance between these planes is called the astigmatic difference or interval. To avoid confusion, this alternative definition will not be used in this standard.

(3) Because of the symmetry imposed by laser cavities, most beams emitted by lasers are either circular or simple astigmatic beams. However, it is possible to obtain a general astigmatic beam, which is unlike either of these types. This is easily done by sending a simple astigmatic beam through a cylindrical lens whose axis is tilted with respect to the principal axes of the simple astigmatic beam. The resulting isophotes (lines of constant irradiance) and isophases (lines of constant phase) are ellipses oriented in different directions that rotate as the beam propagates.

single return, *n*—the signal returned to a single detector element from an illuminated object perceived as a single surface by the 3D imaging system.

Discussion—

(1) Historically, the word "return" applies to active systems that illuminate the target. However, the above definition of single return also applies to passive systems that use ambient illumination.

(2) Signals can be electromagnetic or acoustic.

(3) The criteria of what is perceived as a single surface depends on the 3D imaging system and is established by the test method for single-return range resolution.

(4) The return from a tilted continuous surface is considered a single return, i.e., devices that can only measure single returns are expected to measure a tilted surface with reasonable accuracy.

(5) Returns from multi-path propagation are excluded from this definition.

(6) See related term *multiple returns*.

single-return range resolution, *n*—the range resolution where each range measurement is obtained from a single return and is determined by a standard or a formal test method.

Discussion—

(1) The single-return range resolution is dependent on several factors such as beam width, object reflectivity, distance to the object, angles of incidence and observation with the object, object material/texture, scan speed (for scanning

[6] Siegman, A. E., Nemes, G., and Serna, J., "How to (Maybe) Measure Laser Beam Quality," in *DPSS (DIODE Pumped Solid State) Lasers: Applications and Issues*, M. Dowley, Ed., Vol 17 of OSA Trends in Optics and Photonics (Optical Society of America, 1998).

systems), point density, and orientation of the surface with respect to the scan direction.

(2) For 3D imaging systems where the measurement is with respect to a reference plane (e.g., triangulation systems) see *depth resolution*.

(3) Range precision is a term that has also been applied to mean range resolution. To avoid confusion, we recommend that the term range precision not be used.

(4) See related terms, *single return*, *multiple-return resolution*, and *range resolution*.

spot size, *n*—not a recommended term.

Discussion—

(1) The term spot size has been used to mean the radius or the diameter of the laser beam. To avoid confusion, we recommend that spot size not be used.

voxel, *n*—a discrete volumetric element in a 3D grid representation of data.

Discussion—

(1) The term voxel is derived from volumetric pixel.

3.3 *Acronyms:*

APD, *n*—avalanche photo diode.

CCD, *n*—charge-coupled device.

FOV, *n*—field of view.

FPA, *n*—focal plane array.

LADAR, *n*—laser detection and ranging system.

LIDAR, *n*—light detection and ranging system.

4. Keywords

4.1 3D imaging system; LADAR; laser detection and ranging system; LIDAR; three-dimensional imaging system