Astronomical Coordinates and Coordinate Systems

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Abstract

In creating version 2 of the "Space-Time Coordinate Metadata for the Virtual Observatory" (STC) Data Model (Rots, 2007), it was decided to split the content into various component models which focus on particular aspects of the previous model scope.

This model describes the Coordinates model and covers the following concepts.

- Description of single and multi-dimensional coordinate space, and coordinates within that space.
- Coordinate Frames, providing metadata describing the origin and orientation of the coordinate space.
- Definition of simple domain-specific coordinate types for the most common use cases.
- Coordinate Systems, description of the coordinate domain space.

Status of this document

This is an IVOA Proposed Recommendation made available for public review. It is appropriate to reference this document only as a recommended standard that is under review and which may be changed before it is accepted as a full Recommendation.

A list of current IVOA Recommendations and other technical documents can be found at http://www.ivoa.net/documents/.

Contents

Acknowledgments

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projects (European Commission 7th program): Euro-VO Aida, VO-ICE and CoSADIE.

Conformance-related definitions

The words "MUST", "SHALL", "SHOULD", "MAY", "RECOMMENDED", and "OPTIONAL" (in upper or lower case) used in this document are to be interpreted as described in IETF standard RFC2119 (Bradner, 1997).

The *Virtual Observatory (VO)* is a general term for a collection of federated resources that can be used to conduct astronomical research, education, and outreach. The International Virtual Observatory Alliance (IVOA) is a global collaboration of separately funded projects to develop standards and infrastructure that enable VO applications.

1 Introduction

1.1 Motivation

Astronomy, being primarily a science that crucially depends on observations, has a very basic need for complete, accurate, and unambiguous metadata regarding coordinate information, meaning all coordinates of the observable space and noting that several of these are intertwined. The Data Model described in this document aims to provide a model for such metadata.

1.2 Context and Scope

This document results from updating the "Space-Time Coordinate Metadata for the Virtual Observatory" (STC) (Rots, 2007) model for use in VO-DML compliant models. That model provides metadata describing Space-Time related, and other Coordinates. These metadata are to be used for specifying coordinate-related information for datasets, catalogs, and queries. In this work, our primary focus is to support the use cases described below, while keeping the broader scope in mind to inform design decisions for future expansion.

The update and revision of the STC model has sub-divided the content into component models, each covering a portion of the scope of the parent model. This allows for a better description of the relations between the various components, allows for independent development of the component models, and creates smaller, more digestible content for users.

In the astronomical community, the terms "quantity", "coordinate", and "measurement" are used interchangably, but not always with the same meaning. The "coordinate" of a star is typically a measured location, while the "coordinate" of the center of a circular region is not. We provide here a short glossary of these terms in the IVOA data model context.

- Quantity: [ivoa model] A number with a unit.
- Coordinate: [coords model] An absolute location within a coordinate space. Comprised of a 'value' (often a Quantity), associated with an axis in a coordinate space, and a coordinate frame providing additional metadata about the orientation and origin of the coordinate space. In other words, a location in a domain space.
- Measurement: [meas model] For 'measured', or 'determined' data. Combines a Coordinate (ie: the determined value) with corresponding Error(s). For the majority of cases dealing with astronomical data, this is what we are referring to.
- Coordinate System: [coords model] The term 'Coordinate System' is used to mean both "the space in which a coordinate resides", and "a unique domain space, factoring in specific reference frame metadata". In this model, we adopt the latter definition. A Coordinate System provides a complete description of the domain space, including both the coordinate space description and any associated Frame metadata.

This document describes the Coordinates model which provides the metadata describing:

- the coordinate space; axes, and domain ranges
- coordinate frames with metadata describing the origin and orientation of the coordinate space
- a general model for specifying coordinate values within the coordinate space
- coordinate systems for defining various domain spaces.

2 Use Cases and Requirements

2.1 Use Cases

2.1.1 Cube model support

The primary use case for this work is in support of the CubeDM.
The CubeDM is a N-Dimensional model for pixelated images and sparse cube data. The following is a brief outline of the most relevant features pertaining to the development of the Measurement, Coordinates, and Transform component models.

- General
  - knowledge of the pixel and physical domain spaces provided at a high level
  - definition of the domain space includes the following criteria
    - dimensionality (typically 1,2 or 3 for physical domain), pixel domain may be of any dimension
    - axis configuration (for spatial domain which has >1D). The most common configurations for astronomical data are Cartesian and Spherical, but others may be used as well.
    - domain range along each axis, typically +/- Inf, but may be limited due to physical constraints (e.g. physical size of a detector, sensitivity limitiations, etc)
    - association with additional metadata further describing the nature of the domain space (Frame). This is especially true for the Spatial and Temporal domains, but may apply to others as well. Examples include:
      - reference position (location of origin)
      - reference frame (orientation of the domain space)
      - planetary ephemeris
      - equinox
- Pixelated Image Cube
  - complete specification of pixel coordinate domain; number of axes, number of pixels per axis
  - mappings of various pixel axes to corresponding physical axes
    - spatial domain typically mapping 2-3 pixel axes to physical axes
    - other domains are typically 1 dimensional
    - pixel axes may be involved in multiple mappings to different physical spaces
  - mappings may be stacked to define progressive transitions through a domain (e.g.: pixel -> ccd -> detector -> sky -> wcs)
    - intermediate stages may or may not be explicitely defined
  - image data value is typically given in a physical domain, but may itself be mapped to other domains
- Sparse Cube
  - data axes cover a wide array of physical domains including, but not limited to Spatial, Temporal, Spectral, Polarization,

- individual domains may be represented multiple times in different frames (ccd, detector, sky; pha, energy)
- data values may have associated errors
  - typical error forms include: symmetric(+/- a), asymmetric(+a:-b), interval (a:b), matrix, elliptical
  - can become quite complex: probability distributions, error maps, etc.
  - quality indicators:
    - global status, typically numeric
    - bit array, where each bit is associated with a particular quality state
  - associated errors may be separable or correlated among multiple data axes
- data axes may be virtual, defined as a mapping from other data axes (same description as above)

- Physical Data (Observables)
  - focus on the following domains which are frequently included in astronomical data cubes: Spatial, Spectral, Temporal, Polarization
  - Spatial
    - Cartesian space: chip, detector, sky
    - Spherical space: Equatorial, Ecliptic, Galactic, LongLat
  - Time
    - 1-Dimensional: JD, MJD, ISOTime, TimeOffset
  - Polarization
    - Discrete space: Polarization states (Stokes, Linear, Circular, Vector)
  - Spectral
    - 1-Dimensional: energy, frequency, wavelength

2.1.2 Transform workflow

An implementation project focused on the Transform model. The purpose of which is to exercise the Transform model through a workflow consisting of:

- serialization in YAML of complete WCS metadata, including source/target frames and the various Transform operation sequences between them.
- the generation and passing thereof between two Transform library implementations (AST, gWCS)

2.2 Requirements

Examination and implementation of the above cases leads to a set of requirements distributed through the various STC component models. Here we itemize those relevant to the coordinates model specifically. We note that some elements of this model are included based on the knowledge and experience incorporated into previous STC data model and not from direct requirements from the given use cases.

In Appendix A, we provide a mapping of the data model elements to the various requirements they serve.

2.2.1 General

Requirements pertaining to the overall criteria that the model must satisfy.

[vodml.001]: The model shall be vo-dml compliant

[vodml.002]: shall re-use, or refer to, dependent models for objects and concepts already defined in other models

[vodml.003]: shall produce a validated vo-dml XML description

[vodml.004]: shall produce documentation in vo-dml HTML format

[vodml.005]: shall produce documentation in standard PDF format

2.2.2 Application/Usage

Requirements pertaining to the user experience. Note, as a data model, users will not typically interact directly with the model,

[user.001]: Users should be able to identify and use basic content with minimal specialized information. In other words, a generic utility should be able to find and use core elements without knowing a lot about the various extensions and uses of those elements.

[user.002]: When applicable, the model should support usability by simplifying common scenarios. i.e. common things simple, complex things possible

2.2.3 Content

Requirements pertaining to the elements to be defined by the model.

- Domains

  [dom.001]: Shall accommodate the description of data in any observable domain

  [dom.002]: Shall provide enhanced/specialized description for data pertaining to

    [dom.002.1]: Pixel domain: binned, integerized, n-dimensional domain

    [dom.002.2]: Spatial domain: continuous domain, typically in 2-3 dimensional cartesian or spherical spaces

    [dom.002.3]: Time domain: continuous 1D domain, typically provided in JD, MJD, ISO, or as an Offset from a zero point

    [dom.002.4]: Polarization domain: discrete 1D domain of polarization states.

- Coordinates

  - Coordinate Spaces:

    [coords.001]: Shall facilitate the description of the domain space

      [coords.001.1]: Coordinate space shall consist of 1 to N dimensional axes

      [coords.001.2]: Shall support the description of axes which are continuous, binned, and discrete in nature

      [coords.001.3]: Each dimensional axis shall define the domain range of that axis as appropriate for its nature

  - Coordinate frames:

[coords.002]: Shall facilitate the specification of the nature of the domain, providing additional metadata relevant to the interpretation of coordinates in that domain.

- Coordinates:

  [coords.003]: Shall identify a location within the coordinate domain space

  [coords.004]: Shall be associated with a corresponding coordinate frame providing metadata relevant to the interpretation of the coordinate

  [coords.005]: Shall be associated with a particular axis of the coordinate space to provide context for the coordinate and facilitate the application of mapping Transforms

  [coords.006]: Shall be complete quantities, including value and units as appropriate

  [coords.007]: Shall support the association of atomic coordinates into a multi-dimensional compound grouping

- Coordinate systems:

  [coords.008]: Shall provide for encapsulating the description of the entire domain space

  [coords.009]: for Pixel domain, this must include the full coordinate space description

  [coords.010]: for Physical domains, this must include the Frame specifications, as it is this metadata that is more relevant to users. The coordinate space is typically well defined or implied by the coordinate itself.

- Transforms

[trans.001]: Shall facilitate the relation of two coordinate systems through a mathematical formula (Transforms)

[trans.001.1]: Shall facilitate the transport of same independent of any actual data.

2.3 Role within the VO Architecture

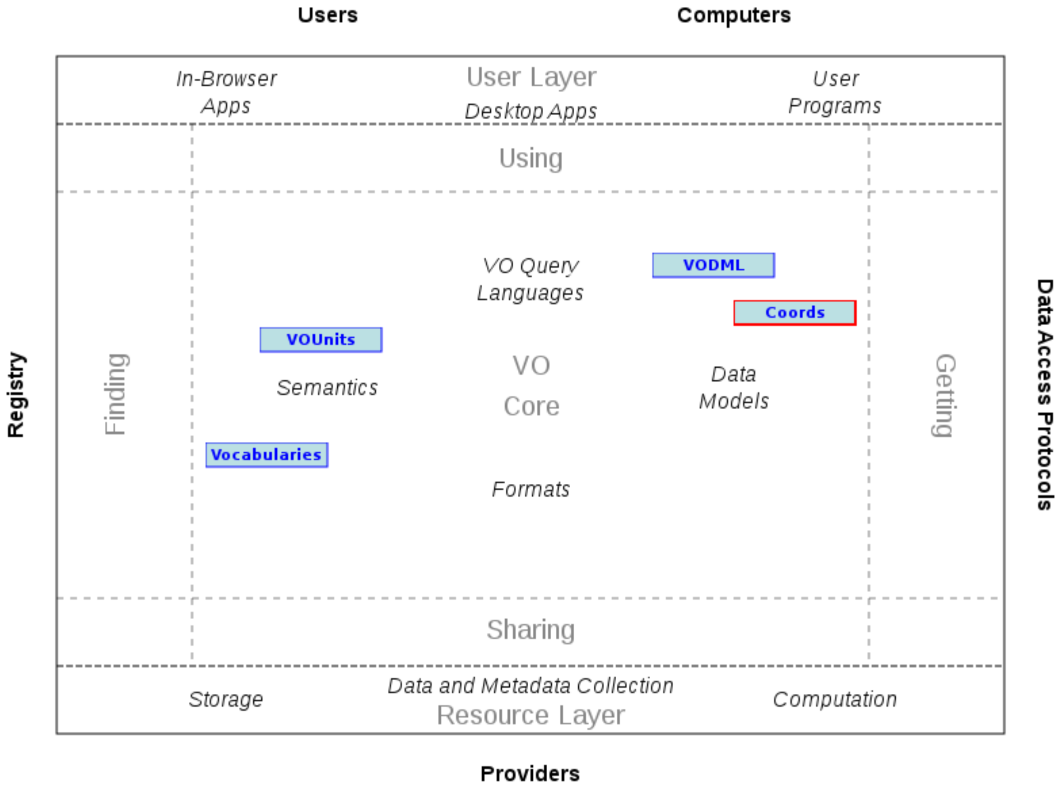


Figure 1: Architecture diagram for this document

Fig. 1 shows the role this document plays within the IVOA architecture (Arviset and Gaudet et al., 2010).

3 Model: coords

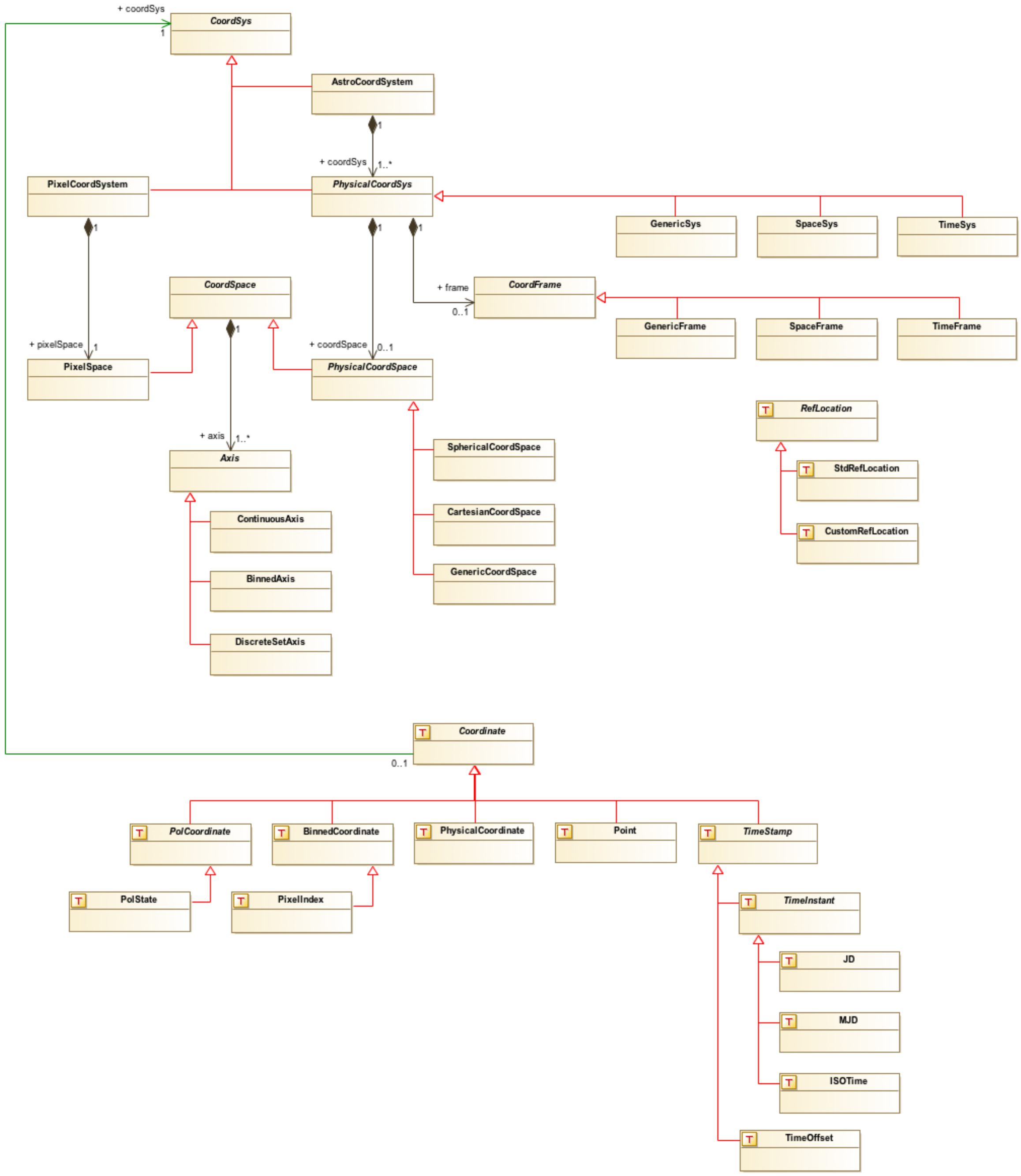


Figure 2: Model Overview

This model defines objects which describe the coordinate space, coordinates within that space, and frames, which provide additional metadata regarding the origin, orientation, etc, of the coordinate space. The model also defines a coordinate system, bundling frames into associated groups.

4 Coordinates

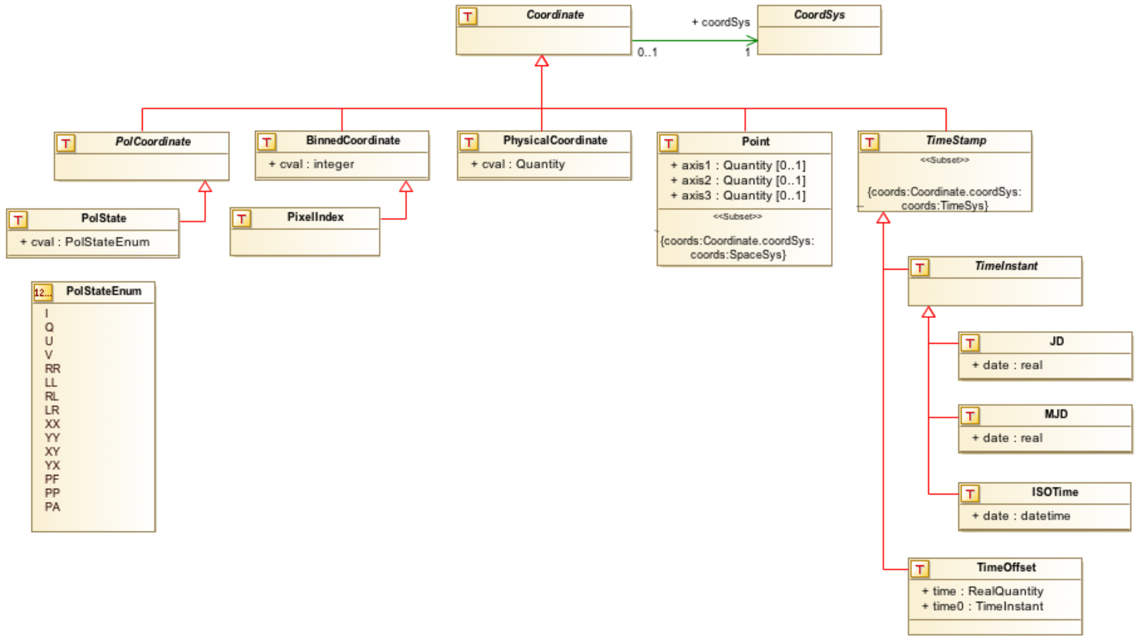


Figure 3: Coordinate elements

This section provides support for the most commonly used coordinate types. The design allows for the specification of custom coordinate spaces, but leverages the fact that most data will reside in well defined standard spaces. **It is expected that these coordinates will be used in the vast majority of cases.**

4.1 Coordinate (Abstract)

Abstract base class for the Coordinate data types which represent an absolute location within a coordinate space. Coordinates MUST refer to a coordinate system, providing additional metadata relevant to interpreting the coordinate value, and its representation.

4.1.1 Coordinate.coordSys

vodml-id: Coordinate.coordSys
type: coords:CoordSys
multiplicity: 1
Provided additional metadata relevant to interpreting the coordinate value; for example, the spatial reference position, or time scale, axis descriptions.

4.2 BinnedCoordinate

Coordinate value type specifically intended for binned data (e.g.: pixel indexes).

4.2.1 BinnedCoordinate.cval

vodml-id: BinnedCoordinate.cval
type: ivoa:integer
multiplicity: 1
The binned coordinate value, expressed as an integer. e.g.: bin number, pixel index.

4.3 PhysicalCoordinate

The most common type of coordinate value. This type is appropriate for any data whose values can be described by an ivoa:Quantity (numeric, with unit).

4.3.1 PhysicalCoordinate.cval

vodml-id: PhysicalCoordinate.cval
type: ivoa:Quantity
multiplicity: 1
This coordinate MUST contain a value expressed as an ivoa:Quantity.

4.4 Point

Multi-dimensional spatial coordinate. The Point MUST refer to a spatial coordinate system (SpaceSys). The coordinate values map, in order, to the axes described by the associated CoordSpace. Values for unused/undefined dimensions need not be provided.
subset
role: coords:Coordinate.coordSys
type: coords:SpaceSys

4.4.1 Point.axis1

vodml-id: Point.axis1
type: ivoa:Quantity
multiplicity: 0..1
Coordinate value along the first axis of the associated coordinate space, expressed as an ivoa:Quantity.

4.4.2 Point.axis2

vodml-id: Point.axis2
type: ivoa:Quantity
multiplicity: 0..1
Coordinate value along the second axis of the associated coordinate space, expressed as an ivoa:Quantity.

4.4.3 Point.axis3

vodml-id: Point.axis3
type: ivoa:Quantity
multiplicity: 0..1

Coordinate value along the third axis of the associated coordinate space, expressed as an ivoa:Quantity.

4.5 TimeStamp (Abstract)

This is the abstract basis for a set of simple time domain coordinates which are expected to accommodate the vast majority of use cases. All TimeStamps, by definition, exist in a standard 1-D coordinate space, with domainMin|Max of +/-Infinity. All TimeStamps MUST refer to an appropriate TimeSys.

A Brief Primer on Time Metadata; for reference and more information, see: FITS WCS Paper IV (Rots and Bunclark et al., 2015).

1. Required:
   * Record time stamps in JD, MJD, ISO-8601, or elapsed time. If in elapsed time, a zero point MUST be given in a time stamp which is not itself an elapsed time.
   * Provide the time scale used (e.g. TT, TDB, TAI, GPS, ET, UTC, TCG, TCB).
   * Provide the reference position (place where the time is measured).

2. Note the following:
   * JD and MJD do not imply a time scale; it needs to be provided separately.
   * JD and MJD are dimensionless, though a unit of 'day' is implied.
   * It is a bad idea to mix UTC with JD or MJD, since not all UTC days are the same length. Instead, use the restricted form of ISO-8601: [[+|-]c]ccyy-mm-dd[Thh[:mm[:ss[.ss...]]]], with no time zone characters.
   * TDB runs on average synchronously with TT, but corrects for the relativistic effects caused by deviations in the orbit of the Earth from perfect circularity and constant gravitational potential.

3. Recommendations:
   * Avoid UTC. It is trivial to convert the times provided by, e.g., space agencies, to TT immediately when you get them, and it will save headaches later on.
   * Use TT: it is the official IAU time scale, continuous with ET and the one which solar system ephemerides are based upon.
   * TAI and GPS are acceptable alternatives, with constant offsets from TT.
   * Use the same reference position for time and space and make sure it is commensurate with your time scale. For instance, when you convert to the barycenter, also convert to TDB.
   * Be aware that the barycenter is not the heliocenter
   * Be specific in labeling the time axis; e.g.: JD(TT;GEOCENTER) or MJD(TDB; BARYCENTER).
   * Use proleptic Gregorian dates for ISO-8601.

4. Never use:
   * TJD, HJD, BJD, etc. These are not officially recognized and suggest certain metadata values, but leave considerable ambiguity as to what those metadata values actually are. Instead, specify your metadata explicitly. It avoids confusion later on and is not much more work.

5. What if you deal with incomplete data?
   * If you do not know the time scale and/or reference position, you can provide them as

UNKNOWN and set the systematic error/uncertainty to, say, 1000 s. 100 s will do if only the time scale is unknown.

6. What else is there to know?
   * Quite a lot, especially the so-called coordinate time scales (TCG and TCB). Because TDB runs, on average, synchronously with TT, but in a very different potential well, which requires different values for fundamental physical constants in the barycenter. That is awkward and the coordinate time scales fix that by running at different rates. More in the above cited A&A paper.

subset
  role: coords:Coordinate.coordSys
  type: coords:TimeSys

4.6 TimeInstant (Abstract)

TimeStamps which specify a specific instant in time. We define three subtypes (ISOTime, JD, MJD), which allow users to explicitly identify the representation and interpretation of the TimeInstant.

4.7 ISOTime

Extension of TimeInstant for time expressed as a structured datetime string. The string representation of a datetime value should follow the FITS convention for representing dates (Hanish and Farris et al, 2001). The FITS standard is effectively ISO8601 format without the 'Z' tag to indicate UTC: YYYY-MM-DD['T'hh:mm:ss[.SSS]]. The TimeScale is provided in the associated TimeFrame.

4.7.1 ISOTime.date

vodml-id: ISOTime.date
type: ivoa:datetime
multiplicity: 1
The ISOTime coordinate value.

4.8 JD

Extension of TimeInstant for time expressed in Julian days. Note that JD does not properly specify a time stamp unless it is related to a time scale and reference position. Precision can easily become an issue with JD, as the numbers tend to be large.

4.8.1 JD.date

vodml-id: JD.date
type: ivoa:real
multiplicity: 1
The JD coordinate value. JD dates are dimensionless, with implied units in days.

4.9 MJD

Extension of TimeInstant for time expressed in Modified Julian Days. T(MJD) = T(JD) - 2400000.5.

4.9.1 MJD.date

vodml-id: MJD.date
type: ivoa:real
multiplicity: 1
The MJD coordinate value. MJD dates are dimensionless, with implied units in days.

4.10 TimeOffset

Time is given as an offset from a specific point in time (time0).

4.10.1 TimeOffset.time

vodml-id: TimeOffset.time
type: ivoa:RealQuantity
multiplicity: 1
The TimeOffset coordinate value.

4.10.2 TimeOffset.time0

vodml-id: TimeOffset.time0
type: coords:TimeInstant
multiplicity: 1
The reference time from which the offset is calculated. This MUST be given as a TimeInstant (e.g.: JD, MJD, ISOTime).

4.11 PixelIndex

Specialized BinnedCoordinate for the pixel domain for a 1-dimensional pixel index. PixelIndex MUST refer to a PixelCoordSystem.

4.12 PolCoordinate (Abstract)

Abstract head of the polarization coordinate types. Current use cases only require support for discrete polarization states, however, we include this head class to facilitate extension for other types (eg: polarization fraction and angle).

4.13 PolState

Coordinate type for discrete polarization states.

4.13.1 PolState.cval

vodml-id: PolState.cval
type: coords:PolStateEnum
multiplicity: 1
The coordinate value MUST be from the PolStateEnum enumerated set.

4.14 PolStateEnum

Polarization states: Stokes, Circular, Linear and Vector states
Enumeration Literals

- **I** : **vodml-id:** PolStateEnum.I
- **Q** : **vodml-id:** PolStateEnum.Q
- **U** : **vodml-id:** PolStateEnum.U
- **V** : **vodml-id:** PolStateEnum.V
- **RR** : **vodml-id:** PolStateEnum.RR
- **LL** : **vodml-id:** PolStateEnum.LL
- **RL** : **vodml-id:** PolStateEnum.RL
- **LR** : **vodml-id:** PolStateEnum.LR
- **XX** : **vodml-id:** PolStateEnum.XX
- **YY** : **vodml-id:** PolStateEnum.YY
- **XY** : **vodml-id:** PolStateEnum.XY
- **YX** : **vodml-id:** PolStateEnum.YX
- **PF** : **vodml-id:** PolStateEnum.PF
- **PP** : **vodml-id:** PolStateEnum.PP
- **PA** : **vodml-id:** PolStateEnum.PA

5 Coordinate Frames

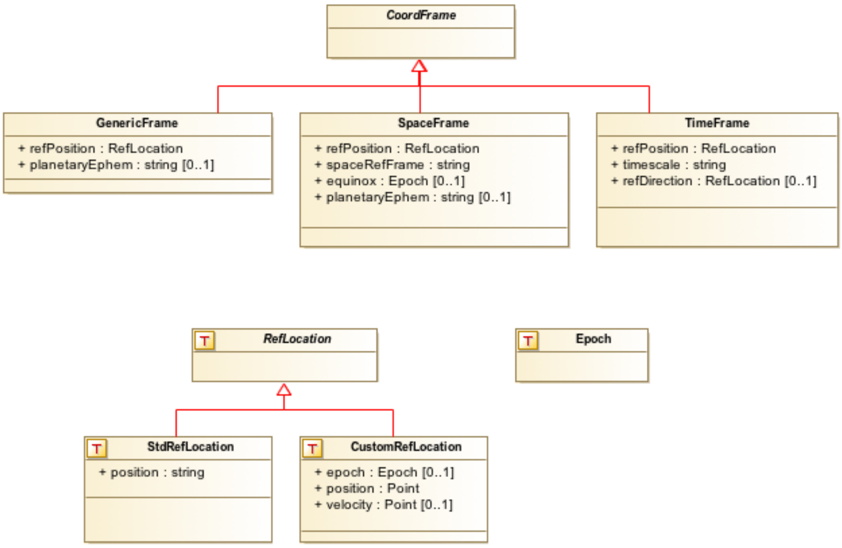


Figure 4: Coordinate Frame elements

5.1 CoordFrame (Abstract)

This is the abstract, empty, base class for all coordinate frames. Coordinate frames provide metadata associated with the coordinate domain space. Typically, this will be related to the origin and orientation of the axes, but might include any metadata which pertains to the definition of the domain.

5.2 GenericFrame

The generic coordinate frame is for cases where a domain-specific frame (e.g.: Space, Time), is not required, but the relevant reference metadata is still needed (e.g.: for Redshift or Spectral data)

5.2.1 GenericFrame.refPosition

vodml-id: GenericFrame.refPosition
type: coords:RefLocation
multiplicity: 1
Spatial location in phase space (position and velocity) at which the observed value is considered to have been taken. This will typically be given by a standard reference position, but we allow for custom locations as well.

5.2.2 GenericFrame.planetaryEphem

vodml-id: GenericFrame.planetaryEphem
type: ivoa:string
multiplicity: 0..1

A planetary ephemeris MAY be provided, and SHOULD be provided whenever appropriate, to indicate which solar system ephemeris was used. If needed, but not provided, it is assumed to be "DE405"

5.3 SpaceFrame

A SpaceFrame is specified by its reference frame (orientation), and a reference position (origin). Currently only standard reference frames are allowed. An equinox MUST be provided for pre-ICRS reference frames. A planetary ephemeris MAY be provided if relevant. If needed, but not provided, it is assumed to be "DE405".

5.3.1 SpaceFrame.refPosition

vodml-id: SpaceFrame.refPosition
type: coords:RefLocation
multiplicity: 1
The spatial location at which the coordinates are considered to have been determined. This model supports locations provided as either a standard reference position (e.g. GEOCENTER), or a coordinate specifying a custom location (e.g. long, lat, height).

5.3.2 SpaceFrame.spaceRefFrame

vodml-id: SpaceFrame.spaceRefFrame
type: ivoa:string
vocabulary: http://www.ivoa.net/rdf/refframe
multiplicity: 1
The spatial reference frame. Values MUST be selected from the controlled vocabulary at the given URL.

5.3.3 SpaceFrame.equinox

vodml-id: SpaceFrame.equinox
type: coords:Epoch
multiplicity: 0..1
Reference date for the frame, required for pre-ICRS reference frames.

5.3.4 SpaceFrame.planetaryEphem

vodml-id: SpaceFrame.planetaryEphem
type: ivoa:string
multiplicity: 0..1
Ephemeris file for solar system objects SHOULD be specified whenever relevant.

5.4 TimeFrame

A TimeFrame SHALL include a time scale and reference position. It MAY also include a reference direction.

5.4.1 TimeFrame.refPosition

vodml-id: TimeFrame.refPosition
type: coords:RefLocation
multiplicity: 1
The spatial location at which the coordinate is considered to have been taken. This model supports locations provided as either a standard reference position (e.g. GEOCENTER), or a coordinate specifying a custom location (e.g. long, lat, height).

5.4.2 TimeFrame.timescale

vodml-id: TimeFrame.timescale
type: ivoa:string
vocabulary: http://www.ivoa.net/rdf/timescale
multiplicity: 1
The time scale sets the reference frame. The value MUST be selected from the controlled vocabulary at the given URL.

5.4.3 TimeFrame.refDirection

vodml-id: TimeFrame.refDirection
type: coords:RefLocation
multiplicity: 0..1
The reference direction is needed if the time stamps are transformed to a time frame with a different reference position. In those situations, the solar system ephemeris also comes into play. See: FITS WCS Paper IV for details, but in short: The reference direction, presumably the direction to the thing being observed, is used in conjunction with the reference position and planetary ephemeris to determine the correction applied for the path length change. To be fully useful, one also needs to know the location at which the observation was made (i.e. the observatory location), which is not considered to be Frame metadata.

5.5 Epoch

We define epoch as a primitive data type with the expected form "<type><year>" where type = "J" or "B" for Julian or Besselian respectively, and year is expressed as a decimal year. e.g.: "B1950", "J2000.0"

5.6 RefLocation (Abstract)

RefLocation defines the origin of the spatial coordinate space. This location is represented either by a standard reference position (for which the absolute location in phase space is known by definition), or a specified point in another Spatial frame. This object is used as the origin of the SpaceFrame here, but also to specify the Spatial Reference Position (refPosition) associated with other domain Frames. For example, in the Time domain, the Spatial Reference Position indicates that the 'time' values are the time that the 'event' occured at that location, which might be different from the detector location.

5.7 StdRefLocation

An absolute a-priori known location in phase space (position and velocity). Values are selected from the StdRefPosition vocabulary. Considering that the GEOCENTER is really the only place for which we know the absolute location at all times, all other locations require the specification of a planetary ephemeris. LSR[KD] are reserved for spectral and reshift frames. TOPOCENTER (location of the observer) is special in that it assumes that the observing location is available through other means (e.g. a geographic location or an orbit ephemeris). RELOCATABLE is available for simulations. UNKNOWN should only be used if absolutely necessary.

5.7.1 StdRefLocation.position

vodml-id: StdRefLocation.position
type: ivoa:string
vocabulary: http://www.ivoa.net/rdf/refposition
multiplicity: 1
Standard reference location. Values MUST be selected from the controlled vocabulary at the given URL.

5.8 CustomRefLocation

A custom reference location in phase space (position and velocity). Position and velocity are given as coordinates with an associated SpaceFrame. An epoch MAY be provided to further refine the location.

5.8.1 CustomRefLocation.epoch

vodml-id: CustomRefLocation.epoch
type: coords:Epoch
multiplicity: 0..1
Epoch for the reference location.

5.8.2 CustomRefLocation.position

vodml-id: CustomRefLocation.position
type: coords:Point
multiplicity: 1
The spatial coordinates of the reference location.

5.8.3 CustomRefLocation.velocity

vodml-id: CustomRefLocation.velocity
type: coords:Point
multiplicity: 0..1
The velocity of the reference location.

6 Coordinate Systems

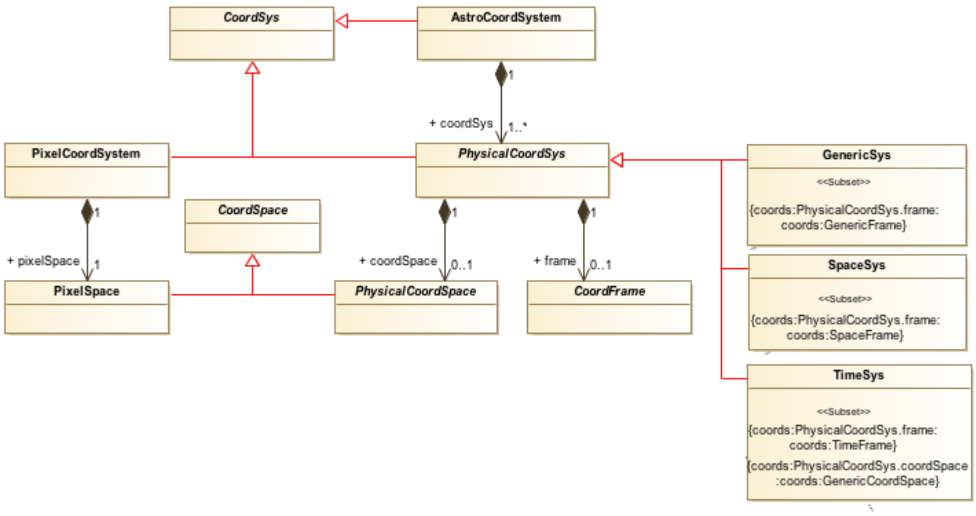


Figure 5: Coordinate Systems

In the astronomical community, the term 'Coordinate System' is used to mean both "the space in which a coordinate resides", and "a unique domain space", folding in specific reference frame metadata. In this model, we adopt the latter definition. A Coordinate System provides a complete description of the domain space, including both the coordinate space description and associated Frame metadata. To simplify the usage of these objects for the most common cases, we provide a set of standard CoordSpace instances which serve as defaults when not explicitely included in serializations.

6.1 CoordSys (Abstract)

Abstract head of the coordinate system object tree.

6.2 AstroCoordSystem

The AstroCoordSystem object holds a collection of component coordinate system descriptions across all represented physical domains.

6.2.1 AstroCoordSystem.coordSys

vodml-id: AstroCoordSystem.coordSys
type: coords:PhysicalCoordSys
multiplicity: 1..*
Coordinate system description for each physical domain (Space, Time, etc).

6.3 PhysicalCoordSys (Abstract)

Coordinate system description for any physical domain, such as Time, Space, Redshift, Temperature, Flux, etc.

6.3.1 PhysicalCoordSys.coordSpace

vodml-id: PhysicalCoordSys.coordSpace
type: coords:PhysicalCoordSpace
multiplicity: 0..1
Description of the coordinate space occupied by the property.

6.3.2 PhysicalCoordSys.frame

vodml-id: PhysicalCoordSys.frame
type: coords:CoordFrame
multiplicity: 0..1
Associated Frame metadata.

6.4 PixelCoordSystem

The PixelCoordSystem provides a complete description of the pixel coordinate space. It SHALL contain one PixelSpace instance describing each pixel axis.

6.4.1 PixelCoordSystem.pixelSpace

vodml-id: PixelCoordSystem.pixelSpace
type: coords:PixelSpace
multiplicity: 1
The pixel space completely defines the pixel coordinate axes. Each axis MUST be defined as a BinnedAxis type.

6.5 GenericSys

Specialized coordinate system for generic, one-dimensional domains not covered by other, more concrete objects. If a CoordSpace is not provided, it is assumed to be represented by a Standard 1-Dimensional Coordinate Space as described in Appendix B.
subset
 role: coords:PhysicalCoordSys.frame
 type: coords:GenericFrame

6.6 SpaceSys

Specialized coordinate system for the Spatial domain. This object SHOULD include an appropriate SpaceFrame. In Appendix B, we define two standard spatial coordinate space instances (Spherical and Cartesian), which may be referenced in serializations. If a CoordSpace is not provided, it is assumed to be represented by a Standard Spherical Coordinate Space.
subset
 role: coords:PhysicalCoordSys.frame
 type: coords:SpaceFrame

6.7 TimeSys

Specialized coordinate system for the Temporal domain. This object SHOULD include an appropriate TimeFrame. If a CoordSpace is not provided, it is assumed to be represented by a Standard 1-Dimensional Coordinate Space as described in Appendix B.

subset
  role: coords:PhysicalCoordSys.frame
  type: coords:TimeFrame

subset
  role: coords:PhysicalCoordSys.coordSpace
  type: coords:GenericCoordSpace

7 Coordinate Space

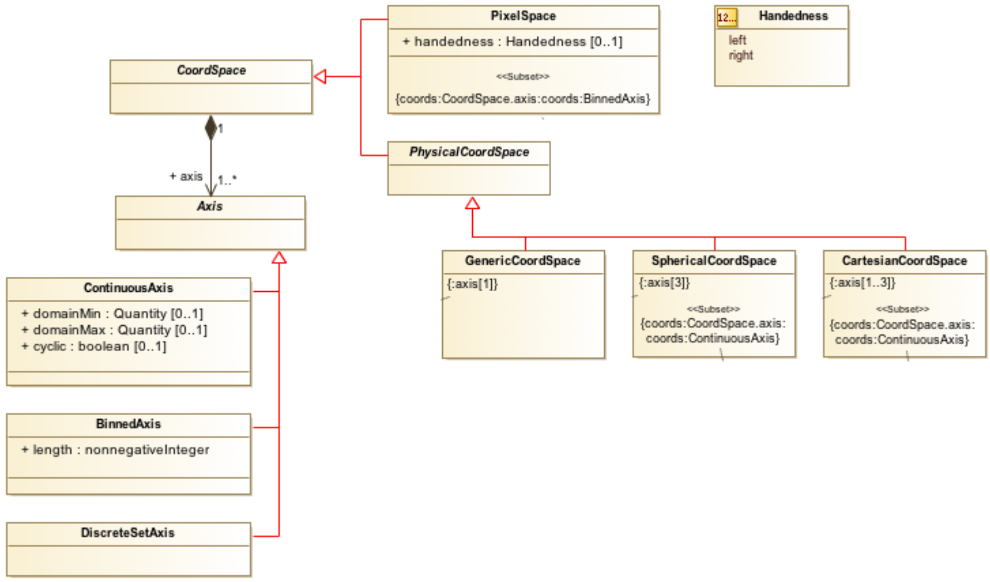


Figure 6: Coordinate Spaces

7.1 CoordSpace (Abstract)

This object defines a domain space. i.e.: it describes the set of possible coordinate values.

7.1.1 CoordSpace.axis

vodml-id: CoordSpace.axis
type: coords:Axis
multiplicity: 1..*
Describes an axis of the coordinate space.

7.2 Axis (Abstract)

The abstract parent class for all coordinate axis types. We provide concrete classes for the most common types of data, Continuous, Binned, and Discrete, but allow extension for other types as needed.

7.2.1 Axis.name

vodml-id: Axis.name
type: ivoa:string
multiplicity: 0..1
Freeform string, provides the name or label for the axis.

7.3 ContinuousAxis

Axis description for continuous data. This object describes the domain for a particular axis of the domain space. It allows for the specification of the legal domain range (min,max), and a flag indicating if the axis is cyclic.

7.3.1 ContinuousAxis.domainMin

vodml-id: ContinuousAxis.domainMin
type: ivoa:Quantity
multiplicity: 0..1
Minimum extent of the axis domain space. If not provided, the domain space is considered to have no lower bound (-INFINITY).

7.3.2 ContinuousAxis.domainMax

vodml-id: ContinuousAxis.domainMax
type: ivoa:Quantity
multiplicity: 0..1
Maximum extent of the axis domain space. If not provided, the domain space is considered to have no upper bound (+INFINITY).

7.3.3 ContinuousAxis.cyclic

vodml-id: ContinuousAxis.cyclic
type: ivoa:boolean
multiplicity: 0..1
Flag indicating if the axis is cyclic in nature. If not provided, it is assumed to be FALSE.

7.4 BinnedAxis

Axis description for binned data, where values along the axis correspond to a bin number.

7.4.1 BinnedAxis.length

vodml-id: BinnedAxis.length
type: ivoa:nonnegativeInteger
multiplicity: 1
The length, or number of bins, along the axis.

7.5 DiscreteSetAxis

Axis type specifically intended for enumerated coordinates. Since the content and nature of this axis type is heavily dependent on the use case, we define no additional metadata here. Extensions of this type may include additional metadata relevant to the particular use cases. For example, an extension could include the allowed set of values.

7.6 PhysicalCoordSpace (Abstract)

Abstract head of coordinate spaces related to physical properties.

7.7 SphericalCoordSpace

Spatial domain, three-dimensional spherical coordinate space. The particulars of the axis descriptions depend on the flavor of space being instantiated. In Appendix B., we provide a Standard Spherical Coordinate Space instance which applies to many Astronomical use cases. It provides the default space for SpaceSys instances, and may be referenced in serializations.

subset
  role: coords:CoordSpace.axis
  type: coords:ContinuousAxis

constraint
  detail: SphericalCoordSpace.axis[3]

7.8 CartesianCoordSpace

Spatial domain, three-dimensional cartesian coordinate space. The particulars of the axis descriptions depend on the physical constraints of the instance. In Appendix B, we provide the description of a Standard Cartesian Coordinate Space instance which applies to many Astronomical cases, and may be referenced in serializations.

subset
  role: coords:CoordSpace.axis
  type: coords:ContinuousAxis

constraint
  detail: CartesianCoordSpace.axis[1..3]

7.9 GenericCoordSpace

Generic, one-dimensional coordinate space suitable for use with most non-spatial properties. In Appendix B, we provide the description of a Standard 1D Coordinate Space instance which may be referenced in serializations.

constraint
  detail: GenericCoordSpace.axis[1]

7.10 PixelSpace

The Pixel coordinate space is defined as a 'virtual' binned space, with no physical meaning. The axes in this space provide integer indices into that space. A PixelSpace SHALL include one or more BinnedAxis objects describing the pixel coordinate space. A handedness value MAY be provided to specify the relative orientation of the axes.

subset
  role: coords:CoordSpace.axis
  type: coords:BinnedAxis

7.10.1 PixelSpace.handedness

vodml-id: PixelSpace.handedness
type: coords:Handedness
multiplicity: 0..1
Specifies the handedness of the coordinate space.

7.11 Handedness

The handedness of a coordinate space. For most cases, this will be a fixed value in the specification of the coordinate space. We provide this element to allow this flexibility when needed. In this document, it is used in the Pixel domain.
Enumeration Literals

left : **vodml-id:** Handedness.left
description: positive x and y axes point right and up, the positive z axis points inward

right : **vodml-id:** Handedness.right
description: positive x and y axes point right and up, the positive z axis points outward

A Requirements Mapping

The table below provides a mapping of the various elements of this model to requirements served by that object.

vodml-id	pertains to
AstroCoordSystem	coords.008, coords.010
Axis	coords.001.1, coords.001.2
BinnedAxis	dom.002.1, coords.001.2
BinnedAxis.length	coords.001.3
BinnedCoordinate	coords.006
CartesianCoordSpace	user.002
ContinuousAxis	dom.002.2, dom.002.3, coords.001.2
ContinuousAxis.cyclic	coords.001.3
ContinuousAxis.domainMax	coords.001.3
ContinuousAxis.domainMin	coords.001.3
CoordFrame	coords.002, coords.004
Coordinate	user.001, coords.003, coords.007
Coordinate.coordSys	user.001, coords.004
CoordSpace	coords.001
CoordSys	coords.008
CustomRefLocation	dom.002.2, coords.002
DiscreteSetAxis	dom.002.4, coords.001.2
Epoch	dom.002.2, coords.001.2
GenericCoordSpace	user.002
GenericCoordSys	user.002
GenericFrame	coords.002
Handedness	coords.001
ISOTime	user.002, coords.006
JD	user.002, coords.006
MJD	user.002, coords.006
PhysicalCoordinate	user.001, user.002, dom.001, coords.003, coords.005, coords.006
PhysicalCoordSpace	coords.001
PhysicalCoordSys	dom.001, coords.001, coords.002
PixelCoordSystem	dom.002.1, coords.008
PixelCoordSystem.pixelSpace	dom.002.1, coords.008, coords.009
PixelIndex	dom.002.1, coords.003, coords.005
PixelSpace	dom.002.1, coords.001.1
Point	dom.002.2, user.001, user.002, coords.003, coords.005, coords.006, coords.007
PolCoordinate	dom.002.4, coords.005
PolState	dom.002.4, coords.003
RefLocation	dom.002.2, coords.002
SpaceFrame	dom.002.2, coords.002
SpaceSys	user.002
SphericalCoordSpace	user.002
StdRefLocation	dom.002.2, coords.002
TimeFrame	dom.002.3, coords.002
TimeInstant	dom.002.3
TimeOffset	dom.002.3, user.002, coords.006
TimeStamp	dom.002.3, user.002, coords.003, coords.005, coords.007
TimeSys	user.002

B Standard Coordinate Spaces

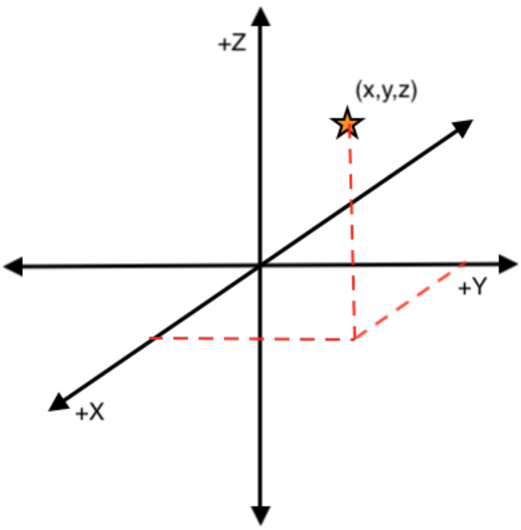
We provide standard instances of commonly used coordinate spaces as instances of elements from this model. Each element has a formal identifier (ID) which can be used to reference the instance given here.

B.1 Standard Cartesian Coordinate Space

id: _CARTESIAN_CoordSpace
Coordinate space comprised of 3 orthogonal axes.
Axis1
id: _CARTESIAN_X_Axis
domainMin: -Infinity
domainMax: +Infinity
cyclic: False

Axis2
id: _CARTESIAN_Y_Axis
domainMin: -Infinity
domainMax: +Infinity
cyclic: False

Axis3
id: _CARTESIAN_Z_Axis
domainMin: -Infinity
domainMax: +Infinity
cyclic: False

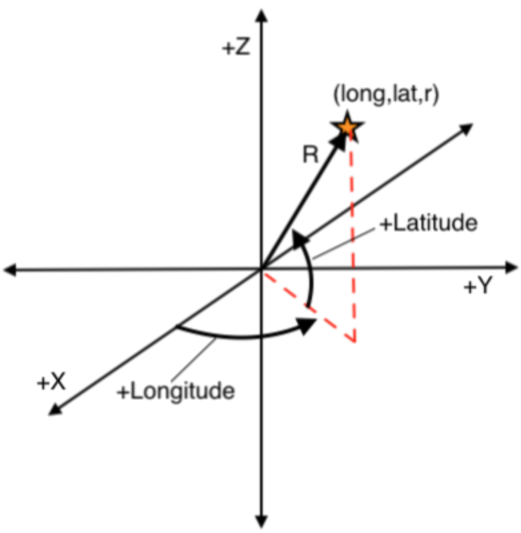


B.2 Standard Spherical Coordinate Space

id: _SPHERICAL_CoordSpace
A 3 dimensional spherical coordinate space, comprised of 2 angular axes and 1 radial axis.
Axis1
id: _SPHERICAL_Lat_Axis
domainMin: -90.0 deg
domainMax: +90.0 deg
cyclic: False

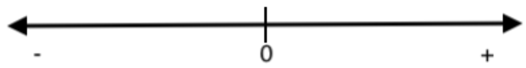
Axis2
id: _Spherical_Long_Axis
domainMin: 0.0 deg
domainMax: 360.0 deg
cyclic: True

Axis3
id: _Spherical_R_Axis
domainMin: 0.0
domainMax: +Infinity
cyclic: False



B.3 Standard 1D Coordinate Space

id: _STANDARD_1D_CoordSpace
Coordinate space comprised of 1 axis.
Axis1
id: Standard_1D_Axis
domainMin: -Infinity
domainMax: +Infinity
cyclic: False



C Standard Vocabularies

C.1 Standard Reference Frame (StdRefFrame)

BaseURL: http://www.ivoa.net/rdf
Vocabulary: refframe

We include here the initial Standard Reference Frame Vocabulary. The formal list is stored and maintained as a controlled vocabulary external to this document at the URL listed above. The URI for each term is built as <BaseURL>/<Vocabulary>/<Term>, where Term is one of:

EQUATORIAL Frames

ICRS : International Celestial Reference System

FK4 : Fundamental Katalog, system 4; Besselian.
Requires Equinox; default B1950.0

FK5 : Fundamental Katalog, system 5; Julian.
Requires Equinox; default J2000.0

ECLIPTIC Frames

ECLIPTIC : Ecliptic coordinates

GALACTIC Frames

GALACTIC_I : Old Galactic coordinates

GALACTIC : "New" Galactic coordinates

SUPER_GALACTIC : Super-galactic coordinates
pole at GALACTIC (47.37, +6.32); origin at GALACTIC (137.37, 0)

OTHER Frames

AZ_EL : Local azimuth and elevation
Ground-based observations; Azimuth from North through East

BODY : Generic "BODY" coordinates

UNKNOWN : Unknown reference frame
Only to be used as a last resort or for simulations. The client is responsible for assigning a suitable default.

C.2 Standard Reference Position (StdRefPos)

BaseURL: http://www.ivoa.net/rdf
Vocabulary: refposition

We include here the initial Standard Reference Position Vocabulary. The formal list is stored and maintained as a controlled vocabulary external to this document at the URL listed above. The URI for each term is built as <BaseURL>/<Vocabulary>/<Term>, where Term is one of:

TOPOCENTER : "Local"; in most cases this will mean: The location of the telescope.

BARYCENTER : Center of the solar system barycenter

HELIOCENTER : Center of the sun.

GEOCENTER : Center of the Earth.

EMBARYCENTER : Earth-moon barycenter

UNKNOWN : Unknown reference position.
Only to be used as a last resort. The client is responsible for assigning a suitable default.

C.3 Standard Time Scale (TimeScale)

BaseURL: http://www.ivoa.net/rdf
Vocabulary: timescale

We include here the initial Standard Time Scale Vocabulary. The formal list is stored and maintained as a controlled vocabulary external to this document at the URL listed above. The URI for each term is built as <BaseURL>/<Vocabulary>/<Term>, where Term is one of:

TAI : International Atomic Time; 32.184 s behind TT.

TT : Terrestrial Time

UT : Earth rotation time;
We do not distinguish between UT0, UT1, and UT2.

UTC : Coordinated Universal Time; 32 s behind TAI in 2000-2005.
Includes leap seconds. Pre-1972 times will be assumed to be UT/GMT.

GPS : Global Positioning System time scale; 19 s behind TAI, 51.184 s behind TT.

TCG : Geocentric Coordinate Time; properly relativistic time, running a factor $7*10^{-10}$ faster than TT

TCB : Barycentric Coordinate Time; properly relativistic time, running a factor of $1.5*10^{-8}$ faster than TDB.

TDB : Barycentric Dynamical Time; synchronous with TT, except for variations in Earth ortial motion.
Requires specification of the solar system and planetary ephemeris used.

UNKNOWN : Unknown or unavailable.

D Changes from Previous Versions

D.1 Changes from WD-2019-03-20

- Section 1.2: added clarifying text on the distinction between Quantity, Coordinate, and Measurement in the IVOA models.
- Updated URLs for vocabularies
- Appendix B: changed 'Class' to 'ObjectType' to better align with the VO-DML description.
- Appendix C: brought initial vocabulary content in line with URL content.

D.2 Changes from PR-2019-08-30

- Migrate CoordSys element to include both CoordSpace and CoordFrame concepts.
- Coordinate element to reference CoordSys, rather than CoordFrame and CoordSpace.axis
- Removed specialized Coordinate types linked to standard spatial coordinate spaces, replace with Point
- Corrected multiplicity of SpaceFrame.planetaryEphem
- Corrected URLs for vocabularies ('http' not 'https')
- Corrected LaTex for TCG and TCB records to fix display

E Modeling Conventions

This model follows the VO-DML modeling practices, however, the UML representations may vary depending on the tool used. Below we describe the graphical representation of the modeling concepts and relations.

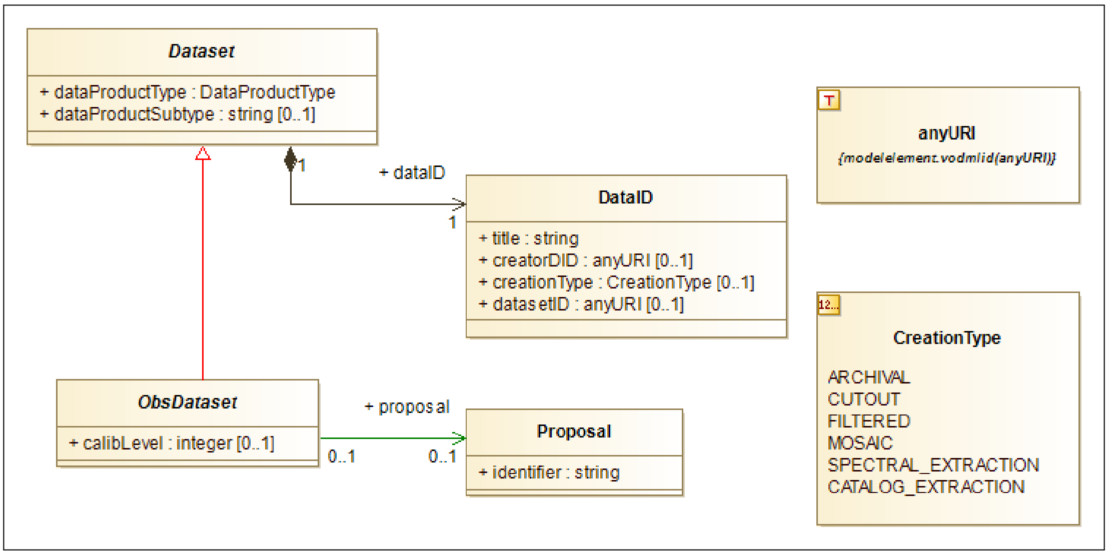


Figure 7: Notation example diagram

E.1 ObjectType

ObjectTypes are represented by a plain box. The type name is annotated in the top window, abstract types use italic typeface. Attributes, if any, are listed in the lower panel. Attributes may only be of primitive type (real, string, etc), a defined DataType, or an Enumeration type. Relationships to other objects are defined via the composition and reference relation arrows.

E.2 DataType

DataTypes are represented by a box shape similar to ObjectType, but annotated with a "T" symbol in the top left corner.

E.3 Enumerations

Enumerations are represented by a box shape similar to ObjectType, but annotated with a "1,2.." symbol in the top left corner. Enumeration Literals (possible values) are listed below the enumeration type name.

E.4 Generalization

Generalizations are represented by a red line, with open triangle at the end of the source, or more general, object.

E.5 Composition

The composition relation is indicated by a black line with a solid diamond attached to the containing object, and an arrow pointing to the object being contained. The composition relation is very tight, where the container is responsible for the creation and existence of the target. Any object may be in no more than one composition relation with any container. The attribute name for the composition relation is annotated at the destination of the relation (e.g. "+ dataID"). This is typically a lower-cased version of the destination type name, but this is not required.

E.6 Reference

The reference relation is indicated by a green line, with an arrow pointing to the object being referenced. The reference relation is much looser than composition, the container has no ownership of the target, but merely holds a pointer, or other indirect connection to it. The attribute name is annotated at the destination of the relation (e.g. "+ proposal"). This is typically a lower-cased version of the destination type name, but may be another name indicating the role that the element is playing in this context.

E.7 Multiplicity

All attributes and relations have a multiplicity associated with them. For attributes, the multiplicity is contained within brackets just after the attribute name. If no bracket is displayed, this is equivalent to '[1]'.

- 1 = one and only one value must be provided.
- 0..1 = zero or one value may be provided.
- * = zero or more values may be provided (open ended).

F Data Types

F.1 Base Data Types

Provides a set of standardized primitive data types as well as types for representing quantities (values with associated units). We provide a diagram of the model here, and refer the reader to Section 5 of the VO-DML modeling specification document (Lemson and Laurino et al., 2018) for more information.

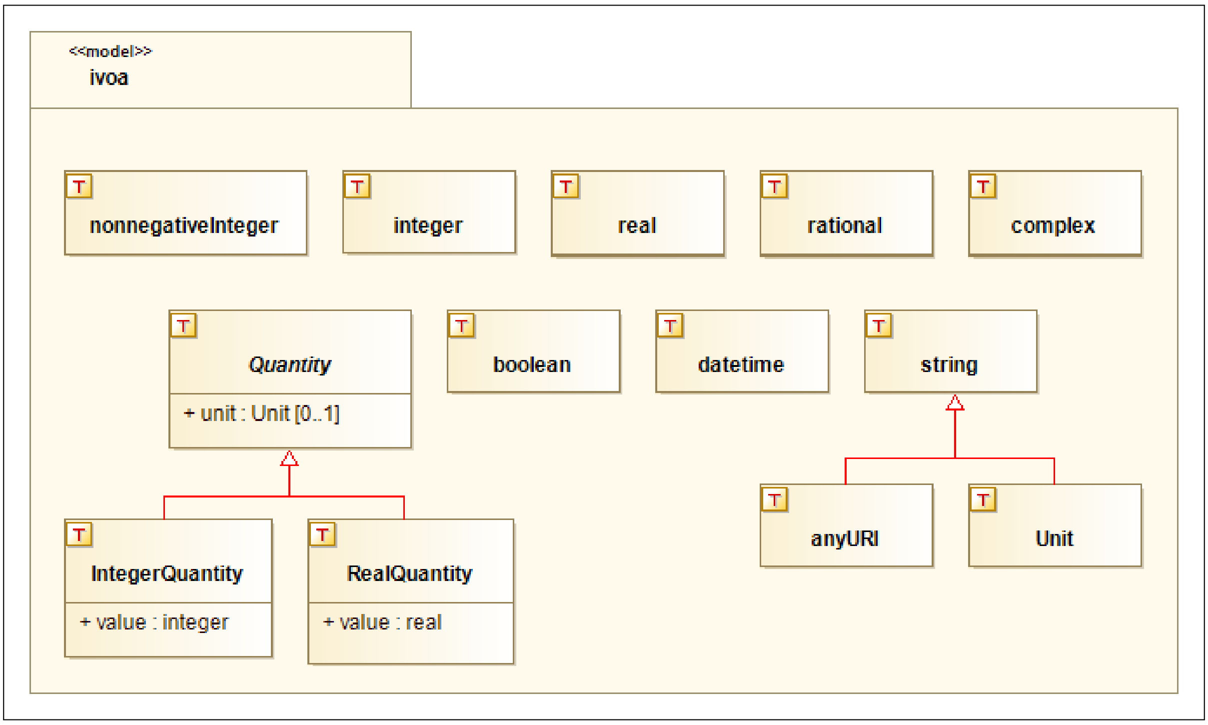


Figure 8: Base Data Types

F.1.1 Units

This model requires the use of the IVOA VOUnits Standard (Demleitner and Derriere et al., 2014) for representing units of physical quantities. This standard reconciles common practices and current standards for use within the IVOA community.

F.1.2 Dates

The 'datetime' datatype is for expressing date-time values. The string representation of a date-time value should follow the FITS convention for representing dates. The FITS standard is effectively ISO8601 format without the "Z" tag to indicate UTC (YYYY-MM-DDThh:mm:ss). Values are nominally expressed in UTC.

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