TECHNICAL SPECIFICATION

ISO/TS 19124-1

First edition
2023-04

Geographic information — Calibration and validation of remote sensing data and derived products —

Part 1: **Fundamentals**

Reference number
ISO/TS 19124-1:2023(E)

Contents

Page

Foreword

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

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).

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. ISO shall not be held responsible for identifying any or all such patent rights. Details of any patent rights identified during the development of the document will be in the Introduction and/or on the ISO list of patent declarations received (see www.iso.org/patents).

Any trade name used in this document is information given for the convenience of users and does not constitute an endorsement.

For an explanation of the voluntary nature of standards, the meaning of ISO specific terms and expressions related to conformity assessment, as well as information about ISO's adherence to the World Trade Organization (WTO) principles in the Technical Barriers to Trade (TBT), see www.iso.org/iso/foreword.html.

This document was prepared by Technical Committee ISO/TC 211, *Geographic information/Geomatics*.

A list of all parts in the ISO 19124 series can be found on the ISO website.

Any feedback or questions on this document should be directed to the user's national standards body. A complete listing of these bodies can be found at www.iso.org/members.html.

Introduction

The ISO 19124 series addresses post-launch calibration and validation (Cal/Val) of remotely sensed data and products derived from the data. This document, ISO 19124-1, provides the fundamentals and a common framework on Cal/Val of remote-sensing data and derived products. Subsequent parts of the ISO 19124 series deal with sensor- or product-specific Cal/Val.

NOTE In contrast to the ISO 19124 series, the ISO 19159 series focuses on the pre-launch Cal/Val process of the sensor and hardware.

This document was drafted based on material provided by the major organizations that are active in this field such as CEOS (international), NASA (USA), ESA (Europe), JAXA (Japan), CSIRO (Australia) and the Chinese space agency.

In accordance with the ISO/IEC Directives, Part 2, 2018, Rules for the structure and drafting of International Standards, in International Standards the decimal sign is a comma on the line. However, the General Conference on Weights and Measures (Conférence Générale des Poids et Mesures) at its meeting in 2003 passed unanimously the following resolution:

"The decimal marker shall be either a point on the line or a comma on the line."

In practice, the choice between these alternatives depends on customary use in the language concerned. In the technical areas of geodesy and geographic information it is customary for the decimal point always to be used, for all languages. That practice is used throughout this document.

Geographic information — Calibration and validation of remote sensing data and derived products —

Part 1: Fundamentals

1 Scope

The ISO 19124 series is focused on calibration and validation (Cal/Val) of remote sensing data, which are collected by a sensor on-board a platform in a mission, and products derived in part or whole from the data. The ISO 19124 series defines the metadata related to the calibration and validation process that has not been defined in other ISO/TC 211 International Standards. The metadata allows the data providers to provide a standardized description of the Cal/Val process they have applied to the data. It allows the data users to get the same forms of metadata from different data providers.

This document addresses the overall framework and common calibration and validation processes related to Earth observation data and derived products from different types of remote sensors.

Subsequent parts in the ISO 19124 series will target data from specific sensors, for example, infrared, ultraviolet/visible/near-infrared, microwave, or broadband, products derived from those data, and calibration and validation sites.

Calibration addresses a geometric, radiometric, or spectral correction of the data. Validation addresses an evaluation of the quality and the accuracy of the data and the derived products.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 19157-1, *Geographic information — Data quality — Part 1: General requirements*

3 Terms and definitions

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

ISO and IEC maintain terminology databases for use in standardization at the following addresses:

— ISO Online browsing platform: available at https://www.iso.org/obp

— IEC Electropedia: available at https://www.electropedia.org/

3.1
accuracy
closeness of agreement between a test result or measurement result and the true value

[SOURCE: ISO 3534-2:2006, 3.1.1, modified — Notes to entry have been removed.]

3.2
bias
magnitude of the non-random or systematic errors of a result

Note 1 to entry: A bias can be positive or negative.

Note 2 to entry: This entry is adapted from Reference [9].

3.3
calibration
process of quantitatively defining a system's responses to the known, controlled signal inputs

[SOURCE: ISO 19101-2:2018, 3.2]

3.4
calibration curve
expression of the relation between indication and corresponding measured quantity value

[SOURCE: ISO/IEC Guide 99:2007, 4.31, modified — Note 1 to entry has been removed.]

3.5
calibration equation
equation relating the primary measure and that of the radiometer, for example the brightness temperature, to subsidiary measurands, such as powers, and to calibration quantities, such as standard values

[SOURCE: ISO/TS 19159-4:2022, 3.15]

3.6
calibration parameters
information generated (or that will be generated) during the course of a calibration that quantifies and/or describes the Earth observation (EO) sensor performance

Note 1 to entry: These parameters may be laboratory measurement, thermal vacuum (TVAC) performance plots, or sheets (as allowed).

Note 2 to entry: This entry is adapted from Reference [12].

3.7
co-location
<coordinate> procedure to match the location of two or more spatial datasets

3.8
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]

3.9
cross-calibration
process of relating the measurements of one instrument to another instrument which is usually well-calibrated, serving as a reference

Note 1 to entry: Cross-calibration of instruments operating during the same period requires careful collocation wherein instrument outputs are compared when the instruments are viewing the same Earth scenes, at the same times, from the same viewing angles.

[SOURCE: ISO/TS 19159-4:2022, 3.18]

3.10
derived product
<earth observation> product that is not directly measured by sensors but derived from direct sensor measures by algorithms or models

3.11
detector
<electro-optical> sensing element that generates an output signal in response to an energy input

[SOURCE: ISO 19130-1:2018, 3.18, modified — The domain <electro-optical> has been added to the entry and "device" has been replaced by "sensing element" at the beginning of the definition.]

3.12
emissivity
ratio of the energy radiated by an emissive surface relative to that of an ideal blackbody source at the same temperature

Note 1 to entry: It is generally related as a function of wavelength or frequency, emissivity values range from 0 to 1.

Note 2 to entry: This entry is adapted from Reference [12].

3.13
evaluation
<earth observation> systematic determination of the extent to which an entity meets its specified criteria

Note 1 to entry: The entity can be an item or activity.

[SOURCE: ISO/IEC 25001:2014, 4.1, modified — The domain <earth observation> and a new Note 1 to entry have been added.]

3.14
filter
<earth observation> optical device that is placed in the optical path of an Earth observation (EO) sensor to select, restrict, reject, limit or adjust an EO sensor response

Note 1 to entry: The range of desired wavelengths/frequencies to be passed by an optical filter is called the "bandpass". This is generally defined by the cut-on and cut-off wavelengths/frequencies of the optical filter.

Note 2 to entry: The EO sensor response to the optical wavelengths/frequencies within the desired optical filter bandpass is called the "in-band response".

Note 3 to entry: The ability of an optical filter (or optical system) to reject optical energy outside the desired wavelengths/frequencies is referred to as "out-of-band (OOB) blocking". This can also refer to filter design specifications regarding the ability to reject optical energy outside the desired filter bandpass.

Note 4 to entry: Undesired optical energy that passes through an optical filter (or optical system) that has a spectral location outside the desired spectral bandpass is called " OOB leakage".

Note 5 to entry: An EO sensor’s response to OOB leakage is called the "OOB response".

Note 6 to entry: The ratio of the open-path throughput of an optical path with and without the filter is called "transmittance". Generally expressed as a function of wavelength or optical frequency, transmittance values range from 0 to 1, or 0 % to 100 % if expressed in percent transmittance.

Note 7 to entry: This entry is adapted from Reference [12].

3.15
irradiance
electro-magnetic radiation energy per unit area per unit time

[SOURCE: ISO/TS 19159-1:2014, 4.13, modified —Note 1 to entry has been removed.]

3.16
measure
<GML> value described using a numeric amount with a scale or using a scalar reference system

Note 1 to entry: When used as a noun, measure is a synonym for physical quantity.

[SOURCE: ISO 19136-1:2020, 3.1.41]

3.17
measurement
set of operations having the object of determining the value of a quantity

[SOURCE: ISO 19101-2:2018, 3.21]

3.18
measurement error
error of measurement
error
measured quantity value minus a reference quantity value

[SOURCE: ISO/TS 19159-1:2014, 4.18, modified — Notes to entry have been removed.]

3.19
noise
unwanted signal which can corrupt the measurement

Note 1 to entry: In most measurement scenarios, measurement noise limitations challenge measurement objectives and are a major contributor to overall measurement uncertainty.

Note 2 to entry: Noise equivalent radiance (NER) is the entity of radiance that is most appropriate for the description of radiant flux from an extended area source. The NER is the amount of radiant flux that produces a signal equal to the system's noise when viewing an extended source.

[SOURCE: ISO/TS 19159-1:2014, 4.22, modified — The original Note 1 to entry has been removed and two new Notes to entry have been added.]

3.20
point source
source of electromagnetic radiation that is resolved in the ideal case to a single point or direction in space

Note 1 to entry: A natural star is an ideal point source. In the laboratory on the ground, a point source is simulated using an optical collimator.

Note 2 to entry: This entry is adapted from Reference [12].

3.21
post-launch calibration
all calibration activities that occur after a satellite-based Earth observation (EO) sensor is on-orbit

Note 1 to entry: The post-launch calibration may also be referred to as on-orbit calibration.

Note 2 to entry: The scope of the post-launch calibration varies from program to program and sensor to sensor, and includes considerations such as mission objectives, measurement requirements, mission operations capabilities, sensor data collection capabilities, and the ability to downlink low-level sensor response data to the ground.

Note 3 to entry: Post-launch calibration activities are included in the calibration plan and are executed according to the post-launch calibration procedures.

Note 4 to entry: This entry is adapted from Reference [12].

3.22
precision
measurement precision
closeness of agreement between indications or measured quantity values obtained by replicate measurements on the same or similar objects under specified conditions

[SOURCE: ISO/TS 19159-2:2016, 4.23, modified — Notes to entry have been removed and the original preferred term and admitted terms have been inversed.]

3.23
pre-launch calibration
sequence of measurement and characterization that takes place during and after instrument assembly and integration, prior to launch

Note 1 to entry: Pre-launch calibration provides the best or only chance to measure calibration key data (CKD) such as spectral response, linearity and polarization sensitivity, and also provides an important quality control and validation function to prevent unpleasant surprises and disappointment after launch.

Note 2 to entry: Pre-launch calibration is also called ground calibration.

Note 3 to entry: This entry is adapted from Reference [12].

3.24
quality
degree to which a set of inherent characteristics of an object fulfils requirements

[SOURCE: ISO 9000:2015, 3.6.2, modified — Notes 1 and 2 to entry have been removed.]

3.25
radiance
at a point on a surface and in a given direction, the radiant intensity of an element of the surface, divided by the area of the orthogonal projection of this element on a plane perpendicular to the given direction

[SOURCE: ISO 19101-2:2018, 3.30]

3.26
radiometric calibration
process of deriving coefficients, identifying and describing behaviours, and characterizing all aspects of a remote sensing instrument to relate the response of the sensor to a known quantity of flux entering the system

Note 1 to entry: A system that has undergone this process can then infer the value of an unknown quantity of flux based on the response of the instrument.

Note 2 to entry: This entry is adapted from Reference [12].

3.27
remote sensing
collection and interpretation of information about an object without being in physical contact with the object

[SOURCE: ISO 19101-2:2018, 3.33]

3.28
repeatability
stability of the response of a remote sensing instrument over time

Note 1 to entry: Repeatability or stability of a measurement between adjacent samples or within a single integrated measurement interval is referred to as "short-term" repeatability. Short-term repeatability is quantified from measurement noise with a timescale of typically seconds to minutes.

Note 2 to entry: Repeatability or stability of response from a stable input between consecutive or succeeding integrated measurement intervals is referred to as "medium-term" repeatability. Medium-term repeatability is typically quantified via benchmark tests that are included as part of a measurement sequence. Medium-term repeatability sources may include on-board stimulator sources, vicarious ground sources and stellar references. The medium-term repeatability timescale is typically minutes to hours.

Note 3 to entry: Repeatability or stability between widely separated measurement intervals is referred to as "long-term" repeatability. Long-term repeatability is typically quantified via benchmark tests that periodically measure constant radiometric source(s) over the life of the sensor. Long-term repeatability sources may include on-board stimulator sources, vicarious ground sources and stellar references. The long-term repeatability timescale is typically hours to days, up to the lifetime of the sensor.

Note 4 to entry: This entry is adapted from Reference [12].

3.29
sensor
element of a measuring system that is directly affected by a phenomenon, body, or substance carrying a quantity to be measured

[SOURCE: ISO/IEC Guide 99:2007, 3.8, modified — The Example and Note 1 to entry have been removed.]

3.30
spectral irradiance
entity of flux that describes a point source or a source of a fixed size and distance such as the Sun when viewed from Earth

Note 1 to entry: When irradiance includes wavelength dependence it is called spectral irradiance. Generalized units of spectral radiance are Watts/ ($cm^2 \cdot \mu m$) or Photons/sec/($cm^2 \cdot \mu m$).

Note 2 to entry: This entry is adapted from [12].

3.31
stability
ability of a measuring instrument or measuring system to maintain its metrological characteristics constant with time

[SOURCE: ISO/TS 19159-4:2022, 3.38]

3.32
temporal stability
consistency of a linear trend

3.33
uncertainty
measurement uncertainty
parameter, associated with the result of measurement, that characterizes the dispersion of values that could reasonably be attributed to the measurand

Note 1 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.

[SOURCE: ISO 19116:2019, 3.28, modified — "measurement uncertainty" has been added as an admitted term; Note 1 to entry has been replaced with Note 2 to entry from ISO 19101-2: 2018, 3.40.]

3.34
validation
process of assessing, by independent means, the quality of the data products derived from the system outputs

Note 1 to entry: Reference [4] defines "validation" as the process of evaluating by independent means the accuracy of satellite-derived land products and quantifying their uncertainties by analytical comparison with reference data.

Note 2 to entry: Reference [12] defines "validation" as the process of confirming that the specifications and requirements set out in the design of an operation were sufficient to meet the objectives of the operation.

[SOURCE: ISO 19101-2:2018, 3.41, modified — Notes 1 and 2 to entry have been added.]

3.35
verification
provision of objective evidence that a given item fulfils specified requirements

[SOURCE: ISO/IEC Guide 99:2007, 2.44, modified — The EXAMPLEs and Notes to entry have been removed.]

3.36
vicarious calibration
post-launch calibration of sensors that make use of natural or artificial sites on the surface of the Earth

[SOURCE: ISO/TS 19159-1:2014, 4.41]

4 Symbols and abbreviated terms

AK	averaging kernel
BRDF	bidirectional reflectance distribution function
Cal/Val	calibration and validation
CEOS	Committee on Earth Observing Satellites
CEOS WGCV	Committee on Earth Observing Satellites Working Group on Calibration and Validation
DFS	degree of freedom for signal
EO	Earth observation
FOV	field of view
FRM	fiducial reference measurement
GUM	Guide to the Expression of Uncertainty Measurement
InSAR	interferometric SAR
IR	infrared
K	Kelvin
LED	light-emitting diode
LEO	low Earth orbit
Lidar	light detection and ranging

MI	mutual information
MIPAS	Michelson Interferometer for Passive Atmospheric Sounding
MW	microwave
MWIR	mid-wave infrared
NIR	near infrared (spectral region)
PDF	probability density function
PICS	pseudo-invariant calibration sites
PUM	product user manual
RAR	real aperture radar
RMS	root mean square
RMSD	root-mean-square deviation
RMSE	root-mean-square error
SAR	synthetic aperture radar
SNO	simultaneous nadir overpass
SNR	signal to noise ratio
SONAR	sound navigation and ranging
SWIR	shortwave infrared
TIR	thermal infrared
TVAC	thermal vacuum
UAV	unmanned aerial vehicle
UV	ultraviolet
VIM	Vocabulary of International Metrology
VIS	visible
WLS	white light source

Table 1 provides the parameters and definitions used throughout this document, notably in Annex C.

Table 1 — Parameters and their definitions

Parameter	Definition
$\vec{x}$	first observation vector; can be either point-like (1D), an area (2D), or a volume (3D)
$\vec{y}$	second observation vector
$\theta(t,r)$	continuous geophysical field in space and time (t : time, r : space)
θ^{α}	first field of a true, but unknown geophysical variable
θ^{β}	second field of a true, but unknown geophysical variable

Table 1 *(continued)*

Parameter	Definition
α, β	multi-indices summarizing information on temporal and spatial resolution/averaging
n	number of samples in both space and time
h	first nonlinear mapping function, also called measurement operator
k	second nonlinear mapping function, also called measurement operator
$\vec{u}_x$	vector of measurement errors in x
$\vec{u}_y$	vector of measurement errors in y
$\vec{e}_x$	vector of differences between the sampled observation and the true, but unknown, state of the geophysical field
$\vec{\delta}$	vector of differences between the two sample vectors
$\vec{d}_\theta$	vector of differences between the two fields of geophysical variables
f_δ	probability density function (PDF) of δ
M	error model M that allows the prediction of the PDF of δ
μ_δ	mean of δ
σ_δ^2	variance of δ
$\hat{\mu}_\delta$	empirical estimator (denoted by the circumflex) of the mean of δ
$\hat{\sigma}_\delta^2$	empirical estimator (denoted by the circumflex) of the variance of δ
$E[\delta]$	expectation operator
f_x	1-dimensional function of x
f_y	1-dimensional function of y
$f_{x,y}$	2-dimensional function of x and y
x	first observation data set
y	second observation data set
σ_{xy}	covariance between the data sets x and y
b	bias
$\hat{\mu}_x$	empirical estimator (denoted by the circumflex) of the mean of x
$\hat{\mu}_y$	empirical estimator (denoted by the circumflex) of the mean of y
L_i	is the radiance measure of pixel i. The summation covers all pixels on the Moon, N.
md	median
p_x^{50}	median of x
p_y^{50}	median of y
R	linear (Pearson) product-moment correlation coefficient
R^t	unknown truth
ρ	Spearman’s rank correlation coefficient (nonparametric, nonlinear)
$\hat{\sigma}_x^2$	empirical estimator (denoted by the circumflex) of the variance of x
$\hat{\sigma}_y^2$	empirical estimator (denoted by the circumflex) of the variance of y

Table 1 *(continued)*

Parameter	Definition
$\hat{\sigma}_{xy}$	empirical estimator (denoted by the circumflex) of the covariance between the data sets x and y
$\hat{\sigma}_{xz}$	empirical estimator (denoted by the circumflex) of the covariance between the data sets x and z
$\hat{\sigma}_{yz}$	empirical estimator (denoted by the circumflex) of the covariance between the data sets y and z
$\hat{\sigma}^2_{r_x}$	empirical estimator (denoted by the circumflex) of the variance of r_x
$\hat{\sigma}^2_{r_y}$	empirical estimator (denoted by the circumflex) of the variance of r_y
$\hat{\sigma}_{r_{xy}}$	empirical estimator (denoted by the hat symbol) of the covariance of r_{xy}
τ	Kendall's Tau (nonparametric, nonlinear)
n_c	number of data pairs with concordant ranks
n_d	number of pairs with discordant ranks
n_0	number of all possible data pairs
$I,(MI)$	mutual information
t	time
c	constant value
β	temporal stability, slope of a linear trend
S_t	seasonal signal with predefined periodicity
U_t	shift in the mean of the time series at time t
N_t	data noise represented by a stationary autoregressive process of order 1
Ω_{pix}	solid angle subtended by one pixel
Σ	additional variance

5 Calibration of remote sensing data

5.1 Introduction

Remote sensing is the science and technology for acquiring information about an object or phenomenon without making physical contact with it. The object or phenomenon can be terrestrial or extra-terrestrial. This document only deals with terrestrial remote sensing.

The acquisition of information is conducted by sensors which collect data. The acquired data are further processed into information by algorithms or models. The sensors sensed an object or phenomenon through recording the energy of electromagnetic or mechanical waves either reflected or emitted by the object or phenomenon. Each type of sensors works on a specific range of wavelengths based on specific physical principles. For example, passive optical sensors work on solar visible and infrared wavelengths reflected by objects or phenomenon.

Remote sensors are usually mounted on a platform. The common platforms include satellites, aircrafts, unmanned aerial vehicles (UAVs), ground vehicles, ships, etc. The information derived from the remotely sensed data describes properties of the object or phenomenon, such as land surface temperature, ocean salinity, and crop yield. Such information is widely used in applications and decision making in almost all Earth science disciplines and socioeconomical activities.

In order for the information to be useful in the applications and decision making, the information has to be validated against the truths and errors in the information shall be measured either quantitively or qualitatively. To do so, the quality of remote sensing data shall be known so that the data users can determine if the data can be used as the inputs to derive information for their applications. Due to sensor internal and environmental noises, remotely sensed data always contain errors. Many of the errors can be corrected and the remaining errors in data can be quantified. Such a process is called the calibration and validation (Cal/Val) of remotely sensed data.

5.2 Relationship between the data calibration and sensor calibration

Errors in remotely sensed data come from two sources, the sensor and the sensing environment. Therefore, to calibrate the remotely sensed data, errors from the sensor and the sensing environment shall be quantified. Before a sensor is commissioned, the errors from the sensor can be quantified in a laboratory environment. Such an effort is called pre-launch calibration. The ISO 19159 series addresses the prelaunch calibration and validation of remote sensors.

After the sensor is launched, the sensor can potentially degrade due to sensor aging or exposure to the operational environment. Therefore, the sensor's performance needs to be monitored and sensor calibration parameters obtained in the pre-launch calibration need to be modified continuously after the sensor is launched. These activities constitute the post-launch sensor calibration and validation. The post-launch sensor Cal/Val is covered by ISO 19124 series.

Another portion of errors in the remote sensing data comes from the sensing environment. For example, data acquired by a satellite sensor for measuring the land surface radiance are contaminated by the atmospheric radiance. Therefore, errors from the sensing environment are often time- and location-dependant and can only be quantified after the remote-sensing data are acquired. In summary, the Cal/Val of remote-sensing data needs the support of post-launch Cal/Val of sensors, and post-launch sensor Cal/Val modifies the results of pre-launch sensor Cal/Val.

5.3 General framework

This subclause discusses the overall UML model of this document.

Figure 1 shows the top-level UML model of this document. CA_CalibrationValidation shall be a specified class of MD_ContentInfo. CA_CalibrationValidation is aggregated from the CA_Methods class, which describes the Cal/Val methods common to different types of sensors and data, and CA_RefSources class, which describes reference sources commonly used for Cal/Val of data acquired by multiple types of sensors. The details of CA_Methods and its subclasses are shown in Figure 2 and described in Clause 9. The details of CA_RefSources and its subclasses are shown in Figure 3 and described in Clause 8. Details of sensor-type-specific methods and reference sources are defined in the corresponding part of the ISO 19124 series.

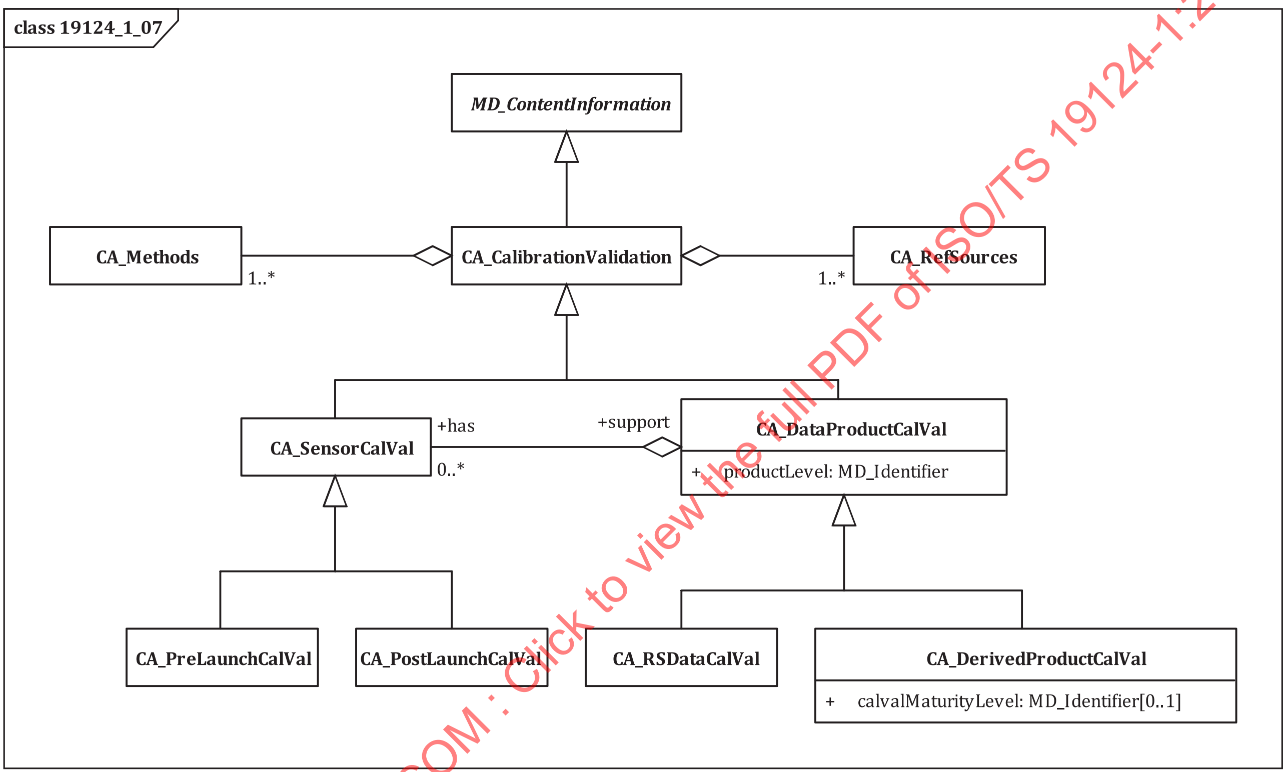
CA_CalibrationValidation has two specialized subclasses: CA_SensorCalVal, which describes the Cal/Val of sensor, and CA_DataProductCalVal, which describes the Cal/Val of remotely sensed data and derived products and is supported by CA_SensorCalVal. CA_SensorCalVal has two specialized subclasses, CA_PreLaunchCalVal and CA_PostLaunchCalVal. A brief description of CA_PreLaunchCalVal is presented in Clause 6 and details and subclasses of CA_PreLaunchCalVal are defined in the ISO 19159 series.

CA_PostLaunchCalVal shall define the post launch Cal/Val of specific type of sensors. The details and subclasses of CA_PostLaunchCalVal are shown in Figure 4 and described in Clause 7. Figure 4 only shows the subclasses at the sensor type level. Further details are provided in the sensor-type-specific parts of the ISO 19124 series.

The CA_DataProductCalVal class has two specialized classes, CA_RSDataCalVal and CA_DerivedProductCalVal. CA_RSDataCalVal defines the Cal/Val of remotely sensed data, whose attribute values are still in a sensor unit (e.g. digital number or radiance). The subclasses of CA_RSDataCalVal are shown in Figure 5 and details on each subclass are defined in the corresponding part of the ISO 19124 series. Active Microwaves (SAR, synthetic aperture radar) will be covered by the ISO/TS 19124-2:—.[1)]

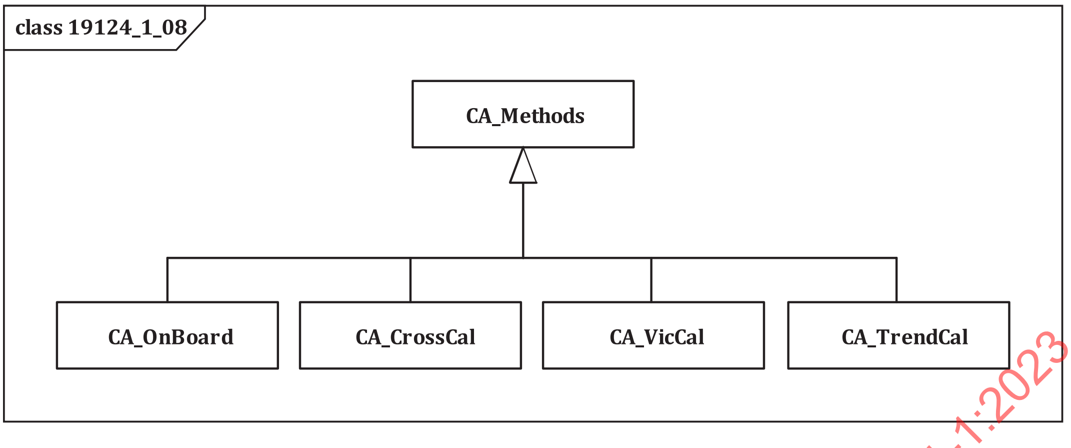
1) Under preparation. Stage at the time of publication: ISO/TS AWI 19124-2:2023.

The CA_DerivedProductCalVal class defines the validation of thematic products derived at least in part from remotely sensed data via algorithms or models. As shown in Figure 6, it is aggregated from CA_ValidationPlan and CA_ValidationProcess and contains an optional property, calvalMaturityLevel, whose type is MD_Identifier to describe the maturity level of product Cal/Val. The CA_DerivedProductCalVal class has two specialized subclasses, CA_NumericalProduct and CA_CategoricalProduct. CA_NumericalProduct class deals with the validation of thematic products whose attribute values are continuous physically, such as land surface temperature, wind speed and volumetric soil moisture content. CA_CategoricalProduct class deals with the validation of thematic products whose attribute values are categorical physically, such as land use type, soil type and crop type. Clause 10 provides a general description of product validation concepts and the classes in Figure 6. The classes in Figure 6 shall be further specialized for specific types of thematic products in the corresponding parts of the ISO 19124 series.



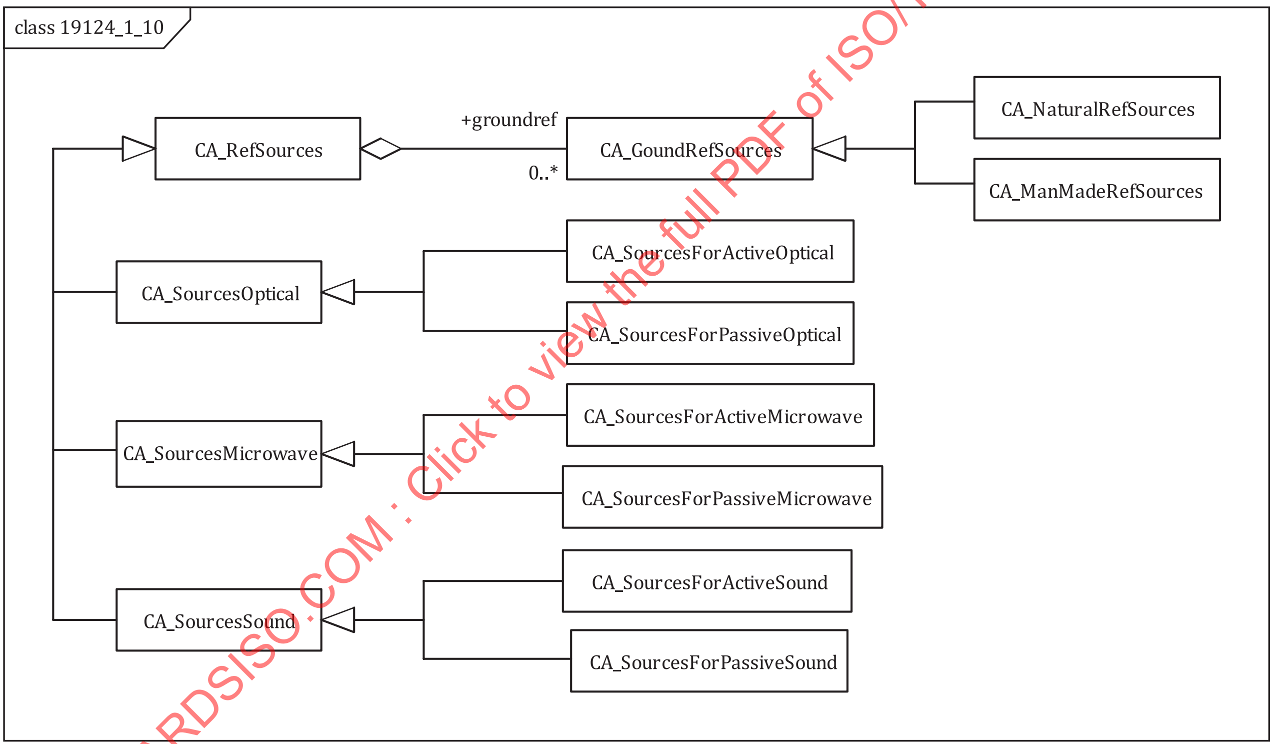
NOTE Model CA_CalibrationValidation is a specialization of the class MD_ContentInformation which is defined in ISO 19115-1. See also Table B.2.

Figure 1 — Model CA_CalibrationValidation



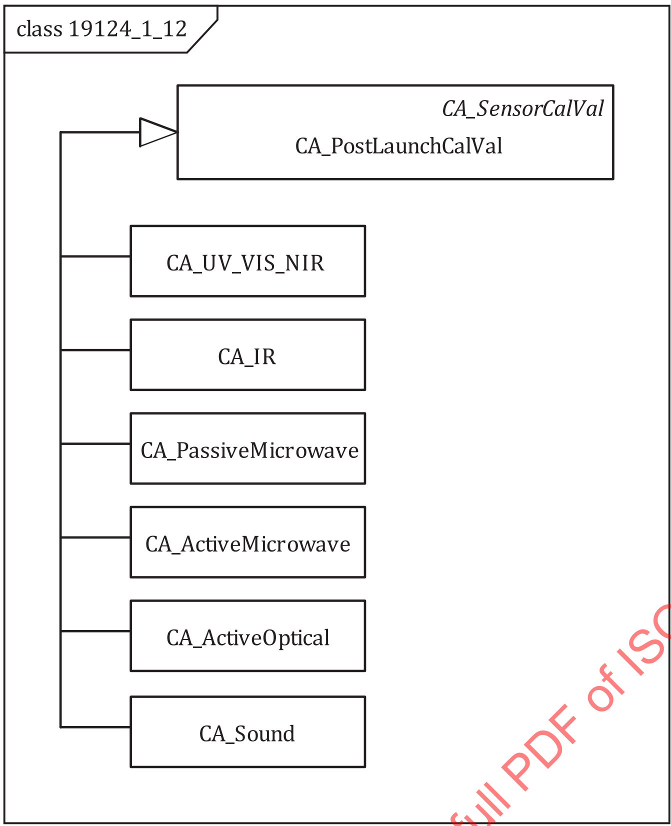
NOTE See also Table B.2.

Figure 2 — Model CA_Methods



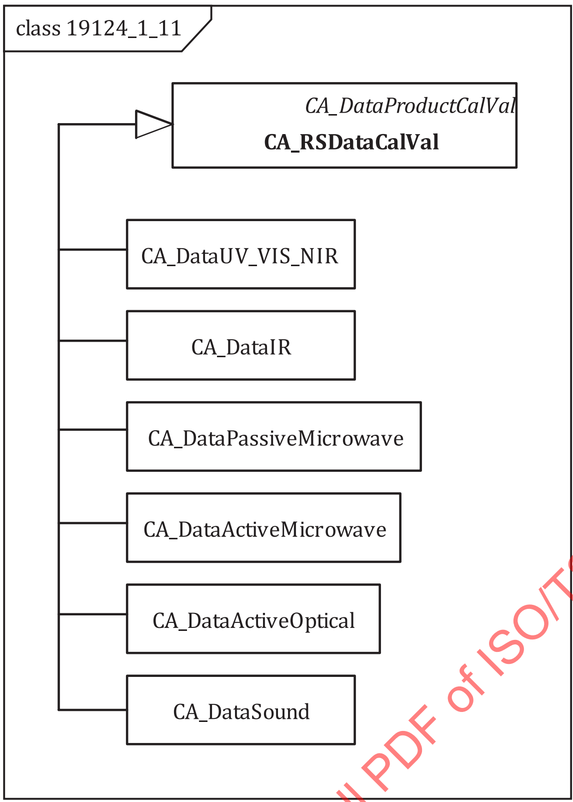
NOTE See also Table B.2.

Figure 3 — Model CA_RefSources



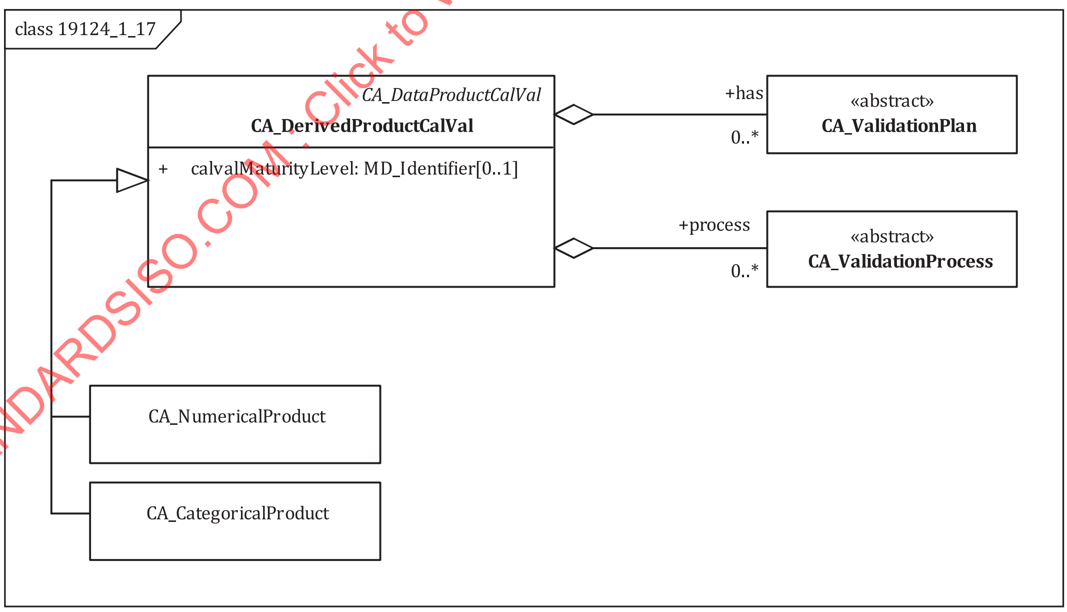
NOTE See also Table B.2.

Figure 4 — Model CA_PostLaunchCalVal



NOTE See also Table B.2.

Figure 5 — Model CA_RSDataCalVal



NOTE See also Table B.2.

Figure 6 — Model CA_DerivedProductCalVal

The Abstract test suite can be found in Annex A.

6 Pre-launch calibration

6.1 Introduction

Pre-launch calibration, or ground calibration, provides the capability to perform tests in a controlled environment with known sources that cannot be duplicated on-orbit, and has the advantage of discovering and resolving anomalies prior to launch. These measurements include component-level or bench-top subsystem tests, as well as system-level tests.

Measurements made during pre-launch calibration are used to verify proper instrument operation, to quantify calibration equation and radiometric model parameters, and to estimate measurement uncertainties. Pre-launch calibration is essential for understanding sensor performance nuances so that they can be addressed and understood before launch. Options to correct sensor performance on orbit are limited and expensive.[12] The pre-launch calibration of sensors is covered by the ISO 19159 series.

6.2 Use of pre-launch calibration results in data calibration

In general, the results of pre-launch sensor calibration need to be evaluated, revised and validated through the post-launch sensor calibration before the results can be applied to calibrate the remote sensing data. In the event of lacking post-launch calibration, the results of pre-launch sensor calibration may be applied to calibrate the remote sensing data.

7 Post-launch calibration

7.1 Goals

The goals of post-launch calibration are to verify and validate the calibration parameters determined pre-launch, characterize or update parameters that are more successfully characterized from on-board measurements, quantify on-board calibration uncertainty, and trend sensor performance and update calibration coefficients, if necessary.[12]

Phases of post-launch calibration include:

— early on-orbit calibration operations;

— intensive calibration and validation (Cal/Val); and

— sensor performance trending during planned operations.

Reasons for post-launch calibration include:

a) outgassing;

b) space environment;

c) variation in filter transmittance and spectral response;

d) slow deterioration of the electronic or optical system;

e) mechanical malfunction following the intense rigors of launch.

7.2 General demands

The calibration frequencies are determined to ensure the mission performance.

Operational constraints are as follows: the low Earth orbit (LEO) mission calibrations involving on-board calibration sources are mainly performed over the poles. The mechanism movement duration, the number of acquisitions and acquisition time are optimized to ensure the required calibration performance while minimizing the calibration time.

The lifetime of the calibration equipment is limited by the following elements:

a) alteration of sources performances, e.g. ageing of solar diffusers due to sun exposition which limits the number of sun exposures, or source ageing which limits the number of operation hours due to intensity decrease;

b) lifetime of support functions, e.g. mechanism ageing because the qualification is performed for a defined number of cycles, or electronics ageing due to radiation and numbers of ON/OFF.[15]

7.3 On-board calibration against known sources

On-board calibration against known sources provide the capability of periodically stimulating the sensor response with known and/or repeatable flux levels.

Operational considerations, requirements and design trade-offs for these sensors include:

a) volume, mass and power;

b) long-term source output repeatability;

c) magnitude, dynamic range and stability;

d) temporal properties (such as time required for source to be considered stable and repeatable);

e) radiation sensitivity to the on-orbit environment;

f) spectral content;

g) sensor response uniformity and repeatability over the sensor field of view (FOV);

h) absolute traceability to standards;

i) ability to exercise elements of system that have been identified to have potential degradation properties due to long term changes in optical transmissive properties and/or contamination;

j) the extent of making internal calibration source measurements simulate on-orbit measurement, e.g. overfill sensor entrance pupil, the number of optical elements illuminated by internal calibration source, and component angular considerations.

7.4 Early operations

Early post-launch calibration operations begin once the instrument reaches orbit, completes its initial bake out and checkouts, and is deemed functional. These activities include:

a) sensor optimization;

b) in-flight calibration source calibration;

c) amplifier gain check and adjustment;

d) bit trim and impulse mask checks;

e) noise equivalent radiance difference check;

f) initial on-orbit trending;

g) anomaly investigation.

7.5 Intensive calibration and validation

The main goal of the intensive Cal/Val portion is to verify that the sensor is ready for operations. Testing during this phase includes deriving/verifying parameters that were not measured during ground testing or updating those parameters that can be determined during both pre- and post-launch.

The activities during the intensive Cal/Val period include:

a) investigating anomalies, such as changes in the responsivity or noise;

b) checking the spectral calibration using atmospheric lines or celestial emission line sources;

c) checking and adjusting the linearity of the detectors;

d) performing pointing calibration;

e) assessing and fine tuning the in-flight calibration source radiance model;

f) characterizing responsivity and sensitivity;

g) analysing for spikes and ice contamination;

h) characterizing correlated/uncorrelated noise;

i) tuning and analysing residual uncertainty;

j) performing cross comparisons with other sensors;

k) establishing on orbit trending baseline;

l) updating and finalizing calibration monitoring plans for mission operations.

8 Calibration reference sources

8.1 Introduction

In order to quantitively measure the sensor performance, calibrations are performed by evaluating the sensor measurements against sources that have been measured with higher accuracy or known quantities. Different types of sensors may use different types of sources for calibration.

8.2 Active optical instruments

This subclause contains calibration sources about active optical instruments, mainly lidar (light detection and ranging).

In recent decades, multiple space-borne lidar systems have been deployed by space agencies such as NASA and ESA. The lidar systems are used to measure the land surface properties such as elevation and height change of glaciers (e.g. the NASA's ICESat missions), the land surface biomass (e.g. NASA's GEDI mission), the cloud and aerosol properties (e.g. the joint NASA-CNES CALIPSO mission), and wind profile measurements (e.g. ESA's ADM-Aeolus mission). The calibration and validation sources of those space-borne systems are typically the airborne lidar systems of same or similar sensors or ground plots of known properties. The metadata about the calibration reference sources of space-borne lidar systems will be detailed in a subsequent part of ISO 19124 series.

The calibration of an airborne lidar-system is a complex task. It involves the calibration of the laser-scanner, and it also involves the calibration of the navigation system with its GNSS-component for measuring the position and its INS-component for measuring the attitude, as well as the relationship between both systems, laser and navigation. The spatial relationship between the navigation sensors and the laser scanner is called the boresight, and must be known with high accuracy.

8.3 Passive optical instruments, visible and NIR, SWIR, MWIR, TIR, and FIR spectrum

8.3.1 Introduction

This subclause contains information about post-launch calibration sources for passive optical instruments, which work in the spectrum from visible (VIS), near infrared (NIR), short wavelength infrared (SWIR), mid wavelength infrared (MWIR), long wavelength infrared or thermal infrared (LWIR or TIR), and far infrared (FIR). The passive optical instruments don't emit electric magnetic radiation to illuminate the objects but measure the radiation either reflected or emitted by the objects.

8.3.2 On-orbit calibration sources

Table 2 gives a short overview over common on-orbit calibration sources.

Table 2 — Common on-orbit calibration sources[12]

Name	Subclause
Solar diffusers	8.3.3
White light sources	8.3.4
LEDs	8.3.5
Tuneable laser	8.3.6
Black bodies	8.3.7
Celestial objects	8.3.8

8.3.3 Solar diffusers

8.3.3.1 Introduction

Solar diffusers are used in the on-orbit radiometric calibration of UV/VIS/NIR/SWIR remote sensing instruments. Solar diffusers have the advantage that the colour-temperature difference between the source illuminating the on-board diffuser and the source illuminating the Earth scene are eliminated since in both cases the source is the Sun.

Several conditions have to be met in order to successfully use a solar diffuser.[12]

a) Solar diffusers have the disadvantage of requiring an extensive pre-launch characterization of the bidirectional reflectance distribution function (BRDF) as a function of illumination angle for each of the sensor spectral bands.

b) The measurements of solar diffusers alone are insufficient for providing sensor calibration over the lifetime of the mission since the diffuser reflectance continually changes on orbit, including possibly its angular dependence. The challenge in using solar diffusers is to accurately track this reflectance degradation over the full mission lifetime.

c) Changes in the diffuser reflectance properties need to be separated from changes in the performance of other instrument components:

   1) solar diffuser stability monitors;

   2) multiple diffusers with varying Sun exposure times.

8.3.3.2 Solar diffuser stability monitors

One solar diffuser stability monitor uses an on-board Hg lamp to measure the reflectance of the diffuser by comparing the measured intensity of the lamp output with the intensity of the lamp output reflected from the diffuser. The ratio of these two measurements gives the diffuser reflectance. Since the diffuser is monitored with a Hg lamp, it is necessary to transform the changes in reflectivity measured at the wavelengths of the lamp emission lines into estimates of changes in reflectivity at the operating wavelengths of the sensor.[9]

One factor which complicates the use of a lamp to monitor drift in the diffuser reflectance is that changes in the spatial distribution of the lamp footprint on the diffuser over time will lead to an apparent change in reflectivity of the diffuser.

Alternatively, the Sun can be used as the source for monitoring the change in reflectance of the diffuser.

8.3.3.3 Multiple diffusers with varying Sun exposure times

With two diffusers, regular frequent measurements are made with one diffuser (termed the working diffuser) while less frequent measurements are made with a second diffuser (termed the reference diffuser), perhaps only once or twice a year. The hope is that the reference diffuser which experiences significantly reduced solar exposure will see little change between uses, thus providing a monitor of the degradation trend in the working diffuser.[9]

Given the complexity of diffuser changes and the angle dependence of the BRDF, it is advisable to have repeatable solar viewing angles from year to year. To achieve such repeatability requires stable orbits.

8.3.4 White light sources

The white light source (WLS) calibration assemblies are a complementary method to ensure radiometric calibration. The WLS provides a smooth broadband spectrum which is dispersed by the spectrometer. The WLS is composed of a broadband spectrum lamp and, in some cases, an integrating sphere. The integrating sphere output port provides a uniform illumination (angular and spatial).[15]

8.3.5 Light-emitting diodes (LEDs)

On atmospheric missions, LEDs, which are installed on the satellite-platform for other (“common”) purposes, are often used for calibration purposes, too. They are designated as “common” compared to the spectrally tuneable laser diodes.[15]

8.3.6 Tuneable laser diodes

Tuneable laser diodes also designated as spectral light sources are used for the monitoring of the instrument spectral response function stability, in SWIR, NIR and SWIR bands. The laser wavelength can be scanned on a small spectral range, allowing the instrument spectral response function retrieval on specific pixels.[15]

8.3.7 Black bodies

A black body is used for the calibration of the thermal bands. It is designed to be non-reflective (black) and kept at a precise temperature. If the instrument receives photons from the black body, their temperature can be determined.[14]

8.3.8 Celestial objects

8.3.8.1 Moon

The Moon is accessible as a calibration target to all satellites, regardless of orbit. It is a spatially extended source that can utilize the full optical train of an Earth-viewing instrument. Its brightness is similar to that of clear land at solar reflectance wavelengths, 350 nm to 2450 nm. The primary challenges to using the Moon are its non-uniform distribution of albedo, and the variation in its brightness due to illumination and view geometry (primarily the lunar phase) and a surface reflectance function. However, the Moon’s diffuse reflectance is considered to be radiometrically stable to better than one part in 108 per year.[9]

Observing techniques for acquiring lunar calibration measurements vary depending on how the Moon is to be used, the sensor type and the spacecraft orbit. To use the lunar spectral irradiance, the entire disk of the Moon needs to be captured in some manner, with quantitative accounting for any oversampling.

An instrument that normally observes the Earth in nadir view from low Earth orbit requires viewing the Moon either through an alternative optical path or by executing a spacecraft attitude manoeuvre.

Extending lunar calibration to infrared wavelengths requires characterizing the Moon's thermal behaviour with sufficient detail for modelling.

Using the Moon as a spatially resolved target, i.e. as a radiance source, adds complexity to the lunar calibration task. Images of the Moon taken by an instrument need to be spatially co-registered with the radiance model reference. This typically involves spatial scaling, and possibly also corrections for distortions, typically employing a camera model for the imager.

Realization of a lunar calibration consists of comparing radiometric measurements of the Moon derived from instrument observations against the corresponding reference quantity provided by a lunar model. Irradiance measurements from images involve summing pixels on the lunar disk after correcting for detector artefacts and converting the pixels to radiance, as shown in Formula (1):

$$E = \Omega_{\text{pix}} \sum_{i}^{N} L_i \tag{1}$$

where

Ω_{pix} is the solid angle subtended by one pixel;

L_i is the radiance measure of pixel i, the summation covers all pixels on the Moon, N.

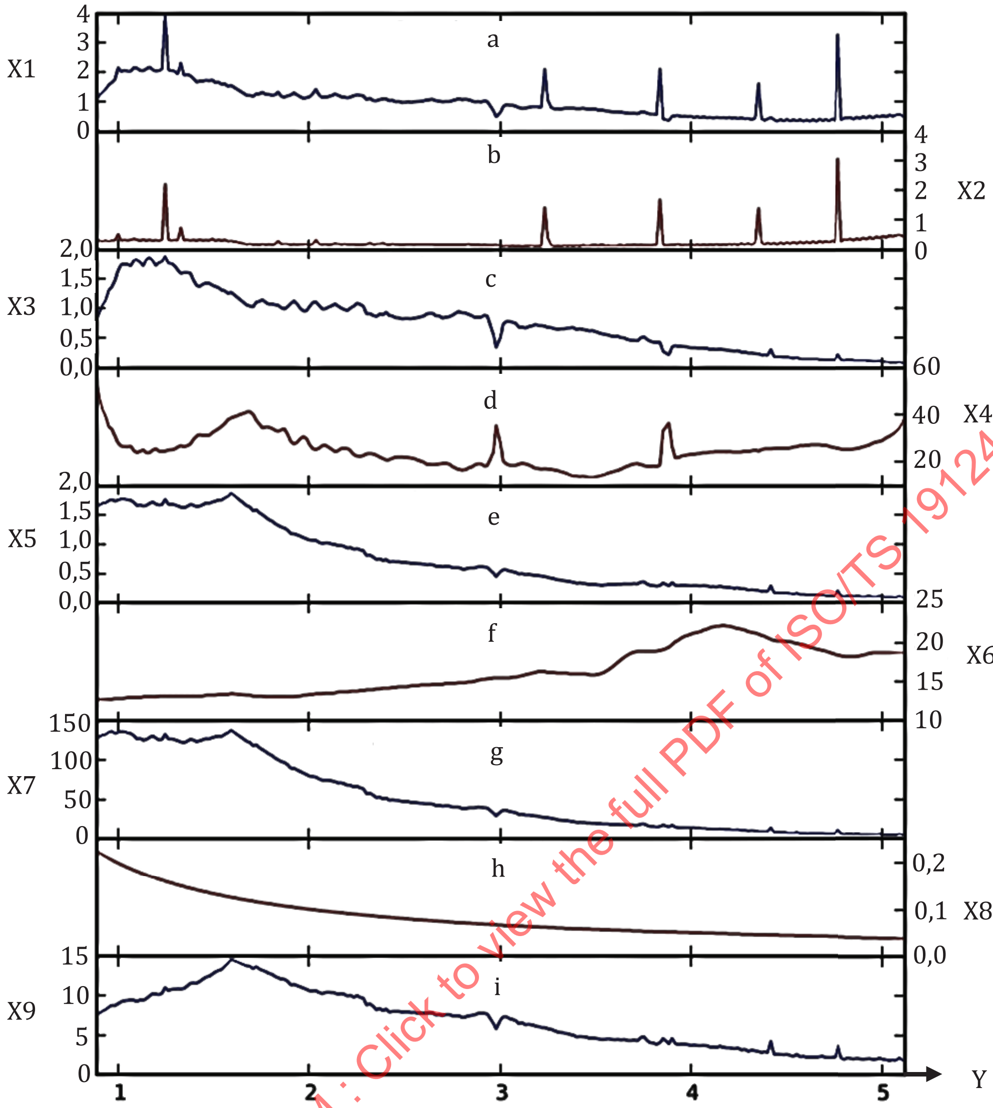
8.3.8.2 Stars

Stars provide true point sources. At the time of publication of this document, the visible and NIR calibration intensity are measured with a relative standard deviation of approximately 1 % or less, and the IR calibration (~ 2 µm out to 14 µm) is good to 5 % or slightly better. The relative spectral uncertainty is believed to be < 1 % in the visible and ~ 1 % in the infrared.

Typically, an IR sensor such as the Michelson Interferometer for Passive Atmospheric Sounding (MIPAS) on board the ENVISAT, will be tasked to view the brighter IR stars to maximize SNR for the observation and to minimize the length of time required to perform the calibration (see Table 3 and Figures 7 and 8).

Table 3 — IR irradiance of selected stars[12]

Star		Irradiance (W/cm^2)*10^{-14}		
		K Band (2.0 µm – 2.4 µm)	L Band (3.0 µm – 4.0 µm)	M Band (4.6 µm – 5.0 µm)
α Boo	Arcturus	27.4	13.2	1.25
α CMa	Sirius	5.96	2.66	0.296
α Lyr	Vega	1.64	0.744	0.0837
α Tau	Aldebaran	24.0	11.7	1.05
β Gem	Pollux	3.01	2.18	0.221

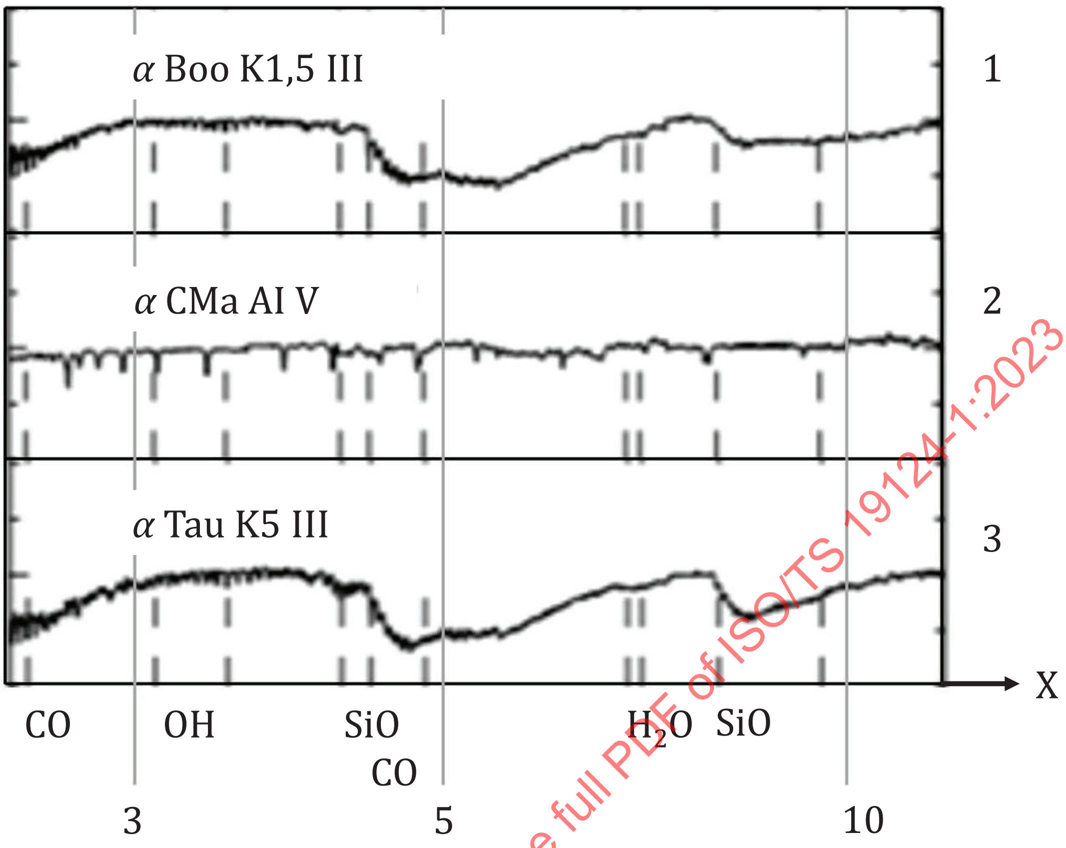


Key

a	raw detector counts	X1	(×10³ dn)	f	bandpass function	X6	(×10⁻³ µm)
b	measured background	X2	(×10³ dn)	g	apply bandpass function	X7	$(\times 10^{12}\ \frac{\text{photons}}{\text{m}^2\ \text{s¼m}})$
c	background subtracted	X3	(×10³ dn)	h	photon energy	X8	$(\times 10^{-18}\ \frac{\text{J}}{\text{photons}})$
d	sensitivity function	X4	$(\times 10^{3}\ \frac{\text{photons}}{\text{dn}})$	i	final spectrum in janskys	X9	(×10³ Jy)
e	apply sensitivity function	X5	$(\times 10^{9}\ \frac{\text{photons}}{\text{m}^2\text{s}})$	Y	wavelength (µm)		

NOTE Data reduction process illustrated for a single 320 ms exposure of α Boo (α Boötis, the star Arcturus). Curves a, c, e, g and i show the data progressing through the reduction process, while curves b, d, f and h show the requisite calibration curves.

Figure 7 — Data reduction process



Key

X wavelength (µm)

1 arcturus

2 sirius

3 aldebaran

Figure 8 — Spectra of three selected stars normalized to the continuum fit to the Engelke function[16]

8.3.8.3 Other celestial objects

In addition to the more obvious celestial sources, asteroids and planets can also be used as calibration sources. Asteroids are bright, near room temperature targets that can be used as point sources for all but the highest spatial resolution sensors. Mars can also be a point target or “fat spot” target, depending upon its distance from the sensor and the spatial resolution of the sensor, and has a temperature around 245 K.[12]

8.4 Active microwave instruments

8.4.1 Introduction

Several instruments fall into the category of active microwave instruments, e.g. RAR (real aperture radar) and SAR (synthetic aperture radar). Among these, SAR-technology is most widely used.

8.4.2 SAR missions

8.4.2.1 In-flight calibration

8.4.2.1.1 Calibration frequency

The two methods of on-board instrument calibration allow different calibration frequencies to be addressed.

The internal calibration allows the collection of data for each data take as part of the nominal acquisition timeline. It allows the capture of variations of the PG (product of transmit power and receive gain) along the image acquisition. It is possible to increase the frequency of PG measurements by changing the timeline of the acquisition's modes.

The radio frequency characterization mode allows more detailed measurements to be performed and for the instrument health to be evaluated. More specifically it makes it possible to monitor the status of the transmit and receive module and the excitation coefficient that are required as input of the antenna model that is used to derive a first evaluation of the antenna pattern in both elevation and azimuth.

8.4.2.1.2 Calibration modes

Within the context of the frequency of calibration actions, the calibration timeline shall:

a) maintain a minimum survey of the instrument performance for operational mode;

b) cover the ageing of the instrument.

External calibration allows the measurement of the whole impulse response of the instrument, including the antenna contribution. External calibration is based on the a priori knowledge of a reflecting target, which can be implemented by a dual frequency transponder.

The external calibration also allows the calibration of the following parameters of the instrument:

— absolute range measurements (primary objective);

— antenna gain pattern check (along track);

— geolocation and dating accuracy system check.

NOTE See Reference [15].

8.5 Passive microwave instruments

This subclause contains information about passive microwave instruments, e.g. microwave radiometers. Microwave radiometers are very sensitive instruments that measure the power of the thermal noise emitted by bodies at a physical temperature above 0 K. Microwave radiometers are utilized in a variety of applications, including remote sensing, weather forecasting, climate monitoring, radio astronomy and radio propagation studies.

8.6 Instruments with a sensitivity in other regions of the electro-magnetic spectrum

This subclause contains information about instruments that are sensitive in other regions of the electro-magnetic spectrum apart from optical (VIS, NIR, thermal IR) and microwave. Those ranges include gamma-rays, X-rays, and ultraviolet with shorter waves than the visible light, and radio-waves with longer waves than the visible light.

8.7 Sound

This subclause contains information about instruments that perform their measurements based on sound. This technology is mainly applied for the measurement of the depth of water-bodies and is called SONAR (sound navigation and ranging).

8.8 Calibration and validation sites

8.8.1 Introduction

Calibration and validation sites provide the ground truth and are thus necessary as an absolute reference. The test sites are classified in the following way:

1) Depending on the location and purpose, the test sites are divided into:

— land sites, for assessing the coordinate-measuring indicators of the quality of remote sensing data;

— land sites, to assess the spatial-frequency indicators of the quality of remote sensing data;

— land sites, for assessing radiometric indicators of the quality of remote sensing data;

— marine sites, for assessing radiometric indicators of the quality of remote sensing data.

2) Depending on the origin, the test sites are divided into:

— sites of artificial (technogenic) origin;

— sites of natural origin.

8.8.2 Pseudo invariant calibration/validation sites (PICS)

Pseudo invariant calibration sites (PICS) are sites on the Earth’s surface that do not change radiometrically as a function of time. While in theory this is impossible, in practice it has been found to be a good approximation with an uncertainty in the range of 1 % to 3 % (k = 1), which is significant given that the atmosphere is included in the overall PICS concept.[12]

Common PICS include dry lakebeds, salt flats and desert sand sites in arid regions that have low probability of cloud cover, are spatially homogeneous, and have relatively constant surface spectral reflectance and bi-directional reflectance distribution function (BRDF) over long periods of time. In the case of microwave-calibration, a typical PICS is the “Amazon rain forest”.

8.8.3 Calibration and validation sites

The calibration and validation sites are subdivided into natural and artificial sites (Figure 3). Details will be defined in the following parts of the ISO 19124 series.

A validation site serves as a reference on the surface of the Earth for the calibration of the on-board sensors and for the validation of the resulting data product. A validation site shall fulfil a number of criteria which are listed in Table 4.

Table 4 — Validation site requirements[11]

Count	Requirement
1	be accessible to researchers
2	encompass existing facilities such as flux towers, which collect measurements of biophysical variables over extended periods of time
3	have a long history and long-term commitment to scientific studies
4	represent significant areas of homogenous or uniformly mixed land cover

Table 4 *(continued)*

Count	Requirement
5	be representative of extensive biomes globally
6	be complementary to existing validation sites

9 Calibration methods

9.1 Introduction

This subclause addresses calibration methods including cross-calibration, calibration sites and the detection of trends.

9.2 On-orbit cross-calibration

On-orbit instruments must be cross-calibrated to assess the consistency of observations across satellites.[9]

The simultaneous nadir overpass (SNO) method is based on the fact that any pair of polar-orbiting satellites with different altitudes can regularly observe the Earth at orbital intersections at nearly the same time, and that these events are predictable.

One weakness of the SNO method is the fact that it relies on the assumption that a stable reference satellite can be used in the cross-calibration. Other methods, such as the vicarious method, can determine absolute values more accurately. Therefore, the SNO method should be used in conjunction with other methods for cross-calibrating on-orbit instruments.

9.3 Vicarious calibration

Vicarious calibration is a generic term indicating a calibration performed in a manner not directly connected to the satellite system under consideration.[12]

However, over the years, the term "vicarious calibration" has come to be closely associated with a particular calibration methodology that involves viewing the Earth and deploying a team to make ground level measurements of the test site at the time of satellite overpass.

Vicarious calibration typically denotes making measurements of the Earth's surface to obtain estimates of the surface reflectance at a particular location. Simultaneous measurements are made of the atmosphere so that the propagation of the electromagnetic radiation through the atmosphere is adequately understood. These two sets of measurements allow characterization of both the Earth's surface reflectance and the atmosphere so that, in combination with a model for solar radiation, a prediction can be made of the radiance present at the top of the atmosphere and at the aperture of an orbiting satellite. The last element needed in this modelling effort is a radiative transfer code that uses the surface reflectance and atmospheric measurements as inputs and predicts top of atmosphere radiance. Calibration then occurs by comparing the measurement made by the satellite to the prediction based on the surface measurements and calculating a correction factor that is essentially just a ratio of the predicted and measured value.

Preferred locations are those where the surface and the atmosphere are stable and relatively easy to characterize. Bright surfaces are often preferred simply because of the higher SNR that they offer, which leads to better precision in the calibration estimates. Measurements over dark surfaces are nevertheless needed to cover the full range of related influence quantities, e.g. low surface albedo or low surface emissivity.

Spatial homogeneity is preferred because it makes characterization of the surface reflectance easier to accomplish.

9.4 Sensor performance trending

Sensor performance trending tracks long-term changes in sensor behaviour due to component aging and/or sensor contamination, and provides a means for their correction, if necessary. This allows sensor calibration to be maintained throughout the mission life.

Sensor performance trending involves making repeated measurements of stable source(s) and deriving long-term sensor-response changes. Potential on-orbit sources include on-board sources and celestial objects.

In view of thermal sensor performance trending, deep space acts as a good source.

Information obtained from:

a) vicarious calibration,

b) pseudo-invariant calibration sites (PICS),

c) on-orbit cross-calibration,

can also be used for sensor performance trending.

Other means to monitor sensor performance are:

— dark target measurements;

— comparison of sensor models and performance trending data to identify changes in specific components.

Long-term performance changes can occur in the sensor spectral, spatial, radiometric and/or polarimetric responsivity, and these changes can be interrelated.

10 Validation of derived products

10.1 Validation process

10.1.1 General

Figure 9 provides an overview over the validation process. The schema assumes two data sets, shows their co-location and storage, and ends with the analysis and the interpretation.

10.1.2 Data

The input data are x and y, e.g., satellite data and reference data. In theory, the validation process would be traceable to SI reference standards. In practice this is rarely the case. The choice of reference data, in particular, is often a pragmatic decision. The following questions have typically to be taken into consideration:

1) Do the data provide scientifically meaningful estimates of the investigated geophysical quantity?

2) Do the data sufficiently cover the potential parameter space?

3) Are the data expected to be accurate enough to be able to draw desired conclusions from the validation process?

4) Are the data publicly available and accessible?[6]

10.1.3 Quality check / Homogenization

Every dataset that shall be validated is required to undergo a quality assessment. Many data providers include information on data quality within their datasets.[6]

In many cases, further homogenization between the two datasets is necessary before actual differences can be computed, for instance, regarding units and georeference.

10.1.4 Spatio-temporal co-location

When performing a spatio-temporal co-location, the following conditions should be obeyed, though 1) and 3) are often at odds and cannot be fulfilled at the same time.

1) Co-located measurements should be close to each other relative to the spatio-temporal scale on which the variability of the geophysical field becomes comparable to the measurement uncertainties, especially when intermittent and highly variable parameters are considered.

2) If possible, differences in spatiotemporal resolution (horizontal, vertical, and temporal) should be minimized.

3) The co-location criteria should take into account the need for sufficient co-located pairs for robust statistical analysis.

Whichever co-location approach is chosen, a remaining mismatch is almost inevitable. The resulting differences are required to be taken into account by an additional variance, Σ.[6]

10.1.5 Metric calculation

The applied metric depends on the application and on the available data. Annex C provides a listing of typical metrics.

10.1.6 Analysis and interpretation

Once the final metrics have been obtained, it needs to be judged if the results are compliant with the requirements.

In its most fundamental form, the consistency check between the differences between two measurements and the reported measurement uncertainties can be written as shown in Formula (2):

$$|x-y| < k\sqrt{u_x^2 + u_y^2 + \Sigma^2} \quad (2)$$

where

x and y	are the reference and EO measurements;
u_x and u_y	are their respective uncertainties;
k	is the coverage factor;
Σ	is the additional variance of the differences due to co-location mismatch.

The coverage factor allows the combined uncertainties to be scaled to a particular confidence level. Where $k = 1$, the combined uncertainty is consistent with 1 standard deviation. The value $k = 2$ is frequently used to give a confidence level of 95 %, assuming a normal distribution of the combined uncertainty.[6]

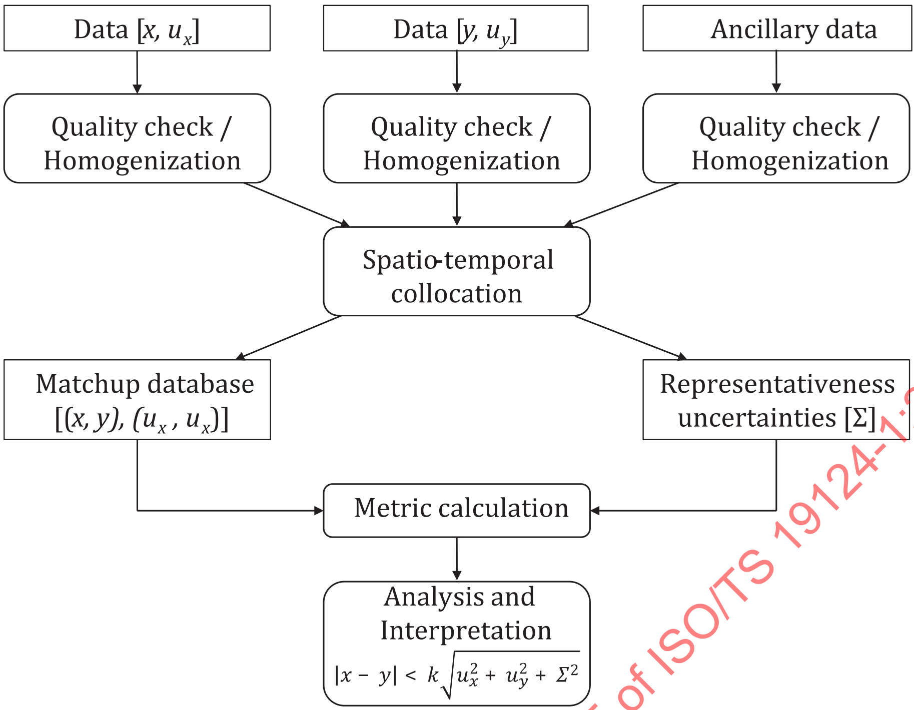
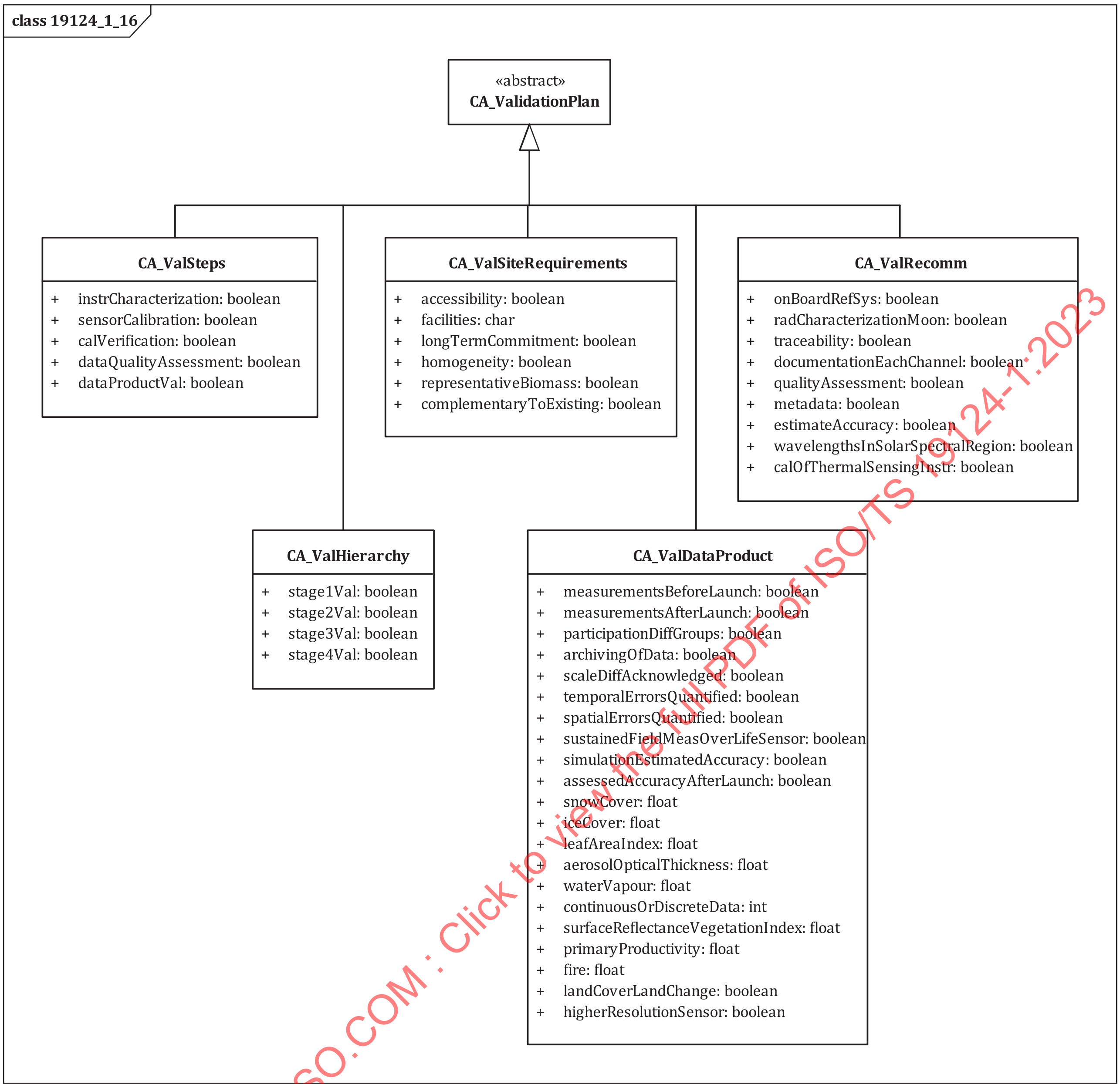


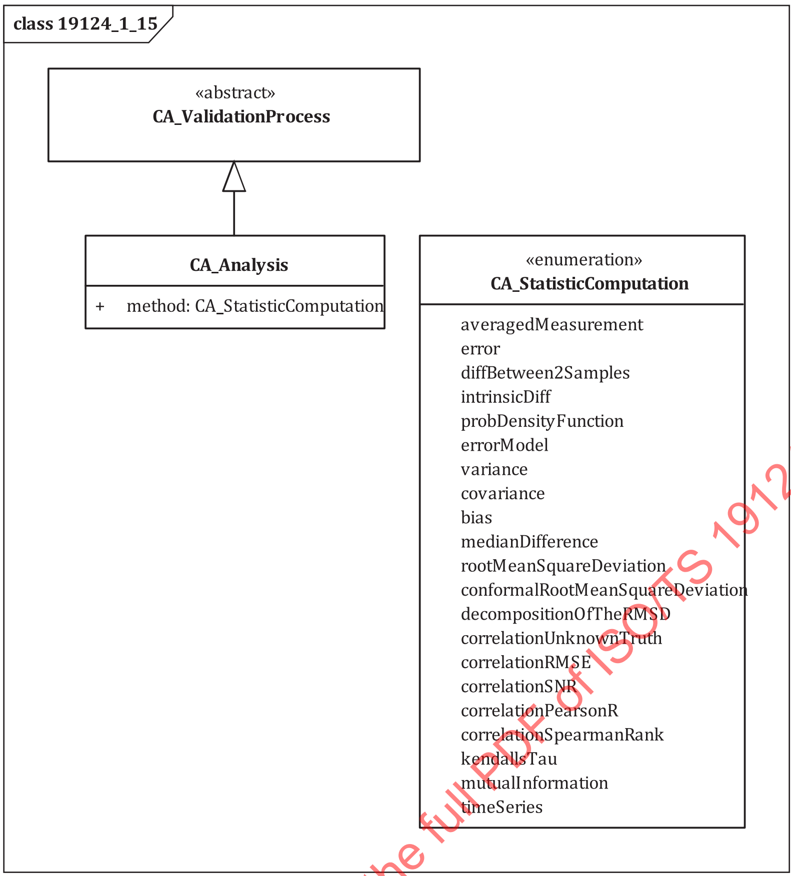
Figure 9 — Schematic overview of the general validation process[6]

Figures 10 and 11 give overviews over the classes of this document. They address the planning of the validation (CA_ValidationPlan) and its analysis (CA_ValidationProcess).



NOTE See Table B.2.

Figure 10 — Classes of CA_ValidationPlan



NOTE See Table B.2.

Figure 11 — Classes of CA_ValidationProcessValidation steps

The process of calibration and validation is subdivided into five key steps from pre-launch sensor characterization and calibration to on-orbit data product validation (Figure 12). This process shall be described and the results shall be documented in accordance with ISO 19157-1.

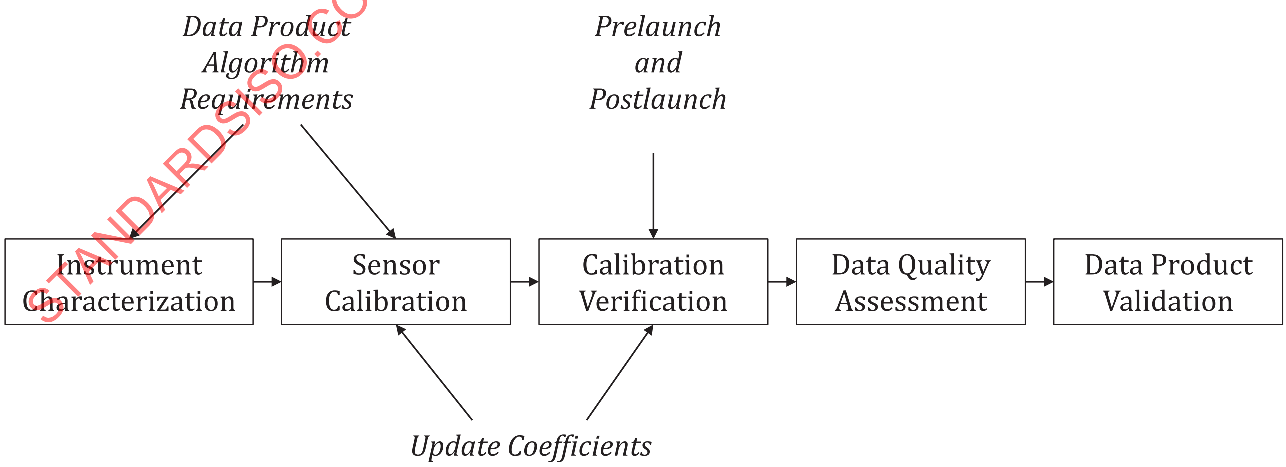


Figure 12 — Five key steps from prelaunch sensor calibration to on-orbit data product validation[3]

10.2 Generic validation process

A generic validation process chain covers typical steps of the validation of remote sensing data products and may serve as a basis for the elaboration of Cal/Val plans and for gap analysis (Table 5).

Table 5 — Generic validation process for the Level 2 data products of atmospheric composition satellites[13]

Operation	Input	Task	Output
1) Design of the validation study	Data quality requirements	Design validation objectives: quality indicators to produce, domains and ranges to address, etc.	Set-up of following steps, including set of targeted quality indicators
2) Data selection and post-processing	Original datasets, quality flags, usage recommendations, etc.	Quality screening of satellite and validation data sets	Original datasets and cleared datasets
3) Data content analysis	Original and cleared satellite datasets	Analysis of satellite data set	Validity of quality flags, identification of geographical/time coverage and horizontal resolution
4) Information content analysis	Averaging kernels, a priori profiles, covariance	Algebraic analysis of vertical averaging kernel matrixes: eigenvectors, DFS, Backus-Gilbert spread, etc.	Information content metrics, vertical sensitivity and resolution, height registration
5) Spatio-temporal co-location	Cleared satellite and validation data sets, co-location criteria	Identification and extraction of co-located data pairs, optimisation of overlap between datasets	Co-located satellite and validation datasets and metadata
6) Co-location analysis	Co-located pairs dataset and metadata	Analysis of co-located pairs and associated parameters (influence quantities, ancillary data, etc.)	Identification of geographical/time coverage of co-locations, of the covered ranges of measurand and influence quantities etc.
7) Data harmonization	Co-located pairs dataset, associated averaging kernels, a priori and covariance	Change in coordinates, regridding, vertical and horizontal smoothing...	Co-located satellite and validation datasets with comparable vertical grid and reduced representativeness differences, ready for comparison
8) Data comparison and analysis	Cleared, co-located, harmonized datasets	Visual comparison of time series and maps, quantitative comparison of measurand values as a function of time, classified by range of influence quantity, etc.	Time series, maps, histograms, oscillations, statistical estimates (bias, spread, drift, etc.)
9) Quality information	Outcome of previous step	Sum up the findings of the previous steps, assign to every targeted quality indicator a range of values	List of qualitative and quantitative quality indicators, statements and recommendations
10) Acceptance	All results above, quality criteria (e.g. mission requirements)	Verification of satellite data quality compliance with mission and/or user requirements	Consistency of the co-located data sets, compliance with mission/user requirements, validity of ex-ante uncertainty estimates (systematic and random effects)
11) Reporting	All results above, quality criteria (e.g. mission requirements)	Reporting of validation; method, datasets, derived quality indicators	Reporting
12) Feedback	Validation report, intermediate results	Collect feedback from validation activities, audit validation process	Feedback to validation stakeholders: fiducial reference measurement (FRM) data providers, infrastructure

10.3 Data product validation

Data product validation should begin before launch with the laboratory, field and airborne measurements. Validation measurements should be made available for the measurand itself, but also for the quantities influencing the measured value of the data product under validation. After launch, the data product validations cannot be a one-time exercise but need to be repeated periodically to ensure continued validity and to test any improvements to the algorithms. Several different groups should participate in the data product validation exercises, preferably with international representation. Finally, the validation data and associated ancillary data need to be archived with the same attention paid to the continuous data stream from the satellite.

When making the comparison of surface measurements with satellite measurements, it is necessary to pay attention to scaling up surface point measurements to the satellite spatial resolution and to take into account the impacts of the atmosphere on the satellite measurement at the time of overpass. Quantifying the temporal and spatial error fields associated with a data product is especially important in the modelling and analysis of long time series for climate research. These assessments require a commitment to sustained field measurements over the life of the sensor.

Preliminary estimates of accuracy can be obtained for a particular algorithm before launch using simulation or modelling. This is referred to as “ex-ante uncertainty estimate,” usually based on the measurement equation or retrieval sensitivity/perturbation studies. However, accuracy is assessed primarily after launch, once the instrument and algorithm have stabilized.

Validation of higher-order data products for parameters such as snow cover, leaf area index, aerosol optical thickness and water vapour requires different approaches. A useful distinction can be made between continuous and discrete data products and the methods for their validation. The CEOS WGCV land product validation community has identified a new set of validation test sites from well-established networks, so-called supersites, useful for the validation of satellite land products including albedo, land surface temperature, leaf area index, above-ground biomass, and soil moisture. The supersites are super-characterized sites in terms of canopy structure and bio-geophysical variables, following well established protocols, useful for the validation of multiple (at least 3) satellite land geophysical variables and for 3D radiative transfer modelling approaches, with long-term operation and infrastructural capacity and supported by airborne acquisitions. The need for measuring multiple variables was specifically driven by the requirement to assess physical inter-consistency within satellite land products. These sites provide a focus for the operational satellite land product validation over a global scale, and international efforts have been initiated to develop new supersites to fill geographical gaps. Satellite data products such as changes in snow and ice cover, fire and land cover/change are validated at locations suited to specific product validation. Validation efforts also include information collected by higher-resolution sensors. Finally, operational validation systems have been developed to ensure that different satellite-based land products are validated and inter-compared using standardized methodologies, following community-agreed-upon validation good practices against a set of globally representative FRMs.

NOTE See References [3], [18], [19].

10.4 Maturity of data product validation

For the convenience of product management and usage, it is common practice among product producers and distributors to introduce the concept of product validation maturity level for capturing the representativeness and quality of the validation data, the validation method used, and the validation results. For example, the Data Management and Stewardship Maturity Matrix for data product validation of the ESA introduces four levels of maturity of the data product validation and its process, as shown in Table 6.

Unfortunately, there are many schemas of maturity levels defined and used by product producers and distributors around the world. There is no single schema accepted worldwide as the standard, although the CEOS CAL/VAL working group is intended to develop a CEOS-recommended one. This document does not intend to specify a specific schema as the maturity level standard since the community currently has no consensus on it. Instead, this document introduces an optional property, calvalMaturityLevel, whose type is MD_Identifier to allow the product producers to record the maturity level and describe the schema on which the maturity level is defined. Such an approach shall accommodate all schemas currently being used or to be produced in the future without specifying a "standard" schema or modifying this document. An organization or an agency can specify a specific schema as the standard when they develop an implementation specification of this document for the organization or agency.

Table 6 — Maturity matrix for EO satellite data product validation[13]

Stage	Description
Level-0 Not managed	— **Reference data representativeness:** No validation activity performed. — **Reference data quality:** No validation activity performed. — **Validation method:** No validation activity performed. — **Validation results:** No validation activity performed.
Level-1 Limit managed	— **Reference data representativeness:** Reference measurements assessed to be mostly representative of the satellite measurements, covering a primary range satellite of measurements and at ad-hoc opportunities (no formal documented regular timescale). — **Reference data quality:** Reference data comes with a single uncertainty estimate for the entire dataset. — **Validation method:** Methodology assesses satellite measurements, simple uncertainty estimated (e.g. from statistical spread for results). — **Validation results:** Validation results show good agreement between satellite and reference measurements within uncertainties in most cases.
Level-2 Managed	— **Reference data representativeness:** Reference measurements assessed to be well representative of the satellite measurements, covering a reasonable range of the satellite's measurements and carried out using FRM or community-approved methods. Carried out on a regular timescale of approximately annual basis but not necessarily based on need. — **Reference data quality:** Reference data comes with full uncertainty information, assessed following the GUM and traceable to community reference or SI (e.g. FRM). — **Validation method:** Methodology assesses satellite measurements and reference data with regard to their uncertainties. — **Validation results:** Validation results show excellent agreement between satellite and reference measurements, within uncertainties. Analysis performed independently of satellite mission owner.
Level-3 Well managed	— **Reference data representativeness:** Reference measurements independently assessed to be fully representative of the satellite measurements, covering the satellite's full range of measurements and with full assessment of uncertainties and carried out on a regular basis determined by product performance. — **Reference data quality:** Reference data comes with full uncertainty and error-correlation information, assessed following the GUM and traceable to SI (e.g. FRM). — **Validation method:** Methodology assess satellite measurements and reference data with regard to their error-covariance and validates those uncertainties. — **Validation results:** Validation results show excellent agreement between satellite and reference measurements, within uncertainties. Uncertainty validated. Analysis performed independently of satellite mission owner.

10.5 Validation planning

10.5.1 Phase E1

The commissioning phase is a period of intense and exhaustive calibration and validation activities:

— switch on of the payload, heating for decontamination, cooling, thermomechanical stabilization, functional testing, etc.;

— adjust some thresholds in the Level-1 processing, check the quality of Level-1 data after first in-flight calibration;

— check Level-1 calibration with other methods or targets;

- verification and characterization of the first data retrievals performed on real satellite data, among others through investigation of the vertical averaging kernels and other retrieval diagnostics (DFS, RMS, AK-based vertical resolution, along-track resolution, etc.);
- acquisition of FRM and other correlative measurements;
- test of validation procedures and tools on real data;
- first comparisons of satellite data to ground-, balloon- and satellite-based correlative measurements;
- first assessment of the validity of ancillary parameters and auxiliary parameters;
- derivation of preliminary quality indicators: bias and dispersion as a function of latitude and altitude, and, where possible, dependence on time and influence quantities;
- first assessment of the validity of uncertainty estimates;
- verification of effects of quality flags and other data screening recommendations on the validation results;
- validation support to the go/no-go decision on public dissemination and on the ingestion of the data into operational services;
- contribution of quality information to public documentation, e.g. in product Readme files and in product user manuals (PUMs).

10.5.2 Phase E2 / main validation phase

In-depth validation of the data products initiated during Phase E1 shall continue into Phase E2 to ensure that validation is carried out over the full range of influence quantities, ancillary parameters and other parameters. Depending on the parameter, the range may be browsed entirely in a couple of months (e.g. cloud properties), 6 months (e.g. solar zenith angle for LEO satellites), or even one year.

10.5.3 Phase E2 / routine operation validation

Routine operations validation consists in frequent data comparisons with respect to FRMs and other validation data, frequent verification of associated diagnostics (averaging kernels, chi-square, etc.) and cyclic reporting to the responsible data producers, algorithm prototypes, core users and agencies.

10.5.4 Phase E2 / data and algorithm evolution

After each major upgrade of the calibration and/or of the Level-1-to-2 retrieval algorithm, dedicated validation activities shall be designed and performed.

10.5.5 Phase F

Even after termination of the satellite mission, further evolution of data and associated retrieval algorithms is undertaken or continued, e.g. to consolidate fundamental data records and to meet new user requirements.

NOTE See Reference [13].

10.6 Recommendations

Table 7 shows a number of recommendations for the setup of a validation process.

Table 7 — Recommendations for the setup of a validation process

Count	Recommendation
1	A continuous and effective on-board reference system should be provided to verify the stability of the calibration and sensor characteristics from the launch through the life of the mission.
2	Radiometric characterization of the Moon should be continued and possibly expanded to include measurements made at multiple institutions.
3	The establishment of traceability by national measurement institutions should be considered to determine if improved accuracy, reduced uncertainty in the measurement chain, and/or better documentation might be achieved.
4	The results of sensitivity studies on the parameters in the data product algorithms should be summarized in a document specifying requirements that specifies the characterization measurements for each channel in the sensor.
5	Quality assessment should be an intrinsic part of operational data production and should be provided in the form of metadata with the data product.
6	Validation, an essential part of the information system, should be undertaken for each data product or data record to provide an evaluation of the product over the range of environmental conditions for which the product is provided.
7	Wavelengths and bandwidths of channels in the solar spectral region should be selected to avoid absorption features of the atmosphere.
8	Calibration of thermal sensing instruments should continue to be traceable to the SI unit of temperature via the Planckian radiator, blackbody technology.

11 The ISO 19124 series

11.1 Introduction

The various parts of the ISO 19124 series are listed in Figures 1 – 6.

Broadband-instruments belong to an overarching category and are therefore not the subject of a specific International Standard. Broadband instruments relevant for climate change studies are those which measure spectrally integrated radiative power incident on or emitted from the Earth. The incoming radiation is from the Sun and is centred in the visible with large contributions in the near infrared. The outgoing radiation from the Earth is either scattered incident sunlight or thermal blackbody emission characteristic of the region from which it is emitted. This radiation shows large variations spatially across the Earth's surface as well as through the Earth's atmosphere, and has spectral components including both the reflected sunlight and the mid-infrared thermal emission. Nominally the net broadband outgoing radiation carries the same energy as the total incident radiation, except for a small ocean heating.

11.2 Imaging instruments

11.2.1 Infrared instruments

Infrared radiation measurements are sensitive to critical climate forcing (carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), chlorofluorocarbons (CFCs), ozone, and aerosols) and response (water vapour, clouds and temperature) variables. Infrared radiation measurements address many thematic domains such as air quality, tropospheric chemistry, tropospheric and stratospheric ozone, as well as ozone-depleting substances, and are thus a component of a climate monitoring system. In other words, such measurements, if performed over the entire infrared spectrum, capture the entire magnitude and the details of the anthropogenic greenhouse effect, as well as the details of the Earth's adjustment to this enhanced greenhouse forcing.

11.2.2 Ultraviolet, visible and near-infrared instruments

Ultraviolet (UV), visible (VIS) and near-infrared (NIR) instruments observe spectral solar radiation that has been reflected or scattered back to space by the Earth's surface, clouds and atmosphere. These observations are also used to measure surface albedo such as snow and ice cover, health and vigour of vegetation, ocean chlorophyll, cloud amounts and thicknesses, atmospheric aerosol amounts, aerosol layer height and thickness, and the total amount and vertical profile of atmospheric ozone (O_3) and other trace gases.

11.2.3 Microwave instruments

11.2.3.1 Overview

Satellite microwave observations of the atmosphere, land and oceans provide pertinent information to better predict and understand the changes in weather and climate. The instruments provide information on atmospheric and sea surface temperatures, sea ice and snow cover, cloud properties, precipitation rates, atmospheric water vapour as well as other atmospheric trace gases, ocean surface winds, and temperature profiles.

The ISO 19124 series addresses SAR (synthetic aperture radar), InSAR (interferometric SAR), and SAR altimetry (Figure 4).

11.2.3.2 Impediments to post-launch calibration of microwave sensors

— Difficulty to correct for satellite orbit drift in trend analysis.

— Calibration uncertainty from instrument non-linearity.

— Anomalous emission from unknown targets.

— Warm load instability and solar and stray slight contamination.

— Difficulty to characterize the radio frequency interference by anthropogenic emissions.

— Pre-launch characterization, antenna patterns, brightness temperature standard, well characterized target, pointing accuracy, antenna pointing, co- and cross-polar gain pattern, antenna efficiency, etc.

11.3 Non-imaging instruments

Active instruments offer advantages over passive remote sensing techniques in measuring some climate variables, particularly those involving elevation or altitude. Active instruments operate by sending out pulses of light or microwave energy and measuring the time-varying signal scattered back to the instrument as the pulse passes through the atmosphere to the Earth's surface.

Annex A
(normative)

Abstract test suite

A.1 Semantics

Conformance to this annex consists of either service conformance or data conformance.

A.2 Introduction

A.2.1 On-board calibration sources

a) Test purpose: to verify the appropriate selection of the sensors

b) Test method: inspect this document and verify the use of sensors named in the listing

c) Reference: 7.3

A.2.2 Early operations

a) Test purpose: to verify the appropriate optimization of the sensors

b) Test method: inspect this document and verify the implementation of actions

c) Reference: 7.4

A.2.3 Intensive calibration and validation

a) Test purpose: to verify the appropriate application of calibration and validation

b) Test method: inspect this document and verify the implementation of activities

c) Reference: 7.5

A.3 Passive optical instruments, visible and NIR spectrum

A.3.1 General demands

a) Test purpose: to verify conformance with the general requirements

b) Test method: inspect this document and verify the implementation of activities

c) Reference: 8.3

A.3.2 Solar diffusers

a) Test purpose: to verify conformance with the requirements for solar diffusers

b) Test method: inspect this document and verify the implementation of activities

c) Reference: 8.3.3

A.3.3 White light sources

a) Test purpose: to verify conformance with the requirements for white light sources

b) Test method: inspect this document and verify the implementation of activities

c) Reference: 8.3.4

A.3.4 LEDs

a) Test purpose: to verify conformance with the requirements for LEDs

b) Test method: inspect this document and verify the implementation of activities

c) Reference: 8.3.5

A.3.5 Tuneable laser diodes

a) Test purpose: to verify conformance with the requirements for tuneable laser diodes

b) Test method: inspect this document and verify the implementation of activities

c) Reference: 8.3.6

A.3.6 Black bodies

a) Test purpose: to verify conformance with the requirements for black bodies

b) Test method: inspect this document and verify the implementation of activities

c) Reference: 8.3.7

A.3.7 Celestial objects

a) Test purpose: to verify conformance with the requirements for celestial objects

b) Test method: inspect this document and verify the implementation of activities

c) Reference: 8.3.8

A.4 Validation process

A.4.1 Data

a) Test purpose: to verify conformance with the requirements for input data

b) Test method: inspect this document and verify the implementation of activities

c) Reference: 10.1.1

A.4.2 Quality check / Homogenization

a) Test purpose: to verify conformance with the requirements for the quality assessment

b) Test method: inspect this document and verify the implementation of activities

c) Reference: 10.1.3

A.4.3 Spatio-temporal co-location

a) Test purpose: to verify conformance with the requirements for the location of measurements

b) Test method: inspect this document and verify the implementation of activities

c) Reference: 10.1.4

A.4.4 Metric calculation

a) Test purpose: to verify conformance with the metrics defined in this document

b) Test method: inspect this document and verify the implementation of activities

c) Reference: 10.1.5

A.4.5 Analysis and interpretation

a) Test purpose: to verify conformance with the analysis methods defined in this document

b) Test method: inspect this document and verify the implementation of activities

c) Reference: 10.1.6

A.5 Validation site requirements

a) Test purpose: to verify conformance with the requirements of a validation site

b) Test method: inspect this document and verify the implementation of activities

c) Reference: 8.8

A.6 Data product validation

a) Test purpose: to verify conformance with the requirements for data products

b) Test method: inspect this document and verify the implementation of activities

c) Reference: 10.4

A.7 Validation planning

a) Test purpose: to verify conformance with the recommendations for the validation planning

b) Test method: inspect this document and verify the implementation of activities

c) Reference: 10.6

Annex B
(normative)

Data dictionary

B.1 General

The following clauses provide a detailed description of each of the classes and each class attribute in the models presented in this document in the form of a tabular data dictionary. Entries with attributes are white. All other entries are shaded.

The following abbreviations are used in Table B.1: M = mandatory, N = multiple times.

B.2 Validation classes

Table B.1 — Classes and attributes

No.	Name/Role name	Definition	Obligation/ Condition	Max occurrence	Data type/Class	Domain
1.	CA_CalibrationValidation 5.3, Figure 1	root entity that defines information about calibration and validation	Use obligation/ condition from referencing object	Use maximum occurrence from referencing object	Aggregated Class (MD_Coverage Description)	
2.	CA_Methods 5.3, Figure 2	root class that provides information about the methods for calibration and validation	Use obligation/ condition from referencing object	Use maximum occurrence from referencing object	Aggregated Class (CA_CalibrationValidation)	
3.	CA_OnBoard	calibration source that provides the capability of periodically stimulating the sensor response with known and/or repeatable flux levels	M	Use maximum occurrence from referencing object	Specialized Class (CA_Methods)	
4.	CA_CrossCal	method to assess the consistency of observations across satellites	M	Use maximum occurrence from referencing object	Specialized Class (CA_Methods)	
5.	CA_VicCal	generic term indicating a calibration performed in a manner not directly connected to the satellite system under consideration	M	Use maximum occurrence from referencing object	Specialized Class (CA_Methods)	
6.	CA_TrendCal	sensor performance trending tracks long-term changes in sensor behaviour due to component aging and/or sensor contamination, and provides a means for their correction, if necessary.	Use obligation/ condition from referencing object	Use maximum occurrence from referencing object	Specialized Class (CA_Methods)	
7.	CA_RefSources 5.3, Figure 3	root class that provides information about the data sources	Use obligation/ condition from referencing object	Use maximum occurrence from referencing object	Aggregated Class (CA_CalibrationValidation)	
8.	groundref	the class CA_GroundRefSources provides the ground reference information for the class CA_RefSources	Use obligation/ condition from CA_GroundRefSources	Use maximum occurrence from CA_GroundRefSources	Role	

Table B.1 *(continued)*

No.	Name/Role name	Definition	Obligation/ Condition	Max occurrence	Data type/Class	Domain
9.	CA_SourcesOptical	root class for optical instruments as data sources	Use obligation/ condition from referencing object	Use maximum occurrence from referencing object	Specialized Class (CA_RefSources)	
10.	CA_SourcesForActiveOptical	active optical instruments emit light and receive the reflection. An example is lidar	Use obligation/ condition from referencing object	Use maximum occurrence from referencing object	Specialized Class (CA_SourcesOptical)	
11.	CA_SourcesForPassiveOptical	passive optical instruments receive the reflection from objects which are illuminated mostly by the sun. An example is a camera	Use obligation/ condition from referencing object	Use maximum occurrence from referencing object	Specialized Class (CA_SourcesOptical)	
12.	CA_SourcesMicrowave	root class for microwave instruments as data sources	Use obligation/ condition from referencing object	Use maximum occurrence from referencing object	Specialized Class (CA_RefSources)	
13.	CA_SourcesForActiveMicrowave	active microwave instruments emit microwave radiation and receive the reflection. An example is SAR	Use obligation/ condition from referencing object	Use maximum occurrence from referencing object	Specialized Class (CA_SourcesMicrowave)	
14.	CA_SourcesForPassiveMicrowave	passive microwave instruments receive the reflection from objects. An example is a microwave radiometer	Use obligation/ condition from referencing object	Use maximum occurrence from referencing object	Specialized Class (CA_SourcesMicrowave)	
15.	CA_SourcesSound	root class for sound instruments as data sources	Use obligation/ condition from referencing object	Use maximum occurrence from referencing object	Specialized Class (CA_RefSources)	
16.	CA_SourcesForActiveSound	instruments that emit a sound and receive the echo	Use obligation/ condition from referencing object	Use maximum occurrence from referencing object	Specialized Class (CA_SourcesSound)	
17.	CA_SourcesForPassiveSound	instruments that measure sound	Use obligation/ condition from referencing object	Use maximum occurrence from referencing object	Specialized Class (CA_SourcesSound)	
18.	CA_GroundRefSources	root class for reference areas on the ground	Use obligation/ condition from referencing object	Use maximum occurrence from referencing object	Aggregated Class (CA_RefSources)	
19.	CA_NaturalRefSources	reference areas that are not or are only minimally modified compared to their original natural status	Use obligation/ condition from referencing object	Use maximum occurrence from referencing object	Specialized Class (CA_GroundRefSources)	
20.	CA_ManMadeRefSources	reference areas that were built for calibration and validation purposes	Use obligation/ condition from referencing object	Use maximum occurrence from referencing object	Specialized Class (CA_GroundRefSources)	
21.	CA_SensorCalVal	root class for sensor calibration and validation activities	Use obligation/ condition from referencing object	Use maximum occurrence from referencing object	Specialized Class (CA_CalibrationValidation)	

Table B.1 *(continued)*

No.	Name/Role name	Definition	Obligation/ Condition	Max occurrence	Data type/Class	Domain
22.	support	the class CA_SensorCalVal supports the class CA_DataProductCalVal. This means that CA_SensorCalVal is subordinate to CA_DataProductCalVal	Use obligation/ condition from CA_DataProductCalVal	Use maximum occurrence from CA_DataProductCalVal	Role	
23.	CA_PreLaunchCalVal	abstract class that covers the classes of pre-launch calibration and validation	Use obligation/ condition from referencing object	Use maximum occurrence from referencing object	Specialized Class (CA_SensorCalVal)	
24.	CA_PostLaunchCalVal 5.3, Figure 4	abstract class that covers the classes of post-launch calibration and validation	Use obligation/ condition from referencing object	Use maximum occurrence from referencing object	Specialized Class (CA_SensorCalVal)	
25.	CA_UV_VIS_NIR 11.2.2	instruments that observe ultraviolet, visible, and near-infrared radiation	M	Use maximum occurrence from referencing object	Specialized class (CA_PostLaunchCalVal)	
26.	CA_IR 11.2.1	instruments that observe infrared radiation except near-infrared radiation	M	Use maximum occurrence from referencing object	Specialized class (CA_PostLaunchCalVal)	
27.	CA_PassiveMicrowave 11.2.3.2	instruments that observe passively microwave radiation	M	Use maximum occurrence from referencing object	Specialized class (CA_PostLaunchCalVal)	
28.	CA_ActiveMicrowave 11.2.3.2	instruments that emit microwave radiation and observe the reflection	M	Use maximum occurrence from referencing object	Specialized class (CA_PostLaunchCalVal)	
29.	CA_ActiveOptical	instruments that emit visible or IR-light and observe the reflection	M	Use maximum occurrence from referencing object	Specialized class (CA_PostLaunchCalVal)	
30.	CA_Sound	instruments that emit a sound and observe the reflection	M	Use maximum occurrence from referencing object	Specialized class (CA_PostLaunchCalVal)	
31.	CA_DataProductCalVal	root class for information related to the calibration and validation of data products	Use obligation/ condition from referencing object	Use maximum occurrence from referencing object	Specialized class (CA_CalibrationValidation)	
32.	has	the class CA_DataProductCalVal has CA_SensorCalVal as a subordinate class.	Use obligation/ condition from CA_SensorCalVal	Use maximum occurrence from CA_SensorCalVal	Role	
33.	productLevel	information about the product level	M	1	MD_Identifier	
34.	CA_RSDataCalVal 5.3, Figure 5	root class for data products from remotely sensed data	Use obligation/ condition from referencing object	Use maximum occurrence from referencing object	Specialized class (CA_DataProductCalVal)	
35.	CA_DataUV_VIS_NIR	data products from UV-, VIS- and NIR-sensors	Use obligation/ condition from referencing object	Use maximum occurrence from referencing object	Specialized class (CA_RSDataCalVal)	
36.	CA_DataIR	data products from IR-sensors	Use obligation/ condition from referencing object	Use maximum occurrence from referencing object	Specialized class (CA_RSDataCalVal)	