TECHNICAL SPECIFICATION

ISO/TS 19159-2

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Geographic information — Calibration and validation of remote sensing imagery sensors and data —

Part 2: **Lidar**

Information géographique – Calibration et validation de capteurs de télédétection —

Partie 2: Lidar

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Foreword

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

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For an explanation on the meaning of ISO specific terms and expressions related to conformity assessment, as well as information about ISO's adherence to the WTO principles in the Technical Barriers to Trade (TBT) see the following URL: Foreword - Supplementary information

The committee responsible for this document is ISO/TC 211 *Geographic information/Geomatics*.

ISO/TS 19159 consists of the following parts, under the general title *Geographic information — Calibration and validation of remote sensing imagery sensors and data*:

— Part 1: *Optical sensors* [Technical Specification]

— Part 2: *Lidar* [Technical Specification]

The following parts are planned:

— Part 3: *SAR/InSAR*

— Part 4: *SONAR*

Introduction

Imaging sensors are one of the major data sources for geographic information. The image data capture spatial and spectral measurements are applied for numerous applications ranging from road/town planning to geological mapping. Typical spatial outcomes of the production process are vector maps, Digital Elevation Models, and 3-dimensional city models. There are typically two streams of spectral analysis data, i.e. the statistical method, which includes image segmentation and the physics-based method which relies on characterisation of specific spectral absorption features.

In each of the cases the quality of the end products fully depends on the quality of the measuring instruments that has originally sensed the data. The quality of measuring instruments is determined and documented by calibration.

A calibration is often a costly and time consuming process. Therefore, a number of different strategies are in place that combine longer time intervals between subsequent calibrations with simplified intermediate calibration procedures that bridge the time gap and still guarantee a traceable level of quality. Those intermediate calibrations are called validations in this part of ISO/TS 19159.

The ISO 19159 series standardizes the calibration of remote sensing imagery sensors and the validation of the calibration information and procedures. It does not address the validation of the data and the derived products.

Many types of imagery sensors exist for remote sensing tasks. Apart from the different technologies the need for a standardization of the various sensor types has different levels of priority. In order to meet those requirements, the ISO 19159 series has been split into more than one part.

This part of ISO/TS 19159 covers the airborne land lidar sensor (light detection and ranging). It includes the data capture and the calibration. The result of a lidar data capture is a lidar cloud according to the ISO 19156:2011. The bathymetric lidar is not included in the ISO 19159 series.

ISO 19159-3 and ISO 19159-4 are planned to cover RADAR (Radio detection and ranging) with the subtopics SAR (Synthetic Aperture RADAR) and InSAR (Interferometric SAR) as well as SONAR (Sound detection and ranging) that is applied in hydrography.

Geographic information — Calibration and validation of remote sensing imagery sensors and data —

Part 2: **Lidar**

1 Scope

This part of ISO/TS 19159 defines the data capture method, the relationships between the coordinate reference systems and their parameters, as well as the calibration of airborne lidar (light detection and ranging) sensors.

This part of ISO/TS 19159 also standardizes the service metadata for the data capture method, the relationships between the coordinate reference systems and their parameters and the calibration procedures of airborne lidar systems as well as the associated data types and code lists that have not been defined in other ISO geographic information international standards.

2 Conformance

This part of ISO/TS 19159 standardizes the metadata for the data recording and the calibration procedures of airborne lidar systems as well as the associated data types and code lists. Therefore conformance depends on the type of entity declaring conformance.

Mechanisms for the transfer of data are conformant to this part of ISO/TS 19159 if they can be considered to consist of transfer record and type definitions that implement or extend a consistent subset of the object types described within this part of ISO/TS 19159.

Details of the conformance classes are given in the Abstract test suite in Annex A.

3 Normative references

The following documents, in whole or in part, are normatively referenced in this document and are indispensable for its application. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO/TS 19130:2010, *Geographic information - Imagery sensor models for geopositioning*

ISO 19157:2013, *Geographic information — Data quality*

4 Terms and definitions

4.1
absolute accuracy
closeness of reported coordinate values to values accepted as or being true

Note 1 to entry: Absolute accuracy is stated with respect to a defined *datum* (4.11) or reference system.

Note 2 to entry: Absolute accuracy is also termed “external accuracy”.

4.2
attitude
orientation of a body, described by the angles between the axes of that body's coordinate system and the axes of an external coordinate system

Note 1 to entry: In photogrammetry, the attitude is the angular orientation of a camera (roll, pitch, yaw), or of the photograph taken with that camera, with respect to some external reference system. With *lidar* (4.19) and Interferometric Synthetic Aperature Radar (IFSAR), the attitude is normally defined as the roll, pitch and heading of the instrument at the instant an active pulse is emitted from the *sensor* (4.39).

[SOURCE: ISO 19116:2004, 4.2, modified — Note 1 to entry has been added.]

4.3
bare earth elevation
height (4.16) of the natural terrain free from vegetation as well as buildings and other man-made structures

4.4
boresight
calibration (4.6) of a *lidar* (4.19) *sensor* (4.36) system, equipped with an Inertial *Measurement* (4.20) Unit (IMU) and a Global Navigation Satellite System (GNSS), to accurately determine or establish its position and orientation

Note 1 to entry: The position of the lidar sensor system (x, y, z) is determined with respect to the GNSS antenna. The orientation (roll, pitch, heading) of the lidar sensor system is determined with respect to straight and level flight.

4.5
breakline
linear feature that describes a change in the smoothness or continuity of a surface

Note 1 to entry: A soft breakline ensures that known z-values along a linear feature are maintained (for example, elevations along a pipeline, road centreline or drainage ditch), and ensures that linear features and polygon edges are maintained in a *Triangulated Irregular Network (TIN)* (4.39) surface model, by enforcing the breaklines as TIN edges. They are generally synonymous with 3-D breaklines because they are depicted with series of x/y/z coordinates. Somewhat rounded ridges or the trough of a drain may be collected using soft breaklines.

Note 2 to entry: A hard breakline defines interruptions in surface smoothness, for example, to define streams, shorelines, dams, ridges, building footprints, and other locations with abrupt surface changes.

4.6
calibration
process of quantitatively defining a system's responses to known, controlled signal inputs

Note 1 to entry: A calibration is an operation that, under specified conditions, in a first step, establishes a relation between indications[with associated *measurement* (4.20) uncertainties] and the physical *quantity* (4.30) values (with measurement uncertainties) provided by measurement standards.

Note 2 to entry: Determining the systematic errors in a measuring device by comparing its measurements with the markings or measurements of a device that is considered correct. Airborne *sensors* (4.36) can be calibrated geometrically and radiometrically.

Note 3 to entry: An instrument calibration means the factory calibration includes radiometric and geometric calibration unique to each manufacturer's hardware and tuned to meet the performance specifications for the model being calibrated. Instrument calibration can only be assessed and corrected by the factory.

Note 4 to entry: The data calibration includes the lever-arm and *boresight* (4.4) calibration. It determines the sensor-to-GNSS-antenna offset vector (*lever arm*) (4.18) components relative to the antenna phase centre. The offset vector components are re-determined each time the sensor or aircraft GNSS antenna is moved or repositioned in any way. Because normal aircraft operations can induce slight variations in component mounting, field calibration is normally performed for each project, or even daily, to determine *corrections* (4.9) to the roll, pitch, yaw, instrument mounting alignment error and scale calibration parameters.

[SOURCE: ISO/TS 19101-2:2008, 4.2, modified — Notes 1 through 4 to entry have been added.]

4.7
calibration validation
process of assessing the validity of parameters

Note 1 to entry: With respect to the general definition of *validation* (4.41) the "dataset validation" only refers to a small set of parameters (attribute values) such as the result of a *sensor* (4.36) *calibration* (4.6).

[SOURCE: ISO/TS 19159-1:2014, 4.4]

4.8
check point
checkpoint
point in object space (ground) used to estimate the *positional accuracy* (4.29) of a geospatial dataset against an independent source of greater accuracy

4.9
correction
compensation for an estimated systematic effect

Note 1 to entry: See ISO/IEC Guide 98-3:2008, 3.2.3, for an explanation of 'systematic effect'.

Note 2 to entry: The compensation can take different forms, such as an addend or a factor, or can be deduced from a table.

[SOURCE: ISO/IEC Guide 99:2007, 2.53]

4.10
datum
parameter or set of parameters that define the position of the origin, the scale, and the orientation of a *coordinate system*

[SOURCE: ISO 19111:2007, 4.14]

4.11
digital elevation model
DEM
dataset of elevation values that are assigned algorithmically to 2-dimensional coordinates

[SOURCE: ISO/TS 19101-2:2008, 4.5]

4.12
digital surface model
DSM
digital elevation model (DEM) (4.11) that depicts the elevations of the top surfaces of buildings, trees, towers, and other features elevated above the bare earth

Note 1 to entry: DSMs are especially relevant for telecommunications management, air safety, forest management, and 3-D modelling and simulation.

4.13
digital terrain model
DTM
digital elevation model (DEM) (4.11) that incorporates the elevation of important topographic features on the land.

Note 1 to entry: DTMs are comprised of mass points and *breaklines* (4.5) that are irregularly spaced to better characterize the true shape of the bare-earth terrain. The net result of DTMs is that the distinctive terrain features are more clearly defined and precisely located, and contours generated from DTMs more closely approximate the real shape of the terrain.

4.14
field of view
FOV
instantaneous region seen by a *sensor* (4.36), provided in angular measure

Note 1 to entry: In the airborne case, this would be *swath* (4.38) width for a linear array, ground footprint for an area array, and for a whiskbroom scanner it refers to the swath width.

Note 2 to entry: To avoid confusion, a typical airborne *lidar* (4.19) sensor with a field of view of 30 degrees is commonly depicted as ±15 degrees on either side of *nadir* (4.26).

[SOURCE: ISO/TS 19130-2:2014, 4.20 modified, — Note 2 to entry has been added.]

4.15
geographic information system
information system dealing with information concerning phenomena associated with location relative to the Earth

[SOURCE: ISO 19101-1:2014, 4.1.20]

4.16
height
h, *H*
distance of a point from a chosen reference surface measured upward along a line perpendicular to that surface

Note 1 to entry: A height below the reference surface will have a negative value.

Note 2 to entry: The terms elevation and height are synonyms.

[SOURCE: ISO 19111:2007, 4.29, modified – Note 2 to entry have been added.]

4.17
horizontal accuracy
positional accuracy (4.29) of a dataset with respect to a horizontal *datum* (4.10)

4.18
lever arm
relative position vector of one *sensor* (4.36) with respect to another in a direct georeferencing system

Note 1 to entry: For example, with aerial mapping cameras, there are lever arms between the inertial centre of the Inertial *Measurement* (4.20) Unit (IMU) and the phase centre of the Global Navigation Satellite System (GNSS) antenna, each with respect to the camera perspective centre within the lens of the camera.

4.19
lidar
light detection and ranging
system consisting of 1) a photon source (frequently, but not necessarily, a laser), 2) a photon detection system, 3) a timing circuit, and 4) optics for both the source and the receiver that uses emitted laser light to measure ranges to and/or properties of solid objects, gases, or particulates in the atmosphere

Note 1 to entry: Time of flight (TOF) lidars use short laser pulses and precisely record the time each laser pulse was emitted and the time each reflected return(s) is received in order to calculate the distance(s) to the scatterer(s) encountered by the emitted pulse. For topographic lidar , these time-of-flight measurements are then combined with precise platform location/attitude data along with pointing data to produce a three dimensional product of the illuminated scene of interest.

[SOURCE: ISO/TS 19130-2:2014, 4.40]

4.20
measurement
set of operations having the object of determining the value of a *quantity* (4.30)

[SOURCE: ISO/TS 19101-2:2008, 4.20]

4.21
measurement accuracy
accuracy of measurement
accuracy
closeness of agreement between a test result or *measurement* (4.20) result and the true value

Note 1 to entry: The concept 'measurement accuracy' is not a *quantity* (4.30) and is not given a numerical *quantity* (4.30) value. A measurement is said to be more accurate when it offers a smaller *measurement error* (4.22).

Note 2 to entry: The term 'measurement accuracy' should not be used for measurement trueness and the term *measurement precision* (4.23) should not be used for 'measurement accuracy', which, however, is related to both these concepts.

Note 3 to entry: 'Measurement accuracy' is sometimes understood as closeness of agreement between measured quantity values that are being attributed to the measurand.

Note 4 to entry: In this part of ISO/TS 19159, the true value can be a reference value that is accepted as true.

Note 5 to entry: With the exception of Continuously Operating Reference Stations (CORS), assumed to be known with zero errors relative to established *datums* (4.10), the true locations of 3-D spatial coordinates of other points are not truly known, but only estimated; therefore, the accuracy of other coordinate information is unknown and can only be estimated.

Note 6 to entry: Accuracy is not a quantity and is not given a numerical quantity value.

[SOURCE: ISO 3534-2:2006, 3.3.1, modified, — Notes 1 through 6 to entry have been added.]

4.22
measurement error
error of measurement
error
measured *quantity* (4.30) value minus a reference quantity value

Note 1 to entry: The concept of 'measurement error' can be used both

a) when there is a single reference *quantity* (4.30) value to refer to, which occurs if a *calibration* (4.6) is made by means of a *measurement* (4.20) standard with a measured quantity value having a negligible measurement *uncertainty* (4.40) 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.

Note 2 to entry: Measurement error should not be confused with production error or mistake.

[SOURCE: ISO/IEC Guide 99:2007, 2.16]

4.23
measurement precision
precision
closeness of agreement between indications or measured *quantity* (4.30) values obtained by replicate *measurements* (4.20) on the same or similar objects under specified conditions

Note 1 to entry: Measurement precision is usually expressed numerically by measures of imprecision, such as standard deviation, variance, or coefficient of variation under the specified conditions of measurement.

Note 2 to entry: The 'specified conditions' can be, for example, repeatability conditions of measurement, intermediate precision conditions of measurement, or reproducibility conditions of measurement (see ISO 5725-3:1994).

Note 3 to entry: Measurement precision is used to define measurement repeatability, intermediate measurement precision, and measurement reproducibility.

Note 4 to entry: Sometimes 'measurement precision' is erroneously used to mean *measurement accuracy* (4.21).

[SOURCE: ISO/IEC Guide 99:2007, 2.15]

4.24
metadata
information about a resource

[SOURCE: ISO 19115-1:2014, 4.10]

4.25
metric traceability
property of the result of a *measurement* (4.20) or the value of a standard whereby it can be related to stated references, usually national or international standards, through an unbroken chain of comparisons all having stated uncertainties

[SOURCE: ISO/TS 19101-2:2008, 4.23]

4.26
nadir
point directly beneath a position

4.27
noise
unwanted signal which can corrupt the *measurement* (4.20)

Note 1 to entry: Noise is a random fluctuation in a signal disturbing the recognition of a carried information.

[SOURCE: ISO 12718:2008, 2.26, modified, — Note 1 to entry has been added.]

4.28
point cloud
collection of data points in 3D space

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

Note 2 to entry: As a basic geographic information system (GIS) data type, a point cloud is differentiated from a typical point dataset in several key ways:

- Point clouds are almost always 3D,
- Point clouds have an order of magnitude more features than point datasets, and
- Individual point features in point clouds do not typically possess individually meaningful attributes; the informational value in a point cloud is derived from the relations among large numbers of features

[SOURCE: ISO/TS 19130-2:2014, 4.51, modified – Note 2 to entry has been added.]

4.29
positional accuracy
closeness of coordinate value to the true or accepted value in a specified reference system

Note 1 to entry: The positional accuracy consists of the data quality elements absolute, relative, and gridded data accuracy.

[SOURCE: ISO 19116:2004, 4.20, modified, — Note 1 to entry has been added.]

4.30
quantity
property of a phenomenon, body, or substance, where the property has a magnitude that can be expressed as a number and a reference

Note 1 to entry: A reference can be a *measurement* (4.20) unit, a measurement procedure, a reference material, or a combination of such.

Note 2 to entry: Symbols for quantities are given in the ISO 80000 and IEC 80000 series *Quantities and units.* The symbols for quantities are written in italics. A given symbol can indicate different quantities.

Note 3 to entry: A quantity as defined here is a scalar. However, a vector or a tensor, the components of which are quantities, is also considered to be a quantity.

Note 4 to entry: Note4 to entry: The concept 'quantity' may be generically divided into, e.g. 'physical quantity', 'chemical quantity', and 'biological quantity', or 'base quantity' and 'derived quantity'.

[SOURCE: ISO/IEC Guide 99:2007, 1.1]

4.31
reference standard
measurement (4.20) standard designated for the *calibration* (4.6) of other measurement standards for quantities of a given kind in a given organization or at a given location

[SOURCE: ISO/TS 19159-1:2014, 4.28]

4.32
relative accuracy
internal accuracy
closeness of the relative positions of features in a dataset to their respective relative positions accepted as or being true

Note 1 to entry: Relative accuracy may also be referred to as point-to-point accuracy. The general measure of relative accuracy is an evaluation of the random errors (systematic errors and blunders removed) in determining the positional orientation (for example, distance and azimuth) of one point or feature with respect to another. In *lidar* (4.19), this also may specifically mean the accuracy between adjacent *swaths* (4.38) within a lift, adjacent lifts within a project, or between adjacent projects.

4.33
remote sensing
collection and interpretation of information about an object without being in physical contact with the object

[SOURCE: ISO/TS 19101-2:2008, 4.33]

4.34
resolution
<imagery> smallest distance between two uniformly illuminated objects that can be separately resolved in an image

Note 1 to entry: This definition refers to the spatial resolution.

Note 2 to entry: In the general case, the resolution determines the possibility to distinguish between contrasting neighbouring features (objects).

Note 3 to entry: Resolution can also refer to the spectral and the temporal resolution.

[SOURCE: ISO/TS 19130-2:2014, 4.61, modified, — Notes 1 through 3 to entry have been added.]

4.35
resolution
<sensor> smallest difference between indications of a *sensor* (4.36) that can be meaningfully distinguished

Note 1 to entry: For imagery, resolution refers to radiometric, spectral, spatial and temporal resolutions.

Note 2 to entry: The definition according to ISO/TS 19101-2:2008 is associated with the term resolution (of a sensor).

[SOURCE: ISO/TS 19101-2:2008, 4.34, modified — Note 2 to entry has been added.]

4.36
sensor
element of a measuring system that is directly affected by a phenomenon, body, or substance carrying a *quantity* (4.30) to be measured

Note 1 to entry: Active or passive sensors exist. Often two or more sensors are combined to a measuring system.

[SOURCE: ISO/IEC Guide 99:2007, 3.8 modified, Note 1 to entry has been added]

4.37
strip adjustment
adjustment of observations that were made from a strip of aerial or satellite images, or *lidar* (4.19) *measurements* (4.20)

4.38
swath
sensed data resulting from a single flightline of collection

4.39
triangulated irregular network
TIN
tessellation composed of triangles

[SOURCE: ISO 19123:2005, 4.1.42]

4.40
uncertainty
parameter, associated with the result of *measurement* (4.20), that characterizes the dispersion of values that could reasonably be attributed to the measurand

Note 1 to entry: 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.

Note 2 to entry: 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.

Note 3 to entry: 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* (4.9) and *reference standards* (4.31), contribute to the dispersion.

Note 4 to entry: When the quality of accuracy or precision of measured values, such as coordinates, is to be characterized quantitatively, the quality parameter is an estimate of the uncertainty of the measurement results. Because accuracy is a qualitative concept, one should not use it quantitatively, that is associate numbers with it; numbers should be associated with measures of uncertainty instead.

Note 5 to entry: Measurement uncertainty includes components arising from systematic effects, such as components associated with corrections and the assigned *quantity* (4.30) 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

Note 6 to entry: 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.

Note 7 to entry: In general, for a given set of information, it is understood that the measurement uncertainty is associated with a stated quality value attributed to the measurand. A modification of this value results in a modification of the associated uncertainty.

[SOURCE: ISO 19116:2004, 4.26, modified, —Notes 1 through 3 to entry and Notes 5 through 7 have been added.]

4.41
validation
process of assessing, by independent means, the quality of the data products derived from the system outputs

Note 1 to entry: In this part of ISO/TS 19159 the term validation is used in a limited sense and only relates to the validation of *calibration* (4.6) data in order to control their change over time.

[SOURCE: ISO/TS 19101-2:2008, 4.41, modified – Note 1 to entry has been added.]

4.42
verification
provision of objective evidence that a given item fulfils specified requirements

Note 1 to entry: When applicable, *measurement* (4.20) *uncertainty* (4.40) should be taken into consideration.

Note 2 to entry: The item may be, e.g. a process, measurement procedure, material, compound, or measuring system.

Note 3 to entry: The specified requirements may be, e.g. that a manufacturer's specifications are met.

Note 4 to entry: Verification should not be confused with *calibration* (4.6). Not every verification is a *validation* (4.41).

[SOURCE: ISO/IEC Guide 99:2007, 2.44]

4.43
vertical accuracy
measure of the *positional accuracy* (4.29) of a *dataset* with respect to a specified vertical *datum* (4.10)

5 Symbols and abbreviated terms

5.1 Abbreviated terms

CA Calibration and Validation. The acronym denotes the ISO/TS 19159-x (this part of ISO/TS 19159)

FOV Field-of-View

RMSE Root mean square error

5.2 Symbols

Θ_s solar angle

5.3 Conventions

Some of the classes and attributes are defined in other standards of the ISO 19100- series. Those classes and attributes are identified by one of the following two-character codes.

CA = ISO/TS 19159-1 “Calibration and validation of remote sensing imagery sensors and data – Part 1: Optical sensors” and ISO/TS 19159-2 “… Part 2: Lidar”

MD = ISO 19115-1 “Metadata”

6 Calibration

6.1 Project

This part of ISO/TS 19159 addresses lidar-sensors (light detection and ranging).

All measures of this part of ISO/TS 19159 relating to positional accuracy lead to quantitative results according to ISO 19157.

Figure 1 depicts a package diagram that shows all intended parts of ISO/TS 19159 as of the time when this part of ISO/TS 19159 was developed.

The package CalibrationValidation represents the top level with only a little additional information.

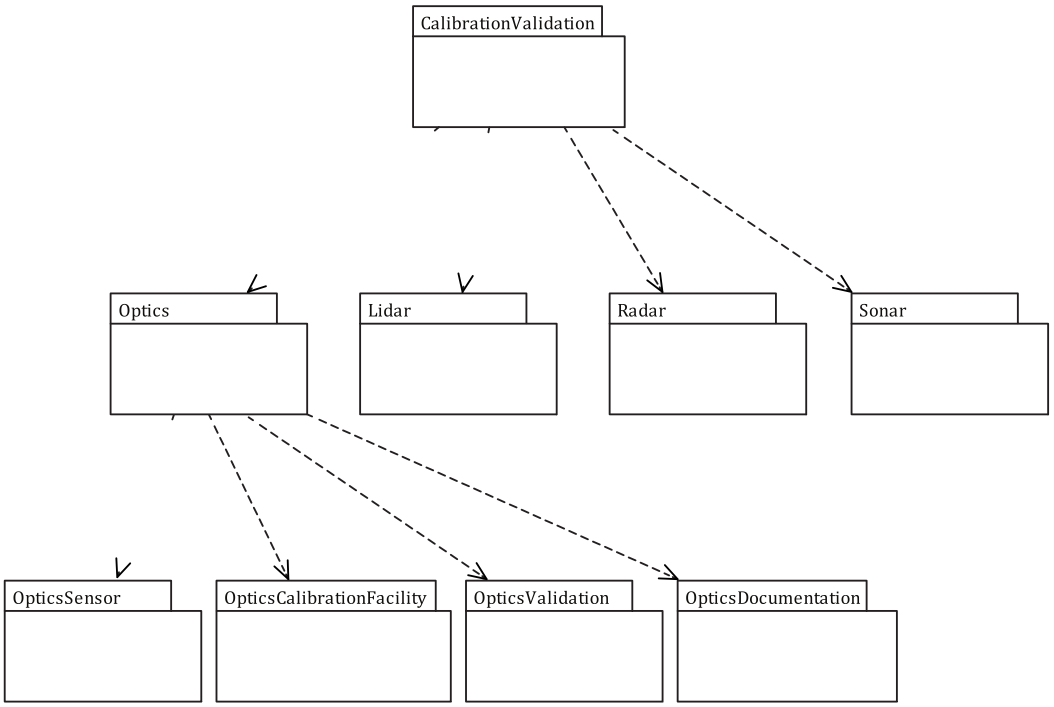

Figure 1 — Package diagram of the package CalibrationValidation

Figure 2 depicts the class diagram of this part of ISO/TS 19159.

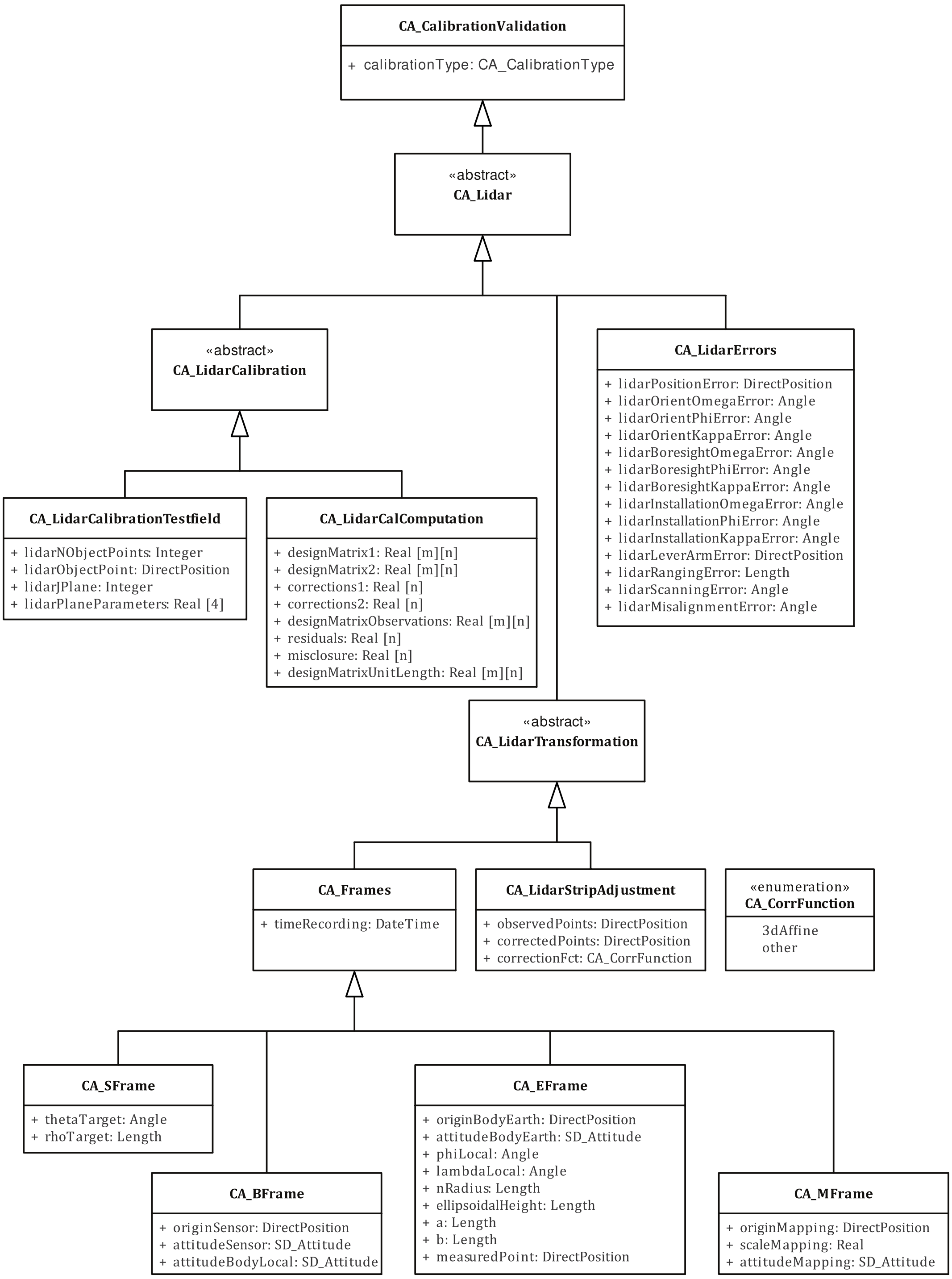

Figure 2 — Class diagram of the ISO/TS 19159-2

6.2 Coordinate Reference Systems

6.2.1 General

6.2 defines the five coordinate reference systems (CRS) that are used for building the transformation chain from sensor to ground.

The sensor frame, or s-frame in short, is the CRS which is defined by the principal axes of the laser scanner and used to describe the measurement that consists of the range ρ and the angle θ, which both depend on the time.

The body frame, or b-frame in short, is a three-dimensional right-handed Cartesian CRS related to the platform. In practical applications it is often bound to the Inertial Measurement Unit (IMU).

The local-level frame, or l-frame in short, is a three-dimensional right-handed Cartesian CRS with its origin at the intersection of the reference ellipsoid and the plumb line from the origin of the b-frame to the ellipsoid. The axes are North, East and Down.

The earth-centred, earth-fixed frame, or e-frame in short, is a three-dimensional right-handed Cartesian CRS bound to the earth with its origin at the centre of the earth.

The mapping frame, or m-frame in short, stands for any national CRS into which the laser point cloud is finally transformed.

Table 1 — Coordinate reference systems relevant for the transformations of lidar-data

ID	Description	Reference
s	Sensor frame. Frame of the laser sensor, defined by the principal axes of an optical instrument; e.g. xy-axes define an image plane in the frame imagery, yz-defines the scanning plane of a 2D scanner.	The definition of the axes depends on the type of the sensor.
b	Body frame. Frame materialized by the triad of accelerometers within an IMU.	The definition of the axes depends on the type of the sensor.
l	Local-level Frame. This frame is tangent to the global ellipsoid (normally WGS84), with the orthogonal components usually defined as N-orth (x), E-ast (y) and D-own (z).	The definition of the zero-direction of the angles depends on the type of the sensor.
e	ECEF frame (earth-centred earth-fixed frame). The origin is the geocentre of the earth, x-axis points towards the Greenwich meridian and the z-axis is the mean direction of the earth rotation axis. The y-axis is completed by the right-handed Cartesian system.	The angles count counter-clockwise with zero in the direction of the axes.
m	Mapping frame. Cartesian Frame with E-ast (x), N-orth (y) and U-p (z) component. The easiest implementation is the local tangent plane frame, but this frame can also be represented by a projection and/or national datum.	The angles count counter-clockwise with zero in the direction of the axes.

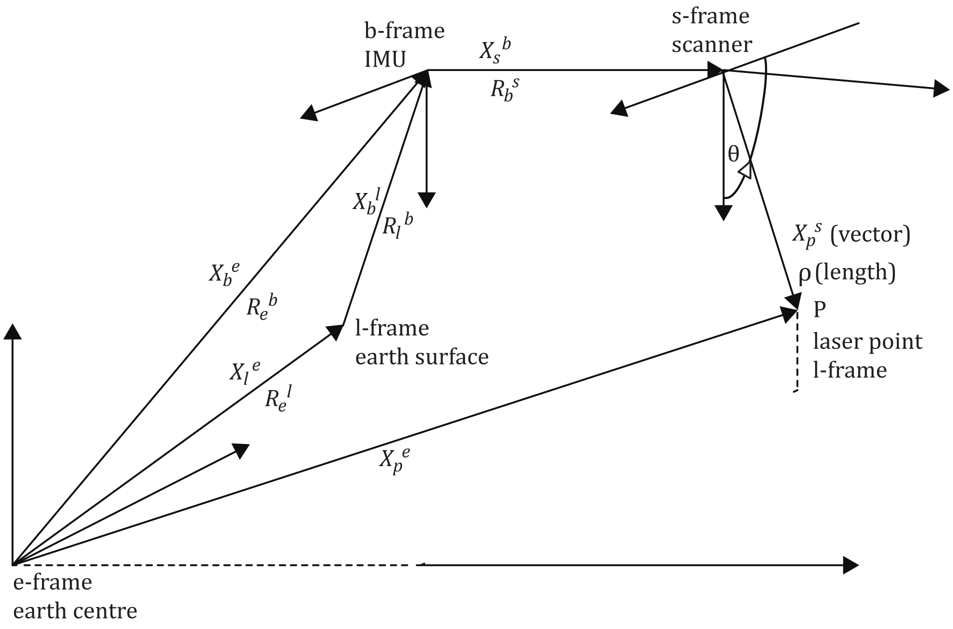

Figure 3 — Coordinate reference system for the transformation chain of lidar data[14]

6.2.2 Sensor frame – s

The transformation from the sensor frame to the body frame shall be defined by Formula (1).

$$x_p^s(t) = \rho(t) \cdot \begin{pmatrix} 0 \\ \sin\theta(t) \\ \cos\theta(t) \end{pmatrix} \tag{1}$$

where

x_p^s is vector from the laser scanner to the object point, given in the scanner coordinate reference system (thetaTarget);

ρ is range that follows from the run-time measurement of the laser pulse (rhoTarget);

θ is encoding angle of the scanner that reflects the current orientation of the laser beam with respect to the sensor frame (thetaTarget);

t is time.

6.2.3 Body frame – b

The transformation from the body frame to the sensor frame shall be defined by Formula (2).

$$x^b = x_s^b + R_s^b(\omega, \varphi, \kappa) \cdot x^s \tag{2}$$

where

x^b is vector expressed in the b-frame;

x_s^b is origin of the s-frame expressed in the b-frame, also known as lever-arm;

R_s^b is rotation-matrix representing the misalignment between the s- and the b-frame, also called the boresight (attitudeSensor);

ω, φ, κ are boresight angles around the x-, y-, and z-axis respectively;

x^s is vector expressed in the s-frame.

The rotation from the body frame to the local-level frame shall be defined by Formula (3).

$$R_{l_{NED}}^b = R_3(y) R_2(p) R_1(r) \quad (3)$$

where

$R_{l_{NED}}^b$ is rotation of the body frame to the local-level reference frame l_{NED} (NED = North-East-Down) (inverse of attitudeBodyLocal);

$R_1(r)$ is roll: rotation around the axis along track;

$R_2(p)$ is pitch: rotation around the axis across-track;

$R_3(y)$ is yaw: rotation around the vertical axis (flight direction).

A rotation is positive if it appears clockwise when looking in the positive direction of the axis around which the rotation takes place. The order of rotation shall be specified since the results of a sequence of rotations are not commutative (ISO/TS 19130:2010).

6.2.4 Earth-centred, earth-fixed – e

The transformation from the earth-centred, earth-fixed frame to the local-level frame shall use the rotation matrix defined by Formula (4).

$$R_{l_{NED}}^e = \begin{pmatrix} -\sin\varphi\cos\lambda & -\sin\lambda & -\cos\varphi\cos\lambda \\ -\sin\varphi\sin\lambda & \cos\lambda & -\cos\varphi\sin\lambda \\ \cos\varphi & 0 & -\sin\varphi \end{pmatrix} \quad (4)$$

where

φ is latitude of the local position (phiLocal);

λ is longitude of the local position (lambdaLocal).

The transformation from the earth-centred, earth-fixed earth-centred frame to the body frame shall be defined by Formula (5).

$$x^e = x_b^e + R_b^e \cdot x^b \quad (5)$$

where

x^e is vector expressed in the e-frame;

x_b^e is origin of the b-frame expressed in the e-frame;

R_b^e is rotation-matrix representing the misalignment between the b- and the e-frame;

x^b is vector expressed in the b-frame.

The rotation matrix R_b^e can be computed as the product of R_l^e and R_b^l, as in Formula (6).

$$R_b^e = R_{l_{NED}}^e \cdot R_b^l \tag{6}$$

where

$R_{l_{NED}}^e$ is rotation of the earth-centred, earth-fixed frame to the local-level reference frame;

R_b^l is rotation of the local-level reference frame to the body frame.

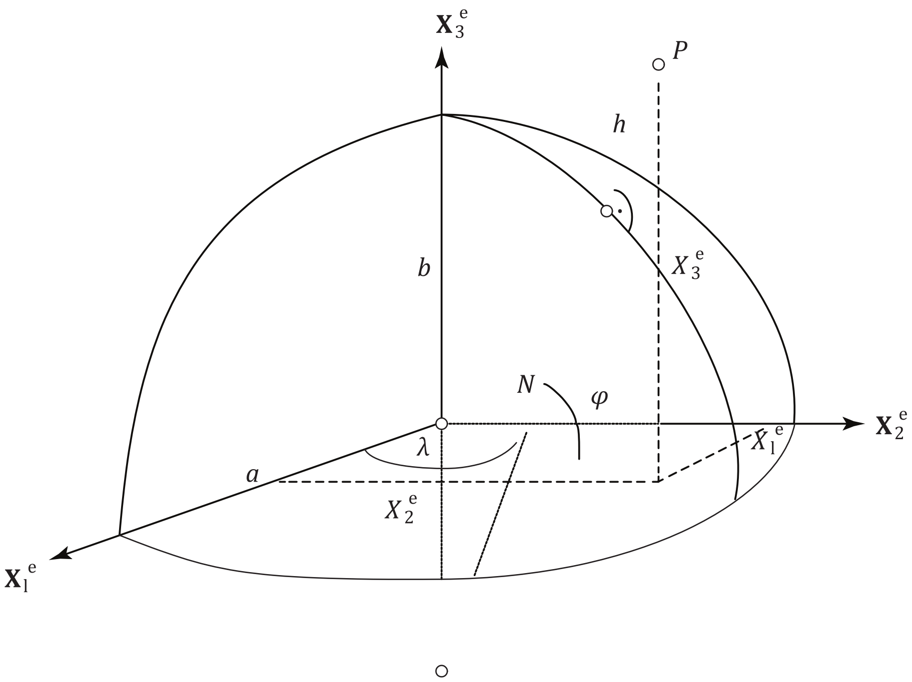

Figure 4 — Cartesian and ellipsoidal coordinates [14]

Formula (7) defines the transformation from a local-level frame to the earth-fixed earth centred frame.

$$x^e = \begin{pmatrix} x_1^e \\ x_2^e \\ x_3^e \end{pmatrix} = \begin{pmatrix} (N+h)\cos\varphi\cos\lambda \\ (N+h)\cos\varphi\sin\lambda \\ \left(\frac{b^2}{a^2}N+h\right)\sin\varphi \end{pmatrix} \quad (7)$$

where

x^e is vector from the centre of the earth to the object point, given in the ECEF coordinate reference system;

φ is latitude of the local position (phiLocal);

λ is longitude of the local position (lambdaLocal);

N is radius of the curvature of the prime vertical (nRadius);

h is ellipsoidal height (ellipsoidalHeight);

a is semi-major axis of the ellipsoid;

b is semi-minor axis of the ellipsoid.

6.2.5 Mapping frame – m

The transformation from the earth-centred, earth-fixed frame to the m-frame (mapping frame) shall be defined by Formula (8).

$$x_p^m = x_e^m + \mu^m R_e^m x_p^e \quad (8)$$

where

x_p^m is position vector to a laser point in the m-frame;

x_e^m is origin of the e-frame given in the m-frame;

μ^m is common scale factor of the national datum;

R_e^m is datum rotation matrix;

x_p^e is position vector of a laser point in the e-frame.

6.3 Transformations

6.3.1 General

6.3 defines the transformation from the sensor frame to the earth-centred, earth-fixed frame (e-frame) termed the “Airborne laser scanning observation equation” and the transformation from the e-frame to the mapping frame.

6.3.2 Airborne laser scanner observation equation

Equation 9 (Formula 9) contains the transformation from the s-frame to the e-frame with the intermediate coordinate reference systems bound to the b-frame and the l-frame.

$$x_p^e(t) = x_l^e + R_l^e(t)\left(x_b^l(t) + R_b^l\left(x_s^b + R_s^b \cdot \rho(t)\begin{pmatrix} 0 \\ \sin\theta(t) \\ \cos\theta(t) \end{pmatrix}\right)\right) \tag{9}$$

Equation 10 (Formula 10) contains the transformation from the s-frame to the e-frame with the intermediate coordinate reference system bound to the b-frame only.

$$x_p^e(t) = x_b^e + R_b^e(t)\left(x_s^b + R_s^b \cdot \rho(t)\begin{pmatrix} 0 \\ \sin\theta(t) \\ \cos\theta(t) \end{pmatrix}\right) \tag{10}$$

Equation 11 (Formula 11) contains the same elements as Equation 9 (Formula 9). However, the vector between the b-frame and the s-frame, the lever arm, points from the s-frame to the b-frame, i.e. $x_b^s = -x_s^b$.

This allows expressing this vector in the coordinate reference system of the s-frame. The resulting Equation 11 (Formula 11) is sometimes called the observation equation of airborne laser scanning.

$$x_p^e(t) = x_b^e + R_l^e(\varphi(t),\lambda(t)) \cdot R_b^l(r(t),p(t),y(t)) \cdot R_s^b(\omega,\varphi,\kappa)\left(x_b^s + \cdot\rho(t)\begin{pmatrix} 0 \\ \sin\theta(t) \\ \cos\theta(t) \end{pmatrix}\right) \tag{11}$$

where

x_p^e is vector from the centre of the earth to the object point, given in the ECEF coordinate reference system;

x_l^e is vector from the centre of the earth to the origin of the local coordinate reference system, given in the ECEF coordinate reference system;

R_b^l is rotation of the reference local-level frame l to the body frame;

x_b^l is vector from the local coordinate reference system to the origin of the body frame;

R_s^b is rotation of the body frame to the sensor coordinate reference system;

x_s^b is origin of the s-frame expressed in the b-frame, also known as lever-arm;

x_b^s is origin of the b-frame expressed in the s-frame, also known as lever-arm;

ρ is range that follows from the run-time measurement of the laser pulse (rhoTarget);

θ is encoding angle of the scanner that reflects the current orientation of the laser beam with respect to the sensor frame (thetaTarget);

x_b^e is vector from the centre of the earth to the origin of the body frame, given in the ECEF coordinate reference system;

R_b^e is rotation from the earth coordinate reference system to the body frame.

For further explanation of the variables see Formulae (2) to (6).

The transformation from the sensor frame to the mapping frame shall be defined by one of the equations 9, 10, or 11 (Formulae 9, 10 or 11).

6.3.3 Strip adjustment

The strip adjustment is a method of correcting unmodelled systematic errors by making use of the strong geometry of a block of a series of overlapping strips and cross-strips. A sufficient overlap of the strips is required in order to identify tie and control features.

The correction function for each strip is given by Formula (12).

$$x'^{e}_{p}(s) = x^{e}_{p}(s) + f(s) \tag{12}$$

where

$x^{e}_{p}(s)$ is observed point in strip s;

$x'^{e}_{p}(s)$ is corrected point;

$f(s)$ is correction function for strip s.

6.4 Intensity

The intensity of the echo of a laser pulse often is a value relevant for calibration. The class CA_Intensity holds the relevant parameters.

6.5 Error model

6.5.1 General

A measurement of an airborne laser scanner suffers from systematic errors of the models and systematic and random errors caused by an imperfect instrumentation. A typical example for a systematic error are the boresight angles which are a part of the transformation from the s-frame to the b-frame, and which relatively often require calibration.

The airborne laser scanning position vector is a function of the estimated GNSS/IMU trajectory, the observed laser scanning range and the encoding angle.

$$l_p = \begin{pmatrix} x^{e}_{b} & y^{e}_{b} & z^{e}_{b} & r & p & y & \rho & \theta \end{pmatrix}^T \tag{13}$$

where

l_p is laser scanning position vector [vector x^{e}_{p} in Formula (16)];

$x^{e}_{b} = \begin{pmatrix} x^{e}_{b} & y^{e}_{b} & z^{e}_{b} \end{pmatrix}^T$ is GNSS/IMU position;

$\begin{pmatrix} r & p & y \end{pmatrix}^T$ is GNSS/IMU orientation;

ρ is laser scanning range;

θ is encoding angle.

The transformation from the body frame to the sensor frame is not relevant for the error model because the lever-arm and the boresight angles are recalibrated often and can thus be considered as error-free during a mission.

Based on Equation 11 (Formula 11) the following general error model applies to this part of ISO/TS 19159.

$$x_p^e = x_b^e + \Delta\hat{x}_b^e + R_l^e R_b^l \left(\hat{r}\hat{p}\hat{y}\right) R_b^{b'} \left(\Delta r \Delta p \Delta y\right) R_{s'}^b \left(\Delta\omega\Delta\varphi\Delta\kappa\right) T_s^{s'} \left(\hat{\omega}\hat{\varphi}\hat{\kappa}\right) \times \begin{pmatrix} -\left(\hat{\rho} + \Delta\rho\right)\sin\left(\Delta\eta\right) \\ \left(\hat{\rho} + \Delta\rho\right)\sin\left(\hat{\theta} + \Delta\theta\right)\cos\left(\Delta\eta\right) + \hat{x}_b^s + \Delta x_b^s \\ \left(\hat{\rho} + \Delta\rho\right)\cos\left(\hat{\theta} + \Delta\theta\right)\cos\left(\Delta\eta\right) \end{pmatrix} \tag{14}$$

where

x_p^e	is object point, given in the earth-centred, earth-fixed frame;
x_b^e	is origin of the body frame, given in the earth-centred, earth-fixed frame;
$\Delta\hat{x}_b^e$	is GNSS/IMU positioning errors;
$R_{\mathrm{b}}^{\mathrm{b'}}\left(\Delta r \Delta p \Delta y\right)$	is GNSS/IMU orientation errors (delta roll, delta pitch, delta yaw);
$R_{s'}^b\left(\Delta\omega\Delta\varphi\Delta\kappa\right)$	is boresight orientation error matrix;
$T_s^{s'}\left(\hat{\omega}\hat{\varphi}\hat{\kappa}\right)$	is known part of the installation matrix;
Δx_b^s	is lever-arm error;
$\Delta\rho$	is overall ranging error;
$\Delta\theta$	is overall encoding/scanner error;
$\Delta\eta$	is misalignment between the angular encoder and the scanning plane.

6.5.2 Trajectory positioning and orientation

The trajectory positioning errors Δx_b^e are relatively small if precise relative positioning is applied. However, the trajectory orientation errors $R_b^{b'}$ cannot be completely removed by the GNSS/IMU Kalman filter/smoother. This means that the orientation errors belong to the weakest part of the system.

6.5.3 Boresight error and misalignment matrix

The boresight error represents the uncertainty of the relative orientation between the body frame, mostly the IMU, and the laser scanner. It is the most critical error component of the error budget.

The product of the matrices $R_{s'}^{b}$ and $T_{s}^{s'}$ is named the misalignment matrix R_{s}^{b}:

$$R_s^b = R_{s'}^b \cdot T_s^{s'}$$

In this formula $T_{s}^{s'}$ is named the installation matrix which is usually composed of 90°or 180°rotations and $R_{s'}^{b}$ the residual boresight matrix of small angle. Therefore, $R_{s'}^{b}$ can be approximated by Formula (15).

$$R_{s'}^{b} \approx \begin{pmatrix} 1 & -\Delta\kappa & \Delta\varphi \\ \Delta\kappa & 1 & -\Delta\omega \\ -\Delta\varphi & \Delta\omega & 1 \end{pmatrix} = I + dR_{s'}^{b} \tag{15}$$

where

$$dR_{s'}^{b} = \begin{pmatrix} 0 & -\Delta\kappa & \Delta\varphi \\ \Delta\kappa & 0 & -\Delta\omega \\ -\Delta\varphi & \Delta\omega & 0 \end{pmatrix}$$

6.5.4 Lever-arm

The lever-arm error Δx_{b}^{s} is twofold. The component caused by lever-arm from the IMU to the scanner is almost always negligible because the length is small and the calibration done by the manufacturer. However, the lever-arm from the GNSS-antenna to the IMU is longer and has a predominant influence on Δx_{b}^{s}.

6.5.5 Scanner

The sources of the scanner component errors of $\Delta\rho$ and $\Delta\theta$ are complex and instrument dependent.

6.5.6 Scanner assembly error $\Delta\eta$

This error is caused by the fact that the scanner-angle encoders are not exactly mounted perpendicular to the mirror's rotation angle.

6.6 In-flight calibration

An airborne laser scanning assembly requires the calibration of several individual components. The totality of those components is referred to as the calibration of the laser scanning assembly.

The calibration of the two lever-arms between the laser scanner and the IMU as well as the GNSS-antenna is performed by surveying methods which lead to a sufficient calibration accuracy.

The lever-arm calibration is done on the ground. Lever arm calibration and instrument laboratory calibration are very important but not discussed further in this part of ISO/TS 19159.

The orientation errors of the laser scanner relative to the platform are determined by an in-flight procedure, because laboratory methods do not yet exist. These orientation errors include the boresight angles and the scanner assembly errors.

This part of ISO/TS 19159 sets the in-flight, surface-based self-calibration method as the standard model for the calibration of a laser scanning assembly[14].

Several calibration methods have been proposed. They rely on terrain gradients, control points or building profiles extracted from overlapping point clouds. Some of them are labour intensive, non-rigorous, or have no statistical quality assurance measures.

Therefore, the model of the ISO 19159 series is based on the condition that the georeferenced object points lie on planes. The parameters of these planes are estimated together with the calibration parameters. For an optimal model, the chosen planes must point in different directions, i.e., the not all normal vectors of the planes must be parallel. The eight observables per point are the three position and the three rotation estimates of the GNSS/IMU system as well as the range and angle measurements of the laser scanner.

The observation equation of an object point *i* with the position vector $x_{p_i}^e$ is given by Formula (16).

$$\left\langle s_j, \begin{pmatrix} x_{p_i}^e \\ 1 \end{pmatrix} \right\rangle = 0 \tag{16}$$

where

i	is number of object point;
$x_{p_i}^e$	is object point;
j	is number of plane.

The plane parameters are given by Formula (17).

$$s_j = \begin{pmatrix} s_1 & s_2 & s_3 & s_4 \end{pmatrix}^T \tag{17}$$

where

$s_1 \quad s_2 \quad s_3$	is direction cosines;
s_4	is negative orthogonal distance between the plane and the coordinate system origin.

The direction cosines must satisfy the unit length constraint of Formula (18).

$$s_1^2 + s_2^2 + s_3^2 - 1 = 0 \tag{18}$$

The linearized system of observation equations of the plane normal vector parameters is given by Formula (19).

$$A_1\hat{\delta}_1 + A_2\hat{\delta}_2 + B\hat{v} + w = 0 \tag{19}$$

where

$A_1 \quad A_2$	is design matrices of partial derivatives of the function;
$\hat{\delta}_1 \hat{\delta}_2$	is corresponding correction vectors;
B	is design matrix of the partial derivatives taken with respect to the observations;
$\hat{v}$	is vector of residuals;
w	is misclosure vector.

The linearized system of weighted constraints of the plane normal vector parameters is given by Formula (20).

$$G_c\hat{\delta}_2 + w_c = \hat{v}_c \tag{20}$$

where

G_c is design matrix of the partial derivatives of the unit length constraint taken with respect to the plane parameters;

$\hat{\delta}_2$ is corresponding correction vector;

$\hat{v}_c$ is vector of residuals;

w_c is misclosure vector.

6.7 Residual strip errors

Residual strip error seeks to quantify the quality of calibration process (both data, in-flight and factory) by measuring the error in relative positioning of tie and control features in overlapping strips and cross strips.

Like for strip adjustment, sufficient overlap of the strips is required in order to identify tie and control features.

The residual strip errors are determined by measuring the point-to-plane distance between check points in one swath and the least squares best fit plane formed by using its neighbours in the second swath. The measurements are valid only in planar regions of the overlap.

6.8 Validation

In order to validate a calibration this part of ISO/TS 19159 provides six methods: testfield, cross strip flight, second flight, second altitude, measurementActualParameters, and other.

A validation of a calibration shall contain the time when the validation was done.

Annex A
(normative)

Abstract test suite

A.1 Semantics

Conformance to this part of ISO/TS 19159 consists of either service conformance or data conformance.

Conformance to this part of ISO/TS 19159 does not require an application of the formulae given in Clause 6 since they are a description of standard geometry. However, the standard requires the documentation of the given variables.

The Abstract test suite has four conformance classes.

1) Coordinate reference systems

2) Transformations

3) Error model

4) Calibration

A.2 Coordinate reference systems

A.2.1 Sensor frame – s

a) Test purpose: to verify the use of the appropriate interface for a sensor frame.

b) Test method: Inspect the documentation of the interface to verify the use of an interface defined in A.2.1 c).

c) Reference: 6.2.2

A.2.2 Body frame – b

a) Test purpose: to verify the use of the appropriate interface for a body frame.

b) Test method: Inspect the documentation of the interface to verify the use of an interface defined in A.2.2 c).

c) Reference: 6.2.3

A.2.3 Earth centred, earth fixed frame – e

a) Test purpose: to verify the use of the appropriate interface for an earth centred, earth fixed frame.

b) Test method: Inspect the documentation of the interface to verify the use of an interface defined in A.2.3 c).

c) Reference: 6.2.4

A.2.4 Mapping frame – m

a) Test purpose: to verify the use of the appropriate interface for a mapping frame.

b) Test method: Inspect the documentation of the interface to verify the use of an interface defined in A.2.4 c).

c) Reference: 6.2.5

A.3 Transformations

A.3.1 General

a) Test purpose: to verify the use of the appropriate interface for a transformation service.

b) Test method: Inspect the documentation of the interface to verify the use of interfaces defined in A.3.1 c).

c) References: 6.3

A.3.2 Airborne laser scanner observation equation

a) Test purpose: to verify the use of the appropriate interface for an airborne laser scanner observation equation.

b) Test method: Inspect the documentation of the interface to verify the use of an interface defined in A.3.2 c).

c) Reference: 6.3.2

A.3.3 Strip adjustment

a) Test purpose: to verify the use of the appropriate interface for the strip adjustment equation.

b) Test method: Inspect the documentation of the application schema or profile to verify the use of an interface defined in A.3.3 c).

c) Reference: 6.3.3

A.4 Error model

a) Test purpose: to verify the use of an appropriate application class for an error model.

b) Test method: Inspect the documentation of the application schema or profile to verify the use defined in A.4 c).

c) References: 6.5

A.5 Calibration

a) Test purpose: to verify the use of the appropriate interface for a calibration service.

b) Test method: Inspect the documentation of the interface to verify the use of interfaces defined in A.5 c).

c) References: 6.6

Annex B
(normative)

Data dictionary

	Name/Role name	Definition	Obligation/Condition	Max occurrence	Data type/Class	Domain
1.	CA_CalibrationValidation	root entity that defines information about calibration	Use obligation/condition from referencing object	Use maximum occurrence from referencing object	Aggregated Class (MD_Coverage Description)	
2.	CA_Lidar	root entry of the lidar calibration and measurement	Use obligation/condition from referencing object	Use maximum occurrence from referencing object	Specialized Abstract Class (CA_Calibration Validation)	
3.	CA_LidarCalibration	root entry of the lidar calibration	Use obligation/condition from referencing object	Use maximum occurrence from referencing object	Specialized Abstract Class (CA_Lidar)	
4.	CA_LidarCalibrationTestfield	class that contains all information about the setup of the testfield	Use obligation/condition from referencing object	Use maximum occurrence from referencing object	Specialized Class (CA_LidarCalibration)	
5.	lidarNObjectPoints	number of object points given for the calibration	M	1	Integer	
6.	lidarObjectPoint	object points	M	N	DirectPosition	
7.	lidarJPlane	number of planes	M	1	Integer	
8.	lidarPlaneParameters	direction cosines of the plane's normal vector (first three) and negative orthogonal distance between the plane and the coordinate system origin (fourth)	M	4 x N	Real	
9.	CA_LidarCalComputation	class that contains all information about the computation of the calibration	Use obligation/condition from referencing object	Use maximum occurrence from referencing object	Specialized Class (CA_LidarCalibration)	
10.	designMatrix1	A-matrix of the adjustment containing the partial derivatives regarding the calibration parameters	M	M x N	Real	

	Name/Role name	Definition	Obligation/ Condition	Max occurrence	Data type/Class	Domain
11.	designMatrix2	A-matrix of the adjustment containing the partial derivatives regarding the plane parameters	M	M x N	Real	
12.	corrections1	correction vector for the calibration parameters	M	N	Real	
13.	corrections2	correction vector for the plane parameters	M	N	Real	
14.	designMatrixObservations	A-matrix of the adjustment containing the partial derivatives regarding the observation functions	M	M x N	Real	
15.	residuals	residuals of the observations	M	N	Real	
16.	misclosure	misclosure vector	M	N	Real	
17.	designMatrixUnitLength	A-matrix of the adjustment containing the partial derivatives of the unit lengths regarding the plane parameters	M	M x N	Real	
18.	CA_LidarTransformation	class that serves as the superclass for all parameters necessary to define the transformation	Use obligation/ condition from referencing object	1	Specialized Abstract Class (CA_Lidar)	
19.	CA_Frames	class that serves as the superclass for all parameters necessary to define the coordinate reference systems	Use obligation/ condition from referencing object	1	Specialized Class (CA_LidarTransformation)	
20.	timeRecording	time when the laser pulse was sent and recorded	M	1	DateTime	
21.	CA_SFrame	scanner system that forms a right-handed coordinate reference system	Use obligation/ condition from referencing object	1	Specialized Class (CA_Frames)	
22.	thetaTarget	angle between the measurement vector from the sensor to the target and the z-axis of the sensor coordinate reference system (crs). This angle is rotated anticlockwise around the x-axis of the sensor crs.	M	1	Angle	
23.	rhoTarget	length of the measurement vector from the sensor to the target	M	1	Length	
24.	CA_BFrame	information about the body-frame, which is related to the system carrier, conveniently chosen to be at the navigation centre of the inertial navigation system	Use obligation/ condition from referencing object	1	Specialized Class (CA_Frames)	

	Name/Role name	Definition	Obligation/Condition	Max occurrence	Data type/Class	Domain
25.	originSensor	position vector to the origin of the sensor given in the body-crs (coordinate reference system), usually called "lever-arm"	M	1	DirectPosition	
26.	attitudeSensor	rotation of the sensor coordinate reference system against the body-crs (see previous entry), usually given by the angles ω, φ, and κ	M	1	SD_Attitude	
27.	attitudeBodyLocal	rotation of the local coordinate reference system (crs) against the body-crs, usually given by the angles roll, pitch, and yaw	M	1	SD_Attitude	
28.	CA_EFrame	information about the ECEF-frame (earth-centred earth-fixed)	Use obligation/condition from referencing object	1	Specialized Class (CA_Frames)	
29.	originBodyEarth	position vector to the origin of the body given in the ECEF-crs (earth-centred earth-fixed coordinate reference system)	M	1	DirectPosition	
30.	attitudeBodyEarth	rotation of the body coordinate reference system against the ECEF-crs (see previous entry)	M	1	SD_Attitude	
31.	phiLocal	latitude of the local position	M	1	Angle	
32.	lambdaLocal	longitude of the local position	M	1	Angle	
33.	nRadius	radius of the curvature of the prime vertical	M	1	Length	
34.	ellipsoidalHeight	ellipsoidal height	M	1	Length	
35.	a	semi-major axis of the ellipsoid	M	1	Length	
36.	b	semi-minor axis of the ellipsoid	M	1	Length	
37.	measuredPoint	position vector to the measured point given in the earth centred earth fixed (ECEF) coordinate reference system	M	1	DirectPosition	
38.	CA_MFrame	information about the national frame (national coordinate reference system)	Use obligation/condition from referencing object	1	Specialized Class (CA_Frames)	
39.	originMapping	position vector to the origin of the national coordinate reference system given in the ECEF-crs (earth-centred earth-fixed coordinate reference system)	M	1	DirectPosition	

	Name/Role name	Definition	Obligation/ Condition	Max occurrence	Data type/Class	Domain
40.	scaleMapping	common scale factor of the national datum	M	1	Real	
41.	attitudeMapping	rotation of national coordinate reference system against the ECEF-crs (see last but one entry)	M	1	SD_Attitude	
42.	CA_LidarStripAdjustment	information about strip adjustment	Use obligation/ condition from referencing object	1	Specialized Class (CA_LidarTransformation)	
43.	observedPoints	points that are input of the transformation towards a corrected point set	M	N	DirectPosition	
44.	correctedPoints	output points after the transformation	M	N	DirectPosition	
45.	correctionFct	defines the mathematical method used for joining neighbouring strips	M	1	CA_CorrFunction	
46.	CA_LidarErrors	information about the measurement errors of an individual laser point	Use obligation/ condition from referencing object	1	Specialized Class (CA_Lidar)	
47.	lidarPositionError	GNSS/IMU positioning errors	M	1	DirectPosition	
48.	lidarOrientOmegaError	orientation error of omega	M	1	Angle	
49.	lidarOrientPhiError	orientation error of phi	M	1	Angle	
50.	lidarOrientKappaError	orientation error of kappa	M	1	Angle	
51.	lidarBoresightOmegaError	boresight error of omega	M	1	Angle	
52.	lidarBoresightPhiError	boresight error of phi	M	1	Angle	
53.	lidarBoresightKappaError	boresight error of kappa	M	1	Angle	
54.	lidarInstallationOmegaError	installation error of omega	M	1	Angle	
55.	lidarInstallationPhiError	installation error of phi	M	1	Angle	
56.	lidarInstallationKappaError	installation error of kappa	M	1	Angle	
57.	lidarLeverArmError	lever arm error	M	1	DirectPosition	

	Name/Role name	Definition	Obliga-tion/ Condition	Max occur-rence	Data type/Class	Domain
58.	lidarRangingError	ranging error with respect to the measured length	M	1	Length	
59.	lidarScanningError	scanning error with respect to the measured angle	M	1	Angle	
60.	lidarMisalignmen-tError	misalignment between the angular encoder and the scanning plane	M	1	Angle	

	Name/Role name	Domain code	Definition
1.	CA_CorrFunction	caCoFu	function applied for the strip adjustment
2.	3dAffine	001	3D-affine transformation
3.	other	002	other method

Annex C
(informative)

Rotations

Annex C provides further information regarding the transformation.

C.1 Rotation around the axis x_j-axis (j = 1, 2, 3) by an angle θ

$$R_1(\theta)=\begin{pmatrix}1 & 0 & 0\\ 0 & \cos\theta & \sin\theta\\ 0 & -\sin\theta & \cos\theta\end{pmatrix}$$

$$R_2(\theta)=\begin{pmatrix}\cos\theta & 0 & -\sin\theta\\ 0 & 1 & 0\\ \sin\theta & 0 & \cos\theta\end{pmatrix}$$

$$R_3(\theta)=\begin{pmatrix}\cos\theta & \sin\theta & 0\\ -\sin\theta & \cos\theta & 0\\ 0 & 0 & 1\end{pmatrix}$$

Rotation from p-frame to q-frame around the axis x_i^p -axis $(i=1,2,3)$ by an angle θ

$$R_p^q=R_3(\kappa)R_2(\varphi)R_1(\omega)$$

C.2 One rotation angle θ about an axis n

$$n=(n_1,n_2,n_3)^T$$

$$R=\begin{pmatrix}\cos\theta+n_1^2(1-\cos\theta) & n_1n_2(1-\cos\theta)+n_3\sin\theta & n_1n_3(1-\cos\theta)-n_2\sin\theta\\ n_1n_2(1-\cos\theta)-n_3\sin\theta & \cos\theta+n_2^2(1-\cos\theta) & n_2n_3(1-\cos\theta)+n_1\sin\theta\\ n_1n_3(1-\cos\theta)+n_2\sin\theta & n_2n_3(1-\cos\theta)-n_1\sin\theta & \cos\theta+n_3^2(1-\cos\theta)\end{pmatrix}$$

C.3 Four algebraic parameters as the unit quaternion

$$\dot{q} = q_0 + q_1 i + q_2 j + q_3 k = q_0 + q$$

where

$$q_0^2 + q_1^2 + q_2^2 + q_3^2 = 1$$

A quaternion can be considered as a vector plus a scalar or a complex number with three imaginary components

$$R = \begin{pmatrix} q_0^2 + q_1^2 - q_2^2 - q_3^2 & 2\left(q_1 q_2 + q_0 q_3\right) & 2\left(q_1 q_3 + q_0 q_2\right) \\ 2\left(q_1 q_2 - q_0 q_3\right) & q_0^2 - q_1^2 + q_2^2 - q_3^2 & 2\left(q_2 q_3 + q_0 q_1\right) \\ 2\left(q_1 q_3 + q_0 q_2\right) & 2\left(q_2 q_3 - q_0 q_1\right) & q_0^2 - q_1^2 - q_2^2 + q_3^2 \end{pmatrix}$$

unit quaternion

$$\dot{q} = \cos\left(\frac{\theta}{2}\right) + \sin\left(\frac{\theta}{2}\right) n_1 i + \sin\left(\frac{\theta}{2}\right) n_2 j + \sin\left(\frac{\theta}{2}\right) n_3 k$$

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