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Geographic information — Imagery sensor models for geopositioning

Information géographique — Modèles de capteurs d'images de géopositionnement

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Foreword

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ISO/TS 19130 was prepared by Technical Committee ISO/TC 211, *Geographic information/Geomatics*.

Introduction

The purpose of this Technical Specification is to specify the geolocation information that an imagery data provider shall supply in order for the user to be able to find the earth location of the data using a Physical Sensor Model, a True Replacement Model or a Correspondence Model. Detailed Physical Sensor Models are defined for passive electro-optical visible/infrared (IR) sensors (frame, pushbroom and whiskbroom) and for an active microwave sensing system (Synthetic Aperture Radar). A set of components from which models for other sensors can be constructed is also provided. Metadata required for geopositioning using a True Replacement Model, a Correspondence Model, or ground control points are also specified. The intent is to standardize sensor descriptions and specify the minimum geolocation metadata requirements for data providers and geopositioning imagery systems.

Vast amounts of data from imaging systems are collected, processed and distributed by government mapping and remote sensing agencies and commercial data vendors. In order for this data to be useful in extraction of geographic information, it requires further processing. Geopositioning, which determines the ground coordinates of an object from image coordinates, is a fundamental processing step. Because of the diversity of sensor types and the lack of a common sensor model standard, data from different producers can contain different parametric information, lack parameters required to describe the sensor that produces the data, or lack ancillary information necessary for geopositioning and analysing the data. Consequently, a separate software package often has to be developed to deal with data from each individual sensor or data producer. Standard sensor models and geolocation metadata allow agencies or vendors to develop generalized software products that are applicable to data from multiple data producers or from multiple sensors. With such a standard, different producers can describe the geolocation information of their data in the same way, thus promoting interoperability of data between application systems and facilitating data exchange.

This Technical Specification defines the set of metadata elements specified for providing sensor model and other geopositioning data to users. For the case where a Physical Sensor Model is provided, it includes a location model and metadata relevant to all sensors; it also includes metadata specific to whiskbroom, pushbroom, frame, and SAR sensors. It also includes metadata for functional fit geopositioning, where the function is part of a Correspondence Model or a True Replacement Model. This Technical Specification also provides a schema for all of these metadata elements.

Geographic information — Imagery sensor models for geopositioning

1 Scope

This Technical Specification identifies the information required to determine the relationship between the position of a remotely sensed pixel in image coordinates and its geoposition. It supports exploitation of remotely sensed images. It defines the metadata to be distributed with the image to enable user determination of geographic position from the observations.

This Technical Specification specifies several ways in which information in support of geopositioning may be provided.

a) It may be provided as a sensor description with the associated physical and geometric information necessary to rigorously construct a Physical Sensor Model. For the case where precise geoposition information is needed, this Technical Specification identifies the mathematical formulae for rigorously constructing Physical Sensor Models that relate two-dimensional image space to three-dimensional ground space and the calculation of the associated propagated errors. This Technical Specification provides detailed information for three types of passive electro-optical/infrared (IR) sensors (frame, pushbroom and whiskbroom) and for an active microwave sensing system [Synthetic Aperture Radar (SAR)]. It provides a framework by which these sensor models can be extended to other sensor types.

b) It may be provided as a True Replacement Model, using functions whose coefficients are based on a Physical Sensor Model so that they provide information for precise geopositioning, including the calculation of errors, as precisely as the Physical Sensor Model they replace.

c) It may be provided as a Correspondence Model that provides a functional fitting based on observed relationships between the geopositions of a set of ground control points and their image coordinates.

d) It may be provided as a set of ground control points that can be used to develop a Correspondence Model or to refine a Physical Sensor Model or True Replacement Model.

This Technical Specification does not specify either how users derive geoposition data or the format or content of the data the users generate.

2 Conformance

This Technical Specification specifies four conformance classes. There is one conformance class for each of the methods specified for providing geopositioning information. Any set of geopositioning information claiming conformance to this Technical Specification shall satisfy the requirements for at least one conformance class as specified in Table 1. The requirements for each class are shown by the presence of an X in the boxes for all clauses in the application test suite (ATS) required for that class. If the requirement is conditional, the box contains a C.

Table 1 — Conformance classes

			Subclause										
			A.1	**A.2.1**	**A.2.2**	**A.3.1**	**A.3.2**	**A.3.3**	**A.3.4**	**A.3.5**	**A.4**	**A.5**	**A.6**
Conformance Class	Correspondence Model		X	X	X						X		X
	Physical Sensor Model	SAR	X			X	X	X		X			
		electro-optical	X			X	X	X	X				
	True Replacement Model		X								X	X	
	GCP Collection		X	X	X	C	C	C	C	C	C	C	C

3 Normative references

The following referenced documents are indispensable for the application 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/TS 19103:2005, *Geographic information — Conceptual schema language*

ISO 19107, *Geographic information — Spatial schema*

ISO 19108, *Geographic information — Temporal schema*

ISO 19111:2007, *Geographic information — Spatial referencing by coordinates*

ISO 19115:2003, *Geographic information — Metadata*

ISO 19115-2:2009, *Geographic information — Metadata — Part 2: Extensions for imagery and gridded data*

ISO 19123, *Geographic information — Schema for coverage geometry and functions*

ISO/TS 19138:2006 *Geographic information — Data quality measures*

4 Terms and definitions

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

4.1
active sensing system
sensing system that emits energy that the **sensor** uses to perform sensing

4.2
adjustable model parameters
model parameters that can be refined using available additional information, such as **ground control points**, to improve or enhance modelling corrections

4.3
along-track
direction in which the **sensor** platform moves

4.4
ARP
aperture reference point
3D location of the centre of the synthetic aperture

NOTE It is usually expressed in ECEF **coordinates** in metres.

4.5
attitude
orientation of a body, described by the angles between the axes of that body's **coordinate system** and the axes of an external coordinate system

[ISO 19116:2004, definition 4.2]

4.6
attribute
named property of an entity

[ISO/IEC 2382-17:1999, definition 17.02.12]

NOTE In this Technical Specification, the property relates to a geometrical, topological, thematic, or other characteristic of an entity.

4.7
azimuth resolution
⟨SAR⟩ resolution in the cross-range direction

NOTE This is usually measured in terms of the **impulse response** of the **SAR sensor** and processing system. It is a function of the size of the synthetic aperture, or alternatively the dwell time (i.e. a larger aperture results in a longer dwell time results in better resolution).

4.8
beam width
⟨SAR⟩ useful angular width of the beam of electromagnetic energy

NOTE Beam width is usually measured in radians and as the angular width between two points that have 50 % of the power (3 dB below) of the centre of the beam. It is a property of the antenna. Power emitted outside of this angle is too little to provide a usable return.

4.9
broadside
⟨SAR⟩ direction orthogonal to the velocity vector and parallel to the plane tangent to the Earth's **ellipsoid** at the nadir point of the **ARP**

4.10
calibrated focal length
distance between the **perspective centre** and the **image plane** that is the result of balancing positive and negative radial lens distortions during **sensor** calibration

4.11
coordinate
one of a sequence of n numbers designating the position of a point in n-dimensional space

[ISO 19111:2007, definition 4.5]

NOTE In a **coordinate reference system**, the coordinate numbers are qualified by units.

4.12
coordinate reference system
coordinate system that is related to an object by a **datum**

[ISO 19111:2007, definition 4.8]

NOTE For geodetic and vertical datums, the object will be the Earth.

4.13
coordinate system
set of mathematical rules for specifying how **coordinates** are to be assigned to points

[ISO 19111:2007, definition 4.10]

4.14
Correspondence Model
functional relationship between ground and **image coordinates** based on the correlation between a set of **ground control points** and their corresponding image coordinates

4.15
cross-track
perpendicular to the direction in which the collection platform moves

4.16
data
reinterpretable representation of information in a formalised manner suitable for communication, interpretation, or processing

[ISO/IEC 2382-1:1993, definition 01.01.02]

4.17
datum
parameter or set of parameters that define the position of the origin, the scale, and the orientation of a **coordinate system**

[ISO 19111:2007, definition 4.14]

4.18
detector
device that generates an output signal in response to an energy input

4.19
Doppler angle
⟨SAR⟩ angle between the velocity vector and the **range vector**

4.20
Doppler shift
wavelength change resulting from relative motion of source and **detector**

NOTE In the **SAR** context, it is the frequency shift imposed on a radar signal due to relative motion between the transmitter and the object being illuminated.

4.21
ellipsoid
surface formed by the rotation of an ellipse about a main axis

[ISO 19111:2007, definition 4.17]

NOTE The Earth ellipsoid is a mathematical ellipsoid figure of the Earth which is used as a reference frame for computations in geodesy, astronomy and the geosciences.

4.22

ellipsoidal coordinate system

geodetic coordinate system

coordinate system in which position is specified by **geodetic latitude**, **geodetic longitude** and (in the three-dimensional case) **ellipsoidal height**

[ISO 19111:2007, definition 4.18]

4.23

ellipsoidal height

geodetic height

h

distance of a point from the **ellipsoid** measured along the perpendicular from the ellipsoid to this point, positive if upwards or outside of the ellipsoid

[ISO 19111:2007, definition 4.19]

NOTE Only used as part of a three-dimensional **ellipsoidal coordinate system** and never on its own.

4.24

error propagation

process of determining the uncertainties of derived quantities from the known uncertainties of the quantities on which the derived quantity is dependent

NOTE Error propagation is governed by the mathematical function relating the derived quantity to the quantities from which it was derived.

4.25

external coordinate reference system

coordinate reference system whose **datum** is independent of the object that is located by it

4.26

fiducial centre

point determined on the basis of the camera **fiducial marks**

NOTE When there are four fiducial marks, fiducial centre is the intersection of the two lines connecting the pairs of opposite fiducial marks.

4.27

fiducial mark

index marks, typically four or eight rigidly connected with the camera body, which form **images** on the film negative and define the **image coordinate reference system**

NOTE When a camera is calibrated the distances between fiducial marks are precisely measured and assigned **coordinates** that assist in correcting for film distortion.

4.28

frame sensor

sensor that detects and collects all of the **data** for an **image** (frame / rectangle) at an instant of time

4.29

geodetic datum

datum describing the relationship of a two- or three-dimensional **coordinate system** to the Earth

[ISO 19111:2007, definition 4.24]

NOTE In most cases, the geodetic datum includes an **ellipsoid** description.

4.30
geodetic latitude
ellipsoidal latitude
φ
angle from the equatorial plane to the perpendicular to the ellipsoid through a given point, northwards treated as positive

[ISO 19111:2007, definition 4.25]

4.31
geodetic longitude
ellipsoidal longitude
λ
angle from the prime meridian plane to the meridian plane of a given point, eastward treated as positive

[ISO 19111:2007, definition 4.26]

4.32
geoid
equipotential surface of the Earth's gravity field which is everywhere perpendicular to the direction of gravity and which best fits mean sea level either locally or globally

[ISO 19111:2007, definition 4.27]

4.33
geographic information
information concerning phenomena implicitly or explicitly associated with a location relative to the Earth

[ISO 19101:2002, definition 4.16]

4.34
geolocating
geopositioning an object using a **Physical Sensor Model** or a **True Replacement Model**

4.35
geolocation information
information used to determine geographic location corresponding to **image** location

[ISO 19115-2:2009, definition 4.11]

4.36
geopositioning
determining the geographic position of an object

NOTE While there are many methods for geopositioning, this Technical Specification is focused on geopositioning from **image coordinates**.

4.37
georeferencing
geopositioning an object using a **Correspondence Model** derived from a set of points for which both ground and **image coordinate**s are known

4.38
gimbal
mechanical device consisting of two or more rings connected in such a way that each rotates freely around an axis that is a diameter of the next ring toward the outermost ring of the set

NOTE An object mounted on a three-ring gimbal will remain horizontally suspended on a plane between the rings regardless as to the stability of the base.

4.39

grazing angle

⟨SAR⟩ vertical angle from the local surface tangent plane to the **slant range** direction

4.40

grid

network composed of two or more sets of curves in which the members of each set intersect the members of the other sets in an algorithmic way

[ISO 19123:2005, definition 4.1.23]

NOTE The curves partition a space into grid cells.

4.41

grid coordinates

sequence of two or more numbers specifying a position with respect to its location on a **grid**

[ISO 19115-2:2009, definition 4.16]

4.42

ground control point

point on the earth that has an accurately known geographic position

[ISO 19115-2:2009, definition 4.18]

4.43

ground range

⟨SAR⟩ magnitude of the **range vector** projected onto the ground

NOTE Ground range of an **image** is represented by the distance from the nadir point of the antenna to a point in the scene. Usually measured in the horizontal plane, but can also be measured as true distance along the ground, DEM, **geoid** or **ellipsoid** surface.

4.44

GRP

ground reference point

3D position of a reference point on the ground for a given synthetic aperture

NOTE It is usually the centre point of an **image** (Spotlight) or an image line (Stripmap). It is usually expressed in ECEF **coordinates** in metres.

4.45

ground sampling distance

linear distance between **pixel** centres on the ground

NOTE This definition also applies for water surfaces.

4.46

gyroscope

device consisting of a spinning rotor mounted in a **gimbal** so that its axis of rotation maintains a fixed orientation

NOTE The rotor spins on a fixed axis while the structure around it rotates or tilts. In airplanes, the pitch and orientation of the airplane is measured against the steady spin of the gyroscope. In space, where the four compass points are meaningless, the gyroscope's axis of rotation is used as a reference point for navigation. An inertial navigation system includes three gimbal-mounted gyroscopes, used to measure roll, pitch, and yaw.

4.47

image

gridded coverage whose **attribute** values are a numerical representation of a physical parameter

[ISO 19115-2:2009, definition 4.19]

NOTE The physical parameters are the result of measurement by a **sensor** or a prediction from a model.

4.48
image coordinate reference system
coordinate reference system based on an **image datum**

[ISO 19111:2007, definition 4.30]

4.49
image datum
engineering **datum** which defines the relationship of a **coordinate system** to an **image**

[ISO 19111:2007, definition 4.31]

4.50
image distortion
deviation between the actual location of an **image point** and the location that theoretically would result from the geometry of the imaging process without any errors

4.51
image formation
⟨SAR⟩ process by which an **image** is generated from collected Phase History Data in a **SAR** system

4.52
image-identifiable ground control point
ground control point associated with a marker or other object on the ground that can be recognized in an **image**

NOTE The ground control point may be marked in the image, or the user may be provided with an unambiguous description of the ground control point so that it can be found in the image.

4.53
image plane
plane behind an imaging lens where **images** of objects within the depth of field of the lens are in focus

4.54
image point
point on the **image** that uniquely represents an **object point**

4.55
imagery
representation of phenomena as **images** produced by electronic and/or optical techniques

[ISO/TS 19101-2:2008, definition 4.14]

NOTE In this Technical Specification, it is assumed that the phenomena have been sensed or detected by one or more devices such as radars, cameras, photometers and infrared and multispectral scanners.

4.56
impulse response
width of the return generated by a small point reflector, which equates to the smallest distance between two point reflectors that can be distinguished as two objects

4.57
incident angle
vertical angle between the line from the detected element to the **sensor** and the local surface normal (tangent plane normal)

4.58
internal coordinate reference system
coordinate reference system having a **datum** specified with reference to the object itself

4.59
metadata
data about data

[ISO 19115:2003, definition 4.5]

4.60
object point
point in the object space that is imaged by a **sensor**

NOTE In **remote sensing** and aerial photogrammetry an object point is a point defined in an Earth-fixed **coordinate reference system**.

4.61
passive sensor
sensor that detects and collects energy from an independent source

EXAMPLE Many optical sensors collect reflected solar energy.

4.62
perspective centre
projection centre
point located in three dimensions through which all rays between **object points** and **image points** appear to pass geometrically

4.63
Physical Sensor Model
sensor model based on the physical configuration of a sensing system

4.64
pixel
smallest element of a digital **image** to which **attributes** are assigned

[ISO/TS 19101-2:2008, definition 4.28]

NOTE 1 This term originated as a contraction of “picture element”.

NOTE 2 Related to the concept of a **grid** cell.

4.65
platform coordinate reference system
engineering **coordinate reference system** fixed to the collection platform within which positions on the collection platform are defined

4.66
principal point of autocollimation
point of intersection between the **image plane** and the normal from the **perspective centre**

4.67
principal point of best symmetry
centre of the circles of equal distortion of the lens positioned in the **image plane**

4.68
pushbroom sensor
sensor that collects a single **cross-track image** line at one time and constructs a larger image from a set of adjacent lines resulting from the **along-track** motion of the sensor

4.69
range bin
⟨SAR⟩ group of radar returns that all have the same range

4.70
range direction
slant range direction
⟨SAR⟩ direction of the **range vector**

4.71
range resolution
spatial **resolution** in the **range direction**

NOTE For a **SAR sensor**, it is usually measured in terms of the **impulse response** of the sensor and processing system. It is a function of the bandwidth of the pulse.

4.72
range vector
vector from the antenna to a point in the scene

4.73
rectified grid
grid for which there is an affine transformation between the **grid coordinates** and the **coordinates** of an **external coordinate reference system**

[ISO 19123:2005, definition 4.1.32]

NOTE If the **coordinate reference system** is related to the Earth by a **datum**, the grid is a georectified grid.

4.74
remote sensing
collection and interpretation of information about an object without being in physical contact with the object

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

4.75
resolution (of a sensor)
smallest difference between indications of a **sensor** that can be meaningfully distinguished

[ISO/TS 19101-2:2008, definition 4.34]

NOTE For **imagery**, resolution refers to radiometric, spectral, spatial and temporal resolutions.

4.76
SAR
Synthetic Aperture Radar
imaging radar system that simulates the use of a long physical antenna by collecting multiple returns from each target as the actual antenna moves along the track

NOTE The electromagnetic radiation is at microwave frequencies and is sent in pulses.

4.77
scan mode
SAR mode in which the antenna beam is steered to illuminate a swath of ground at various angles relative to flight path throughout the collection

NOTE Steering the antenna also allows dwell time to be increased and provides the ability to collect strips at angles non-parallel to the flight direction and with better resolution than **Stripmap mode**.

4.78
ScanSAR mode
special case of **stripmap mode** that uses an electronically steerable antenna to quickly change the swath being imaged during collection to collect multiple parallel swaths in one pass

4.79
sensor
element of a measuring system that is directly affected by a phenomenon, body, or substance carrying a quantity to be measured

[ISO/IEC Guide 99:2007, definition 3.8]

4.80
sensor model
⟨geopositioning⟩ mathematical description of the relationship between the three-dimensional object space and the two-dimensional plane of the associated **image** produced by a **sensor**

4.81
slant plane
⟨SAR⟩ plane that passes through the **sensor** velocity vector and the GRP

4.82
slant range
⟨SAR⟩ magnitude of the **range vector**

4.83
spotlight mode
⟨SAR⟩ **SAR** mode in which the antenna beam is steered to illuminate one area during collection

NOTE Spotlight mode provides the ability to collect higher resolution SAR **data** over relatively smaller patches of ground surface.

4.84
squint angle
⟨SAR⟩ angle measured from the **broadside** direction vector to the **range direction** vector in the **slant plane**

4.85
stripmap mode
⟨SAR⟩ **SAR** mode in which the antenna beam is fixed throughout the collection of an **image**

NOTE **Doppler angle** in processed products is fixed for all **pixels**. It provides the ability to collect SAR **data** over strips of land over a fixed swath of **ground range** parallel to the direction of flight.

4.86
True Replacement Model
model using functions whose coefficients are based on a **Physical Sensor Model**

4.87
whiskbroom sensor
sensor that sweeps a **detector** forming **cross-track image** line(s) and constructs a larger image from a set of adjacent lines using the **along-track** motion of the sensor’s collection platform

5 Symbols and abbreviated terms

5.1 Abbreviated terms

ARP	Aperture Reference Point
CCD	Charge-Coupled Device
CCS	Common Coordinate System

CM	Correspondence Model
CRS	Coordinate Reference System
DEM	Digital Elevation Model
DLT	Direct Linear Transform
ECEF	Earth-Centred, Earth-Fixed
ENU	East-North-Up
EO	Exterior Orientation
FSP	Flight Stabilization Platform
GCP	Ground Control Point
GNSS	Global Navigation Satellite System
GRP	Ground Reference Point
GSD	Ground Sample Distance
IMU	Inertial Measurement Unit
INS	Inertial Navigation System
IRF	Inertial Reference Frame
IPR	Impulse Response
IR	Infrared
MSL	Mean Sea Level
NED	North-East-Down
PHD	Phase History Data
PSM	Physical Sensor Model
RAR	Real Aperture Radar
RMS	Root Mean Square
RPC	Rational Polynomial Coefficient
RSM	Replacement Sensor Model
SAR	Synthetic Aperture Radar
SCS	Sensor Coordinate System
TRM	True Replacement Model
WGS 84	World Geodetic System 1984
2D	Two-dimensional
3D	Three-dimensional

5.2 Notation

Clauses 6, 7, and 8 of this Technical Specification present a conceptual schema, specified in the Unified Modeling Language (UML), describing the characteristics of sensor models. ISO/TS 19103 describes the way in which UML is used in the ISO 19100 family of standards. It differs from standard UML only in the existence and interpretation of some special stereotypes, in particular, “CodeList” and “Union”. ISO/TS 19103 specifies the basic data types used in the UML model and the data dictionary in this Technical Specification.

Annex B contains a data dictionary for the UML diagrams in this schema.

ISO/TS 19103 requires that names of UML classes, with the exception of basic data type classes, include a two-letter prefix that identifies the standard and the UML package in which the class is defined. Table 2 lists the prefixes used in this Technical Specification, the International Standard in which each is defined and the package each identifies. UML classes defined in this Technical Specification belong to a package named Sensor Data and have the two letter prefix SD.

Table 2 — UML class prefixes

Prefix	Standard	Package
CI	ISO 19115	Citation
CV	ISO 19123	Coverages
DQ	ISO 19115	Data quality
GM	ISO 19107	Geometry
MD	ISO 19115	Metadata
MI	ISO 19115-2	Metadata for Imagery
SC	ISO 19111	Spatial Coordinates
SD	ISO 19130	Sensor Data
TM	ISO 19108	Temporal Schema

6 Image geopositioning: overview and common elements

6.1 Introduction

An “image” is a two-dimensional set of contiguous pixels. Associated with each pixel in the image is either a single response value, as in a panchromatic image; three response values in red, green, and blue, as in a colour image; or many values, as in multi-and hyper-spectral images. Geopositioning information applies to the pixel, regardless of how many response values are associated with that pixel.

Image geopositioning is the process of determining the Earth coordinates of an object from image coordinates. Geolocation information is the information necessary for the geopositioning methods to work. Features in Earth imagery can be geopositioned by different approaches. The data provider shall identify to the user which method was used.

In order to determine the three-dimensional Earth coordinates of features and the quality associated with those coordinates (rigorously expressed by covariance matrices) accurately, two approaches exist, both ultimately based on the physical configuration of the sensor:

a) Physical Sensor Models (PSMs)

b) True Replacement Models (TRMs)

A third approach is based on:

c) Correspondence Models (CMs)

The most rigorous approach for geopositioning of imagery is to use the mathematical representation of the physics and geometry of the image sensing system, which is referred to as the Physical Sensor Model. That model is used extensively in photogrammetric applications for precise geopositioning. In order to precisely determine geoposition from imagery, certain steps need to be performed. The first and most fundamental step is to construct, mathematically, the sensor model that corresponds to the type of sensor under consideration. Then, information relating the sensing event to the ground reference coordinate system is needed to apply the model to a given image. This information can be in one of two forms:

a) accurate data about the position, attitude, and dynamics of the sensor during imaging; or

b) ground control information such as a set of Global Navigation Satellite System (GNSS)-determined ground control points (GCPs).

TRMs are produced using Physical Sensor Models. The equations that describe the sensor and its relationship to the Earth coordinate reference system are replaced with a set of equations that directly describe the relationship between image coordinates and Earth coordinates.

Geopositioning that applies correspondence modelling, called georeferencing, uses image information and ground control points only. CMs are quite varied and may deal with only horizontal (e.g., longitude and latitude) coordinates, or with all three coordinates (e.g., longitude, latitude and elevation). They all have in common the fact that they do not make use of the Physical Sensor Model and consequently cannot apply rigorous error propagation. Thus, Correspondence Models are generally less accurate than methods based on Physical Sensor Models. Neither a geometric model of the sensor that took the image nor information about its position and orientation is required. This georeferencing method has been widely applied to remotely sensed imagery. For instance, the geographic location of an image can be established using a two-dimensional polynomial function based on a number of common points that relate the image to the surface of the Earth. The simplest way to georeference an image is by defining the Earth coordinates of the image corners.

This Technical Specification defines the geopositioning information for supporting the above-stated approaches for geopositioning images. Clause 7 covers the Physical Sensor Model approach and Clause 8 covers True Replacement Models and Correspondence Models.

6.2 Type of geopositioning information

Geopositioning information shall be provided in one of the ways shown in Figure 1:

a) A set of ground control points (MI_GCPCollection) and optional quality information as specified in ISO 19115-2 and further specified in 6.4 of this Technical Specification. The recipient can use this information to generate his own fitting function for use in a Correspondence Model.

b) A sensor model (SD_SensorModel) as specified in this Technical Specification. An instance of SD_SensorModel provides geopositioning information for the single image identified by the attribute forImageID. SD_SensorModel is an aggregate of one or more instances of one, but no more than one, of the three sensor model types specified in this Technical Specification. This allows for spatial segmentation of the image such that there is one instance of the model type for each segment. The three specified sensor model types are:

   1) Physical Sensor Model (SD_PhysicalSensorModel),

   2) True Replacement Model (SD_TrueReplacementModel), and

   3) Correspondence Model (SD_CorrespondenceModel).

The classes shown in Figure 1, their attributes and their associations shall be used as specified in the data dictionary of B.2.1.

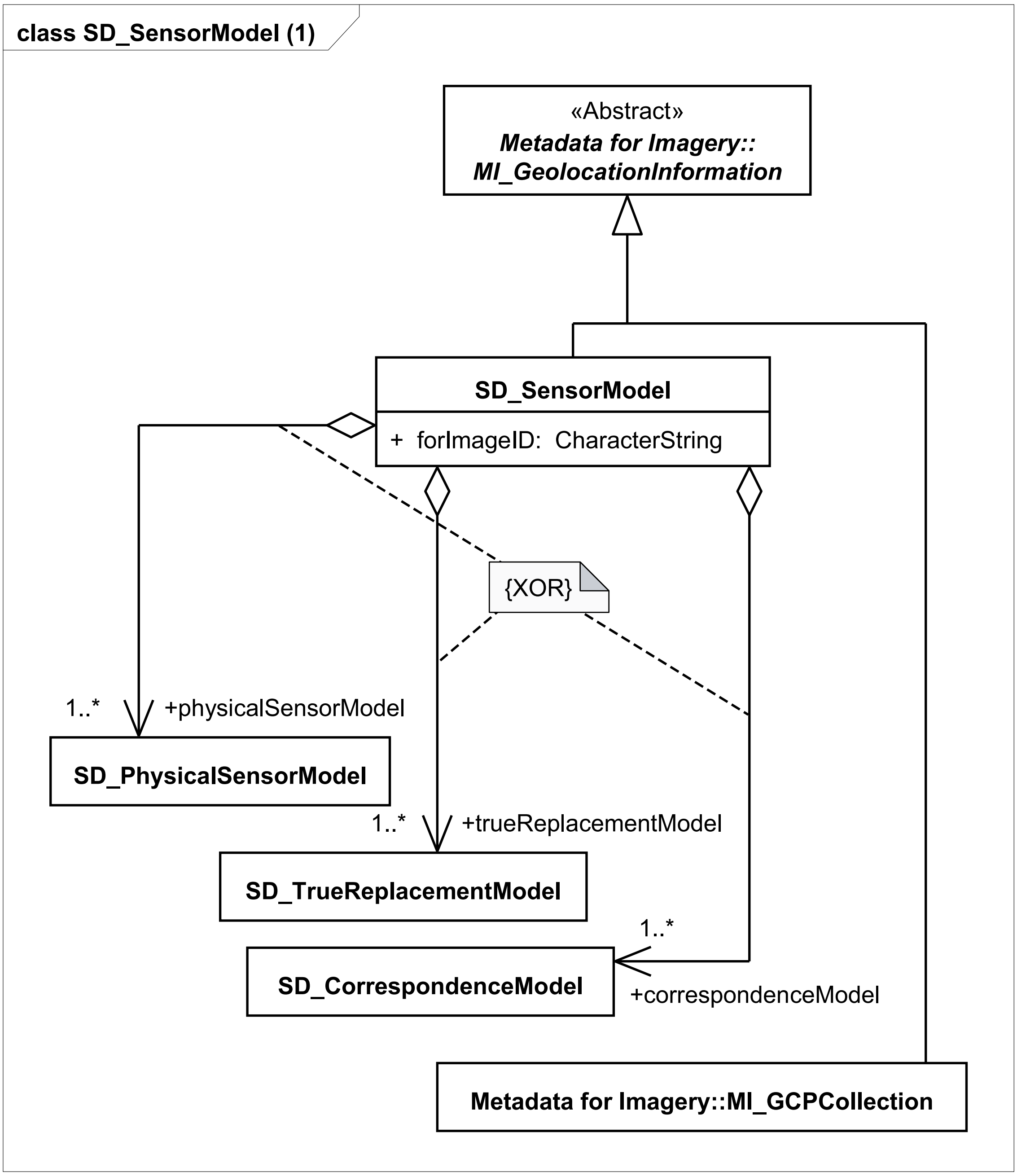


Figure 1 — SD_SensorModel

6.3 Calibration data

6.3.1 Introduction

Sensor calibration is a significant input to sensor modelling. There are two types of calibration data: geometric and radiometric. Geometric calibration data is critical for precise geopositioning from imagery. Radiometric calibration is needed for quantitative estimation of geophysical parameters and interpretation of the physical and geographical significance of the measurements.

6.3.2 Geometric calibration

Sensor geometric calibration data are either available in the metadata from laboratory calibration or can actually be determined during photogrammetric processing of the imagery. Calibration parameters are defined according to the type of sensor. For electro-optical sensors, common parameters include calibrated focal length, principal point offset, radial lens distortion coefficients, tangential or decentring lens distortion coefficients and sensor array distortions such as differential scale and skew.

6.3.3 Radiometric calibration

Radiometric calibration refers to operations intended to remove systematic or random noise that affect the amplitude of the image function. Radiometric calibration includes correcting the data for sensor irregularities and unwanted sensor or atmospheric noise, and converting the data so they accurately represent the reflected or emitted radiation measured by the sensor.

This specification is concerned with those aspects of radiometric calibration that involve adjustment of the non-uniform response of the different elements of the sensor array to improve the relative spectral and temporal fidelity of the current data acquisition. In particular, the process which normalizes these responses and the values from in-flight and laboratory measured pre-flight radiometric empirical adjustments shall be available.

The image location of pixels corresponding to failed or degraded detectors and line losses as well as the methods used to address such failure or degradation shall also be recorded and available.

Except for atmospheric correction, radiometric corrections for environmental effects due to seasons, terrain, sensor operation, and sampling methods within and across data acquisitions are outside the scope of this document.

6.4 Ground control points

6.4.1 Introduction

As specified by ISO 19115-2, geolocation information may consist of no more than a collection of ground control points. In that approach, a set of ground control points and their corresponding image points are identified and provided to the user, who can then derive the object (ground) coordinates of other image points based on these correspondences. The method used for the derivation of these additional point coordinates is left to the user’s choice, depending upon the application. For example, a 3D-to-2D or 2D-to-2D function may be first fit, for 3D and 2D control, respectively, and then the function used to calculate the coordinates of the additional points. Alternatively, an interpolation scheme may be used such as nearest neighbour, bilinear or bicubic for 2D; and trilinear or triquadratic for 3D.

NOTE For 3D-to-2D transformations, it is not possible to derive the 3D object coordinates of an additional point from a single image

However, ground control points are also used in the development of sensor models and may be provided as ancillary information with any sensor model. They are often used to adjust the values of parameters for Physical Sensor Models and True Replacement Models and are the basis from which a Correspondence Model is developed.

6.4.2 Control point types

A full GCP consists of three parameters: two horizontal coordinates, (X, Y) and one vertical coordinate (Z). A horizontal GCP has no vertical coordinate and a vertical GCP has horizontal coordinates. A few horizontal GCPs may suffice for small scale applications with limited accuracy requirements. More points and full GCPs are required for greater accuracy.

The use of ground control points to georeference an image requires knowledge of both the object space coordinates of a point on the ground and the position of the image of that point in an image. There are two mechanisms for specifying the image position.

One method is to mark the ground control point in the image or to provide the user an unambiguous description of the ground control point so that the user can find the image of the ground control point and determine its image coordinates. A common mechanism for doing this is to place a distinctive marker on the ground prior to image acquisition. The ground control point might also be associated with an image-identifiable feature on the ground.

The second method is to provide previously determined image coordinates for each ground control point. Often, the image coordinates of these points are determined by using a Physical Sensor Model. This means is often used because the organization responsible for image acquisition does not wish to reveal detailed characteristics of the sensor to users of the imagery.

There are also two mechanisms for providing ground control point information to the user. One is to provide all information with the image; the other is to provide a pointer to a remote source of the information. The second method is often used when the image provider wishes to provide a functional fit model and to restrict access to information about the ground control points.

6.4.3 Control point schema

Figure 2 presents a UML model for ground control points. The classes shown in Figure 2, their attributes and their associations shall be used as described in the data dictionary of B.2.2 and in ISO 19107, ISO 19115, ISO 19115-2 and ISO 19123.

MI_GCPCollection is a set of ground control points as defined in ISO 19115-2.

The class MI_GCP specifies a ground control point as defined in ISO 19115-2. The attribute geographicCoordinates provides the ground coordinates of the ground control point using the data type DirectPosition specified in ISO 19107. DirectPosition has an association to the coordinate reference system to which the position is referenced.

The subclass SD_LocationGCP specifies a ground control point for which image coordinates have been determined. The attribute gridCoordinates contains those coordinates using the data type CV_GridCoordinates specified in ISO 19123.

The subclass SD_ImageIdentifiableGCP specifies a ground control point that is either marked in the image or described so that the user can find its image. The attribute description provides a description of the ground control point sufficient to enable the user to find the image of the ground control point in the image to be geopositioned.

The class SD_GCPRepository is an optional library of ground control points that may be used as a remote source of control point information if such information is not provided with the image. The attribute accessRestricted indicates that the image provider wishes to control or restrict access to the ground control point data. A value of 'true' indicates that access is restricted, while a value of 'false' indicates that the data is publicly available. The attribute accessInformation uses the data type CI_Contact specified in ISO 19115. If access is restricted, this attribute provides information for a point of contact who may authorize access to the data; if access is unrestricted, the attribute identifies the mechanism for obtaining the ground control point data.

The class SD_GriddedGCPCollection represents a collection of instances of SD_LocationGCP that is structured as a rectified grid. The GCPs can be regularly spaced either in image space defined by SD_ImageGridGCPCollection, where CV_GridCoordinates defines the location of the first GCP in the image space, or in an object space defined by SD_ObjectGridGCPCollection, where DirectPosition is the origin of the grid in object space.

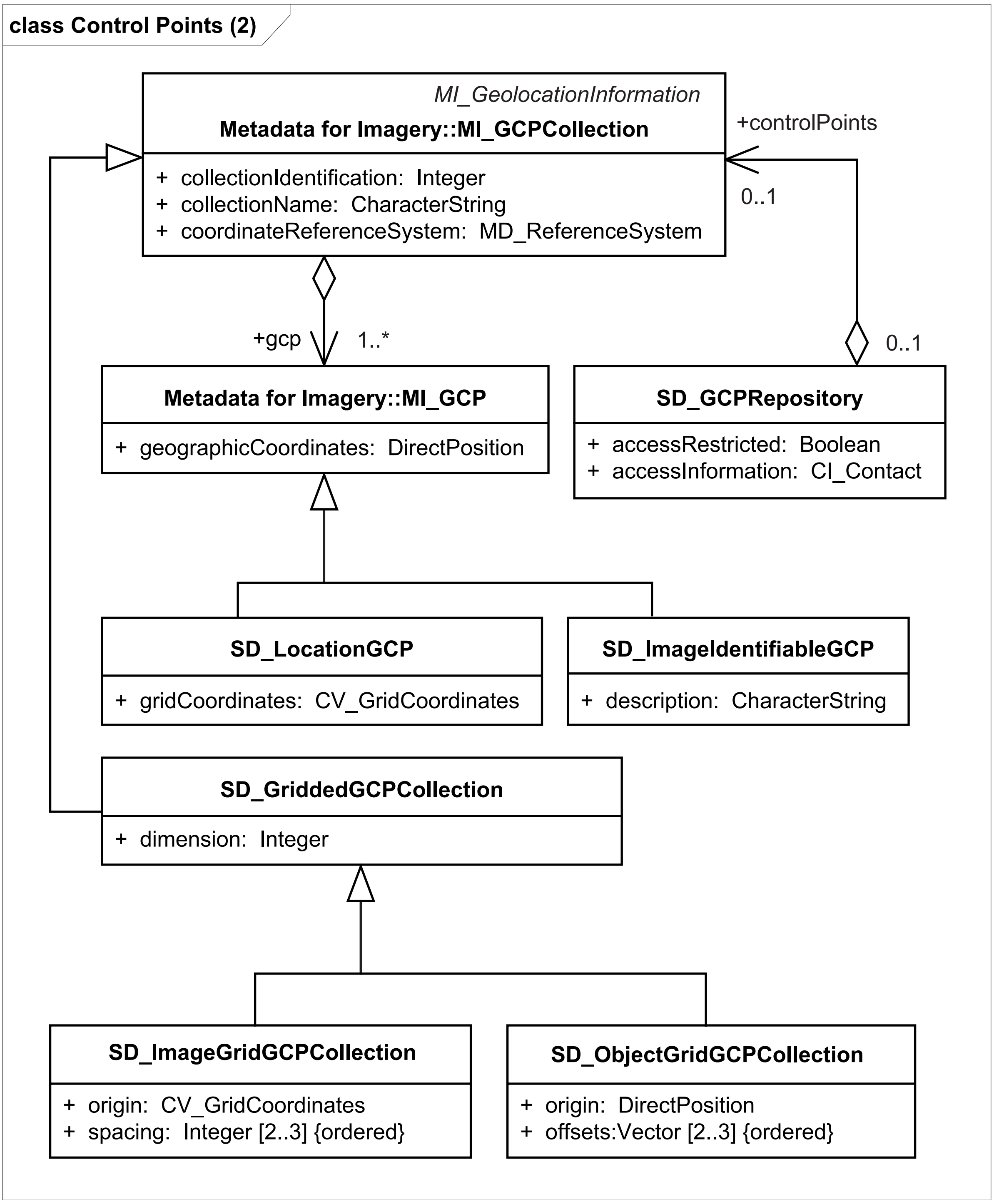


Figure 2 — GCP model

7 Physical Sensor Models

7.1 Sensor types

7.1.1 Introduction

Remote sensors can be classified in different ways. They can be classified, for example, by their mounting platforms, such as spaceborne and airborne, or by the measurand of the sensor, e.g., optical radiation, microwave energy, sonar (acoustic) energy.

A sensor collects radiation and reports its intensity, usually as a function of position. Separate components generally perform the functions that are part of the process. A pointing system determines the direction from which radiation comes. An optical or antenna system collects the radiation incident on the instrument and directs it to the detector. A detector measures the intensity of the incident radiation. Each type of sensor has its own components to perform these functions. Parameters describing components such as the imaging focal plane and sensor coordinate systems, the positions of these two coordinate systems, and the angles and offset between them are used in geolocating. Precise geolocation requires information about the quality (ISO 19113) of the parameters.

Sensor systems and their components are described in 7.1.2 through 7.1.5. Positions of and in a sensor system shall be expressed in a coordinate system as defined in Annex C. Geolocation using each of the sensor types is described in greater detail in an informative annex for that type.

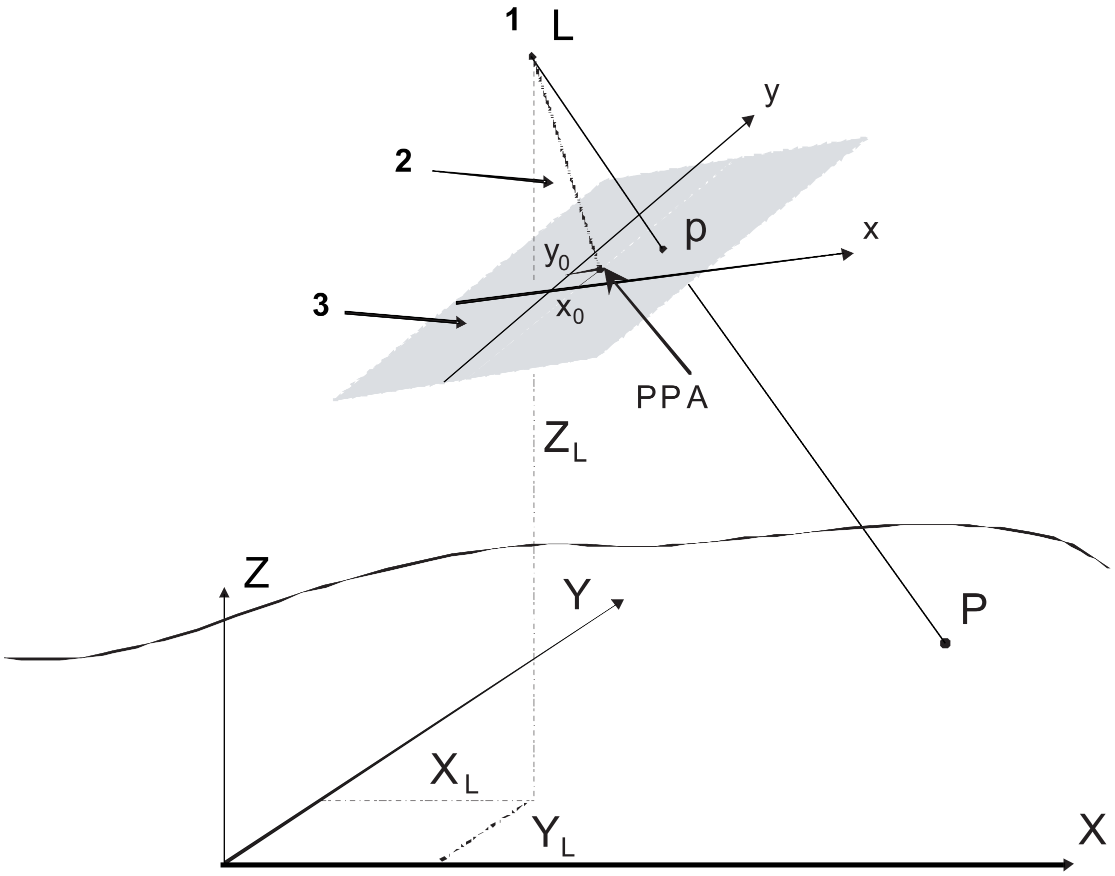
7.1.2 Frame sensor

A frame sensor is one that acquires all of the data for an image (frame) at a single instant of time. Typically, a sensor of this class has a fixed exposure and consists of a two-dimensional detector array, e.g., a Charge-Coupled Device (CCD) array. While “sensor” refers to digital collectors, “camera” is typically used to denote film-based collectors. Although the descriptions in this Technical Specification are of electro-optical (visible/near infrared) frame sensors, the definitions and development apply equally to film and thermal infrared (IR) array sensors.

A film camera is called a frame camera if it has a frame with fiducial marks that allow the determination of the position of the film in the sensor coordinate reference system. During the exposure, the fiducial marks are imaged on the film border. For the purposes of this Technical Specification, a frame camera is treated as a source of digital data. An image recorded on film needs to be scanned if a digital image is desired. The images of the fiducial marks allow for the three-dimensional algorithmic reconstruction of the perspective centre. This leads to the complete reconstruction of the bundle of the rays to all object points. After the film has been scanned, the position of every pixel of the image is known or can be determined in the area sensor coordinate reference system. A digital frame sensor has sensor elements that have individual known positions in the area sensor coordinate reference system.

Frame sensors with several heads are in use. Joining the partial images is a matter of the individual post-processing software of the sensor system. This Technical Specification always refers to the complete image, independent of whether it is joined partial images or taken at one shot such as a film image.

Figure 3 depicts the geometry of a frame sensor. With frame sensors, the central perspective model relates image points to object points. This model represents all light rays from the object, e.g. the surface of the Earth, to the image as running through one single point that is called the perspective centre L. To allow reconstruction of every ray according to its point measurement on the image plane, the three-dimensional position of the perspective centre L in relation to the image plane shall be provided. This relation shall be established through a three-dimensional image coordinate reference system in which both the image point and the perspective centre can be expressed. In the case of a frame camera, the relation of the image coordinate reference system to the image is defined by the calibrated positions of the fiducial marks. The three-dimensional position of the perspective centre is defined by the coordinates of the principal point of autocollimation (PPA), x_0 and y_0 and by the calibrated focal length f_c (z-value). The origin of the x, y, z coordinate system in Figure 3 is shifted from the Indicated Principal Point, IPP (or fiducial centre) to the PPA (see Figure C.12).



Key

1 Sensor perspective centre
2 Calibrated focal length, f_c
3 Positive image plane

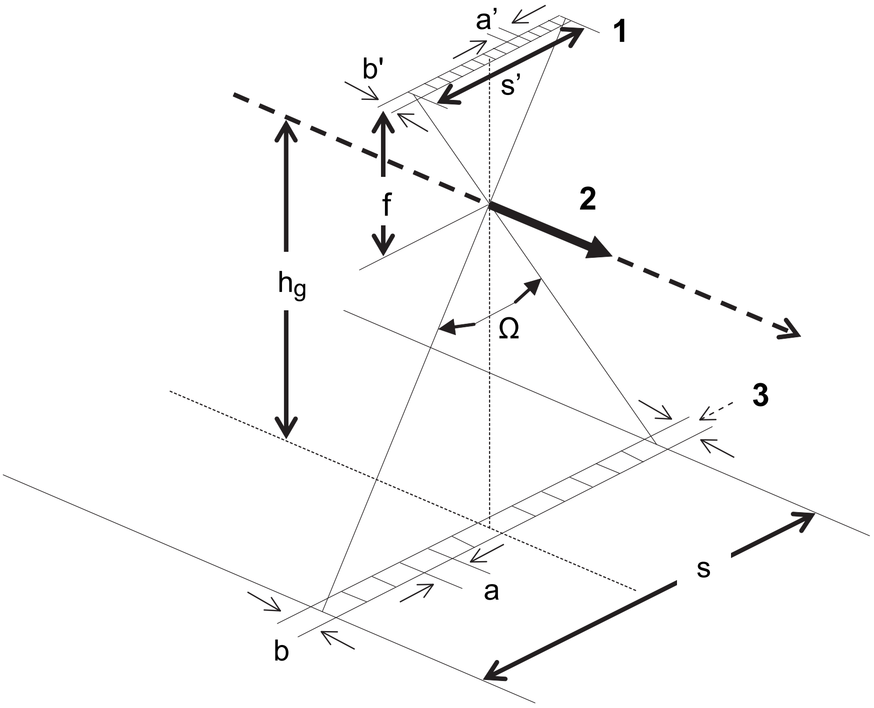
Figure 3 — Frame sensor image and perspective centre

Frame sensors are discussed in more detail in Annex D.

7.1.3 Pushbroom sensor

A pushbroom sensor is a digital collector with a collection array made up of a line of detectors at the focal plane to scan over a two dimensional scene. For the pushbroom sensor model, the along track displacement of all recorded pixels of a scan line is set to zero. For the across track pixel coordinates, a constant spacing of successive pixels is assumed. A typical pushbroom sensor contains one or more linear arrays of detectors. The array is lined up perpendicular to the direction of platform motion, allowing the sensor to simultaneously collect and record data for a complete line of samples. In Figure 4, f is the calibrated focal length, h_g height above surface, s the swath width, s' the length of the detector array, Ω the field of view, a' the sensor detector size in the cross-track direction and the corresponding image plane field of view (IFOV), a the ground sample distance (GSD) across track, b' the sensor detector size in the along track direction and the corresponding image plane field of view and $b = v\Delta t$ the ground sample distance (GSD) along track, where v is the along-track platform velocity and Δt is the dwell time.

To obtain geolocation using a Physical Sensor Model for a pushbroom sensor, it is necessary to know its geometric properties, including the focal plane coordinate system and the number, size and spatial distribution of detectors. If the data provider intends to let the data users derive geolocation using a Physical Sensor Model, this information shall be provided to them. Pushbroom sensors are described in more detail in Annex E.



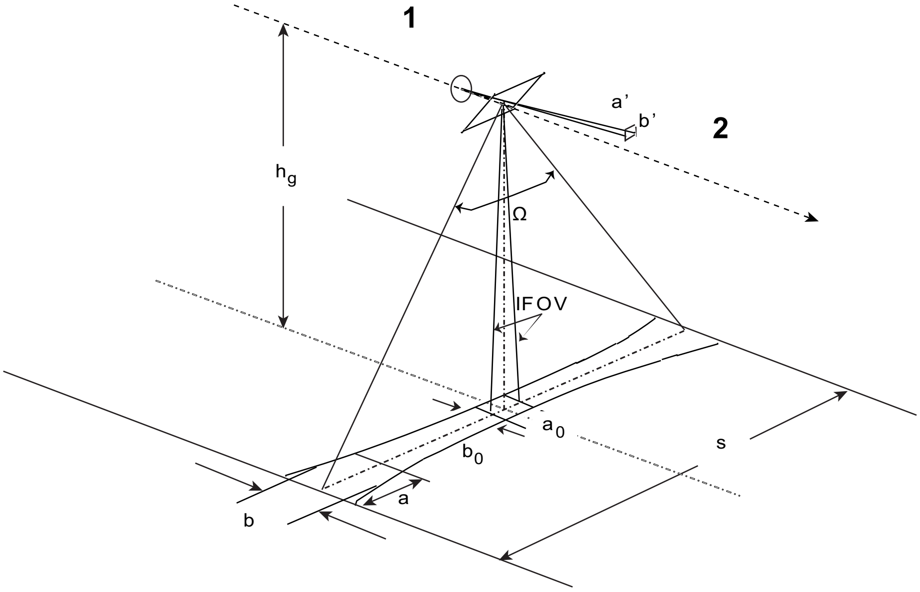
Key

1 Focal plane
2 Velocity vector
3 Corresponds to Δt

Figure 4 — Optical layout of a pushbroom array

7.1.4 Whiskbroom sensor

A whiskbroom scanning sensor has one or more detectors scanning perpendicular to the platform moving direction, allowing the sensor to simultaneously take one or more scan lines of data during a scan, as shown in Figure 5. In Figure 5, h_g is height above ground, s the swath width, Ω the swath field of view, IFOV the instantaneous field of View, a' and b' the dimensions of the sensor detector size, a_0 the GSD across track, $b_0 = v\Delta t$ the GSD along track, v the platform velocity and Δt the dwell time. Whiskbroom sensors are described in more detail in Annex E.



Key

1 Optical system
2 Focal plane

Figure 5 — Optical layout of a whiskbroom scanning sensor

7.1.5 Synthetic aperture radar

Remote sensing systems using radar (radio detection and ranging) send radio signals towards an object and measure the intensity and phase of the reflected wave. The time and the phase difference between the sending of the signal and its return provide the distance to the object. With the measurement of the time it takes for a signal transmitted by an antenna to return to that antenna (or, in some cases, a different antenna), as well as the magnitude of the returned signal, as shown in Figure F.2. being combined with the position and attitude of the sensor, the position of a target object can be derived. The intensity of the reflectance allows different types of surfaces to be distinguished.

Synthetic Aperture Radar (SAR) is a kind of radar that uses a series of radar pulses transmitted and received over time from a moving platform to create an image. SAR differs from other kinds of radars, known as Real Aperture Radars, by creating a large virtual antenna, known as the synthetic aperture, that allows tight focusing of the virtual beam in the along-track direction.

In SAR, the size of the antenna is synthetically enlarged by treating a series of returns from a much smaller physical antenna that is moving relative to the target as one long antenna (aperture). The distance the platform moves in synthesizing the antenna is known as the synthetic aperture. By synthesizing a large array, SAR can enjoy the benefits of improved angular resolution that come with large physical antennas without the technical and physical problems associated with them. In fact, much larger synthetic apertures can be formed than would be possible using a real physical antenna. This method improves the geometric resolution of the system considerably. Real Aperture Radar (RAR) images points along a line perpendicular to the flight track; it takes advantage of the Doppler shift of the reflected radiation to filter out returns from points ahead of or behind that line. SAR uses the Doppler shift together with the return time to determine the position (angle and distance) from which the return was reflected; because of that, it can sum the returns received from any given point over the time in which the physical antenna is moved along the length of the synthetic antenna.

Raw SAR data can be processed into many products, one of which, known as a "detected image", is commonly referred to as a SAR image. SAR geopositioning is primarily dependent upon the accurate measurement of the sensor position and sensor velocity, with acceleration being a secondary factor. SAR geometric sensor models are completely independent of the sensor's pointing attitude. This behaviour is quite different from geopositioning with passive light-sensing systems, such as frame and pushbroom sensors, because SAR images or other products are created by processing the radar signal's time and frequency characteristics, rather than physical pointing characteristics. Only the quality of the product (e.g., noise level, dynamic range) is a function of the pointing direction of the antenna, since the magnitude of the returned signal depends upon the amount of energy illuminating the region processed into the image, which is a function of the antenna beam pointing. (This is analogous to a camera with an independently pointed light source, in which the camera can point in any direction, but the quality of the image depends upon where the light is pointing relative to the camera.) Annex F describes SAR imaging in more detail. 7.6.5 describes content that shall be provided in order to geolocate SAR images.

ISO/TS 19101-2:2008, 7.1.4.1 has discussed the resolution of imagery. The spatial resolution of a SAR system is measured in terms of the system's Impulse Response (IPR). This is the width of the return generated by a small point reflector, which equates to the smallest distance between two point reflectors that can be distinguished as two objects shown in Figure F.1.[13] SAR images are very often oversampled in order to retain as much information as possible. The Nyquist–Shannon Sampling Theorem states that exact reconstruction of a continuous-time baseband signal from its samples is possible if the signal is band limited and the sampling frequency is greater than twice the signal bandwidth.

The minimum sampling rate is sometimes referred to as the *Nyquist Rate* or the *Nyquist Frequency*. This theorem also applies to spatial signals, such as images, and the practical application of this to imaging is that in order to retain all of the information acquired by a sensor (e.g., radar or optical), the image should be sampled at twice the resolution of the signal reaching the sampling device. Other considerations, such as cost, efficiency and value, may result in decisions to sample at lower rates. For SAR, it is common to see sampling rates in the range from the Nyquist Rate to 1/2 the Nyquist Rate, which translates to GSDs of 1/2 the IPR width to the IPR width, respectively. From the standpoint of SAR photogrammetry, the GSD of the pixels is more important than the IPR; although understanding the range and azimuth resolution equations is fundamental to the photogrammetric process.

The spatial resolution in the range direction (i.e., radially away from the antenna) is dependent upon the ability to measure the pulse arrival times. These times can be measured with high accuracy in modern radar systems. When a radar system is used to image the ground, the term *slant range resolution* is used to refer to the resolution in the range direction. Ground range resolution, r_{GR}, refers to the resolution of the radar information projected onto the ground surface, which varies with the grazing angle – the angle between the ground surface and the direction of travel of the radar energy (Equation (F.2)). Thus, the ground range resolution is always coarser than the slant range resolution, and the ground range resolution is poorer (i.e., decreasing resolvability) at nearer ranges when the platform is at constant height (Figure F.3). This situation is opposite of the range-to-resolution relationship for optical systems. As the ground range nears zero (i.e., the sensor is pointed nearly straight down), the $cos(\gamma)$ term in Equation (F.2) goes to zero and the range resolution approaches infinity. This explains why radar imaging systems cannot image directly along the ground track of the aircraft, and why they have a near-range limit for practical utility. This is often set to around a 60° grazing angle, at which the ground range resolution is twice the slant range resolution.

Real Aperture Radar systems change the position or pointing of the antenna in order to measure signal returns in different directions. Their resolution in the direction of rotation or translation, known as azimuth resolution, r_A, is dependent upon the width of the beam at the target (Equation F.3). Since the azimuth resolution is inversely proportional to antenna size and proportional to range to the target, long range imaging at even moderate resolution may require an antenna size that exceeds what can be practically built and carried on an aircraft. The invention of Synthetic Aperture Radar resolved this problem by using motion of the radar to synthesize a very large antenna.

SAR systems employ a chirped pulse, which imposes a frequency modulation on each radar pulse. Using this technique, the radar can better distinguish between overlapping pulses (Equation F.4). Chirped pulses are used by many types of radars, not just SARs.

7.2 Physical Sensor Model approach

7.2.1 Physical Sensor Model introduction

This approach is the most fundamental way of modelling the relationship between image space and object (ground) space coordinates. The PSM uses information on the sensor's properties, attitude and position to mathematically derive the geometric relationship between the location of any pixel in the image and its location in the object (ground). This mathematical description is in the form of equations that relate pixel (line, sample) coordinates to the their corresponding three-dimensional ground coordinates, either geographic (λ, φ, h) or Cartesian (X,Y,Z).

7.2.2 Physical Sensor Model parameters

The mathematical functions describing the PSM contain the most important parameters involved in image acquisition, both

a) internal sensor characteristics (such as focal length, principal point offset, pixel size and distortion coefficients), and

b) external parameters dependent upon the collection platform (such as sensor location in the object space, sensor orientation and collection platform velocity). Whereas the interior parameters are usually independent of time, exterior parameters may or may not be.

For imaging by a passive frame sensor, all pixels in a single frame have one set of exterior orientation parameters since they are imaged at the same time. On the other hand, all other sensors involve scanning and therefore the elements of exterior orientation are time-dependent functions.

7.2.3 Interior sensor parameters

These parameters pertain exclusively to the sensor and the mode in which it operates. For all passive electro-optical sensors, a lens is used to collect and focus the energy emanating from the object onto the sensing medium. This medium may be film (which is later scanned to convert the image to digital form) or a sensing element such as a CCD. Film and rectangular arrays of sensing elements are used for frame (area recording) imagery. Linear arrays are used for pushbroom imaging, while a single element (or one or a few arrays each with very few elements) is used to sweep across-track in whiskbroom imaging. Interior orientation parameters are listed below:

a) The calibrated focal length of the lens.

b) Lens distortion characteristics. They are in the form of coefficients of polynomials that are specifically derived to fit the distortion curves, both for radial as well as decentring (also sometimes called tangential or asymmetric) distortion.

c) Size and shape of a single detector in the array.

d) Geometric distortion of the image record. This represents film deformation for cameras and array deformations for digital imagery. Usually such distortion is represented by coefficients of a transformation, determined by calibration, using reference points (such as fiducial marks in a frame camera). The most common transformation is the six-parameter affine transformation, which accounts for two translations, two scales, one rotation and a skew.

e) The location x_o, y_o, of the intersection of the optical axis and the image plane, which is usually called the principal point offset.

Items a) through e) constitute a complete list of interior orientation elements that apply to frame imagery. For pushbroom and whiskbroom passive imagery, only subsets that are physically relevant are used. Model formulation for all cases includes the pertinent elements.

For what are termed metric sensors, the interior orientation parameters are usually determined a priori, through laboratory calibration or special field calibration. In some cases, full calibration of the sensor prior to the imaging is not possible. In such cases, it is possible to refine the available interior parameters and determine those through a self-calibration.

7.2.4 Exterior sensor/platform parameters

Exterior orientation parameters pertain to the trajectory of the platform that carries the sensor, and are, in general, dependent on time. For passive optical sensors, an image coordinate reference system is established with its origin at the perspective centre, which is physically located at the front node of the lens, the single point through which the bundle of rays from the object being imaged passes. The position of the origin (often called perspective centre for frame images) together with the orientation of this coordinate system with respect to the established ground coordinate system constitutes exterior orientation. The position is determined by three coordinates and orientation by three independent parameters, usually a sequence of three angles.

The position of the origin of the sensor coordinate system shall be described in the simplest case by a set of object space coordinates; the external coordinate reference system may be a global geocentric or geodetic CRS or an engineering CRS referenced to a point on the surface of the Earth.

More often, the position of the origin of the sensor coordinate system is specified in relation to a coordinate system defined for the platform upon which the sensor is mounted. In this case, the position of the origin of the sensor coordinate system shall be described by an offset vector from the origin of the platform coordinate reference system. The position of the origin of the platform CRS shall be specified in relation to the object space CRS.

For a gimbal mounted sensor, a local coordinate reference system shall be defined for each stage of the gimbal, with the origin of the coordinate reference system for the first stage being located at the point where it is mounted to the platform and the origin for the CRS of each subsequent stage being at its centre of rotation. In this case, the origin of the sensor coordinate system shall be described by a sequence of offset vectors from the origin of the platform CRS to the origin of the sensor coordinate system.

Attitude describes the orientation of the internal coordinate system of a body such as a sensor relative to an external CRS. This description may consist of a sequence of angles, each of which describes a rotation of the internal coordinate system around one axis of the external CRS. Generally, ω (roll) is the angle of rotation around the x axis, φ (pitch) the rotation around the y axis, and κ (yaw) the rotation around the z axis. A rotation is positive if it appears clockwise when looking in the positive direction of the axis around which the rotation takes place. The order of rotation shall be specified since the results of a sequence of rotations are not commutative.

Alternatively, attitude may be described by a 3x3 rotation matrix built up by the multiplication of three matrices that consecutively rotate the internal coordinate system around each axis of the external CRS.

As in the case of position, the attitude of a sensor may be described relative to the object space CRS, to the platform CRS, or to the CRS of the final stage of a gimbal mounting.

In photogrammetric applications, the exterior orientation information of the sensor at exposure time, either directly from the sensor or derived from the platform, is critical since it provides the parameters included in the collinearity equation.

For pushbroom and whiskbroom sensors, which acquire imagery by scanning the object (terrain), the exterior orientation parameters are time-dependent. Each exterior orientation element or parameter is determined for a detector at a specific instance of time. This is usually accomplished by a polynomial, fitting to non-time congruent platform exterior orientation data but could also be accomplished through interpolating such tabulated data.

The data set may provide the attitude and position information directly or it may contain other information from which attitude and position can be calculated. Two examples are shown.

EXAMPLE 1 Figure 6 shows a geolocation table that contains Date, Time and three columns each for Attitude (ω, φ, κ) and Position (X,Y,Z) for deriving geolocation information for scans.

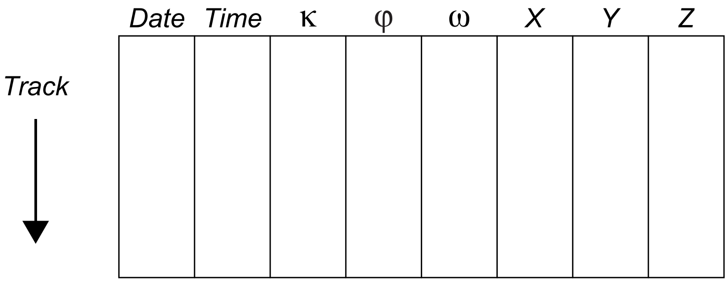


Figure 6 — One-dimensional attitude/position table of geolocation information

EXAMPLE 2 Figure 7 shows an example where multiple sets of attitude and position information are available for an image. The six 2D arrays of Attitude and Position components have been combined into a single 3D array for convenience. Geolocation information may not be needed for every scan; depending upon accuracy requirements, providing it at intervals of several scans may be sufficient.

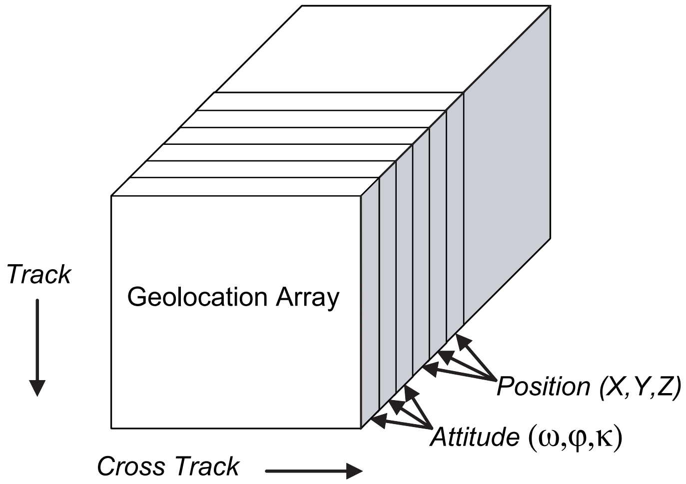


Figure 7 — Geolocation array containing attitude and position planes

The physical arrangement aboard the platform is very important in the proper construction of the mathematical model for the sensor. The sensor may be separated from the GNSS antenna (which provides position) and from the inertial navigation system (INS) (which provides orientation angles). Therefore, the offset vectors from the origin of the platform coordinate reference system to the sensor, the GNSS, and the INS are critical to determining the exterior orientation of the sensor unless the position and orientation of the sensor are measured directly.

7.2.5 Ground-to-image function

The Ground-to-Image Function is one of the two forms of the fundamental relationship that mathematically expresses the sensor model. The other form is the reverse Image-to-Ground Function that is discussed in 7.2.6. Figure 8 schematically depicts the role of the ground-to-image function, which applies equally to the original physical/geometric sensor model currently under discussion, or the TRM, which will be discussed in 8.2. The inputs to this function are the ground coordinates, either geographic (λ, φ, h) or Cartesian (X,Y,Z), and their statistical quality, as represented by a 3-by-3 covariance matrix, Σ . The output is the pair of image coordinates in the image record corresponding to the object point represented by the ground coordinates. Image coordinates can be either grid (line, sample) coordinates in pixels or Cartesian coordinates (x,y) in linear units such as mm. Also output is the quality of the image coordinates in the form of a 2-by-2 covariance matrix. The construction of the Ground-to-Image Function depends upon the entire set of parameters involved in the imaging event. For a Physical Sensor Model, these are the interior and exterior orientation parameters discussed in the preceding subclauses, and their covariance information. A different set of parameters is used in the TRMs discussed in 8.2.

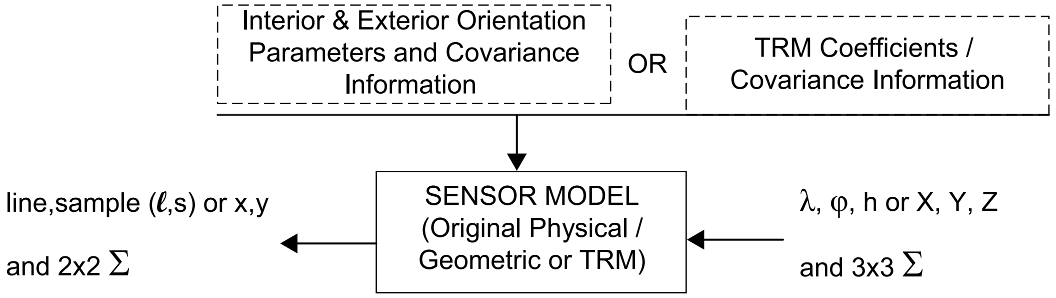


Figure 8 — Ground-to-image function

For a frame image, the ground-to-image function is expressed by two collinearity equations. For fully calibrated cameras, they are:

$$x' = -f\frac{U}{W}$$
$$y' = -f\frac{V}{W} \qquad (1)$$

in which

$$\begin{bmatrix} U \\ V \\ W \end{bmatrix} = M \begin{bmatrix} X - X_L \\ Y - Y_L \\ Z - Z_L \end{bmatrix} \qquad (2)$$

where

x', y'	are image point coordinates which have been corrected for all systematic errors, including shift to the principal point (x_o,y_o), as the origin;
x_o, y_o, f	are the elements of interior orientation of the calibrated camera; x_o,y_o are the coordinates of the principal point, and f is the calibrated focal length;
X_L, Y_L, Z_L	are three positional elements of exterior orientation in the object (ground) CRS;
M	is the orthogonal matrix representing the sensor orientation, constructed in terms of the other three elements of exterior orientation. These elements are usually a set of sequential rotations, ω, φ, κ, called roll, pitch, and yaw;
X, Y, Z	are ground coordinates of the object point in the object (ground) CRS whose image is given by the coordinates x,y.

If uncalibrated or partially calibrated sensors are used, the collinearity equations are extended to accommodate self-calibration. A pair of equations that include a set of self-calibration parameters is given as follows:

Replace

x', y' by: $x' = \bar{x} + \Delta x \qquad y' = \bar{y} - \Delta y$

in which:

$\bar{x} = x - x_0 \quad \bar{y} = y - y_0$ and $r^2 = \bar{x}^2 + \bar{y}^2$ in the following:

$$\begin{aligned} \Delta x &= \frac{\bar{x}}{f}\Delta f + \bar{x}(k_1 r^2 + k_2 r^4 + k_3 r^6) + p_1(2\bar{x}^2 + r^2) + p_2(2\overline{xy}) + b_1\bar{x} + b_2\bar{y} \\ \Delta y &= \frac{\bar{y}}{f}\Delta f + \bar{y}(k_1 r^2 + k_2 r^4 + k_3 r^6) + p_1(2\overline{xy}) + p_2(2\bar{y}^2 + r^2) \end{aligned} \tag{3}$$

where there are 10 added self-calibration parameters

x_0, y_0, Δf	is the interior orientation (Δf is a correction to the focal length f, which will also accommodate a uniform scale change);
k_1, k_2, k_3	are the radial lens distortion coefficients;
p_1, p_2	are the decentring lens distortion coefficients;
b_1, b_2	are parameters which collectively accommodate a differential scale in one axis compared to the other, and a skew between the two axes.

7.2.6 Image-to-ground function

For some sensor/sensing systems, the ground-to-image function is mathematically invertible uniquely. Such is the case for calibrated frame imagery, resulting directly in the following image-to-ground transformation.

$$\begin{aligned} X &= X_L + (Z - Z_L)\frac{u}{w} \\ Y &= Y_L + (Z - Z_L)\frac{v}{w} \end{aligned} \tag{4}$$

in which

$$\begin{bmatrix} u \\ v \\ w \end{bmatrix} = M^T \begin{bmatrix} x' \\ y' \\ -f \end{bmatrix} \tag{5}$$

NOTE In order to determine (X,Y) of an object point from Equation (4), its third dimension Z (elevation) is required. This is because one cannot recover all three coordinates of an object point from its two image point coordinates. Once the third dimension is lost in the imaging process, it cannot be recovered from a single image. It can, however, be calculated if two or more images of the same object point are used.

For time-dependent imaging systems, such as pushbroom and whiskbroom, the ground-to-image function cannot be directly inverted algebraically as it is for frame imagery. The image-to-ground function is instead derived numerically from the ground-to-image function by an iterative procedure, or as

$$\begin{bmatrix} X - X_L(t) \\ Y - Y_L(t) \\ Z - Z_L(t) \end{bmatrix} = kR(t) \begin{bmatrix} x \\ y \\ z \end{bmatrix} \tag{6}$$

where

X,Y,Z are object point coordinates;

$X_L(t)$, $Y_L(t)$, $Z_L(t)$ are coordinates of the perspective centre in the object (ground) coordinate reference system. They are continuous functions of time, t;

k is the scale factor which varies from point to point;

$R(t)$ is a 3-by-3 rotation matrix which brings a framelet (which is usually a single image line for a pushbroom image) coordinate system parallel to the object coordinate system. R is a continuous function of time;

x,y,z are framelet coordinates of the image point, in the image CRS, corresponding to X,Y,Z.

This image-to-ground form of the collinearity is chosen because time is usually determined by the image line, thus making this a direct, rather than iterative, approach.

Z can be determined if two or more images from different viewing angles are used.

Both the ground-to-image and image-to-ground functions form the basis of the Physical Sensor Model, which allows rigorous exploitation of imagery for precise geopositioning based on well established photogrammetric processes. These two functions, together with error propagation and adjustability, which provide the ability to refine or upgrade the sensor parameters, make up the four basic elements of a Physical Sensor Model.

7.2.7 Error propagation

Most, if not all, variables involved in sensor models, whether known a priori or estimated, are random (or stochastic) variables. This means that variances and covariances are associated with the variables. When a sensor model is applied, a set of unknown quantities is calculated from known values. The operation of determining the covariances of the calculated quantities from the covariances of the known input values is called error propagation. Rigorous error propagation associated with geopositioning is as important as the determination of the Earth coordinates themselves.

7.2.8 Adjustable model parameters

Frequently the values of the sensor parameters available in the metadata are not sufficiently accurate to lead to quality geopositioning. Photogrammetric techniques exist that allow refinement of some or all of those parameters. The parameters selected for this refinement are called adjustable model parameters.

7.3 Quality associated with Physical Sensor Models

Quality information for Physical Sensor Models shall be provided using the appropriate quality measures specified in ISO/TS 19138:2006, C.3 and D.3. The quality parameters associated with Physical Sensor Models fall into two categories: interior, which pertain predominantly to the sensor design, and exterior, which reflect more the properties of the collection platform trajectory than those of the sensor. Variances and covariances should be provided for the interior parameters since any or all of them may be carried as adjustable parameters. The primary source of error in object expositions comes from the exterior parameters. The covariance matrix of the exterior orientation elements is:

$$\Sigma_{EO} = \begin{bmatrix} \sigma^2_{X_L} & \sigma_{X_L Y_L} & \sigma_{X_L Z_L} & \sigma_{X_L\omega} & \sigma_{X_L\varphi} & \sigma_{X_L\kappa} \\ & \sigma^2_{Y_L} & \sigma_{Y_L Z_L} & \sigma_{Y_L\omega} & \sigma_{Y_L\varphi} & \sigma_{Y_L\kappa} \\ & & \sigma^2_{Z_L} & \sigma_{Z_L\omega} & \sigma_{Z_L\varphi} & \sigma_{Z_L\kappa} \\ & & & \sigma^2_{\omega} & \sigma_{\omega\varphi} & \sigma_{\omega\kappa} \\ & symmetric & & & \sigma^2_{\varphi} & \sigma_{\varphi\kappa} \\ & & & & & \sigma^2_{\kappa} \end{bmatrix} \tag{7}$$

where

Σ_{EO} is the covariance matrix of the exterior orientation elements;

$\sigma^2{}_i$ are variances;

σ_{ij} are covariances;

X_L, Y_L, Z_L is the position of the perspective centre;

ω, φ, κ are the angles that describe the attitude of the sensor.

The diagonal elements of the square symmetric non-singular matrix, Σ_{EO} are the variances of the position (X_L, Y_L, Z_L) and orientation (ω, φ, κ) of the sensor. The off-diagonal elements are the covariances among the six orientation elements. Covariance matrices, as described by Equation (7), shall be provided with all images from passive sensors for which geolocation information is provided as a Physical Sensor Model.

Covariances will always exist if the image has been processed through either single image resection or as part of multi-image triangulation. For an unprocessed image, Σ_{EO} may simply be a diagonal matrix containing variances, with all off-diagonal elements being zero. On the other hand, for a processed image, Σ_{EO} will be a full matrix. In fact, for two processed images, i, j, their total covariance matrix, Σ_{EO_T} will be a 12-by-12 symmetric non-singular matrix of the form:

$$\Sigma_{EOT} = \begin{bmatrix} \Sigma_{EOi} & \Sigma_{EOij} \\ \Sigma^T_{EOij} & \Sigma_{EOj} \end{bmatrix} \tag{8}$$

where

$\sum_{EO_T}$ is the total covariance matrix for two images;

$\sum_{EOi}$ is the covariance matrix for image i;

$\sum_{EOj}$ is the covariance matrix for image j;

$\sum_{EOij}$ is the covariance matrix between the two images;

$\sum^T_{EOij}$ is the transpose of the covariance matrix between the two images.

For a pair of correlated images, the matrix in Equation (8) shall be provided in order to calculate quality measures associated with Physical Sensor Models.

7.4 Physical Sensor Model metadata

7.4.1 Introduction

The sensor interior and exterior parameters and their associated quality information shall be supplied to enable the user to construct the sensor model for use in the geolocation of object features. The remainder of this clause specifies the content of that information about the sensor needed to georeference the data.

This subclause provides an overview of the schema for Physical Sensor Model metadata. The information needed to determine the location of the platform on which the sensor is located and the position and motion of the sensor is specified in 7.5. The information needed to describe the internal properties of the sensor and detector system is specified in 7.6. It provides specific information for frame, scanning and radar sensors.

The content specified in this clause provides components that can be used to construct sensor models for many of the different systems used for remote sensing, such as those described in 7.1. It can apply to radiation measurements at many wavelengths and to sound waves. It can apply to sensors of varying degrees of complexity. Separate content for radar systems may apply to echoing systems in general. Many satellite systems use scanning sensors. Location might be determined through time and the satellite orbit. The classes for optics are used to describe the optical systems and the scans. Frame camera photogrammetry is generally from airborne platforms, and it uses the optical system and possibly the distortion classes. Radar is an echo system used from airborne or satellite platforms. For each kind of sensor, a model can be constructed using the UML models in this clause.

7.4.2 Overview of the Physical Sensor Model schema

Figure 9 illustrates the top of the schema for Physical Sensor Models. SD_PlatformParameters and its subordinate elements are specified in 7.5, as is SD_PositionAndOrientation; the sensor specific elements of and subordinate to SD_SensorParameters are specified in 7.6. The classes shown in Figure 9, their attributes and their associations shall be used as specified in the data dictionary of B.2.3.1.

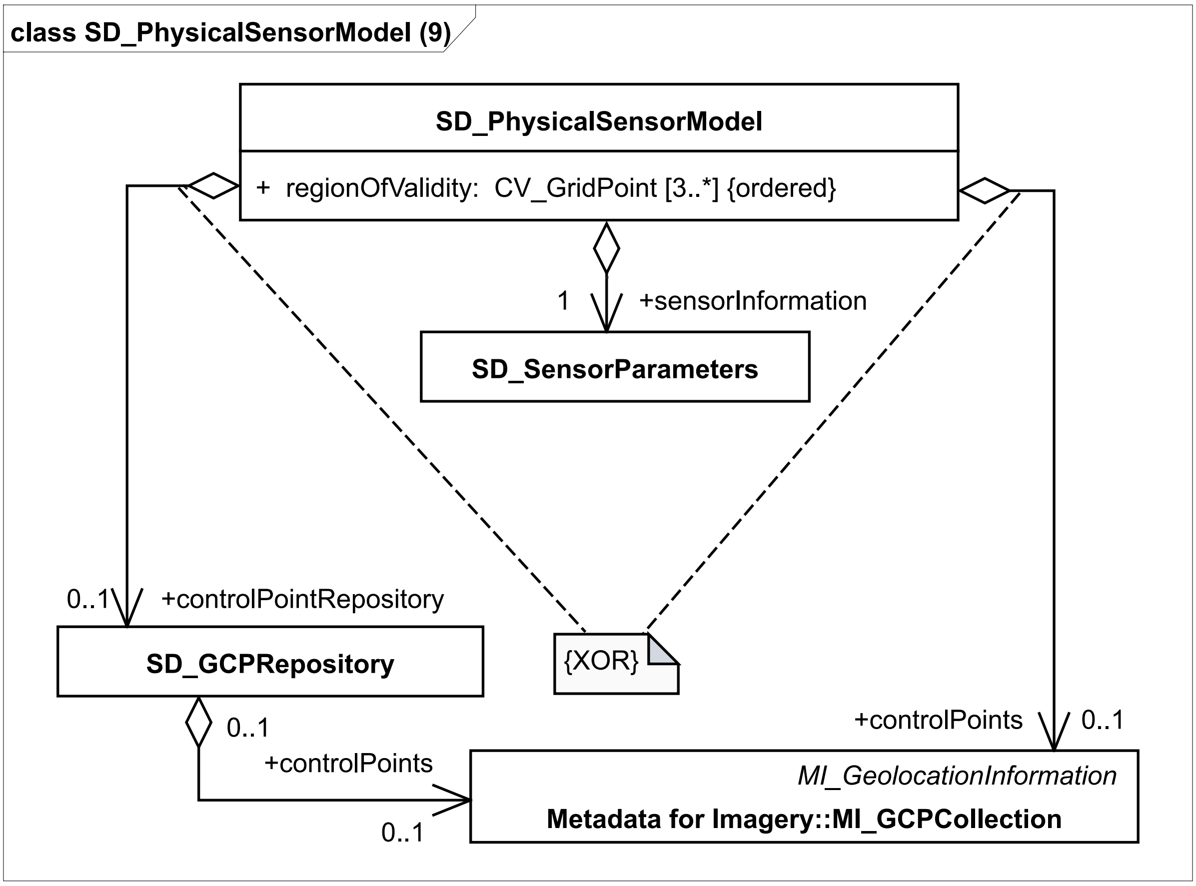


Figure 9 — Overall view of Physical Sensor Model parameters

7.5 Location and orientation

7.5.1 Overview

The location information specified in this subclause may be used to describe spatial relationships among the components of a sensor, between sensor and platform, between a sensor and the Earth, and between a platform and the Earth. The relative spatial positions and attitudes of the two objects involved shall be described in terms of two different coordinate reference systems (Annex C). Each of the two objects has its own coordinate reference system. That of the object to be located is the internal coordinate reference system, and that of the object on which it is located is called the external coordinate reference system. In the process of location, the axes of the internal coordinate reference system are defined in terms of the external coordinate reference system. The coordinate and location information is independent of any specific sensor class.

In the simplest case, the location of a sensor coordinate reference system is given directly relative to a ground coordinate reference system. In other cases, a series of transformations, from the ground to the platform, from the platform to the sensor and finally from the sensor to the detector are used. The location of a sensor relative to a platform is called the mounting of the sensor.

If the platform is airborne, land based or waterborne, its location is determined by the platform's internal flight/tracking/cruising control system or from the Global Navigation Satellite System. In spaceborne applications, the position is often derived from the platform orbit. For this reason, the satellite ephemeris data are a subclass of the location model.

Some applications determine platform position by interpolating between known positions along the track so this Technical Specification also specifies velocity and acceleration attributes.

7.5.2 Position

The position vector in three-dimensional space defines the position of a remote sensing platform or a sensor at a given time. It is measured relative to a coordinate reference system such as a Cartesian system or the geographic system (latitude, longitude, altitude).

Position information shall be provided as shown in the UML diagram Figure 10. The classes shown in Figure 10, their attributes and their associations shall be used as specified in the data dictionary of B.2.3.2.

If the platform is airborne, land based, or waterborne, its position is determined by the platform's internal flight/tracking/cruising control system or from the Global Navigation Satellite System. That information is represented by the class SD_EarthMeasuredLocation

If the platform is a spacecraft, its position can be determined from its orbital characteristics. An orbit can be described using the Keplerian elements (C.2.2.5 – C.2.2.7).

The spacecraft's orbital tracking data are received by ground stations and are used to determine the platform's instantaneous position and velocity.

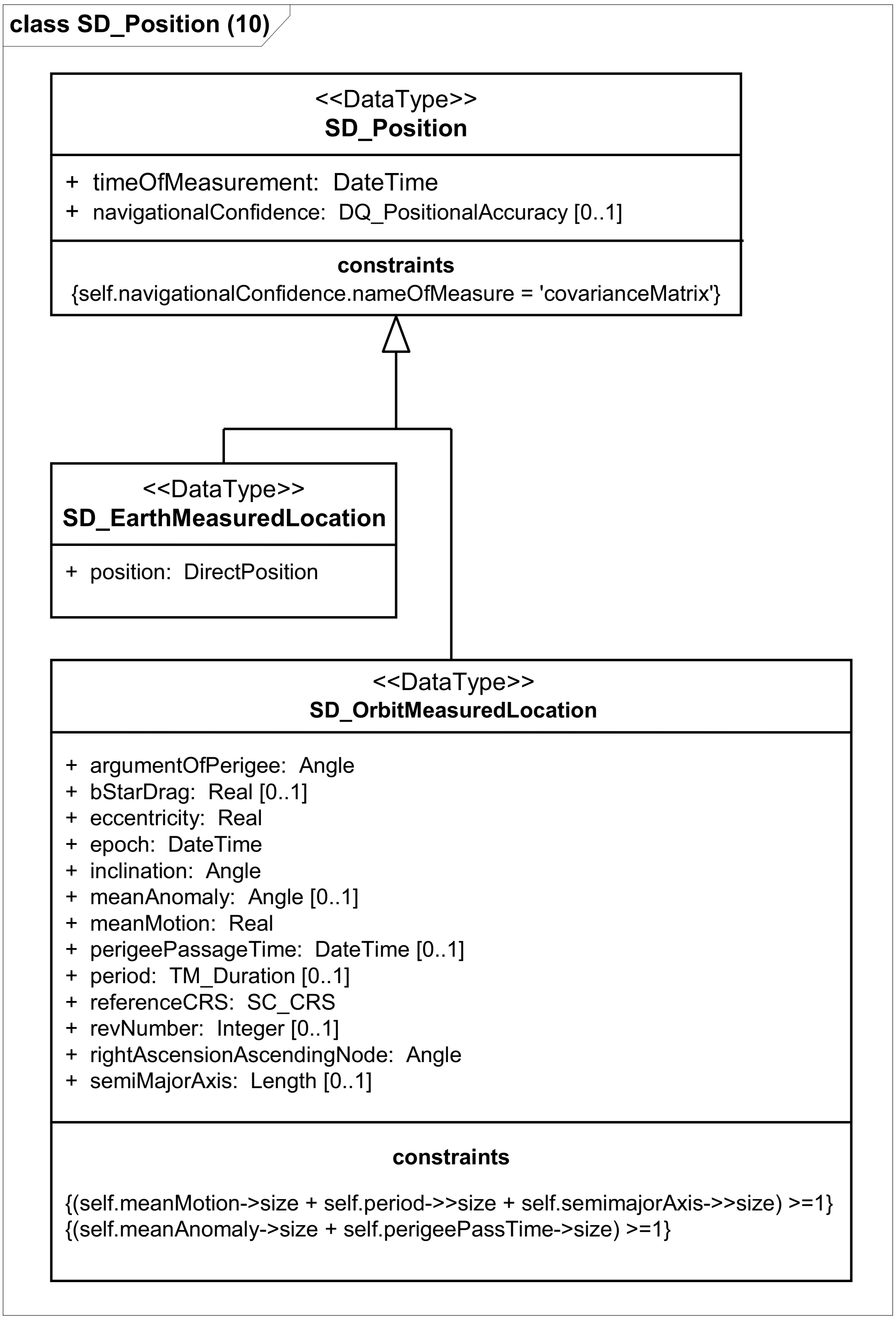


Figure 10 — SD_Position

7.5.3 Attitude

Attitude (Figure 11) describes the orientation of one coordinate reference system with respect to another. It does this using either a set of rotation angles, one for each axis (SD_AngleAttitude), or using a rotation matrix (SD_MatrixAttitude). See 7.2.4 and Annex C for more detailed discussion. Attitude information shall be provided using the classes shown in Figure 11 and their attributes as further specified in B.2.3.3 and B.2.5.4.

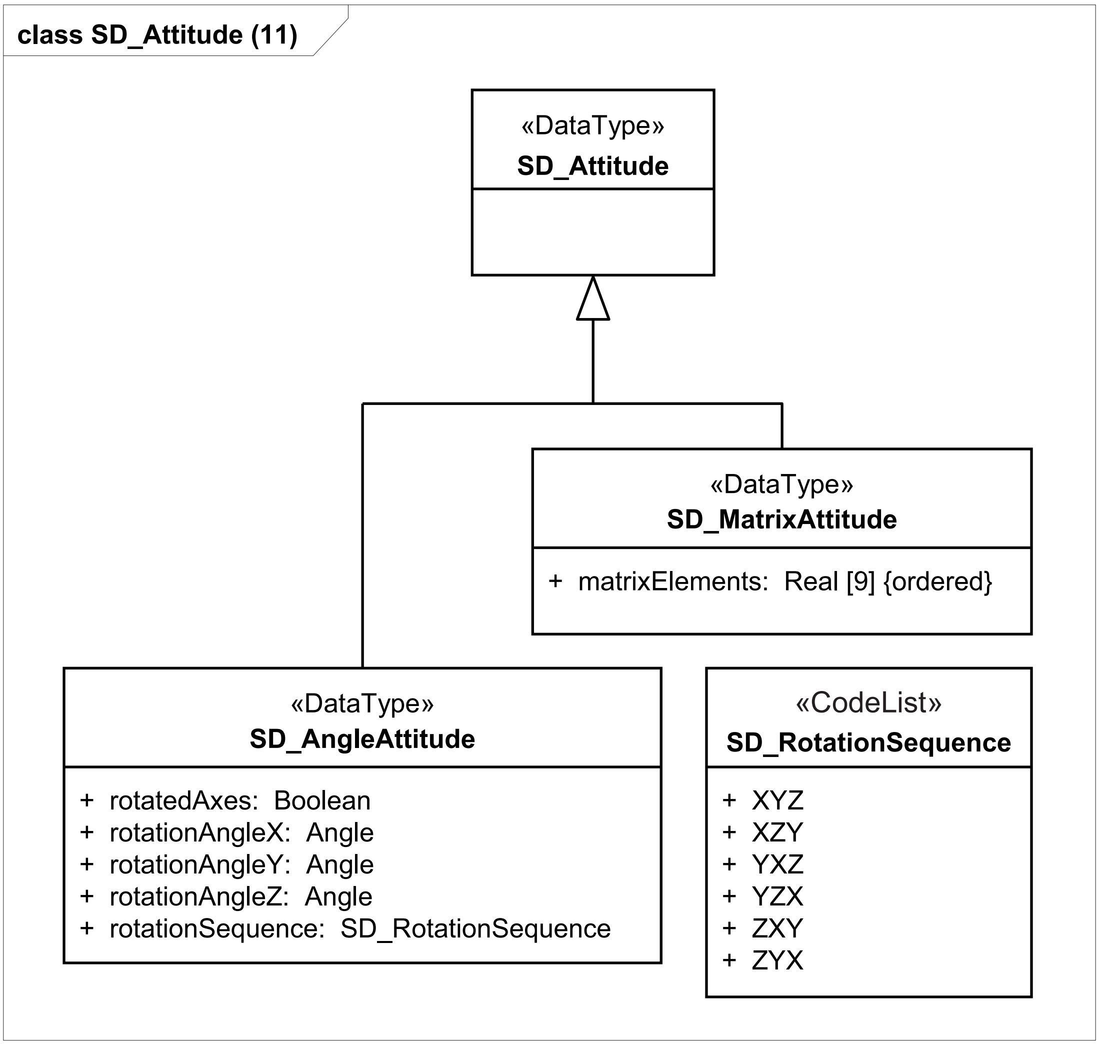


Figure 11 — SD_Attitude

7.5.4 Dynamics

The class SD_Dynamics (Figure 12) provides a set of elements for describing the rates at which elements of position and attitude change over time. The classes shown in Figure 12, their attributes and their associations shall be used as specified in the data dictionary of B.2.3.4.

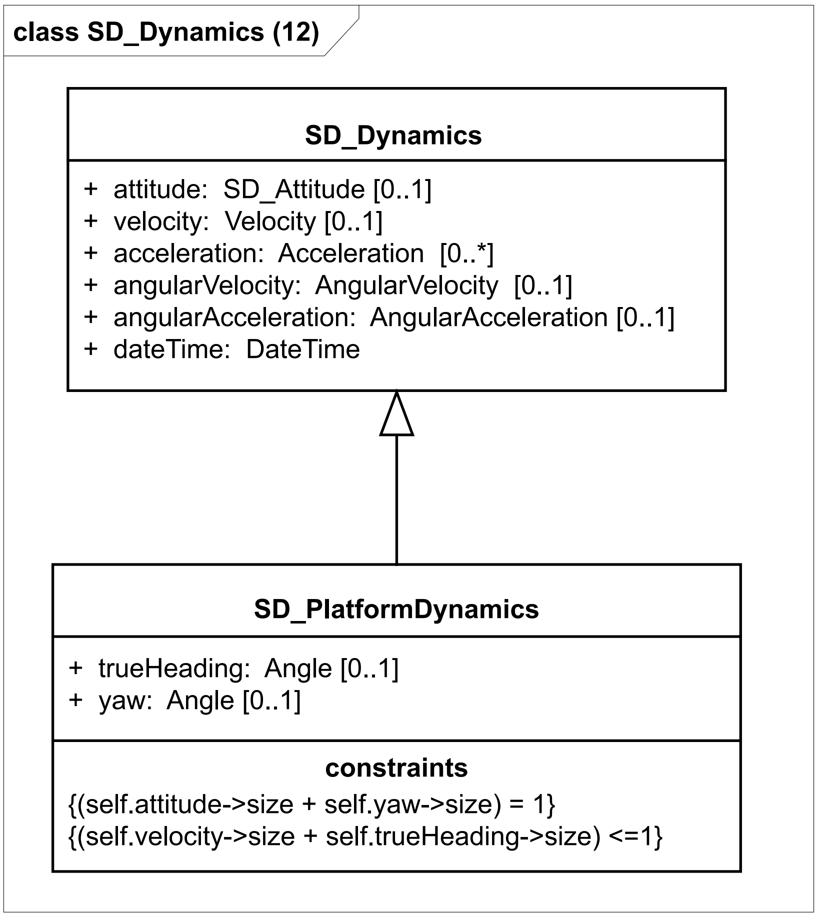


Figure 12 — SD_Dynamics

7.5.5 Position and orientation of a sensor relative to the platform

The class SD_PositionAndOrientation (Figure 13) provides a mechanism for specifying the relative positions and orientations of the components of the platform/sensor system. In the simplest case, the position and orientation of the sensor are described directly with respect to an earth-fixed geodetic or engineering coordinate reference system; in this case, the associations terminating in the role names ‘platform’ and ‘mountingObject’ shall both be empty. The other simple case is that in which the sensor is mounted directly on the platform. Its position and orientation are described in terms of the platform coordinate reference system. In this case, the multiplicity of the role name ‘platform’ shall be one, while that of the role name ‘mountingObject’ shall be zero.

However, sensors are often mounted on a series of one or more gimbals or other movable devices. More than one instance of SD_PositionAndOrientation will be needed to describe this situation. Starting from the sensor, there shall be an instance of SD_PositionAndOrientation for each object in the series, ending with the object that is attached directly to the platform. For every instance of SD_PositionAndOrientation except the last, the multiplicity of ‘mountingObject’ shall be one and that of ‘platform’ shall be zero. For the instance that describes the object mounted directly to the platform the reverse shall be true: the multiplicity for ‘platform’ shall be one and that of ‘mountingObject’ shall be zero. See C.3 for a more detailed discussion of relative orientation. The classes shown in Figure 13, their attributes and their associations shall be used as specified in the data dictionary of B.2.3.5.

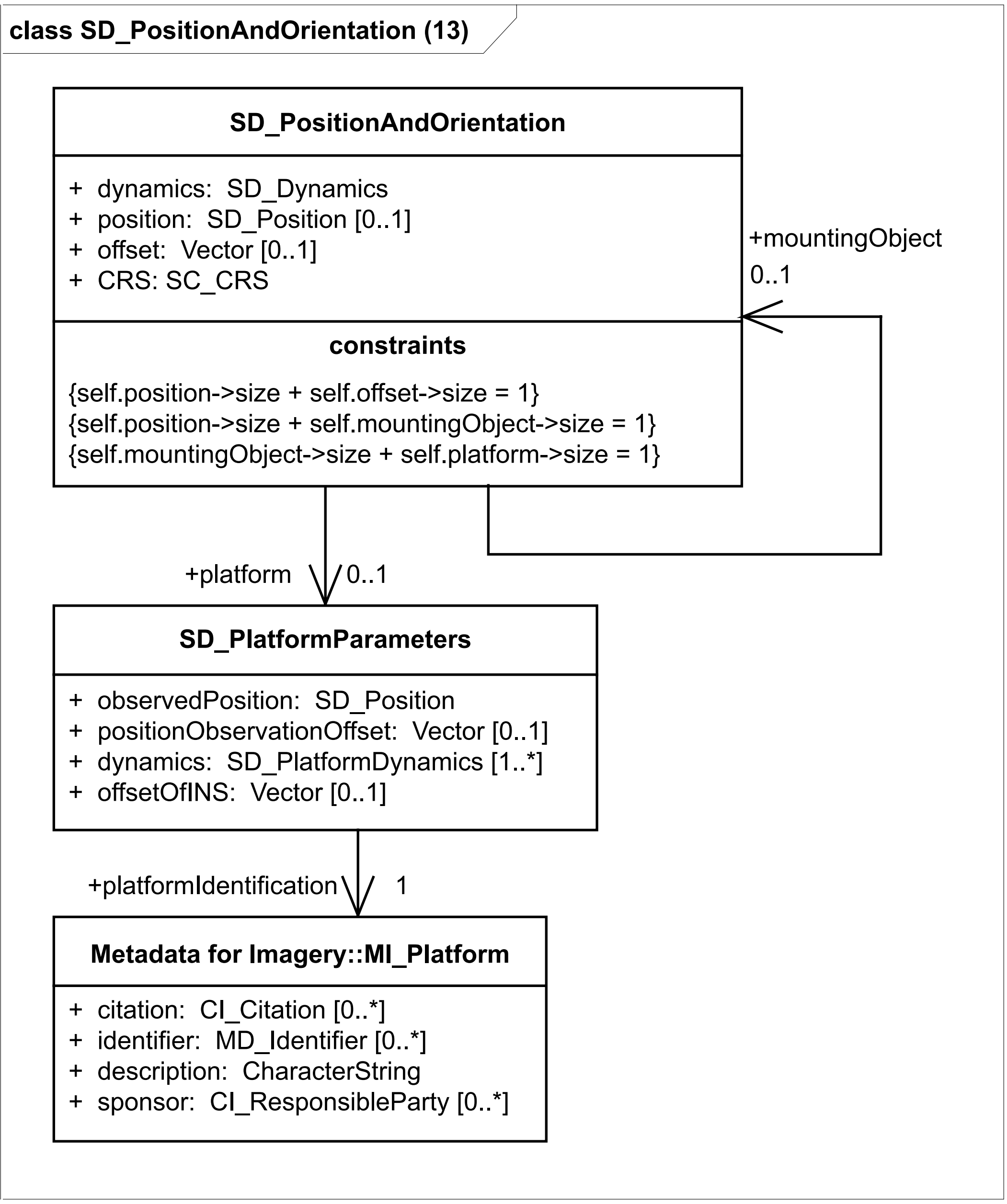


Figure 13 — SD_PositionAndOrientation

7.6 Sensor parameters

7.6.1 SD_SensorParameters

The class SD_SensorParameters represents information about the sensor itself, including its position and orientation relative to the platform (offsetAndOrientation) and its internal characteristics. In addition to its attributes, it aggregates another four classes that describe specific aspects of the sensor. The classes shown in Figure 14, their attributes and their associations shall be used as specified in the data dictionary of B.2.3.6 and B.2.5.2.

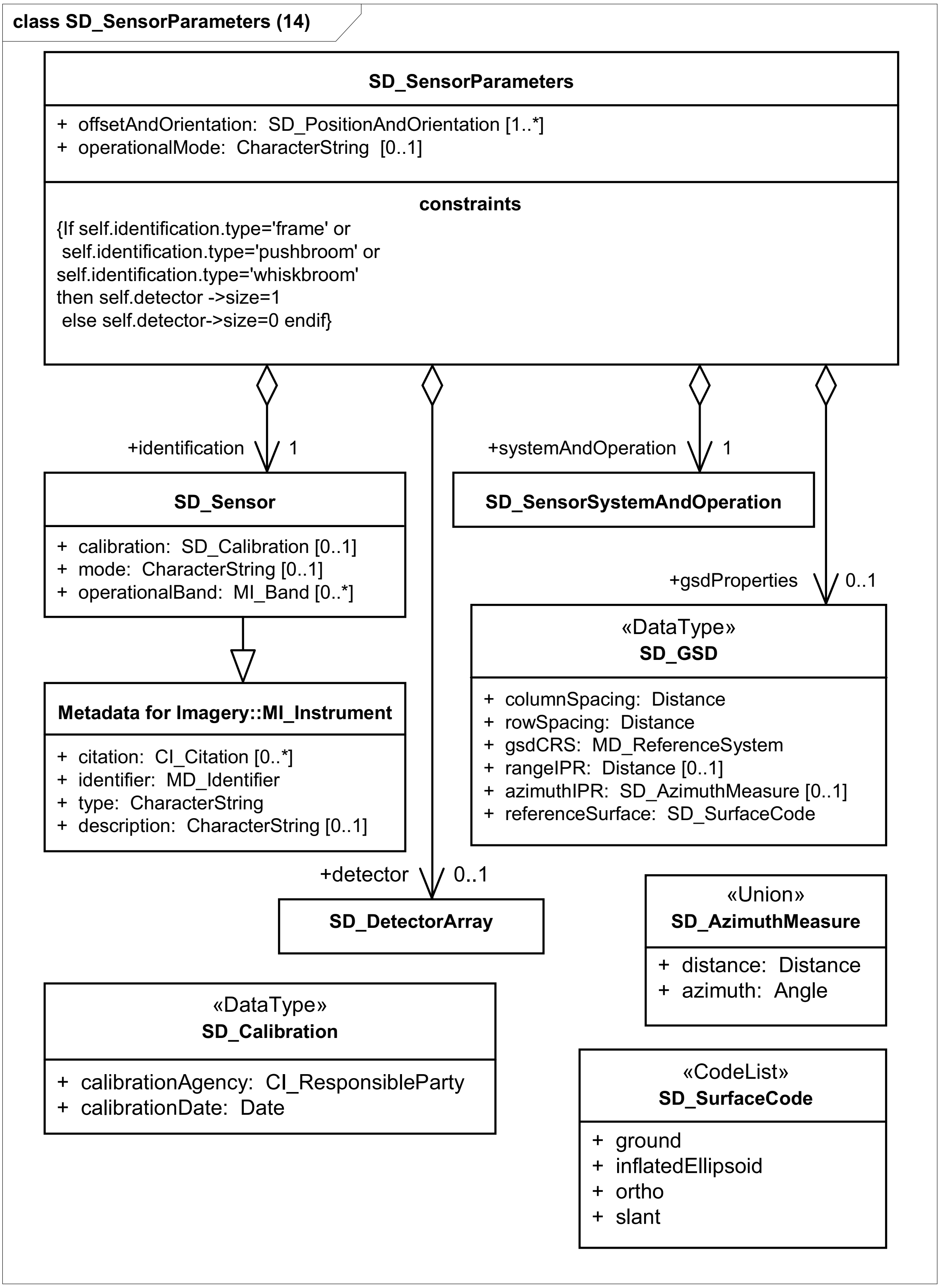


Figure 14 — SD_SensorParameters

7.6.2 Detector array

The class SD_DetectorArray (Figure 15) describes the geometry of the set of detectors used to collect the image values. The attribute numberOfDimensions indicates whether the array is one- or two-dimensional. The attribute arrayOrigin specifies the position relative to the internal coordinate reference system of the sensor of the centre of a detector at one of the corners of the array. The attribute arrayDimensions provides the name and of each dimension and its size, which is the number of detectors along that dimension. The attribute offsetVectors describes the orientation of each axis (i.e., dimension) of the array. The magnitude of each vector specifies the spacing between detectors in that direction. The values of the offsetVectors shall be ordered such that each corresponds to the appropriate dimension in the sequence of arrayDimensions. The attribute detectorSize specifies the magnitude of each dimension of a detector; its values are also ordered such that each corresponds to the appropriate dimension in the sequence of arrayDimensions. The attribute detectorShape specifies the shape of each detector. The optional attribute distortion describes any known distortions from the geometry described by the other attributes of the class. The classes shown in Figure 15, their attributes and their associations shall be used as specified in the data dictionary of B.2.3.7 and B.2.5.1.

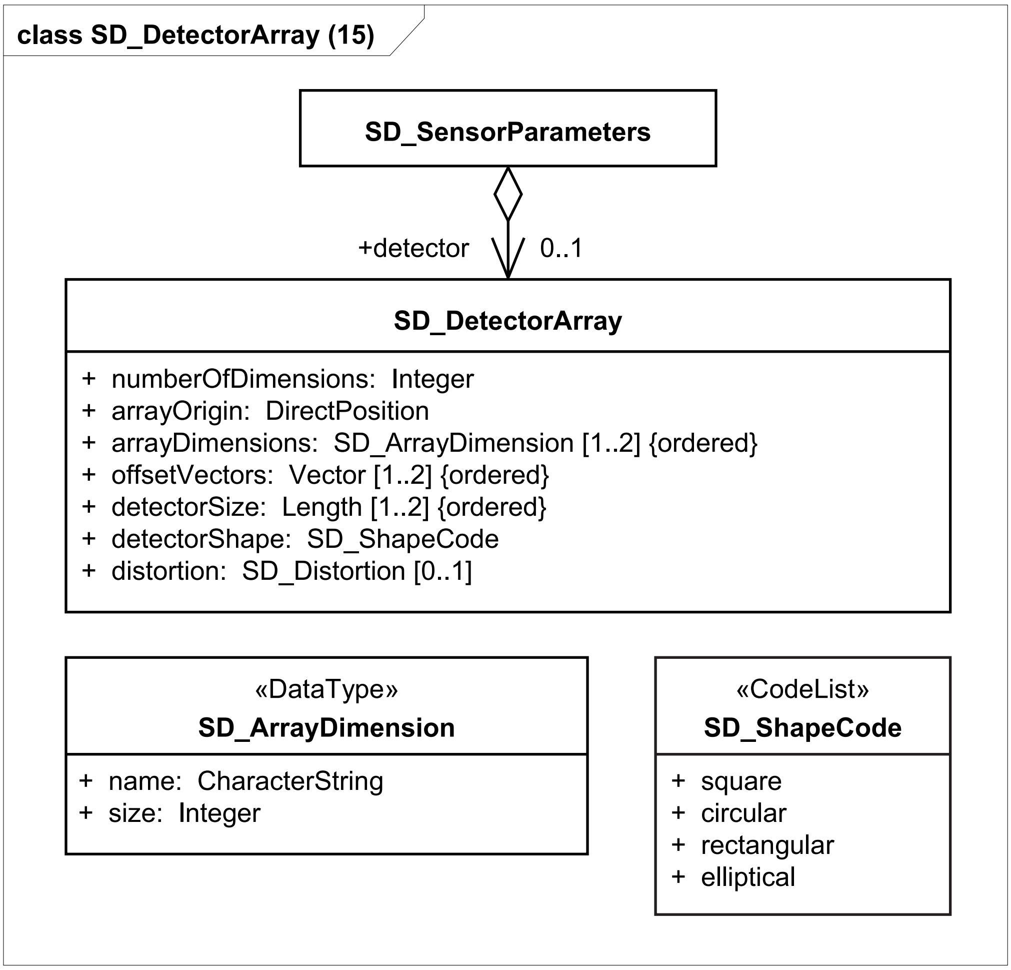


Figure 15 — SD_DetectorArray

7.6.3 Sensor system and operation

The SD_SensorSystemAndOperation class (Figure 16) describes the properties and operational mechanics of the sensor system. Two subclasses are defined based on the wavelength on which the sensor works: SD_Optics and SD_Microwave. The classes shown in Figure 16, their attributes and their associations shall be used as specified in the data dictionary of B.2.3.8 and B. 2.5.3.

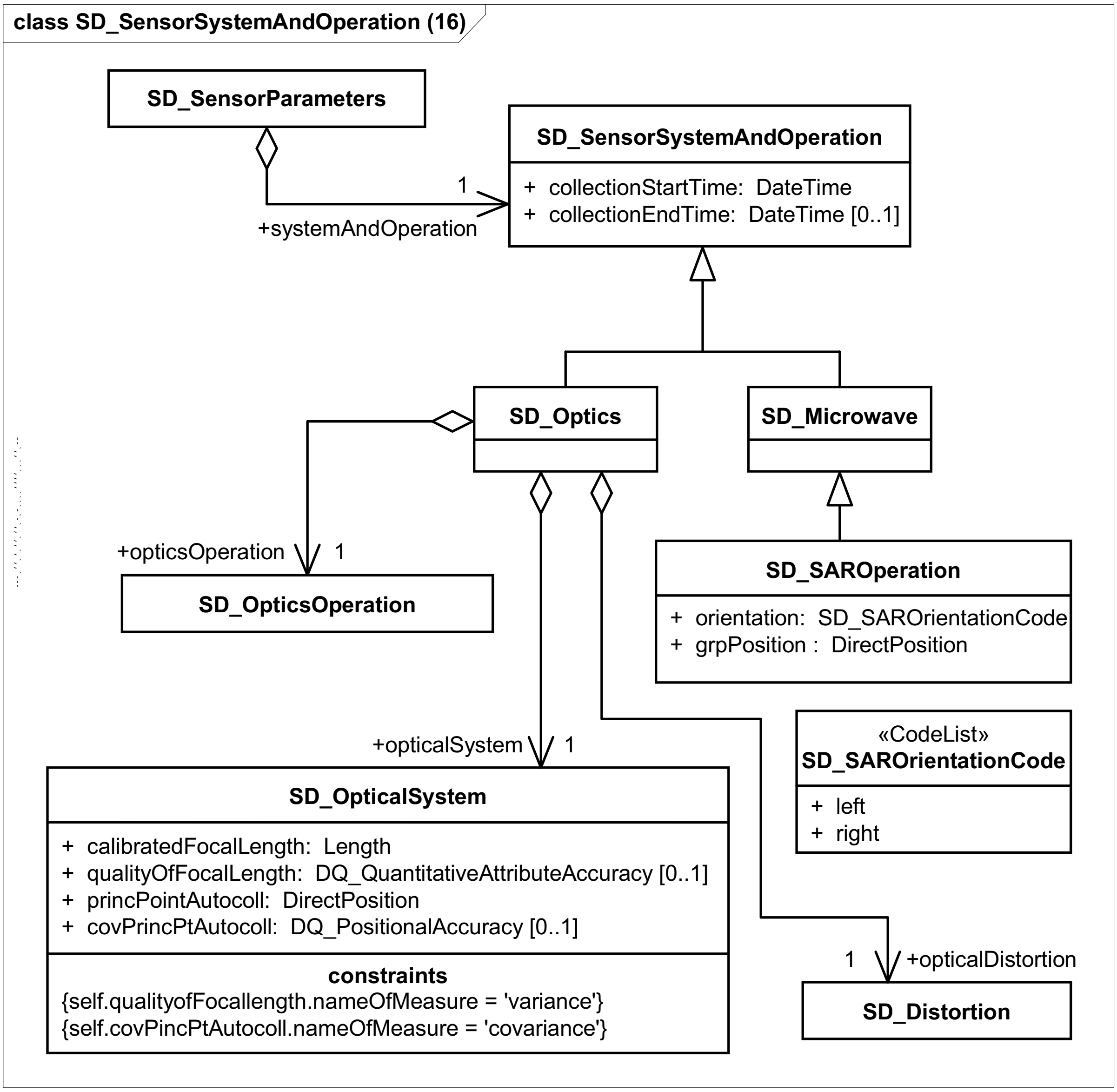


Figure 16 — SD_SensorSystemAndOperation

7.6.4 SD_OpticsOperation

Information on the optical properties and operation of the optical system shall be provided as shown in the UML model of Figure 17. The classes shown in Figure 17, their attributes and their associations shall be used as specified in the data dictionary of B.2.3.9.

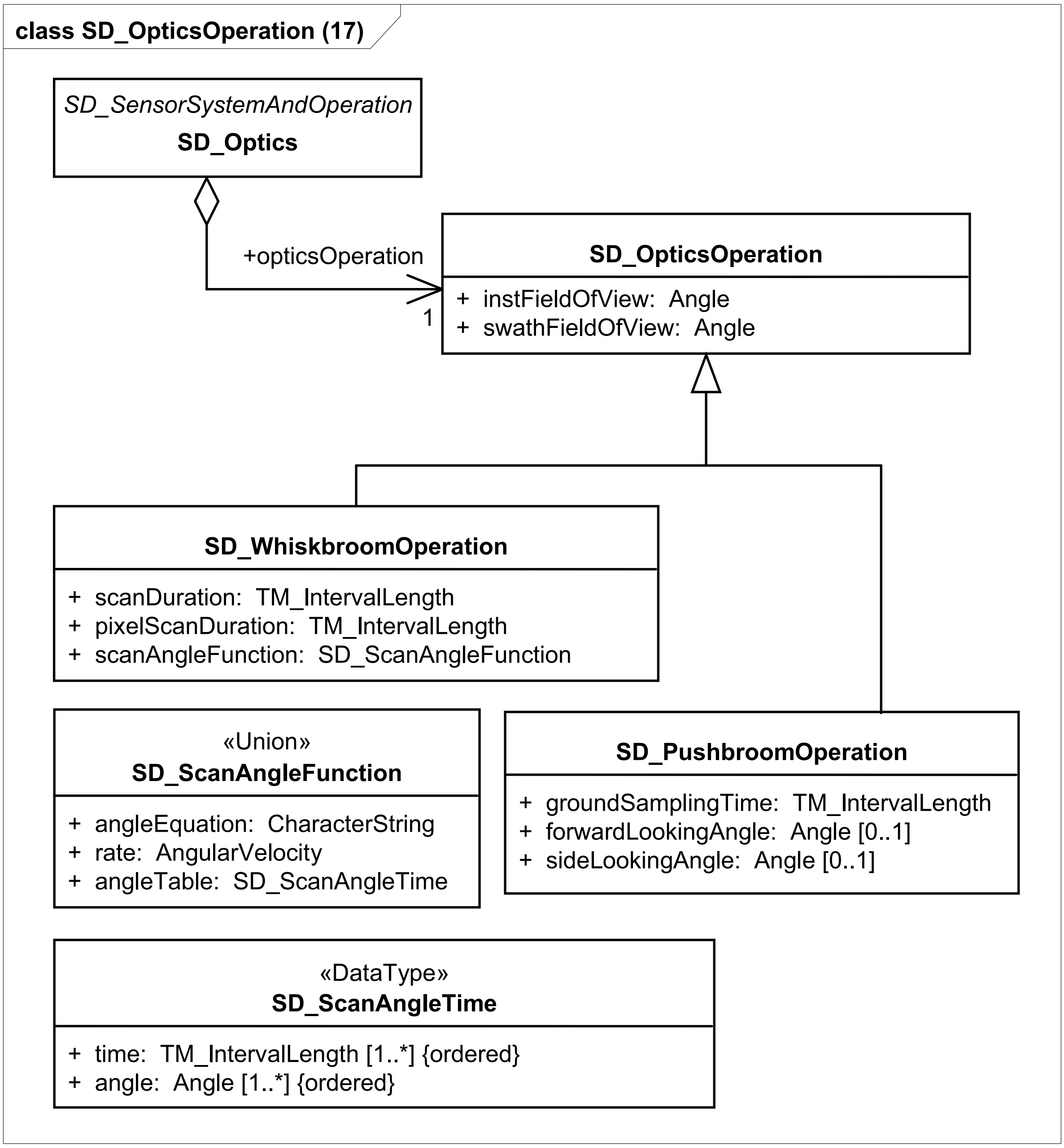


Figure 17 — SD_OpticsOperation

7.6.5 Distortion correction

The class SD_Distortion provides information on different types of distortion in either the optical system (7.2.5) or the detector array (7.6.2). This information shall be provided as shown in the UML model of Figure 18. The classes shown in Figure 18, their attributes and their associations shall be used as specified in the data dictionary of B.2.3.10.

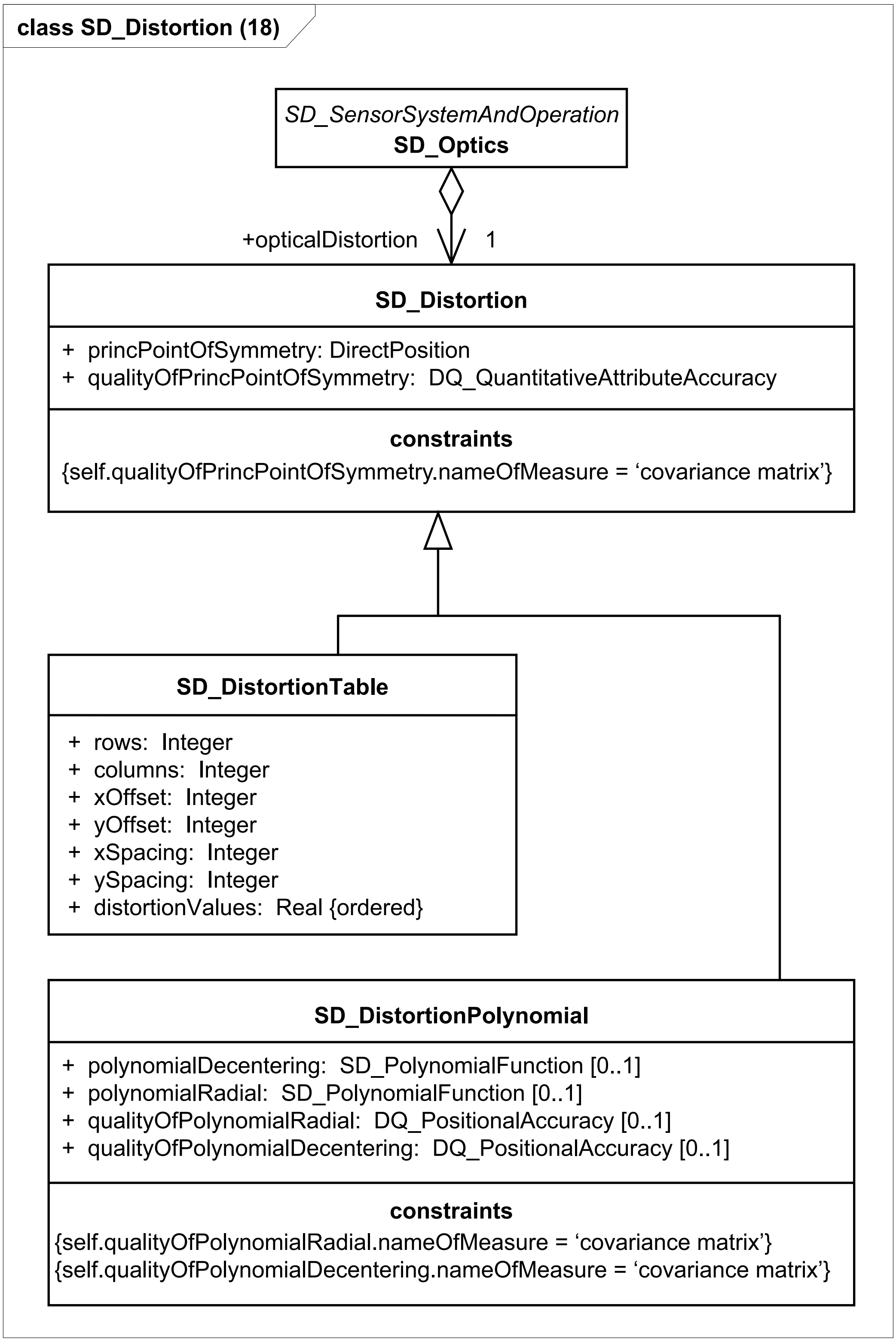


Figure 18 — SD_Distortion

7.6.6 Microwave sensors

This Technical Specification defines one kind of microwave sensor – Synthetic Aperture Radar (SAR). The SAR-specific information is defined in classes SD_GSD in Figure 14 and SD_SAROperation in Figure 16.

These two classes, their attributes and their associations shall be used as specified in the data dictionary of B.2.3.6, B.2.3.8 and B.2.5.3.

8 True Replacement Models and Correspondence Models

8.1 Functional fitting

A functional fit between image and geographic coordinates may be used to geoposition the image. This function may be based on a Physical Sensor Model, as in the case of a TRM, or it may be a simple Correspondence Model based upon ground control points. The function may be a single polynomial applying to the entire image or may be a set of polynomials, each applying to a separate partition. The fit may also be derived by interpolating between points in a grid where both the grid and geographic coordinates are known. A function produced by interpolation cannot be expressed in a simple analytic form over the entire image; its first derivative is discontinuous at grid cell boundaries. The information for functional fitting shall be as shown in the UML model of Figure 19. The classes shown in Figure 19, their attributes and their associations shall be used as specified in the data dictionary in B.2.4.1 and as described in 8.2, 7.3, and 8.5.

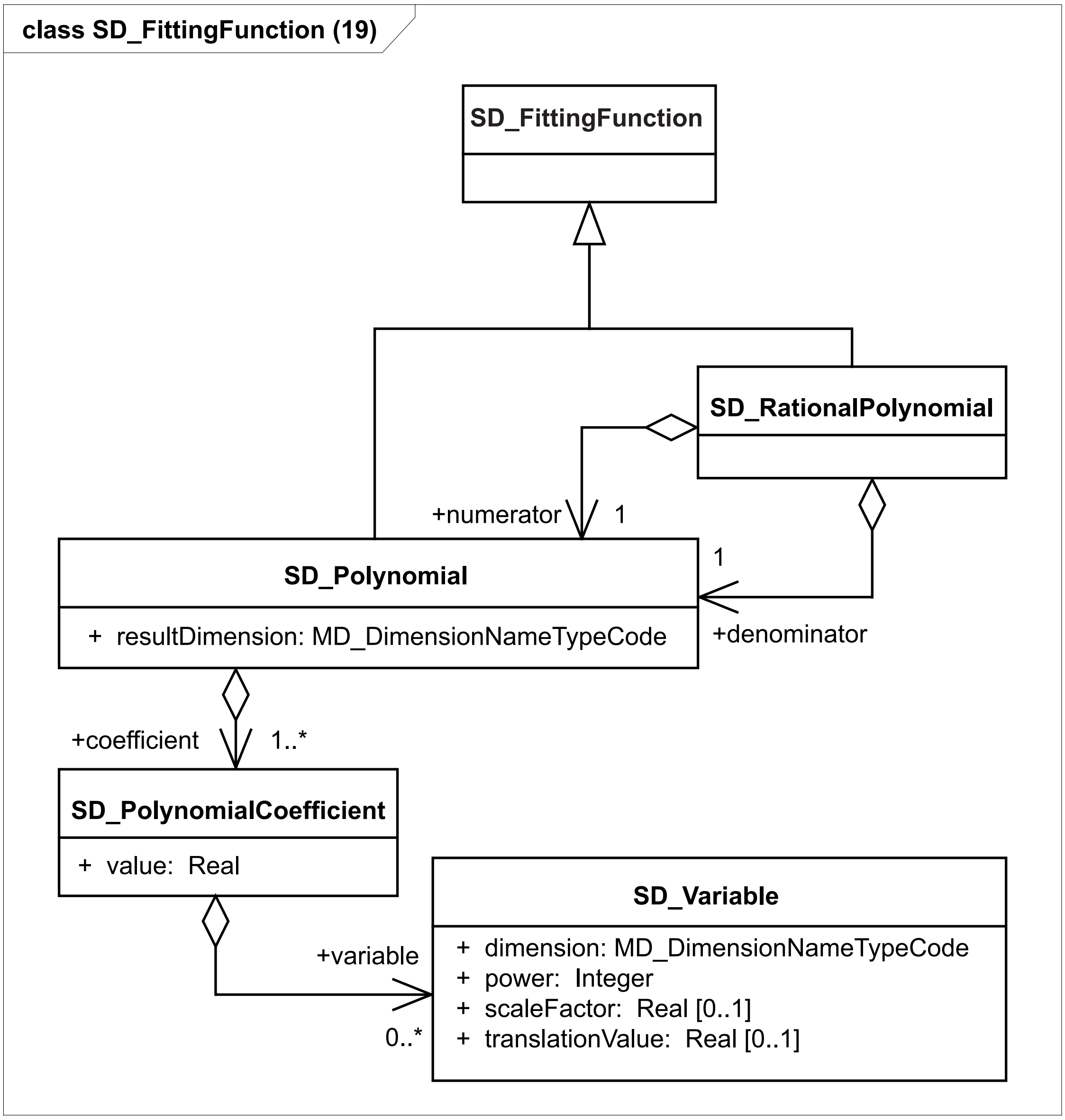


Figure 19 — SD_FittingFunction

8.2 True Replacement Model approach

8.2.1 Introduction

Rigorous Physical Sensor Models (PSMs) are required for obtaining reliable, accurate, and consistent geolocation of imaged objects (terrain). For many sensors, PSMs are complex and their direct use in exploitation tools may not be the best approach for various reasons, including

a) the mathematical complexity of PSMs makes them difficult to implement in easy-to-use exploitation software,

b) the software may require long computation time,

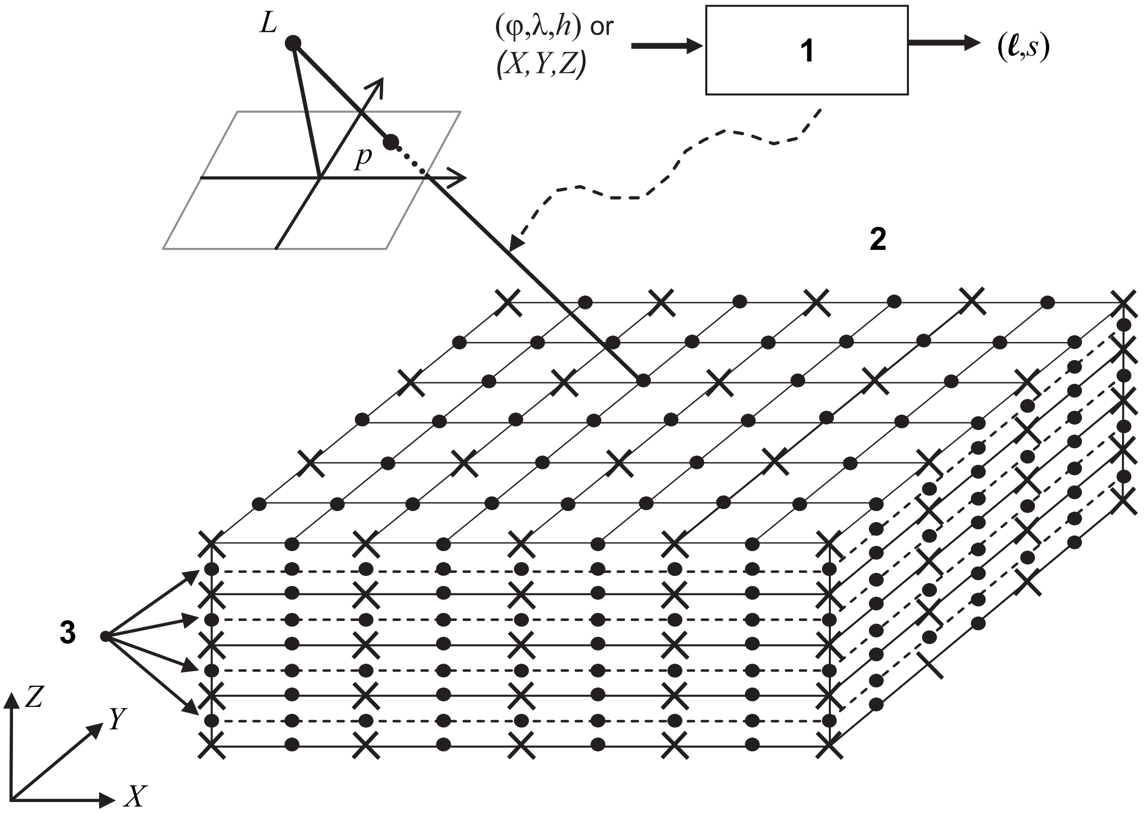
c) it may be necessary to develop new software every time there is either a sensor modification/upgrade or a new sensor, thus incurring additional software cost. Furthermore, every time there is a change, it impacts many user systems,

d) configuration management problems may occur due to having different implementation of the same complex model by different software developers, and

e) use of PSMs may be precluded due to security or proprietary information issues.

Because of these disadvantages of directly using PSMs in exploitation tools, an approach has been developed that negates these drawbacks. The approach is to use PSMs to produce replacement models that have a standard form, have the same characteristics, and perform very nearly the same as PSMs. Such models are referred to as True Replacement Models (TRMs). TRMs have a form that is sufficiently general to replace Physical Sensor Models for all types of sensors, thus simplifying the exploitation task.

An original Physical Sensor Model needs to be developed before a TRM can be constructed. The PSM is used to construct a large, dense volume of 3D ground points and the corresponding 2D image points that fully encompasses the imaged object space (see Figure 20). One of the forms of the TRM is equations, such as polynomials or rational polynomials (i.e., ratio of two polynomials), the coefficients of which are estimated using the dense grid. Another dense grid of check points is always generated from the PSM in order to check the accuracy of the fit of the equations to the fit grid. One can always ascertain that the fitting accuracy is within a specified level, such as a few tenths of a pixel, by increasing the density of the grid used to derive the polynomial coefficients, or segmenting the image, or both. When these procedures become impractical, the grids themselves and an interpolation become the TRM, as discussed in 8.2.2.4.



✕ Fit Point
● Check Point

Key

1 Physical Model
2 3D grid of points encapsulates the entire range of practical X, Y, Z values
3 Check Planes

Figure 20 — True Replacement Model generation of points

A TRM shall have the following properties of the PSM, namely

a) ground-to-image and image-to-ground functions,

b) complete and rigorous error propagation, and

c) adjustability, using carefully designed parameters, is possible.

8.2.2 Types of True Replacement Models

8.2.2.1 Polynomials

There are two approaches to the equations used to construct a TRM: either

a) a single polynomial in the object coordinates for the line and another for the sample; or,

b) a ratio of polynomials for each.

The “ratio of polynomials” approach is referred to as rational polynomials. In order to achieve high fit accuracy, the polynomials are usually of third or higher order. Since the very dense grid contains an extensive number of points (in the hundreds and even thousands), a correspondingly large number of equations result that are then used to estimate coefficients.

A third order polynomial in the object (ground) point coordinates, X, Y, Z, is of the form:

$$\begin{aligned}\boldsymbol{P}_1 = a_0 + a_1X + a_2Y + a_3Z + a_4XY + a_5XZ + a_6YZ + a_7X^2 + a_8Y^2 + a_9Z^2 + \\ a_{10}XYZ + a_{11}X^3 + a_{12}XY^2 + a_{13}XZ^2 + a_{14}X^2Y + a_{15}Y^3 + a_{16}YZ^2 + a_{17}X^2Z + a_{18}Y^2Z + a_{19}Z^3\end{aligned} \quad (9)$$

$\mathbf{P}_1$ is a polynomial;

a_0, a_1, a_2, a_3, a_4, a_5, a_6, a_7, a_8, a_9, a_{10}, a_{11}, a_{12}, a_{13}, a_{14}, a_{15}, a_{16}, a_{17}, a_{18} and a_{19} are the polynomial coefficients;

X, Y, Z are the object’s ground coordinates.

There are 20 coefficients for this single polynomial. If one polynomial is used for line l and another polynomial is used for sample s then the TRM will involve the estimation of 40 coefficients. Alternatively, a rational polynomial may be used for ℓ, and another for s, or:

$$\ell = \frac{\boldsymbol{P}_1(X,Y,Z)}{\boldsymbol{P}_2(X,Y,Z)} \qquad s = \frac{\boldsymbol{P}_3(X,Y,Z)}{\boldsymbol{P}_4(X,Y,Z)} \quad (10)$$

where

$\mathbf{P}_1$, $\mathbf{P}_2$, $\mathbf{P}_3$, $\mathbf{P}_4$ are the polynomials;

ℓ is the image line coordinate;

s is the image sample coordinate.

The coefficients within each polynomial, $\mathbf{P}_1$ through $\mathbf{P}_4$, are designated a_i through d_i, respectively. There are 20 coefficients, a_i, in $\mathbf{P}_1$, and 20 coefficients, c_i, in $\mathbf{P}_3$. However, there are only 19 coefficients in each of $\mathbf{P}_2$ and $\mathbf{P}_4$, because b_0 and d_0 are both selected to have a unit value to avoid singularities (zero denominators). Consequently, there are 78 rational polynomial coefficients (RPCs). The most common form of the TRM – the one used by commercial vendors of satellite imagery – uses RPCs.

Rearranging the terms in Equation (10):

$$\boldsymbol{P}_2'\ell - \boldsymbol{P}_1 = -\ell \qquad \boldsymbol{P}_4's - \boldsymbol{P}_3 = -s \tag{11}$$

where

$\mathbf{P}_2$’ is the same as $\mathbf{P}_2$ except that it does not have the unit terms (corresponding to b_0 as noted before);

$\mathbf{P}_4$’ is the same as $\mathbf{P}_4$ except that it does not have the unit terms (corresponding to d_0 as noted before).

When a pair of equations is written for each of the grid points and there are n grid points a set of 2n linear equations results as follows:

$$\underset{2n,78}{\boldsymbol{A}}\ \underset{78,1}{\boldsymbol{x}} = \underset{2n,1}{\boldsymbol{b}} \tag{12}$$

where

$\mathbf{A}$ is the matrix containing the X, Y, and Z terms of the 3rd degree polynomials at each point;

$\mathbf{x}$ is an array containing the 78 coefficients of the third degree rational polynomial;

$\mathbf{b}$ is a matrix of ℓ and s values at each point.

To summarize, two equations are written for each 3D/2D combination of object/image point correspondence. With n such combined 3D/2D points, the number of linear equations would be 2n. The n can be in the hundreds or even thousands, depending upon the size of the image and the extent of the object space it covers.

8.2.2.2 Coordinate normalization

Because of the high power of the polynomials and the likely large numbers involved, it is a good practice to normalize these original observed coordinates, referred to hereafter as $\text{coord}_{\text{obs}}$. All five different coordinates involved, ℓ, s, X, Y and Z, are normalized by applying shifts and scales such that the normalized values fall between -1 and +1.

Let: max = maximum value of a coordinate

min = minimum value of a coordinate

Then, the shift and scale for the coordinate is given by:

$$\text{shift} = -(\text{max} + \text{min}) / 2 \qquad \text{scale} = 2 / (\text{max} - \text{min}) \tag{13}$$

Thus, if $\text{coord}_{\text{obs}}$ is the given (un-normalized) coordinate, then the normalized coordinate, coord_{n} is given by:

$$\text{coord}_{\text{n}} = [\text{coord}_{\text{obs}} + \text{shift}] \bullet \text{scale} \tag{14}$$

and, the un-normalized coordinate given by:

$$\text{coord}_{\text{un}} = (\text{coord}_{\text{n}} / \text{scale}) - \text{shift} \tag{15}$$

recognizing that coord_{un} refers to the same variable as does $\text{coord}_{\text{obs}}$.

8.2.2.3 Direct Linear Transform

The choice between single polynomial and rational polynomial depends on the type of imagery. For frame imagery, the RPC usually works well when the object (ground) coordinate system is geographic, or λ, φ, h. When the ground coordinates are in a Cartesian system, such as geocentric or local space rectangular, the RPC model reduces to the special case containing only eleven coefficients of the form:

$$\ell = \frac{a_0 + a_1 X + a_2 Y + a_3 Z}{1 + c_1 X + c_2 Y + c_3 Z} \qquad s = \frac{b_0 + b_1 X + b_2 Y + b_3 Z}{1 + c_1 X + c_2 Y + c_3 Z} \tag{16}$$

where

ℓ	is a line coordinate;
s	is a sample coordinate;
X, Y, Z	are object space coordinates;
a_0, a_1, a_2, a_3	are the coefficients of the numerator of the rational polynomial that produces a line coordinate;
b_0, b_1, b_2, b_3	are the coefficients of the numerator of the rational polynomial that produces a row coordinate;
c_1, c_2, c_3	are the coefficients of the denominator of the rational polynomials.

These equations are known as the direct linear transform (DLT). If one attempts to solve for all 78 RPC coefficients, the result will be those 11 non-zero coefficients and the remaining 67 will all be zero.

8.2.2.4 True Replacement Model based on grid interpolation

For some pushbroom and whiskbroom systems, the images may need to be segmented and a separate set of polynomial coefficients estimated for each segment. As the number of such segments increases, this process may become either impractical or uneconomical, or the fit accuracy may simply not be acceptable. In such situations, the grid of 3D ground/2D image point coordinates becomes the replacement model. In the place of using numerical values of the polynomial coefficients to calculate the (ℓ, s) for a given (X, Y, Z), a pair of interpolation equations is used to evaluate (ℓ, s) on the basis of the 3D grid neighbours surrounding the given (X, Y, Z), as depicted in Figure 21.

If a trilinear interpolator is used, 16 parameters are involved; eight for line and eight for sample. This will require the use of the eight 3D grid points that surround the given point, which is the case depicted in Figure 21. The trilinear interpolation equations are of the form: $(\ell, s)_{\mathrm{int}}$.

$$\begin{aligned} \ell &= a_0 + a_1 X + a_2 Y + a_3 Z + a_4 XY + a_5 YZ + a_6 ZX + a_7 XYZ \\ s &= b_0 + b_1 X + b_2 Y + b_3 Z + b_4 XY + b_5 YZ + b_6 ZX + b_7 XYZ \end{aligned} \tag{17}$$

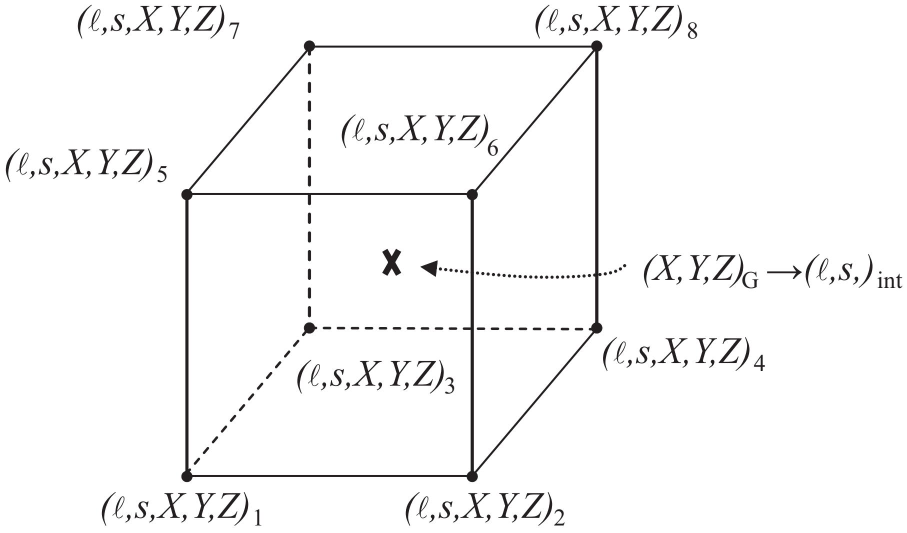


Figure 21 — Grid interpolation as a replacement model

The known values $(\ell, s, X,Y,Z)_j$, for j = 1, …, 8, result in 16 linear equations in the sixteen unknown parameters a_i and b_i, for i = 0, …, 7. Once the estimates, $\hat{a}_i, \hat{b}_i$, are determined, the same pair of equations is used to calculate $(\ell, s)_{int}$ for the given point $(X,Y,Z)_G$. When trilinear interpolation is not adequate, triquadratic interpolation, which requires 27 grid points nearest to the given point, may be used, or tricubic interpolation, which uses 64 grid points to estimate a_i and b_i, may be used. As with the case of a polynomial fit, a 3D check grid must be created to assess the quality of the selected interpolator. In general, the denser the grid, the higher the interpolation accuracy.

8.2.2.5 Ground-to-image and image-to-ground transformations

Unlike the Physical Sensor Model, which may be expressed directly as either a ground-to-image or image-to-ground transformation depending on the type of sensor, a TRM is usually expressed as a ground-to-image function. Consequently, the image-to-ground transformation is effected through a numerical iterative procedure. Nevertheless, the availability of both transformations constitutes one of the three primary characteristics of both Physical Sensor Models and True Replacement Models. The other two are rigorous error propagation and adjustability; discussed in the following subclauses.

8.2.2.6 Rigorous error propagation with a True Replacement Model

TRMs use mathematical functions such as single polynomials and ratios of polynomials in place of the mathematical representation of the Physical Sensor Model (PSM). The number of coefficients in these functions is usually much higher than the number of parameters involved in the PSM. For example, frame imagery has six exterior orientation parameters in its model. The corresponding frame image model TRM has 11 coefficients in the DLT, or as many as 78 coefficients in the RPC, depending upon whether a Cartesian or geographic object coordinate system, respectively, is used. The size of the PSM's *a priori* covariance matrix of the exterior orientation parameters is 6-by-6. If this is propagated into the TRM coefficients, an 11-by-11 or 78-by-78 covariance matrix would result. Both covariance matrices are singular, so each has a rank of 6, that of the original exterior orientation parameters covariance matrix.

There are two approaches to error propagation in TRMs. The first is to add a set of parameters to the TRM coefficients. These parameters can be added either on the object side or the image side. For error propagation only, these added parameters have zero values. However, a covariance matrix can be associated with them. Such a covariance matrix would play a role similar to the original covariance of the Physical Sensor Model in the error propagation process. For example, if deriving an object point from two images, its 3-by-3 covariance matrix would have essentially the same value regardless whether it is derived from the physical model or from its TRM.

The second approach (called the eigen approach) does not include added parameters. Instead, it propagates the original covariance matrix of the Physical Sensor Model into a covariance matrix associated with the TRM coefficients as an intermediate step. However, since this intermediate covariance matrix is singular, its eigenvalues and eigenvectors are calculated. There will be as many non-zero eigenvalues as the size and rank of the original covariance matrix. These eigenvalues and their corresponding eigenvectors are then used in subsequent error propagation, again yielding essentially the same results as those from the original physical model.

8.2.2.7 Adjustability for True Replacement Model

Adjustability is the third characteristic that makes a TRM equivalent to the Physical Sensor Model. In many situations, values of the parameters of the Physical Sensor Model, position, attitude, velocity etc., may not be of sufficiently good quality for certain applications; such as precision geopositioning. Therefore, additional information, such as ground control information, is used to update the *a priori* values of the model parameters. With TRM, there is an equivalent process to “upgrade” the TRM so that its performance is similarly improved. The term “upgrade” is used instead of “update”, because none of the coefficients in the TRM functions is actually updated in value. Instead, the TRM as a whole is upgraded by one of two approaches. The first approach is to estimate the same set of added parameters used in error propagation. Therefore, there will be numerical values for these added parameters, as well as a covariance matrix associated with them. In the second approach, the eigen approach, a set of equivalent parameters associated with the non-zero eigenvalues is estimated on the basis of the available ground control information. These new parameters are linear combinations of the original sensor model parameters. While the original parameters may have a full covariance matrix, the covariance matrix of the new set is diagonal in form; the elements are the non zero eigenvalues. Their estimation involves transformations based on the corresponding normalized eigenvectors, the details of which are beyond the scope of this Technical Specification. For more details see [42].

8.2.2.8 Summary

A TRM is developed on the basis of the Physical Sensor Model, which is used to construct two extensive grids of (often thousands of) object points and their corresponding image points for each image. One grid, a fit grid, is used to fit a selected function, and the other, a check grid, to evaluate the quality of the estimated function. To minimize potential numerical problems, values of all five coordinates (object and image) are first normalized such that those for each coordinate have a range of +1 to -1, and these normalized coordinates are used in estimating the unknowns of the selected function. Next, the function thus determined is applied to all the points of the check grid and both the root-mean-square (RMS) and maximum discrepancies in line and sample calculated to assess the fit quality. Usually the RMS should be a small fraction of a pixel, such as 0.1 to 0.3, and the maximum discrepancy less than one pixel. If both of these requirements are not met when attempting to fit the function to the whole image, then an attempt is made to fit a separate function to segments of the image. When image segmentation still does not reduce the errors below the stated fit tolerances, the object/image combined grids are then themselves considered to be the TRM and a 3-dimensional interpolation function is used to implement the object-to-image function. Both error propagation and adjustability are applied, whether the TRM is accomplished by a functional fit or the very dense grid.

8.3 Quality associated with a True Replacement Model

Added parameters can be either at the ground side or the image side of the TRM ground-to-image function. It is with this set of added (adjustable) parameters that a covariance matrix is associated, replacing the quality measures expressed by the covariance matrix, Σ_{EO}, of the exterior orientation parameters of the original model, or Σ_{EO}. Consider image side adjustable parameters:

$$(X,Y,Z) \rightarrow (TRM) \rightarrow \{(\ell',s') + \Delta i\} \rightarrow (\ell,s) \tag{18}$$

$$\Delta i = \begin{bmatrix} \delta\ell \\ \delta s \end{bmatrix} = \begin{bmatrix} p_{10} + p_{11}X + p_{12}Y \\ p_{20} + p_{21}X + p_{22}Y \end{bmatrix} \tag{19}$$

where

Δi is the adjustment;

$\delta \ell$ is the adjustment in the image line coordinate;

δs is the adjustment in the image sample coordinate;

$p_{10}, p_{11}, p_{12}, p_{20}, p_{21}, p_{22}$ are the adjustment polynomial coefficients;

X, Y, Z are the ground coordinates of an object.

The covariance matrix is then associated with the six p_{ij} parameters, or:

$$\Sigma_{pp} = \begin{bmatrix} \sigma^2_{p_{10}} & \sigma_{p_{10}p_{11}} & \sigma_{p_{10}p_{12}} & \sigma_{p_{10}p_{20}} & \sigma_{p_{10}p_{21}} & \sigma_{p_{10}p_{22}} \\ & \sigma^2_{p_{11}} & \sigma_{p_{11}p_{12}} & \sigma_{p_{11}p_{20}} & \sigma_{p_{11}p_{21}} & \sigma_{p_{11}p_{22}} \\ & & \sigma^2_{p_{12}} & \sigma_{p_{12}p_{20}} & \sigma_{p_{12}p_{21}} & \sigma_{p_{12}p_{22}} \\ & & & \sigma^2_{p_{20}} & \sigma_{p_{20}p_{21}} & \sigma_{p_{20}p_{22}} \\ & symmetric & & & \sigma^2_{p_{21}} & \sigma_{p_{21}p_{22}} \\ & & & & & \sigma^2_{p_{22}} \end{bmatrix} \tag{20}$$

where

Σ_{pp} is the covariance matrix;

σ^2_i are variances;

σ_{ij} are covariances;

p_i is the ith polynomial coefficient.

A covariance matrix as specified by Equation (20) shall be provided with the TRM of an image whose adjustable parameters are associated with the image side in order to calculate quality measures associated with the TRM.

For ground side adjustable parameters, then:

$$\{(X,Y,Z)+\Delta X\} \to (X',Y',Z') \to (TRM) \to (\ell,s) \tag{21}$$

with

$$\Delta X = \begin{bmatrix} \delta X \\ \delta Y \\ \delta Z \end{bmatrix} = \begin{bmatrix} q_X + q_1 X + q_2 Y - q_3 Z \\ q_Y - q_2 X + q_1 Y + q_4 Z \\ q_Z + q_3 X - q_4 Y + q_1 Z \end{bmatrix} \tag{22}$$

where

ΔX is the adjustment matrix;

δX is the adjustment in X coordinate;

δY is the adjustment in Y coordinate;

δZ is the adjustment in Z coordinate;

q_i are the coefficients;

X, Y, Z are the object's ground coordinates.

The covariance matrix Σ_{qq} is constructed similarly to Σ_{pp} in Equation (20). This matrix shall be provided with the TRM of an image with ground side adjustable parameters in order to calculate quality measures associated with the TRM.

The approach above is that used in the widely accepted RSM. An alternative approach, introduced in 8.2.2.4, is the eigen approach. The covariance matrix in this approach is simply a diagonal matrix of as many eigenvalues as the number of exterior orientation parameters. For a passive frame image, it is a matrix of order 6:

$$\Sigma_e = \begin{bmatrix} \lambda_1 & 0 & 0 & 0 & 0 & 0 \\ 0 & \lambda_2 & 0 & 0 & 0 & 0 \\ 0 & 0 & \lambda_3 & 0 & 0 & 0 \\ 0 & 0 & 0 & \lambda_4 & 0 & 0 \\ 0 & 0 & 0 & 0 & \lambda_5 & 0 \\ 0 & 0 & 0 & 0 & 0 & \lambda_6 \end{bmatrix} \quad (23)$$

where

Σ_e is the covariance matrix of the RSM;

λ_i are variances.

In order to perform error propagation, the six eigenvectors, **e₁, e₂, …, e₆** associated with $\lambda_1, \lambda_2, \ldots \lambda_6$, respectively, are also required. For a frame image, each **e** is an 11-by-1 vector.

8.4 Schema for True Replacement Model

As required by 8.2 and 8.3, a TRM shall provide the following with each image:

a) either the coefficients of the single polynomial or those of the ratio of polynomials used in the Ground-to-Image Function (SD_FittingFunction), or the 2D/3D combination of object / image point correspondence.

b) the optional scale and shift values used to normalize each of the image and ground coordinates (8.2.2.2) as part of SD_FittingFunction.

c) a covariance matrix to allow rigorous error propagation.

A set of ground control points may also be provided as ancillary information.

The classes shown in Figure 22, their attributes and their associations shall be used as described in the data dictionary of B.2.4.2.

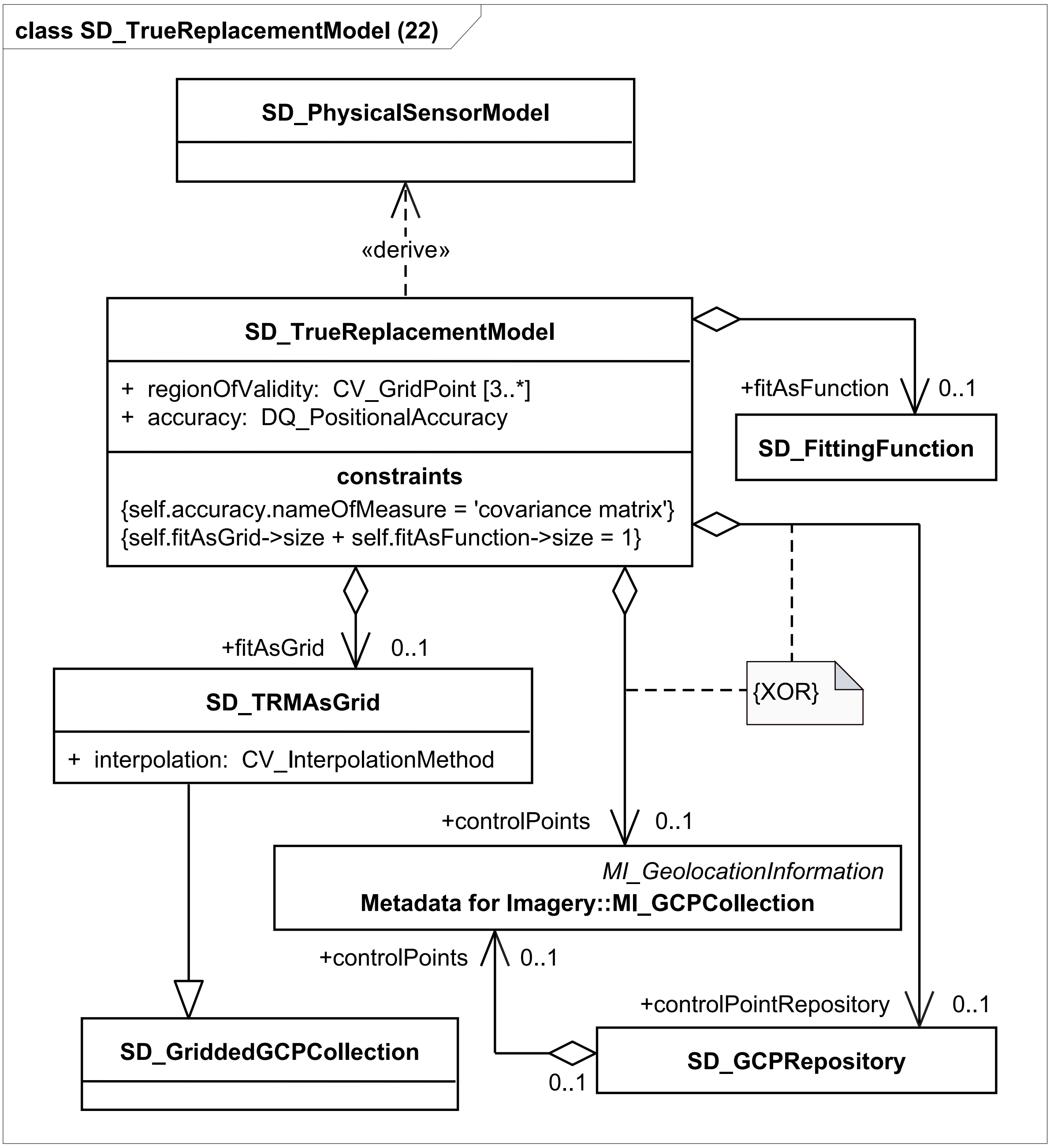


Figure 22 — True Replacement Model

8.5 Correspondence Model approach

8.5.1 Introduction

The Correspondence Model (CM) is a class of approaches to modelling that is not based on the Physical Sensor Model, even though it may have a functional fit similar to that of a TRM. The Correspondence Model derives the functional relationship between the image and ground coordinates from ground control points. CMs are typically used in remote sensing applications.

There are two groups of functional fits for CMs: three-dimensional-to-two-dimensional (3D-to-2D) form and two-dimensional-to-two-dimensional (2D-to-2D) form. Like TRMs, the first group has the ground-to-image transformation in analytical form, although the function is not as good a representation as a TRM. The second group is a significantly different approach, as it either deals with the image space only, or with object (ground) and image spaces but considers the object as being only a plane (thus disregarding elevations). Correspondence Models are sometimes described as ‘rubbersheeting’ or ’warping’ of one plane to match another.

8.5.2 Limitations of Correspondence Models

In general, CM approaches are not as precise as TRMs and do not have the well-defined error propagation needed for precise geopositioning. In particular, the contribution of the sensor errors, which can be significant, cannot be taken into account. CMs have the following limitations:

a) The parameters involved in CM have no physical significance.

b) The 2D-to-2D transformations do not take the terrain shape or ground elevation into account. Even when the 3D-to-2D transformation is used, the use of only a few object control points cannot fully account for the terrain surface. Points between the usually sparse set of ground control points may have significant errors resulting from the inadequacy of the functional fit to the few points.

c) Since the Physical Sensor Model is not used, including the covariance information associated with its parameters, complete and rigorous geopositioning error propagation is not possible. In the simpler approaches to CM, even approximate error propagation is not attempted. For other approaches to CM, error propagation can only partially account for error sources.

d) For Correspondence Models, very limited, if any, check point evaluation is possible, rigorous error propagation cannot be done and there is no adjustability.

For image-to-image transformation, only errors in image measurements can be included in the estimation of the transformation parameters. Errors in the ground control coordinates, in addition to image measurement errors, can be considered for 3D-to-2D transformations and also when interpolators are used in the case of image/ground control correspondence (8.2.2.4).

8.5.3 3D-to-2D Correspondence Models

The form of these models can appear to be quite similar to the TRMs. The polynomial coefficients of 3D-to-2D Correspondence Models are not derived from the entire 3D object space volume, as is the case with TRMs, but instead are derived on the basis of ground control points.

In general, the equations used for the TRM such as the single polynomial or the rational polynomials as shown in Equations (9) and (10) in 8.2.2 may also be used in the CM. These equations, with the large number of coefficients to be estimated, require a significantly large number of control points. If the image is a frame, then the DLT equations (Equation (16)) containing only 11 coefficients would be used.

The application of this approach is often based on very specific sensor assumptions, two of which are very narrow field of view (e.g., 1°-3°) and long distance from the sensor to the object being imaged. These assumptions may apply to satellite imaging systems, but may not easily apply to airborne sensors. When these assumptions do not apply, the image is quite often segmented into sections with different polynomials used for each section, similar to the procedure followed in the TRM method.

Variations on the equations mentioned above have been proposed. One is used for linear pushbroom geometry as it modifies the DLT equations to a single image line, or:

$$\begin{aligned} \ell &= a_0 + a_1 X + a_2 Y + a_3 Z \\ s &= \frac{b_0 + b_1 X + b_2 Y + b_3 Z}{1 + c_1 X + c_2 Y + c_3 Z} \end{aligned} \qquad (24)$$

where

ℓ	is a line coordinate;
s	is a sample coordinate;
X, Y, Z	are object space coordinates;
a_0, a_1, a_2, a_3	are the coefficients of the polynomial that generates the line coordinate;
b_0, b_1, b_2, b_3	are the coefficients of the numerator of the rational polynomial that generates the sample coordinate;
c_1, c_2, c_3	are the coefficients of the denominator of the rational polynomial that generates the sample coordinate.

This pair of Equations (24) is often referred to as the “parallel” perspective.

A further simplification is to limit the equations to only the numerators of the DLT equations, or:

$$\begin{aligned} \ell &= a_0 + a_1 X + a_2 Y + a_3 Z \\ s &= b_0 + b_1 X + b_2 Y + b_3 Z \end{aligned} \tag{25}$$

These equations have been given the name “orthographic projection”. For best applicability, the field of view should be small and the distance to the object large, so that the imaging rays would essentially be parallel. However, these restrictions are quite likely violated in the case of segments of optical imagery from airborne sensors.

8.5.4 2D-to-2D Correspondence Models

2D-to-2D Correspondence Models are similar to the process of “registration” used in the early days of remote sensing. At that time, remote sensing imagery from space had a considerably larger ground sample distance (GSD) than the current 1-metre and 0.61-metre commercial satellite imagery. Consequently, for specific remote sensing applications at the time, terrain relief was ignored and the terrain was considered to be flat (2D object). The equations used represented a transformation of the 2D object space coordinates (X,Y) to the 2D image space coordinates (ℓ , s). Current 2D-to-2D Correspondence Models use some form of this type of transformation such as the general polynomial:

$$\begin{aligned} \ell &= \sum_{i=0}^{m} \sum_{j=0}^{n} a_{ij} X^i Y^j \\ s &= \sum_{i=0}^{m} \sum_{j=0}^{n} b_{ij} X^i Y^j \end{aligned} \tag{26}$$

Such polynomials are applicable only in the following cases:

a) Large GSD

b) Narrow field of view

c) Essentially nadir view of the terrain

d) Terrain is flat (minimal to no elevation variation)

e) No elevated objects above the terrain

f) Relatively small image segment to minimize distortion effects

With each image that is warped using Equation (26), the coefficients a_{ij} and b_{ij} shall be provided as parameters in the fitting function (see Figure 19).

8.6 Schema for Correspondence Models

If an image provider chooses to support approximate geopositioning using the Correspondence Model approach, the information about the fitting function shall be provided as shown in Figure 23. The classes shown and their attributes and associations shall be used as described in the data dictionaries of B.2.4.3 as well as in ISO 19115-2.

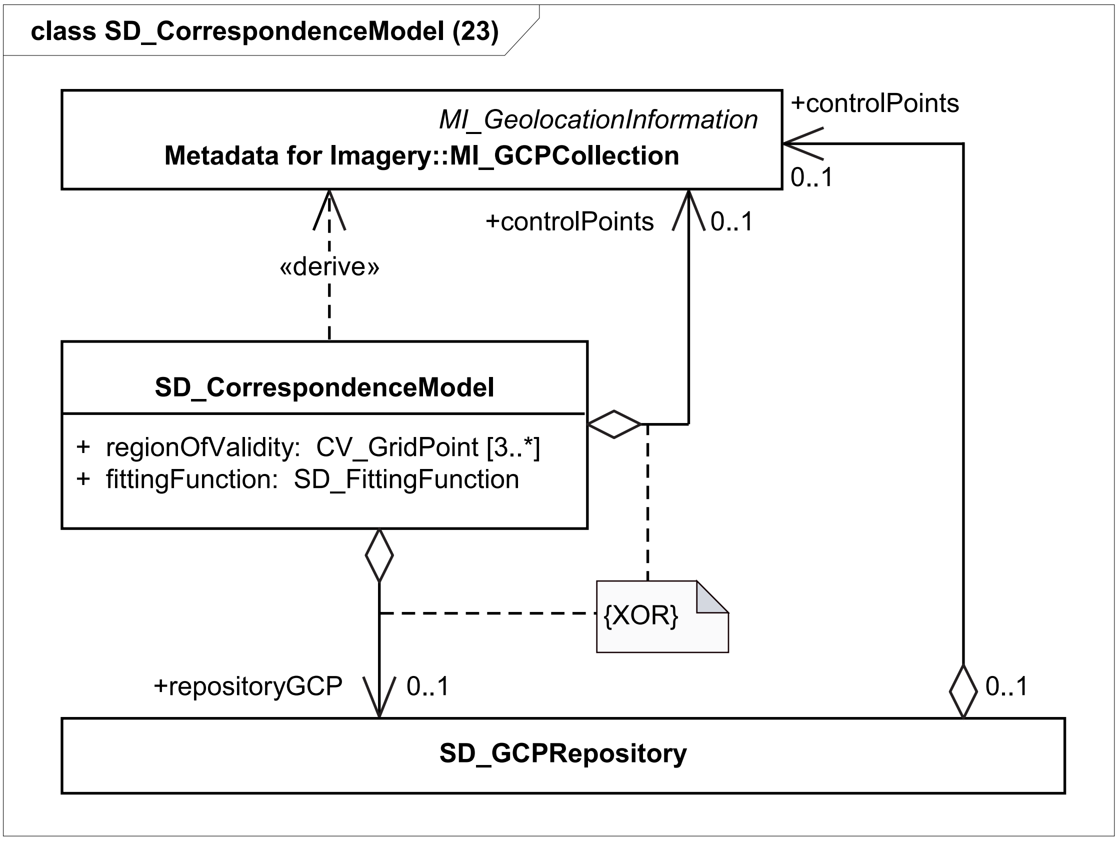


Figure 23 — Correspondence Model

Annex A
(normative)

Conformance and testing

A.1 Geopositioning information

a) Test purpose: Verify that geopositioning information provided with the image data instantiates one of the subclasses of MI_GeolocationInformation.

b) Test Method: Inspect the content of the metadata intended to support geopositioning.

c) Reference: 6.2

d) Test Type: Basic

A.2 Ground control points

A.2.1 GCP collection

a) Test purpose: If the metadata intended to support geopositioning contains ground control points, verify that it properly instantiates MI_GCPCollection and all of its attributes, associated classes, and their subclasses and their attributes and associated classes.

b) Test Method: Inspect the content of the metadata intended to support geopositioning.

c) Reference: 6.4, ISO 19115-2

d) Test Type: Capability

A.2.2 GCP repository

a) Test purpose: If the metadata intended to support geopositioning contains a reference to a remote repository of ground control points, verify that it properly instantiates SD_GCPRepository and its attributes and associated classes.

b) Test Method: Inspect the content of the metadata intended to support geopositioning.

c) Reference: 6.4.3

d) Test Type: Capability

A.3 Physical Sensor Model

A.3.1 Sensor model completeness

a) Test purpose: Verify that a sensor description is provided with the image data, that the classes instantiated are those required to describe the sensor used and that a platform description is present if the location of the sensor is provided relative to the platform rather than in object space coordinates.

b) Test Method: Inspect the metadata provided with the image.

c) Reference: 7

d) Test Type: Basic

A.3.2 Platform Information

a) Test purpose: If sensor position and orientation are provided relative to platform position and orientation, verify that metadata intended to support geopositioning instantiates the class SD_PlatformParameters with its attributes and instantiates the associated class MI_Platform.

b) Test Method: Inspect the metadata provided with the image.

c) Reference: 7.4.2, 7.5.4; ISO 19111:2007; ISO 19115-2:2009, A.2.5.1

d) Test Type: Capability

A.3.3 Sensor information

a) Test purpose: Verify that metadata intended to support geopositioning instantiates SD_SensorParameters with its attributes and associated classes.

b) Test Method: Inspect the metadata provided with the image.

c) Reference: 7.6

d) Test Type: Capability

A.3.4 Optics

a) Test purpose: Verify that, when an optical system is part of the sensor, metadata intended to support geopositioning includes SD_Optics, its attributes, and associated classes.

b) Test Method: Inspect the metadata provided with the image.

c) Reference: 7.6.4, 7.6.5

d) Test Type: Capability

A.3.5 SAR

a) Test purpose: Verify that, when the sensor is a SAR, metadata intended to support geopositioning includes SD_SAROperation, SD_GSD, and their attributes.

b) Test Method: Inspect the metadata provided with the image.

c) Reference: 7.6.1, 7.6.3, 7.6.6

d) Test Type: Capability

A.4 Functional fitting

a) Test purpose: Verify that if the metadata accompanying an image is an instance of SD_TrueReplacementModel or an instance of SD_CorrespondenceModel, it properly instantiates SD_FittingFunction and its subclasses.

b) Test Method: Inspect the content of the metadata intended to support geopositioning.

c) Reference: 8.1

d) Test Type: Capability

A.5 True Replacement Model

a) Test purpose: Verify that metadata sets instantiate SD_TrueReplacementModel.

b) Test Method: Inspect the content of the metadata intended to support geolocating.

c) Reference: 8.4

d) Test Type: Capability

A.6 Correspondence Model

a) Test purpose: Verify that metadata sets instantiate SD_CorrespondenceModel.

b) Test method: Inspect the content of the metadata intended to support georeferencing.

c) Reference: 8.6

d) Test Type: Capability

Annex B
(normative)

Geolocation information data dictionary

B.1 Data dictionary overview

B.1.1 Introduction

The layout is as described in ISO 19115:2003, Annex B except as described in the remainder of B.1.

B.1.2 Data type/class

Specifies a set of distinct values for representing the metadata elements: for example, integer, real, string, DateTime and Boolean. The data type attribute is also used to define metadata entities, stereotypes and metadata associations. If the data type of an entity or element is a class, it specifies the name of the class, if it is an association, it specifies the associated class.

B.1.3 Obligation/Condition

ISO 19115:2003, B.1.5.3, in describing conditional values for Obligation/Condition, states “If the answer to the condition is positive, then the metadata entity or the metadata element shall be mandatory.” Some of obligations/conditions in Annex B use this question/answer style of conditions. In addition, Annex B also uses Object Condition Language (OCL) constraints from the UML diagrams to express a number of conditions. OCL constraints are not questions and do not have answers either positive or negative. In many cases, OCL constraints provide more concise expression of conditions than question/answer conditions.

B.1.4 Domain

For an entity, specifies the line numbers covered by that entity.

For a metadata element, the domain specifies the values allowed or the use of free text. “Unrestricted” indicates that no restrictions are placed upon the content of the field. Integer-based codes shall be used to represent values for domains containing codelists. If the type of a metadata element is a class, the domain specifies the ISO standard where the class is defined, and if the domain is blank, the class is defined in this Technical Specification.

B.2 UML models for geolocation information

B.2.1 Overview of geopositioning information (Figure 1)

	Name/Role Name	Definition	Obligation/ Condition	Max Occurrence	Data Type/Class	Domain
1.	MI_GeolocationInformation	information used to determine geographic location corresponding to image location	Use obligation/ condition from referencing object	Use maximum occurrence from referencing object	Class <<Abstract>>	ISO 19115-2
2.	SD_SensorModel	information on sensor Model for sensor collecting the image	Use obligation/ condition from referencing object	Use maximum occurrence from referencing object	Specialised Class (MI_GeolocationInformation) Aggregated Class (SD_PhysicalSensorModel) (SD_TrueReplacementModel) (SD_CorrespondenceModel)	Line 3-6
3.	forImageID	identification of image to which the sensor model applies	M	1	CharacterString	Unrestricted
4.	*Role name:* physicalSensorModel	Physical Sensor Model for geopositioning of the image	C/ trueReplacement Model or correspondence Model not present?	N	SD_PhysicalSensorModel	
5.	*Role name:* trueReplacementModel	True Replacement Model for geopositioning of the image	C/ physcialSensorM odel or correspondence Model not present?	N	SD_TrueReplacementMode	
6.	*Role name:* correspondenceModel	Correspondence Model for geopositioning of the image	C/XOR physcialSensorM odel or trueReplacement Model not present?	N	SD_CorrespondenceModel	

B.2.2 Ground control points (Figure 2)

	Name/Role Name	Definition	Obligation/ Condition	Max Occurrence	Data Type/Class	Domain
7.	MI_GCPCollection	information about a control point collection	Use obligation/ condition from referencing object	Use maximum occurrence from referencing object	Specialised Class (MI_GeolocationInformation) Aggregated Class <MI_GCP>	line 8-11
8.	collectionIdentification	identifier of the GCP collection	M	1	Integer	Unrestricted
9.	collectionName	name of the GCP collection	M	1	CharacterString	Free Text
10.	coordinateReferenceSystem	coordinate system in which the ground control points are defined	M	1	MD_ReferenceSystem	ISO 19115
11.	*Role name*: gcp	ground control point(s) used in the collection	M	N	MI_GCP	ISO 19115-2
12.	SD_GCPRepository	information required to obtain ground control point information from a repository of ground control points	Use obligation/ condition from referencing object	Use maximum occurrence from referencing object	Aggregated Class (MI_GCPCollection)	Lines 13-15

	Name/Role Name	Definition	Obligation/ Condition	Max Occurrence	Data Type/Class	Domain
13.	accessRestricted	whether image provider is limiting access to ground control point information	M	1	Boolean	1=true 0=false
14.	accessInformation	if accessRestricted is true, point of contact who may authorize access to the data; if accessRestricted false, mechanism for obtaining the ground control point data.	M	1	CI_Contact	ISO 19115
15.	*Role Name:* controlPoints	individual GCP collection defined by MI_GCPCollection	C/{if self.accessRestricted = 'false' then self.controlPoints ->size = 1 else self.controlPoints ->size >= 0 endif}	1	MI_GeolocationInformation	ISO 19115-2
16.	MI_GCP	information on ground control point	Use obligation/ condition from referencing object	Use maximum occurrence from referencing object	Class	Line 17, also ISO 19115-2
17.	geographicCoordinates	geographic or map position of the control point, in either two or three dimensions	M	1	DirectPosition	ISO/TS 19103
18.	SD_LocationGCP	ground control point for which image coordinates have been determined.	Use obligation/ condition from referencing object	Use maximum occurrence from referencing object	Specialised Class (MI_GCP)	Line 19
19.	gridCoordinates	coordinates of control point in imagery grid	M	1	CV_GridCoordinates	ISO 19123
20.	SD_ImageIdentifiableGCP	ground control point that is either marked in the image or described so that the user can find it in the image.	Use obligation/ condition from referencing object	Use maximum occurrence from referencing object	Specialised Class (MI_GCP)	Line 21
21.	description	description of the ground control point sufficient to enable the user to find the image of the ground control point in the larger image.	M	1	CharacterString	Unrestricted
22.	SD_GriddedGCPCollection	ground control points regularly spaced in either image coordinates or ground coordinates and given as a grid	Use obligation/ condition from referencing object	Use maximum occurrence from referencing object	Specialised Class (MI_GCPCollection)	Line 23
23.	dimension	number of dimensions in the GCP grid	M	1	Integer	>=1
24.	SD_ImageGridGCPCollection	ground control points regularly spaced in object coordinates and given as a grid	Use obligation/ condition from referencing object	Use maximum occurrence from referencing object	Specialised Class (SD_GriddedGCPCollection)	Lines 25-26
25.	origin	position of the first grid cell with coordinate [0,0,(0)]	M	1	CV_GridCoordinates	ISO 19123
26.	spacing	size of the step in the number of pixels for each dimension in image coordinates	M	1	Integer[2..3] {ordered}	>=1

	Name/Role Name	Definition	Obligation/ Condition	Max Occurrence	Data Type/Class	Domain
27.	SD_objectGridGCPCollection	ground control points regularly spaced in object coordinates (e.g., ground coordinates) and given as a grid	Use obligation/ condition from referencing object	Use maximum occurrence from referencing object	Specialised Class (SD_GriddedGCPCollection)	Line 28-29
28.	origin	position of the first grid cell, with coordinate [0,0,(0)], of the GCP grid in object coordinates	M	1	DirectPosition	ISO/TS 19103
29.	offsets	size of the steps in the object coordinates for each dimension in object coordinates	M	1	Vector[2..3] {ordered}	ISO/TS 19103

B.2.3 Physical Sensor Model

B.2.3.1 Overall view (Figure 9)

	Name/Role Name	Definition	Obligation/ Condition	Max Occurrence	Data Type/Class	Domain
30.	SD_PhysicalSensorModel	Information describing the Physical Sensor Model	Use obligation/ condition from referencing object	Use maximum occurrence from referencing object	Aggregated Class (SD_PlatformParameters) (SD_SensroParameters)	Lines 31-34
31.	regionOfValidity	grid points that mark the boundary of the region of the image to which the geolocation information applies	M	N	CV_GridPoint	ISO 19123 Minimum three ordered grid points ("CV_GridPoint [3..*]{ordered})
32.	*Role name:* sensorInformation	sensor parameters used to construct a Physical Sensor Model	M	1	SD_SensorParameters	
33.	*Role name:* controlPointRepository	ground control point repository used to check or refine the Physical Sensor Model	C/SD_GCPRepository->size+MI_GCPCollection->size <=1	1	SD_GCPRespository	
34.	*Role name:* controlPoints	ground control points used to check or refine the Physical Sensor Model	C/SD_GCPRepository->size+MI_GCPCollection->size <=1	1	MI_GCPCollection	ISO 19115-2

B.2.3.2 Position (Figure 10)

	Name/Role Name	Definition	Obligation/ Condition	Max Occurrence	Data Type/Class	Domain
35.	SD_Position	location of either sensor or platform	Use obligation/condition from referencing object	Use maximum occurrence from referencing object	Class <<DataType>>	Lines 36-37
36.	timeOfMeasurement	time when the position is measured	M	1	DateTime	ISO/TS 19103

	Name/Role Name	Definition	Obligation/ Condition	Max Occurrence	Data Type/Class	Domain
37.	navigationalConfidence	accuracy of position	O	1	DQ_PositionalAccuracy	self.navigationalConfidence.nameOfMeasure=’covarianceMatrix’
38.	SD_EarthMeasuredLocation	location relative to the Earth	Use obligation/condition from referencing object	Use maximum occurrence from referencing object	Specialised Class (SD_Position)	Line 39
39.	position	position of the sensor or platform in Earth coordinates	M	1	DirectPosition	ISO/TS 19103
40.	SD_OrbitMeasuredLocation	location given by position in orbit	Use obligation/condition from referencing object	Use maximum occurrence from referencing object	Specialised Class (SD_Position)	Lines 41-53
41.	argumentOfPerigee	angle in the orbital plane from the ascending node to the point of perigee, in the direction of spacecraft motion	M	1	Angle	0.0<=argumentOfPerigee ‘Value <360.0
42.	bStarDrag	rate of change of the mean motion	O	1	Real	Unrestricted
43.	eccentricity	eccentricity of the spacecraft orbit	M	1	Real	0.0<=eccentricity Value<1,0
44.	epoch	time for which the values provided for other orbital elements are true	M	1	DateTime	Unrestricted
45.	inclination	angle at which the orbit plane crosses the equatorial plane	M	1	Angle	0.0=< inclination Value<180.0
46.	meanAnomaly	angle between perigee and the position of a hypothetical body that has the same orbital period as the real satellite but travels at a constant angular speed	C / self.meanAnomaly->size + self.perigreePassTime->size > =1	1	Angle	0.0<=meanAnomaly->Value <360.0
47.	meanMotion	constant angular speed that would be required for a body travelling in an undisturbed elliptical orbit of the specified semimajor axis to complete one revolution in the actual orbital period, expressed as number of revolutions per day	M	1	Real	>=0.0
48.	perigeePassageTime	any one date and time at which the spacecraft passes perigee	C / self.meanAnomaly->size + self.perigreePassTime->size > =1	1	DateTime	As specified by ISO 8601
49.	period	spacecraft orbital period	C / self.meanMotion->size + self.period->size + self.semiMajorAxis->size >= 1	1	TM_Duration	ISO 19108
50.	referenceCRS	coordinate reference system of the orbital coordinates	M	1	SC_CRS	ISO 19111
51.	revNumber	ordinal number of the satellite revolution at the time given by epoch	O	1	Integer	Unrestricted
52.	rightAscensionAscendingNode	angle eastward on the equatorial plane from the vernal equinox to the orbit ascending node	M	1	Angle	0.0<= rightAscensionAscendingNode ‘Value <360.0

	Name/Role Name	Definition	Obligation/ Condition	Max Occurrence	Data Type/Class	Domain
53.	semiMajorAxis	length of the semimajor axis of the spacecraft orbit	C / self.meanMotion->size + self.period->size + self.semiMajorAxis->size >= 1	1	Length	Unrestricted

B.2.3.3 Attitude (Figure 11)

	Name/Role Name	Definition	Obligation/ Condition	Max Occurrence	Data Type/Class	Domain
54.	SD_Attitude	attitude information	Use obligation/condition from referencing object	Use maximum occurrence from referencing object	Class <<DataType>>	
55.	SD_AngleAttitude	attitude information as three angles of rotation	Use obligation/condition from referencing object	Use maximum occurrence from referencing object	Specialised Class (SD_Attitude) <<DataType>>	Lines 56-60
56.	rotatedAxes	indication whether or not the axes are rotated. True equals to rotated	M	1	Boolean	True=rotated False=not rotated
57.	rotationAngleX	angle of the rotation around the external x axis, often called roll or abbreviated as “ω”.	M	1	Angle	Unrestricted
58.	rotationAngleY	angle of the rotation around the external y axis often called pitch or abbreviated as “φ”.	M	1	Angle	Unrestricted
59.	rotationAngleZ	angle of the rotation around the external z axis, often called yaw or abbreviated as “κ”.	M	1	Angle	Unrestricted
60.	rotationSequence	sequence of rotations about the axes	M	1	SD_RotationSequence	
61.	SD_MatrixAttitude	rotation matrix that describes attitude	Use obligation/condition from referencing object	Use maximum occurrence from referencing object	Specialised Class (SD_Attitude)	Line 62
62.	matrixElements	elements of the 3-by-3 rotation matrix	M	9	{ordered} < Real>	Real

B.2.3.4 Dynamics (Figure 12)

	Name/Role Name	Definition	Obligation/ Condition	Max Occurrence	Data Type/Class	Domain
63.	SD_Dynamics	motion of a body	Use obligation/condition from referencing object	Use maximum occurrence from referencing object	Class	Lines 64-69
64.	attitude	orientation of the body	O	1	SD_Attitude	
65.	velocity	linear velocity of the body	O	1	Velocity	ISO/TS 19103 Unrestricted
66.	acceleration	rate of change of velocity of the body	O	1	Acceleration	ISO/TS 19103 Unrestricted
67.	angularVelocity	angular velocity of the body	O	1	AngularVelocity	ISO/TS 19103 Unrestricted
68.	angularAcceleration	rate of change of the angular velocity of the a body	O	1	AngularAcceleration	ISO/TS 19103 Unrestricted
69.	dateTime	date and time at which attitude and motion information are valid	M	1	DateTime	ISO/TS 19103 Unrestricted
70.	SD_PlatformDynamics	directions of platform travel and pointing	Use obligation/condition from referencing object	Use maximum occurrence from referencing object	Specialised Class (SD_Dynamics)	Lines 71-72
71.	trueHeading	actual direction in which the platform is travelling relative to North	C/ self.velocity->size + self. trueHeading->size <= 1	1	Angle	ISO/TS 19103 Unrestricted
72.	yaw	offset between the true heading and the direction of the platform positive x-axis	C /self.attitude->size + self.yaw->size =1	1	Angle	ISO/TS 19103 Unrestricted

B.2.3.5 Position and orientation (Figure 13)

	Name/Role Name	Definition	Obligation/ Condition	Max Occurrence	Data Type/Class	Domain
73.	SD_PositionAndOrientation	position and orientation of axes of a coordinate system of a body relative to an external coordinate system	Use obligation/condition from referencing object	Use maximum occurrence from referencing object	Class	Lines 74-79
74.	dynamics	motion and orientation of the coordinate reference system of a body relative to an external coordinate system	M	1	SD_Dynamics	
75.	position	position of a body	C/{self.position->size + self.offset->size = 1 & self.position->size +self.mountingObject->size =1 & self.mountingObject->size + self.platform->size = 1}	1	SD_Position	

	Name/Role Name	Definition	Obligation/ Condition	Max Occurrence	Data Type/Class	Domain
76.	offset	displacement between origin of the coordinate system of a body and origin of external coordinate system	C/ self.position->size + self.offset->size = 1	1	Vector	ISO/TS 19103
77.	CRS	coordinate reference system on which the measures are taken	M	1	SC_CRS	
78.	*Role name:* mountingObject	description of relative spatial relationship between a body and another body upon which the latter is mounted	C/ {self.position->size +self.mountingObject->size =1 & self.mountingObject->size + self.platform->size = 1}	1	SD_PositionAndOrientation	
79.	*Role name*: platform	description of the platform on which an object is mounted	C/ {self.mountingObject->size + self.platform->size = 1}	1	SD_PlatformParameters	
80.	SD_PlatformParameters	information about motion and configuration of platform	Use obligation/ condition from referencing object	Use maximum occurrence from referencing object	Class	Lines 81-85
81.	observedPosition	position of the platform at the location of the position measurement instrument on the platform	M	1	SD_Position	
82.	positionObservationOffset	offset from the origin of the platform CRS to the position where the position measurement instrument is mounted	O	1	Vector	ISO/TS 19103
83.	dynamics	parameters describing the dynamic behaviour of the platform	M	N	SD_PlatformDynamics	ISO/TS 19103
84.	offsetOfINS	vector from GNSS to INS. If platform geolocation is provided by INS, this lever arm is unnecessary	O	1	Vector	ISO/TS 19103
85.	*Role name:* platformIdentification	identification information of the platform	M	1	MI_Platform	ISO 19115-2

B.2.3.6 Sensor Parameters (Figure 14)

	Name/Role Name	Definition	Obligation/ Condition	Max Occurrence	Data Type/Class	Domain
86.	SD_SensorParameters	information about sensor properties	Use obligation/ condition from referencing object	Use maximum occurrence from referencing object	Aggregated Class (SD_GSD) (SD_SensorSystemAndOperation) (SD_DetectorArray) (SD_Sensor)	Lines 87-92
87.	offsetAndOrientation	orientation and offset relative to the object on which the sensor is mounted	M	N	SD_PositionAndOrientation	
88.	operationalMode	description of the operational mode of sensor	O	1	CharacterString	Unrestricted

	Name/Role Name	Definition	Obligation/ Condition	Max Occurrence	Data Type/Class	Domain
89.	*Role Name:* detector	properties of sensor detector array	C/if(self.identification.type=’frame’ or self.identification.type=’pushbroom’ or self.identification.type=’whiskbroom’) then self.detector->size=1 else self.detector->size=0 endif	1	SD_DetectorArray	
90.	*Role Name:* gsdProperties	properties of ground sample distance	O	1	SD_GSD	
91.	*Role Name:* identification	provides identification information for sensor	M	1	SD_Sensor	
92.	*Role Name:* systemAndOperation	information describing the sensor specific properties and operations	M	1	SD_SensorSystemAndOperation	
93.	SD_Sensor	characteristics of the sensor	Use obligation/ condition from referencing object	Use maximum occurrence from referencing object	Specialised Class (MI_Instrument)	Lines 94-96
94.	calibration	information about determination of relation between instrument readings and physical parameters	O	1	SD_Calibration	
95.	mode	type of observation being made by sensor	O	1	CharacterString	Unrestricted
96.	operationalBand	wavelengths of the electromagnetic spectrum being observed by the sensor	O	N	MI_Band	ISO 19115-2
97.	SD_Calibration	circumstances of determination of relation between instrument readings and physical parameters	Use obligation/ condition from referencing object	Use maximum occurrence from referencing object	<<DataType>>	Lines 98-99
98.	calibrationAgency	authority under which calibration took place	M	1	CI_ResponsibleParty	ISO 19115
99.	calibrationDate	date calibration was carried out	M	1	Date	ISO/TS 19103
100.	SD_GSD	properties of ground space distance between neighbouring pixels of the image	Use obligation/ condition from referencing object	Use maximum occurrence from referencing object	Class <<Data Type>>	Lines 101-106
101.	columnSpacing	ground distance between neighbouring columns in image	M	1	Distance	ISO/TS 19103
102.	rowSpacing	ground distance between neighbouring rows in image	M	1	Distance	ISO/TS 19103
103.	gsdCRS	coordinate system used in the reference surface onto which the image is projected	M	1	MD_ReferenceSystem	ISO 19115
104.	rangeIPR	impulse response width in the Range direction relative to the reference plane	O	1	Distance	ISO/TS 19103
105.	azimuthIPR	impulse response width in the azimuth direction relative to the reference plane	O	1	SD_AzimuthMeasure	

	Name/Role Name	Definition	Obligation/ Condition	Max Occurrence	Data Type/Class	Domain
106.	referenceSurface	surface on which image is projected	M	1	SD_SurfaceCode	
107.	SD_AzimuthMeasure	information about the measurement of azimuth properties	Use obligation/ condition from referencing object	Use maximum occurrence from referencing object	Class <<Union>>	Lines 108-109
108.	distance	smallest distance between two point reflectors that can be distinguished as two objects	M	1	Distance	ISO/TS 19103 > 0.0
109.	azimuth	smallest difference in azimuth angle between two point reflectors that can be distinguished as two objects	M	1	Angle	ISO/TS 19103 Unrestricted

B.2.3.7 Sensor System and Operation (Figure 15)

	Name/Role Name	Definition	Obligation/ Condition	Max Occurrence	Data Type/Class	Domain
110.	SD_DetectorArray	dimensions and shapes of detector array	Use obligation/ condition from referencing object	Use maximum occurrence from referencing object	Class	Lines 111-117
111.	numberOfDimensions	number of dimensions of the detector array	M	1	Integer	> 0
112.	arrayOrigin	position of the origin of the detector array coordinate system in external coordinate system	M	1	DirectPosition	ISO/TS 19103
113.	arrayDimensions	names and sizes of the dimensions of the detector array	M	2	{ordered} <SD_ArrayDimension>	
114.	offsetVectors	displacement between origin of the detector array coordinate system and the location of the first detector in the detector array	M	2	{ordered} Sequence <Vector>	ISO/TS 19103
115.	detectorSize	size of a detector in a detector array dimension specified by detectorDimensionName	M	2	{ordered} Sequence <Length>	ISO/TS 19103
116.	detectorShape	shape of a detector	M	1	SD_ShapeCode	
117.	distortion	distortion of detector array	O	1	SD_Distortion	
118.	SD_ArrayDimension	information about one dimension of a detector array	Use obligation/ condition from referencing object	Use maximum occurrence from referencing object	<<Data Type>>	Lines 119-120
119.	name	name of a dimension of the detector array	M	1	CharacterString	free text
120.	size	size of a dimension of the detector array	M	1	Integer	>=1

B.2.3.8 Sensor System and Operation (Figure 16)

	Name/Role Name	Definition	Obligation/ Condition	Max Occurrence	Data Type/Class	Domain
121.	SD_SensorSystemAndOperation	specific properties of sensor system and operation	Use obligation/ condition from referencing object	Use maximum occurrence from referencing object	Class	Lines 122-123
122.	collectionStartTime	time data collection starts	M	1	DateTime	ISO/TS 19103 Unrestricted
123.	collectionEndTime	time data collection ends	O	1	DateTime	ISO/TS 19103 Unrestricted
124.	SD_Microwave	specific properties of microwave sensor and its operation	Use obligation/ condition from referencing object	Use maximum occurrence from referencing object	Specialised Class (SD_SensorSystemAndOperation)	
125.	SD_Optics	specific properties of optical sensor and its operation	Use obligation/ condition from referencing object	Use maximum occurrence from referencing object	Specialised Class (SD_SensorSystemAndOperation) Aggregated Class (SD_OpticsOperation, SD_OpticalSystem, SD_Distortion)	Lines 126-128
126.	*Role Name:* opticsOperation	information describing the operation of sensor optics	M	1	SD_OpticsOperation	
127.	*Role Name:* opticalSystem	properties of the sensor optical system	M	1	SD_OpticalSystem	
128.	*Role Name*: opticalDistortion	information describing the distortion of the sensor optical system	M	1	SD_Distortion	
129.	SD_OpticalSystem	information about the geometry of the sensor's optical system	Use obligation/ condition from referencing object	Use maximum occurrence from referencing object	Class	Lines 130-133
130.	calibratedFocalLength	focal length adjusted to distribute the effects of lens distortion more uniformly over the image	M	1	Length	ISO/TS 19103
131.	qualityOfFocalLength	variance of the calibrated focal length	O	1	DQ_QuantitativeAttributeAccuracy	self.qualityofFocallength.nameOfMeasure = 'variance'
132.	princPointAutocoll	principal point of autocollimation; coordinates of the foot of the perpendicular dropped from perspective centre (focal point) of the camera lens to the focal plane.	M	1	DirectPosition	ISO/TS 19103
133.	covPrincPtAutocoll	covariance of the location of the principal point of autocollimation	O	1	DQ_PositionalAccuracy	self.nameOfMeasure = covariance
134.	SD_SAROperation	operation properties of SAR system	Use obligation/ condition from referencing object	Use maximum occurrence from referencing object	Specialised Class of (SD_Microwave)	Lines 135-136
135.	orientation	SAR antenna orientation	M	1	SD_SAROrientationCode	
136.	grpPosition	coordinates of ground reference position of SAR image	M	1	DirectPosition	ISO/TS 19103

B.2.3.9 Optics Operation (Figure 17)

	Name/Role Name	Definition	Obligation/ Condition	Max Occurrence	Data Type/Class	Domain
137.	SD_OpticsOperation	configuration and operation of sensor optics	Use obligation/ condition from referencing object	Use maximum occurrence from referencing object	Class	Lines 138-139
138.	instFieldOfView	range of incident angles seen by the sensor at a single instant of time	M	1	Angle	ISO/TS 19103 >=0
139.	swathFieldOfView	nominal object field of view of the sensor, which is the range of angles from which the incident radiation can be collected by the detector array	M	1	Angle	>=0
140.	SD_WhiskbroomOperation	configuration and operation of whiskbroom optics	Use obligation/ condition from referencing object	Use maximum occurrence from referencing object	Specialised class of <<SD_OpticsOperation>>	Lines 141-143
141.	scanDuration	time required to acquire one scan line of an image	M	1	TM_IntervalLength	ISO 19108
142.	pixelScanDuration	time required to acquire one pixel of the whiskbroom sensor	M	1	TM_IntervalLength	ISO 19108
143.	scanAngleFunction	description of relationship between scan angle and time	M	1	SD_ScanAngleFunction	
144.	SD_PushbroomOperation	configuration and operation of Pushbroom optics	Use obligation/ condition from referencing object	Use maximum occurrence from referencing object	Specialised class of <<SD_OpticsOperation>>	Lines 145-147
145.	groundSamplingTime	time required to acquire one strip of image in pushbroom operation	M	1	TM_IntervalLength	ISO 19108
146.	forwardLookingAngle	angle in the along-track direction between the optical axis of the sensor lens and the vector from the platform to nadir. Positive if the sensor looks forward	O	1	Angle	ISO/TS 19103 Unrestricted
147.	sideLookingAngle	angle in the cross-track direction between the optical axis of the sensor lens and the vector from the platform to nadir. Positive if the sensor looks right side.	O	1	Angle	ISO/TS 19103 Unrestricted
148.	SD_ScanAngleFunction	alternative ways to provide the scan rate	Use obligation/ condition from referencing object	Use maximum occurrence from referencing object	Class <<Union>>	Lines 149-151
149.	angleEquation	equation to calculate scan angle given time	M	1	CharacterString	free text
150.	rate	angular velocity of the scan	M	1	AngularVelocity	ISO/TS 19103 Unrestricted
151.	angleTable	table containing scanning angle and time pairs	M	1	SD_ScanAngleTime	

	Name/Role Name	Definition	Obligation/ Condition	Max Occurrence	Data Type/Class	Domain
152.	SD_ScanAngleTime	table of times and corresponding scan angles	Use obligation/ condition from referencing object	Use maximum occurrence from referencing object	Class <<Data Type>>	Lines 153-154
153.	time	list of times elapsed since start of scan	M	N	{ordered} Sequence <TM_IntervalLength>	ISO 19108
154.	angle	list of scan angles corresponding to the elapsed times	M	N	{ordered} Sequence <Angle>	ISO/TS 19103

B.2.3.10 Distortion (Figure 18)

	Name/Role Name	Definition	Obligation/ Condition	Max Occurrence	Data Type/Class	Domain
155.	SD_Distortion	information on distortions relevant to remotely sensed imagery	Use obligation/ condition from referencing object	Use maximum occurrence from referencing object	Class	Lines 156-157
156.	princPointOfSymmetry	principal point of best symmetry, the centre of the circles of equal distortions of the lens	M	1	DirectPosition	ISO/TS 19103
157.	qualityOfPrincPointOfSymmetry	accuracy of the principal point of symmetry	M	1	DQ_QuantitativeAttributeAccuracy	qualityOfPrincPointOfSymmetry.nameOfMeasure="covariance matrix"
158.	SD_DistortionPolynomial	distortion described using a polynomial	Use obligation/ condition from referencing object	Use maximum occurrence from referencing object	Specialised Class (SD_Distortion)	Lines 159-162
159.	polynomialDecentering	polynomial that describes decentring distortion	O	1	SD_Polynomial	
160.	polynomialRadial	polynomial that describes radially symmetrical distortion	O	1	SD_Polynomial	
161.	qualityOfPolynomialRadial	covariance of the polynomial coefficients for radial distortion	O	1	DQ_PositionalAccuracy	ISO 19115 qualityOfPolynomialRadial.nameOfMeasure='covariance matrix'
162.	qualityOfPolynomialDecentering	covariance of the polynomial coefficients for decentring distortion	O	1	DQ_PositionalAccuracy	ISO 19115 qualityOfPolynomialDecentering.nameOfMeasure='covariance matrix'
163.	SD_DistortionTable	table providing distortion information	Use obligation/ condition from referencing object	Use maximum occurrence from referencing object	Specialised Class (SD_Distortion)	Lines 164-170
164.	rows	number of rows in the table	M	1	Integer	>=1
165.	columns	number of columns in the table	M	1	integer	>=1
166.	xOffset	image column number corresponding to the first cell in the table	M	1	integer	Unrestricted

	Name/Role Name	Definition	Obligation/ Condition	Max Occurrence	Data Type/Class	Domain
167.	yOffset	image row number corresponding to the first cell in the table	M	1	integer	Unrestricted
168.	xSpacing	number of columns in the image corresponding to an interval of one table column	M	1	Integer	>=1
169.	ySpacing	number of rows in the image corresponding to an interval of one table row	M	1	integer	>=1
170.	distortionValues	array of values describing image distortion	M	1	{ordered}Sequence <Real>>	real

B.2.4 True Replacement and Correspondence Models

B.2.4.1 Fitting Function (Figure 19)

	Name/Role Name	Definition	Obligation/ Condition	Max Occurrence	Data Type/Class	Domain
171.	SD_FittingFunction	function relating image and ground coordinates	Use obligation/ condition from referencing object	Use maximum occurrence from referencing object	Class	
172.	SD_Polynomial	polynomial used in the fitting function	Use obligation/ condition from referencing object	Use maximum occurrence from referencing object	Aggregated Class (SD_PolynomialCoefficient) Specialised Class (SD_FittingFunction)	Lines 173-174
173.	resultDimension	name of the dependent variable derived from the functional fit	M	1	MD_DimensionNameTypeCode <<Codelist>>	
174.	*Role name:* coefficient	coefficient of a term in the polynomial function	M	N	SD_PolynomialCoefficient	
175.	SD_RationalPolynomial	rational polynomial used as fitting function	Use obligation/ condition from referencing object	Use maximum occurrence from referencing object	Aggregated Class (SD_Polynomial) Specialised Class (SD_FittingFunction)	Lines 176-177
176.	*Role name:* numerator	numerator of the rational polynomial	M	1	SD_Polynomial	
177.	*Role name:* denominator	denominator of rational polynomial	M	1	SD_Polynomial	
178.	SD_PolynomialCoefficient	coefficient of one term of a polynomial function	Use obligation/ condition from referencing object	Use maximum occurrence from referencing object	Aggregated Class (SD_Variable)	Lines 179-180
179.	value	numerical value of a coefficient	M	1	Real	Unrestricted
180.	*Role name:* variable	set of variables to which the coefficient applies	O	N	SD_Variable	
181.	SD_Variable	independent variable used in polynomial function	Use obligation/ condition from referencing object	Use maximum occurrence from referencing object	Class	Lines 182-185
182.	dimension	name of the independent variable	M	1	MD_DimensionNameTypeCode	ISO 19115

	Name/Role Name	Definition	Obligation/ Condition	Max Occurrence	Data Type/Class	Domain
183.	power	the power of the variable	M	1	Integer	>=1
184.	scaleFactor	scale factor for transforming the normalized variable to its true value	O	1	Real	real
185.	translationValue	offset for translating the normalized variable to its true value	O	1	Real	real

B.2.4.2 True Replacement Model (Figure 22)

	Name/Role Name	Definition	Obligation/ Condition	Max Occurrence	Data Type/Class	Domain
186.	SD_TrueReplacementModel	information describing the True Replacement Model	Use obligation/ condition from referencing object	Use maximum occurrence from referencing object	Class Aggregated Class (SD_FittingFunction) (SD_GCPRepository) (MI_GCPCollection) (SD_TRMAsGrid)	Lines 187-192
187.	regionOfValidity	region of the image to which the fitting function applies	M	N	CV_GridPoint	ISO 19123 minimum 3 grid points. (CV_GridPoint[3..*])
188.	accuracy	accuracy of the result produced by the fitting function	M	1	DQ_PositionalAccuracy	accuracy.nameOfMeasure='covariance matrix'
189.	*Role name:* fitAsFunction	using fitting function to relate image and ground coordinates	C/{self.fitAsGrid + self.fitAsFunction->size=1}	1	SD_FittingFunction	
190.	*Role name:* fitAsGrid	use of gridded GCP to relate image and ground coordinates	C/{self.fitAsGrid->size + self.fitAsFunction->size=1}	1	SD_TRMAsGrid	
191.	*Role name:* controlPoints	ground control points used to check or refine the True Replacement Model	C/{self.controlPoints->size + self.controlPointRepository->size<=1}	1	MI_GCPCollection	ISO 19115-2
192.	*Role name:* controlPointRepository	information about repository from which the collection of GCP used for checking or refining the True Replacement Model may be obtained	C/{self.controlPoints->size + self.controlPointRepository->size<=1}	1	SD_GCPRepository	
193.	SD_TRMAsGrid	True Replacement Model as gridded GCPs	Use obligation/ condition from referencing object	Use maximum occurrence from referencing object	Specialised Class (SD_GriddedGCPCollection)	Line 194
194.	interpolation	method to interpolate the location between GCPs	M	1	CV_InterpolationMethod	ISO 19123

B.2.4.3 Correspondence Model (Figure 23)

	Name/Role Name	Definition	Obligation/ Condition	Max Occurrence	Data Type/Class	Domain
195.	SD_CorrespondenceModel	information about the Correspondence Model	Use obligation/ condition from referencing object	Use maximum occurrence from referencing object	Aggregated Class (MI_GCPCollection) (SD_GCPRepository)	Lines 196-199
196.	regionOfValidity	region of the image to which the fitting function applies	M	N	CV_GridPoint	ISO 19123 minimum 3 grid points. (CV_GridPoint[3..*])
197.	fittingFunction	function relating image and ground coordinates	M	1	SD_FittingFunction	
198.	*Role name:* controlPoints	collection of control points used to derive the fitting functions	C/(self.controlPoints->size + self.repositoryGCP->size <= 1)	1	MI_GCPCollection	ISO 19115-2
199.	*Role name:* repositoryGCP	information about repository from which the collection of GCP used for deriving the fitting function may be obtained	C/(self.controlPoints->size + self.repositoryGCP->size <= 1)	1	SD_GCPRepository	

B.2.5 Codelists

B.2.5.1 ShapeCode (Figure 15)

	Name	Domain Code	Definition
1.	SD_ShapeCode	ShapeCode	shape
2.	circular	001	circle
3.	square	002	square
4.	rectangular	003	rectangle
5.	elliptical	004	ellipse

B.2.5.2 SurfaceCode (Figure 14)

	Name	Domain Code	Definition
1	SD_SurfaceCode	SurfaceCode	Surface onto which the SAR image is projected
2.	ground	001	ground
3	inflatedEllipsoid	002	inflated ellipsoid
4	ortho	003	orthorectified surface
5	slant	004	slant plane

B.2.5.3 SAROrientationCode (Figure 16)

	Name	Domain Code	Definition
1.	SD_SAROrientationCode	SAROrientationCode	Orientation of SAR antenna on the platform
2.	left	001	antenna on left side of the platform
3.	right	002	antenna on right side of the platform

B.2.5.4 Rotation Sequence Code (Figure 11)

	Name	Domain Code	Definition
1.	SD_RotationSequence	RotationSequenceCode	sequence of rotations used in the description of angular attitude
2.	XYZ	001	rotation around X axis first, then Y, then Z
3.	XZY	002	rotation around X axis first, then Z, then Y
4.	YXZ	003	rotation around Y axis first, then X, then Z
5.	YZX	004	rotation around Y axis first, then Z, then X
6.	ZXY	005	rotation around Z axis first, then X, then Y
7.	ZYX	006	rotation around Z axis first, then Y, then X

Annex C
(normative)

Coordinate systems

C.1 Introduction

C.1.1 Overview

The objective of geopositioning is to develop a mathematical relationship between the position of an object on Earth and its image as recorded by a sensor. In order to algorithmically describe the data flow beginning with measurements by an individual sensor and ending with a geopositioned product, it is necessary to introduce coordinate reference systems. These coordinate reference systems are each defined with reference to a physical entity. They serve as a reference for related metadata and describe the steps required to convert the sensor measurements into geographical data. This annex defines those coordinate reference systems that are needed for geopositioning but are not defined in other ISO standards. The structure and the terminology in the descriptions are taken from ISO 19111:2007. Coordinate reference systems already defined in other ISO standards are not redefined in this document.

Typically, an image's spatial position will be given, at least initially or in its raw form, in relation to a coordinate reference system that is locally defined or attached to the engineering datum of the sensor. The corresponding object's geographical or map position will be defined with respect to a coordinate reference system attached to an Earth-based datum. Therefore, transformation from a sensor-based coordinate reference system to an Earth-based coordinate reference system must be accomplished via a sequence of translations and rotations of the sensor coordinate reference system origin and axes until they coincide with the Earth coordinate reference system origin and axes.

C.1.2 Earth coordinates

The Earth location may be given in geographical coordinates or on a map projection. Many projections are available. In projecting, it is not possible to preserve shape, size and direction at the same time. The choice of projection depends on which property is considered most important.

The flow of coordinate conversions and transformations required to relate image coordinates to coordinates referenced to the Earth is:

Image CRS > Platform CRS > Global geodetic CRS > National geodetic CRS > Projected CRS (map grid)

In some cases, for example when the imagery is presented as georeferenced to a global geodetic CRS, one or more of these steps may be unnecessary. In other cases there may be additional steps. The transformations and conversions that may be required between a global geodetic CRS such as WGS 84 and a map grid are not discussed in this Technical Specification.

C.1.3 Sensor coordinates

A Physical Sensor Model uses position and attitude information relevant to the sensor in question and the platform carrying it to find the geographic location corresponding to the coordinates of the measurements in the detector system. This process requires determination of the relation between the coordinate reference system for the detector and the geographic coordinate reference system.

In general, it is not possible to do so directly; the position and attitude of the sensor relative to the ground are not known. The location of the platform is generally expressible in geographic coordinates. The sensor may be mounted directly on the platform or on one or a series of gimbals. Each component of the mounting has its own coordinate reference system, and, by finding the relation between these systems, it is possible to find the relation between the detector coordinates and those used to geographically locate the platform. This process is a series of steps; the coordinate reference system for each component is defined in terms of the coordinate reference system of the component on which it is mounted.

C.2 Platform position with respect to the Earth

C.2.1 Introduction

The position of the platform is described in one of two ways. For an aircraft, platform position is normally described directly in a geodetic coordinate reference system such as the latitude and longitude and height of the aircraft referenced to a surface point or the Inertial Navigation System's Inertial Reference Frame (IRF) that is updated by the Inertial Measurement Unit (IMU). For a satellite, the position may be described in the same way, but it also may be described using the spacecraft orbital position. In that case, the ephemeris information must be converted into geodetic coordinates.

C.2.2 Geodetic coordinate reference system

C.2.2.1 Discussion

Geodetic coordinates can be provided directly for a collection platform by furnishing its latitude, longitude and height. The developer/manufacturer shall define the platform's coordinate origin and the offsets to position and attitude sensors to that platform's origin (IRF) and the offsets from that point to the sensor.

For an aircraft, height may be given by radar altimeter or barometric pressure, and it can be assumed that these heights are referenced to mean sea level at the given latitude and longitude. When a GNSS is used to determine platform position, height may be given relative to the surface of the ellipsoid of the CRS used by the GNSS.

C.2.2.2 Global geodetic coordinate reference systems

Three dimensional global CRSs include geographic CRSs, which use ellipsoidal coordinates, and geocentric CRSs, which use Cartesian coordinates. They will be based on a realization of the International Terrestrial Reference System (ITRS). They will usually be included in registers of geodetic parameters and it may be possible to identify them through register reference as well as through the explicit definitions. ISO 19111:2007 and ISO 19127 specify how such coordinate reference systems shall be defined or registered.

C.2.2.3 Topocentric coordinate system

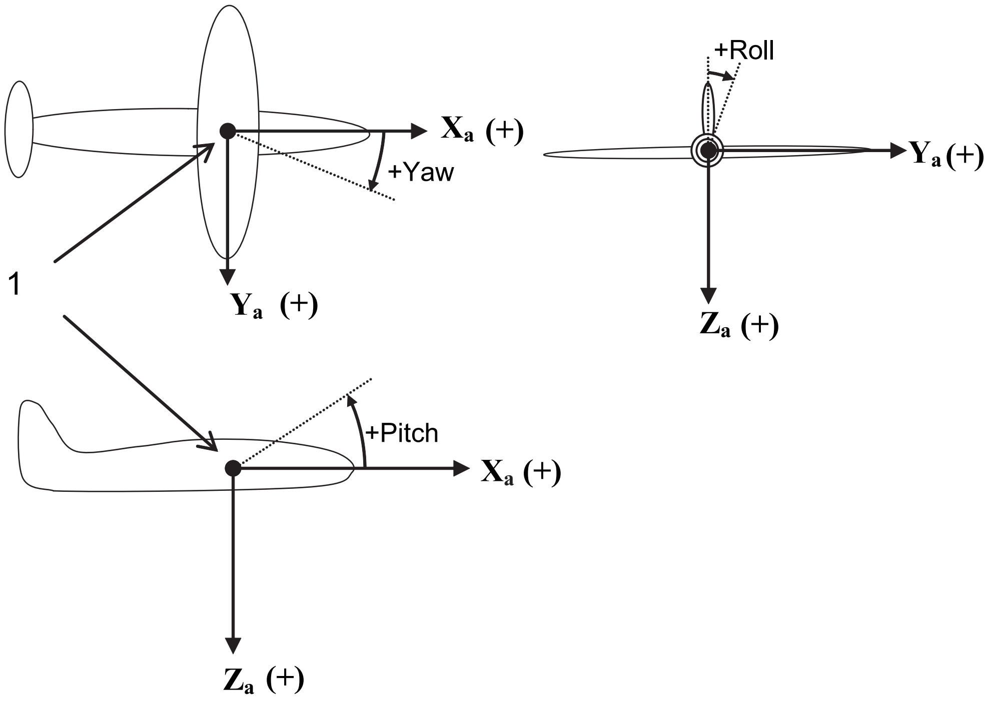
To perform tasks such as target marking, the position and height of an aircraft may have to be described in a topocentric coordinate system. A topocentric coordinate system is a 3-D Cartesian system having mutually perpendicular axes U, V, W with an origin on or near the surface of the Earth. The U-axis is locally east, the V-axis is locally north and the W-axis is up, forming a right-handed coordinate system. In the context of imagery, it has an origin that is of relevance to the imagery, for example the position on the surface of the Earth of the principal point. The topocentric coordinate system is based on and derived from either a geographic 3D CRS or a geocentric Cartesian CRS. ISO 19111:2007 specifies how to define elements of a derived CRS.

C.2.2.4 Platform coordinate reference systems

C.2.2.4.1 Basic platform CRS

The platform coordinate reference system is fixed to the platform structure; e.g. an aircraft as shown in Figure C.1. The axes are defined such that X is positive along the heading of the platform, the platform roll axis; Y is positive in the starboard direction along the pitch axis such that the XY plane is horizontal when the platform is at rest; and Z positive down, along the yaw axis, forming a right-handed Cartesian coordinate system. The platform CRS origin may be the platform navigation system reference point; in the example below, for a platform named abc, the reference point is not at the CRS origin.

Attribute	**Entry**
Engineering CRS name	Platform abc CRS, where ‘abc’ is platform name described by MI_Platform
CRS scope	Used for describing position with respect to the abc platform
Cartesian coordinate system name	Platform abc in metres
Coordinate system axis name	Roll axis
Coordinate system axis abbreviation	X
Coordinate system axis direction	Forward
Coordinate system axis unit identifier	metre
Coordinate system axis name	Pitch axis
Coordinate system axis abbreviation	Y
Coordinate system axis direction	Starboard
Coordinate system axis unit identifier	metre
Coordinate system axis name	Yaw axis
Coordinate system axis abbreviation	Z
Coordinate system axis direction	Down, forming a right-handed Cartesian system with the X and Y axes
Coordinate system axis unit identifier	metre
Coordinate system remarks	The X axis is approximately along the ground track direction of the platform, the Z-axis is approximately in the direction of the nadir
Engineering datum name	Platform abc
Datum scope	Used for describing position with respect to the abc platform
Datum anchor	Intersection of the roll, pitch and yaw axes.



Key

1 Centre of navigation

Figure C.1 — Platform CRS and attitude

C.2.2.4.2 Platform CRS corrected for attitude

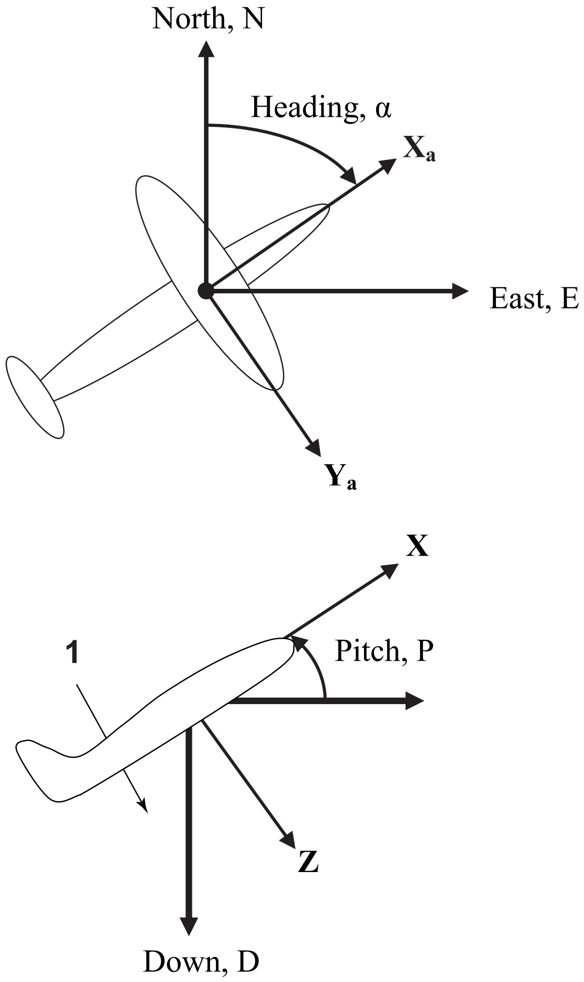
When the attitude of a platform changes, the platform CRS rotates and an attitude correction shall be applied to correct. After correction for roll, pitch and yaw the platform CRS may be transformed into an attitude-corrected platform coordinate reference system. The following is the altitude-corrected platform coordinate reference system, defined for an aircraft platform named abc in a flying project named xxxx:

Attribute	**Entry**
Engineering CRS name	Platform abc Attitude Corrected CRS
CRS scope	Used for describing position with respect to the abc platform
CRS remarks	Derived from the Platform abc CRS after application of roll, pitch and yaw corrections
Cartesian coordinate system name	Platform abc attitude corrected, in metres
Coordinate system axis name	Roll axis after roll correction applied
Coordinate system axis abbreviation	X_a
Coordinate system axis direction	Forward
Coordinate system axis unit identifier	metre
Coordinate system axis name	Pitch axis after pitch correction applied

Coordinate system axis abbreviation	Y_a
Coordinate system axis direction	Starboard
Coordinate system axis unit identifier	metre
Coordinate system axis name	Yaw axis after yaw correction applied
Coordinate system axis abbreviation	Z_a
Coordinate system axis direction	Down, forming a right-handed Cartesian system with the X_a and Y_a axes
Coordinate system axis unit identifier	metre
Coordinate system remarks	The X_a axis is along the ground track direction of the platform, the Z_a-axis is in the direction of the nadir
Base CRS	Platform abc CRS
Engineering datum name	Platform abc
Engineering datum scope	Used for describing position with respect to the abc platform
Datum anchor	Intersection of the roll, pitch and yaw axes.
Coordinate operation name	Project xxxx topocentric origin definition
Coordinate operation scope	Defines the origin of the project xxxx topocentric coordinate system with respect to the global WGS 84 CRS
Coordinate operation method name	Attitude correction
Coordinate operation method formula	rotation matrix from XYZ to $X_aY_aZ_a$
Operation parameter name	Roll correction
Operation parameter value	x degrees
Operation parameter name	Pitch correction
Operation parameter value	y degrees
Operation parameter name	Yaw correction
Operation parameter value	z degrees

C.2.2.4.3 Platform CRS corrected for attitude and heading

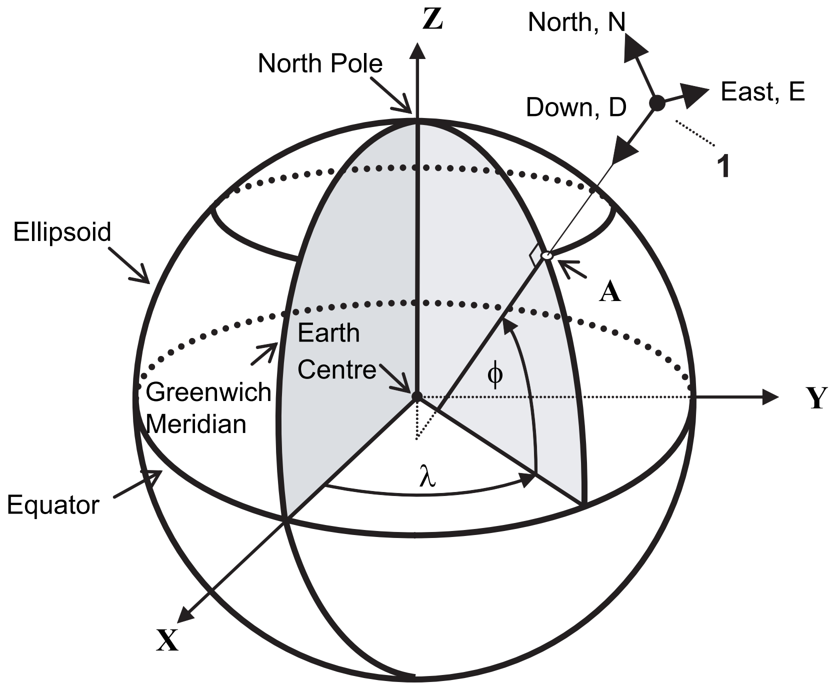
If the heading of the platform (the angle from north to the X axis) is known, Figure C2, the attitude-corrected platform CRS can be rotated to form a North, East, Down (NED) system, Figure C3. Alternatively the attitude and heading corrections may be applied in one operation.



Key

1 Centre of navigation

Figure C.2 — Platform CRS, heading



Φ Latitude
λ Longitude

Key

1 Platform attitude and heading corrected (NED) coordinate reference system

Figure C.3 — Platform attitude and heading corrected and global coordinate reference systems

The following is the altitude- and heading-corrected platform coordinate reference system, defined for an aircraft platform named abc in a flying project named xxxx:

Attribute	**Entry**
Engineering CRS name	Platform abc Attitude and Heading Corrected
CRS alias	NED CRS
CRS scope	Used for describing position with respect to the abc platform
CRS remarks	Platform abc CRS after application of attitude and heading corrections.
Cartesian coordinate system name	Platform abc attitude corrected, in metres
Coordinate system axis name	Roll axis after roll and heading corrections applied
Coordinate system axis abbreviation	N
Coordinate system axis direction	North
Coordinate system axis unit identifier	Metre
Coordinate system axis name	Pitch axis after pitch and heading corrections applied

Coordinate system axis abbreviation	E
Coordinate system axis direction	East
Coordinate system axis unit identifier	Metre
Coordinate system axis name	Yaw axis after yaw correction applied
Coordinate system axis abbreviation	D
Coordinate system axis direction	Down, forming a right-handed Cartesian system with the N and E axes
Coordinate system axis unit identifier	Metre
Base CRS	Platform abc CRS
Engineering datum name	Platform abc
Datum scope	Used for describing position with respect to the abc platform
Datum anchor	Intersection of the roll, pitch and yaw axes.
Coordinate operation name	Project xxxx topocentric origin definition
Coordinate operation scope	Defines the origin of the project xxxx topocentric coordinate system with respect to the global WGS 84 CRS
Coordinate operation method name	Attitude and heading correction
Coordinate operation method formula	Rotation matrices from XYZ to NED
Operation parameter name	Roll correction
Operation parameter value	x degrees
Operation parameter name	Pitch correction
Operation parameter value	y degrees
Operation parameter name	Yaw correction
Operation parameter value	z degrees
Operation parameter name	Heading correction
Operation parameter value	A degrees

If the coordinates of the platform navigation point have not been given directly in a global CRS, for example by using a GNSS, it can now be found indirectly if the platform altitude is known. The coordinates of the platform navigation point referenced to the attitude and heading corrected platform CRS may be transformed to be referenced to a topocentric CRS (C.2.2.3) with an origin at the intersection of the platform’s nadir and the Earth and then to a global geocentric Cartesian or geographic 3D CRS (C.2.2.2). If required, the coordinates referenced to the global CRS may be transformed to be referenced to a national CRS or map grid.

C.2.2.4.4 Satellite platform coordinate reference system

In contrast to an airborne or marine platform, a satellite may employ a North-East-UP platform coordinate reference system. The platform coordinate reference system is defined with the yaw axis (Z_P) as an extension of the vector from the geocentre (the origin of the global geocentric CRS) through the satellite inertial reference point (IRP), the roll axis (Y_P) is in the orbital plane perpendicular to the yaw axis, along the velocity vector; and the pitch axis (X_P) is perpendicular to both the yaw and roll axes forming a right-handed coordinate system. Satellite attitude rotational values are generally computed in this coordinate reference system, often from stellar observations or the on-board INS data. In stabilized platform systems, the Inertial Measurement Unit can be kept aligned to a particular navigation frame of interest (for example the global geocentric Cartesian coordinate reference system) using external torques derived from the measured angular rates.[46] However, in a strap down inertial system, the IMU is rigidly mounted to the vehicle to be positioned and thus can have an arbitrary orientation.

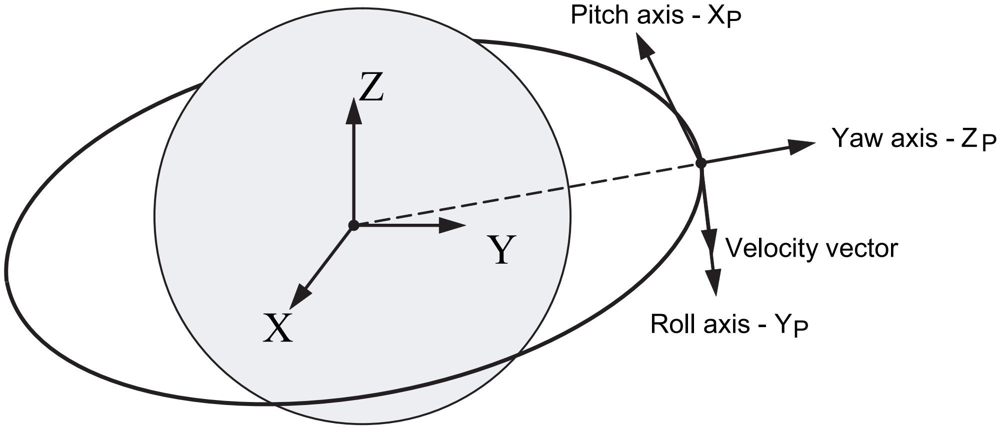


Figure C.4 — Satellite platform CRS with respect to geocentric Cartesian CRS

The following is the satellite platform coordinate reference system, defined for a satellite platform named abc:

Attribute	**Entry**
Engineering CRS name	Satellite abc CRS
CRS scope	Used for describing position with respect to the abc platform
Cartesian coordinate system name	Satellite abc Universal Space Rectangular
Coordinate system axis name	Pitch axis
Coordinate system axis abbreviation	X_P
Coordinate system axis direction	Perpendicular to the Y_P and Z_P axes forming a right-handed coordinate system
Coordinate system axis unit identifier	Metre
Coordinate system axis name	Roll axis
Coordinate system axis abbreviation	Y_P
Coordinate system axis direction	Velocity vector
Coordinate system axis unit identifier	Metre

Coordinate system axis name	Yaw axis, extension of the vector in the orbital plan from the geocentre (the origin of the global geocentric CRS) through the satellite IRP
Coordinate system axis abbreviation	Z_P
Coordinate system axis direction	Up
Coordinate system axis unit identifier	Metre
Coordinate system remarks	The X axis is approximately along the ground track direction of the platform, the Z-axis is approximately in the direction of the nadir
Engineering datum name	Satellite abc
Datum scope	Used for describing position with respect to the abc satellite
Datum anchor	Inertial reference point (IRP).

C.2.2.5 Platform position extensions for satellite implementation

A satellite provides a stable and, more importantly, a predictable platform. Thus one can employ constraints dictated by Kepler's laws of motion to achieve convergence in calculation of the satellite position. In particular, the following laws can be used to calculate the position of a satellite in its orbit at a particular time.

- The orbits are elliptical.
- The vector from the Earth's centre to the satellite sweeps equal areas in equal intervals of time.
- The orbital period (P) is given by $P^2 = \frac{4\pi^2 a^3}{GM_e}$ where a is the semi-major axis of the orbital ellipse, G is the gravitational constant, and M_e is the mass of the Earth (GM_e = 398600.4415 km^3/s^2).

The ideal elliptical orbit, with the Earth at one node, is described by 6 Keplerian elements depicted in Figures C.5 and C.6:

τ	true anomaly (instantaneous angle from satellite to perigee);
ω	argument of perigee – angle between the point of perigee and the ascending node, measured from the ascending node in the direction of the platform's motion along the plane of the orbit;
Ω	right ascension of the ascending node – angle eastward from the vernal equinox to the point where the satellite orbit crosses the equator when moving northward;
a	semi-major axis of the elliptical orbit – half the major axis of the satellite's elliptical orbit around the Earth. Instead of the semi-major axis, the orbital period may be provided directly or as mean motion, the constant angular speed that would be required for a body travelling in an undisturbed elliptical orbit to complete one revolution in the actual orbital period, often expressed as number of revolutions per day. The period and semi-major axis are related;
e	eccentricity of the orbit;
i	inclination of the orbital plane with respect to the equatorial plane, measured clockwise from East.

The size and shape of the orbital ellipse is defined by the semi-major axis of the ellipse “ a ” and the numerical eccentricity “*e*”. The orientation of the orbital plane relative to the equator is defined by orbital inclination i and the right ascension of the ascending node Ω. The argument of perigee ω and the true anomaly τ define the position of the satellite on the ellipse at a particular time *t*. The satellite platform position is also represented by the geocentric vector **R**. In terms of polar coordinates, the vector **R** is defined by the geocentric latitude Ψ, the geographic longitude λ and the geocentric radius R as a function of time. The following elements are also used for orbits:

Epoch – The time for which the values provided for other orbital elements are true.

Mean motion – constant angular speed that would be required for a body travelling in an undisturbed elliptical orbit of the specified semimajor axis to complete one revolution in the actual orbital period, often expressed as number of revolutions per day.

Mean anomaly – the angle between the satellite position and perigee at the time given by the epoch.

The orbital elements are time-variant and are defined at a particular time of the orbit of a satellite. A parameter, epoch, is used to specify the time at which the orbital elements are valid. Instead of true anomaly, another parameter, mean anomaly at epoch, is often used to specify the angle between the position of a satellite and perigee at the time given by the epoch. It is also common to use the orbital period parameter or the mean motion parameter, often expressed as number of revolutions a satellite travelling in an orbit per day, instead of the semimajor axis parameter. Because an ideal orbit defined by the Keplerian elements is subject to perturbations, such as gravitational pull by other celestial bodies and atmospheric drag, an additional parameter, drag, may be used to describe the rate of change in mean motion due to perturbations.

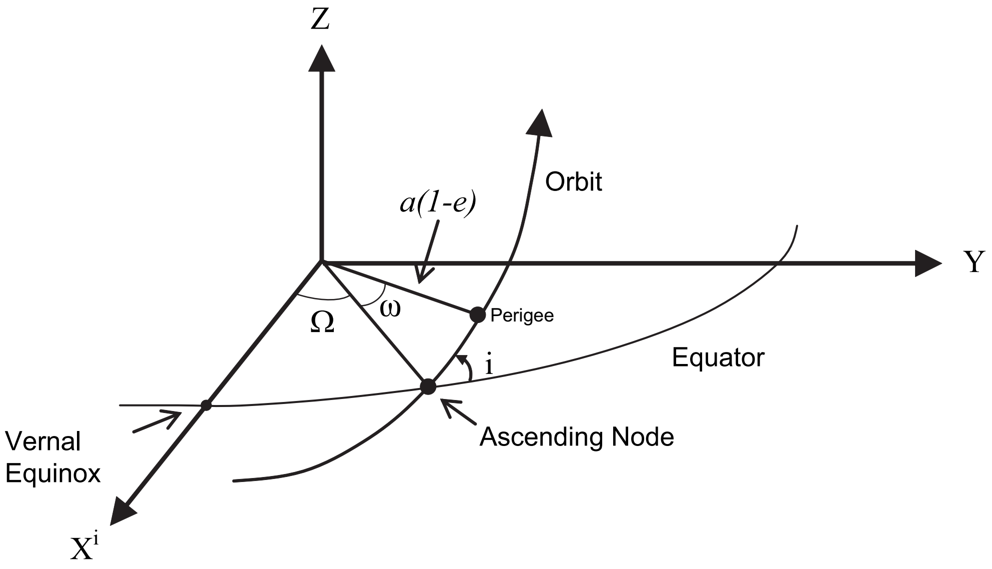
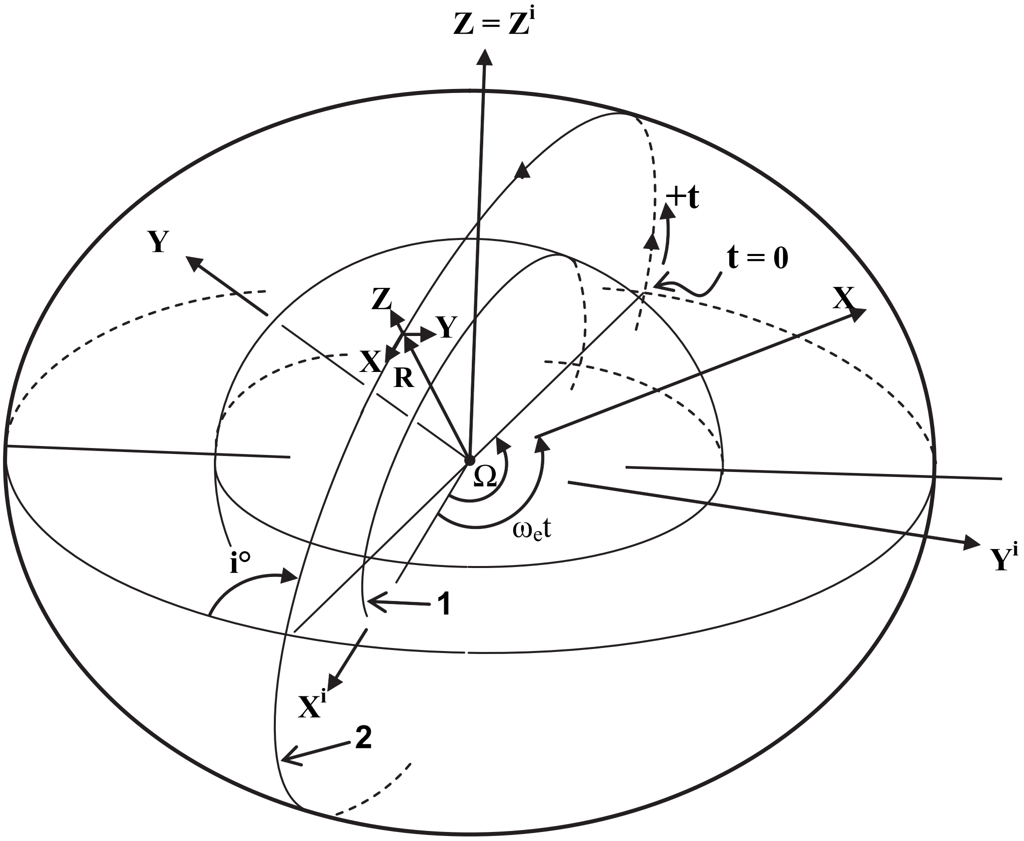


Figure C.5 — Orbital geometry



Key

1 Satellite Ground Track
2 Satellite Orbit

Figure C.6 — Keplerian orbit

C.2.2.6 Satellite Platform Time

Time t is the only independent variable in the orbital relations. Because of the Keplerian character of the satellite motion, the travel angle τ is not directly proportional to the elapsed time. With knowledge of the mean angular velocity ω_m, the relation between τ and t is established by the following three equations:

$$\cos E = \frac{e + \cos\tau}{1 + e\cos\tau} \qquad \text{(C.1)}$$

$$M = E - e\sin E \qquad \text{(C.2)}$$

$$t = M / \omega_m \qquad \text{(C.3)}$$

where

E	is the eccentric anomaly;
e	is the eccentricity of the orbital ellipse;
τ	is the true anomaly;
M	is the mean anomaly;

t is time;

ω is the argument of perigee.

Equations (C.1) – (C.3) express the τ –to–t time conversion:

$$t = F_{(t)}(\tau) \tag{C.4}$$

where

F is the function relating t to τ.

C.2.2.7 Earth rotation effect

The combination of satellite travel and Earth motion results in a composite motion which causes the satellite ground track on Earth. The effect of Earth rotation with respect to the satellite travel angle τ can be expressed by the geocentric latitude Ψ and the geodetic longitude λ of the subsatellite point as:

$$\begin{aligned} &\sin\psi = \sin(\omega+\tau)\sin i \\ &\tan\lambda_s = \tan(\omega+\tau)\cos i \\ &\lambda = \lambda_s + \lambda_E \end{aligned} \tag{C.5}$$

where

Ψ is geocentric latitude;

λ_S is geographic longitude;

ω is the argument of perigee;

τ is satellite travel angle;

i is inclination of the orbital plane;

λ_E is the longitude change with the angular velocity of the Earth;

λ is geodetic longitude;

and $\lambda_E = \omega_E t$, where ω_E is the angular velocity of the Earth.

Given the orbital ellipse semi-major and semi-minor axes as “a” and “b” respectively, the geographic latitude, Φ, can then be derived from the geocentric latitude by:

$$\tan \Phi = (b^2 / a^2) \cdot \tan \Psi \tag{C.6}$$

Φ = geographic latitude;

a = orbital ellipse semi-major axis;

b = orbital ellipse semi-minor axis.

C.3 Sensor position relative to platform

C.3.1 Overview

Except for the simplest case in which the position and orientation are described directly with respect to an earth coordinate reference system, the next stage in finding the geographic location corresponding to a point in a sensor coordinate is to determine the relationship between the coordinate reference system in which the sensor measurements are expressed and the platform coordinate reference system.

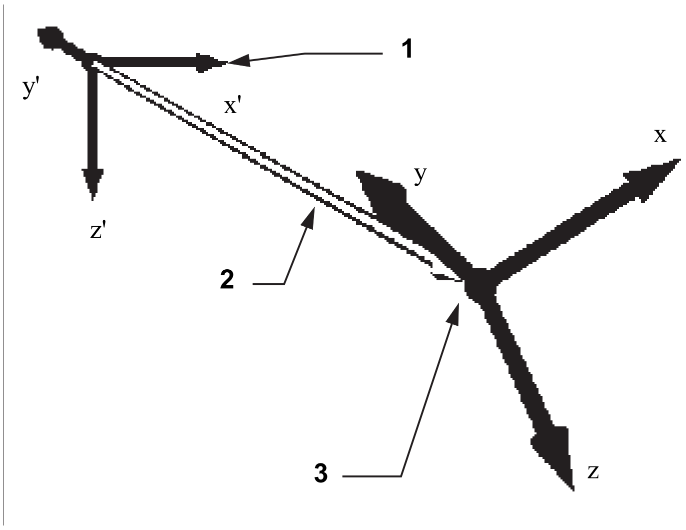
In the simplest case of sensor to platform mounting, the sensor position and attitude may be described directly with respect to the origin of the platform coordinate reference system. Each sensor has its own coordinate reference system which shall be defined for accurate photogrammetric applications.

However, the system may consist of several components and a progression, either from platform to sensor or from sensor to platform, of position and attitude vectors, which define the position and attitude of the collection platform, the sensor mounting and the sensor itself, is needed. Each stage in this progression consists of a position vector and an attitude vector described relative to the coordinate system for the previous stage, and these stages form a chain of position and attitude vectors. When transforming from the position and attitude vectors from platform to those of a sensor, the first stage of the sensor mounting has its position and attitude defined in the platform coordinate reference system. The last stage describes the position and attitude or the sensor itself. All position vectors are measured as x, y and z offsets in meters from the origin of the preceding coordinate system. All attitude vectors are measured in radians as rotations about the x, y and z axis with the order of rotation defined and applied sequentially to the preceding coordinate system. When the mounting system uses gimbals, it may be necessary to define a single physical gimbal ring using multiple stages because gimbals may not have coaxial axial centres of rotation.

C.3.2 Gimbals

C.3.2.1 Overview

Figure C.7 shows the position and attitude for a gimbal stage relative to the previous one. Figure C.8 contrasts single and multiple stage gimbals.



Key

1 Coordinate System defined by previous stage
2 Gimbals Position Vector
3 Gimbals attitude vector defines new coordinate system

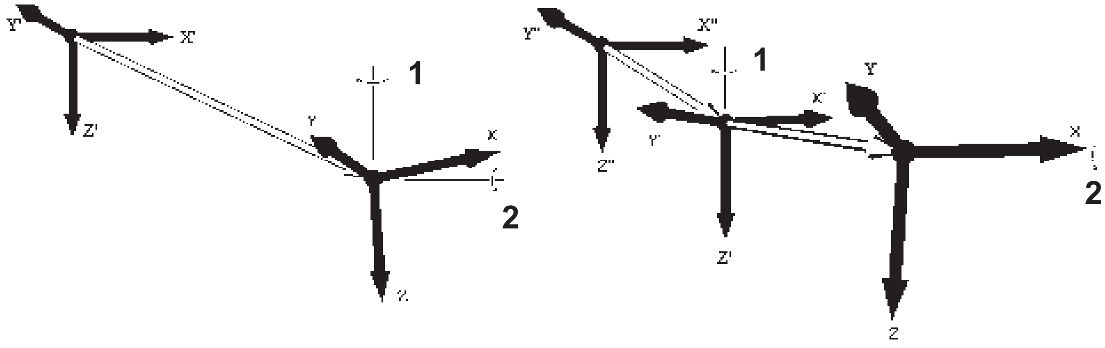
Figure C.7 — Gimbal position and attitude

C.3.2.2 Gimbal position vectors

The gimbal position vector defines the offset of the axis of rotation from the gimbal's mounting point. Depending upon the type of gimbals being described, this vector may vary from one stage to the next. Typically, however, this vector will be used to describe the static or stationary offset of the centre of the rotation of this gimbal stage with respect to the previous stage's coordinate system.

C.3.2.3 Gimbal attitude

The gimbal attitude vector defines the rotation of a gimbal with respect to the previous stage's coordinate system. If the physical gimbal axes of rotation all cross at a single point then a single gimbal attitude vector can be used to describe the rotations possible with the gimbals, as in case 1 in Figure C.8. If the gimbals are not coaxial then multiple gimbal stages will be needed, as in case 2.



Key

1 Rotation about Z'
2 Rotation about X'

Figure C.8 — Single and multiple stage gimbals

C.3.2.4 Gimbal stage reference system

Attribute	**Entry**
Engineering CRS name	Gimbal stage CRS
CRS scope	Used for describing position with respect to a gimbal
Cartesian coordinate system name	Gimbal Universal Space Rectangular
Coordinate system axis name	x
Coordinate system axis abbreviation	x
Coordinate system axis direction	defined from the previous gimbal stage. The initial origin is with respect to the platform
Coordinate system axis unit identifier	Radian
Coordinate system axis name	y
Coordinate system axis abbreviation	y

Coordinate system axis direction	perpendicular to x-axis and z-axis, in right hand sense
Coordinate system axis unit identifier	Radian
Coordinate system axis name	z
Coordinate system axis abbreviation	z
Coordinate system axis direction	perpendicular to x-axis and y-axis; completes right handed coordinate system
Coordinate system axis unit identifier	Radian
Coordinate reference system remarks	The axes of a gimbal stage coordinate reference system are defined with respect to the previous stage, or for stage zero, with respect to the platform. The origin is provided by a position vector in the coordinate reference system of the previous frame and the movement of the axes by attitude direction cosine rotations in the coordinate reference system from the previous frame.
Engineering datum name	Gimbal stage datum
Datum scope	Used for describing position with respect to a gimbal stage
Datum anchor	Intersection of the x, y and z axes

C.4 Passive detector coordinates

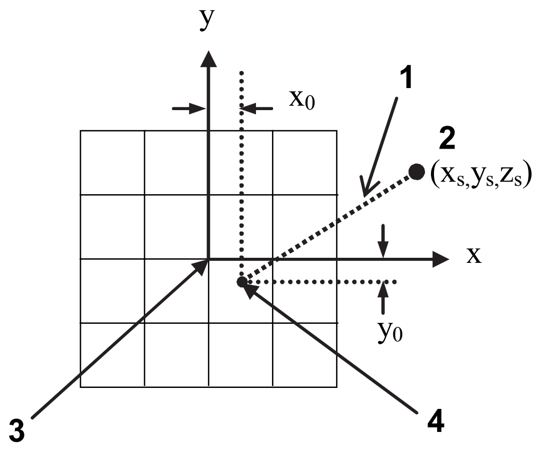
C.4.1 Introduction

Detector coordinates or sensor sample coordinates are given for a particular (x, y) sample. If they are not given directly, they will need to be calculated from the coordinates of the sensor components. The remainder of this clause describes such coordinate systems.

C.4.2 Frame (area) sensor

Attribute	**Entry**
Engineering CRS name	Frame sensor CRS
CRS scope	Used for describing position with respect to a frame sensor
Cartesian coordinate system name	Frame sensor Universal Space Rectangular
Coordinate system axis name	x
Coordinate system axis abbreviation	x
Coordinate system axis direction	Parallel to the image plane and approximately parallel to one image border. With film-cameras, the positive direction points towards the side of the image on which the identification is recorded.
Coordinate system axis unit identifier	Millimetre
Coordinate system axis name	y

Coordinate system axis abbreviation	y
Coordinate system axis direction	perpendicular to x-axis and parallel to the image plane
Coordinate system axis unit identifier	Millimetre
Coordinate system axis name	z
Coordinate system axis abbreviation	z
Coordinate system axis direction	perpendicular to x-axis and y-axis; completes right handed coordinate system
Coordinate system axis unit identifier	Millimetre
Coordinate reference system remarks	The image coordinate reference system of a frame camera (Figure C.9) is a right-handed three-dimensional Cartesian system that represents the camera geometry. The origin, defined by the intersection of the fiducials, is near the perspective centre defined by the autocollimation process. Normally, the origin and the perspective centre differ by only a few microns in the ‘x-coordinate’ direction and the ‘y-coordinate’ direction. The perpendicular distance between the image plane and the origin is the calibrated focal length. The exact definition of the coordinate system is accomplished during the calibration of the camera. The image point with the coordinates x = y = 0 is set exactly to the principal point of symmetry, which is the centre of symmetry of the radial distortion influence. The coordinate system is attached to the camera body by giving two-dimensional coordinates to every fiducial mark. The image point vertically below the perspective centre is called the principal point of autocollimation (PPA). Its coordinates x_0, y_0 mostly are only a few microns off the point x = y = 0. If the camera is a film camera, then the calibrated coordinates of the four or more fiducial marks on the camera frame define the xy-coordinates. If the camera is a digital camera, then the pixels of the image have a calibrated position in relation to the perspective centre.
Engineering datum name	Frame sensor datum
Datum scope	Used for describing position with respect to a frame sensor
Datum anchor	The intersection of the fiducials of frame sensor



Key

1 Lens (optical) axis (perpendicular to the page)
2 Perspective centre
3 Indicated Principal Point (IPP)
4 Principal Point of Autocollimation (PPA)

Figure C.9 — Frame camera coordinate system

C.4.3 Common Coordinate System

The Common Coordinate System (CCS) (Figure C.10) is an image coordinate reference system originally specified in ISO/IEC 12087 using a different format.

Attribute	Entry
CRS name	Common Coordinate System
CRS alias	CCS
CRS scope	Used for describing position within an image
Cartesian coordinate system name	Common Coordinate System Rectangular
Coordinate system axis name	Row
Coordinate system axis abbreviation	R
Coordinate system axis direction	Row positive
Coordinate system axis unit identifier	pixel
Coordinate system axis minimum value	0
Coordinate system axis name	Column
Coordinate system axis abbreviation	C
Coordinate system axis direction	Column positive
Coordinate system axis unit identifier	pixel
Coordinate system axis minimum value	0

Coordinate reference system remarks	The column axis points 90º to the right of the row axis. If the row axis is considered to be horizontal, the column axis points down, placing the origin of the coordinate system at the upper left corner of the image.
Image datum name	CCS image datum
Datum scope	Used for describing position within an image
Datum anchor	Outer corner of the first pixel
Datum pixel in cell	Cell Corner

C.4.4 Pushbroom sensor

The pushbroom detector plane coordinate reference system is a three-dimensional orthogonal engineering CRS. The origin of this CRS is at its perspective centre (x_s,y_s,z_s), for which principal point offsets may or may not have been provided. The positive *x*-axis is aligned with the direction of the platform motion, and the *z*-axis is perpendicular to the lens and pointing away from the collection array (Figure C.10). The origin of the sensor coordinate system (SCS) (x_s,y_s,z_s) in Figure E.3 is the instantaneous perspective centre. Typical of common imagery formats, and in particular that specified in ISO/IEC 12087-5, picture elements (pixels) in a pushbroom image are indexed according to placement within a CCS, as described in C.4.3. The row and column axes of image CCS are often referred to as line and sample axes, respectively. In a pushbroom sensor, the coordinate system for a composite image aggregates the framelets. Each of those framelets effectively has only y (the array) and z (the focal length) dimensions, since x is always a singular value, 0 (zero) as shown in Figure C.10. Some references denote framelets as “one-dimensional.” At some point of time, the detector array energy values are recorded and one framelet of imagery consisting of a line of pixels is acquired. Since each is scanned at a different time, each scan line of pixels requires its own set of exterior orientation parameters $(x_{s(t)}$, $y_{s(t)}$, $z_{s(t)}$, $\omega_{s(t)}$, $\phi_{s(t)}$, and $\kappa_{s(t)})$ after transformation into the SCS coordinate system. A strip image consists of a number of consecutive framelets.

Attribute	**Entry**
Engineering CRS name	Pushbroom sensor CRS
CRS scope	Used for describing position with respect to a pushbroom sensor
Cartesian coordinate system name	pushbroom sensor Universal Space Rectangular
Coordinate system axis name	x
Coordinate system axis abbreviation	x
Coordinate system axis direction	The x-axis is perpendicular to the line of detectors in the pushbroom detector array. It is normally aligned with the direction of sensor or platform motion.
Coordinate system axis unit identifier	Metre
Coordinate system axis name	y
Coordinate system axis abbreviation	y
Coordinate system axis direction	The y-axis is aligned with the detector array long direction.
Coordinate system axis unit identifier	Metre

Coordinate system axis name	z
Coordinate system axis abbreviation	z
Coordinate system axis direction	The z-axis is perpendicular to the xy plane and along the axis of the sensor's lens (optics).
Coordinate system axis unit identifier	Metre
Coordinate reference system remarks	This is the coordinate system for a pushbroom sensor's detector plane. Typically, the origin is at the intersection between the detector plane and the lens optical axis.
Engineering datum name	Pushbroom sensor datum
Datum scope	Used for describing position with respect to a pushbroom sensor.
Datum anchor	The intersection between the detector plane and the lens optical axis of a pushbroom sensor.

In accordance with the convention above, conversion of the line and sample pixel coordinates ($\ell_{(t)}$, $s_{(t)}$) to image coordinates ($x_{s(t)}$ and $y_{s(t)}$) shall be as follows for the common coordinate system of the framelet.

$$x_{s(t)} = \left(\ell_{(t)} - \left(Int\left(\ell_{(t)}\right) + 0.5\right)\right) \qquad \text{(C.7)}$$

$$y_{s(t)} = (s_{(t)} - (N_y / 2) + 0.5) \qquad \text{(C.8)}$$

where

$\ell_{(t)}$, $s_{(t)}$	are line (row) and sample (column) in image CRS, respectively at scan time (t) (starting with $\ell = 0$) with $\ell_{(t)}$ nominally determined by dividing image coordinates by d_x;
$x_{s(t)}$, $y_{s(t)}$	are coordinate values in image CRS corresponding to $\ell_{(t)}$, $s_{(t)}$, respectively;
$Int(\ell_{(t)})$	is the largest integer which does not exceed ($\ell_{(t)}$);
d_x	is the lineal dimension of detector, i.e., pixel size; in line of scan direction (typically the line-of-flight);
d_y	is the lineal dimension of detector, i.e., pixel size in the cross track direction;
N_y	are the number of pixels (columns or samples) in the array.

Pixel coordinates for the pushbroom sensor are then given as follows:

$$y_i = -\frac{N-1}{2} + i \ ; \ x_i = 0, \text{ with } i = 0, \ldots, N-1 \qquad \text{(C.9)}$$

and the focal length in pixel units given as:

$$f = \frac{N-1}{2} \Big/ \tan\frac{\theta_{\max}}{2} \qquad \text{(C.10)}$$

where

f	is the focal length;
N	is number of pixels in the array;
θ_{max}	is the maximum angular coverage of the array.

This mode of imaging is called “Pushbroom” imaging. The centre of each pixel has integer values in both row and column, or line (ℓ) and sample (s) coordinates for the aggregate strip image. However, when the image of a target is measured, both line and sample can have fractional values and need not be limited to integer values. Modern measuring techniques allows for sub-pixel capability.

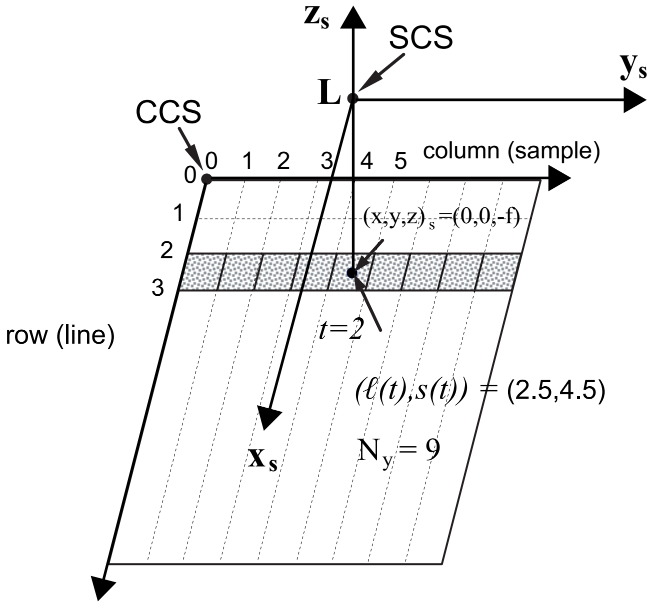


Figure C.10 — Pushbroom Detector Coordinate System

Time is proportional to the integer line number coordinate of a point measured in an axis parallel to the scan direction. For pushbroom sensors, the formula for time is:

$$t = t_0 + dt_{COORD}\left(\text{coord} - \text{coord}_0\right) \qquad \text{(C.11)}$$

where

t	is the time corresponding to a framelet containing a point on the image;
coord	is the line number parallel to the sensor scan direction of the framelet containing the point;
t_0	is the time corresponding to the framelet containing the reference point 0;
coord_0	is the line number coordinate parallel to the scan direction of the framelet containing the reference point 0;
dt_{COORD}	is the time interval corresponding to a unit interval in line coordinates.

For all sensors on an airborne platform the reference point 0 can be the same as the image centre and t_0 can be set to zero without loss of generality in the time equations if this value is not known a priori.

For all sensors on a satellite platform if the value of t_0 is not known, the satellite orbit is assumed circular. Refined estimates of t_0 and other unknown orbit parameters are solved for in a resection or triangulation procedure where the correction parameters are initialized to zeros and are not adjusted.

C.4.5 Whiskbroom sensor

The origin of the orthogonal, three-dimensional, sensor coordinate system (SCS) is at the perspective centre (x_s,y_s,z_s) of the lens,[31] for which principal point offsets may or may not have been provided (Figure E.5). The positive *x*-axis is aligned with the direction of forward platform motion and the *z*-axis is perpendicular to the lens and pointing away from the collection array. Sometimes the lens axis is defined as the *x*-axis, which is satisfactory if translations and rotations are consistently applied.[45] Similarly, the focal plane may be defined with its associated *x* and *y* axes in opposite directions than shown, to account for the "negative" image plane orientation. For purposes of this development of the image-to-ground transformation, a positive image plane will be used for simplicity.

Since the sensor scans across-track, each pixel in the scan line is scanned at a different time and each pixel in the line of pixels has its own SCS set of exterior orientation parameters ($x_{s(t)}$, $y_{s(t)}$, $z_{s(t)}$, $\omega_{s(t)}$, $\Phi_{s(t)}$, and $\kappa_{s(t)}$). A strip image consists of a number of consecutive framelets, each with its own exterior orientation parameters.

The operation of the whiskbroom sensor is similar to that of the pushbroom in the sense that both sensor detector arrays scan. The pushbroom sensor scans with the motion of the sensor or the platform while the whiskbroom sensor scans across the sensor or platform's track of motion. Thus the whiskbroom sensor detector coordinate reference system is defined similarly to that of the pushbroom

Attribute	**Entry**
Engineering CRS name	Whiskbroom sensor CRS
CRS scope	Used for describing position with respect to a whiskbroom sensor
Cartesian coordinate system name	Whiskbroom sensor Universal Space Rectangular
Coordinate system axis name	x
Coordinate system axis abbreviation	x
Coordinate system axis direction	The x-axis is normally aligned with the direction of sensor or platform forward motion. It is perpendicular to the whiskbroom sensor's across-platform-track scan direction.
Coordinate system axis unit identifier	Metre
Coordinate system axis name	y
Coordinate system axis abbreviation	y
Coordinate system axis direction	The y-axis is aligned with the across-platform-track scan mirror direction, which normally is perpendicular to the forward direction of sensor or platform motion. Scan mirror angles are rotations about the sensor x-axis and are measured in the sensor y-z plane with the z-axis corresponding to a zero scan angle.
Coordinate system axis unit identifier	Metre
Coordinate system axis name	z
Coordinate system axis abbreviation	z

Coordinate system axis direction	The z-axis is perpendicular to the xy plane and along the axis of the sensor’s lens (optics).
Coordinate system axis unit identifier	Metre
Coordinate reference system remarks	This is the coordinate system for a whiskbroom sensor’s detector plane. Typically, the origin is at the intersection between the detector plane and the lens optical axis.
Engineering datum name	Whiskbroom sensor datum
Datum scope	Used for describing position with respect to a whiskbroom sensor.
Datum anchor	The intersection between the detector plane and the lens optical axis of a whiskbroom sensor.

The whiskbroom demonstrates a panoramic effect since the ray-of-sight rotates across the flight direction around the sensor’s projection centre and each pixel is projected onto some part of a circle around the projection centre. In the pushbroom system each cross-track framelet is formed optically as if in a conventional frame camera. The detector elements are equally spaced and therefore the cross-track IFOV changes across the array as a function of the cross-track view angle. However the cross-track view angle is limited and the pixels do not significantly change their quadratic shape. But for the whiskbroom, each pixel has a different ground dimension in the x and y direction, with pixels at nadir quadratic in shape and those at the maximum scan angle demonstrating a trapezoidal shape.

For the whiskbroom sensor model, as shown in Figure C.11, the recorded pixels in a scan are assumed to be on a straight line. For the across platform track pixel coordinates, y_i, a constant scan angle increment of successive pixels is assumed.

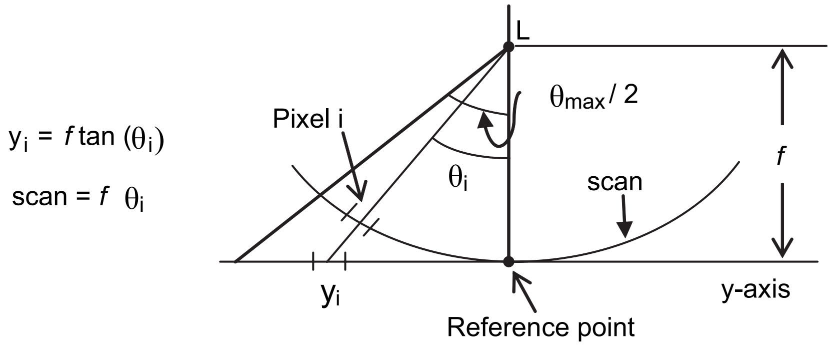


Figure C.11 — Whiskbroom sensor model

Using the maximum scan angle (θ_{max}) shown in Figure C.11 and the number of pixels (N) in one scan line leads to the pixel coordinates:

$y_i = f \tan(\theta_i)$, for i = 0, …, N-1

and

$x_i = 0$ for i = 0, …, N-1 (C.12)

with the focal length in pixel units given as:

$f = N\text{-}1/\ \theta_{max}$

and the actual scan angle given as:

$$\theta_i = -\left(\frac{\theta_{\max}}{2}\right) + i\left(\frac{\theta_{\max}}{N-1}\right)$$

where

x_i, y_i	are pixel coordinates;
f	is the focal length in pixel units;
θ_i	is the actual scan angle;
$\theta_{\max}$	is the maximum scan angle;
N	is the number of pixels in one scan line.

C.5 SAR coordinates

C.5.1 Introduction

The fundamental reference data needed for performing photogrammetric processing with SAR images are the Aperture Reference Point (ARP), S_0, the Ground Reference Point (GRP), G_0, and the Sensor Velocity Vector, $\dot{S}$. Unlike passive projective imaging sensors (e.g., frame or pushbroom optical sensors), SAR sensors do not strictly have an “interior orientation” that can be physically modelled. This is because the SAR images or image-like products are generated synthetically from the phase history data (PHD). Pulses are transmitted by the sensor; the magnitude, phase, Doppler-angle, and time of the returned signal are sensed; and then the SAR processor calculates an aggregate magnitude and phase for each pixel, within the desired footprint. These calculations can be output in any desirable coordinate system or projection, although a few common methods for calculating the ground coordinates are discussed in C.5.2, C.5.3 and C.5.4.

The three most common methods for image formation are to use the Slant Plane, the Ground Plane, and an Inflated Ellipsoid.

C.5.2 Slant plane coordinates

The slant plane is a plane that passes through the sensor velocity vector and the Ground Reference Point (GRP) for an image. The sequence of velocity vectors within a given synthetic aperture usually follows a straight line, however, it often has some variation from it. As a result, the velocity vector is defined at the ARP for practical purposes in Spotlight mode imagery. In the other modes, the variation in the velocity vector is accommodated by the time-dependent nature of the metadata. The GRP is somewhat of a misnomer, as there is no assurance that the GRP is actually located on the ground. Instead, it is a predefined coordinate for a target location or targeted centreline that is presumed to be on the ground (based, for example, on a DEM or other information with unknown reliability). SAR products are almost always formed with the GRP at the centre of the image in the range direction. For Spotlight mode, it is usually placed at the centre of the image in azimuth as well. For other modes, the centre of each image line is defined as the GRP for that line. For non-Spotlight modes, the variable nature of the GRP and velocity vector implies that the slant plane may vary with each line and so the image may not actually be formed on a single plane. Nevertheless, it is still usually called a slant plane image.

The slant plane coordinate system is defined by a unit vector in the range direction, *r*, that points from the GRP to the ARP, and an azimuth unit vector, θ, that is in the slant plane, but orthogonal to *r* and parallel to the velocity vector.

Attribute	**Entry**
Engineering CRS name	SAR Slant Plane CRS
CRS scope	Used for describing position with respect to SAR Slant Plane
Cartesian coordinate system name	SAR Slant Plane Universal Space Rectangular
Coordinate system axis name	θ
Coordinate system axis abbreviation	θ
Coordinate system axis direction	The θ-axis is aligned with the azimuthal direction in the slant plane, orthogonal to the range direction and parallel to SAR's velocity vector.
Coordinate system axis unit identifier	Radian
Coordinate system axis name	*r*
Coordinate system axis abbreviation	*r*
Coordinate system axis direction	The r-axis is in the slant direction and points from GRP to APR.
Coordinate system axis unit identifier	Metre
Coordinate system remarks	This is the coordinate system for a SAR slant plane. The origin is at the SAR ground reference point.
Engineering datum name	SAR Slant Plane datum
Datum scope	Used for describing position with respect to SAR Slant Plane
Datum anchor	The SAR ground reference point

Typically, the image row / sample direction (x-axis) is aligned with θ and the column/line direction (y-axis) is aligned with *r*.

NOTE If an image is collected off of broadside (i.e., with a non-zero squint angle), then the slant plane image will be approximately a parallelogram when projected to the ground.

While a polar format can be used for the coordinate system, images are usually generated, either directly or via resampling, onto a pixel coordinate system with pixel spacings that are equidistant along both orthogonal axes – as opposed to the polar format, which is equidistant in range and equiangular in azimuth. The mapping from pixel coordinates to range and Doppler angle is accomplished as follows:

Given the line, *l*, and sample, *s*, of a pixel, the offset of the pixel in pixel coordinates is calculated from the GRP

$$\Delta l = l - l_0 \ \ and \ \Delta s = s - s_0 \tag{C.13}$$

where

l, s are the line and sample of a pixel;

l_0, s_0 are the line and sample coordinates of the GRP.

Calculate the vector, $\overline{\mathbf{Q}}_{\mathbf{0}}$ from the ARP, $\mathbf{S}_{\mathbf{0}}$, to the GRP, $\mathbf{G}_{\mathbf{0}}$, in the ECEF coordinate system

$$\bar{\boldsymbol{Q}}_{\boldsymbol{0}} = \boldsymbol{S}_{\boldsymbol{0}} - \boldsymbol{G}_{\boldsymbol{0}} \tag{C.14}$$

where

$\overline{\mathbf{Q}}_{\mathbf{0}}$	is the vector from the ARP to the GRP;
$\mathbf{S}_{\mathbf{0}}$	is the vector of Aperture Reference Point (ARP) coordinates;
$\mathbf{G}_{\mathbf{0}}$,	is the vector of Ground Reference Point (GRP) coordinates.

Project the vector $\overline{\mathbf{Q}}_{\mathbf{0}}$ into the slant plane (ARP as origin)

$$\boldsymbol{Q}_{\boldsymbol{0}} = \left|\bar{\boldsymbol{Q}}_{\boldsymbol{0}}\right| \hat{\boldsymbol{U}}_{\boldsymbol{R}} \tag{C.15}$$

where

$\hat{\mathbf{U}}_{\mathbf{R}}$	is a unit vector along the range.

Then, calculate the pixel’s 3D vector in the slant plane (ARP as origin)

$$\boldsymbol{Q} = \boldsymbol{Q}_{\boldsymbol{0}} + \begin{bmatrix} \Delta l \; p_l \\ \Delta s \; p_s \\ 0 \end{bmatrix} \tag{C.16}$$

where

p_s , p_l	are slant plane pixel sampling distances in the sample and line directions, respectively.

SAR images are often oversampled during image formation, with pixel sampling distances being smaller than the image resolution in order to retain maximum information. Thus, fields labelled as “Resolution” or “IPR” should not be used for this calculation. Rather, fields marked as “Sample Distance” or “Ground Sample Distance” (a misnomer, since it is actually measured in the slant plane) should be used. The slant range, R_S, and the local Doppler angle, α_L, for the pixel can now be computed by:

$$R_S = \left|\boldsymbol{Q}\right| \; and \; \alpha_L = \cos^{-1}\left(\frac{\boldsymbol{Q} \bullet \boldsymbol{Q}_{\boldsymbol{0}}}{\left|\boldsymbol{Q}\right|\left|\boldsymbol{Q}_{\boldsymbol{0}}\right|}\right) + \alpha_0 \tag{C.17}$$

where

R_S,	is slant range, the magnitude of the 3D vector, $\boldsymbol{Q}$, in the slant plane from the Aperture Reference Point;
α_L,	is local Doppler angle;
α_0	is Doppler angle of the GRP, calculated as the complement of the squint angle at the GRP.

$$\alpha_0 = 90° - \tau \tag{C.18}$$

where

τ	is the squint angle at the GRP.

Alternatively, the Doppler angle can be computed directly using the antenna’s velocity vector, $\dot{S}$

$$\alpha_L = \cos^{-1}\left(\frac{\boldsymbol{Q} \bullet \dot{\boldsymbol{S}}}{|\boldsymbol{Q}|\left|\dot{\boldsymbol{S}}\right|}\right) \tag{C.19}$$

NOTE The slant plane is sometimes called the SAR plane, because the SAR image is generally formed in that plane.

C.5.3 Ground plane coordinates

The ground plane is defined as a plane that is tangent to the Earth’s surface at the GRP. Interestingly, this can be somewhat ambiguous. First, as stated above, the GRP may not be on the Earth’s surface, and second, “the Earth’s surface” can be defined in a number of ways. Most commonly, the plane that is used is orthogonal to the Earth ellipsoid normal and passes through the GRP for Spotlight mode, or through a central GRP for other modes.

Attribute	**Entry**
Engineering CRS name	SAR Ground Plane CRS
CRS scope	Used for describing position with respect to SAR ground Plane
Cartesian coordinate system name	SAR Ground Plane Universal Space Rectangular
Coordinate system axis name	x
Coordinate system axis abbreviation	x
Coordinate system axis direction	The x-axis is in the ground plane and is typically aligned with the azimuthal and orthogonal to the projection of the range vector.
Coordinate system axis unit identifier	Metre
Coordinate system axis name	y
Coordinate system axis abbreviation	y
Coordinate system axis direction	The y-axis is in the ground plane and is typically aligned with the projection of the range vector and orthogonal to the azimuthal vector.
Coordinate system axis unit identifier	Metre
Coordinate system remarks	This is the image coordinate reference system for a ground plane. The origin is at centre of image.
Engineering datum name	SAR Ground Plane datum
Datum scope	Used for describing position with respect to SAR ground Plane
Datum anchor	The origin is at centre of image

Ground plane images are most often created by projecting the slant plane image into the ground plane, requiring a resampling of the slant plane image. However, sometimes images are formed directly into the ground plane. Regardless, the mapping from slant plane to ground plane is accomplished using a plane-to-plane coordinate conversion called a 3D affine transform.

$$\mathbf{Y}=\mathbf{A}\mathbf{X}+\mathbf{b} \tag{C.20}$$

where

X	are the slant plane coordinates in ECEF;
Y	are the ground plane coordinates in ECEF;
A	is the 3X3 Affine matrix;
b	is a 3x1 translation vector.

The range and Doppler angle can be calculated from ground plane pixel coordinates by first inverting the affine transform to recover the equivalent slant plane pixel coordinates, then applying the method given above. The projected slant plane coordinates will likely not fall directly on slant plane pixel coordinates, so the use of floating point numbers to encode pixel coordinates is required. The affine transform parameters used to perform the coordinate transform from slant plane to ground plane or their inverse must be provided with a ground plane SAR product in order to allow photogrammetric processing.

The ground plane is also sometimes called the focus plane, because the image formation process must focus each pixel at a particular range. Commonly, the range used is that to the pixel point projected into a plane tangent to an ellipsoid inflated to the GRP elevation at which a particular SAR imaging campaign is targeted.

C.5.4 Inflated ellipsoid coordinates

The inflated ellipsoid coordinate system uses a fixed height, *h*, above the Earth's ellipsoid. The height is usually that of the GRP, for Spotlight mode, or some average height for the other modes. This coordinate system is primarily used with non-Spotlight modes that cover large areas, for which the Earth's curvature makes planar projections impractical. In order for an ellipsoidally projected SAR product to be useful photogrammetrically, the method that the SAR provider uses for defining a pixel's coordinate must be clear. Typically, one axis (usually the x-axis) is defined along the surface of the Earth's ellipsoid in the instantaneous ground range direction, and orthogonal to the projection of the other axis (usually the y-axis) that is defined in the instantaneous velocity vector direction on the surface of the inflated ellipsoid. So for any pixel in the image or product, the x and y coordinates will uniquely determine a three-dimensional point, **M**, in the ECEF coordinate system, on the ellipsoid. **M** must be calculated by inverting the data provider's method for defining the pixel's coordinate.

Attribute	**Entry**
Engineering CRS name	SAR Inflated Ellipsoid CRS
CRS scope	Used for describing position with respect to SAR Inflated Ellipsoid
Cartesian coordinate system name	SAR Inflated Ellipsoid Universal Space Rectangular
Coordinate system axis name	x
Coordinate system axis abbreviation	x
Coordinate system axis direction	The x-axis is in the inflated ellipsoid and is aligned with the azimuthal vector and orthogonal to the projection of the range vector on the inflated ellipsoid.
Coordinate system axis unit identifier	Metre

Coordinate system axis name	y
Coordinate system axis abbreviation	y
Coordinate system axis direction	The y-axis is in the inflated ellipsoid and is aligned with the projection of the range vector on the inflated ellipsoid and orthogonal to the azimuthal vector.
Coordinate system axis unit identifier	Metre
Coordinate system remarks	This is the image coordinate reference system in an inflated ellipsoid at a defined height at the Earth's ellipsoid. The origin is at the centre of image.
Engineering datum name	SAR Inflated Ellipsoid datum
Datum scope	Used for describing position with respect to SAR Inflated Ellipsoid
Datum anchor	The origin is at the centre of the image

For example, for an ellipsoid inflated by h, and image coordinates x and y, one might first determine the geographic coordinates, latitude, Φ, and longitude, λ, from

$$\begin{aligned} \phi &= F(x,y) \\ \lambda &= G(x,y) \end{aligned} \qquad \text{(C.21)}$$

using the product provider's conversion method. Then three-dimensional Cartesian ground coordinates can be calculated by:

$$\begin{aligned} x &= \frac{(a+h)\cdot\cos(\phi)\cdot\cos(\lambda)}{\sqrt{1-\left(e'\cdot\sin(\phi)\right)^2}} \\ y &= \frac{(a+h)\cdot\cos(\phi)\cdot\sin(\lambda)}{\sqrt{1-\left(e'\cdot\sin(\phi)\right)^2}} \\ z &= \frac{(1-e'^2)\sin(\phi)}{\sqrt{1-\left(e'\cdot\sin(\phi)\right)^2}} \end{aligned} \qquad \text{(C.22)}$$

here

$$e' = \sqrt{1-\left\{(b+h)/(a+h)\right\}^2} \qquad \text{(C.23)}$$

The slant range, R_S, and the local Doppler angle, α_L, can now be computed directly as

$$R_S = \left|\boldsymbol{M}-\boldsymbol{S}(t)\right| = \sqrt{\left(M_x-S_x(t)\right)^2+\left(M_y-S_y(t)\right)^2+\left(M_z-S_z(t)\right)^2} \qquad \text{(C.24)}$$

$$\alpha_L = \cos^{-1}\left(\frac{S_x(t)\left(M_x-S_x(t)\right)+S_y(t)\left(M_y-S_y(t)\right)+S_z(t)\left(M_z-S_z(t)\right)}{R_S\left|\dot{S}(t)\right|}\right) \qquad \text{(C.25)}$$

Annex D
(informative)

Frame sensor model metadata profile supporting precise geopositioning

D.1 Introduction

The purpose of this annex is to show how to use a minimum set of the metadata defined in this Technical Specification to accomplish precise geopositioning of images from a frame sensor imagery system. This annex is intended to give an example for using the common terminology and a common frame of reference established in this Technical Specification to perform precise geopositioning using a physical frame sensor model. Specifically, 7.1.2, 7.2.3 to 7.2.8, 7.3, 7.5, and 7.6 excluding 7.6.4 and 7.6.6 identify relevant metadata classes and Annex B provides the expanded definition of these items.

D.2 Frame sensor interior descriptions

D.2.1 Typical imagery sensor storage layout

Typical of common imagery formats, and in particular that specified in ISO/IEC 12087-5, picture elements (pixels) are indexed according to a two-dimensional array of rows and columns, as illustrated in the array examples in Figure D.1. There are three coordinate systems commonly associated with digital and digitized imagery: a) the row, column (r, c) coordinate system with origin being at the outside corner of the first pixel, i.e., the Common Coordinate Reference System (CCS) defined in C.4.3; b) the line, sample (l, s) coordinate system, with the origin being at the centre of the image; and c) the x, y coordinate system. The units used in the first two systems are pixels (and decimals thereof), while the x, y are linear measures such as mm (and decimals thereof), as will be introduced in D.2.1 to D.2.3, and Figure D.1. The origin of the CCS, as shown in Figure D.1, is the upper left corner of the first (or 0,0) pixel, which in turn is the upper left of the array. Because the CCS origin is the pixel corner, and the r, c associated with a designated pixel refers to its centre, the coordinates of the various pixels, (0.5, 0.5), (0.5, 1.5), …, etc., are as shown in Figure D.1.

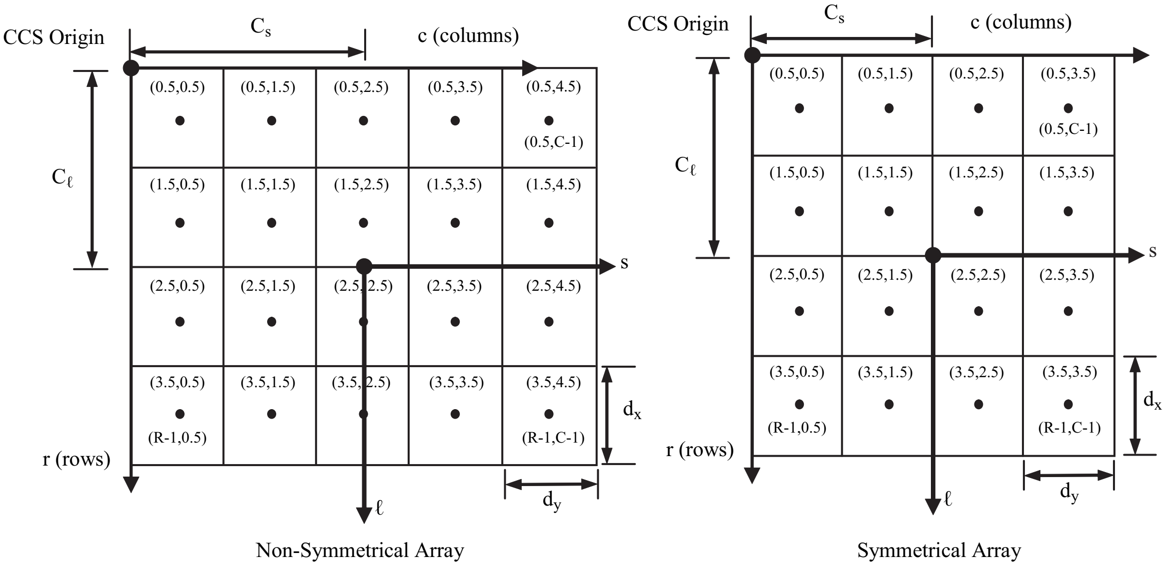


Figure D.1 — Pixel orientation within the frame sensor coordinate system

D.2.2 Pixel-to-image line, sample coordinate transformation

Since all mathematical development to follow is based on the geometric centre of the image as the origin, the row, column (r, c) system is replaced by the line, sample (ℓ, s) system through two simple translations:

$$\begin{aligned} \ell &= r - C_\ell \\ s &= c - C_s \end{aligned} \tag{D.1}$$

where

C_ℓ and C_s are half the image pixel array size, in pixels, in the row and column directions, respectively.

EXAMPLE 1

Figure D.1 (Non-symmetrical): For $C_\ell = 4/2 = 2.0$ $C_s = 5/2 = 2.5$

$$r_p = 1.6\,pixel \qquad c_p = 4.7\,pixel$$

$$\ell_p = r_p - C_\ell = 1.6 - 2.0 = -0.4\,pixel$$

$$s_p = c_p - C_s = 4.7 - 2.5 = 2.2\,pixel$$

EXAMPLE 2

Figure D.1 (Symmetrical): For $C_\ell = 4/2 = 2.0$ $C_s = 4/2 = 2.0$

$$r_\mathrm{Q} = 1.4\,pixel \qquad c_\mathrm{Q} = 3.1\,pixel$$

$$\ell_\mathrm{Q} = r_\mathrm{Q} - C_\ell = 1.4 - 2.0 = -0.6\,pixel$$

$$s_\mathrm{Q} = c_\mathrm{Q} - C_s = 3.1 - 2.0 = 1.1\,pixel$$

D.2.3 Film and charged coupled device array distortions

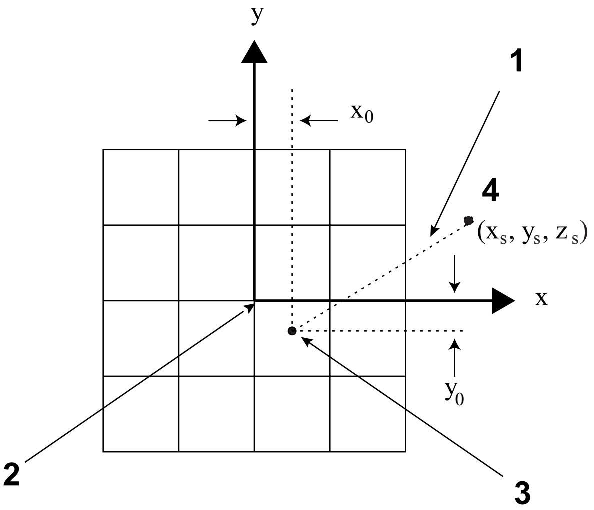
In the case of film medium, film deformations are accounted for as follows:

$$\begin{aligned} x &= a_1\ell + b_1 s + c_1 \\ y &= a_2\ell + b_2 s + c_2 \end{aligned} \tag{D.2}$$

This transformation accounts for two scales, a rotation, a skew, and two translations. The six parameters are usually estimated on the basis of (calibrated) reference points, such as camera fiducial marks, or their equivalent corner pixels for digital arrays. Here, the (*x,y*) image coordinate system, as shown in Figure D.2, is used in the construction of the mathematical model, and applies to both film and digital sensors.

D.2.4 Principal point

Ideally the lens axis would, as in Figure D.2, intersect the collection array at its centre, (*x,y*) or (0,0). However, this is not always the case due to lens flaws, imperfections, or design, and is accounted for by offsets x_0 and y_0, as shown in the figure. x_0 and y_0 are in the same linear measure (e.g., mm) as the image coordinates (*x,y*) and the focal length, *f*.



Key

1 Lens (optical) axis (perpendicular to the page)
2 Indicated Principal Point (IPP)
3 Principal Point of Autocollimation (PPA)
4 Perspective centre

Figure D.2 — Placement of lens axis

D.2.5 Optical distortions

Effects due to optical (lens) distortion are measured in terms of radial components. The radial distortion normally is approximated by a polynomial function applied to the x and y components, see Figure D.3. The polynomial may take different forms; e.g., odd powers of the radial distance, or a scalar applied to the square of the radial distance.

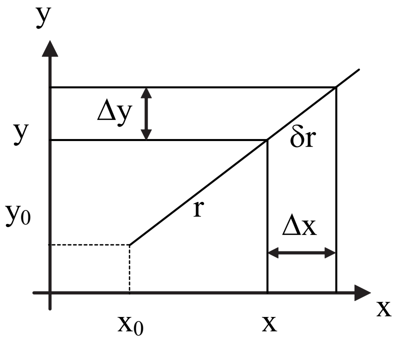


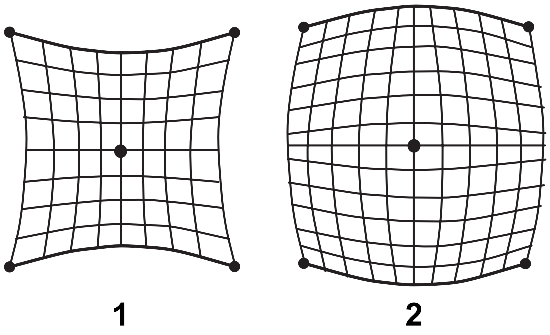
Figure D.3 — Radial optical distortion

$$\delta r = \mathrm{k}_1 r^3 + \mathrm{k}_2 r^5 + \mathrm{k}_3 r^7 \quad \text{(D.3)}$$

where:

$$r = \sqrt{\bar{x}^2 + \bar{y}^2} \qquad \bar{x} = x - x_0 \qquad \bar{y} = y - y_0 \quad \text{(D.4)}$$

and k represents the third, fifth, and seventh-order radial distortion coefficients. These k coefficients are obtained by fitting a polynomial to the distortion curve or tabular data from a camera calibration or the least squares adjustment results of collinearity equations augmented with additional parameters for self-calibration. Although the distortion described by the first order terms of the polynomial can be corrected by adjusting the focal length, the discussion that follows is focussed on the use of polynomials to describe the distortion. The influence of this distortion is typically described as either a “pincushion” or “barrel” distortion, as shown in Figure D.4.



Key

1 Pincushion (positive)
2 Barrel (negative)

Figure D.4 — Optical radial distortion effects

The resultant x and y radial optical distortion components are then:

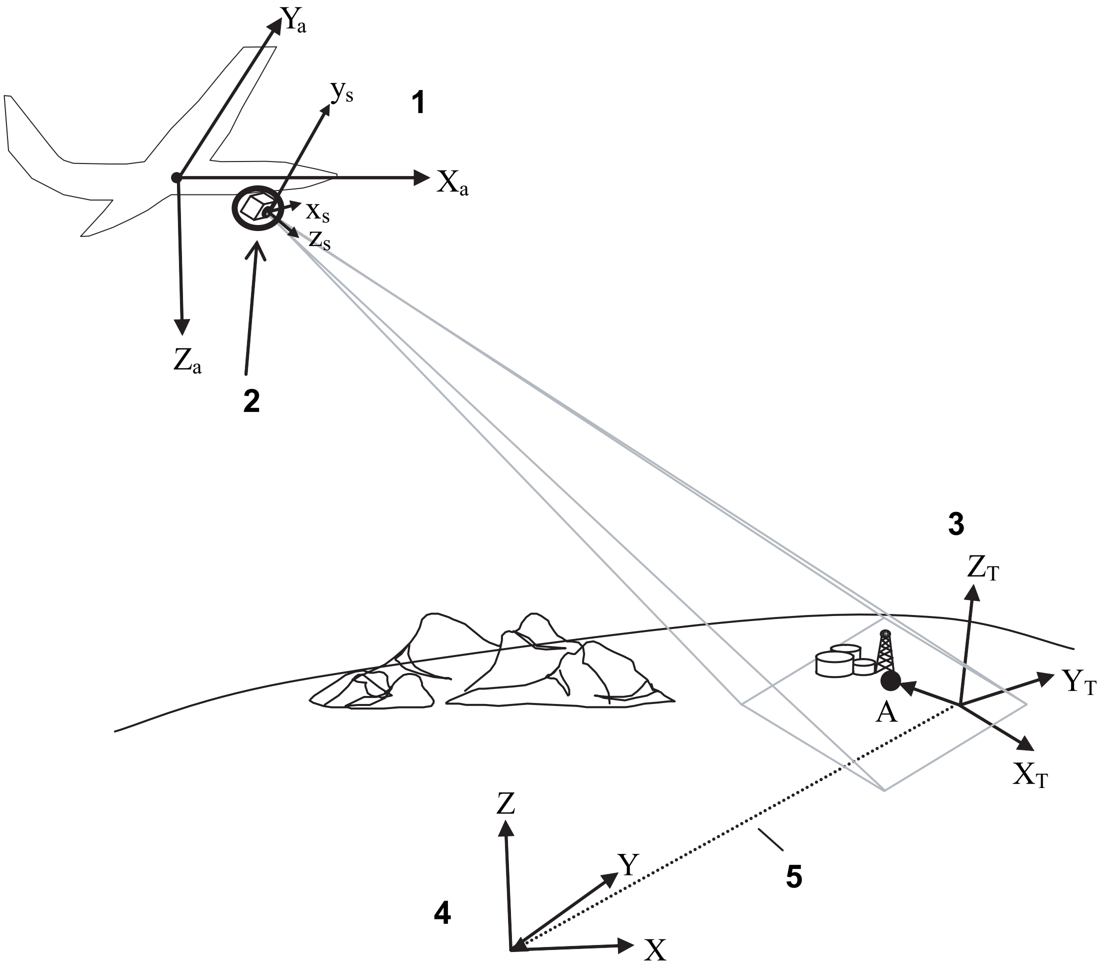
$$\begin{aligned} \Delta x_{radial} &= \bar{x}\frac{\delta r}{r} = \bar{x}\frac{\mathrm{k}_1 r^3 + \mathrm{k}_2 r^5 + \mathrm{k}_3 r^7}{r} = \bar{x}(\mathrm{k}_1 r^2 + \mathrm{k}_2 r^4 + \mathrm{k}_3 r^6) \\ \Delta y_{radial} &= \bar{y}\frac{\delta r}{r} = \bar{y}\frac{\mathrm{k}_1 r^3 + \mathrm{k}_2 r^5 + \mathrm{k}_3 r^7}{r} = \bar{y}(\mathrm{k}_1 r^2 + \mathrm{k}_2 r^4 + \mathrm{k}_3 r^6) \end{aligned} \tag{D.5}$$

Another interior imperfection is described in terms of rotational symmetry, or “decentring.” While in general these effects may be assumed to be minimal, they may be more prominent in variable focus or zoom cameras. Consideration of this effect is given via reference. [37]

$$\begin{aligned} \Delta x_{decen} &= \mathrm{p}_1(2\bar{x}^2 + r^2) + \mathrm{p}_2(2\overline{xy}) \\ \Delta y_{decen} &= \mathrm{p}_1(2\overline{xy}) + \mathrm{p}_2(2\bar{y}^2 + r^2) \end{aligned} \tag{D.6}$$

where Δx_{decen} and Δy_{decen} are the x and y components of the decentring effect, respectively; p_1 and p_2 are decentring coefficients. The referenced document included a third coefficient; however, for all practical purposes, this influence is so small that it can be ignored. Therefore, the contributions of lens radial distortions and decentring of x and y components are:

$$\begin{aligned} \Delta x_{lens} &= \Delta x_{radial} + \Delta x_{decen} = \bar{x}(\mathrm{k}_1 r^2 + \mathrm{k}_2 r^4 + \mathrm{k}_3 r^6) + \mathrm{p}_1(2\bar{x}^2 + r^2) + \mathrm{p}_2(2\overline{xy}) \\ \Delta y_{lens} &= \Delta y_{radial} + \Delta y_{decen} = \bar{y}(\mathrm{k}_1 r^2 + \mathrm{k}_2 r^4 + \mathrm{k}_3 r^6) + \mathrm{p}_1(2\overline{xy}) + \mathrm{p}_2(2\bar{y}^2 + r^2) \end{aligned} \tag{D.7}$$



Key

1 Platform Coordinate Reference System: $(X,Y,Z)_a$
2 Sensor Coordinate Reference System: $(x,y,z)_s$
3 Object Local Coordinate Reference System: $(X,Y,Z)_T$
4 Earth Coordinate Reference System: (X,Y,Z)
5 Vector between local reference and Earth reference

Figure D.5 — Multiple coordinate reference frames

D.2.6 Atmospheric refraction

Adjustments may be required to account for bending of the image ray path as a result of atmospheric effects. These influences generally increase as altitude and look angles (vertical angles from the platform down direction) increase. Several methods, of varying complexity, are available to approximate the needed adjustments, including, for example, consideration of temperature, pressure, relative humidity, and wavelength. The following simple approximation is adopted:

$$\Delta d = K \tan \alpha$$

where α is the angle the refracted ray makes with the local vertical, Δd (micro-radians) the angular displacement, and

$$K = \frac{2410 \times H_{msl}}{H_{msl}^{2} - 6H_{msl} + 250} - \frac{2410 \times h_{msl}}{h_{msl}^{2} - 6h_{msl} + 250}\left(\frac{h_{msl}}{H_{msl}}\right)$$

and

$$\alpha = \tan^{-1}\left(r/f\right) \tag{D.8}$$

H_{msl} is altitude (km, MSL) of the sensor, h_{msl} is the object elevation (km, MSL), and K is the refraction constant (micro-radians). This equation is a good approximation for collection parameters resulting when the optical axis coincides with the vertical axis (**Z**$_T$, Figure D.1) from the ground object. Depending on the level of precision required, off-vertical collections may require more rigorous models.

Therefore, given image coordinates ($\overline{x}$, $\overline{y}$), the resulting coordinates (x'_{ref},y'_{ref}) are:

$$x'_{ref} = \overline{x}\frac{r'_{ref}}{r}$$
$$y'_{ref} = \overline{y}\frac{r'_{ref}}{r}$$

where:

$$\begin{aligned} \Delta x_{ref} &= x'_{ref} - \overline{x} = \overline{x}\left(\frac{r'_{ref}}{r} - 1\right) \\ \Delta y_{ref} &= y'_{ref} - \overline{y} = \overline{y}\left(\frac{r'_{ref}}{r} - 1\right) \end{aligned} \tag{D.9}$$

It follows, then, that the refraction correction components (Δx_{ref}, Δy_{ref}) are:

$$\begin{aligned} \Delta x_{ref} &= x'_{ref} - \overline{x} = \overline{x}\left(\frac{r'_{ref}}{r} - 1\right) \\ \Delta y_{ref} &= y'_{ref} - \overline{y} = \overline{y}\left(\frac{r'_{ref}}{r} - 1\right) \end{aligned} \tag{D.10}$$

D.2.7 Summary

Lastly, the corrections to the original image coordinates (*x,y*) are combined to establish the corrected image coordinates as follows:

$$\begin{aligned} x' &= \overline{x} + \Delta x_{lens} + \Delta x_{ref} \\ &= \overline{x} + \overline{x}(\mathrm{k}_1 r^2 + \mathrm{k}_2 r^4 + \mathrm{k}_3 r^6) + \mathrm{p}_1(2\overline{x}^2 + r^2) + \mathrm{p}_2(2\overline{xy}) + \overline{x}\left(\frac{r'_{ref}}{r} - 1\right) \\ y' &= \overline{y} + \Delta y_{lens} + \Delta y_{ref} \\ &= \overline{y} + \overline{y}(\mathrm{k}_1 r^2 + \mathrm{k}_2 r^4 + \mathrm{k}_3 r^6) + \mathrm{p}_1(2\overline{xy}) + \mathrm{p}_2(2\overline{y}^2 + r^2) + \overline{y}\left(\frac{r'_{ref}}{r} - 1\right) \end{aligned} \tag{D.11}$$

where

x' and *y'* are the resulting corrected image coordinates.

Simplifying Equation (D.11):

$$\begin{aligned} x' &= \overline{x}(\mathrm{k}_1 r^2 + \mathrm{k}_2 r^4 + \mathrm{k}_3 r^6 + \frac{r'_{ref}}{r}) + \mathrm{p}_1(2\overline{x}^2 + r^2) + \mathrm{p}_2(2\overline{xy}) \\ y' &= \overline{y}(\mathrm{k}_1 r^2 + \mathrm{k}_2 r^4 + \mathrm{k}_3 r^6 + \frac{r'_{ref}}{r}) + \mathrm{p}_1(2\overline{xy}) + \mathrm{p}_2(2\overline{y}^2 + r^2) \end{aligned} \tag{D.12}$$

Therefore, given pixel coordinates (r,c), calculating the image coordinates, including correction factors considered, may be accomplished through the use of Equations (D.1), (D.2), (D.4), (D.8), (D.11), and (D.12). Therefore, (*x',y'*) are the image coordinates required for the image-to-object transformation.

D.3 Collinearity equations

Deriving the relation between image coordinates and the corresponding point on the Earth's surface via translation and rotation from one coordinate system to the other requires a common coordinate system. The geometry is that shown in Figure 3.

Geometrically, the sensor perspective centre (L), the "ideal" image point (**p**), and the corresponding object point (**P**) are collinear. The "ideal" image point is represented by image coordinates *after* having been corrected for all systematic effects (lens distortions, atmospheric refraction, etc.), as given in the preceding clause.

For two vectors to be collinear, one must be a scalar multiple of the other. Therefore, vectors from the perspective centre (L) to the image point and object point, **p** and **P** respectively, are directly proportional. Further, in order to associate their components, these vector components must be defined with respect to the same coordinate system. Therefore, define this association via the following equation:

$$\mathbf{a} = \mathrm{k}\mathbf{MA} \qquad \text{(D.13)}$$

where

a	is the vector from the perspective centre to an image point;
k	is a scalar multiplier;
M	is the orientation matrix that accounts for the rotations (roll, pitch, and yaw);
A	is the vector from the perspective centre to the object point.

M is required to place the Earth coordinate system parallel to the sensor coordinate system. Therefore, the collinearity conditions represented in the figure become:

$$\left[\begin{pmatrix} x \\ y \\ 0 \end{pmatrix} - \begin{pmatrix} 0 \\ 0 \\ f \end{pmatrix}\right] = \mathrm{k}\boldsymbol{M}\left[\begin{pmatrix} X \\ Y \\ Z \end{pmatrix} - \begin{pmatrix} X \\ Y \\ Z \end{pmatrix}_L\right] \qquad \text{(D.14)}$$

The orientation matrix **M** is the result of three sequence-dependent rotations:

$$\mathrm{M} = \mathrm{M}_\kappa \mathrm{M}_\phi \mathrm{M}_\omega = \begin{bmatrix} \cos\kappa & \sin\kappa & 0 \\ -\sin\kappa & \cos\kappa & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \cos\phi & 0 & -\sin\phi \\ 0 & 1 & 0 \\ \sin\phi & 0 & \cos\phi \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\omega & \sin\omega \\ 0 & -\sin\omega & \cos\omega \end{bmatrix} \qquad \text{(D.15)}$$

Where the rotation ω is about the X-axis (roll), ϕ is about the once rotated Y-axis (pitch), and κ is about the twice rotated Z-axis (yaw), the orientation matrix **M** becomes:

$$\mathrm{M} = \begin{bmatrix} \cos\phi\cos\kappa & \cos\omega\sin\kappa + \sin\omega\sin\phi\cos\kappa & \sin\omega\sin\kappa - \cos\omega\sin\phi\cos\kappa \\ -\cos\phi\sin\kappa & \cos\omega\cos\kappa - \sin\omega\sin\phi\sin\kappa & \sin\omega\cos\kappa + \cos\omega\sin\phi\sin\kappa \\ \sin\phi & -\sin\omega\cos\phi & \cos\omega\cos\phi \end{bmatrix} \qquad \text{(D.16)}$$

Although the earlier derivation expressed coordinates with regard to the image plane ("negative" plane), the image point **p** in Figure 3 is represented by coordinates (*x,y*), whose relation is simply a mirror of the image plane. Thus the components of **a** will have opposite signs of their mirror components (*x, y*) as follows:

$$\begin{aligned}\bar{x} &= -(x - x_0) \\ \bar{y} &= -(y - y_0)\end{aligned} \tag{D.17}$$

Therefore, for any given object, its "World" coordinates (*X, Y, Z*) are related to coordinates (*x,y*) via:

$$\begin{aligned}x &= -f\left[\frac{\cos\phi\cos\kappa\left(X - X_L\right) + \left(\cos\omega\sin\kappa + \sin\omega\sin\phi\cos\kappa\right)\left(Y - Y_L\right) + \left(\sin\omega\sin\kappa - \cos\omega\sin\phi\cos\kappa\right)\left(Z - Z_L\right)}{\sin\phi\left(X - X_L\right) - \sin\omega\cos\phi\left(Y - Y_L\right) + \cos\omega\cos\phi\left(Z - Z_L\right)}\right] \\ y &= -f\left[\frac{\cos\phi\sin\kappa\left(X - X_L\right) + \left(\cos\omega\cos\kappa - \sin\omega\sin\phi\sin\kappa\right)\left(Y - Y_L\right) + \left(\sin\omega\cos\kappa + \cos\omega\sin\phi\sin\kappa\right)\left(Z - Z_L\right)}{\sin\phi\left(X - X_L\right) - \sin\omega\cos\phi\left(Y - Y_L\right) + \cos\omega\cos\phi\left(Z - Z_L\right)}\right]\end{aligned} \tag{D.18}$$

where the (*x, y*) represent the "corrected" pair, (*x',y'*) from Equation (D.12). The equations above also rely upon the positional and orientation information of the sensor. Unfortunately, inability to measure the sensor position accurately, due, for example, to system latency (such as timing delays in detector, position, attitude, or gimbal readout, or transmission) or Global Navigation Satellite System/Inertial Navigation System (GNSS/INS) errors, can be the source for a substantial amount of uncertainty. The degree to which the accuracy of these results is required will determine the degree to which modelling of the collection system parameters is required.

Annex E
(informative)

Pushbroom / Whiskbroom sensor model metadata profile

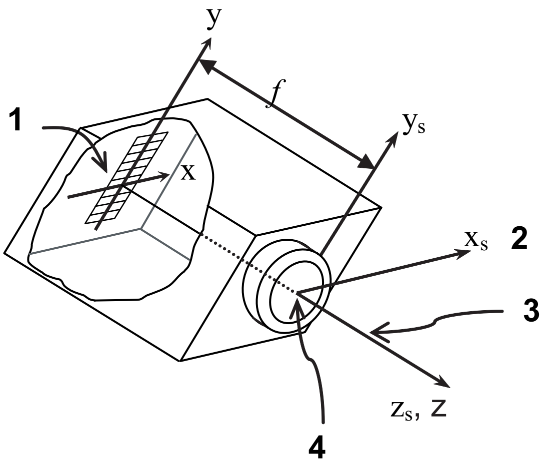
E.1 Introduction

The purpose of this annex is to show how to use metadata defined in this Technical Specification to accomplish precise geopositioning of images from pushbroom and whiskbroom sensor imagery systems. This annex is intended to give an example for using the common terminology and a common frame of reference established in this Technical Specification to perform precise geopositioning using a physical frame sensor model. Specifically, 7.1.2, 7.2.3 to 7.2.8, 7.3, 7.5, and 7.6 excluding 7.6.6 identify relevant metadata classes and Annex B provides the expanded definition of these items.

E.2 Pushbroom sensor Interior description

E.2.1 Pushbroom sensor coordinate system

The detailed description of the Pushbroom Sensor is in 7.1.3 and the Common and Sensor Coordinate Reference Systems are contained in C.4.3 and C.4.4.



Key

1 Linear collection array/Focal Plane Array (FPA)
2 (direction of flight)
3 Lens axis
4 Perspective Centre

Figure E.1 — Sensor coordinate system for a pushbroom sensor

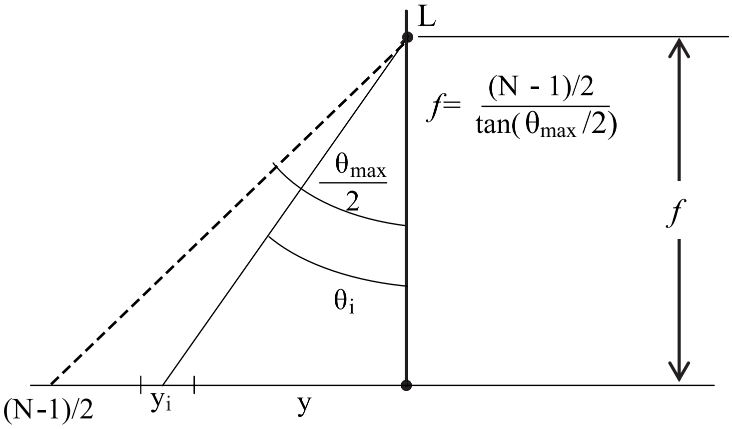


Figure E.2 — Pushbroom sensor model

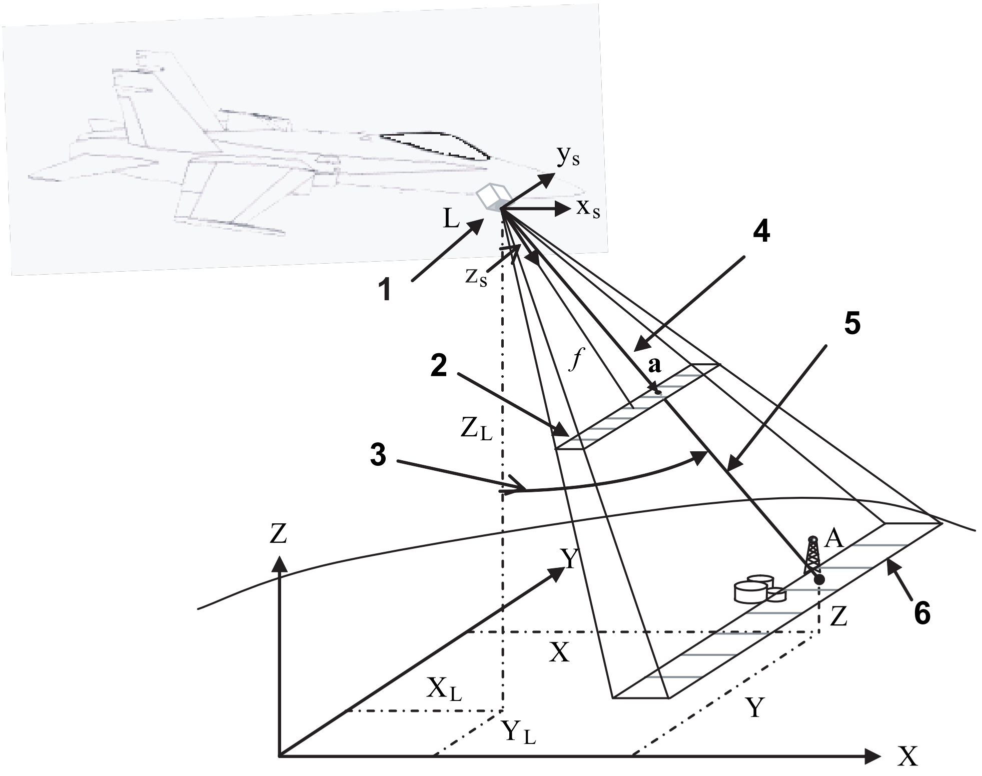
E.2.2 Pushbroom sensor time

The pushbroom sensor scan time is described in C.4.4.

E.2.3 Imaging process

Some pushbroom sensors provide a 'look-forward'/'look-back' capability of up to twenty (20) degrees, shown as the angle Δ in Figure E.3, to minimize glint. Other implementations incorporate multiple arrays. This annex models a pushbroom sensor that employs a single linear array oriented perpendicular to the platform flight direction. As the platform travels along its trajectory, a strip image of the terrain is acquired as the array sweeps forward, one line for each framelet imaged by the array.

Figure E.3 is a schematic of the imaging process. (The positive image plane size is greatly exaggerated for illustration purposes only.) The location of the sensor, as depicted by the instantaneous perspective centre (C) in the figure, and its orientation, vary, based on platform and sensor movement in space and time, from image line to image line. Six Exterior Orientation (EO) unknowns ($X_{s(t)}$, $Y_{s(t)}$, $Z_{s(t)}$, $\omega_{s(t)}$, $\phi_{s(t)}$ and $\kappa_{s(t)}$) exist for each image line, a framelet. As in a frame image, any pixel in that framelet (line) is related to the corresponding (imaged) object point according to the standard collinearity equations. The exterior orientation elements are explicitly time dependent. Every strip image has multiple framelets. Thus, the number of unknown external orientation parameters to be solved for in the aggregated strip image (six for each image line) becomes unwieldy. A bundle adjustment would be impractical since the collinearity solution requires a minimum of three ground control points to solve for the six EO unknowns. A pushbroom strip image adjustment would be overwhelmed by its ground control point dependency. An alternative approach is used, relying on the condition that the elements associated with one scan line are tightly correlated with those of neighbouring lines. This approach is described in E.4.



Key

1 Instantaneous perspective centre
2 Positive Image Plane
3 Rotation Δ
4 Image Vector
5 Vector to Ground Point
6 Ground Swath imaged at time *t*

Figure E.3 — Pushbroom collection (collinearity condition)

E.2.4 System operation dependencies

Due to the narrow linear sensor geometry, in general, for each framelet the sensor attitude is highly correlated with platform motion. The sensor ϕ (pitch) angle is highly correlated with the platform's pitch position along the flight line and the sensor ω (roll) angle is correlated with the cross-strip linear displacement. To improve solving for exterior orientation elements, it is advantageous to use the support information provided with the imaging mission, such as that provided by the Global Navigation Satellite System (GNSS) antenna (position, velocity, and acceleration), the on board INS (angular orientation values and rates of change), and other external information such as sensor engineering estimates, calibration information, or accurate recoverable ground control points.

As an example, for an aircraft system platform monitored at one second intervals, the latitude, longitude, and altitude are recorded in real time from the GNSS, which is operating in differential time mode on board the aircraft. When the system is functioning properly, statistical sub-metre standard deviation accuracies for the horizontal and vertical components of position of the platform are attainable. The assumption is made in this annex that the x_s, y_s, and z_s have been translated and rotated from the GNSS system of the platform such that they can also be represented in the formulation as (X_L,Y_L,Z_L); illustrated in Figure E.3.

Roll, pitch, and yaw angular values and rates of change may be directly supplied by or interpolated from the INS of the aircraft for every framelet of the image; i.e., for each line. These data express the orientation of the platform with respect to an inertial ground system in terms of three angles. Actual sensor behaviour between readings must be interpolated on the assumption that the characteristics of the platform's motion do not change abruptly. Turbulent atmospheric conditions could easily degrade this assumption and the geometry of the imagery. Ideally, a reliable and useable flight stabilization platform (FSP) would be aboard the platform to keep the orientation of the sensor as nearly constant as possible (i.e., nadir looking or at an angle to avoid glint) by attempting to dampen changes in the orientation of the platform. In that case, the non-sequential angles from the FSP are recorded at specific time intervals to be used or interpolated as the roll, pitch, and yaw values for each frame. Often, these FSP readings are not recorded and therefore cannot be used.

E.3 Whiskbroom sensor description

E.3.1 Whiskbroom sensor introduction

A whiskbroom sensor is an electromechanical digital collector with a linear collection array made up of a line of very few detectors, or picture elements (pixels), at the focal plane and mirrors that sweep from one edge of the swath to the other. The whiskbroom sensor depicted in Figure E.4, unlike the pushbroom sensor, actively scans the framelet across the ground. The distortion contributions of platform motion on the framelet scan can be removed with a process called forward motion compensation (FMC). The focal plane geometry of the whiskbroom sensor is very similar to that of the pushbroom. The whiskbroom framelet is the aggregate of very few pixels being scanned across the Field-of-View (FOV). The framelet usually is very short and is rapidly scanned approximately perpendicular to the direction of platform motion. The motion of the sensor platform provides the motion needed between image scans similar to the pushbroom sensor.

The Whiskbroom sensor is a single array of detectors similar to that described for the pushbroom sensor in E.2.1. The whiskbroom demonstrates a panoramic effect since the ray-of-sight rotates across the moving direction of the platform around the sensor's projection centre and each pixel is projected onto some part of a circle around the projection centre. In the pushbroom system each cross-track framelet is formed optically as if in a conventional frame camera. The detector elements are equally spaced and therefore the cross-track IFOV changes across the array as a function of the cross-track view angle. However the cross-track view angle is limited and the pixels do not significantly change their quadratic shape. But for the whiskbroom, each pixel has a different ground dimension in the x and y direction, with pixels at nadir quadratic in shape and those at the maximum scan angle demonstrating a trapezoidal shape. For the whiskbroom sensor model the recorded pixels are assumed to be on a straight line. For the across track pixel coordinates, y_i, a constant scan angle increment of successive pixels is assumed.

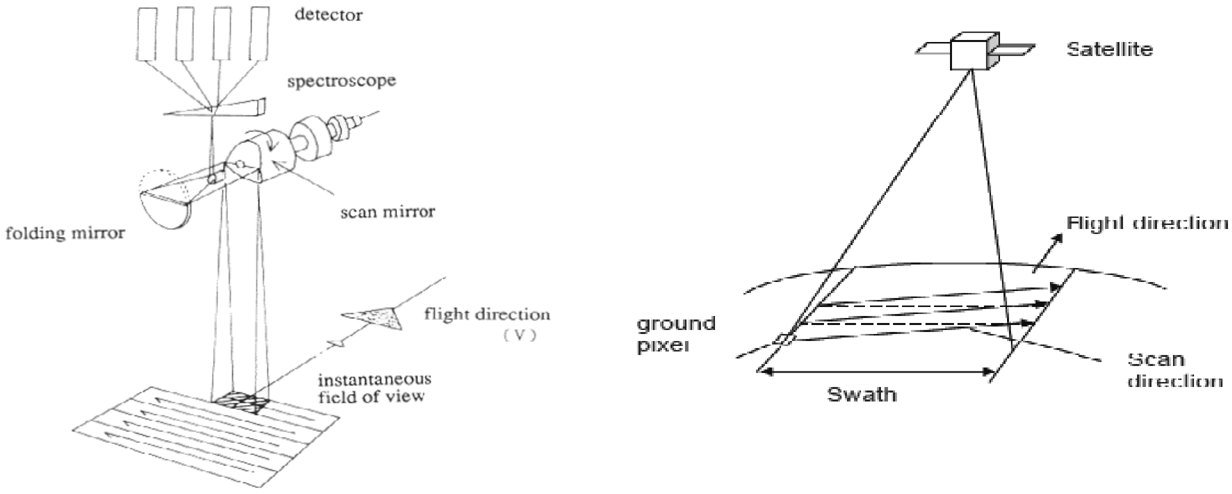
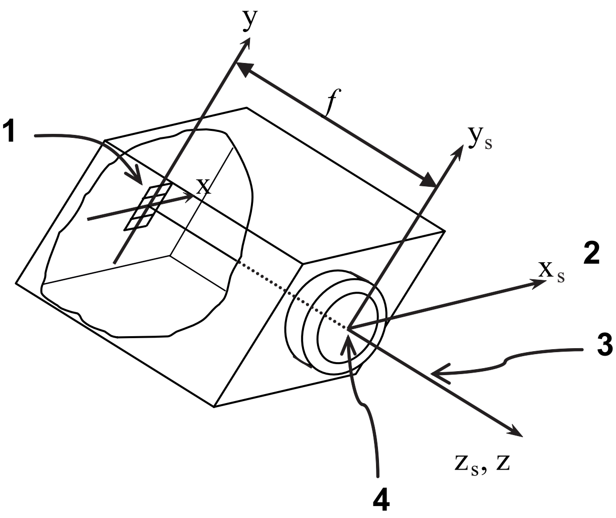


Figure E.4 — Whiskbroom scanner

E.3.2 Whiskbroom sensor coordinate system

The whiskbroom sensor coordinate system is discussed in C.4.5.



Key

1 Linear collection array/Focal plane
2 (direction of flight)
3 Lens axis
4 Perspective centre (L)

Figure E.5 — Sensor coordinate system for a whiskbroom sensor

E.3.3 Whiskbroom pixel-to-image coordinate transform

Since each pixel's dimension is a function of the scan location, the actual image coordinates must be modified to accommodate that fact. Employing the time equations Equation (E.4) through Equation (E.7), the whiskbroom pixel to image coordinate transformation is:

$$x_{s(t)} = (\ell_{(t)} - \mathrm{int}(\ell_{(t)}+0.5)) \qquad \text{(E.1)}$$

$$\theta_s = (s_{(t)} - s_c) \cdot IFOV = (s_{(t)} - s_c) \cdot \left(\frac{\theta_{\max}}{N_y} \right) \qquad \text{(E.2)}$$

$$y_{s(t)} = \left(f \tan(\theta_s) \right) \qquad \text{(E.3)}$$

where

$\ell_{(t)}$	is the line (floating point row) in CCS at scan time (t) (starting with $\ell = 0$) and nominally determined by dividing the measured Common Coordinate System positive x value (CCS_x) from the origin by the pixel x-dimension (dx);
$s_{(t)}$	sample (floating point column in pixels) in CCS at scan time (t);
s_c	sample coordinate of the nominal centre of the framelet containing the point of interest;
$\mathrm{Int}(\ell_{(t)})$	is the largest integer which does not exceed ($\ell_{(t)}$).

E.3.4 Whiskbroom time

For whiskbroom sensors, the formulas for time are as follows:

$$t = t_0 + (scan - scan_0)\,dt_{scan} \pm (s - s_0)\,dt_{sample} \tag{E.4}$$

$$t_c = t_0 + (scan - scan_0)\,dt_{scan} \pm (s_c - s_0)\,dt_{sample} \tag{E.5}$$

$$scan = \mathrm{int}\left({}^{l}\!\big/\!{}_{N_y} \right) \tag{E.6}$$

$$scan_0 = \mathrm{int}\left({}^{l_0}\!\big/\!{}_{N_y} \right) \tag{E.7}$$

where

t	is the time corresponding to a framelet containing the point of interest on the image;
ℓ,s	are line and sample coordinates of the point of interest;
t_0	is the time corresponding to the framelet containing the reference point 0;
ℓ_0, s_0	are line and sample coordinates of the reference point 0;
$scan_0$	is an integer that represents the image scan containing the reference point 0;
t_c	is the time corresponding to the framelet at the nominal centre of the image scan containing the point of interest;
s_c	are sample coordinate of the framelet at the nominal centre of the image scan containing the point of interest;
dt_{sample}	is the time interval corresponding to a unit interval in the sample coordinate;
dt_{scan}	is the time interval between two successive scans;
N_y	is the number of pixels in a framelet;
int( )	is an operator that converts a real number into an integer.

The positive sign is valid if the whiskbroom scan direction is counter clockwise about the direction of platform motion; otherwise the negative sign is valid.

E.4 Methods for solution

E.4.1 Introduction

Given the platform and sensor discussions, deterministic models and stochastic models can be used to solve for the exterior orientation which ensures accurate and precise geopositioning.

— Deterministic Models. The deterministic models assume minimal or no random variation and therefore give a fixed and precisely reproducible result. Deterministic models suppose that statistical variations in the average behaviour of the system's elements are relatively unimportant.

- Stochastic Models. The stochastic models are used where there is reason to expect random events to have an important influence on the behaviour of the system or when there is need to take account of events occurring at random times.

The essential difference between a stochastic and deterministic model is that in a stochastic model different outcomes can result from the same initial conditions.

In this annex the *Spline* model is described to represent the deterministic model methodology. It is widely used to model trajectories in time-dependent systems. Two stochastic models, Gauss-Markov and Gauss-Helmert, are also explained.

E.4.2 Spline Model for the system

The General Spline Model approach involves the recovery of spline coefficients, with time as the independent variable, for the equations reflecting the behaviour of each of the six elements of exterior orientation. To reduce the processing burden of solving for each framelet's exterior orientation, the strip image is sectioned into segments, each consisting of some number of collection lines (see Figure E.6). A different set of coefficients may then be recovered for each segment of an image.

The time interval between exposures of adjacent lines of imagery is handled as a constant. This can be ascertained by time tags in the data file. The six time-dependent elements of exterior orientation are written as a function of line number. The sensor exterior orientation is modelled with piecewise polynomial functions. For the position of the exposure station, the interpolated sensor position from the GNSS data, preferably already translated from the platform GNSS to the sensor coordinate origin, is used as a nominal value. Any discrepancy between this interpolated sensor position and its estimated value is expressed by a polynomial. For sensor orientation angles, zero values are initially used as nominal angles, with the exception of the heading angle. This implementation is based on the fact that the angle information from INS/FSP is not uniformly reliable for many systems. Often only nominal angles for the heading are approximated by computing the direction of the flight from the GNSS data.

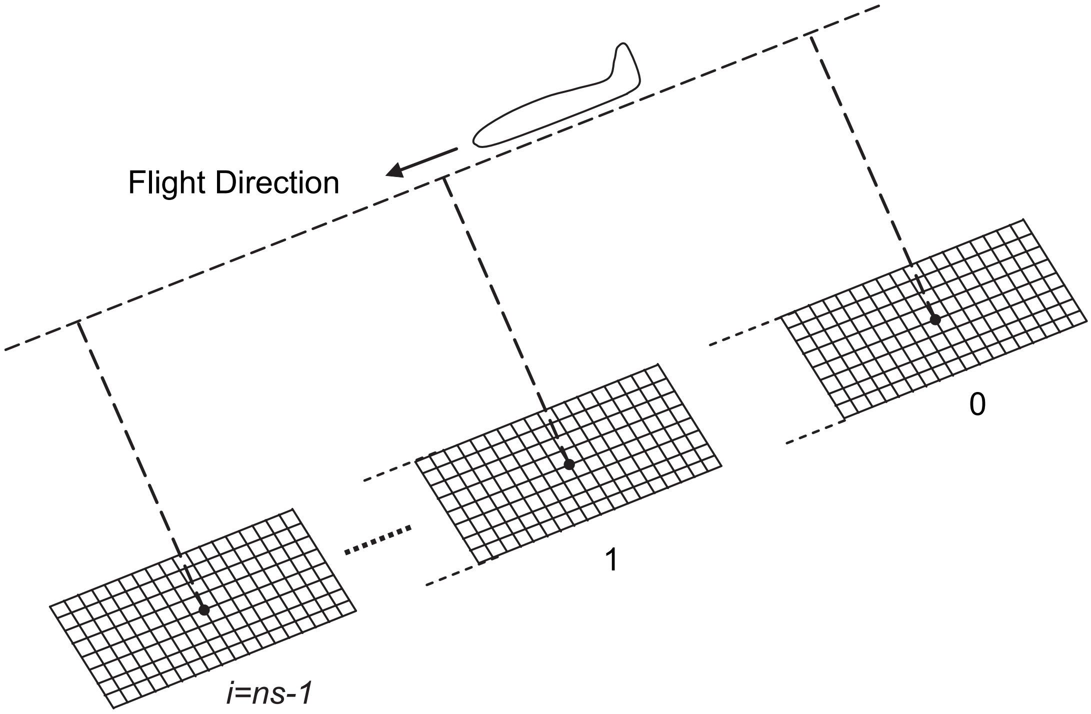


Figure E.6 — Image "segments" for spline modelling

The general form of the spline equation is shown for the X element of the exterior orientation parameters

$$X_{Li} \overset{def}{=} X_G + X_{\Delta i} \tag{E.8}$$

where X_L is the unknown sensor position, X_G is the GNSS estimate of the sensor position (taking care of the antenna offset, if necessary), X_Δ is the unknown correction of the GNSS position given the time at which line (ℓ) in the image segment was collected, and *i* is the segment number in the strip. The following are second-order exemplars of the general form for each parameter.

$$X_L = X_G + X_{Li0} + X_{Li1} \times \ell + X_{Li2} \times \ell^2 \tag{E.9}$$

$$Y_L = Y_G + Y_{Li0} + Y_{Li1} \times \ell + Y_{Li2} \times \ell^2 \tag{E.10}$$

$$Z_L = Z_G + Z_{Li0} + Z_{Li1} \times \ell + Z_{Li2} \times \ell^2 \tag{E.11}$$

$$\omega = \omega_{i0} + \omega_{i1} \times \ell + \omega_{i2} \times \ell^2 \tag{E.12}$$

$$\phi = \phi_{i0} + \phi_{i1} \times \ell + \phi_{i2} \times \ell^2 \tag{E.13}$$

$$\kappa = \kappa_{i0} + \kappa_{i1} \times \ell + \kappa_{i2} \times \ell^2 \tag{E.14}$$

where

X_G, Y_G, Z_G	are interpolated sensor position from the GNSS data;
ℓ	is an image line number of the image segment;
i	is a image section number (i = 0, …, ns-1) (see Figure E.6);
ns	is the number of sections in the spline representations of the trajectory parameters.

The selection of polynomial order (i.e., linear, quadratic, or higher) depends on the behaviour of the particular parameter as a function of time or of line number and also on the length of the splined sections. When GNSS data is available to provide close approximations, a first order polynomial is often used, instead of a second order, to describe the aircraft/sensor position. Additional pseudo-observations, that is, not actual but estimated observations, can fix some or all 2nd order parameters and reduce the polynomial degree to 1st order (linear) functions. Conversely, if accurate differential GNSS data and INS data are not available, higher polynomial order such as cubic would be used.

The total number of parameters in a general second order Spline Model with *ns* sections is (18×*ns* + 1), including updating the focal length. These parameters are as follows:

$$\begin{matrix} X_{Li0}, X_{Li1}, X_{Li2}, Y_{Li0}, Y_{Li1}, Y_{Li2}, Z_{Li0}, Z_{Li1}, Z_{Li2} \\ \omega_{i0}, \omega_{i1}, \omega_{i2}, \phi_{i0}, \phi_{i1}, \phi_{i2}, \kappa_{i0}, \kappa_{i1}, \kappa_{i2} \end{matrix} \quad \text{for } i = (0, ns\text{-}1) \text{ and } f$$

If the position can be modelled with a first order polynomial, then the number of parameters per segment is reduced to 15. The total number of parameters for the strip image would then be (15 times *ns* + 1), since X_{Li2}, Y_{Li2}, and Z_{Li2} are no longer needed.

There are three kinds of constraints that may be applied to each parameter at the section boundaries. The zero order continuity constraints ensure that the value of the function computed from the polynomial in each of two neighbouring sections is equal at their boundary. Equations (E.15) through (E.20) show equations for the boundary between the first and second sections.

$$X_{L00} + X_{L01} \times \ell_{bd} + X_{L02} \times \ell_{bd}^2 = X_{L10} + X_{L11} \times \ell_{bd} + X_{L12} \times \ell_{bd}^2 \quad \text{(E.15)}$$

$$Y_{L00} + Y_{L01} \times \ell_{bd} + Y_{L02} \times \ell_{bd}^2 = Y_{L10} + Y_{L11} \times \ell_{bd} + Y_{L12} \times \ell_{bd}^2 \quad \text{(E.16)}$$

$$Z_{L00} + Z_{L01} \times \ell_{bd} + Z_{L02} \times \ell_{bd}^2 = Z_{L10} + Z_{L11} \times \ell_{bd} + Z_{L12} \times \ell_{bd}^2 \quad \text{(E.17)}$$

$$\omega_{00} + \omega_{01} \times \ell_{bd} + \omega_{02} \times \ell_{bd}^2 = \omega_{10} + \omega_{11} \times \ell_{bd} + \omega_{12} \times \ell_{bd}^2 \quad \text{(E.18)}$$

$$\phi_{00} + \phi_{01} \times \ell_{bd} + \phi_{02} \times \ell_{bd}^2 = \phi_{10} + \phi_{11} \times \ell_{bd} + \phi_{12} \times \ell_{bd}^2 \quad \text{(E.19)}$$

$$\kappa_{00} + \kappa_{01} \times \ell_{bd} + \kappa_{02} \times \ell_{bd}^2 = \kappa_{10} + \kappa_{11} \times \ell_{bd} + \kappa_{12} \times \ell_{bd}^2 \quad \text{(E.20)}$$

where

ℓ_{bd} is image line number at the boundary.

The first order continuity constraint requires that the slope, or first derivative with respect to the boundary line, of the functions in two adjacent sections is forced to have the same value at their boundary. Equations (E.21) through (E.26) provide an example at the boundary between the first and second sections.

$$X_{L01} + 2X_{L02} \times \ell_{bd} = X_{L11} + 2X_{L12} \times \ell_{bd} \quad \text{(E.21)}$$

$$Y_{L01} + 2Y_{L02} \times \ell_{bd} = Y_{L11} + 2Y_{L12} \times \ell_{bd} \quad \text{(E.22)}$$

$$Z_{L01} + 2Z_{L02} \times \ell_{bd} = Z_{L11} + 2Z_{L12} \times \ell_{bd} \quad \text{(E.23)}$$

$$\omega_{01} + 2\omega_{02} \times \ell_{bd} = \omega_{11} + 2\omega_{12} \times \ell_{bd} \quad \text{(E.24)}$$

$$\phi_{01} + 2\phi_{02} \times \ell_{bd} = \phi_{11} + 2\phi_{12} \times \ell_{bd} \quad \text{(E.25)}$$

$$\kappa_{01} + 2\kappa_{02} \times \ell_{bd} = \kappa_{11} + 2\kappa_{12} \times \ell_{bd} \quad \text{(E.26)}$$

The second order continuity constraint requires that the local maxima/minima, or second derivative with respect to the boundary line, of the functions in two adjacent sections is forced to have the same value and direction at their boundary. Equations (E.27) through (E.32) provide an example at the boundary between the first and second sections.

$$X_{L02} = X_{L12} \quad \text{(E.27)}$$

$$Y_{L02} = Y_{L12} \quad \text{(E.28)}$$

$$Z_{L02} = Z_{L12} \quad \text{(E.29)}$$

$$\omega_{02} = \omega_{12} \quad \text{(E.30)}$$

$$\phi_{02} = \phi_{12} \quad \text{(E.31)}$$

$$\kappa_{02} = \kappa_{12} \quad \text{(E.32)}$$

Generally, the polynomial order and the number of sections cannot be determined before considering the data set, including the number and distribution of accurate ground control points. Experiments for the various cases are necessary for making these decisions.

E.4.3 Gauss-Markov and Gauss- Helmert models as stochastic models

E.4.3.1 Stochastic model introduction

The Spline Model, although acceptable for modelling the general trend of a trajectory, is unable to compensate sufficiently for most aircraft reaction to air turbulence and is too restrictive in control point distribution to accurately position airborne pushbroom imagery. The Gauss-Markov model, based on the Gauss-Markov process, can accommodate abrupt changes in the position and orientation of the sensor. If the self-calibrating terms described in E.4.4 are to be included in the mathematical modelling, the Gauss-Helmert model is a recommended approach, given the non-linearity introduced by two sets of unknowns such that each condition equation includes more than one observation. In implementation, the linearization of the collinearity equations in either model is accomplished using the linear terms of the Taylor series expansion. Both approaches are included here.

E.4.3.2 The Gauss–Markov model

In the Gauss-Markov approach, six parameters per line are carried to model the instantaneous exterior orientation for each pushbroom line. Parameters for each image line are tied, or constrained, stochastically to those of the previous image line. This model allows greater flexibility than the preceding spline model, allowing linear feature constraints to contribute to parameter recovery, thereby improving positioning and rectification accuracy. The equations for a continuous Markov process, followed by its associated discrete form, are presented briefly. Then, a set of constraint equations between parameters is developed for implementation in a least-squares bundle adjustment program.

The criterion for a first-order Markov sequence is that the conditional probability distribution of a random variable be dependent only on the one most recent point in the sequence; for a second-order the dependency is on the two most recent points. A Markov process, the continuous case of the Markov sequence, is a solution of a first-order stochastic differential equation: i.e.,

$$\beta_i(t)x = w \tag{E.33}$$

where

$\beta_i(t)$	is a function of time;
x	is the unknown parameter;
w	represents white noise.

If the restriction that the probability density functions of w and, consequently, also of x are Gaussian are accepted, then the process x(t) is a first order Gauss-Markov process. By assuming that the process x(t) is stationary, $\beta_i(t)$ can be expressed as a constant β_1 and the discrete form of Equation (E.33) may be written as:

$$\frac{x_i - x_{i-1}}{\Delta t} + \beta_1 x_{i-1} = w \tag{E.34}$$

Solving for $\boldsymbol{x_i}$ yields:

$$x_i = (1 - \Delta t \beta_1) x_{i-1} + \Delta t w \tag{E.35}$$

Another representation is:

$$x_i = (1 - s) x_{i-1} + n_i \tag{E.36}$$

where n_i for $\Delta t \cdot w$ has mean 0 and variance σ_n^2, Δt is a constant, and s is a constant for $\Delta t\ \beta_1$

In this case, assuming that the interior orientation of the sensor is known, 6L parameters are carried in the least-squares adjustment, where L is the total number of lines in the image. Following the general representation above, for each line in the image starting with the second line, the following six equations are written:

$$F_{G1} = n_{1,i} + (1 - s_{X_i}) \cdot (\Delta X_i)_{i-1} - (\Delta X_i)_i = 0 \tag{E.37}$$

$$F_{G2} = n_{2,i} + (1 - s_{Y_i}) \cdot (\Delta Y_i)_{i-1} - (\Delta Y_i)_i = 0 \tag{E.38}$$

$$F_{G3} = n_{3,i} + (1 - s_{Z_i}) \cdot (\Delta Z_i)_{i-1} - (\Delta Z_i)_i = 0 \tag{E.39}$$

$$F_{G4} = n_{4,i} + (1 - s_{\omega}) \cdot \Delta\omega_{i-1} - \Delta\omega_i \quad = 0 \tag{E.40}$$

$$F_{G5} = n_{5,i} + (1 - s_{\phi}) \cdot \Delta\phi_{i-1} - \Delta\phi_i \quad = 0 \tag{E.41}$$

$$F_{G6} = n_{6,i} + (1 - s_{\kappa}) \cdot \Delta\kappa_{i-1} - \Delta\kappa_i \quad = 0 \tag{E.42}$$

where

> i = line number in the image, $n_{1,i}$ through $n_{6,i}$ are considered fictitious observations assigned an a priori value of zero, and s for each exterior orientation element has a constant value for the entire time (by assuming stationarity).

These equations are the linear Taylor expansion replacing the exponential representation of the Gauss-Markov:

$$F_{GM} = \mathrm{e}^{\mathrm{s_p}}(\Delta \mathrm{P}_{\ell\text{-}1}) - \Delta \mathrm{P}_{\ell} = 0 \tag{E.43}$$

where

ℓ	line number in the total image (ℓ = 2,3,…,L);
s_p	coefficient of each exterior orientation element;
ΔP	correction of each exterior orientation element.

The least squares Gauss-Markov (GM) process, also called the '*adjustment by indirect observations*', solves for the corrections to the exterior orientation parameters:

$$\hat{x} = N^{-1}A^{T}Pl = (\mathbf{A}^{\mathbf{T}}\mathbf{PA})^{-1}\,\mathbf{A}^{\mathbf{T}}\mathbf{Pw} \tag{E.44}$$

This is often referred to as the system of normal equations,

where

N	is $A^{T}PA$;
A	is the Jacobian matrix;
P	is the weight matrix;
l	is the set of observations where **w** = m – f(x^0).

Although the six equations per line are treated as observation equations in the least-squares adjustment algorithm, they are weighted constraint equations, effectively reducing the number of unknown parameters from 6L to 6. Therefore, a unique solution may be obtained if three control points are available.[9] [26]

For each line of imagery in which a point is observed, two collinearity condition equations are written just as in the case for the Spline piecewise polynomial model. As the number of observed points corresponding to control points or linear features increases, the redundant measurements can contribute significantly to the recovery of exterior orientation elements in the vicinity of the observation.

This redundancy effect occurs if the weights assigned to the constraint equations are low enough to allow the parameters to vary significantly from one line to the next. Such an apparent advantage, however, is tempered if widely varying weights are used because this makes the statistical “degrees of freedom” concept ambiguous.

E.4.3.3 The Gauss- Helmert model

If additional parameters, such as principal point offset, are also to be addressed by the model, the Gauss – Helmert method is recommended. The next section on “self-calibration” provides more detail about those parameters. This section describes the modelling technique.

The Gauss-Helmert model was introduced by Helmert in 1872 as the general case of least squares adjustment. It is also called the mixed model.[7] The Gauss-Helmert model is a linearized stochastic model as was Gauss-Markov. The model’s generic nonlinear expression is:

$$F[(l^0 + \Delta l),(x^0 + \Delta x)] = 0 \qquad \text{(E.45)}$$

where

l	represents the observations;
x	is the parameters;
l^0, x^0	are approximations;
Δl , Δx	are corrections.

The linearized form is:

$$F(l^o, x^0) + A\Delta l + B\Delta x = 0 \text{ or } Av + B\Delta = f^0 \qquad \text{(E.46)}$$

where

A	is $\partial F / \partial \ell$;
B	is $\partial F / \partial x$;
f^0	is $-F(l^0, x^0) - A(l - l^0)$.

The least squares Gauss-Helmert process solves for the corrections to the exterior orientation parameters:

$$\hat{x} = (B^T (AP^{-1}A^T)^{-1} B)^{-1} B^T (AP^{-1}A^T)^{-1} f^o \qquad \text{(E.47)}$$

in which P is the weight matrix of the observations, l.

Any constraint equations are functionally given by:

$$G[(x^0 + \Delta x),(y^0 + \Delta y)] = 0 \qquad \text{(E.48)}$$

$$G(x^0, y^0) + C\Delta x + D\Delta y = 0 \text{ or } C\Delta x + D\Delta y = g^0 \qquad \text{(E.49)}$$

where

C is $\partial G / \partial x$;

D is $\partial G / \partial y$;

Δx, Δy are corrections;

g^0 is $G(x^0, y^0)$.

The expression of the linearized form, using the x_0 and y_0 implies that an initial estimate of the parameter must be known before this method can be applied.

E.4.4 Self calibration

Self calibration is a technique used to estimate additional parameters that model the systematic errors due to changes in the interior orientation (principal point position and focal length), lens distortions, and CCD line rotations in the focal plane. Using the same notation adopted for Equation (1) (7.2.5), the collinearity equations are modified for self-calibration, resulting in:

$$F_x = x_i + f\frac{U}{W} + \Delta x \tag{E.50}$$

$$F_y = y_i + f\frac{V}{W} + \Delta y \tag{E.51}$$

where Δ*x* and Δ*y* contain the well-known additional parameters modelling the principal point offset (x_o, y_o), the focal length variation (Δ*f*), the symmetric (k_1, k_2) and decentering (p_1, p_2) lens distortion and the scale factor in the *y* direction (s_y) as described in [3]. These corrections may also include the effect in the *x* direction due to the CCD line rotation θ in the focal plane as shown in Figure E.7 and modelled in Equations (E.52) through (E.56).

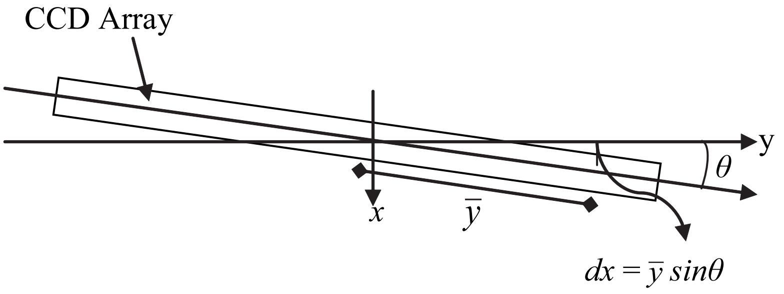


Figure E.7 — CCD linear array displacement in the focal plane

$$\Delta x = \Delta x_0 - \frac{\Delta f}{f}\bar{x} + \bar{x}(k_1 r^2 + k_2 r^4) + p_1(2\bar{x}^2 + r^2) + p_2(2\overline{xy}) + \bar{y}\sin\theta \tag{E.52}$$

$$\Delta y = \Delta y_0 - \frac{\Delta f}{f}\bar{y} + \bar{y}(k_1 r^2 + k_2 r^4) + p_1(2\overline{xy}) + p_2(2\bar{y}^2 + r^2) + s_y\bar{y} \tag{E.53}$$

$$\bar{x} = x - x_0 \tag{E.54}$$

$$\bar{y} = y - y_0 \tag{E.55}$$

$$r^2 = \bar{x}^2 + \bar{y}^2 \tag{E.56}$$

The self-calibration equations above are essentially those derived for a frame image, except for linear array rotation. Whereas one can apply them also for pushbroom and whiskbroom imagery, many of the terms may not be applicable. For example, for a pushbroom sensor, a framelet is essentially a "line image" in the y-direction. Consequently, those terms that would be practical to use are: y_o, Δf, k_1, and k_2. The remaining terms are not practical and may not be possible to recover due to high correlation with the exterior orientation parameters.

Furthermore, in the case of k_1, and k_2, the radial distance r would essentially be the y coordinate. The terms accommodating the linear array rotation are pertinent. Finally, in order to have a robust solution for the self-calibration parameters included in the adjustment, sufficient redundancy is required.

For whiskbroom sensing, the image essentially reduces to a "single pixel." Consequently, none of these added self-calibration parameters are really pertinent except perhaps for Δf. However, if the sweep across the vehicle trajectory is affected through moving mechanical parts, it is possible that other distortions will occur. Either specific modelling of the dynamics of this motion is done, or some of the terms of the self-calibration compensate for these distortions.

There are variations on the single linear array pushbroom discussed above. One system employs three linear arrays rigidly mounted in the focal plane of a single lens, called Three Line Scanner, or TLS. Scanning is performed by sweeping forward due to the forward motion of the aircraft. This allows for triple coverage of the terrain. Another variation is having the three linear arrays, but with three different lenses. The modelling of these systems, including self-calibration, would require modification of that given in the preceding clauses of this Technical Specification.[40]

E.5 Adjustment for atmospheric refraction

Adjustments may be required to account for bending of the image ray path as a result of atmospheric effects, particularly in precise positioning applications. D.2.6 has discussed the approach for adjustments of the atmospheric refractions. The approach can be used in images acquired by pushbroom and whiskbroom sensors.

Annex F
(informative)

Synthetic Aperture Radar sensor model metadata profile supporting precise geopositioning

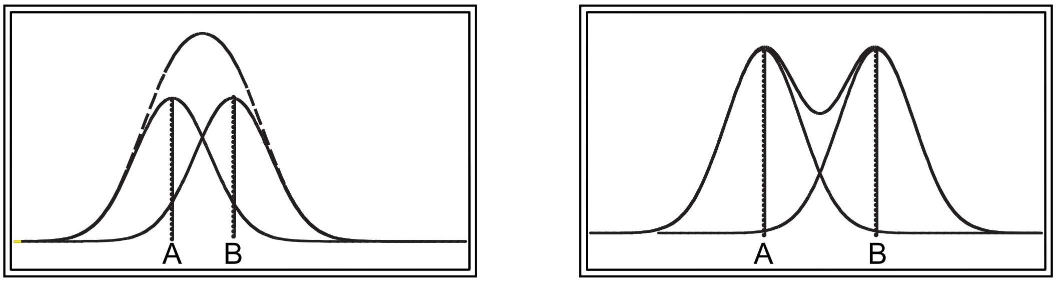
F.1 Introduction

The purpose of this annex is to show how to use metadata defined in this Technical Specification to accomplish precise geopositioning of images from Synthetic Aperture Radar (SAR) imagery systems. This annex is intended to give an example for using the common terminology and a common frame of reference established in this Technical Specification to perform precise geopositioning using a physical SAR sensor model. Specifically, 7.1.5, 7.2.4, 7.2.5, 7.5.2, 7.5.4, 7.5.5, 7.6.3, 7.6.4 and 7.6.6 identify relevant metadata classes and Annex B provides the expanded definition of these items. The relevant coordinate systems can be found in Annex C.

F.2 SAR sensor imagery systems

F.2.1 Introduction

SAR is an active sensor system that uses a series of radar pulses transmitted and received over time from a moving platform to create an image. SAR differs from other types of radars, known as “Real Aperture Radars” (RAR), by creating a large “virtual antenna”, known as the synthetic aperture, which allows tight focusing of the “virtual beam” along the direction of travel. This allows a SAR system to achieve much higher image resolution in the along-track direction than is possible with a RAR system. A more extensive description is provided in 7.1.5.



Distance between A & B is less than IPR

Two point reflectors are indistinguishable from one large reflector

Distance between A & B is greater than IPR

Two point reflectors can be identified as two independent objects

Figure F.1 — Impulse response (IPR) is how resolution is defined for SAR systems

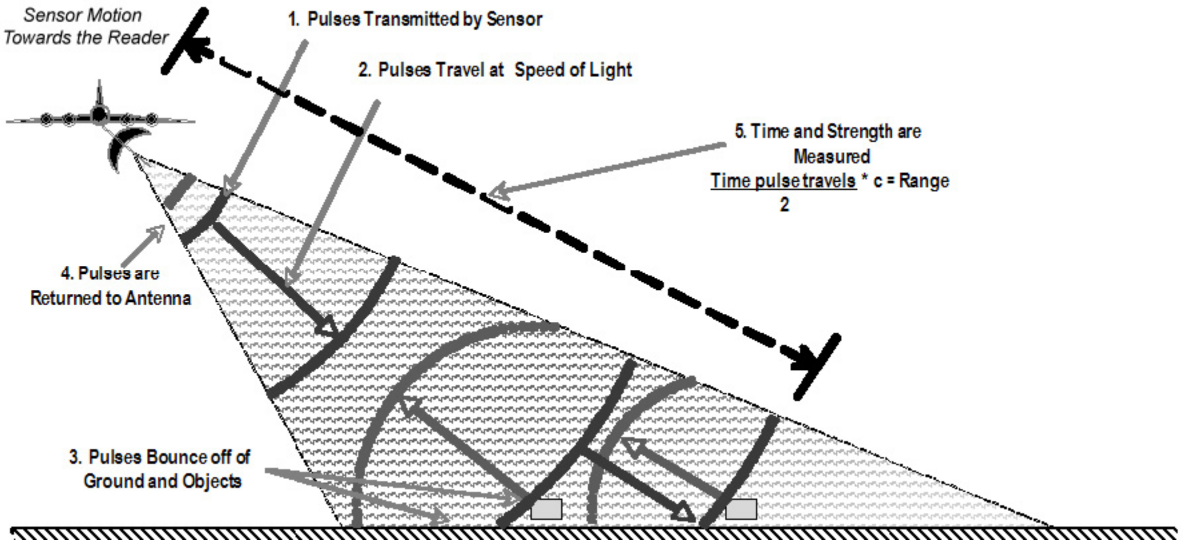


Figure F.2 — RADAR is a ranging system for determining distance using the time for transmitted electromagnetic pulses to return

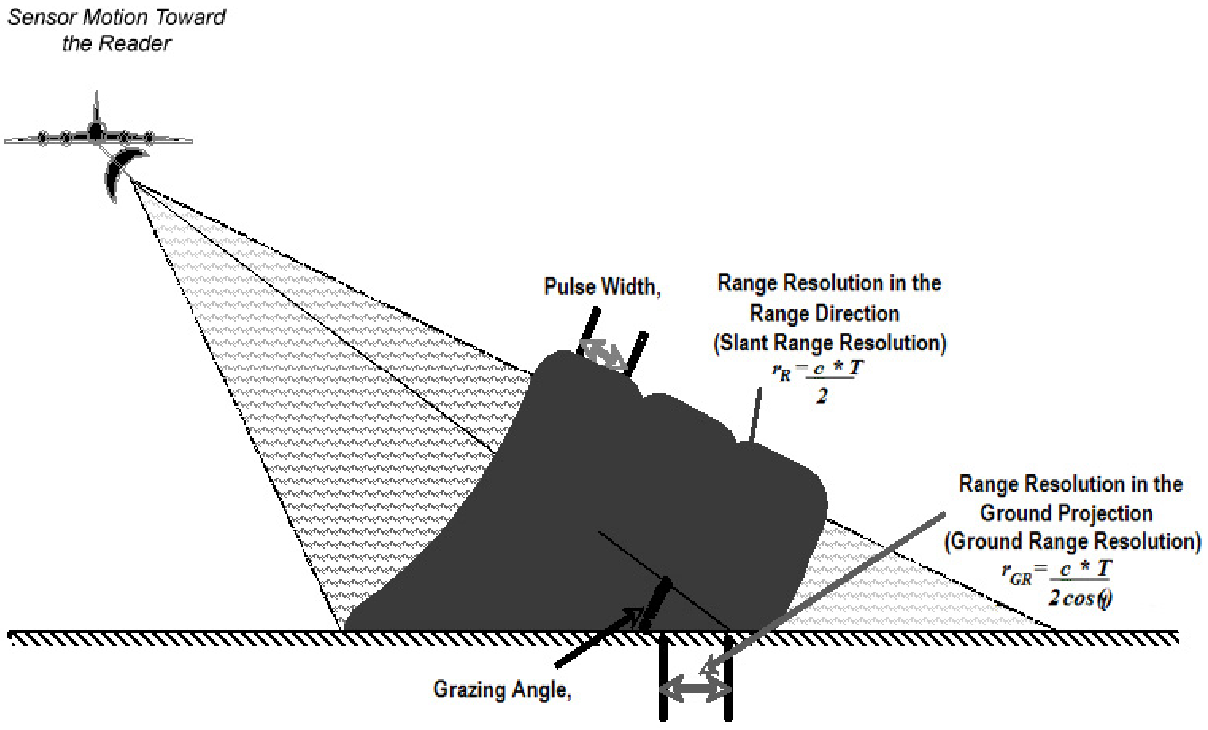


Figure F.3 — Slant range resolution vs. ground range resolution

F.2.2 Basic radar principles

Radar systems, in general, are ranging devices. They measure the time it takes for a signal transmitted by an antenna to return to that antenna (or, in some cases, a different antenna), as well as the magnitude of the returned signal, as shown in Figure F.2. The spatial resolution in the range direction (i.e., radially away from the antenna) is dependent upon the ability to measure the pulse arrival times. These times can be measured with high accuracy in modern radar systems. For a general radar system, range resolution in the range direction is given by the following equation

$$r_R = \frac{cT}{2} \quad \text{(F.1)}$$

where

c	is the speed of light;
T	is the pulse duration.

In Equation (F.1) the range resolution is *independent* of the range, unlike in optical systems.

When a radar system is used to image the ground, the term *slant range resolution* is used to refer to the resolution in the range direction. Ground range resolution, r_{GR}, refers to the resolution of the radar information projected onto the ground surface, which varies with the grazing angle – the angle between the ground surface and the direction of travel of the radar energy (Equation (F.2)). Thus, the ground range resolution is always larger than the slant range resolution, and the ground range resolution is poorer (i.e., decreasing resolvability) at nearer ranges when the platform is at constant height. This situation is opposite of the range-to-resolution relationship for optical systems. As the ground range nears zero (i.e., the sensor is pointed nearly straight down), the $cos(\gamma)$ term in Equation (F.2) goes to zero and the range resolution approaches infinity. This explains why radar imaging systems cannot image directly along the ground track of the aircraft, and why they have a near-range limit for practical utility. This is often set to around a 60° grazing angle, at which the ground range resolution is twice the slant range resolution.

$$r_{GR} = \frac{cT}{2\cos(\gamma)} \quad \text{(F.2)}$$

RAR systems change the position or pointing of the antenna in order to measure signal returns in different directions. Their resolution in the direction of rotation or translation, known as azimuth resolution, r_A, is dependent upon the width of the beam at the target.

$$r_A = r_{SR}\beta \quad \text{(F.3)}$$

where

r_{SR}	is the (slant) range to the target;
β	is the beam width, approximated by 0.89 * wavelength/antenna_size.

Since the azimuth resolution is inversely proportional to antenna size and proportional to range to the target, long range imaging at even moderate resolution may require an antenna size that exceeds what can be practically built and carried on an aircraft. The invention of Synthetic Aperture Radar resolved this problem by using motion of the radar to synthesize a very large antenna.

F.2.3 SAR radar principles

F.2.3.1 Introduction

The unique aspect of SAR is the method it uses for improving upon azimuth resolution by forming a synthetic virtual antenna that can be much larger than any plausible real antenna. In addition, SAR systems use more advanced ranging techniques than those described above to improve range resolution.

F.2.3.2 Range resolution in SAR

SAR systems employ a chirped pulse, which imposes a frequency modulation on each radar pulse. Using this technique, the radar can better distinguish between overlapping pulses so that the effective range resolution becomes

$$r_R = \frac{c}{2B} \qquad \text{(F.4)}$$

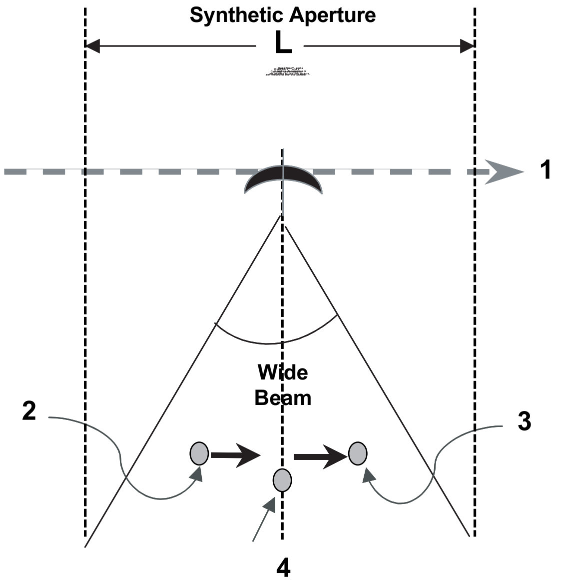
where

B is the bandwidth of the chirped pulse.

Chirped pulses are used by many types of radars, not just SARs.

F.2.3.3 Azimuth resolution in SAR

SAR systems use information collected over many pulses along a path to synthesize a virtual antenna. This is only possible when there is relative motion between the antenna and the object or scene being imaged. This motion creates a Doppler shift (i.e., slight increases or decreases in the frequency) on the returning signal. The amount of the Doppler shift is related to the velocity of the antenna relative to that of the object that caused the signal to return. Objects that lie on a path orthogonal to the antenna's velocity vector, $\dot{S}$, (i.e., broadside to the motion) impose no Doppler shift on the returning signal because there is no relative motion in the range direction between that object and the aircraft. Objects forward of broadside impart a positive Doppler shift and objects aft of broadside impart a negative Doppler shift, as shown in Figure F.4. Moreover, all objects lying along the same radial from the antenna position (i.e., at the same angle from broadside) have the same Doppler shift, hence the term Doppler Angle is often used. Doppler angle is represented by α.



Top View

Key

1 Sensor Motion
2 Sensor is moving away from this scatterer – Doppler Shift < 0
3 Sensor is moving toward this scatterer – Doppler Shift > 0
4 Sensor is moving neither toward no away from this scatterer – Doppler shift = 0

Figure F.4 — The Doppler shift of a returning pulse's frequency is due to forward motion of the sensor relative to the scene

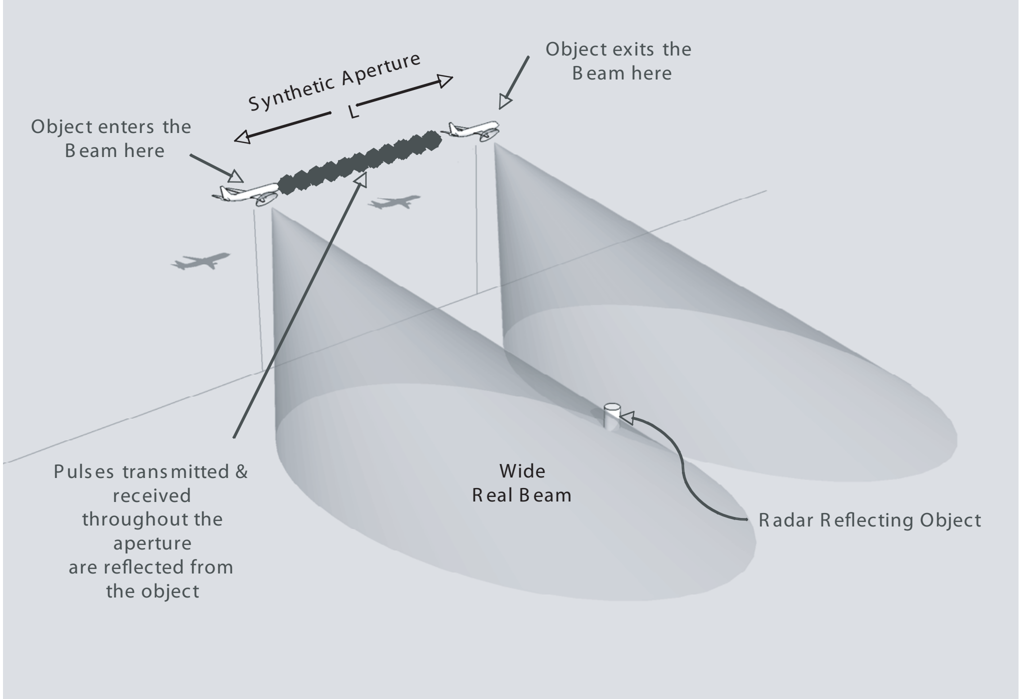


Figure F.5 — The Synthetic Aperture

In order to discern the Doppler shift of a returning pulse, the phase of the signal must be recorded in addition to the magnitude. The phase information provides the information that allows a SAR processor to identify returning signals based on their Doppler shift. For every transmitted pulse, almost every point on the ground and in the beam reflects some return signal. These points are called scatterers. The returned signal is the sum of all returns from all scatterers. Since the antenna moves between pulses, the range and Doppler angle for each scatterer will change. The total distance travelled by the sensor while a scatterer stays illuminated is called the Synthetic Aperture, as illustrated in Figure F.5. As the pulses are decoded, the signals for each discrete range bin are collected into a range line. The “range line” is a misnomer based on the assumption that the surface being imaged is a plane. The range line data actually represents a range sphere, since the location of the ground surface has not yet been defined. The range line contains a collection of the radar signal’s magnitude and phase for each of many returning pulses at that range. This information is usually represented by a complex number with a Real or in-phase component, I, and an Imaginary or quadrature component, Q. The set of range lines recorded during a contiguous time-period is known as the Phase History Data (PHD), or sometimes the Video Phase History Data (VPHD). The PHD is the fundamental data collected by a SAR.

PHD can be processed in different ways to produce various products, the most common of which is a SAR image, which is more properly referred to as a detected SAR image. A detected SAR image is typically a single-banded, 8-bit or 16-bit fixed point image that can be displayed or printed. The detected image (or any SAR product, for that matter) is simply one way to visualize the SAR PHD that was collected. A common intermediate product is a complex SAR image, wherein each pixel value is a complex number that represents the accumulated in-phase and quadrature signal from the scatterers within an area on the ground represented by a range value (±1/2 range resolution) and the Doppler angle value (±1/2 azimuth resolution). The detected SAR image is generated from the complex SAR image by taking the magnitude of the complex pixels, adjusting the dynamic range of the result, and, often, applying a coordinate transformation to a desired output projection.

F.2.4 SAR imaging modes

F.2.4.1 Introduction

There are three primary types of SAR imaging modes used for ground imaging from aircraft and satellites: Stripmap, Spotlight, and Scan. In addition, a fourth mode used by some systems is called ScanSAR, which is not related to the general Scan mode. The modes are a function of the way in which the synthetic apertures are created. Scatterers contribute to the radar signal only during the time that they are in the synthetic aperture, with longer times resulting in better resolution. Thus, different modes have different equations for defining their azimuth resolution.

F.2.4.2 Stripmap mode

In Stripmap Mode, the antenna pointing is fixed relative to the flight path, as shown in Figure F.6. Often, but not always, the beam is pointed at broadside (i.e., orthogonal to the velocity vector). As the platform moves, the beam sweeps a swath along a strip of terrain that is parallel to the path of motion. This mode is used primarily for continuous mapping applications. The synthetic aperture length, L, is equal to the width of the beam on the ground. More importantly, the position of the synthetic aperture is different for each range line, even though its length, L, remains constant. The azimuth resolution for Stripmap mode is defined by:

$$r_A \approx \frac{D}{2\sin(\alpha)} \qquad \text{(F.5)}$$

where

D is the physical antenna aperture and α is the Doppler angle.

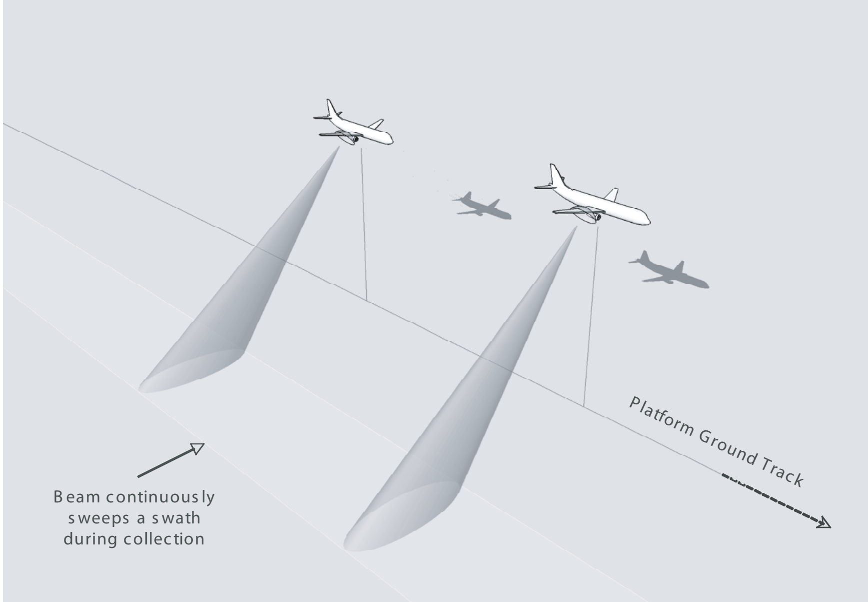


Figure F.6 — SAR stripmap imaging mode

For many SAR systems, the Stripmap mode uses a Doppler angle of 90°, which is directly broadside. For this case, Equation (F.5) simplifies to

$$r_A \approx \frac{D}{2} \qquad \text{(F.6)}$$

F.2.4.3 Spotlight mode

In the Spotlight mode, the antenna is steered to keep approximately the same ground area illuminated by the beam, as illustrated in Figure F.7. The illuminated area can be anywhere in the acquisition region of the SAR. This means that the synthetic aperture can be very large, resulting in better resolution than Stripmap mode. Every line in a Spotlight image has the same synthetic aperture, unlike Stripmap images. Spotlight mode is used primarily for acquisition of point or small area collections at higher resolution than would be achievable with other modes. The azimuth resolution for spotlight mode is defined by:

$$r_A \approx \frac{0.89 r_{SR} \lambda}{2L \sin(\alpha)} \tag{F.7}$$

Where

r_{SR} is the slant range;

L is the length of the synthetic aperture;

λ is the wavelength of the radar;

α is the Doppler angle.

The synthetic aperture, L, for Spotlight is not dependent on the real antenna beam width, as with Stripmap mode. The resolution can be improved by increasing the dwell time (i.e., the time that is spent illuminating the same target area) by moving the antenna beam. This allows for efficient imaging of many small scenes during one flight. It should be noted that Spotlight mode requires an antenna that can steer the beam during flight. This imparts additional complexity in the antenna system to either electronically or physically steer the real antenna aperture.

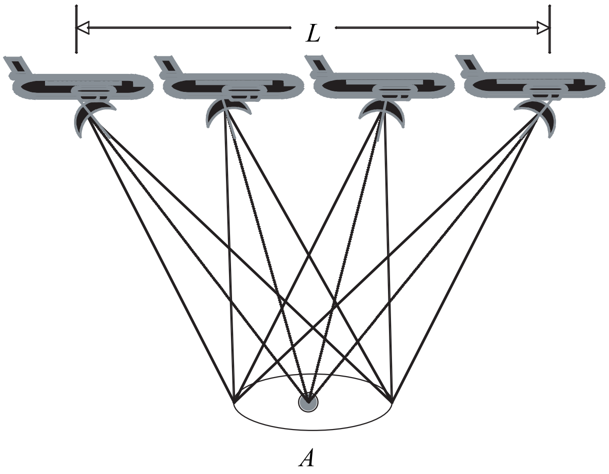


Figure F.7 — Spotlight mode imaging concept

F.2.4.4 Scan mode

Scan mode SAR is actually the most general SAR mode. It combines the characteristics of Spotlight mode and Stripmap mode, each of which can be formulated as special cases of Scan mode. In Scan mode, the beam is steered to illuminate a strip of terrain that can be at any angle with respect to the direction of motion. Because of this, scatterers may be illuminated for differing amounts of time. Moreover, the beam can be steered to both scan and increase dwell, thereby allowing better resolution than Stripmap mode by scanning more slowly than the aircraft motion alone. Scan mode is primarily used for imaging, at medium to high resolution, large scenes that are not parallel to the flight path. This can increase collection efficiency particularly for satellites, because their flight paths are fixed. The azimuth resolution for Scan mode imagery depends upon the scan rate relative to each pixel.

F.2.4.5 ScanSAR mode

ScanSAR mode is an additional mode that has been defined by some SAR data providers. ScanSAR is not a true Scan mode, but rather a special case of the Stripmap mode. ScanSAR incorporates a process for time-sharing an electronically steered phased array antenna in which the beam moves quickly from one strip to a parallel one so that multiple strips can be illuminated in one pass. However, because the strips are not continuously illuminated for as long as they are in Stripmap mode, not as many range lines are collected and, thus, ScanSAR modes have poorer resolution. The strips are typically processed into slightly overlapping images that can then be mosaicked into large area maps at medium resolution. Individual strips from the ScanSAR collections can be treated photogrammetrically as separate Stripmap mode images.

F.2.5 SAR sensor coordinate systems

A number of SAR Sensor Coordinate Systems are defined in C.5.

F.2.6 Important SAR terms

A number of different terms unique to SAR have been defined in Clause 4. Figure F.8 and Figure F.9 illustrate these terms and their relationships.

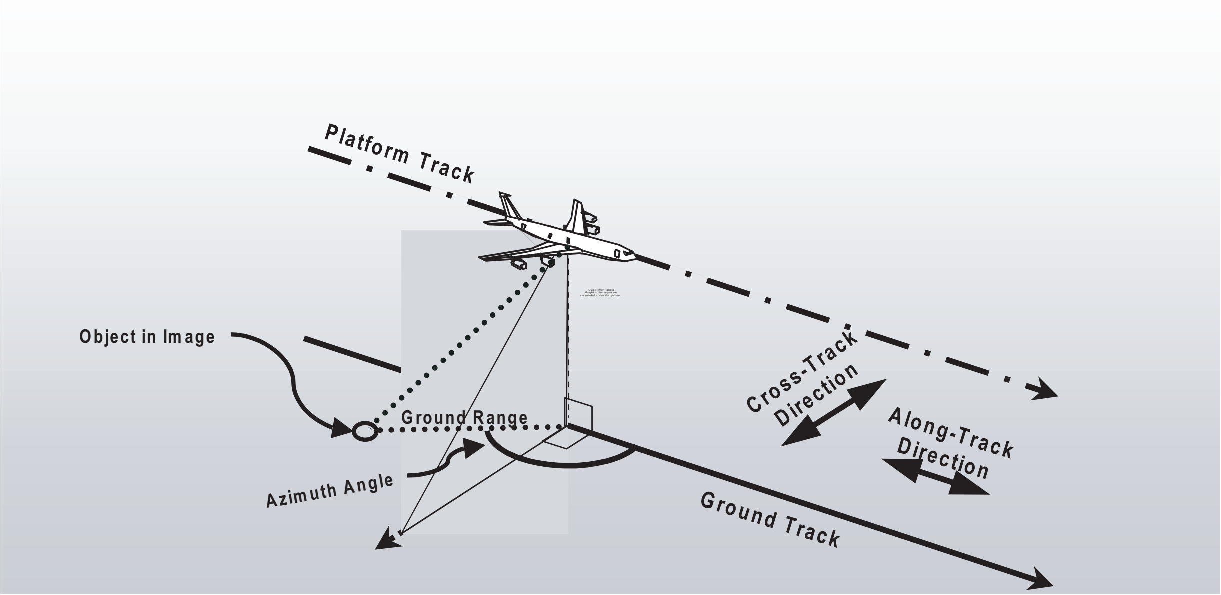


Figure F.8 — Some important SAR terms

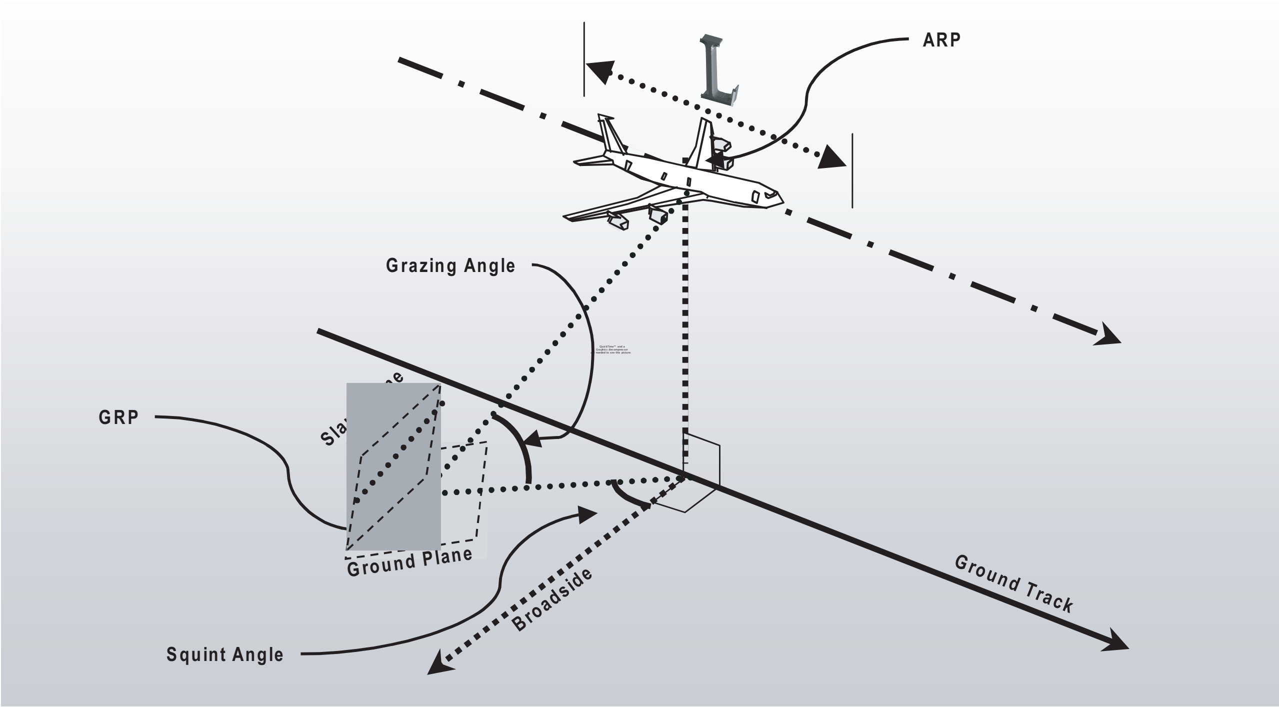


Figure F.9 — Important SAR geometry parameters

F.3 SAR geometry

F.3.1 Equations

As discussed in C.3.5.1, SAR pixel coordinates are defined by range and Doppler angle, each of which places a condition on the pixel's location in space. As described in C.3.5.1 Equation 10, any pixel location in line-sample space can be converted to a coordinate in Range-Doppler space. The range value of a pixel identifies the surface of a sphere of radius, RS, that is governed by the range equation or range condition of Equation (F.8), as developed in C.5.2

$$R_S = |\boldsymbol{Q}| = \left[\left(X - S_{X0}\right)^2 + \left(Y - S_{Y0}\right)^2 + \left(Z - S_{Z0}\right)^2 \right]^{1/2} \tag{F.8}$$

where

$\lvert\boldsymbol{Q}\rvert$	is the magnitude of the ECEF pixel vector from the Aperture Reference Point (ARP) to the Ground Reference Point (GRP) in the slant plane;
[X, Y, Z]	in ECEF coordinates, is the location of a point on the range sphere;
S_0	is the vector composed of the ECEF components [S_{X0}, S_{Y0}, S_{Z0}] of the ARP;
R_S	is the sample range from Equation (C.15).

The Doppler angle value of a pixel identifies the surface of a cone of angle, α, from the antenna's velocity vector that is defined by the Doppler Cone equation or Doppler Cone condition in Equation (F.9):

$$\begin{aligned}&\dot{S}_X\left(X - S_X\right) + \dot{S}_Y\left(Y - S_Y\right) + \dot{S}_Z\left(Z - S_Z\right) = \\ &\qquad \cos\alpha \cdot \left[\dot{S}_X^{\,2} + \dot{S}_Y^{\,2} + \dot{S}_Z^{\,2}\right]^{1/2} \left[\left(X - S_X\right)^2 + \left(Y - S_Y\right)^2 + \left(Z - S_Z\right)^2\right]^{1/2}\end{aligned} \qquad \text{(F.9)}$$

The solution to these two equations traces a circle that represents the intersection of the Doppler Cone with the Range Sphere. The correct 3D location of the radar return could lie anywhere on that circle. It is interesting to note that when the Doppler angle is 90°, the Doppler Cone becomes a plane and the right side of Equation (F.9) goes to zero.

It is apparent, then, that a single Range-Doppler pair does not uniquely define the 3D location for a radar return or its associated position on the Earth's surface. Rather, the slant plane image is simply a convenient way to store the radar signal information gathered from each Range-Doppler circle collected and processed by the SAR system. Conversely, knowing the 3D location of an object point does allow one to calculate the Range-Doppler circle to which it corresponds, and, hence, its corresponding location in the 2D image.

F.3.2 External influences

Atmospheric Refraction. The atmospheric refraction of the microwave radiation should be adjusted for within the image formation processor. Errors in the estimation of this factor during image formation may affect accuracy at longer ranges. Generally, geopositioning should not need to consider this factor.

Curvature of the Earth. The curvature of the Earth should be adjusted for within the image formation processor. Generally, geopositioning should not need to consider this factor.

F.4 Application of sensor model

F.4.1 SAR geopositioning

F.4.1.1 Introduction

Geopositioning from SAR images relies on the ability to associate image coordinates and ground coordinates. Both ground-to-image and image-to-ground functions are needed. They are explained in 8.2.5 and 8.2.6.

For SAR images and products, Equation (F.8) and Equation (F.9) together form the Ground-to-Image Function. Because of the non-linearity of these equations, however, the Image-to-Ground function can be derived directly in only the simplest of cases. Thus, the Image-to-Ground function is nearly always implemented in an iterative fashion using the Ground-to-Image equations, with an initial estimate of ground coordinates using a simplified model, such as the corner coordinates commonly provided in the metadata (see note below).

As with projective sensors and their collinearity equations, there are two methods for performing photogrammetric geopositioning from SAR images. These are:

1) to intersect the Range-Doppler circle for a given pixel with a known elevation, such as a DEM, and

2) to use two or more images of the same ground area and find the intersection of the two or more Range-Doppler circles associated with the corresponding pixels.

NOTE Non-photogrammetric methods can be used for coarse positioning. As with optical images, SAR images often come with Earth coordinates that can be used for rudimentary positioning. For example, given a slant plane or ground plane image, the corners of the image are often projected to a tangent plane or some other simple model of the Earth's surface, such as the Earth Ellipsoid or the Geoid. Combined with the pixel count or pixel GSD, this can be used to estimate surface coordinates. However, since the true location of a pixel from a single image is ambiguous, these methods are only rough approximations.

F.4.1.2 Mono image with an elevation source

Given an elevation source, such as a known object height or a DEM of the Earth's surface, and the equation of the circle for a given pixel, we can calculate the intersection of the two. (This is equivalent to using the collinearity equations for an image from an optical sensor in the same fashion.) Generally, there will be two intersections – one on the left side of the velocity vector and one on the right. Since the pointing direction from the ARP to the GRP is known, only one of these makes sense. This effect is illustrated using a tangent plane in Figure F.10. The equations are solved iteratively due to the non-linear nature of the Range-Doppler condition equations.

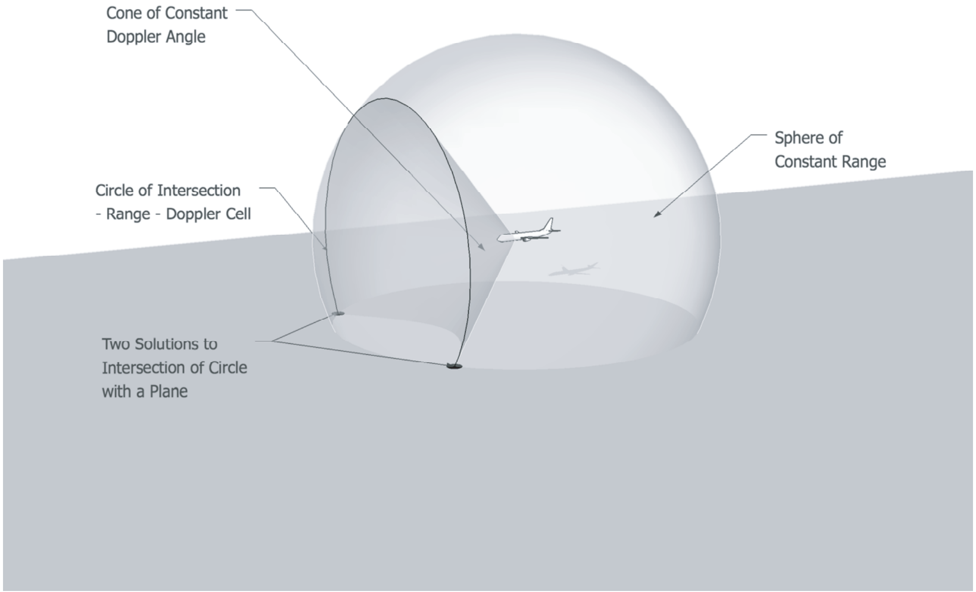


Figure F.10 — Two Solutions when the range-Doppler circle intersects with a plane

When a DEM is used, it is possible for the circle to intersect the DEM more than once on the same side of the sensor, however. This can occur, for example, in mountainous areas where there is significant terrain relief or in urban areas where a high-resolution surface DEM can represent buildings and other structures in great detail. The cause of this multiple-intersection is radar return information in a single Range-Doppler cell that comes from more than one surface location. This is an ambiguity in SAR data that cannot be resolved. The visual image effect of this ambiguity is known as layover, since it appears in the image that the near-vertical face of an object (e.g., mountain, building) appears to "lay-over" on the surfaces in front of the object. When performing geopositioning, this becomes a concern if the resolution of the DEM results in ambiguities where multiple 3D ground or object points map to the same image point.

F.4.1.3 Stereo intersection

When two images are collected of the same ground location (assuming different ARPs), the pixels associated with that location in each image will define distinct Range-Doppler circles. The intersection of those two circles, or more properly the intersection of the two Range Spheres and the two Doppler Cones will define a 3D point. The simultaneous solution of the two Range and two Doppler equations is overdetermined, as there are four equations and three unknowns. Hence, any errors in the range or Doppler information in either image will result in a variety of close solutions. Figuratively, this means that the Range-Doppler circles do not directly intersect, but come very close. Iterative least squares techniques, such as those discussed in [29] must be used to solve for the optimal (in a least squares sense) result.

F.4.2 Adjustable parameters

Adjustable parameters are those parameters in the sensor model that have uncertainty associated with them and that can be adjusted during triangulation, resection, or model-based registration operations. For SAR, the primary measured parameters are the ARP, $\mathbf{S_0}$, and its first derivative, the sensor velocity vector, $\dot{s}$. The other key parameter, the GRP, $\mathbf{G_0}$, is not measured but rather is given, and, thus, is not adjustable.

F.4.3 Covariance matrices

The quality of the six adjustable SAR parameters can be determined via analytical or empirical methods during a calibration process. Since these parameters are carried as adjustable parameters, it is not critical to have good prior error estimates. These prior values can be approximate since, through the adjustment process, they will be refined through rigorous error propagation associated with least squares adjustment. These updated parameter covariances are, in turn, used in a rigorous propagation to produce the final covariance matrix, Σ, associated with each object.

For a SAR sensor, the corresponding covariance matrix is given by:

$$\Sigma_{EO} = \begin{bmatrix} \sigma^2_{S_X} & \sigma_{S_X S_Y} & \sigma_{S_X S_Z} & \sigma_{S_X \dot{S}_X} & \sigma_{S_X \dot{S}_Y} & \sigma_{S_X \dot{S}_Z} \\ & \sigma^2_{S_Y} & \sigma_{S_Y S_Z} & \sigma_{S_Y \dot{S}_X} & \sigma_{S_Y \dot{S}_Y} & \sigma_{S_Y \dot{S}_Z} \\ & & \sigma^2_{S_Z} & \sigma_{S_Z \dot{S}_X} & \sigma_{S_Z \dot{S}_Y} & \sigma_{S_Z \dot{S}_Z} \\ & & & \sigma^2_{\dot{S}_X} & \sigma_{\dot{S}_X \dot{S}_Y} & \sigma_{\dot{S}_X \dot{S}_Z} \\ & & \text{symmetric} & & \sigma^2_{\dot{S}_Y} & \sigma_{\dot{S}_Y \dot{S}_Z} \\ & & & & & \sigma^2_{\dot{S}_Z} \end{bmatrix} \qquad \text{(F.10)}$$

The diagonal elements of the square symmetric non-singular matrix in Equation (F.10) are the variances of the sensor position parameters (S_X, S_Y, S_Z) and their corresponding velocities ($\dot{S}_x, \dot{S}_y, \dot{S}_z$). The off-diagonal elements of the matrix, Σ_{EO}, in Equation (F.10) are the covariances among all six components of the position and velocity.

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