SDP System Data Model View

Contributors: K. Kirkham, P. Wortmann

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ABBREVIATIONS

CBF	Correlator Beamformer
CSP	Central Signal Processor
CDTS	Channelized Detected Time Series
DECJ	Declination (J2000)
DM	Dispersion Measure
DSM	Dynamic Spectrum Mode
FOV	Field Of View
GSM	Global Sky Model
ICD	Interface Control Document
ID	Identification
IVOA	International Virtual Observatory Alliance
LSM	Local Sky Model
LTS	Local Telescope State
MJD	Modified Julian Date
OCL	Optimised Candidate List
OCLD	Optimised Candidate List and Data
PSF	Point Spread Function
PSRFITS	Pulsar Flexible Image Transport System
PSS	Pulsar Search
PST	Pulsar Timing
PTD	Pulsar Timing Data
RAJ	Right Ascension (J2000)
RFI	Radio Frequency Interference
SB	Scheduling Block
SDP	Science Data Processor
SDM	Science Data Model
SKAPM	SKA Project Model
SPOCLD	Single Pulse Optimised Candidate List and Data
SRC	SKA Regional Centre
S/N	Signal to Noise
TBC	To be confirmed
TBD	To be determined
TM	Telescope Manager
TMC	Telescope Monitor & Control
TOA	Time of Arrival

1 Primary Representation

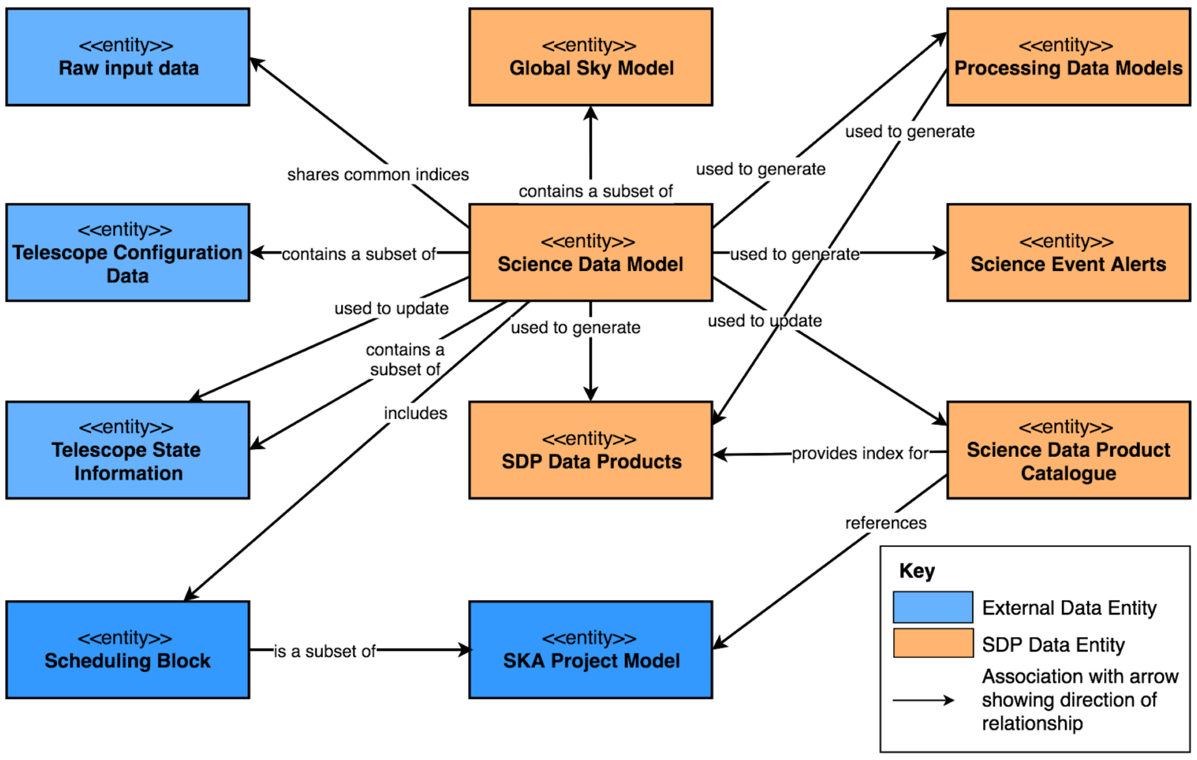

<<entity>> Raw input data
<<entity>> Global Sky Model
<<entity>> Processing Data Models
<<entity>> Telescope Configuration Data
<<entity>> Science Data Model
<<entity>> Science Event Alerts
<<entity>> Telescope State Information
<<entity>> SDP Data Products
<<entity>> Science Data Product Catalogue
<<entity>> Scheduling Block
<<entity>> SKA Project Model
shares common indices
contains a subset of
used to generate
used to generate
contains a subset of
used to generate
used to update
used to generate
used to update
contains a subset of
includes
provides index for
references
is a subset of
Key
External Data Entity
SDP Data Entity
Association with arrow showing direction of relationship

Figure 1: SDP Conceptual Data Model diagram showing relationships between entities. [1]

This document describes the various data models to be found in the Science Data Processor (SDP), the relationships between the SDP data models and relationships to external data models. This document should act as the central reference for SDP data models and other related documents (workflow, pipelines, etc.) should be consistent with it.

What we aim to show here is the decomposition of SDP data models, their relationships, and architectural considerations concerning these data models. Therefore each data model is described briefly and further related architectural views ('View Packets') will support each data model, and provide greater detail. This document does not describe data flows but rather logical data models. These are conceptual entities, and their relationship to data structures and data items (physical models and entities) is not detailed here.

During processing, different elements of the data models will be treated differently by the SDP. For example, gain tables are handled by queues, other elements may go into a DB, and there may be multiple representations of some elements. What is common is that the SDP will create data

[1] *The arrows and their associated words should be read in the following way. Create a sentence in which the subject is the data model in question, followed by the verb (in the direction of the arrow), with the object being the data model on the other end of the arrow, e.g. the Science Data Model is used to generate Processing Data Models.*

products which contain elements of these data models, and these data products will be stored and delivered to SRCs.

Note that this architectural view excludes data items used to configure and manage SDP internal components (e.g. configuration database), because they don't intersect with the data models described here.

2 Element Catalogue

2.1 Elements and Their Properties

Note that these are conceptual data models and therefore certain properties needed for implementation such as primary keys are not mentioned in this document.

2.1.1 Global Sky Model

This is a catalogue of sky components stored as a searchable database. It accommodates the following:

- Point sources with full Stokes parameters
- Time variability
- Resolved sources using compact basis set representations
- Complex spectral structures
- Information on planetary and solar radiation sources
- Images (i.e. pixelated images with world coordinate system, and units)

Multiple ways to represent the sky model position are supported and interpreted by an API. Note that the Global Sky Model is not complete without a module to interpret the data. The Global Sky Model must be extensible and flexible.

2.1.2 Science Data Model

The Science Data Model consists of the following high level data entities:

- Local Sky Model (LSM)
- Subset of the Telescope Configuration Data (refer to Telescope Configuration Data section)
- Subset of the Telescope State Information (refer to Telescope State section)
- Gain Tables (Calibration Solutions)
- SDP Quality Assessment metrics
- Processing Block
- Processing Logs
- Other Data Product Catalogue metadata

Relationships to other data entities:

- Shares common indices with Raw Input Data
- Is used to generate Science Event Alerts
- Is used to update the Science Data Product Catalogue
- Is used to generate Science Data products
- Includes the Scheduling Block
- Contains a subset of the Telescope State Information
- Updates the Telescope State Information

- Contains a subset of the GSM
- Contains a subset of Telescope Configuration Data
- Is used to generate Processing Data Model

The SDM does not include the Raw Input Data, Processing Data Models or SDP Data Products, but does include references to these data entities.

At least one instance of the SDM is associated with each Scheduling Block. The working assumption is that there is one instance of the SDM associated with each Processing Block.

The Science Data Model and its sub-components must be extensible to accommodate changes throughout the lifespan of the Observatory.

2.1.2.1 Local Sky Model

The Local Sky Model (LSM) is a data structure that is initially populated by a subset of the GSM. The structure of the LSM is identical to the GSM. It contains the description of all celestial sources used during the data processing. Initially, the LSM will be populated with the sources from the GSM in the field of view (FOV) and bright sources outside the FOV affecting the visibilities. Depending on the observation type there will be tunable thresholds that determine which sources are part of the LSM. During data processing, newly found sources will be added to the LSM and existing sources in the LSM may be updated.

2.1.2.2 Calibration Solutions (a.k.a. Gain Tables)

The measured data from the telescope is corrupted by various effects. As a result an image produced from the measured data is limited in its quality. To improve the quality of the image, a model of the instrument and its environment is fitted to the measured data and used to correct the measured data for all corrupting effects. The resulting corrected image will have an improved quality.

Calibration Solutions are the fitted parameter values for the model of the instrument and its environment. These solutions are created in the Real-time Calibration pipeline and in the Calibration and Imaging pipelines that run on the Buffer. These solutions are created for each observation, but there may also be dedicated calibration observations that will use dedicated calibration pipelines.

Calibration Solutions are applied throughout the SKA telescope. Therefore, these solutions are fed back to TM. TM makes sure the solutions are distributed to the rest of the SKA System. SDP uses the Calibration Solutions internally, both in its real-time pipelines as well as in its pipelines that run on the Buffer. CSP uses the solutions to calibrate the Tied-Array Beamformer. The solutions may also be fed back to LFAA.

Calibrations Solutions are 2x2 matrices of complex values (so called Jones matrices). There is one matrix solution per Dish / AA-Station, per Direction on the Sky, per time-frequency domain (i.e. its validity domain), and per Primary Beam (only AA-Station will have more than one Primary Beam).

A Calibration Solution matrix may be a general, complex 2x2 matrix which describes all corrupting effects combined, or it may be constructed from a set of special 2x2 matrices that each describe a special effect. In the latter case, the total corrupting effect is described by multiplying all special matrices into one complex 2x2 matrix. Examples of the effects to be calibrated for are:

- Weights
- Ionospheric Faraday Rotation
- Antenna Jones Matrices
- Ionospheric TEC/ ΔTEC
- Model Parameters

Each of these effects will have their own time- and frequency scale on which they vary. This list is not exhaustive because there may be as-yet unknown effects to be calibrated. The Calibration Solution data model is designed to be as general as possible, in order to capture the output of any calibration algorithm, including ones that are developed in future. The types of calibration solutions that are necessary depend on the telescope configuration and frequency band, so they will be different for the two SKA phase 1 telescopes.

2.1.2.3 SDP Quality Assessment metrics

A set of metrics to determine the quality of Science Data Products.

A metric is given by these parameters:

- Name
- Value
- Date/time
- Origin (observation-id, pipeline component, ...)

It should always be possible to produce a new Quality Assessment metric. There is no definitive list of Quality Assessment metrics at this moment. When the QA metrics are further defined, which will occur during prototyping and further development, data/time elements will be accurately specified.

2.1.2.4 Processing Block Configuration

A Processing Block is an atomic unit of processing from the viewpoint of scheduling. A Processing Block is a complete description of all the parameters necessary to run a workflow. The list given below is an example of the sorts of parameters required, and this is extensible. A given Scheduling Block Instance may contain multiple Processing Blocks.

The Processing Block Configuration contains the following items (TBC):

- Processing Block ID
- Type (Real-time/batch)
- Processing Block parameters
- Abstract Resource Requirements
  - Real-time processing Compute Capacity
  - Batch processing Compute Capacity
  - Buffer Storage Capacity
  - Long Term Storage Capacity
- Science Pipeline Workflow Script (referenced by name and code revision)

2.1.2.5 Processing logs

Processing logs are defined by SKA1-SYS_REQ-2336 [AD02] as “a log detailing the processing configuration” and are essential for interpretation of Science Data Products. Processing logs may also contain other information necessary for the interpretation of Science Data Products.

2.1.2.6 Other Data Product Catalogue Metadata

Work still needs to be done to identify these elements. It is not believed that accommodating these elements will require architectural changes to the data model.

2.1.3 Processing Data Models

These were previously called Intermediate Data Models / products. Processing Data Model is a placeholder for all intermediate data that a workflow may create. As such it must be extensible. The Processing Data Models contain data items used during the processing of data. Note that All these image products use the logical data model described in the Image Data Model View Packet.

Data Items	**Logical data model used**	**Physical data model used (data format, etc.)**
Facet		
Visibility Set	Visibility Data Model	
● Block Visibility		
● Coalesced Visibility		
● Model Visibility		
● Partially-corrected Visibility		
UV Grid	GriddedData Model	
Intermediate imaging products[2]		
● Residual Image	Image Data Model	
● Sky Components / shapelets	Image Data Model	
● Dirty Image	Image Data Model	
● PSF Image	Image Data Model	
● Model Image		
Imaging Kernels		
● W-kernel		
● A-kernel		
● Anti-aliasing kernel		
● Over-sampled kernels		

Note that If model and partially-corrected visibilities, and model image need to be stored, will have impact on platform I/O performance and storage capacity.
Also there is on-going discussion as to whether store or recalculate on-the-fly the image kernels.

[2] Note that the intermediate imaging products can be used both in processing and can comprise the final preserved science data products.

2.1.4 SDP Data Products

This section provides a list and description of the data products which the SDP will deliver. SDP Data Products are independent of each other and are not derived from a common object type.

Transient Source Catalogue

Time ordered catalogue of candidate transient objects pertaining to each detection alert from the real-time Fast Imaging.

Science Data Product Catalogue

A database relating to all Science Products which have been processed by the SDP. It includes associated scientific metadata that can be queried and searched and includes all information so that the result of a query can lead to the delivery of data. This includes metadata necessary to support IVOA data models and protocols.

Image Products 1: Image Cubes

1. Imaging data for Continuum, as cleaned restored Taylor term images (n.b. no image products for Slow Transients detection have been specified – maps are made, searched and discarded).
2. Residual image (i.e. residuals after applying CLEAN) in Continuum.
3. Clean component image (or a table, which could be smaller).
4. Spectral line cubes:
    a. Spectral line cube with continuum emission remaining
    b. Spectral line cube after continuum emission subtracted
5. Residual spectral line image (i.e. residuals after CLEAN applied).
6. Representative Point Spread Function for observations (cutout, small in size compared to the field of view (FOV)).
7. Sensitivity Cubes (as per SDP_REQ-397).

Image Products 2: Gridded Data

1. Calibrated visibilities, gridded at the spatial and frequency resolution required by the experiment. One grid per facet (so this grid is the FFT of the dirty map of each facet).
2. Accumulated Weights for each uv cell in each grid (without additional weighting applied).

Calibrated Visibilities

Calibrated visibility data (for example for EoR experiments) and direction dependent calibration information, with time and frequency averaging performed as requested to reduce the data volume. Calibrated visibilities refers to visibilities after direction-independent calibration and subtraction of strong sources with direction-dependent calibration. These are the visibilities being exported to the Regional Centres, so Direction-dependent corrections will be limited to model subtraction at this point.

Sieved Pulsar and Transient Candidates

A data cube which will be folded and de-dispersed at the best Dispersion Measure (DM), period and period derivative determined from the search; a single ranked list of non-imaging transient candidates from each scheduling block; for those transients deemed of sufficient interest, the associated “filterbank” data will also be archived; a set of diagnostics/heuristics that will include metadata associated with the scheduling block and observation.

Pulsar Timing Solutions

For each of the observed pulsars the output data from the pulsar timing section will include the original input data as well as averaged versions of these data products (either averaged in polarisation, frequency or time) in PSRFITs format; the arrival time of the pulse; the residuals from the current best fit model for the pulsar; an updated model of the arrival times.

Dynamic Spectrum Data

1. RFI Cleaned PSRFITS file (for Dynamic spectra mode)
2. Calibrated PSRFITS file (for Dynamic spectra mode)

Transient Buffer Data

Voltage data passed through from the CSP when the transient buffer is triggered. The Transient Buffer in LOW will come from LFAA rather than CSP.

Science Data Model

Each instance of the Science Data Model (refer to section 2.1.2) is stored as a data product when the processing finishes.

2.1.5 Science Event Alerts

Alerts produced by SDP following the detection of astronomical events.

Types of alerts:

- Single Pulse (non-imaging transient) Detection
- Pulsar Detection
- Imaging Transient Detection

The alerts themselves are formatted as IVOA alerts and sent to TM. These are recorded in a Science Alert Catalogue which provides a searchable and retrievable record of past alerts.

This is one part of the data model which will not be extensible.

2.1.6 Science Data Product Catalogue

Catalogue of SDP Data Products. This is in itself a data product which is distributed to regional centres.

The architecture for this catalogue is of a flat data structure - there are no use cases at the present time which would require a more complex data structure. Each element within the catalogue will index all the elements of the *collection of data items* (see below) that form an SDP Data Product. The full metadata associated with a data product will itself be one of these data items. Each entry in the catalogue will however contain a subset of the metadata against which searches can be made. The one relational link is to the SKA project model (SKAPM) to associate each data item with an entry in the SKAPM.

Collection of data items: Physical data files/objects when considered together constitute a single SDP Data Product. Example: a spectral line image cube where *n* multiple files each contain a subset of the channels together with associated metadata file(s).

The SDP will be able to track a quality flag per SDP Data Product. Note that if only partial data products are to be retained, new workflows will need to be created. In particular the Processing Block Controller will need to flag the data appropriately and new workflows will be needed to deal with discarded data.

Independent checks will be carried out on files for data product bitrot. Furthermore, the catalogue will store checksums of all Data Product files. This is meant as a safeguard to detect data corruption, both for data stored in Long Term Storage as well as for data exchanged between SDP instances and SKA Regional Centres.

SDP will track a quality flag per SDP Data Product as catalogue meta data (such as “GOOD”, “BAD” or “JUNK”). This flag will initially be set by the workflow, depending on its assessment of the Data Product’s quality. Depending on the flag, delivery might be prevented or delayed (depending on subscription rules). The quality flag can be updated after the fact using a direct interface to Delivery, as well as by workflows. For example, when data has been identified as unusable, we might want to run a workflow that updates the quality flag as well as data lifecycle policies to cause underlying data to be discarded.

Furthermore, the catalogue will store checksums of all Data Product files. This is meant as a safeguard to detect data corruption, both for data stored in Long Term Storage as well as for data exchanged between SDP instances and SKA Regional Centres.

2.1.7 Raw Input Data

Raw input data:

- Visibility Data
- Pulsar & Transient Search Data
    - Pulsar Search Candidates
    - Single Pulse Candidates (fast transients)
- Pulsar Timing Data
    - Pulsar timing mode data (folded pulse profile data)
    - Dynamic Spectra Data
    - Flow Through mode data (raw beam-formed voltage data)
- Transient Buffer Data

2.1.8 Telescope Configuration Data

SDP requires a subset of the Telescope Configuration Data items for processing.

Minimal set of data items which SDP needs to subset:

- Beam Model:
    - Antenna Voltage Beams (Table defining beam parameters)
        - MID: Dish voltage beam
        - LOW: Embedded element pattern (Antenna dipole voltage beam)

- Antenna Positions
  - MID: Dish position
  - LOW: Station nominal centre position
- RFI (flagging) mask
- Calibration parameters (Jones matrix per antenna, frequency channel and time step)
- Measure data: Table defining leap seconds and all kinds of corrections for celestial movements.

The interface to get a subset of the Telescope Configuration Data needs to provide the ability to subset other items as required in the future.

2.1.9 Telescope State Information

Telescope State Information contains all information about the telescope's state, environment and behaviour. SDP requires a subset of this information for processing, and updates Telescope State Information.

Subset of Telescope State Information needed by SDP:

- Parallactic angle, or (preferred):
  - longitude of telescope
  - latitude of telescope
  - RA of phase centre
  - Declination of phase centre
- *Flags on antennas/stations (missing etc) - if not already applied
- *Antenna/station pointing
  - LOW: station voltage beam (or equivalently station gains and beamformer delays)
  - MID: actual pointing (in same coordinate system as the commanded)
  -
- MID: *Antenna on/off source (noise source)
- Current values of each of the receptor gains
- GPS ionospheric measurements (TEC values) for each station
- Weather

* Telescope State Information data needed in real-time (a.k.a fast telescope state).

SDP updates to Telescope State Information:

- Real-time calibration solutions (Jones Matrices)
- Pointing Solutions
- Antenna/station location and delay calibration solutions

2.1.10 Scheduling Block Configuration

According to [AD02], Scheduling Blocks are the indivisible executable units of a project and contain all information necessary to execute a single observation. A scheduling block may be stopped and cancelled but not paused and resumed.

All Scheduling Block data items are included in the Science Data Model. Scheduling Block data items are needed for processing or for the Science Data Product Catalogue.

Scheduling Block data items are concerned with configuration of the observation, and contain the ‘recipe’ for the observation.

The architecturally important features of the Scheduling Block are that it should be extensible, and that one Scheduling Block contains one or more Processing Blocks. The SDP cannot receive a Processing Block except as part of a Scheduling Block.

The data items in the Telescope Configuration/Telescope State Information may have the same or similar name as those in the Scheduling Block. The Scheduling Block contains observation configuration parameters whereas the Telescope Configuration Data or Telescope State Information contain parameters that describe the state of the telescope, e.g. commanded pointing (in Scheduling Block) vs. actual pointing (in Telescope State Information).

Refer to [RD8] and descriptions of the Observation Configuration Data Model for further details.

2.1.11 SKA Project Model

List of data items that SDP needs to reference (via Scheduling Block ID):

- All data related to a particular project (e.g. Project ID, PI)

Note: There is an SKA system level architectural question about whether SDP should subset required data items in the Science Data Product Catalogue or whether it would be done via a database relation to the SKA Project Model database.

2.2 Relations and Their Properties

The primary representation shows all major relationships between entities. The table below lists these relationships. These are not exceptions to the primary representation diagram, but simply list the relationships depicted in this diagram. Note that the relationships do not represent data flow or interfaces between SDP and other elements. It shows the context of logical data model entities.

Relationship	**Description**
shares common indices with	This means that Item A shares common indices with item B. In this case, the Science Data Model shares common indices with raw input data. These common indices are provided by TM, and are used by SDP in processing. For example, SDP will only process raw data according to the indices provided by TM.
contains a subset of	Item A contains a subset of the data model in item B. For example, the Science Data Model contains a subset of the Telescope State Information, pertaining to the observation. It does not contain the entirety of Telescope State Information for the telescope.

is a subset of	Item A is a subset of item B, for example the Scheduling Block is a subset of the SKA Project Model. It contains information pertinent to the upcoming observation and not the entire SKA Project Model data set.
used to generate	Item A is used to create item B. For example, information in the Science Data Model is used to create Processing Data Models. This was once called intermittent data, and is used for pipeline processing.
used to update	Item A is used to update item B. For example the Science Data Model updates the Science Data Product Catalogue. Metadata concerning a processed observation is stored in the Science Data Product Catalogue, and this will have come from the Science Data Model. This metadata data itself, in the Science Data Model, will have originated from several different locations.
provides index for	Item A provides an index for item B. The Science Data Product Catalogue provides an index for the SDP Data Products stored in long term preservation so that they may be queried and retrieved.
references	Item A references item B. The Science Data Product Catalogue includes information from the SKA Project Model, for example data about the observation proposal, the PI etc..
includes	Item A includes item B. In this model, the Science Data Model (for a given observation) includes all Scheduling Block information relating to that observation.

Table 1: Relationship explanations, relating to the Primary Representation

2.3 Element Interfaces

Interfaces are described in the relevant ICDs.

CSP: The interface to CSP is described in the documents 300-000000-002_04_MID_SDP-CSP-ICD and 100-000000-002_04_LOW_SDP-CSP-ICD (Mid and Low respectively).

LFAA: The interface to LFAA is described in 100-000000-033_01_LOW_SDP-LFAA-ICD.

TM: The interface to TM is described in the 300-000000-029_04_SDP_to_TM_MID_ICD and 100-000000-029_04_SDP_to_TM_LOW_ICD.

The Delivery-centric Component and Connector View Document SKA-TEL-SDP-0000013 describes the relationship to the SRCs and the Observatory. The SDP-SRC Interface Definition Document SKA-TEL-SKO-0000958 describes the relationship between SRCs and the SDP.

3 Context Diagram

The SDP Conceptual Data Model diagram shown in Figure 1 is a context diagram and therefore no additional context diagram is necessary.

4 Variability Guide

There is no variability at this level.

5 Rationale

5.1 Constructability

Requirements: SDP_REQ-828 (Constructability)

We needed to introduce a single high-level data entity called the **Science Data Model**, which encapsulates all information needed to process a particular grouping of data. The grouping of data models in the Science Data Model (and its relationships) allows for the ability to pull together information from a number of sources and provides flexibility in implementation.

We have chosen not to have a unified structure (like ALMA), because of cost and implementation considerations. However, re-use of the ALMA table physical data model for appropriate elements of the data model is not precluded.

5.2 Primary Functionality

Functionality required by L1 requirements is addressed by the following data models.

The **Global Sky Model** is a long-lived data entity which evolves over the course of the project. It is an explicit requirement of the observatory and serves other elements of the telescope.

Processing Data Models are required because the processing is organised as a directed acyclic graph and therefore intermediate data products must be managed explicitly as parts of the graph.

Science Data Products, Science Event Alerts and **Science Data Product Catalogue** are required by L1 requirements.

6 Related Views

Not applicable.

7 References

The following documents are referenced in this document. In the event of conflict between the contents of the referenced documents and this document, **this document** shall take precedence.

[RD1] ALMA SDM Tables Short Description. COMP-70.75.00.00-00?-A-DSN. June 12 2015. Draft. The ALMA Export Data Format, ALMA-70.00.00.00-004-A-SPE: http://docplayer.net/48193909-Alma-export-data-format.html

[RD2]	Data Models for the SDP Pipeline Components, Ger van Diepen et al, 2/12/2016 Rev B. (unclassified).
[RD3]	SKA-TEL-SDP-0000139 SDP Memo 033: Sky Model Considerations. DRAFT. Ian Heywood.
[RD4]	SKA-TEL-SDP-0000210 SDP Memo 105: SDP Intermediate Data Products. DRAFT. Anna Scaife.
[RD8]	SKA-TEL-TM-0000242 TMC Software Architecture Document, Rev 01, Subhrojyoti Roy Chaudhuri.
[RD9]	601-000000-002 OSO Software Architecture Document, Rev 01, Alan Bridger. TM number T4000-0000-AR-002.
[RD10]	SKA-TEL-SKO-0000893, Telescope Model Project Report, Rev 01

8 Execution Control Data Model View Packet

Contributors: P. Wortmann, V. Allan

8.1 Primary Representation

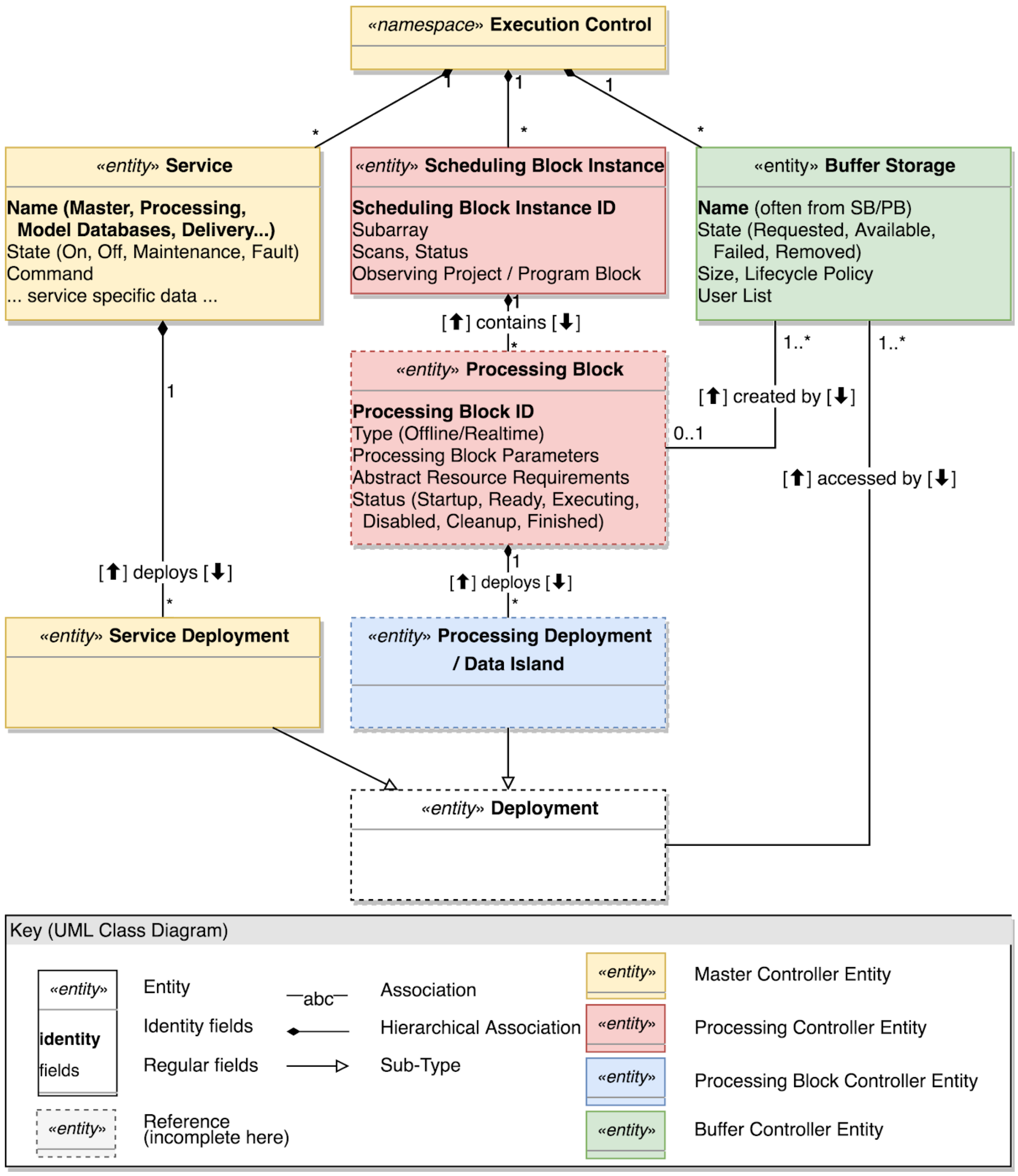

«namespace» Execution Control
«entity» Service
Name (Master, Processing, Model Databases, Delivery...)
State (On, Off, Maintenance, Fault)
Command
... service specific data ...
«entity» Scheduling Block Instance
Scheduling Block Instance ID
Subarray
Scans, Status
Observing Project / Program Block
«entity» Buffer Storage
Name (often from SB/PB)
State (Requested, Available, Failed, Removed)
Size, Lifecycle Policy
User List
[🠅] contains [🠇]
«entity» Processing Block
Processing Block ID
Type (Offline/Realtime)
Processing Block Parameters
Abstract Resource Requirements
Status (Startup, Ready, Executing, Disabled, Cleanup, Finished)
[🠅] created by [🠇]
[🠅] accessed by [🠇]
0..1
1..*
1..*
[🠅] deploys [🠇]
[🠅] deploys [🠇]
«entity» Service Deployment
«entity» Processing Deployment / Data Island
«entity» Deployment
Key (UML Class Diagram)
Entity
Identity fields
Regular fields
Reference (incomplete here)
abc
Association
Hierarchical Association
Sub-Type
Master Controller Entity
Processing Controller Entity
Processing Block Controller Entity
Buffer Controller Entity

Figure 1: Top-Level Execution Control Data Model

This view defines the Execution Control Data Model. In contrast to the System-level Data Models, the data represented here is not consumed or produced by SDP, but is used entirely to maintain the internal state of SDP and facilitate coordination between Operational System components.

Elements shown here are data entities, signifying data stored in the configuration database and possibly replicated in other places as needed. Relations are entity associations. Hierarchical associations determine the structure of the data within the configuration database. This means that the path connecting every element to the root "Execution Control" element qualified with element identity information would determine the full path of the entity within the store.

The data shown here is going to be held and maintained by the Execution Control Component (see Operational System C&C View) using the Configuration Database (see Execution Control C&C View). Note that while we represent it as a database schema, the SDP configuration is purely transient data. Therefore database technologies focused on long-term persistence would not be a suitable choice for implementation, instead we would use configuration services with a focus on reliability and scalable subscription interfaces (such as Apache ZooKeeper, Consul or etcd). In fact, another alternative would be to maintain this data model using transaction queues (for example using Apache Kafka). This document should be seen as a logical data model that could fit a large number of possible physical implementations.

Reading Guide: The controllable entities within SDP are organised in a strictly hierarchical fashion in order to provide clear hierarchies of ownership. What this especially means is that all **Deployments** will have exactly one "owner", so it is uniquely identified at which point a given resource can be released. This ensures that the system does not "leak" resources or Platform configuration changes.

At the upper-most level, the name space is split into three categories. **Services** are long-lived entities and are managed at the upper most level by the Master Controller (see Execution Control C&C View). Examples include the Master and Processing Controller themselves, but also Delivery, Model Databases and Buffer Services. These services will have very different characteristics and might use and store different configuration data internally. On the other hand, all of them must implement the same basic attributes to allow the master controller to track (and command) their state as well as declare how their deployed components are to be managed by the platform.

Furthermore, the most significant category of control entities deals with the primary function of the SDP, which is processing observation data. The top-level structure of this tree is managed by the Processing Controller (see again Execution Control C&C View). In this tree, entities are strongly associated with a **Scheduling Block Instance / Processing Block** path. This means that we see all lower-level processing entities as being associated with exactly one Processing Block at all times. See next section for more detail on those entities.

Finally, **Buffer Storage** exists semi-independently of both services and processing. This means that while services and processing will create and delete storage, the option is left open to control storage directly where appropriate. This means that SDP can fulfil its role as a data store even if associated processing or services are not yet fully automated.

8.1.1 Processing Control Data Model

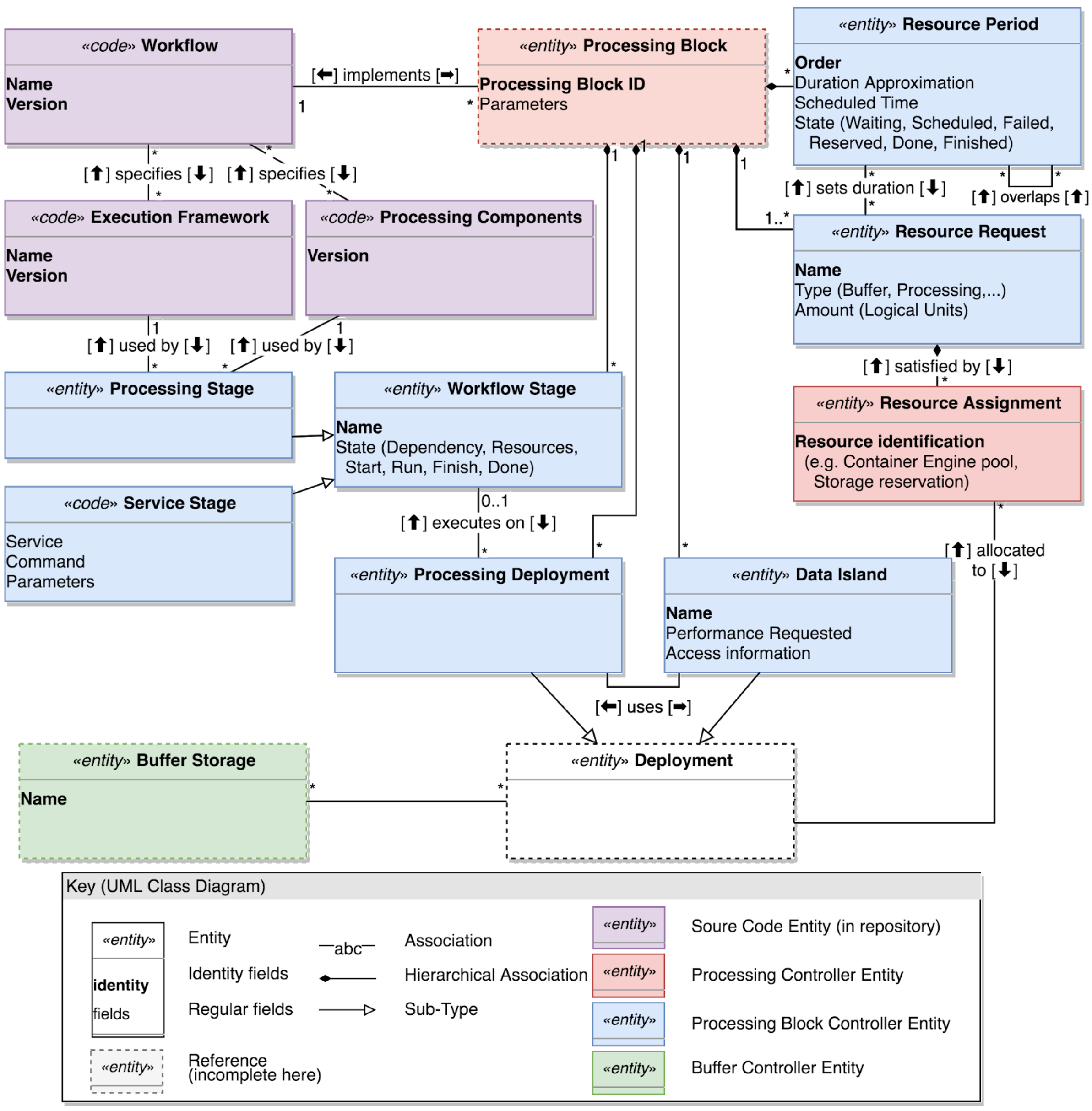


Figure 2: Processing Control Data Model

The Processing Control Data Model details how the execution of a **Processing Block** is controlled. The primary entity deciding the shape of the Processing Block's configuration is the **Workflow** scripts associated with it (see Workflow Module View and Workflow Script & Deployment View). Workflows will further reference other code used by Processing Stages, specifically **Execution Frameworks** and **Processing Components** (see System-level Module View). Such code references will be passed to the Platform as deployment parameters - first when creating the Processing Block Controller, then for executing Processing Stages. Note that the Platform will then use the Artefact Repository to look up the appropriate build artefact - such as a container image - so the source code itself may never enter the SDP operational system. See Platform C&C View and Software Management C&C View.

In contrast to Services, Processing Blocks will require significant amounts of specialised resources for processing, which will have to be scheduled by the Processing Controller. To communicate the resource requirements, the control script of the Workflow (see Workflow Module View) will create Resource Periods & Requirements, documenting upper bounds for what resources will be required in what order and for how long. These resource requests will be used by the the Processing Controller to formulate a schedule that maps resources available to the SDP in the foreseeable future to Processing Blocks. Once the resources in question are available, the Processing Controller will indicate availability to the appropriate Processing Block Controller by adding Resource Assignments to the Processing Block entity in the configuration.

Assigned resources will be used by the Processing Block for two purposes: Executing workflow stages and allocating Data Islands for holding storage. The corresponding configuration is created by the Workflow script when the Processing Block is created, but will be marked as waiting for resources and/or dependencies. As resources become assigned to the Processing Blocks and other workflow stages finish, the Processing Block Controller executing the Workflow script will mark Workflow Stages as ready for execution.

Execution of a Workflow Stage will generally cause deployment of new components. For example, for a Model Databases Stage a Science Data Model Builder component might get started (see Model Databases C&C View), or a Processing Stage might deploy Execution Engines on assigned resources (see Processing C&C View). Note that for the moment we see only Processing Stages and Data Islands as consuming dynamically assigned resources, which makes non-Processing stages “free” for the purpose of Processing Block scheduling. This especially means that only Processing Stages would generally be impacted in case of immediate processing resource shortage.

Another notable case is Buffer stages, which would be used to create data islands involving new or existing storage subjects with some desired performance guarantees. As this might involve migration of data, such service stages could take significant time to execute.

8.1.2 Deployment Data Model

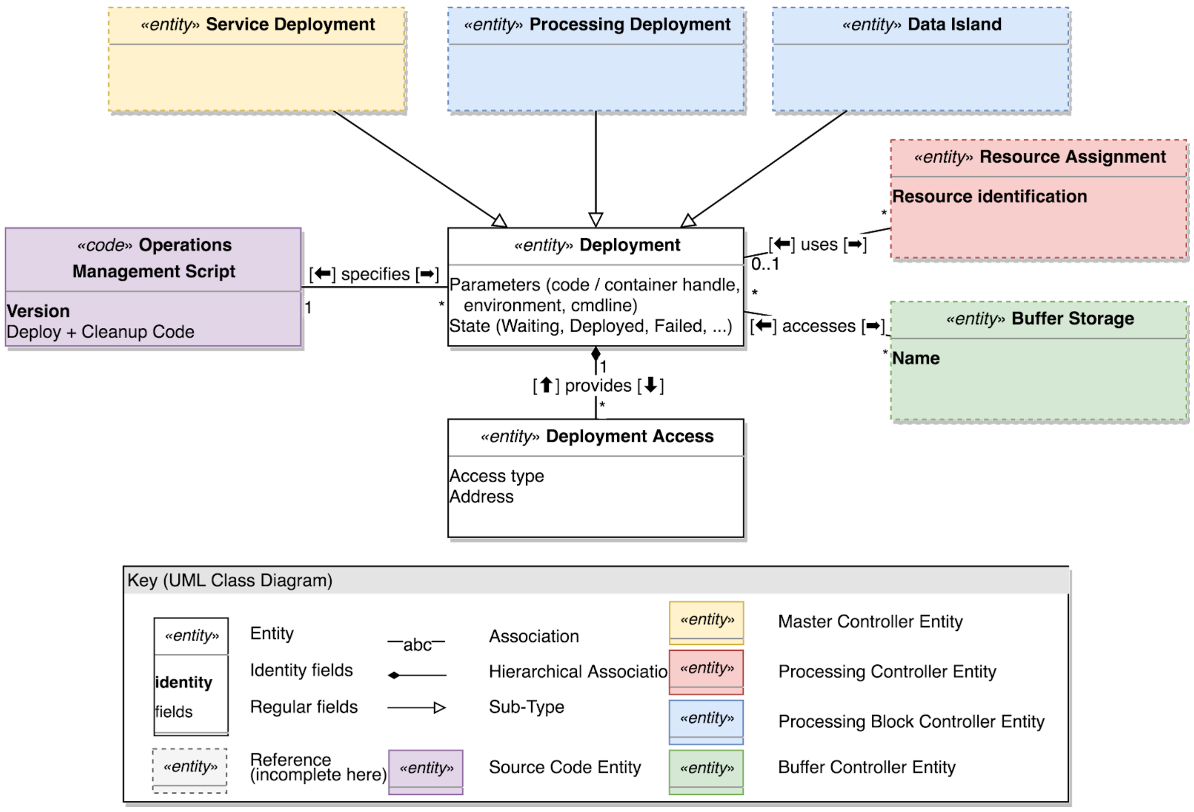

«entity» Service Deployment
«entity» Processing Deployment
«entity» Data Island
«entity» Resource Assignment
Resource identification
«code» Operations Management Script
Version
Deploy + Cleanup Code
[⬅] specifies [➡]
1
*
«entity» Deployment
Parameters (code / container handle, environment, cmdline)
State (Waiting, Deployed, Failed, ...)
[⬅] uses [➡]
0..1
*
[⬅] accesses [➡]
*
*
«entity» Buffer Storage
Name
1
[⬆] provides [⬇]
*
«entity» Deployment Access
Access type
Address
Key (UML Class Diagram)
«entity»
identity
fields
Entity
Identity fields
Regular fields
abc
Association
Hierarchical Association
Sub-Type
«entity»
Reference (incomplete here)
«entity»
Source Code Entity
«entity» Master Controller Entity
«entity» Processing Controller Entity
«entity» Processing Block Controller Entity
«entity» Buffer Controller Entity

Figure 3: Deployment Data Model

All software deployments requested by the Operational System will be tracked in the configuration database. A deployment is defined by Operations Management Scripts (see Platform Module View) that describe the change to made to the cluster configuration. Typically this would involve deploying one or more containers, including setting up network connectivity, replication, health checks, restart policy and everything else required by the component in question. The deployed software should be specified in terms of a code reference / tag such that the Platform can look up a matching build artefact in the Artefact Repository (see Platform C&C view).

In case of processing deployments, the software is expected to get started on specified resources. It might also require access to certain Buffer Storage. It is the responsibility of the platform and the deployment script to instantiate the software runtime environment to specification, i.e. using specified resources and providing access to the given storage.

After the deployment has been performed, the configuration database should be updated with information about how to access the running software. This is to both to provide a mechanism for other software to access provided services as well as document interfaces for direct monitoring and debugging (e.g. SSH access).

8.2 Element Catalogue

8.2.1 Elements and Their Properties

This subsection goes into more detail about Execution Control data entities. Given that the configuration database acts as intermediate between basically all components of the SDP

Operational System, its contents must be carefully considered. Therefore we are going to identify for each entity:

Responsible:	The component(s) responsible for creating and maintaining this data entity of the configuration. This does not mean that the component in question is the only one doing updates to the entity (e.g. the state might get changed by outside intervention). However it is mainly responsible for ensuring that the contained information is valid (e.g. implement the schema).
Lifetime/Count:	Decides when the entity in question will be created and when it will be removed from the configuration. All configuration database entities are transient. Connected to this is the question of how many entities of this type we expect to exist in the configuration at any given time.
Consumers/ Update Rate:	Main components that are going to monitor this entity for change, and order of magnitude for often updates would be expected on average.

8.2.1.1 Execution Control

Responsible:	Master Controller
Lifetime/Count:	SDP Operational System, 1
Consumers/ Update Rate:	Services that take global view of configuration (e.g. Master, TANGO control), updates per service or Scheduling Block (~ minutes).

Root of the Configuration Database name space. Contains all entities stored in the Configuration Database.

8.2.1.2 Service

Responsible:	Master Controller
Lifetime/Count:	SDP Operational System, ~10
Consumers/ Update Rate:	Services, especially the service in question. Updates per service state update (~ hours). Some information (e.g. Platform resource availability or failure recovery data) might be updated more often, but have specialised consumers.

Representation of a service within the configuration database. Will be used to track and control the state of services and collect deployments associated with them. See also the state documentation in the Operational System C&C view [RD01].

The service in question might use the configuration database to store more internal data - for example to implement state recovery after failure as explained in the Execution Control C&C View [RD02] - but that is not specified here.

8.2.1.3 Service Deployment

Responsible:	Service / Master Controller
Lifetime/Count:	Containing Service, ~100
Consumers/ Update Rate:	Platform, service in question, Master Controller for forced shutdown. Updated as service deployments change (~ minutes).

Deployment associated with a service. Initial service deployments will often be static, e.g. created automatically by orchestration scripts, which might or might not be under control of the Master Controller. The service might add further dynamic deployments as needed. A service that is in the

"Off" state is expected to not have active deployments associated with it, and the master controller might use the registered deployments to forcefully shut down a service.

In contrast to Processing Deployments, service resources are not dynamically allocated. Instead it is expected that they use global shared resources, which might have been statically allocated by either the deployment scripts or the service.

8.2.1.4 Buffer Storage

Responsible:	Buffer Controller
Lifetime/Count:	Storage present in Buffer, ~100
Consumers/ Update Rate:	Services, Processing, TANGO interface (~ minutes)

Control object associated with storage managed by the Buffer. This offers an interface to the Buffer's storage lifecycle database, allowing services and processing to create and update entries, as well as requesting the storage in question to be made available.

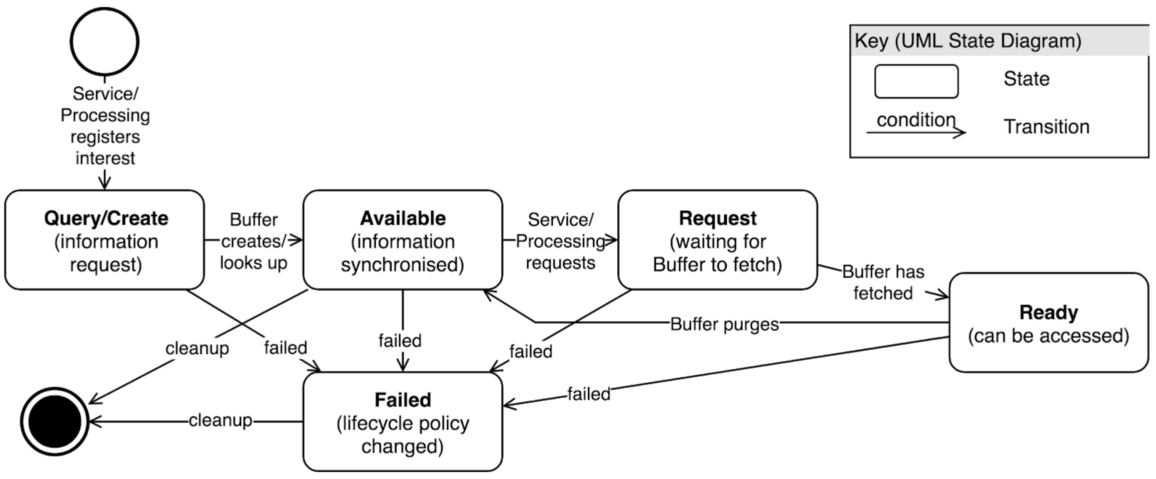

Service/ Processing registers interest
Query/Create (information request)
Buffer creates/ looks up
Available (information synchronised)
Service/ Processing requests
Request (waiting for Buffer to fetch)
Buffer has fetched
Ready (can be accessed)
Buffer purges
cleanup
failed
failed
failed
failed
cleanup
Failed (lifecycle policy changed)
Key (UML State Diagram)
State
condition
Transition

Figure 4: Buffer Storage Entity states

To start an interaction about a Buffer object, a component creates a Buffer Storage entity in state **Query** or **Create** depending on whether it intends to create a new storage object or query information about an existing one. The entity should add a reference to itself to the "usage list". Any further process that wants to query the Buffer storage object in question should add itself to this list in order to prevent the entity from getting cleaned up prematurely (a "locking" mechanism).

Once the Buffer has received the query and created the Storage entry in the lifecycle database, it moves the state to **Available**. This indicates that the buffer object can be requested if enough capacity is available. In this state (as well as Request & Ready) the lifecycle policy of the storage object can be updated by setting the appropriate field (possibly have a separate "commanded" policy field). This means that the lifecycle policy can be changed using this mechanism without actually requesting the underlying storage object.

On the other hand, if a service or processing wants to access the underlying data, it will have to **Request** the Buffer storage in question. This will consume Buffer resources, and might fail for that reason. It is the responsibility of the requestor to ensure that enough resources are available (so e.g.

Delivery is responsible for not requesting more Buffer resources than were allocated to it). Note that available Buffer resources might fluctuate, so this might happen even if resource constraints were observed at the time of the request.

Once the storage is accessible, it will move into the **Ready** state. At this point compute deployments should be able to mount the underlying storage. Note that for high performance access, additional "Data Island" deployment steps might be required in order to provide specialised storage access interfaces.

If the Buffer detects a problem with the storage, it will move it to the **Failed** state. This should indicate the underlying storage actually being lost - a forced purge should just move the storage object to the Available state. In either case, the Buffer Storage entity will remain in the configuration database as long as usage of it is registered. Once the usage list is empty, the Buffer component will clear up the entity. Depending on the data lifecycle policy, this might cause the buffer object to be deleted or migrated to Long Term Storage.

8.2.1.5 Scheduling Block Instance

Responsible:	Processing Controller
Lifetime/Count:	Processing on Scheduling Block, ~100
Consumers/ Update Rate:	Monitoring with global view, especially TANGO interface. Updated as TM adds new scheduling blocks (~minutes).

Observation schedule context for processing created by the Telescope Manager. From the point of view of SDP, this serves to group together activities associated with processing observations.

Scheduling Block Instances are inserted into the configuration database using a control interface implementation such as the SDP Subarray TANGO device, see Execution Control C&C [RD02]. From that point on they become the responsibility of the Processing Controller, which is expected to implement Processing Blocks associated with them. After all processing on a particular Scheduling Block / Scheduling Block Instance is finished (including Delivery persisting information) the Scheduling Block / Scheduling Block Instance will get removed from the configuration.

8.2.1.6 Processing Block

Responsible:	Processing Controller
Lifetime/Count:	Processing on Scheduling Block, ~1000
Consumers/ Update Rate:	Created as TM adds new scheduling blocks (~minutes), populated by Workflow Script, after that only occasionally addition of Workflow Stages (~minutes)

Representation of processing to be done for an observation for the purpose of Execution Control. Associated with workflow scripts to execute, which specify the resources to request and workflow stages to execute. This will result in Processing Deployments and Data Islands to be associated with the Processing Block.

Along with Scheduling Blocks, associated Processing Blocks will be inserted into the configuration database using a control interface. Initially this will just be Processing Block parameters such as the parameterized workflow.

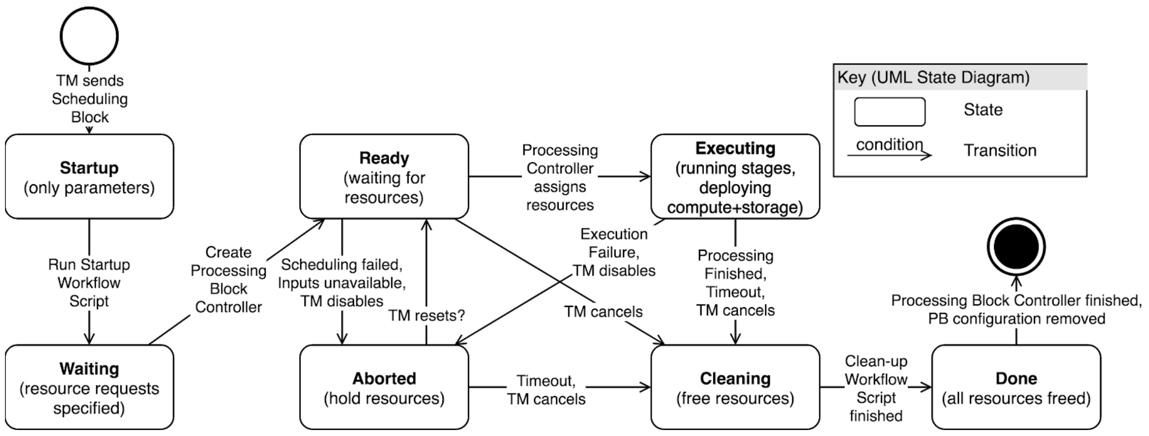

TM sends Scheduling Block
Startup (only parameters)
Run Startup Workflow Script
Waiting (resource requests specified)
Create Processing Block Controller
Ready (waiting for resources)
Scheduling failed, Inputs unavailable, TM disables
TM resets?
Aborted (hold resources)
Processing Controller assigns resources
Executing (running stages, deploying compute+storage)
Execution Failure, TM disables
TM cancels
Processing Finished, Timeout, TM cancels
Timeout, TM cancels
Cleaning (free resources)
Clean-up Workflow Script finished
Done (all resources freed)
Processing Block Controller finished, PB configuration removed
Key (UML State Diagram)
State
condition
Transition

Figure 5: Processing Block Entity states

Once a Processing Block is registered in the configuration, the Processing Controller is expected to run the **Startup** phase of the workflow and populate the remaining Processing Block configuration, especially concerning requested resources (this execution might look like an early version of the Processing Block Controller). This moves the Processing Block into the **Waiting** state. These resource requests will then be scheduled by the Processing Controller. Once scheduled resources are available, the Processing Controller will assign them to the Processing Block, which might cause first Workflow stages to run.

Once enough Resource Assignments are available for the Processing Block Controller to deploy processing and data islands, the Processing Controller will start the Processing Block Controller, moving the Processing Block into the **Ready** state. From there it will progress to the **Executing** state once the Processing Block Controller starts assigning resources to workflow stages. Note that this state means that the Processing Block is currently executing Workflow Stages, so this might not correspond directly to TM states.

At any point after Startup, the Processing Block might enter either the **Aborted** or the **Cleanup** state. This can either happen because the workflow finished or because TM requested the state change. In the **Aborted** state the Processing Block does not release any held resources (especially storage). This is to prevent inputs and intermediate data products from getting discarded, as they might still get used for other (e.g. replacement) Processing Blocks or failure diagnosis. However, eventually the Processing Block will enter the **Cleanup** phase, which will run the appropriate workflow script part in order to free the appropriate resources and publish any useable Data Products as appropriate.

8.2.1.7 Workflow, Processing Components, Execution Engine

Responsible:	Workflow Repository
Lifetime/Count:	Independent, ~1000
Consumers/ Update Rate:	Updated as code gets pushed into code repositories. Only versions deployed to Artefact Repository are valid to reference from configuration.

Workflows and Processing Components/Execution Engines will be maintained independently of each other in different repositories, see also Science Pipeline Management Use Case View. SDP will not interact with these code repositories directly, and will instead learn about these entities indirectly: Continuous Deployment (see Software Management C&C View) would provide the Artefact

Repository (see Platform C&C View) with current build artefacts as they are created, which TM/observation planning would then reference for Processing Blocks.

The code references might still use indirections (e.g. generic workflows like “standard ICAL” or version tags like “latest stable”), which are resolved by the Processing Controller before the Processing Block gets started up by SDP. This should ensure that a consistent set of versions is selected for execution. Note that this means that a Processing Block might have to be restarted or re-issued in order to update the executed code (such as applying bug fixes).

As explained in the Workflow Scripts and Deployment View, the Workflow will define the start-up, execution and clean-up behaviour of the Workflow with respect to the SDP configuration. This might especially deploy processing component specific to the workflow in question. These should have been built as artefacts alongside the workflow, and therefore will be retrieved from the Artefact Repository.

8.2.1.8 Resource Request

Responsible:	Processing Block Controller
Lifetime/Count:	Processing Block, ~1000
Consumers/ Update Rate:	Consumed by Monitoring and Processing Controller. Updated as resources get assigned, typically only once in its lifetime (~ minutes).

Documents an amount of resource that the execution of a Processing Block will require. The duration for which the resources in question will be required is given by association with a number of Resource Periods.

The amount of resources will be given in “logical” units as appropriate to Platform-level resource scheduling. This should mostly be seen as a specification of the desired deployment environment, as the Processing Controller and the Platform should have freedom to satisfy requests by using partial resources (e.g. a part of a more powerful node, or a node with extra unused capabilities).

8.2.1.9 Resource Period

Responsible:	Processing Block Controller
Lifetime:	Processing Block, ~1000
Consumers/ Update Rate:	Consumed by Monitoring and Processing Controller. Updated as execution progresses to new periods (~ minutes).

Resource periods define the phases of a Processing Block’s resource requests. Typical Processing Blocks are expected to have three periods:

1. Acquire and stage inputs (requires storage resources for inputs)
2. Perform processing (requires processing and storage resources for inputs+outputs)
3. Persist and publish Data Products (requires storage resources for outputs)

Furthermore, there might be an extra period associated with the Processing Block in which no processing or stages takes place, but storage resources are still not freed. This would be used for handling dependencies between Processing Blocks, such as that of batch processing on Receive. This would be represented by a “must contain” dependency between Resource Periods of different Processing Blocks.

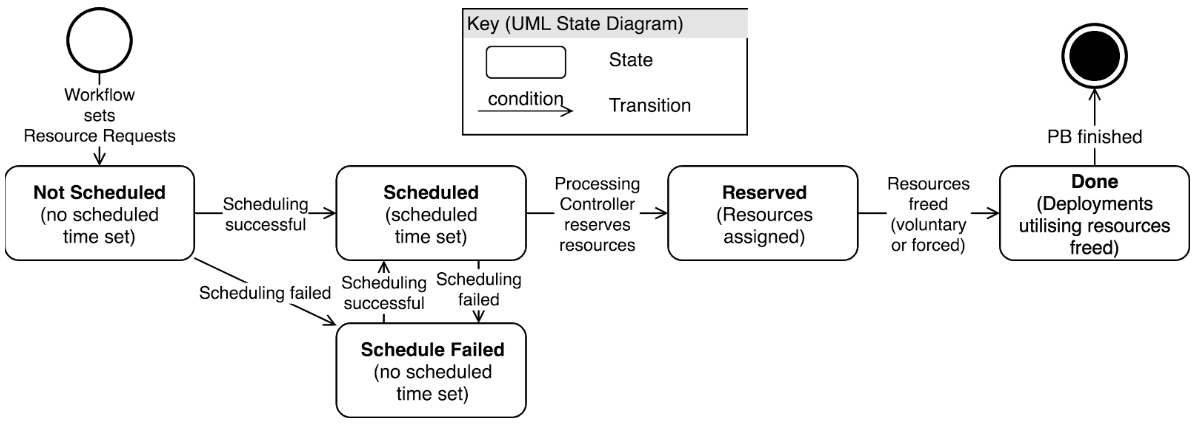

Key (UML State Diagram)
State
condition
Transition
Workflow sets Resource Requests
Not Scheduled (no scheduled time set)
Scheduling successful
Scheduled (scheduled time set)
Processing Controller reserves resources
Reserved (Resources assigned)
Resources freed (voluntary or forced)
Done (Deployments utilising resources freed)
PB finished
Scheduling failed
Scheduling successful
Scheduling failed
Schedule Failed (no scheduled time set)

Figure 6: Resource Period Entity states

Resource Period start in the **Not Scheduled** state. As a result of scheduling, the Resource Period should move to either the **Scheduled** or **Schedule Failed** state. In case scheduling was successful, the information about when the Period is forecast to happen should be added. If scheduling fails - which might happen after the period was scheduled previously no such information will be given, causing an alarm state or even a failure of the Processing Block.

Once the scheduled time has arrived and the Processing Controller has verified the availability of the scheduled resources, it will generate assignments to hand over ownership of the resources in question. This will move the period into the **Reserved** state, which signals to the Processing Block that Workflow Stages requiring the resources in question can be started.

To end the period, the reserved resources must first be freed. Typically this should be done by the Processing Block Controller, either because all necessary processing finished or because the workflow script detected that the period would run out of time and aborted processing. However, after a certain grace period the Processing Controller is expected to forcefully free any resources still in use by deployments or data islands in order to prevent system deadlock. In any case, this should lead to all assignments to be removed and the period getting moved to the **Done** state, which it will stay in until the Processing Block itself gets removed.

Note that resource periods associated with a Processing Block can be in different states. This is important, because we do not want to free resources associated with an earlier period unless we can progress to a later period. This also serves to document exactly at which point scheduling failed. Also note that multiple periods of a Processing Block can be in the "Reserved" state at the same time, as cleaning up an earlier period might overlap with execution of the next.

8.2.1.10 Resource Assignment

Responsible:	Processing Controller
Lifetime/Count:	Resource Periods, ~100 (typically fewer assignments than requests)
Consumers/ Update Rate:	Consumed by Monitoring and Processing Block Controller. Updated as resources get assigned, typically only once in the lifetime of a Resource Request (~ minutes).

Resource Assignments will be granted to the Processing Block by the Processing Controller once the scheduled time for the associated Resource Period(s) has arrived.

The assignment will indicate appropriate logical resources available to the platform such that it can be used in Deployments. This must not necessarily refer to a concrete piece of hardware, so often this will just be a reference to a portion of a resource pool managed by the Platform. However, the Processing Controller will be need to ensure a certain amount of resource locality, so the assignment should be specific enough to provide the necessary tools for locality optimisation (e.g. "12 x 16-core nodes from rack A").

8.2.1.11 Workflow Stage

Responsible:	Processing Block Controller
Lifetime/Count:	Processing Block, ~1000 inactive, <100 running
Consumers/ Update Rate:	Monitoring, Processing Block Controller, Workflow Stage in question. Updated as stage runs (dependent on stage).

Workflow Stages are used for coordinating work on a Processing Block. Each stage identifies a unit of work, which might get performed by a different part of the SDP system (e.g. a SDP service or an Execution Engine). Workflow stages can have dependencies on each other and use resources assigned to the Processing Block to deploy processes and data islands. Both dependencies and resource allocation is specified by the Workflow and implemented by the Processing Block Controller.

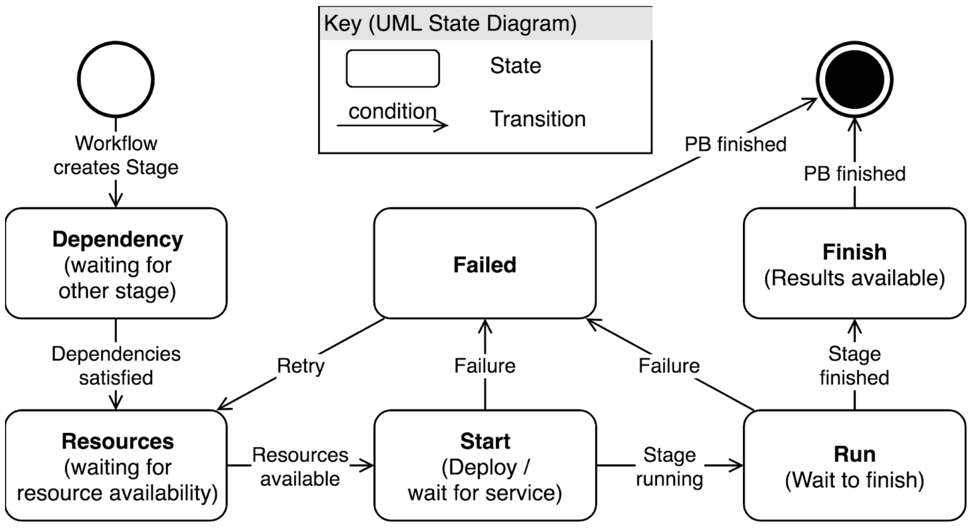


Figure 7: Workflow Stage states

Conceptually, each Workflow Stage starts in the **Dependency** state until all stages it depends on have finished. After this (which might be immediately for stages without dependencies) they enter the **Resources** state, which is where they stay until needed resources are available and have been assigned to the Workflow Stage. For steps that do not require resources - such as stages representing a simple query to an SDP service - this state might also get jumped over.

Once dependencies and resources are available, the stage is moved into the **Start** state by the Processing Block Controller. From here, there are two important cases here that are handled somewhat differently:

1. Service stages are executed by the appropriate SDP service (e.g. Model Databases, Buffer, Delivery…). This means that at this point the service in question is meant to pick up up all necessary information from the configuration database and either do the work or deploy worker components as needed.
2. On the other hand, Execution Engine will be deployed by the Processing Block Controller itself. This will especially deploy the Execution Engine Interface implementation (see Workflow Module View [RD05]), which from that point onwards is in charge of the Workflow Stage.

The component performing the execution (Service / Execution Engine Interface) will perform necessary initialisation steps and set the state to either **Failed** or **Run** depending on success. Failed workflow stages are expected to deallocate resources (but not necessarily intermediate data products) in a way that allows the Workflow Stage to be attempted again. If on the other hand the Workflow Stage finishes successfully, all deployments are going to be freed and the state will be set to **Finished**. This signals to the Processing Block Controller that the (intermediate) Data Products of the stage are available, which might unblock dependent stages or cause the Processing Block to finish.

8.2.1.12 Deployment

Responsible:	Service or Processing Block Controller
Lifetime/Count:	Service or Processing Block / Workflow Stage, ~100
Consumers/ Update Rate:	Platform, Controller that is monitoring deployment, ~minutes

Deployments describe reversible and repeatable changes to the platform configuration, such as starting a container, hanging some hardware configuration - up to booting up an entire infrastructure of hardware and software. The entirety of deployments contained in the configuration database should describe the the exact Platform configuration of all parts of the Operational System.

This should be implemented according to best practices of IT Configuration Management or infrastructure-as-code, which means that the Platform configuration is described by scripts for a Platform-provided Configuration Management system, with Execution Control’s Configuration Database providing the dynamic parameters. These scripts are described as “Configuration” in the Platform Module View. Scripts parameters are going to be stored with the deployment entity.

The key property of deployments is that it should be possible to reliably un-do them without knowledge about the details of the deployment’s function. This is critical to implement forced resource deallocation in case services or Processing Blocks need to get aborted due to failures in services or processing (see Execution Control C&C View).

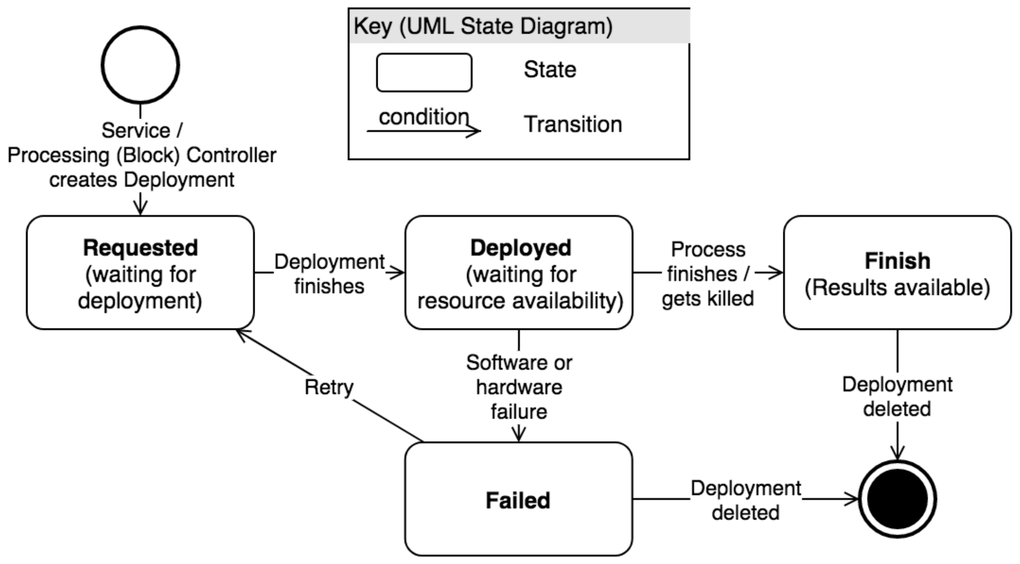

Key (UML State Diagram)
State
condition
Transition
Service / Processing (Block) Controller creates Deployment
Requested (waiting for deployment)
Deployment finishes
Deployed (waiting for resource availability)
Process finishes / gets killed
Finish (Results available)
Software or hardware failure
Retry
Deployment deleted
Failed
Deployment deleted

Figure 8: Deployment States

Deployments have a relatively simple life-cycle: After being **Requested** they might either become **Deployed** or **Failed** depending on whether the Platform managed to execute the deployment. Failed deployments can be retried. A deployment might also fail after it was started, for example because of software or hardware failure. This might include cases such as nodes getting turned off to meet requirements of a low-power-mode. If a deployment either finishes successfully or is forcefully terminated it enters the **Finish** state. Failed or finished deployments are safe to remove from the configuration.

8.2.1.13 Data Island

Responsible:	Processing Block Controller
Lifetime/Count:	Processing Block, ~100
Consumers/ Update Rate:	Processing Block Controller, Buffer Services, ~minutes

The purpose of Data Islands is to provide the Processing Block - and more specifically processing deployments associated with it - access to storage resources. The Data Island entity details the layout of the island we expect, so especially what storage should be accessible.

This specification will be used by the Buffer Master and the Data Island Controller (see Buffer and LTS C&C View) to provide the necessary infrastructure. The interaction will happen through Buffer Workflow Stages, and might cause further Deployments to be associated with the Processing Block so that the Data Island infrastructure can be cleaned up by the Processing Controller if necessary.

Especially note that Data Islands will specify performance requirements expected from storage. This means that data might have to be moved to a different storage tier in order to hit requirements. This means that Buffer Workflow Stages might take hours to complete for large storage instances.

8.2.1.14 Storage

Responsible:	Processing Block Controller
Lifetime/Count:	Processing Block, ~100
Consumers/ Update Rate:	Processing Block Controller, Buffer Services, ~minutes

Represents a storage instance made available to Processing through a Data Island. This can be used by other deployments to read or write data stored in the Buffer.

While storage instances can be created in the context of Data Islands, storage instances are tracked independently by the Buffer in the Storage Lifecycle Database (see Buffer and LTS C&C View). The "Storage identification" is a reference to their canonical name of the Storage Instance for the purpose of the Buffer. This means that if the Storage ID matches a storage instance used for another Data Island, this means that the storage is meant to be shared between the Data Islands. This can especially happen across Processing Blocks, which can be used to data produced by Receive or Data Products of past Processing Blocks (which might have to be brought back from Long Term Storage)

The lifecycle policy of the storage (see Buffer Data Lifecycle View) is another attribute that will be synchronised with (or to) the Storage Lifecycle Database. It decides what happens to the storage in absence of references from the configuration, so i.e. after the processing block as finished or one of the Data Islands gets released. Storage holding Data Products and other "precious" data will typically indicate that the data is to be kept indefinitely (which can obviously be overridden later as appropriate). Even for transient data such as received visibilities we might indicate a certain minimum time that it needs to be kept alive before removal.

8.2.2 Relations and Their Properties

Most relations shown on the primary representation are hierarchical in nature and therefore are expected to map well to a hierarchical namespace of a key-value store.

8.2.3 Element Interfaces

N/A

8.2.4 Element Behavior

Most of the dynamic behaviour of the Execution Control Data Model is about implementing the various behaviours of Execution Control. In the Execution Control C&C View behaviour sections, a lot of the interactions shown will either be accompanied by or accomplished through updates to the SDP configuration managed by Execution Control.

8.3 Context Diagram

The Execution Control Data Model stands mostly on its own, but has links to and overlaps with other data models:

- The System-level Data Model View describes the information that will be exchanged with TM as well as with processing (e.g. in storage or queues). Processing and Scheduling Block data is something that will appear on both sides.
- The data model associated with the Buffer Lifecycle View interacts with the Data Island/Storage management of the configuration.

8.4 Variability Guide

The Execution Control Data Model is meant to be flexible in allowing SDP to add and remove functionality. A few examples:

- Services can easily be added and removed. Adding extra components is just a matter of instructing the Master Controller to bring up a new type of deployment.
- Deployment types are not hard-coded, and resources are only managed at a fairly high level. This means that the Platform is afforded a lot of freedom in how software is actually deployed. Containers are likely going to be the default choice, but other options are still possible - such as deploying images to bare metal, binaries on existing machines or Apache Spark programs to Mesos clusters.
- Resource requirements are associated with coarse-grained Resource Periods, not with Workflow Stages. This keeps scheduling complexity down and allows the Workflow to adjust workflow stages to execute at basically any point.
- Workflow stages especially do not have explicit dependencies, instead the semantics of the "Dependency" state is defined by the workflow in question. This means that we do not have to enumerate all the different types of dependencies (e.g. via storage/queues/databases...).

8.5 Rationale

The most important quality here is modifiability - see variability guide above.

8.6 Related Views

The data shown here is kept in the Configuration Database in Execution Control, see Execution Control C&C View.

8.7 Reference Documents

The following documents are referenced in this document. In the event of conflict between the contents of the referenced documents and this document, **this document** shall take precedence.

(no referenced documents)

9 Sky Model View Packet

Contributors: J. C. Guzman

9.1 Primary Representation

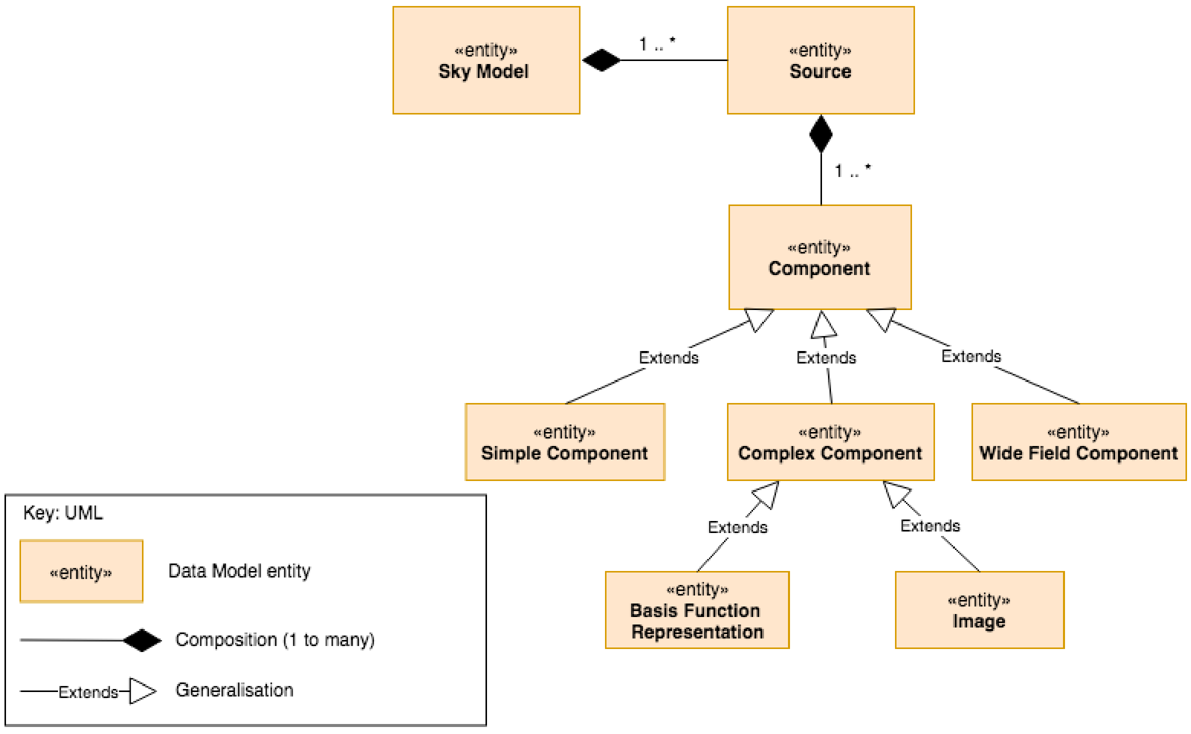


Figure 1: Sky Model Data Model diagram (attributes not shown in this diagram)

The Sky Model Data Model contains a suitably accurate description of the sky brightness distribution as a function of position, frequency and time. It describes the frequency dependence of this brightness distribution over a range suitable for both LOW and MID components of the SKA and is able to capture the temporal behaviour of sources known or found to be variable. There are two instances of the Sky Model: the Global Sky Model (GSM) and Local Sky Model (LSM). The GSM contains a collection of sources and components covering the entire sky (hence Global) visible to the SKA. The LSM contains sources within the region of interest for the calibration and imaging workflows. The LSM is part of the Science Data Model.

Sky Model components can be either point sources, gaussian or complex (shapelet or images). A detailed definition of these terms can be found in the next section. Figure 1 represents the abstract model at the entity level. To simplify the diagram, attributes of the entities are not shown but described in Section 2.1.

The GSM is searchable and a suitable subset of sources spanning the field of view and frequency range of that observation are returned. The list of sources returned usually corresponds to the LSM and it is used by the calibration and imaging workflows.

The GSM contains the following types of information related to astronomical sources:

- Point sources with full Stokes parameters

- Time variability
- Resolved sources using compact basis set representations
- Complex spectral structures
- Information on planetary and solar radiation sources

In the case of planetary and solar radiation sources, it is likely that the models will be taken from existing external ephemeris services. Currently only major solar system objects are needed in the GSM for the purpose of schedule and execute the SDP processes.

Large sources are split into multiple components: collections of Gaussians, shapelets, images, etc. For extremely large sources like diffuse galactic emission, the GSM supports full sky image that includes diffuse emission and it is up to the imager (A-projection, faceting, etc.) to incorporate primary beam structure. Bright components in the galactic plane like supernova remnants (SNR) can be added as separate collections of Gaussians, shapelets, (postage-stamp) images, etc. The imaging workflow predict module, for instance, expects both a sky model image (for degridding) and sky model components (to either be added to the image before degridding or predict using a direct Fourier transform).

9.2 Element Catalogue

9.2.1 Elements and Their Properties

The sky model data model has the following structure:

- **Source** is defined as a 'real' astronomy source. This may consist of a number of separated regions on the sky. For example a double radio source may have two extended 'lobes' of emission with little or no emission in the region between them. A source consists of one or more ***components***.

- **Component** describes a single object component. This is one of:
    - ***Simple component*** described in terms of a Gaussian model appropriate for unresolved or sources which are expected to be marginally resolved
    - ***Complex component*** where the representation is:
        - ***Image***, or multiple sky images at different resolutions
        - ***Basis Function Representation*** where the structure is specified in terms of a specified set of basis vectors. The representation may also have a frequency dependence. The data model allows any basis set to be supported. For each basis set corresponding code to interpret the basis is included in the in-memory data-models module. Common basis sets include
            - Shapelets. Generally a shapelet is an orthonormal polynomial (Hermite) multiplied by a Gaussian. There are rectangular and polar shapelets. A detailed mathematical representation of shapelets can be found in [RD9.1].
            - A series of delta functions - often referred to as “clean components”
            - Spherical harmonics for structure on the sphere
    - ***Wide field component***. This will be supported by the Healpix representation which is a common standard for wide-field or near all-sky images and allows for a multi-resolution representation.

9.2.1.1 Source

Properties of the Source entity:

- Name. Astronomical name of the source (e.g. Fornax A, Cen A)
- Coordinates
    - Coordinate system
    - Epoch
    - Ephemeris data for solar-system objects
- Position expressed in coordinate system
- Extent expressed in coordinate system - used for searching on relevance
- Number of components
- Link or index to each component
- Quality information

9.2.1.2 Component

Component can be either a Simple, Complex (Shapelet or Image) or wide field. A component contains a common list of attributes (frequency independent) and a list of attributes that are dependent of type and frequency. Every component contains or is represented at least as a simple component. Additional types of component can be added as an extension of the simple component with additional attributes for the frequency dependant part.

The frequency-independent attributes of a component are mainly of the type (Simple, Shapelet, Image or Wide-field) and its position in the reference coordinate system defined in the parent source, that is: right ascension (RA) and declination (DEC), and its uncertainty in the measured (or calculated) position.

The component contains frequency-dependant attributes. These attributes are usually of type scalars or array (vector) of scalars with corresponding unit. Each of this attributes also has a uncertainty value. The list of attributes for simple components are taken from [RD9.2] and contains the following kind of attributes:

- Reference frequency
- Time when the attribute's values were last updated
- Polarisation information (I, Q, U, V)
- Rotation Measure
- Spectral Indices per polarisation (as polynomial coefficients describing the model spectrum of the component). There will be special cases of Faraday-complex linearly polarised components (example, primary components) which will require a full spectrum information instead of spectral indices.
- FWHM of the major and minor axis of the Gaussian
- Position angle or orientation of the gaussian

In addition to the list above, there is also an "origin" attribute which contains information of instrument of origin this Model was obtained.

For Complex component that are described as a shapelet, there are additional frequency-dependant attributes the describe the shapelet coefficients (See [RD9.1]).

When the component cannot be described as a shapelet, an image of the component is stored in the data model. This image contains also metadata information and frequency dependant information.

In order to support time variability, for a determined component uniquely identified by position and frequency, there will be multiple values in time. The time will be the time when the attributes were calculated (or the image obtained).

A wide field component is represented as a HEALpix data entity. The logical data model for HEALpix is described in [RD9.7].

9.2.2 Relations and Their Properties

The relations between the entities are either composition (part-of) or generalisation (is an extension) are depicted in Figure 1. The GSM and LSM are instances of the abstract Sky Model entity described here.

The GSM is usually queried by the calibration and/or imaging workflows.

9.2.3 Element Interfaces

This document describes mainly the data structure contained in the Sky Model. Despite not being specific on the implementation, it is important to describe here the intended usage of this data as part of future implementation of the module or service which supports the Sky Model. Access to the Global Sky Model will be an API supported by the service implementation.

The interface to the Sky Model should support:

- Interface for managing source entries
- Insert, Read, Update and Delete operations.

The primary consumer of this data will be the calibration and imaging workflows. This module will query the Global Sky Model “service” in order to obtain the local sky model of the observing field. This query is usually in the form of cone search around a centre position of the sky and frequency. The return will be a list (table) describing each source component in the region of interest.

9.2.4 Element Behavior

Insertion of new values for a component in the internal catalogue are added to the database with a corresponding timestamp. Consumer requesting a cone search by default will return a list of sources and components with the most up-to-date attribute values (simple or complex). Alternatively the GSM will support other type of query parameters such as time or frequency.

The service will likely search the internal catalogue first for sources and components in the region. If no sources are found, the service will search external catalogues.

9.3 Context Diagram

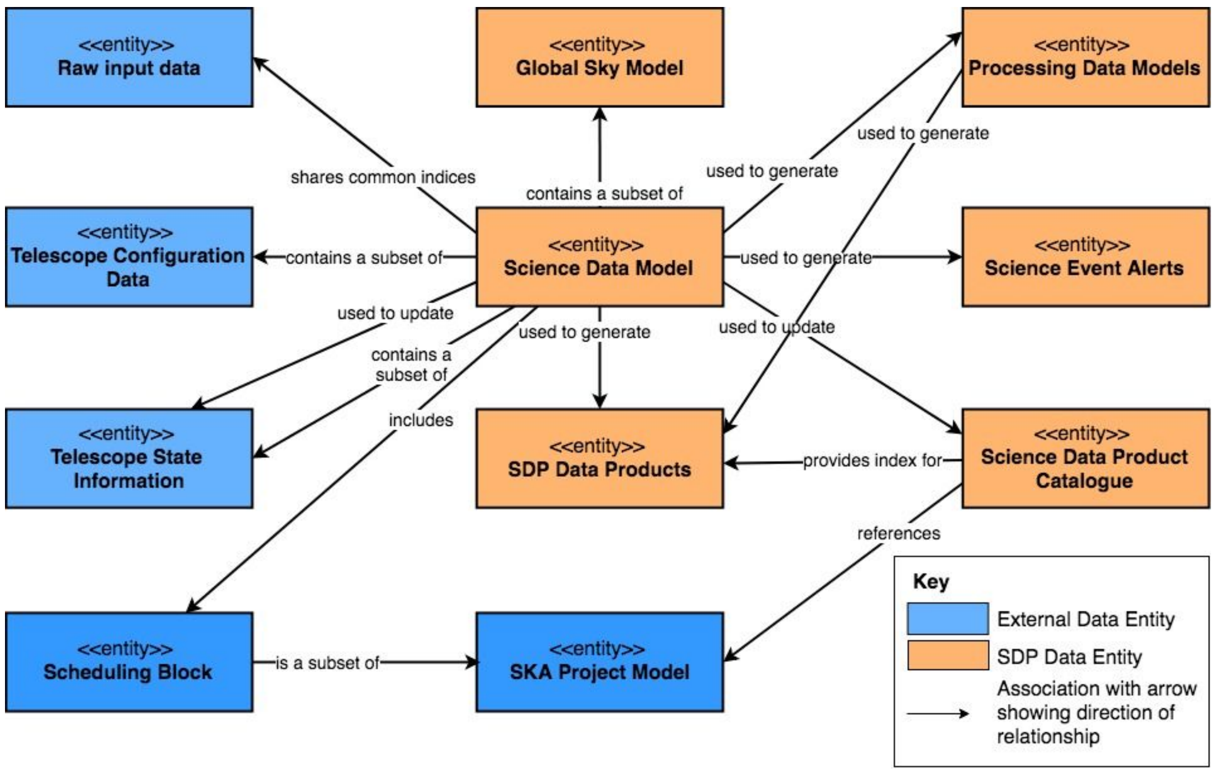

<<entity>> Raw input data
<<entity>> Global Sky Model
<<entity>> Processing Data Models
<<entity>> Telescope Configuration Data
<<entity>> Science Data Model
<<entity>> Science Event Alerts
<<entity>> Telescope State Information
<<entity>> SDP Data Products
<<entity>> Science Data Product Catalogue
<<entity>> Scheduling Block
<<entity>> SKA Project Model
shares common indices
contains a subset of
used to generate
used to generate
contains a subset of
used to generate
used to update
contains a subset of
used to generate
used to update
includes
provides index for
references
is a subset of
Key
External Data Entity
SDP Data Entity
Association with arrow showing direction of relationship

Figure 2: System-level SDP Conceptual Data Model

The Science Data Model contains the Local Sky Model, which is a subset of the Global Sky Model. This is the only relationship between Global Sky Model and other data entities in the SDP System-level Conceptual Data Model [RD9.6].

9.4 Variability Guide

The architecture is structured so that new component types can be added with backwards capability. Similarly new basis vector types can be defined.

Two important variants of the Sky Data Model are implemented:

- Global Sky Model - this is the variant containing all of the sky model. It is maintained at system level.
- Local Sky Model - this is created by subsetting the Global Sky Model and is part of the Science Data Model with one instance per processing block. The Local sky model may be updated during execution.

The Global Sky Model supports time variability by storing timestamp information of when the component's frequency-dependant attributes were measured and calculated. This allows tracking of changes in the component's attributes. There is an additional attribute, ORIGIN which allows capturing the origin of this component, whether internal (SKA instrument) or from an external catalogue or instrument.

9.5 Rationale

The need for a Sky Model is nothing new in radio interferometry. Most of the existing calibration and imaging software packages rely on some form of sky model. LOFAR [RD9.4] and ASKAP [RD9.3] telescopes have implemented similar services that support a Global Sky Model for their calibration and imaging needs. Most of the entities and its attributes are found also in external catalogues (see Section 2 of [RD9.2]).

Most of the entities and attributes described in this document were collated from existing implementations and adapted for SKA, including the option of extending the types of components.

9.6 Related Views

- Image data model view
- System-level Data Model View
- Science Data Model View
- ICAL Workflow View Packet
- Imaging Workflow View Packet

9.7 References

The following documents are referenced in this document. In the event of conflict between the contents of the referenced documents and this document, **this document** shall take precedence.

[RD9.1] Yatawatta, "Shapelets and Related Techniques in Radio-Astronomical Imaging," URSI GA, Istanbul, Turkey, Aug. 2011.

[RD9.2] SKA-TEL-SDP-0000139 SDP Memo 033: Sky Model Considerations

[RD9.3] CSIRO ASKAP Science Data Archive Data Model schema

[RD9.4] The LOFAR Transient Pipeline online documentation https://tkp.readthedocs.io/en/r3.0/devref/database/schema.html#database-schema

[RD9.5] Scheers, L. H. A. (2011). Transient and variable radio sources in the LOFAR sky: an architecture for a detection framework https://dare.uva.nl/search?identifier=68164d5a-7bba-42bf-8638-876678ecb1d4

[RD9.7] https://healpix.jpl.nasa.gov

10 Gridded Data Model View Packet

Contributors: T. Cornwell

10.1 Primary Representation

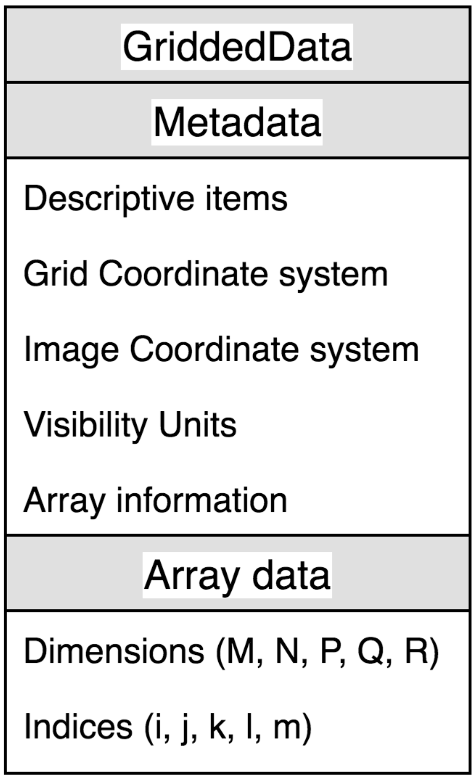


Figure 1: GriddedData model primary representation.

Visibility data require a complex schema to encode all the relevant information necessary to extract the required science. In SDP the Visibility Model View describes the schema. Ultimately the goal of calibration and imaging processing is construction of an image on a regular grid on a sky projection, usually the SIN projection. The Image Model is described in the Image Model View.

The conversion of visibility data into an image is most commonly done by estimating the equivalent data on a regular grid in u, v, w space (gridding to a GriddedData), and then using the FFT to transform to image space. A common intermediate and often transient data product is the visibility data on the regular grid. This must keep track of both the sampling in u, v, w space, and the coordinate system for which u, v, w are defined.

The same structure is also needed for prediction of the visibilities from a model Image. The model Image is transformed via FFT to the gridded u, v, w space (as a GriddedData), and the visibilities estimated from the grid (degridding).

There are three reasons for elevating the gridded data to a well-defined model:

1. GriddedData is a required science product for some HPSOs (e.g. lensing)
2. Binding the grid and coordinates into one Model allows compact interfaces
3. Many gridding/degridding gridding algorithms make use of a set of common functions

In addition to this most commonly used approach to gridding the data prior to an FFT, there are other newer approaches that proceed differently. For example, IDG ([RD10.1]) transforms patches of data to the image plane directly and then performs an inverse transform back to uv space. This in effect grids the data and the GriddedData model can be used as an intermediate product. Another relatively new technique, w-stacking ([RD10.2]) can be implemented as a collection of GriddedData (as done, for example, in the ARL).

10.2 Element Catalogue

10.2.1 Element and Their Properties

The grid data type consists of metadata and array data.

The metadata are

- Grid coordinate system: maps the indices of the array data to the physical coordinates of the pixels. Typically the axes are u, v, w, frequency. The axes u, v, w are conjugate to the image coordinate system. The definition comes from the SDM.
- Image coordinate system: Describes the image plane coordinate system associated with the grid coordinate system i.e. the direction, frame, and projection. The definition comes from the SDM. Note that image coordinate system can be in l, m, n (i.e. a cube encompassing part of the celestial sphere). Note that there is no Image data just the coordinate system.
- Visibility units: the units of the visibility data, such as Jy, None. The definition comes from the SDM.
- Array information: information on the size and layout of the array data. Possible layouts are described in Section 2.6.

The array data consists of a four-dimensional array of pixels (U, V, W, frequency). The elements in the array are can be typed e.g. float, complex, visibility as a 4-vector, visibility as a 2x2 matrix.

10.2.2 Relations and Their Properties

n/a

10.2.3 Element Interfaces

GriddedData plays a central role in imaging. The interfaces are not listed here. Instead we list the functions that must be supported by the GriddedData API:

- Construction from Image Data and Visibility Data.
- Gridding: insertion of visibility values using e.g. convolutional gridding. W, A, and I projection are supported.

- De-gridding: extraction of visibility values using e.g. convolutional degridding. W, A, and I projection are supported.
- Anti-aliasing, including correction in image space.
- Fourier transforms: from Image Model, using a number of algorithms e.g. 2D FFT, W stacking, 3D FFT. Sub-sectioning and shifts in both Image and UVW are required.
- Inverse Fourier transform: to Image Model, using a number of algorithms e.g. 2D FFT, W stacking, 3D FFT. Sub-sectioning and shifts in both Image and UVW are required.
- Weighting such as noise inverse-variance weighting, robust weighting, uniform weighting.
- Tapering with UV coordinate, such as Gaussian or Tukey tapering.
- Bad data flagging, for example by deviation from the gridded data in u,v,w neighbourhood
- Addition, subtraction and other dyadics.
- Insertion into and extraction from other GriddedData,
- Persistence (e.g. via the SDP Buffer)
- Conversion to science data product.

10.2.4 Element Behavior

The element is a passive data holder. It is constructed, manipulated by various functions, persisted and moved as required, and ultimately converted to a Science Data product.

10.2.5 Indices and Keys

The grid array data indices are mapped by the coordinate system to and from the world coordinates of the pixel in the grid. The spatial axes (u, v, w) are in the projection specified by the image coordinate system.

10.2.6 Structure and Access Patterns

GriddedData participates in some of the most resource-hungry processing. The primary access patterns are:

- By pixel (e.g. visibility 4-vector or 2x2-matrix).
- Random access in u,v and possibly w, needed for gridding and degridding. Slowly changing locality can be used to limit access rates.
- Regular access for FFTs, separately for each channel.
- Strided access for GriddedData being used as an oversampled convolution function.

Parallel access is required so that different parts of the grid may be read or written simultaneously.

10.3 Context Diagram

Gridded Data is used in imaging steps Predict and Invert as defined in the Imaging Data Model view. See figure 2. There are summations implied at the termination of the partition loops so that the predicted visibility is the sum over all partitions and the image is the (weighted) sum over all partitions.

Note that in the grid and de-grid steps, only the visibility metadata need be read.

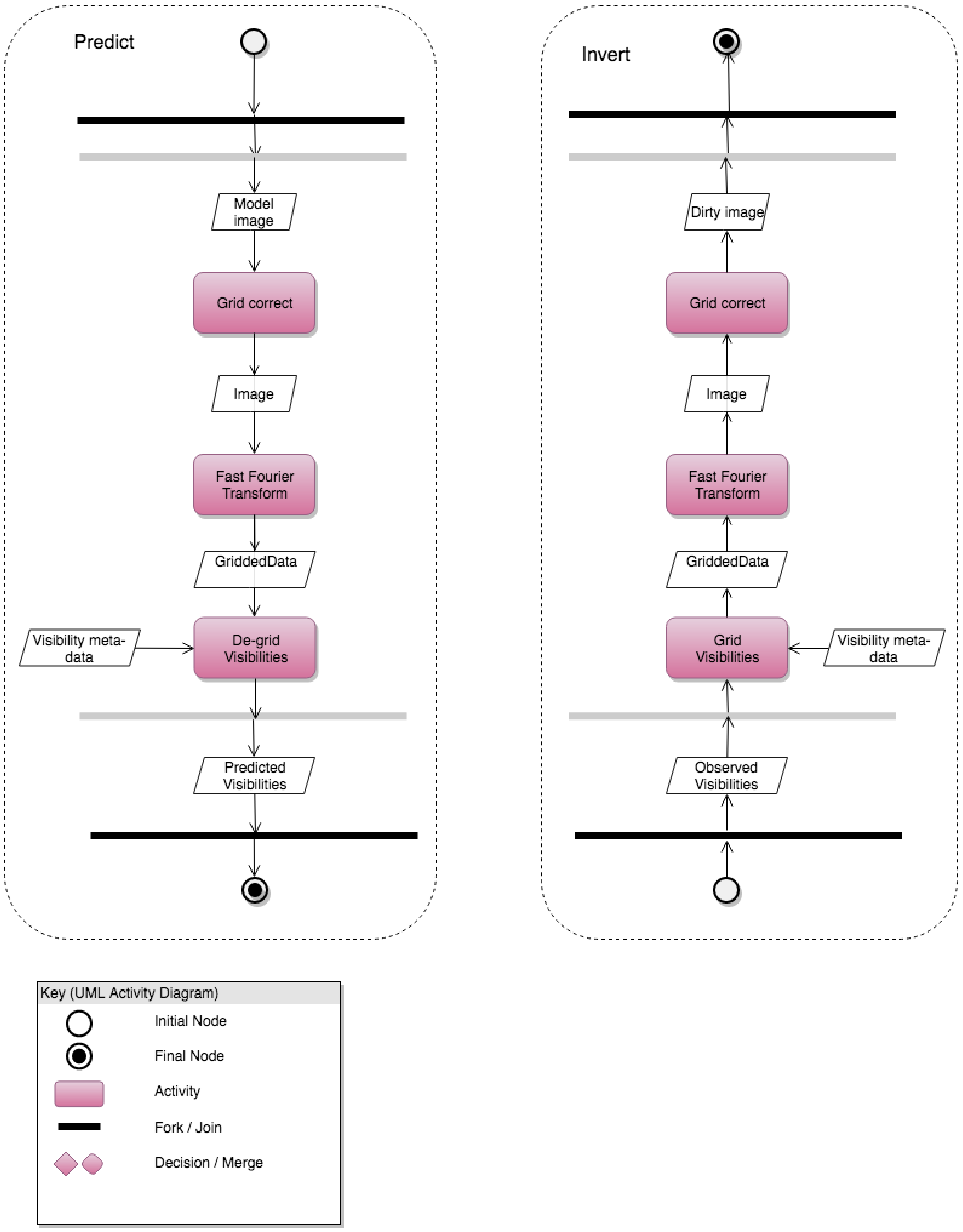


Figure 2: Use of GriddedData in Predict and Invert workflows (see Image Data Model view). Note that the flow directions from left side to right side are opposite but the structure is the same. Distribution is possible over both Image (Grey) and Visibility (Black).

Distribution of these workflows is possible using many methods:

- W stacking: W has multiple planes ([RD10.2])Time slices: a collection of GriddedData, one for each snapshot.
- Facets: a collection of GriddedData, one for each facet
- Image Domain Gridding: IDG ([RD10.1]) decomposes into a collection of multiple DataGrids, one per subsection of uvw space.

10.4 Variability Guide

GriddedData will vary according to algorithm and partitioning. Some examples:

- 2D and w projection imaging: W is a single plane.
- W stacking: W has multiple planes.
- Combined W stacking/W projection is also possible. The range in W is limited to the gap between slices.
- Time slices: a collection of GriddedData, one for each snapshot. Time is not necessarily a regular axis so we use a collection rather than encoding Time into a regular axis.
- Facets: a collection of GriddedData, one for each facet. Similarly to Time, we use a collection rather than encoding facet number into an axis.
- Image Domain Gridding: IDG decomposes into multiple GriddedData.

10.5 Rationale

- GriddedData is a science data product, needed for lensing studies, for example.
- GriddedData may be the result of a complex processing chain including calibration, flagging, model subtraction.
- FFT's for the SKA context often dominate the processing costs. The GriddedData model allows co-addition of grids prior to FFTs instead of co-adding dirty images after FFT's.
- Convolution functions can use the GriddedData interface by specifying an appropriate offset and stride into a GriddedData.
- Development of gridding/degridding algorithms is likely to continue for the foreseeable future. GriddedData is useful in expressing current and new algorithms.
- Detailed tracking of coordinate systems in both Image and Fourier space is essential to problem partitioning.
- Use of GriddedData factors existing algorithms in a more compact and robust form.
- Storing results in GriddedData format allows avoidance of the zero-padding bloat incurred in the FFT (though this also could be done by storing critically sampled images and sinc interpolation before e.g. cleaning.)

10.6 Related Views

- Image Data Model View
- Visibility Data Model View
- Imaging Data Model View

10.7 References

The following documents are referenced in this document. In the event of conflict between the contents of the referenced documents and this document, **this document** shall take precedence.

[RD10.1] Sebastiaan van der Tol, Bram Veenboer, and André R. Offringa, Image Domain Gridding: a fast method for convolutional resampling of visibilities. A&A, Volume 616, August 2018

[RD10.2] T. J. Cornwell, M. A. Voronkov, and B. Humphreys, “Wide field imaging for the Square Kilometre Array,” arXiv.org, vol. astro-ph.IM. SPIE, p. 5861, 25-Jul-2012.

11 Image Data Model View Packet

Contributors: M. Ashdown

11.1 Primary Representation

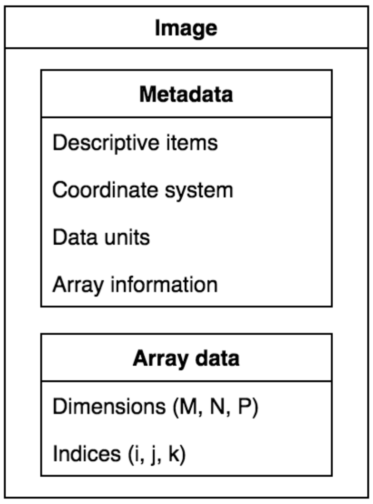


Figure 1: Image data model (ad-hoc notation). Each box represents a logical grouping of data items.

The image data model shown in Figure 1 describes the logical data model for radio astronomy images. In this context, images typically have at least three dimensions, two for spatial position and one for frequency. This model is a data type/class of which multiple instances are used in processing.

11.2 Element Catalogue

11.2.1 Elements and Their Properties

The image data type consists of common metadata and one or more sub-images. Each sub-image consists of metadata and array data.

The metadata are:

- Descriptive items: data to describe the image. This is not further defined here, since the requirements on this will evolve over time.
- Data units: the units of the array data.
- Coordinate system: describes the coordinate system to map the indices of the array data to the physical coordinates of the pixels. The mapping is described in Section 2.5.
- Array information: information on the size and layout of the array data. Possible layouts are described in Section 2.6.

The array data consist of a three-dimensional array of pixel values. Each array is described by its dimensions (M, N, P) with indices (i, j, k). The elements in the array can be scalars or higher-dimensional entities. Higher-dimensional elements are required to support polarisation Stokes parameters (I, Q, U, V) or Taylor terms. (A combination is possible, for example, Taylor terms in Stokes I and V.)

11.2.2 Relations and Their Properties

Not applicable.

11.2.3 Element Interfaces

Not applicable.

11.2.4 Element Behavior

Not applicable.

11.2.5 Indices and Keys

The indices (i, j, k) of the array data are mapped by the coordinate system to the coordinates of the pixel in the image, as shown in Figure 2. The first two indices (i, j) are mapped to the spatial coordinates of the pixel, and the projection used to do this mapping is specified as part of the coordinate system. Pixels can be mapped to local coordinates (x, y), right ascension and declination (α, δ), or Galactic coordinates (l, b). The third index k corresponds to the frequency channel, and this is mapped to the frequency, f.

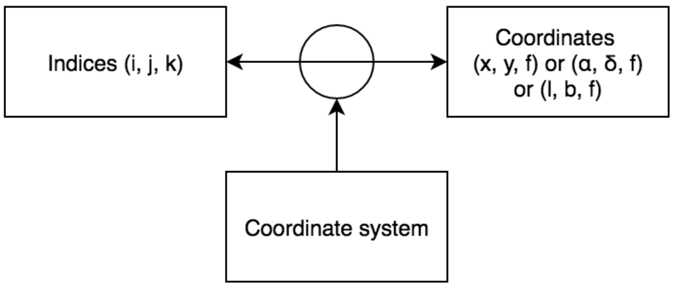


Figure 2: Mapping from array indices to image coordinates is done using the coordinate system.

11.2.6 Structure and Access Patterns

There are three typical access patterns for the array data when processing an image:

- The entire spatial extent for a particular frequency channel or block of frequency channels, where the block will typically be small. This is illustrated in Figure 3.
- By block in both position and frequency, where the block will typically be moderately sized in all dimensions. This is illustrated in Figure 4.
- The entire frequency range for a particular spatial position or block in position, where the block will typically be small in both dimensions. This is illustrated in Figure 5.

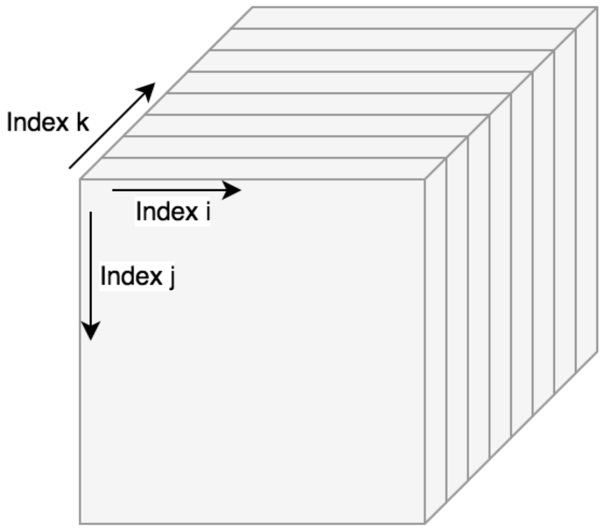


Figure 3: Image array data access by frequency or block in frequency.

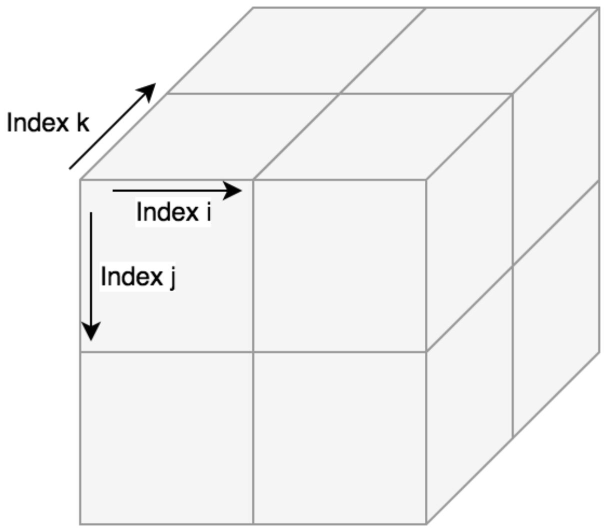


Figure 4: Image array data access by block in position and frequency.

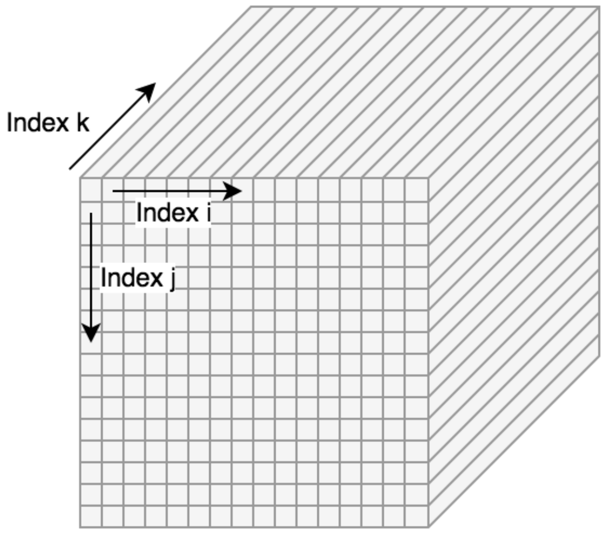


Figure 5: Image array data access by position or block in position.

11.3 Context Diagram

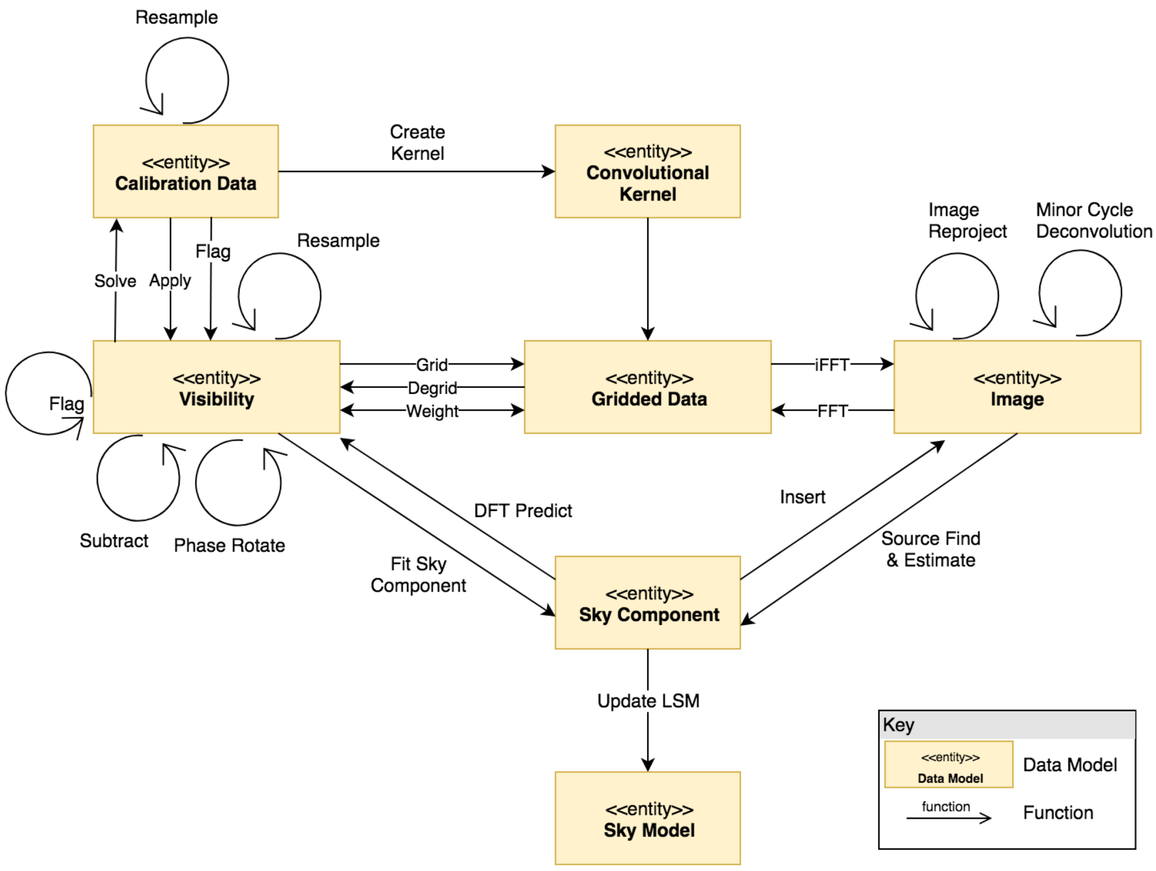


Figure 5: Data transition diagram showing the relationship between the Image Data Model the other processing data models.

The data transition diagram in Figure 5 shows the relationship between the Image Data Model and the other processing data models used in interferometric imaging. The arrows show the operations that convert one data model into another. Image and Gridded Data are related by a 2-D Fourier transform (shown as “FFT” and “iFFT”). The “Source Find and Estimate” operation finds a source in an Image, and then estimates its properties (such as position, amplitude, shape and spectrum) to generate a Sky Component. Its inverse is the “Insert” operation that converts a Sky Component into a pixellated version and inserts it into an Image at the appropriate position.

11.4 Variability Guide

Not applicable.

11.5 Rationale

Conventions for mapping the array indices to physical coordinates have been developed as part of the FITS image standard, see the FITS World Coordinate System (WCS) [RD03]. Even if the FITS format is not used as the physical implementation of this data model, its coordinate system conventions are well-established in astronomy, so it may prove convenient to use them in this data model.

If an observation covers a large bandwidth, the image may be divided into a number of sub-bands. Each sub-band corresponds to a different frequency range, and it may have different spatial extent and pixel size, so each sub-band needs its own coordinate system to describe the mapping between pixel indices and physical coordinates. Figure 6 shows an example of the arrangement of sub-bands in an image and the mapping of indices to position and frequency coordinates. In this example, the sub-bands are shown to adjoin in frequency, but that does not need to be the case. This data model does not support multiple coordinate systems for a image, so an image containing multiple sub-bands would be represented using multiple instances of the image data type.

Images from the SKA may be very large (tens or hundreds of TB), so the physical implementation(s) of this logical data model must take into account that an image may be distributed over many processors. The access patterns described in Section 2.6 should inform the implementation of both the parallel distribution and the storage of image data.

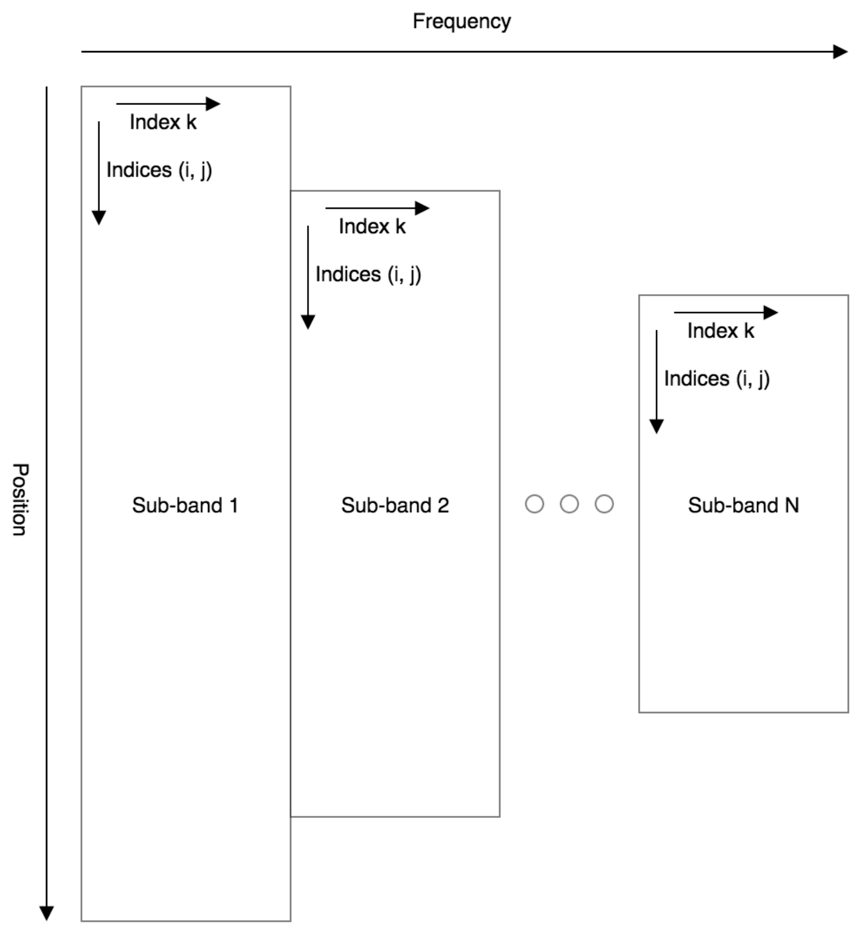


Figure 6: Arrangement of multiple sub-image arrays in the representation of an image with sub-bands. Each sub-band is represented by a sub-image in the data model. The position and spatial indices (i, j) have been represented as a single dimension.

11.6 Related Views

The Processing Component Module View provides the context for this view as shown in Section 3.

11.7 Reference Documents

The following documents are referenced in this document. In the event of conflict between the contents of the referenced documents and this document, **this document** shall take precedence.

[RD11.1] FITS World Coordinate System (WCS), https://fits.gsfc.nasa.gov/fits_wcs.html

12 Processing Data Model View Packet

Contributors: J. C. Guzman

12.1 Primary Representation

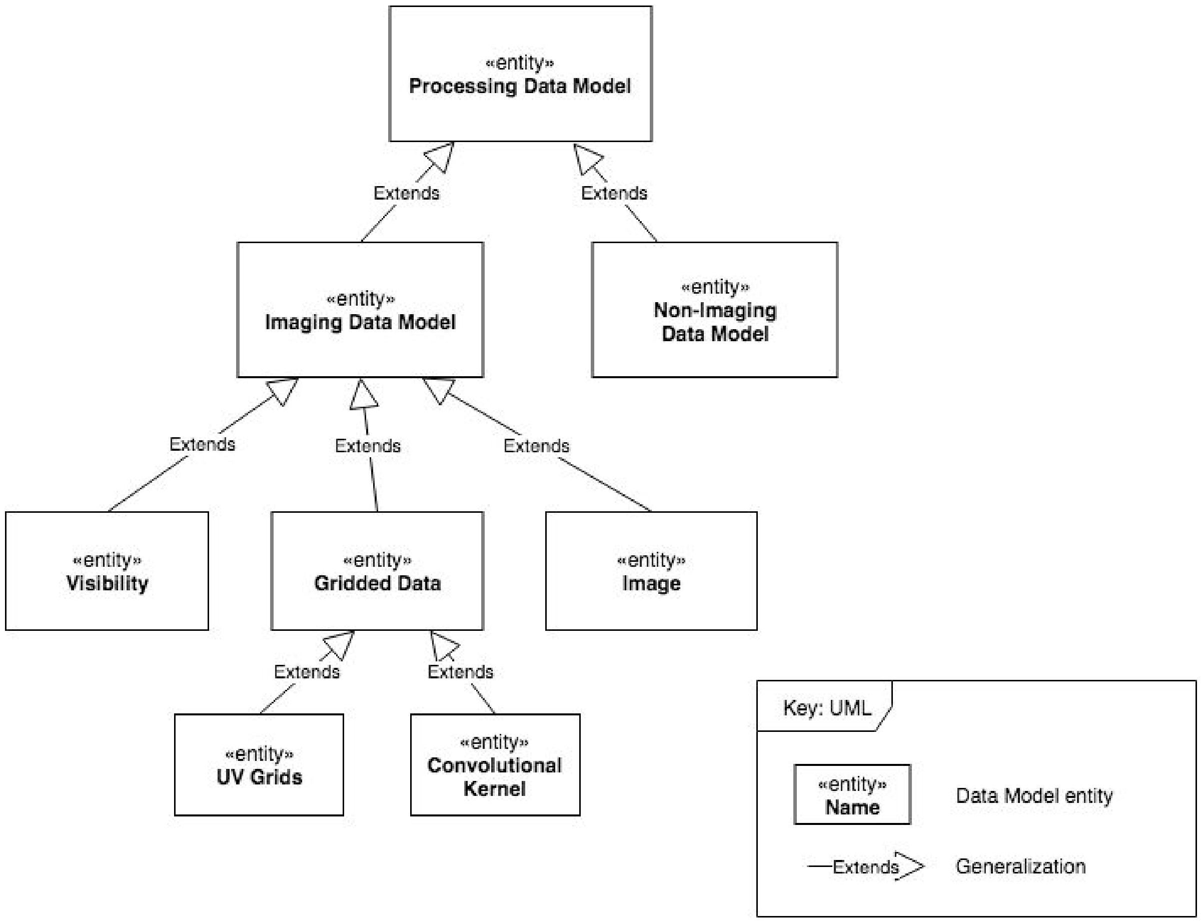


Figure 1: Primary Representation of the Processing Data Model

The Processing Data Model is a placeholder for all data created, updated or transformed by the imaging or non-imaging workflows. The Processing Data Model is mainly a generalisation of different types of data model handled by the workflow pipelines, such as visibilities, gridded data and images as depicted in Figure 1. As a general logical data model, the Processing Data Model contains metadata and n-dimensional data, commonly referred as data cubes. Most of this document (and individual element Views) describes the logical representation of the model.

This data model was previously called intermediate data models as it represents mainly the data consumed and produced by the scientific workflow pipelines that are not required to be sent to the Delivery system, hence stored indefinitely or part of the Science Data Products. This data model currently extends to n-dimensional data such as visibilities, gridded data and images, but could be extended to other intermediate data products in the future.

This document follows from the System-level Data Model View to decompose further into individual data models that are handled by the workflow pipeline. These individual data models are described briefly in the next section and further detailed on their own View packet.

12.2 Element Catalogue

12.2.1 Elements and Their Properties

12.2.1.1 Imaging Data Models

12.2.1.1.1 Visibility

The Visibility Data Model describes the data structures containing visibilities, weights, flags and UVW-coordinates. It does not describe the visibility data format as it comes from the correlator. The latter is described in the CSP - SDP ICD [AD10].

The Visibility Data Model comprises of metadata and a high-dimensional data cube. The metadata contains all necessary information to perform calibration and imaging tasks. The high-dimensional cube of data consists of visibility, weights, flags and UVW coordinates. Different types of axes can be used to access the high-dimensional cube of data: time, frequency, baseline, etc.

A detailed description of the Visibility Data Model can be found following this view.

12.2.1.1.2 Image

The Image Data Model consists of metadata and an array of data. The metadata contains descriptive information about the radio astronomical image (could include instrument information or telescope configuration data), world coordinate system, units of the data and description of the array. The array data consist of a three-dimensional array of pixel values.

There are different types of images depending on the task or algorithms executing within the imaging workflow pipeline:

- Residual Image
- Sky Components / shapelets
- Dirty Image
- PSF Image

Detailed Image Data Model is described above.

12.2.1.1.3 Gridded Data

Gridded data is a rectangular array of complex values. Probably 8-byte floats are needed to have sufficient accuracy. The shape of the array is the same as the shape of the image. Probably it'll even be larger to accommodate image padding. For Continuum Imaging a few Taylor terms have to be used in order to solve for the spectral index. For Spectral Line Imaging one image is made per frequency channel and no Taylor Terms are added.

There are two compositions of Gridded Data:

- Time slices: a collection of GriddedData, one for each snapshot.

- Facets: a collection of GriddedData, one for each facet
- Convolution Kernels such as: w-kernel, a-kernel, anti-aliasing, over-sampled.

The detailed Gridded Data Model is described above.

12.2.1.2 Non-Imaging Data Models

The Non-Imaging Data Models is a generalisation of data used by different non-imaging workflow pipelines:

- Pulsar Search
- Single Pulse (Fast transient) Search
- Pulsar Timing Mode
- Dynamic Spectrum Mode
- Flow Through Mode

The detailed Non-Imaging Data Model is described below.

12.2.2 Relations and Their Properties

Processing Data Models are related to the Science Data Products (Calibrated UV grids) and to the Science Data Model (Local Sky Model). A Local Sky Model is needed by the imaging workflow to generate a Model Image. A detailed description of the relationship between these data models is in the Processing Component Module View.

Gridded Data (UV Grids) generated by the imaging pipeline workflow will be stored as Science Data Products.

Bear in mind that several of the Processing Data Models are also used by the calibration pipeline workflows. There is a Calibration Data Model describing these in greater detail.

12.2.3 Element Behavior

Processing Data Models are primarily consumed or produced by the imaging and non-imaging processing components. Transitions between data models are performed by algorithms present in the processing components module. Details of these transitions are described in the Processing Component Data Module View.

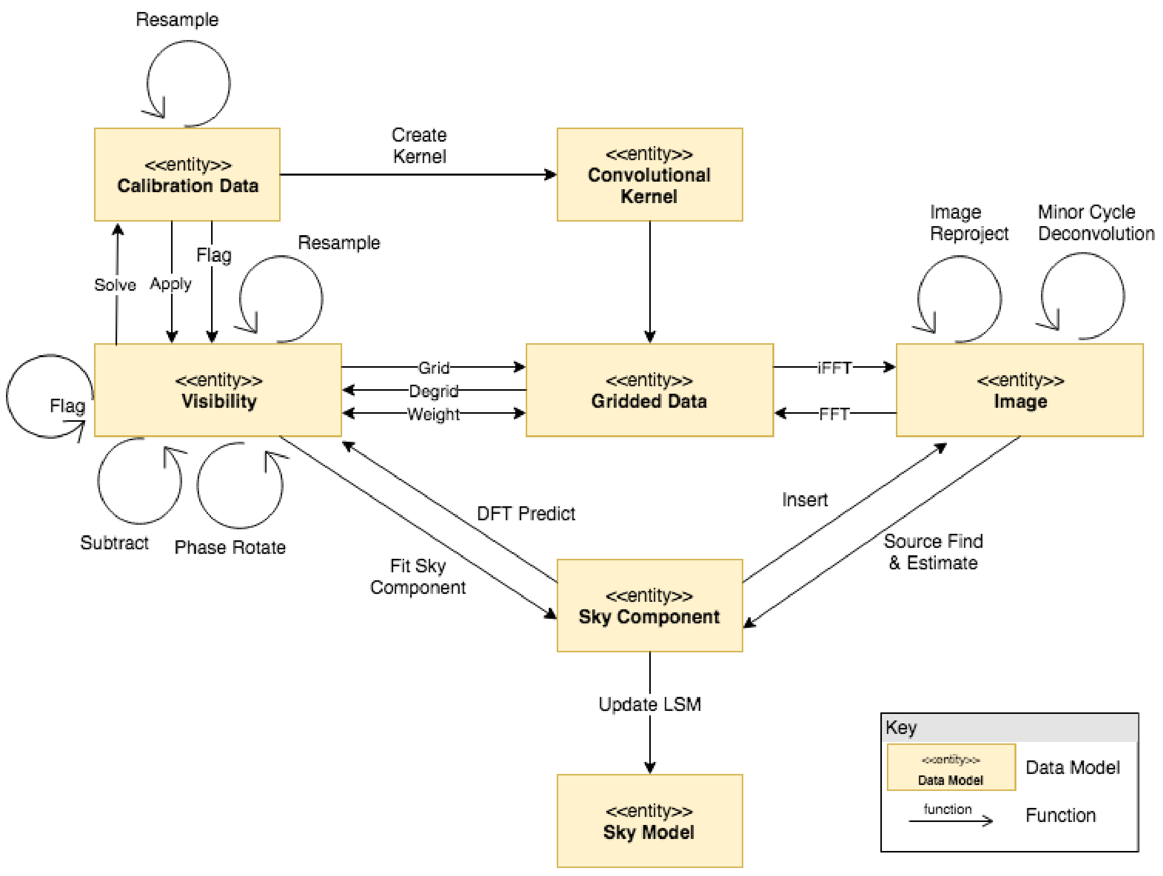


Figure 2: Data transition diagram and relationship between Calibration and Sky Models, copied from Processing Component Module View

12.3 Context Diagram

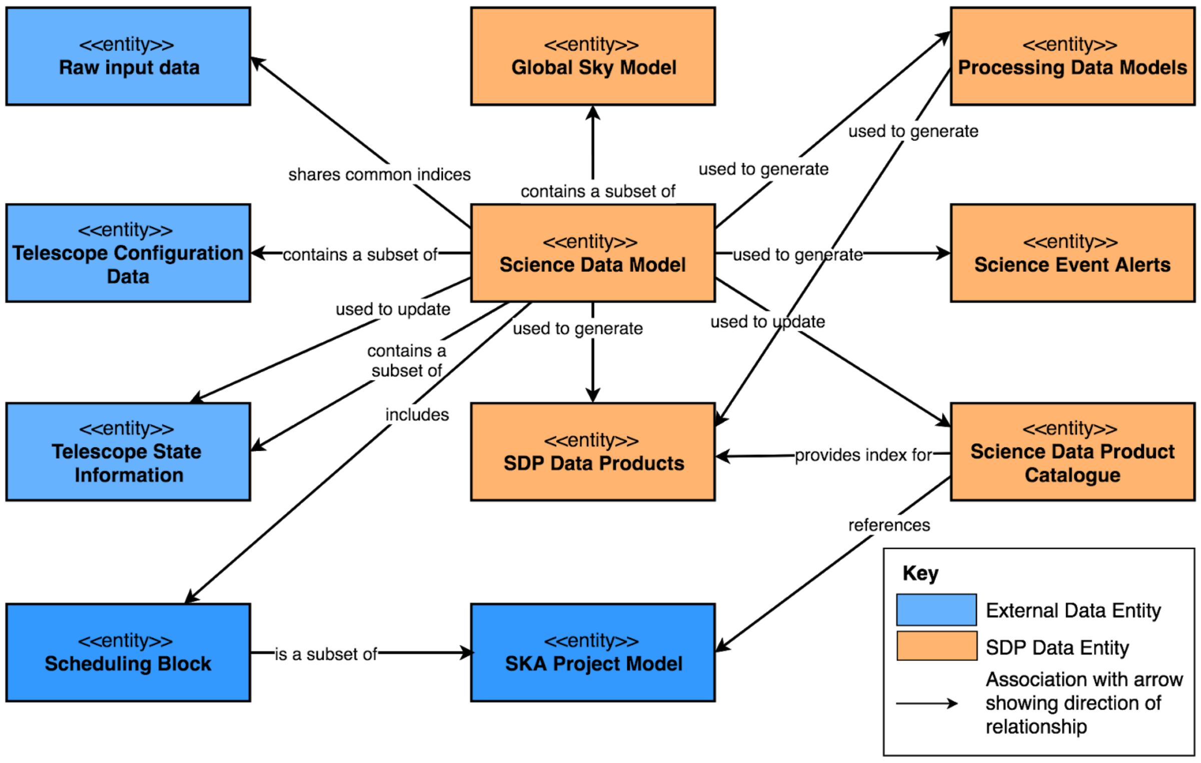


Figure 2: System-level Data Model

12.4 Variability Guide

The Processing Data Model is a generalisation of logical data models handled by imaging or non-imaging workflow pipelines. New kinds of processing data models are possible by simply adding a new specialised processing data model.

12.5 Rationale

The Processing Data Model is simply a generalisation of data created or updated by imaging or non-imaging workflow pipelines. Each specialised processing data model shares the same logical structure (metadata and data cube or array) hence it makes sense to group them together as a similar type as shown in Figure 2 (context diagram).

12.6 Related Views

The Processing Data Model is used to generate Science Data Products (images, GriddedData) and in calibration (Gain Tables). The Local Sky Model (part of the Science Data Model) is needed by processing functions to generate some of the Processing Data Models.

The Processing Data Model contains the following Data Models:

- Visibility data model view
- Image data model view
- Gridded data model view
- Non-Imaging data model view

12.7 Reference Documents

None.

12.8 Non-Imaging Data Model View Packet

Contributors: U. Badenhorst, F. Graser, R. Lyon, L. Levin-Preston

12.8.1 Primary Representation

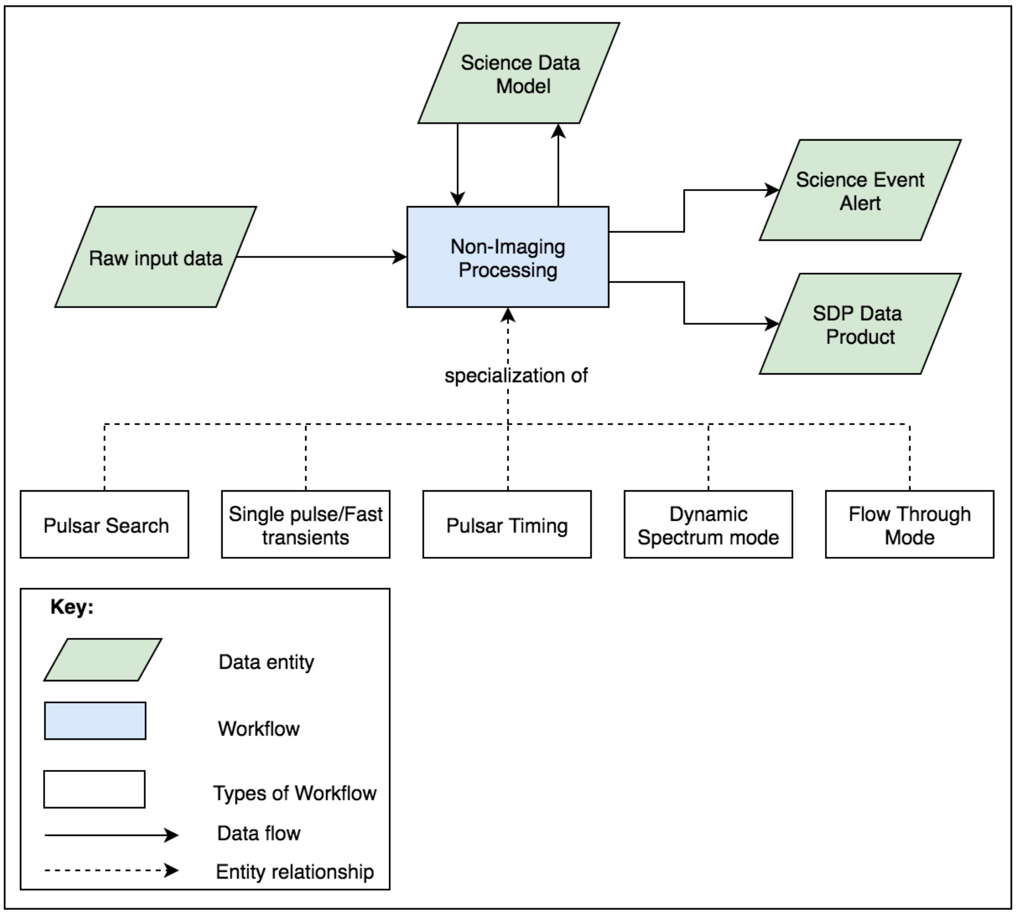


Figure 1: **Non-imaging data context diagram.**

This document describes the data models for the following Non-imaging workflows:

- Pulsar Search
- Single Pulse (Fast transient) Search
- Pulsar Timing Mode
- Dynamic Spectrum Mode
- Flow Through Mode

For each workflow (defined above) the data items (data and metadata), corresponding to the data items from the SDP system-level data model view, shall be described. The data model used for the Input data and the SDP Data Product is the same data model, with additional information (metadata) added during SDP Processing. The data models are the following:

- Raw Input data
- Science Data Model
- Science Event Alert - required for the Single-pulse Search pipeline, optional for the Pulsar Search and Pulsar Timing Pipelines (more details in sections 2.1.1.4, 2.1.2.4 and 2.1.3.4)
- SDP Data Product

This document shall not describe the physical model.

12.8.2 Element Catalogue

12.8.2.1 Element and Their Properties

Note that these are logical data models and therefore certain properties needed for implementation, such as primary keys are not mentioned in this document.

12.8.2.1.1 Pulsar Search Data Model

12.8.2.1.1.1 Raw input data

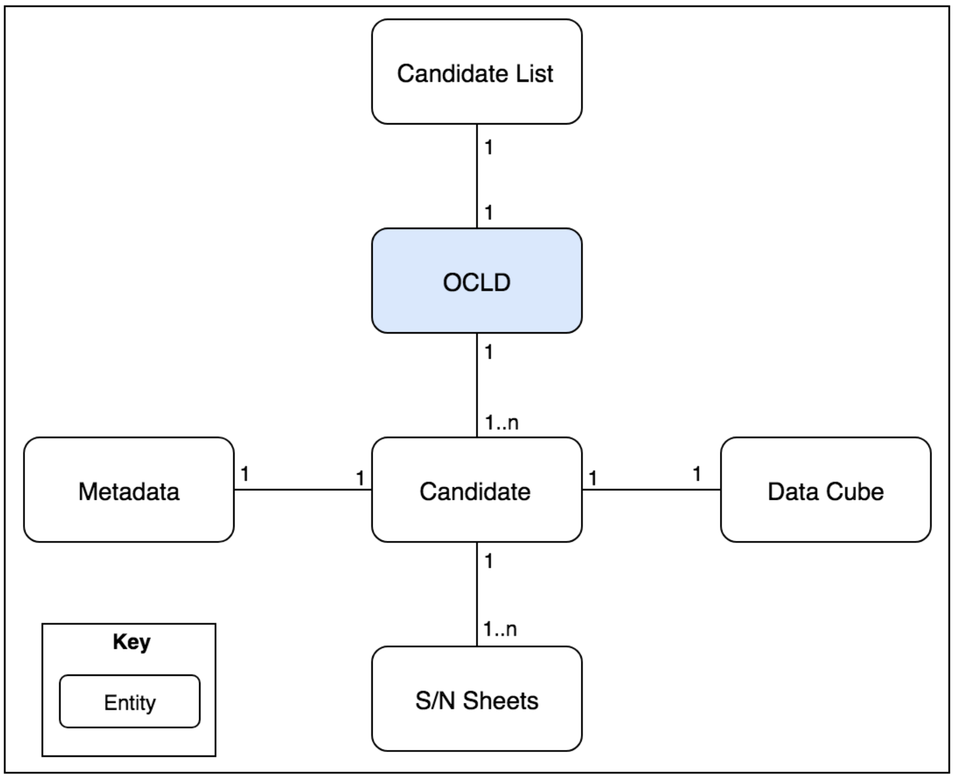


Figure 2: Logical data model of the Pulsar search raw input data

The input data to SDP pulsar search will consist of a large number of pulsar search candidates per scan. The pulsar search candidates, each containing a candidate's associated metadata, Signal-to-noise ratio (S/N) sheets and a datacube, are collectively known as an Optimised Candidate List and Data (OCLD). There shall be one OCLD generated per beam per scan. The OCLD contains only the most promising candidates (and their data cubes/metadata) found after sifting (see Section 2.1.2 in Pulsar Search and Single Pulse/Fast Transient Workflow View packet) within CSP, but the candidate list summarises all candidates detected prior to sifting for auditing/analysis purposes.

Candidate List

The list summarises all candidates detected during the CSP search prior to sifting. The list can have an unbounded length, though in practice it is limited to describing only those detections rising above some controlled significance level. The list will be sorted, most likely according to S/N. Each list entry describes a candidate with respect to sky location in the Equatorial Coordinate System [RD12.8.10], S/N, Dispersion Measure (DM, see [RD12.8.5]), pulse width, acceleration and period. See the table below for the current set of candidate list attributes [RD12.8.1]. This list is not final and more attributes may be added in the future.

Table 1: Current set of candidate list attributes

Item	Description	Type
Candidate ID	The unique identifier for the candidate	Textual or numerical
Beam ID	The beam the candidate was found in	Textual or numerical
RAJ	Right ascension (J2000) of the source	Textual or numerical
DECJ	Declination (J2000) of the source	Textual or numerical
Period	Period found during the search in milliseconds	numerical
Pulse width	Pulse width in milliseconds	numerical
Acceleration	Pulse acceleration	numerical
DM	DM found during the search	numerical
Spectral S/N	The spectral S/N found during the search	numerical
Folded S/N	The folded candidate S/N	numerical
Sifted	A flag indicating whether or not the candidate passed through the sifting procedure	boolean
Duplicate	A flag indicating whether or not the candidate has harmonic duplicates	boolean
Time stamp of detection	Exact time of occurrence	numerical

Candidates

The search data product is primarily comprised of a collection of candidate entities. Each candidate entity is analogous to the traditional pulsar candidate. The 1000 unique (i.e. after sifting) highest S/N candidates from the list, will be accompanied in the OCLD by their corresponding candidate entities. Each candidate entity is comprised of the following components:

- Candidate ID (attribute - TBC).
- Data cube: a single d-dimensional (folded) data cube. It describes a time and frequency averaged version of the detection. The data cube (1 per unique candidate) has the following axes:
  - frequency channels
  - pulse profile bins
  - temporal sub-integrations
- Each candidate is also associated with metadata. Metadata is either numerical or textual, and describes the observation/data product. Metadata will include for example, the pulsar observed, beam position, number of observing beams used, optimised DM etc. The metadata will also describe the (input) data product provenance [RD12.8.1]. Metadata is comprised of one or more metadata tuples. The tuple format is: key:value:type [RD12.8.1].
  - See Appendix A: Table 5: Input data specific metadata [RD12.8.1]

- See Appendix A: Table 6: Provenance specific metadata [RD12.8.1]

- Each candidate is also expected to have three S/N sheets (2-d matrices) computed by the CSP, which contain S/N values found during different optimizations of the folded data. The sheet size is determined from the number of trial periods, period derivatives and DMs. The sheets include:
  - A sheet describing the resulting S/N values for different values of period and period derivative.
  - A sheet describing the resulting S/N values for different values of period and DM.
  - A sheet describing the resulting S/N for different values of period-derivative and DM.

12.8.2.1.1.2 Science Data Model

The Science Data Model for Pulsar Search includes the following:

- Known Pulsar and Fast Transient Sources: Each new pulsar candidate needs to be compared to a database of known pulsars, and flagged as 'new' or 'known' as appropriate. If flagged as 'known', then the details of the known source believed to match the candidate should be attached as metadata. It is possible for a candidate to match 1 or more known sources. In addition, each new candidate also needs to be compared to a database of known Fast Transient Sources (such as Rotating Radio Transients [RRATs,RD12.8.6] and Fast Radio Bursts [FRBs,RD12.8.7]) as for pulsar sources. The database should at least include information about (but not limited to) type of source, source name, position in the sky (e.g. Right Ascension and declination), DM, pulse width, and flux density. For pulsars, the database should include spin period and any potential binary parameters such as binary period, projected semi-major axis, longitude of periastron, and eccentricity.
- Classification Model: The classification model (which comes from the TMC Configuration Repository) is a mathematical model that can apply new classification labels to candidates as they arrive from the CSP (e.g. labels such as noise, interference, pulsar, single-pulse burst, or FRB). Such models are typically stored as serialised objects that contain the classifier configuration parameters, and the learned mathematical function (e.g. [RD8]). In practice the parameters are often stored as many key value pairs. However the 'learned' function can be stored in a variety of ways depending on the classification algorithm used. For example, a neural network model can be represented via 1 or more matrices containing connection weights between artificial neurons. Sometimes classification models are saved in common file formats such as HDF5 or JSON (e.g. see [RD7]). Irrespective of the format used, for each classification model it is important to know which data set was used to train it. This information must be maintained alongside the model. Note that a classification model used to label pulsar candidates, is unsuitable for use on single-pulse data (see Section 4.1 in Pulsar Search and Single Pulse/Fast Transient Workflow View packet). Thus those two classification models must be maintained separately.
- Processing Block Configuration: Configuration of the different processing steps in the processing workflow.
  - Configuration parameters for generate heuristics, classification, selection & evaluation steps in the workflow.

12.8.2.1.1.3 Pulsar Search SDP Data Products

The Pulsar Search SDP Data Product consists of the following:

- Original OCLDs from multiple beams.
- Additional metadata appended to the OCLD (as derived during the processing of the workflow), will comprise the following:
  - Sifting Metadata: This will include “duplicate scores” and labels with additional information e.g. known sources.
  - Heuristics metadata: This will consist of $N_{heuristic}$ (likely less than 100) real numbers (up to 8 bytes) for each candidate.
  - Classification metadata: This will describe the predicted class label for each candidate. The label for each candidate could be a real number, an integer, or even a textual description.
  - Selection metadata (likelihood score). The score could be represented using a 8 byte real value.

12.8.2.1.1.4 Science Event Alert (TBC)

Alert generation for the pulsar search pipeline is not mandated, and there is no requirement to deliver it. This is why this section is labelled as TBC. However there are many reasons why it is useful to generate pulsar search alerts. For example, alerts can help ensure that telescope time is utilised effectively (related to dynamic scheduling).

To enable alerts to be generated, we do not design out an alert generation capability for the pulsar search pipeline. Thus if a known source exhibits unusual behaviour, or a candidate possesses a likelihood score greater than the alert threshold, an alert will be generated. Alerts will be formatted as IVOA alerts and sent to TM. An alert message will consist of:

- alert text (200 x 2 byte (16-bit) unicode characters)
- alert metadata (200 x 2 byte (16-bit) unicode characters)
- the alert threshold (a single 8 byte real value)
- The candidate data (~1-2.6 Mb).

12.8.2.1.2 Single Pulse/Fast Transient Data Model

12.8.2.1.2.1 Raw input data

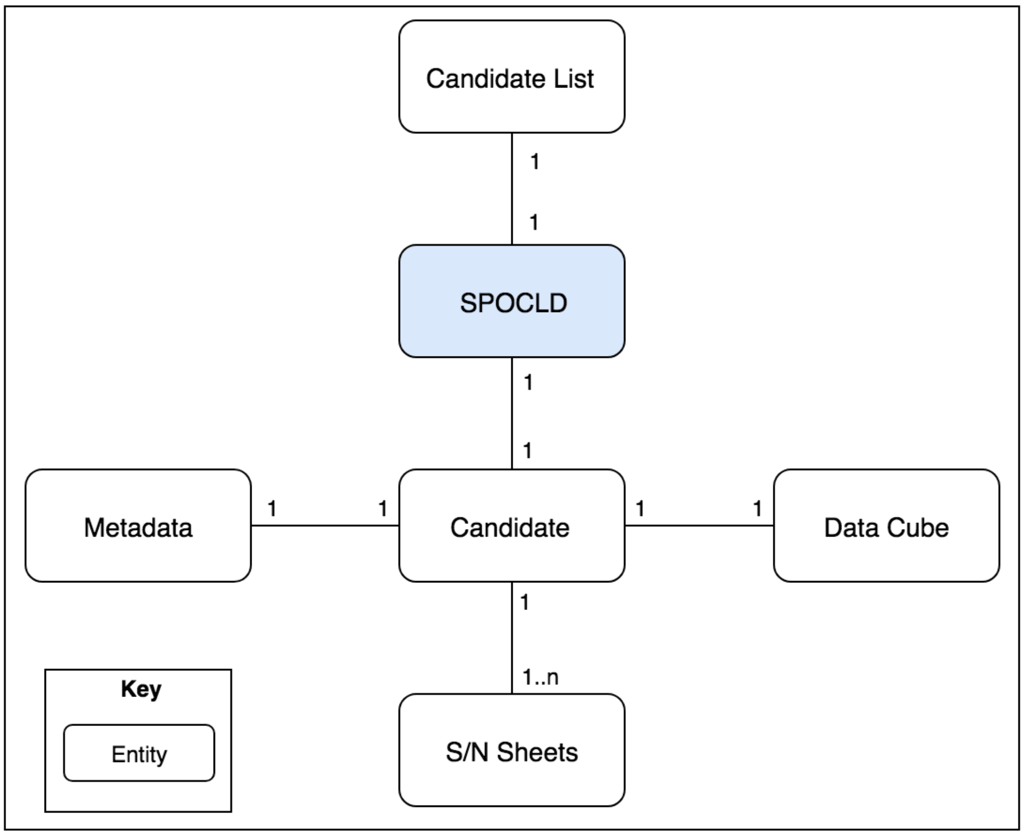


Figure 3: Logical data model of the Single pulse/Fast transient raw input data

The input data shall consist out of a Single Pulse Optimised Candidate List and Data (SPOCLD). There shall be one or more SPOCLDs per beam per scan. A SPOCLD represents a single detection. Each SPOCLD will contain a list which summarises detections made at the same time/frequency/DM/ sky location in the Equatorial Coordinate System [RD12.8.10] etc. Each candidate detection is unique (no duplicates within a SPOCLD) [AD10].

Candidate List
The list summarises all transient candidates detected during the CSP search. See table below for the current set of candidate list attributes [RD12.8.1]. This list is not final and and more attributes may be added in the future.

Table 2: Current set of candidate list attributes

Item	Description	Type
Candidate ID	The unique identifier for the candidate	Textual or numerical
Beam ID	The beam the candidate was found in	Textual or numerical
RAJ	Right ascension (J2000) of the source	Textual or numerical

DECJ	Declination (J2000) of the source	Textual or numerical
Time stamp of detection	Exact time of occurrence	numerical
Pulse width	Pulse width in milliseconds	numerical
Reference frequency	The observing frequency that the timestamp refers to.	numerical
DM	DM found during the search	numerical
Spectral S/N	The spectral S/N found during the search	numerical
Sifted	A flag indicating whether or not the candidate passed through the filtering procedure	boolean
Duplicate	A flag indicating whether or not the candidate has harmonic duplicates	boolean

Candidates

The search data product is comprised of only one candidate entity comprised of the following components:

- Candidate ID (attribute - TBC).
- Data cube: a single d-dimensional (filterbank) data cube (polarisation and power versus frequency and time). The single pulse/fast transient data cube has the following axes:
  - frequency channels
  - polarisations
  - samples
- Each candidate is also associated with metadata. Metadata is either numerical or textual, and describes the observation/data product. Metadata will include for example nearby pulsars, the beam position, number of observing beams used, optimised DM etc. The metadata will also describe the (input) data product provenance [RD12.8.1]. Metadata is comprised of one or more metadata tuples. The tuple format is: key:value:type [RD12.8.1].
  - See Appendix A: Table 5: Input data specific metadata [RD12.8.1]
  - See Appendix A: Table 6: Provenance specific metadata [RD12.8.1]
- Each candidate is also expected to have 2 (TBD) sheets [AD10]:
  - A 1-dimensional matrix describing a frequency vs S/N plot (S/N per frequency channel)
  - A 1-dimensional Dispersion Measure vs S/N plot

12.8.2.1.2.2 Science Data Model

The Science Data Model for Single Pulse/Fast Transient also includes the following:

- Known Pulsar and Fast Transient Sources: Each new Fast Transient candidate needs to be compared to a database of known RRAT Sources [RD12.8.6] and FRBs [RD12.8.7], and flagged as ‘new’ or ‘known’ as appropriate. If flagged as ‘known’, then the details of the known source believed to match the candidate should be attached as metadata. It is possible for a candidate to match 1 or more known sources. The RRAT and FRB known source database should at a minimum include information about (but not limited to) the type of source, source name, position in the sky (e.g. Right Ascension and declination), dispersion measure, pulse width, and flux density. In addition, since some pulsars exhibit very bright single pulses of radio emission, each new candidate also needs to be compared to a database of known pulsars. This known pulsar database should include spin parameters and any potential binary parameters such as binary period, projected semi major axis, longitude of periastron, and eccentricity.

- Classification Model: The classification model (which comes from the TMC Configuration Repository) is a mathematical model that can apply new classification labels to candidates as they arrive from the CSP (e.g. labels such as noise, interference, pulsar, single-pulse burst, or FRB). Such models are typically stored as serialised objects that contain the classifier configuration parameters, and the 'learned' mathematical function (e.g. [RD8]). In practice the parameters are often stored as key value pairs. However the learned function can be stored in a variety of ways depending on the classification algorithm used. For example, a neural network model can be represented via 1 or more matrices containing connection weights between artificial neurons. Sometimes classification models are saved in common file formats such as HDF5 or JSON (e.g. see [RD7]). Irrespective of how the model is persisted, for each classification model it is important to know which data set was used to train it. This information must be maintained alongside the model. Note that a classification model used to label single-pulse events, is unsuitable for use on pulsar candidate data (see Section 4.1 in Pulsar Search and Single Pulse/Fast Transient Workflow View packet). Thus those two classification models must be maintained separately.
- Processing Block Configuration: Configuration of the different processing steps in the Pulsar Search and Single Pulse/Fast Transient Workflow View packet processing workflow.
    - Configuration parameters for generate heuristics, classification, selection & evaluation steps in the workflow.

12.8.2.1.2.3 Single Pulse/Fast Transient SDP Data Products

The Single Pulse/Fast Transient SDP Data Product consists of the following:

- Original SPOCLDs from multiple beams.
- Additional metadata appended to the SPOCLD (as derived during the processing of the workflow), will include the following:
    - Heuristics metadata: This will consist of $N_{heuristic}$ (likely less that 100) real numbers (up to 8 bytes) for each candidate.
    - Classification metadata: This will describe the predicted class label for each candidate. The label for each candidate could be a real number, an integer, or even a textual description.
    - Selection metadata (likelihood score). The score could be represented using a 8 byte real value.

12.8.2.1.2.4 Science Event Alert

If a candidate's likelihood score is greater than a TM defined alert threshold, then an alert will be generated. Alerts will be formatted as IVOA alerts and sent to TM. An alert message will consist of:

- alert text (200 x 2 byte (16-bit) unicode characters)
- alert metadata (200 x 2 byte (16-bit) unicode characters)
- the alert threshold (a single 8 byte real value)
- The candidate data. (~1-2.6 Mb)

12.8.2.1.3 Pulsar Timing Mode Data Model

12.8.2.1.3.1 Raw input data

SDP receives coherently de-dispersed, detected pulsar data cubes in PSRFITS format [RD12.8.8,RD12.8.9] along with associated metadata.

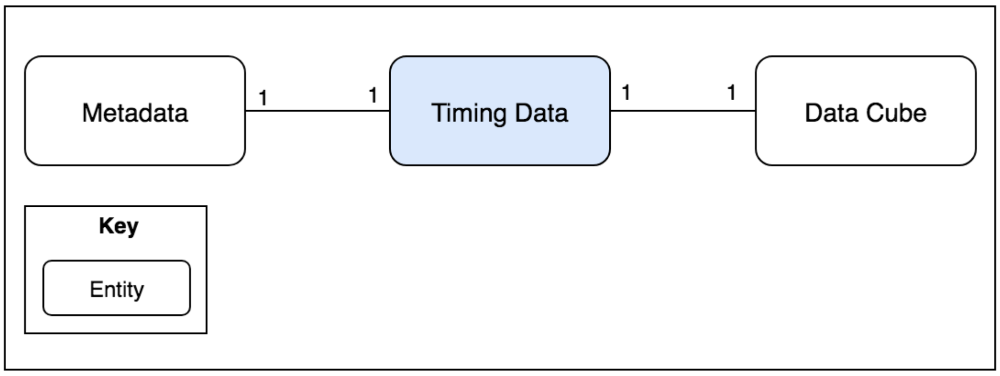


Figure 4: Logical data model of the Pulsar Timing raw input data

Data cube

The folded (d-dimensional) timing data are defined as the second moments of the electric field (e.g. the Stokes parameters) averaged as a function of pulsar longitude, radio frequency and integration epoch. The data cube may be stored in multiple PSRFITS files, with one or more integration per file. See [AD10, par 5.3.1.6.1] for more information.

The pulsar timing data cube will have the following axes:

- Pulse profile bins
- Frequency channels
- Sub-integrations
- Polarisation parameters

Pulsar Timing Metadata [AD10]

The timing data contains a set of metadata information. Metadata describes the observation/data product and is either numerical or textual. Metadata will include for example the pulsar observed, beam position, number of observing beams used, optimised DM etc.

- See Appendix A: Table 5 Input data specific metadata [RD12.8.1].
- See Appendix A: Table 6 Provenance specific metadata [RD12.8.1].

Metadata is comprised of one or more metadata tuples. The tuple format is: key:value:type [RD12.8.1].

12.8.2.1.3.2 Science Data Model

The Science Data Model for Pulsar Timing also includes the following:

- PST RFI mask: Required by the ‘Remove RFI’ step. This is the same or a similar mask used by CSP.PST for RFI mitigation. (stored in the Configuration Repository of the TMC [RD12.8.2]).
- Flux calibration data & polarisation calibration matrix (input to ‘Calibrate data’ step): (stored in the Configuration Repository of the TMC [RD12.8.2]).
- Pulsar ephemeris: A Pulsar ephemerides contains the values for all known parameters of that particular pulsar including its position in the sky. It is version controlled and stored in the TMC Configuration Repository [RD12.8.2]. An updated ephemeris is sent back to the TMC Configuration Repository at the end of the workflow.
- Pulsar specific template: For each pulsar entity, a version controlled description of its characteristic pulse profile (the pulsar signal as a function of pulse phase for the relevant observing frequency) is kept (stored in the Configuration Repository of the TMC [RD12.8.2]).

- List of TOAs (from previous observations) stored in the Configuration Repository of the TMC [RD12.8.2]. An updated list of TOAs is sent back to the TMC Configuration Repository at the end of the workflow.
- Processing Block Configuration: Configuration of the different processing steps in the processing workflow.
  - Configuration for all the processing steps, e.g. calibration, averaging etc.
- The SDM contains a set of QA metrics to determine the quality of the Pulsar Timing Data Products. These include, but are not limited to:
  - S/N of the total observation
  - S/N of each sub-integration
  - Number of channels/sub-integrations/samples removed by RFI mitigation
  - Reduced chi-square of the timing fit.
  - etc. (TBD)

12.8.2.1.3.3 Pulsar Timing SDP Data Products

The Pulsar Timing SDP Data Product [RD12.8.1] consists of the following:

- Original input data.
- Averaged timing data products: Much of the pulsar timing pipeline uses full-resolution data cubes during data processing. This is because interference mitigation and calibration greatly benefit from high resolution data. However some processing steps require higher S/N values rather than high resolution. This requires partly averaged (also known as summed or 'scrunched') data products. One or more averaged intermediate data cubes will be included in the SDP Data Product along with the original data cube. This information is saved for future post-processing. The quantity and size of the averaged cubes is scan specific, but will likely include cubes averaged over frequency (1 x N_{bin} x N_{sub} x N_{pol} x N_{bit}), time (N_{chan} x N_{bin} x 1 x N_{pol} x N_{bit}), frequency & time (1 x N_{bin} x 1 x N_{pol} x N_{bit}), or some combination [RD12.8.1].
- TOA list: A Time-of-arrival (TOA) list describes pulse arrival times for a pulsar with respect to some time reference. There is 1 TOA recorded per sub-integration and frequency channel, as an intermediate data product in the pulsar timing pipeline. The TOA list is represented by a row vector of size N_{chan} x 1 (or cube of N_{chan} x 1 x N_{sub}) [RD12.8.1].
- Timing Residuals describe the difference [modulo the spin period] between the expected pulse arrival times and the actual pulse arrival times. The residuals are represented by a row vector of size N_{chan} x 1 (or cube of N_{chan} x 1 x N_{sub}) [RD12.8.1].

Table 3: List of Pulsar Timing parameters

Parameter	Description
N_{bin}	Number of phase bins
N_{sub}	Number of temporal sub-integrations
N_{pol}	Number of polarisations
N_{bit}	Number of bits per sample in the cube
N_{chan}	Number of frequency channels

12.8.2.1.3.4 Science Event Alert (TBC)

Alert generation for the pulsar timing pipeline is not mandated, and there is no requirement to deliver it. This is why this section is labelled TBC. However there are many reasons why alert generation is useful for the timing pipeline. For example, alerts can help ensure that telescope time is utilised effectively (concerns related to dynamic scheduling). When timing a pulsar an alert would prove useful if any of the following conditions arise:

1. the pulsar is scintillating up right now, thus we should keep observing the source.
2. the pulsar is scintillating down right now, thus we should give up and start observing another source.
3. the pulsar, which is an intermittent source, is now ‘off’ - no need to keep observing.
4. the pulsar, which is an intermittent source, is now ‘on’ - we should continue observing this source as long as possible.
5. the pulsar is in a binary system and it is being eclipsed at the observed frequency - observe at different frequency or change observation target.
6. the pulsar is in a binary system and it is being eclipsed and we want to know when exactly we come out of eclipse (keep observing until the eclipse ends).

To enable such alerts to be generated, we do not design out an alert generation capability for the pulsar timing pipeline. Thus if a known source exhibits unusual behaviour, an alert will be generated. Alerts will be formatted as IVOA alerts and sent to TM. An alert message will consist of:
- alert text (200 x 2 byte (16-bit) unicode characters)
- alert metadata (200 x 2 byte (16-bit) unicode characters)

12.8.2.1.4 Dynamic Spectrum Mode Data Model

12.8.2.1.4.1 Raw input data

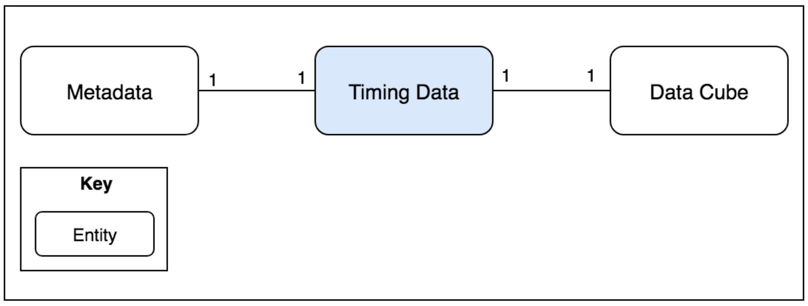


Figure 5: Logical data model of the Dynamic Spectrum Mode raw input data

Data cube
Dynamic spectrum data are defined as the second moments of the electric field (e.g. Stokes parameters), averaged as a function of time, radio frequency and optionally, polarisation (High resolution time, frequency polarisation data [AD10], not folded). The data cube may be stored in multiple PSRFITS files, with many time samples per file (e.g. 10 seconds).

The dynamic spectrum data cube will have the following axes:
- frequency channels
- samples
- stokes (polarisation) parameters

Dynamic Spectrum Metadata [AD10]
The dynamic spectrum data contains a set of metadata information. Metadata describes the observation/data product and is either numerical or textual. Metadata will include for example the pulsar observed, beam position, number of observing beams used, optimised DM etc.
- See Appendix A: Table 5: Input data specific metadata [RD12.8.1]
- See Appendix A: Table 6: Provenance specific metadata [RD12.8.1]

Metadata is comprised of one or more metadata tuples. The tuple format is: key:value:type [RD12.8.1].

12.8.2.1.4.2 Science Data Model

The Science Data Model for Dynamic Spectrum mode also includes the following:
- PST RFI mask (input to the 'Remove RFI' step): (stored in Configuration Repository of the TMC) [RD12.8.2].
- Flux calibration data & polarisation calibration matrix (input to 'Calibrate data' step): (stored in Configuration Repository of the TMC [RD12.8.2]).
- Processing Block Configuration: Configuration of the different processing steps in the processing workflow.
  - Configuration for all the processing steps, e.g. calibration, averaging etc. as appropriate.
- SDM contains a set of QA metrics to determine the quality of the Dynamic Spectrum Data Products. These QA metrics may be a subset of the QA metrics used for the Pulsar Timing Workflow (see par 2.1.3.2).

12.8.2.1.4.3 Dynamic Spectrum SDP Data Products

Dynamic Spectrum mode (DSM) allows the high resolution data product recorded during pulsar timing mode, to be preserved for off-line analysis. This data is called the Channelized Detected Time Series data (CDTS) by the science community. The DSM data is not processed within SDP, simply archived for later use by the science community (e.g. can be searched for pulsars etc.).

The data product is structurally identical to that used for pulsar timing. There are some practical differences: i) DSM data cubes are much higher resolution than pulsar timing data products making them significantly larger in size, and ii) DSM data is not folded [RD12.8.1].

The Dynamic Spectrum SDP Data Product consists of the following [RD12.8.1]:
- Original input data.
- High resolution data product (after RFI mitigation and Calibration).

12.8.2.1.5 Flow Through Mode Data Model

12.8.2.1.5.1 Raw input data

Data cube
The raw beam-formed voltage data are defined as the instantaneous samples of the electric field, with no temporal or spectral averaging, but optional re-quantisation.

The flow through mode data cube will have the following axes:
- frequency channels
- samples
- polarisations
- dimensions

The flow through mode (beamformer) weights cube will have the following axes:
- frequency channels
- time samples

Flow Through Metadata
The dynamic spectrum data contains a set of metadata information. Metadata describes the observation/data product and is either numerical or textual. Metadata will include eg the pulsar observed, beam position, number of observing beams used, optimised dispersion measure (DM), etc.
- See Appendix A: Table 5: Input data specific metadata [RD12.8.1]
- See Appendix A: Table 6: Provenance specific metadata [RD12.8.1]

Metadata is comprised of one or more metadata tuples. The tuple format is: key:value:type [RD12.8.1].

12.8.2.1.5.2 Science Data Model
No Science Data Model for Flow Through Mode is needed, because the data is not processed within SDP; rather it simply passed through the SDP for storage and offline analysis.

12.8.2.1.5.3 Flow Through Mode SDP Data Products
The Flow Through SDP Data Product consists of the following:
- Raw beam-formed voltages (no processing done on input data).

12.8.2.2 Relations and Their Properties
Not applicable

12.8.2.3 Element Interfaces
Not applicable

12.8.2.4 Element Behavior
Not applicable

12.8.2.5 Indices and Keys
Not applicable

12.8.2.6 Structure and Access Patterns

Not applicable.

12.8.3 Context Diagram

Refer to Figure 1 for the Non-Imaging Context diagram.

12.8.4 Variability Guide

Not applicable.

12.8.5 Rationale

The Non-Imaging Data Model has been defined by the following drivers:

- How the data is received by SDP from CSP.
- How the Pulsar Search, Single Pulse/Fast Transient, Pulsar Timing, Dynamic Spectrum and Flow Through Mode workflows are defined.
- The current implementation of the workflows.
- The System-level Data Model View

12.8.6 Related Views

- Pulsar Search and Single Pulse/Fast Transient Workflow View packet
- Pulsar Timing and Dynamic Spectrum Workflow View packet
- System-level Data Model View

12.8.7 Reference Documents

The following documents are referenced in this document. In the event of conflict between the contents of the referenced documents and this document, **this document** shall take precedence.

[RD12.8.1] SDP Memo 42: Data Model Summary for Pulsar/Transient Search & Timing; RevC1
[RD12.8.2] SKA-TEL-TM-0000242: TMC Software Architecture document
[RD12.8.3] Keras: The Python Deep Learning library, https://keras.io/getting-started/faq/
[RD12.8.4] Scikit-Learn Documentation, “3.4 Model Persistence”, http://scikit-learn.org/stable/modules/model_persistence.html
[RD12.8.5] Lorimer D. R. & Kramer M., “Handbook of pulsar astronomy”, Cambridge University Press, 2005.
[RD12.8.6] McLaughlin et al. 2006, Nature, 439, 817
[RD12.8.7] Thornton et al. 2013, Science, 341, 53
[RD12.8.8] Hotan A. W., van Straten W., and Manchester R. N., 2004, arXiv:astro-ph/0404549v1.
[RD12.8.9] van Straten W. et. al ., 2009, arXiv:0912.1662.
[RD12.8.10] Roy A. E. & Clarke D. “Astronomy: Principles and Practice”, 4th Edition, CRC Press, 2003.

12.9 Visibility Data Model

Contributors: T. J. Dijkema

12.9.1 Scope, Terminology

In this document we will refer to Visibility Model as the entity that holds visibility data. The exact properties of the Visibility Model shall be described later. We will refer to the existing storage system for visibilities, the Measurement Set, as MSv2 [RD1].

The Measurement Standard was defined around 2000 and is widely used, and well defined [RD1]. It is used for many telescopes, e.g. LOFAR, VLA, MeerKAT, MWA. The most popular software package CASA is built around the measurement set, but also many other data reduction packages use the measurement set standard. This makes software designed for different telescopes easily usable for the others.

SKA and NRAO have a Memorandum of Understanding [AD19] to work on a new standard of the Measurement Set. We will refer to the standard being developed by the project started by this Memorandum of Understanding as MSv3. This document is not intended to duplicate the work on MSv3, but rather to describe the SKA architectural requirements on the Visibility Model, which may be realized as the Measurement Set.

The Visibility Model shall contain both data and metadata. The *logical data model*, treated in this document, shall describe which data and metadata goes into the Visibility Model. The *physical data model* shall prescribe how data is stored. This document will focus on the logical data model, but will touch on some aspects of the physical data format.

The current MSv2 format supports single dish data, and per [AD19] MSv3 shall also support single dish data. The data model used for single-dish observations will be MSv3 and not a separate data model. In terms of the pipelines, these are not exhaustive and new pipelines can be created as required.In this document however, we will concentrate on interferometric data.

12.9.2 Primary representation

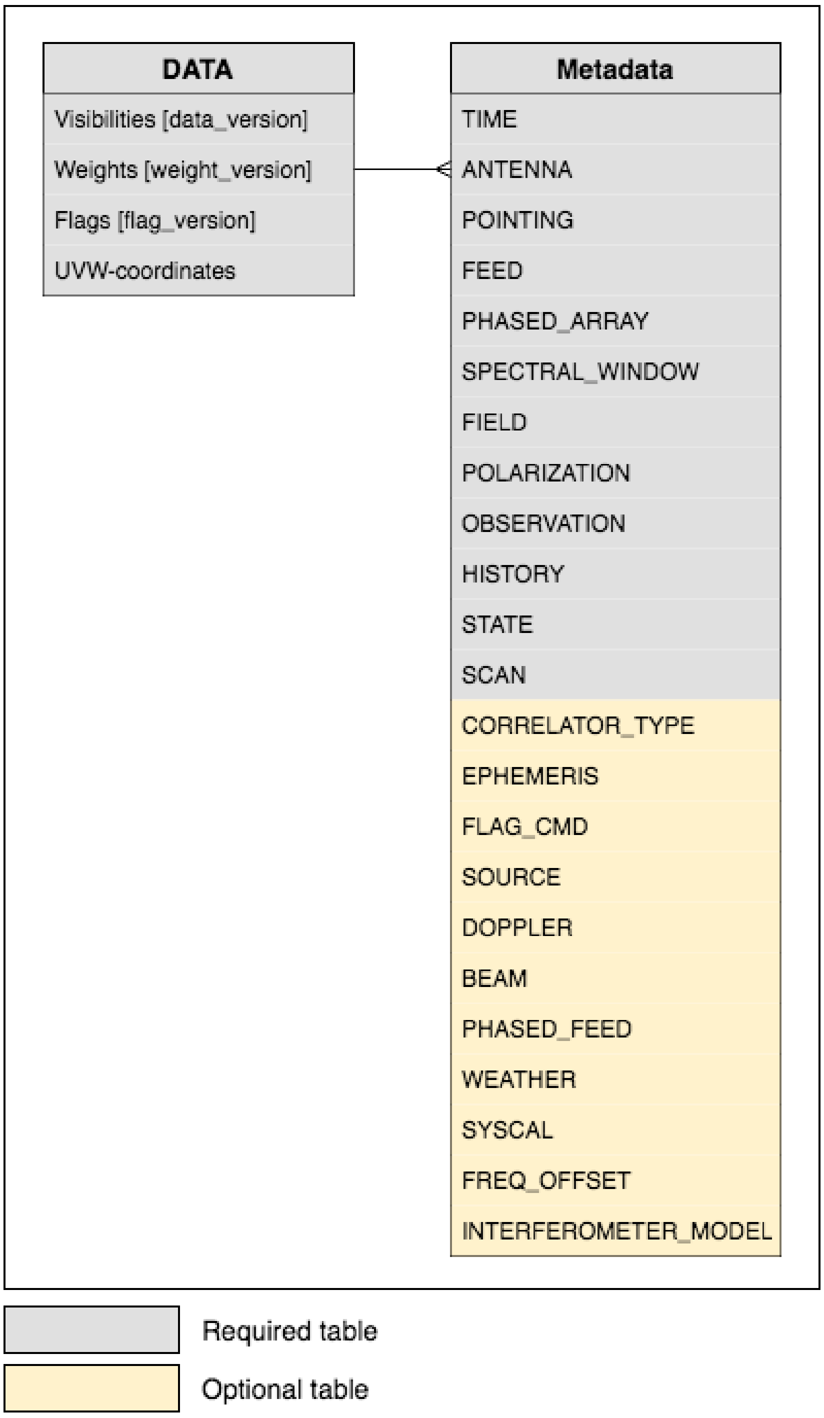


Figure 1. Primary representation

Below is a description of the use of the metadata tables

Subtable name	Description
ANTENNA	Antenna characteristics
PHASED_ARRAY	Phased array setup
SPECTRAL_WINDOW	Spectral window setup
POLARIZATION	Polarization setup
SCAN	Scan information
FEED	Feed characteristics
PHASED_FEED	Phased feed setup
FIELD	Field position
POINTING	Pointing information
PROCESSOR	Processor information
BEAM	Beam model information
STATE	State information
OBSERVATION	Observation metadata
HISTORY	Provenance information
FLAG_CMD	Flag commands
EPHEMERIS	Ephemeris information
SOURCE	Observed sources
DOPPLER	Doppler tracking information
WEATHER	Weather information
SYSCAL	System calibration information
FREQ_OFFSET	Small frequency offsets
INTERFEROMETER_MODEL	Interferometer model used by VLBI
CORRELATOR_TYPE	Correlator information
Calibration tables	Calibration tables, as defined in Calibration Data Model View

Table 1. Metadata tables.

12.9.2.1 Versioning

All tables should be treated as append-only, to make it possible to go back one step. Also, pipeline frameworks typically expect a distinct input and output file. Note that this is not a hard requirement; if file size is a limiting factor, visibilities can be changed in-place.
It should be possible to associate multiple versions of e.g. WEIGHTS with one version of DATA without duplicating data. The way to store these versions is TBD.
Note that this is versioning scheme generalizes typical use of MSv2 [RD12.9.1] where a CORRECTED_DATA is stored next to the DATA column.
For example, to calibrate data (from original DATA[0] column) are read (not changed), and calibration solution are deduced. Applying these solutions will generate a new column DATA[1]. If the calibration does not change the weights, DATA[1] is still associated with WEIGHTS[0] and FLAGS[0].

12.9.2.2 Keywords

Both tables and columns can contain keywords. The value of a keyword can be of a simple type (boolean, integer, float, complex, string), a combination of these, or even a table. If the value of a keyword is a table, we call this a subtable. That is, the main table of a measurement set has a keyword “ANTENNA” which points to the antenna subtable.
Column keywords are used to store information about e.g. units or reference frames. For implementation details in Casacore, see [RD12.9.2].

12.9.3 Element Catalogue

12.9.3.1 Elements and Their Properties

12.9.3.1.1 Data

The main data elements in the Visibility Model shall be visibilities, weights, flags and UVW-coordinates. Visibilities, weights and flags shall have the same number axes, namely polarization and channel.

For different applications, the optimal ordering of visibilities may differ. The main operations on visibilities are flagging, calibration and averaging. For flagging and calibration, typically the data is stored in time-order, as it comes off the telescope. For imaging, where the UVW is the dominant axis, the order is different. In the Algorithm Reference Library (ARL), the two formats are referred to as BlockVisibility and Visibility. The format we describe is intended to support both.

Visibilities can be seen as a high-dimensional cube of data, with the following axes:

- TIME
- ANTENNA1 and ANTENNA2
- FEED1, FEED2
- SPECTRAL_WINDOW_ID
- POLARIZATION_ID
- PROCESSOR_ID
- FIELD_ID
- SCAN_NUMBER
- STATE_ID

12.9.3.1.2 Metadata

The Visibility Model shall contain enough information to reduce (calibrate, image) the data.

There should be an option to append metadata (e.g. calibration solutions) to an existing Visibility Model. Every calibration step (in either CSP or SDP) should append a calibration table to the Visibility Model.

For each data element, the Visibility Model shall store which metadata is attached to it. For example, each data element shall contain links to the associated stations, observation ID, etc. Project-based metadata such as name of PI, their institution and so on, is part of the metadata which eventually is stored as part of a SDP Data Product and searchable via the SDP Data Product Catalogue. See the SKA Project Model element of the Primary Representation in the System-Level Data Model View. This metadata arrives via the Scheduling Block.

12.9.3.2 Relations and Their Properties

Each element in DATA has links to one or more elements in the METADATA tables.
The following diagram, taken from [AD20], describes that Elements of the Visibility Model. Arrows indicate a 1-to-1, 1-to-2 (in the special case of correlation) or 1-to-many relation. E.g. each row in MAIN refers to two rows in ANTENNA, each row in FEED refers to one row in ANTENNA.

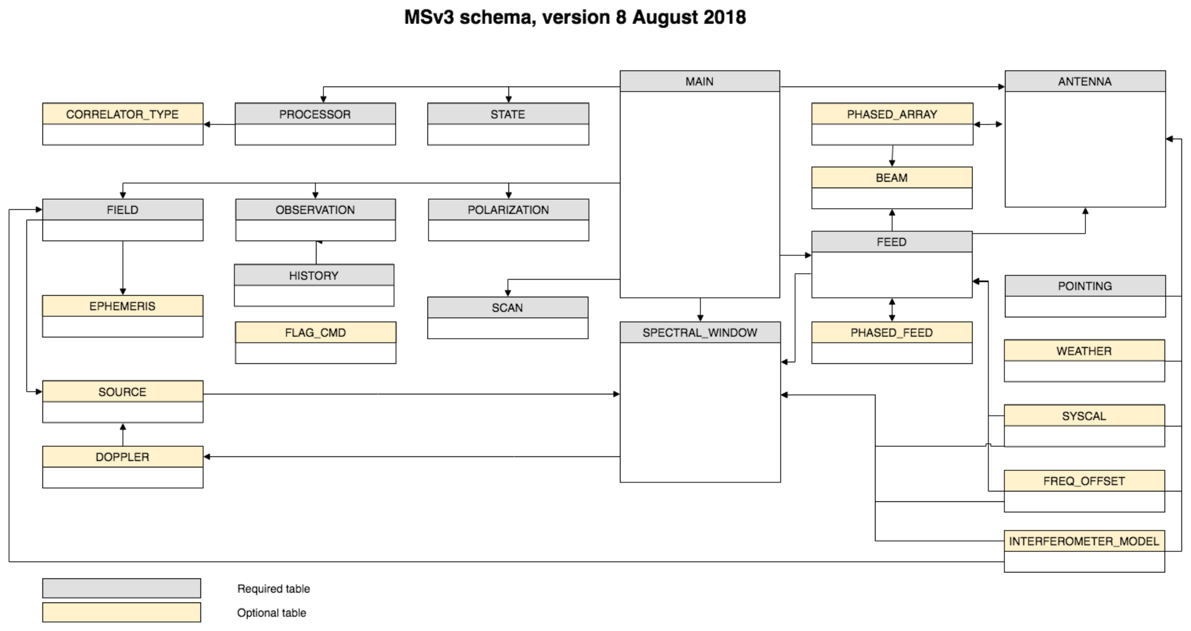


Figure 2. Links between tables.

The full diagram with properties, as described in [AD20], is below:

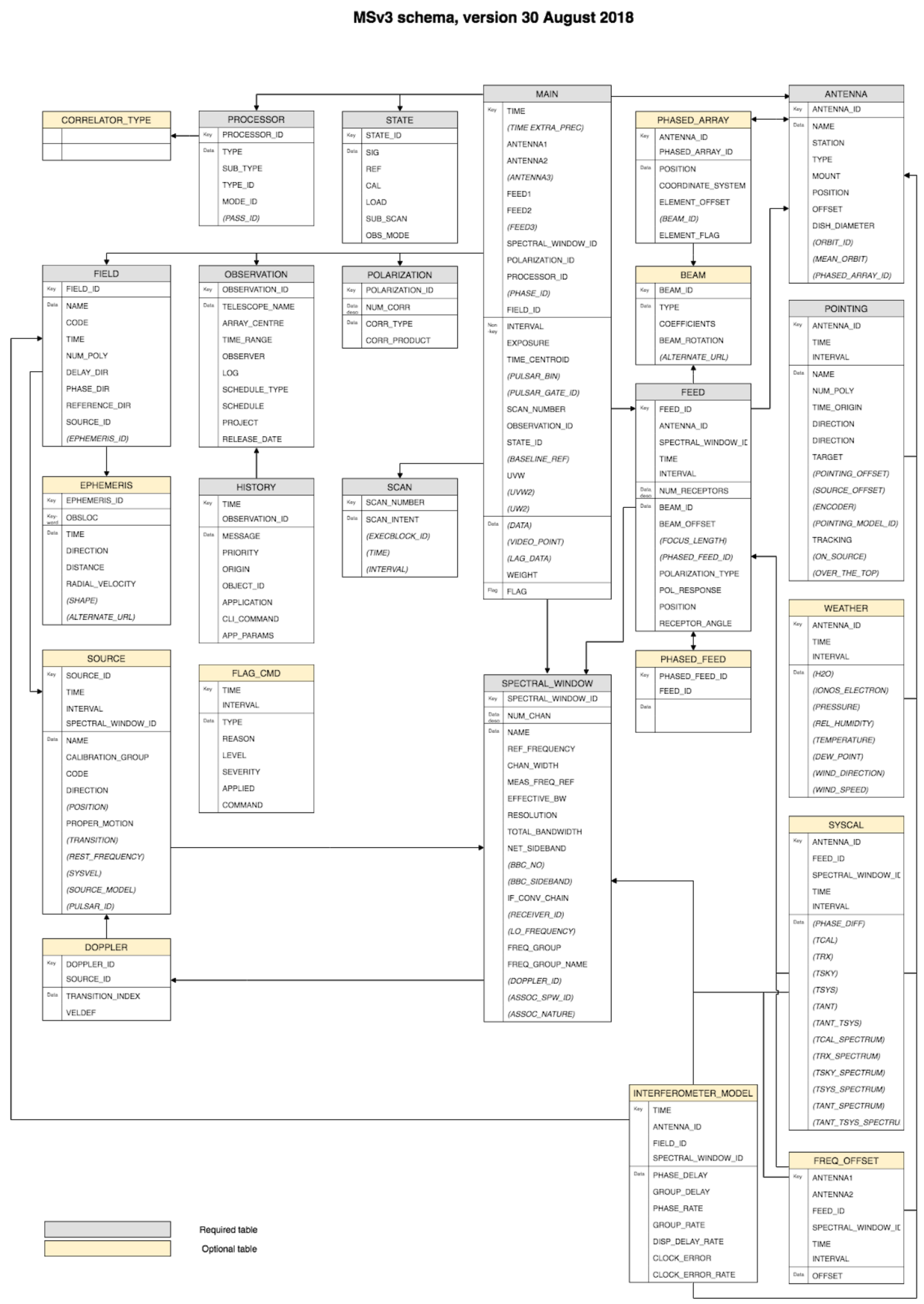

MSv3 schema, version 30 August 2018
CORRELATOR_TYPE
PROCESSOR
Key PROCESSOR_ID
Data TYPE SUB_TYPE TYPE_ID MODE_ID (PASS_ID)
STATE
Key STATE_ID
Data SIG REF CAL LOAD SUB_SCAN OBS_MODE
MAIN
Key TIME (TIME EXTRA_PREC) ANTENNA1 ANTENNA2 (ANTENNA3) FEED1 FEED2 (FEED3) SPECTRAL_WINDOW_ID POLARIZATION_ID PROCESSOR_ID (PHASE_ID) FIELD_ID
Non-key INTERVAL EXPOSURE TIME_CENTROID (PULSAR_BIN) (PULSAR_GATE_ID) SCAN_NUMBER OBSERVATION_ID STATE_ID (BASELINE_REF) UVW (UVW2) (UW2)
Data (DATA) (VIDEO_POINT) (LAG_DATA) WEIGHT
Flag FLAG
PHASED_ARRAY
Key ANTENNA_ID PHASED_ARRAY_ID
Data POSITION COORDINATE_SYSTEM ELEMENT_OFFSET (BEAM_ID) ELEMENT_FLAG
ANTENNA
Key ANTENNA_ID
Data NAME STATION TYPE MOUNT POSITION OFFSET DISH_DIAMETER (ORBIT_ID) (MEAN_ORBIT) (PHASED_ARRAY_ID)
FIELD
Key FIELD_ID
Data NAME CODE TIME NUM_POLY DELAY_DIR PHASE_DIR REFERENCE_DIR SOURCE_ID (EPHEMERIS_ID)
OBSERVATION
Key OBSERVATION_ID
Data TELESCOPE_NAME ARRAY_CENTRE TIME_RANGE OBSERVER LOG SCHEDULE_TYPE SCHEDULE PROJECT RELEASE_DATE
POLARIZATION
Key POLARIZATION_ID
Data desc NUM_CORR
Data CORR_TYPE CORR_PRODUCT
BEAM
Key BEAM_ID
Data TYPE COEFFICIENTS BEAM_ROTATION (ALTERNATE_URL)
POINTING
Key ANTENNA_ID TIME INTERVAL
Data NAME NUM_POLY TIME_ORIGIN DIRECTION DIRECTION TARGET (POINTING_OFFSET) (SOURCE_OFFSET) (ENCODER) (POINTING_MODEL_ID) TRACKING (ON_SOURCE) (OVER_THE_TOP)
FEED
Key FEED_ID ANTENNA_ID SPECTRAL_WINDOW_ID TIME INTERVAL
Data desc NUM_RECEPTORS
Data BEAM_ID BEAM_OFFSET (FOCUS_LENGTH) (PHASED_FEED_ID) POLARIZATION_TYPE POL_RESPONSE POSITION RECEPTOR_ANGLE
EPHEMERIS
Key EPHEMERIS_ID
Key word OBSLOC
Data TIME DIRECTION DISTANCE RADIAL_VELOCITY (SHAPE) (ALTERNATE_URL)
HISTORY
Key TIME OBSERVATION_ID
Data MESSAGE PRIORITY ORIGIN OBJECT_ID APPLICATION CLI_COMMAND APP_PARAMS
SCAN
Key SCAN_NUMBER
Data SCAN_INTENT (EXECBLOCK_ID) (TIME) (INTERVAL)
WEATHER
Key ANTENNA_ID TIME INTERVAL
Data (H2O) (IONOS_ELECTRON) (PRESSURE) (REL_HUMIDITY) (TEMPERATURE) (DEW_POINT) (WIND_DIRECTION) (WIND_SPEED)
SOURCE
Key SOURCE_ID TIME INTERVAL SPECTRAL_WINDOW_ID
Data NAME CALIBRATION_GROUP CODE DIRECTION (POSITION) PROPER_MOTION (TRANSITION) (REST_FREQUENCY) (SYSVEL) (SOURCE_MODEL) (PULSAR_ID)
FLAG_CMD
Key TIME INTERVAL
Data TYPE REASON LEVEL SEVERITY APPLIED COMMAND
SPECTRAL_WINDOW
Key SPECTRAL_WINDOW_ID
Data desc NUM_CHAN
Data NAME REF_FREQUENCY CHAN_WIDTH MEAS_FREQ_REF EFFECTIVE_BW RESOLUTION TOTAL_BANDWIDTH NET_SIDEBAND (BBC_NO) (BBC_SIDEBAND) IF_CONV_CHAIN (RECEIVER_ID) (LO_FREQUENCY) FREQ_GROUP FREQ_GROUP_NAME (DOPPLER_ID) (ASSOC_SPW_ID) (ASSOC_NATURE)
PHASED_FEED
Key PHASED_FEED_ID FEED_ID
Data
SYSCAL
Key ANTENNA_ID FEED_ID SPECTRAL_WINDOW_ID TIME INTERVAL
Data (PHASE_DIFF) (TCAL) (TRX) (TSKY) (TSYS) (TANT) (TANT_TSYS) (TCAL_SPECTRUM) (TRX_SPECTRUM) (TSKY_SPECTRUM) (TSYS_SPECTRUM) (TANT_SPECTRUM) (TANT_TSYS_SPECTRU
DOPPLER
Key DOPPLER_ID SOURCE_ID
Data TRANSITION_INDEX VELDEF
INTERFEROMETER_MODEL
Key TIME ANTENNA_ID FIELD_ID SPECTRAL_WINDOW_ID
Data PHASE_DELAY GROUP_DELAY PHASE_RATE GROUP_RATE DISP_DELAY_RATE CLOCK_ERROR CLOCK_ERROR_RATE
FREQ_OFFSET
Key ANTENNA1 ANTENNA2 FEED_ID SPECTRAL_WINDOW_ID TIME INTERVAL
Data OFFSET
Required table
Optional table

Figure 3. Full metadata model for visibilities, taken from [AD20].

Metadata from processing can be stored in the HISTORY subtable. Also, the MSv3 schema allows for any custom extension tables, with a telescope-specific prefix.

12.9.3.3 Element Interfaces

The interface to the Visibility Data Model is very rich, and complex[3]. The interfaces of the visibility data should support the following:

- Visibility Data can be generated by the correlator, or in simulations.
- Bad data flagging: Visibility Data is searched for RFI, which is then flagged (storing an updated version of the FLAG column).
- Calibration: Visibility Data is compared to modeled visibilities to fit parameters of instrumental and atmospheric models are fitted (which are then stored in Calibration Data).
- Subtracting of bright sources: visibility data as input and visibility data as output (with a new version of the DATA column), where strong sources are subtracted.
- Subtraction of degridded data: subtract visibilities from imaged data from existing visibilities.
- Gridding: Visibility data is converted to Gridded Visibility Data.
- Degridding: Gridded UV Data is converted to visibility data.
- Predict: Convert discrete fourier transforms (DFTs) of components in the Local Sky Model (LSM).
- Conversion to Science Data Product.

12.9.3.4 Element Behavior

Not applicable.

12.9.3.5 Indices and Keys

Each metadata table shall have an explicit key (this differs from MSv2 where row numbers are implicit keys). This is to facilitate coalescing and splitting visibilities for parallelization, as well as combining (joining). These indices and keys are highlighted as such in Figure 3.

12.9.3.6 Structure and Access Patterns

It should be possible to tune the underlying physical data format to a given access pattern.

In view of distributed processing, it should be possible to split a set of visibilities into many smaller sets that can be processed independently. It should also be possible to recombine these smaller sets. The axes over which sets of visibilities are allowed to be split or coalesced can be a subset of all axes.

The storage of the data shall be such that it can be optimized for various access patterns. Some examples of typical access patterns, ranging from slowest to fastest varying axis (where we ignore other axes like ‘scan’ and ‘feed’):

- Calibration: time, spectral window, channel, baseline
- Flagging: spectral window, baseline, spectral channel, time
- Imaging: baseline, spectral window, channel, time (in this way the best ordering in UVW-coordinates is achieved without reading the UVW-coordinates, which are treated as data)

Visibilities are not stored as a full data cube. That is because a generic data format can not assume that they form a full cube, e.g. every scan has the same number of spectral windows, or every baseline has the same number of integrations (baseline dependent averaging).

[3] The interface to the existing MSv2 is documented here.

To elaborate this example: note that because <V_p, V_q> = conj(<V_q, V_p>), only half of the correlations need to be stored.

Instead of storing a full data cube, one element of data shall be a cube of polarizations and channels, with attached to to it links to all other axes, pointing to the metadata.

In computations, it can be efficient to temporarily store visibilities as a full data cube, filling gaps with flagged visibilities. For example, baseline averaged visibilities can be duplicated (upsampled) to the resolution of the longest baseline to get a regular cube of data. In those cases, it is important to retain sufficient metadata to be able to export to the original data format.

12.9.4 Context Diagram

Not applicable.

12.9.5 Variability Guide

- Correlator - Generates visibilities at the highest time resolution
- Flagging, removing strong sources, averaging - Create a new instance of visibilities at reduced resolution
- Direction independent calibration - Create new data column where calibration has been applied

Between LOW and MID telescopes, the main difference is how the location of the different antenna / telescope locations are stored. For the MID telescope, telescope locations are stored in the ANTENNA location. For LOW: the ANTENNA table contains one location per station, the individual antenna locations are stored in the PHASED_ARRAY table.

12.9.6 Rationale

We have followed the existing storage of visibilities quite closely. This will make it easy to use existing software. We envision that the architecture of CTDS [RD12.9.2] is sufficient to allow efficient storage managers to be written to guarantee good I/O performance on various hardware platforms.

12.9.7 Related Views

- Gridded Data Model View
- Calibration Data Model View
- Beam Data Model View

12.9.8 References

The following documents are referenced in this document. In the event of conflict between the contents of the referenced documents and this document, **this document** shall take precedence.

[RD12.9.1] MeasurementSet definition version 2.0. A.J. Kemball and M.H. Wieringa, eds. 2000. http://casacore.github.io/casacore-notes/229.pdf

[RD12.9.2] Casacore Table Data System and its use in the MeasurementSet. Ger van Diepen, Astronomy & Computing, 2015, 12. 10.1016/j.ascom.2015.06.002

[RD12.9.3] Data Models for the SDP Pipeline Components. Ger van Diepen, Chris Skipper, Robert Lyon et al. SDP Design Report, 2016-12-02 https://docs.google.com/document/d/1UPZQn8hVv7TDtFm8G3DxTJx0cf0yan_NrBZylwXr8mM/edit .

13 Science Data Model View Packet

Contributors: B. Nikolic

13.1 Primary Representation

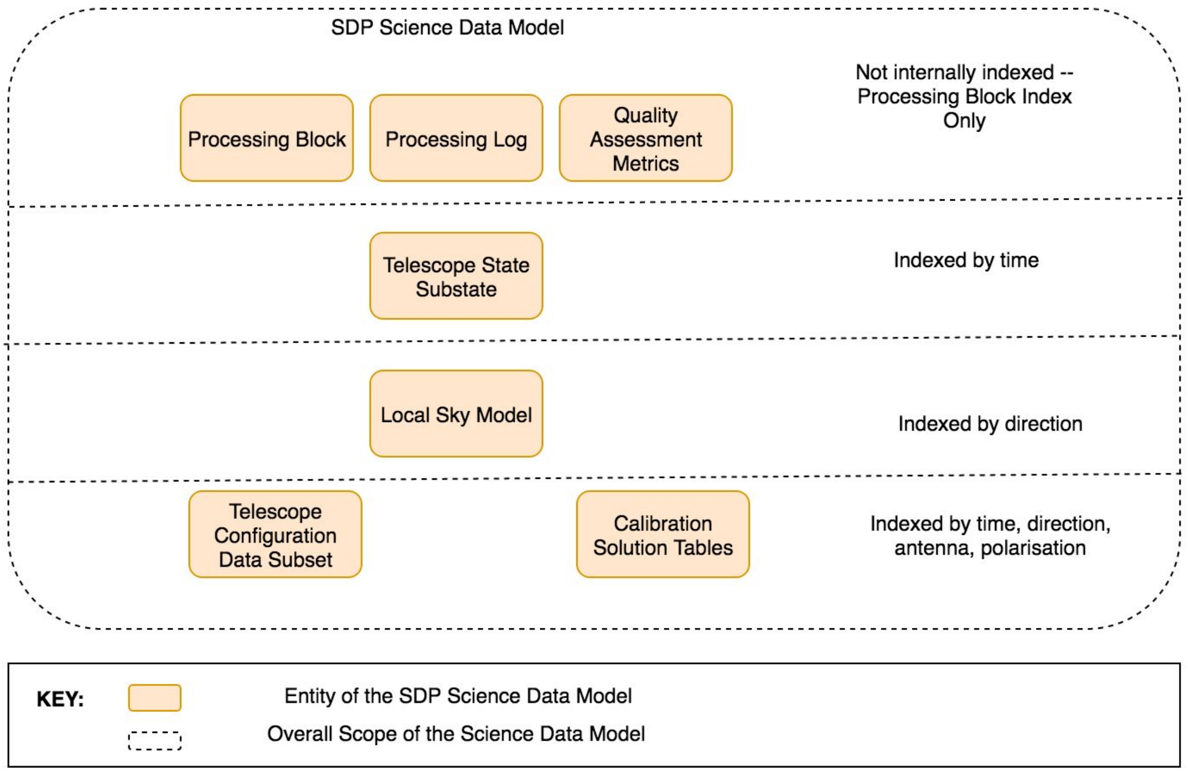

SDP Science Data Model
Processing Block
Processing Log
Quality Assessment Metrics
Not internally indexed -- Processing Block Index Only
Telescope State Substate
Indexed by time
Local Sky Model
Indexed by direction
Telescope Configuration Data Subset
Calibration Solution Tables
Indexed by time, direction, antenna, polarisation
KEY:
Entity of the SDP Science Data Model
Overall Scope of the Science Data Model

Figure 1: Science Data Model Primary Representation

This shows the constituent entities of the Science Data Model and the way they are indexed. Indexing complexity increases from top to bottom. One of key objectives of the Science Data Model is consistent indexing between its constituents.

The Science Data Model is the model of the data associated with observations and their processing that is not already in itself the primary input (observed data, e.g., the output of the correlator) or primary output (final science data product). The reasons for collecting and keeping this information is:

1. To populate the processing data model, and otherwise support the processing of the observed data into final data products
2. To keep information about how the final data products were produced in order to support their scientific interpretation

Examples of information which belongs in the Science Data Model is (completion of this list is part of future work):

- Telescope state / configuration information, both produced by SDP and other sub-systems. This especially covers calibration solutions.
- Intermediate data produced in preparation of processing, such as pipeline configuration or the Local Sky Model.

- Secondary outputs of processing, such as Science Event Alerts or logs.

The primary goal of the Science Data Model is to unify all of this information in a common hierarchical name space. This is to enable queries into the data, both while processing as well as after the fact. The latter allows the Science Data Model to become a Data Product documenting a finished processing run. To serve this function effectively in the face of changing software requirements both from Processing Components and Delivery, the Science Data Model must remain open to modification.

To this end, the Science Data Schema is specified by the Workflow template used by a concrete Processing Block. The Schema defines a hierarchy of Science Model Paths that contain Science Model Fields of certain types. Both paths and fields have names as well as associated indices, which not only allows representing collections of data, but also tracking multiple versions of values (e.g. if they get updated while processing).

13.2 Element Catalogue

13.2.1 Elements and Their Properties

Elements of this view are data entities. Properties:

- **Type** of data entity
- **Indexing** requirements, in particular ones which may drive the design
- **Representations** details the primary ways in which the data entity will get represented in the operational SDP system.

13.2.1.1 Processing Block

Type:	Configuration data -- specification of what processing was requested by TM to be done by SDP
Indexing	Not required
Representations:	Markup language with simple schema

13.2.1.2 Processing Log

Type:	Logging data -- auxiliary data about the processing, i.e., data not known to be required but kept because it may be useful for problem solving or scientific interpretation in complex cases.
Indexing	Not required. Data are time stamped and marked by the ID of where produced in workflow.
Representations:	Stream based representation, probably mixed text & structured data (arrays and tables)

13.2.1.3 Quality Assessment Metrics

Type:	Metrics -- quantitative measurement of quality of the observation, telescope systems and processing.
Indexing	Not required
Representations:	Markup language with simple schema

13.2.1.4 Telescope State Subset

Type:	Numerical and configuration data -- details of the actual (as opposed to commanded) telescope configuration as function of time during observing
Indexing	Time
Representations:	Markup language with simple schema, tables

13.2.1.5 Local Sky Model

Type:	Numerical Data -- relevant information about known sources in the region being observed
Indexing	Direction on celestial sphere
Representations:	Mixed hierarchical representation with code in the in-memory data-model module to interpret the representation which may be both simple (tabular), wide-field (HealPix) and complex (using basis set expansion or rasterised image representations. See the Sky Model Data Model view packet

13.2.1.6 Telescope Configuration Data Subset

Type:	Mixture of computational models and their parameters
Indexing	Time, array element (i.e., antenna or station), direction on sky, polarisation, feed (for Mid)
Representations:	Mostly tables, some markup language with simple schema

13.2.1.7 Calibration Solution Tables

Type:	Numerical Data -- corrections from calibrations computed in SDP
Indexing	Time, array element (i.e., antenna or station), direction on sky, polarisation, feed (for Mid)
Representations:	High efficiency table representations (an example are CASA tables)

13.2.2 Relations and Their Properties

The relations between elements is their common indexing scheme. The top level index is by processing block ID, followed by time (defined on a common basis for elements), and direction and antenna/polarisation at the lowest level.

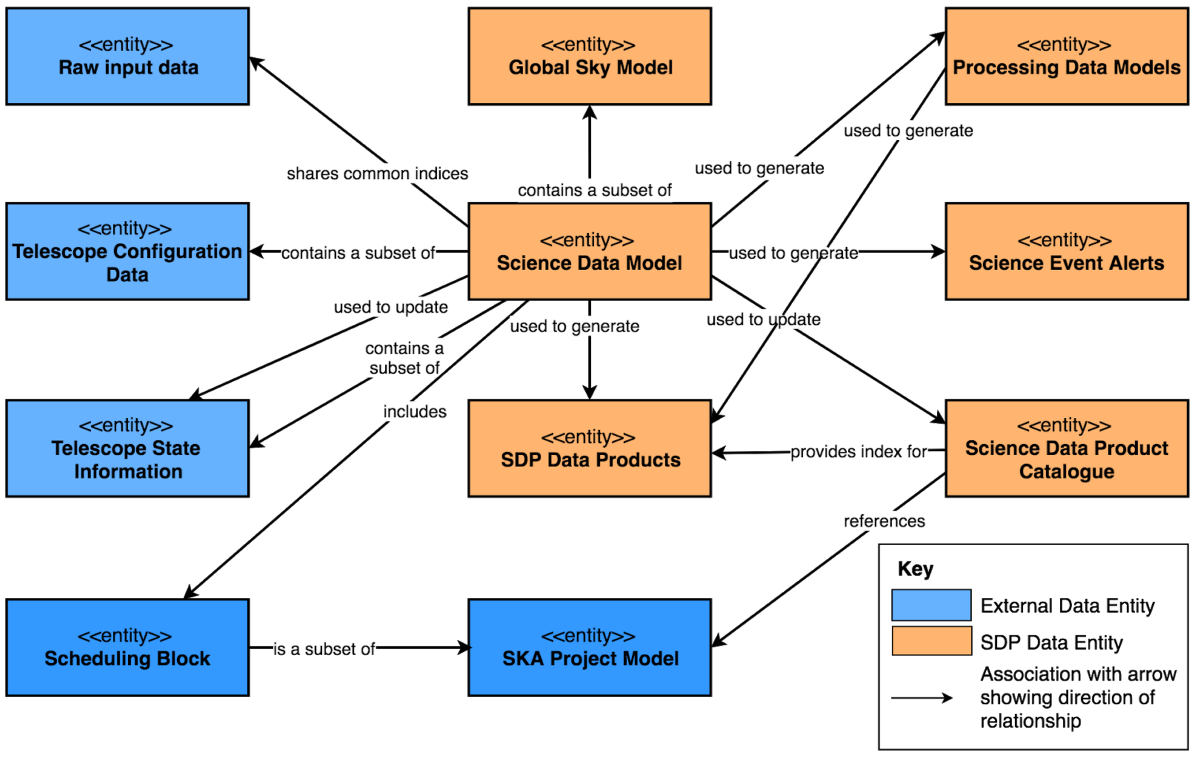
13.2.3 Element Interfaces

Not applicable

13.2.4 Element Behavior

No behaviour to document

13.3 Context Diagram



<<entity>> Raw input data
<<entity>> Global Sky Model
<<entity>> Processing Data Models
<<entity>> Telescope Configuration Data
<<entity>> Science Data Model
<<entity>> Science Event Alerts
<<entity>> Telescope State Information
<<entity>> SDP Data Products
<<entity>> Science Data Product Catalogue
<<entity>> Scheduling Block
<<entity>> SKA Project Model
shares common indices
contains a subset of
used to generate
used to generate
contains a subset of
used to generate
used to update
contains a subset of
used to generate
used to update
includes
provides index for
references
is a subset of
Key
External Data Entity
SDP Data Entity
Association with arrow showing direction of relationship

Figure 2: Context of Science Data Model within the SDP System Data Model

13.4 Variability Guide

Variability is not envisaged at the present time.

13.5 Rationale

1. A single Science Data model enables coherent indexing across a number of otherwise diverse sub-elements that are contained in it
2. The Science Data Model needs to map well to the concrete models used for processing, e.g., Measurement Set V3, Calibration Table formats used in processing.
3. The Science Data Model should be hierarchically organised with the top level partitioned or easily indexed by a **Processing Block**, in order that one partition can be inserted into the **SDP Data Product** to fully document how they are processed.

13.6 Related Views

1. Calibration Data Model View
2. Sky Model Data Model View
3. Execution Control Data Model
4. Processing Data Models (Processing Data Model View, Visibility Data Model View)
5. System-level Data Model View
6. SDP Data Product Catalogue View

13.7 References

[RD13.1] SKA-TEL-TM-0000242, TMC SOFTWARE ARCHITECTURE DOCUMENT, Rev 01

[RD13.2] 601-000000-002, OSO SOFTWARE ARCHITECTURE DOCUMENT, Rev 01

14 SDP Data Product Catalogue View Packet

Contributors: R. Simmonds, K. Kirkham

14.1 Primary Representation

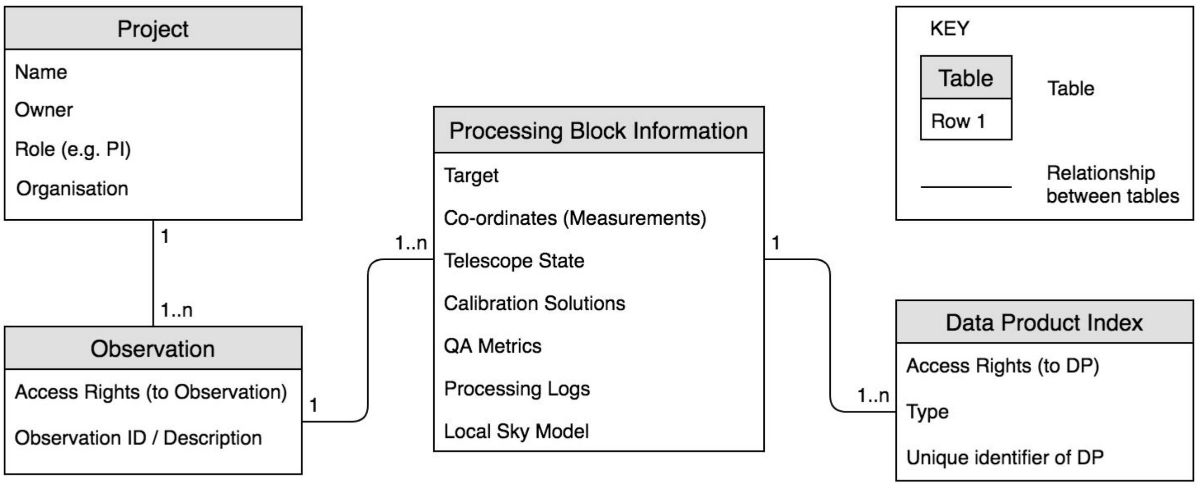


Figure 1: High-level SDP Data Product Catalogue Logical Model

Figure 1 shows the Primary Representation for an entry of the SDP Science Data Product Catalogue. The Catalogue is in itself a database which is replicated at SKA Regional Centres (SRCs).

Words in bold below relate to the elements in the Primary Representation in Figure 1, and not the SKA concepts, although they are similar. Descriptions of the SKA concepts can be found in [RD14.4].

In the SKA a Project may create multiple Observations. Each Observation is associated with one Scheduling Block Instance (generated by TM). The metadata needed to search for data products, that is unique to a Project and to each Observation, is contained in the **Project** and **Observation** elements of a Catalogue entry.

Many Processing Blocks are created per Scheduling Block. Each Processing Block will be associated with collections of metadata. Each **Processing Block Information** element is a collection of metadata which would be associated with data products created while processing an individual Processing Block in the SDP. Each individual data product has a unique identifier, and one **Data Product Index** is used to reference each data product that has been made available by the SDP. Each entry in the catalogue contains a subset of the metadata against which searches can be made.

14.2 Element Catalogue

14.2.1 Elements and Their Properties

14.2.1.1 Project

Project contains all information about the body which successfully proposed the Observing Project, i.e. data relating to the person(s) and institution(s) who requested the observation.

14.2.1.2 Observation

Each Observation has a relationship to the Project class and each Observation is unique and related to a single Scheduling Block Instance, with a unique Scheduling Block ID within SKA. The Observation class also contains data access rights for the person(s) who proposed the observing Project, which governs access to the metadata in this element of the Catalogue.

Related to each Observation there may be an Image Preview (TBD) so the catalogue browser can see a small snapshot (thumbnail/postage stamp) of the image(s) in the final data product. This is not shown in Figure 1.

14.2.1.3 Processing Block Information

This contains all material required for the astronomer to assess the conditions of the observation, processing, and associated metadata. It includes all necessary elements from the IVOA ObsCore model. Each Processing Block Information element may have several data products associated with it depending on what data products were created during the processing of the associated Processing Block in the SDP.

14.2.1.4 Data Product Index

Each individual data product has a unique identifier, and one Data Product Index references one data product. Note that there are two sub-elements (or classes in the logical model) containing access rights (see Section 2.2.1). The Observation sub-element contains access rights for the metadata relating to this observation. The Data Product Index also contains access rights but for the individual data product it represents in the Catalogue.

14.2.2 Relations and Their Properties

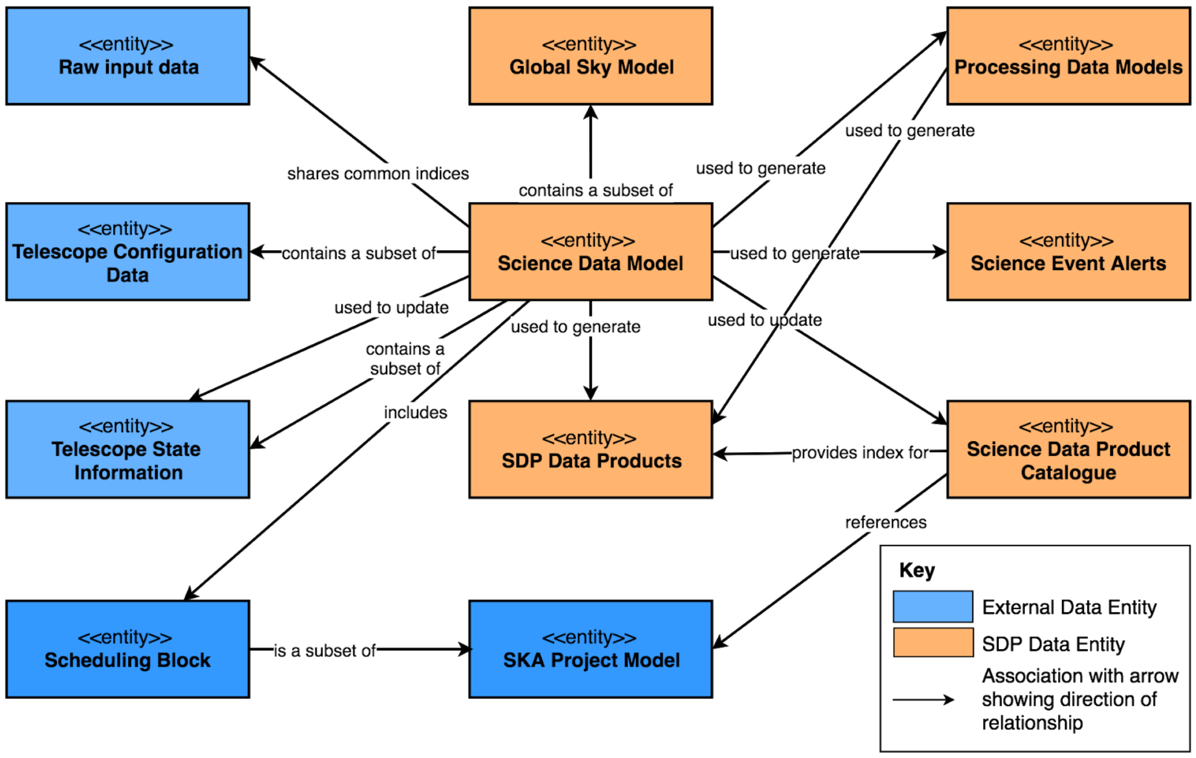
14.2.2.1 Access Rights

This contains an Access Control List (ACL) of groups that can access the entity containing this Access Rights object. It also contains the Proprietary period, which is the time after which the entity is considered to be in the public domain. These objects are contained in Observation and Data Product Index objects in the Catalogue elements (see [RD14.1] and [RD14.2]).

14.2.3 Element Interfaces

This is a static data model, so does not in itself provide interfaces. However it does need to support IVOA Table Access Protocol (TAP) based queries. The the TAP service is described in the Delivery Component and Connector View [RD02].

14.3 Context Diagram



<<entity>> Raw input data
<<entity>> Global Sky Model
<<entity>> Processing Data Models
<<entity>> Telescope Configuration Data
<<entity>> Science Data Model
<<entity>> Science Event Alerts
<<entity>> Telescope State Information
<<entity>> SDP Data Products
<<entity>> Science Data Product Catalogue
<<entity>> Scheduling Block
<<entity>> SKA Project Model
shares common indices
contains a subset of
used to generate
used to generate
contains a subset of
used to generate
used to update
used to update
contains a subset of
used to generate
includes
provides index for
references
is a subset of
Key
External Data Entity
SDP Data Entity
Association with arrow showing direction of relationship

Figure 2: SDP Conceptual Data Model diagram showing relationships between entities [RD01]

The Science Data Product Catalogue is one of the high-level entities in the SDP Conceptual Data Model as shown in Figure 2. The Science Data Model is used to populate entities within the Catalogue, namely the Processing Block Information element, as shown in the logical model (the Primary Representation in Figure 1 of this document). It provides an index to the SDP Data Products, and references the SKA Project Model. The SKA Project Model is represented as the 'Project' entity in the Primary Representation.

14.4 Variability Guide

N/A

14.5 Rationale

The SDP Data Product Catalogue View provides a means to determine what data products have been created and to search for them. It needs to contain metadata that is required by IVOA services, such as described by the CAOM data model [RD14.5], with additional metadata to improve the search capabilities for the next generation radio astronomy instruments. It provides a mapping to metadata that is unique to different levels of processing in different elements in the model. It also provides a means to protect products or the metadata associated with them.

14.6 Related Views

The System Level Data Model provides the context for this View, as shown in section 3.
The Delivery Component and Connector View describes components associated with this view.

14.7 Reference Documents

The following documents are referenced in this document. In the event of conflict between the contents of the referenced documents and this document, this document shall take precedence.

[RD14.1]	SKA-TEL-SKO-0000307, Rev02, SKA1 Operational Concept Document, G.R. Davis, A. Chrysostomou, C. Taljaard,
[RD14.2]	SKA-TEL-SKO-0000958, SKA1 SDP - SRC INTERFACE DEFINITION DOCUMENT,
[RD14.3]	Data Access Rules and Regulations, A. Chrysostomou (TBC).
[RD14.4]	T4000-0000-AR-002, OSO SOFTWARE ARCHITECTURE DOCUMENT
[RD14.5]	CAOM-2.0: The Inevitable Evolution of a Data Model, Dowler, P. (2011)

15 Transient Source Catalogue View Packet

Contributors: M. Ashdown

15.1 Primary Representation

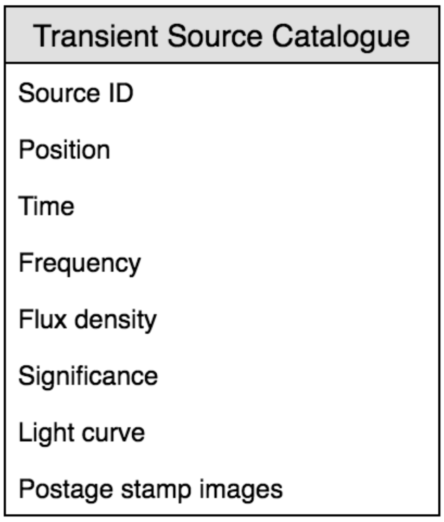


Figure 1: Logical data model for the Transient Source Catalogue. The catalogue is a table-like data structure containing the columns shown here.

The Transient Source Catalogue is generated by the Fast Imaging pipeline as part of the real-time processing. An instance of the catalogue may contain multiple entries, with one entry for each transient source candidate detected during the observation. The catalogue is a table-like data structure with the columns shown in the logical data model in Figure 1.

15.2 Element Catalogue

15.2.1 Elements and Their Properties

The Transient Source Catalogue is a conventional table-like data structure with multiple entries. Each entry corresponds to a source, and contains the following information

- Source ID: an unique identifier for the source, generated automatically from the other data (e.g. position and time of the detection)
- Position: the position of the source
- Time: time at which the source was detected
- Frequency: frequency at which the source was detected
- Flux density: flux density of the source at the time and frequency of detection as described above
- Significance: significance of the detection
- Light curve: information on the light curve of the source from the detection until the end of the observation. This information will be multi-dimensional: the flux density as a function of time and frequency channel.
- Postage stamp images: images of the source before, during and after the detection.

15.2.2 Relations and Their Properties

Not applicable.

15.2.3 Element Interfaces

Not applicable.

15.2.4 Element Behavior

Not applicable.

15.3 Context Diagram

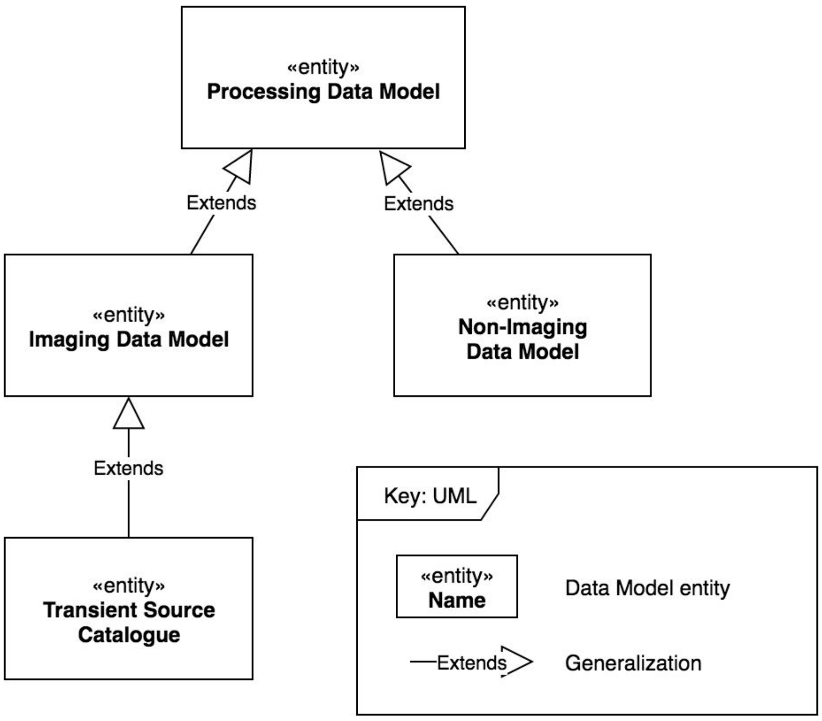


Figure 2: Context diagram for Transient Source Catalogue

The Transient Source Catalogue is a Processing Data Model, as shown in Figure 2.

15.4 Variability Guide

Not applicable.

15.5 Rationale

This data model has been developed under the assumption that the Transient Source Catalogue is generated for each observation (corresponding to a Scheduling Block Instance), and delivered to the SKA Regional Centres (SRCs) as a standard data product. (The alternative would be to maintain a single running catalogue of transients as a database within SDP and replicate this at the SRCs.) This decision was made for a number of reasons. First, it treats the catalogue in the same way as other data products produced by SDP. Second, it avoids adding a special-purpose interface between Delivery and the SRCs. Last, it is consistent with the data analysis philosophy adopted by the SKA: that data from multiple observations is combined at the SRCs, not in SDP.

15.6 Related Views

Processing Data Model View.

15.7 Reference Documents

None

16 Appendix A

16.1 Metadata

Table 5: Data Product specific metadata for Non-imaging workflows [RD12.8.1]. ***This list must be still be tailored for each Non-imaging workflow. Note that sky locations are recorded in the Equatorial Coordinate System [RD12.8.10]***:

Item	**Description**	**Type**	**Input/Updated**	**Workflow**
Pulsar ID	Unique identifier of the observed pulsar	textual		PSS, PST
Candidate count	Candidates in the data product	numerical		PSS
RAJ	Right ascension (J2000) of the source	Textual or numerical		All
DECJ	Declination (J2000) of the source	Textual or numerical		All
Start time	Time stamp (MJD) of the first sample	numerical		All
End time	Time stamp (MJD) of the last sample	numerical		All
Sampling interval	The scan sampling interval	numerical		All
Bits	Bits per time sample	numerical		All
Samples	Total time sample	numerical		All
Centre Frequency	Centre Frequency (MHz) of the first channel	numerical		All
Channel bandwidth	Filterbank channel bandwidth	numerical		All
Bandwidth	Total bandwidth (MHz)	numerical		All
Channels	Number of filterbank channels	numerical		All
DM	Optimised dispersion measure	numerical		All
Known period	Known folding period	numerical		PSS, PST
Search period	Period found during the search	numerical		PSS
Pulsar ephemeris	Ephemeris	textual		PST
Polyco	Polyco file/s used to predict the period	textual		PST
Predictor	Predictor file used to predict the period	textual		PST

Table 6: Provenance specific metadata for Non-imaging workflows [Appendix A RD12.8.1]:

Item	**Description**	**Type**	**Input/Updated**	**Workflow**
Scheduling Block ID	The scheduling block the data was created in	textual	Input	All
Program Block ID	The program block the data was created in	textual	Input	All
Scan ID	The scan the data was created during	textual	Input	All

Subarray ID	The sub-array configuration, if applicable	textual	Input	All
Product ID	The data product identifier	textual	Updated	All
CBF Pipeline Version	Pipeline processing the data	numerical	Input	All
CSP Pipeline Version	Pipeline processing the data	numerical	Input	All
SDP Pipeline Version	Pipeline processing the data	numerical	Updated	All
History	Description of the steps applied to the data	textual	Input & Updated	All
Size	Size of the product in bits	integer	Input & Updated	All
Intermediate Products	Flag indicating if there are child products	textual	?	All

17 Applicable Documents

The following documents are applicable to the extent stated herein. In the event of conflict between the contents of the applicable documents and this document, **the applicable documents** shall take precedence.

This list of applicable documents applies to the whole of the SDP Architecture.

[AD01]	SKA-TEL-SKO-0000002 SKA1 System Baseline Design V2, Rev 03[4]
[AD02]	SKA-TEL-SKO-0000008 SKA1 Phase 1 System Requirement Specification, Rev 11
[AD03]	SKA-TEL-SDP-0000033 SDP Requirements Specification and Compliance Matrix, Rev 04
[AD04]	SKA-TEL-SKO-0000307 SKA1 Operational Concept Documents, Rev 02
[AD05]	000-000000-010 SKA1 Control System Guidelines, Rev 01
[AD06]	100-000000-002 SKA1 LOW SDP to CSP ICD, Rev 06
[AD07]	100-000000-025 SKA1 LOW SDP to SaDT ICD, Rev 05
[AD08]	100-000000-029 SKA1 LOW SDP to TM ICD, Rev 05
[AD09]	100-000000-033 SKA1 LOW SDP to LFAA Interface Control Document (ICD), Rev 02
[AD10]	300-000000-002 SKA1 MID SDP to CSP ICD, Rev 06
[AD11]	300-000000-025 SKA1 MID SDP to SaDT ICD, Rev 05
[AD12]	300-000000-029 SKA1 MID SDP to TM ICD, Rev 05
[AD13]	SKA-TEL-SKO-0000484 SKA1 SDP to INFRA-AUS and SKA SA Interface Control Document, Rev 02

[4] This document is still a draft version and therefore not truly applicable, but will be replaced by an applicable version by System CDR.

[AD14] SKA-TEL-SKO-0000661 Fundamental SKA Software and Hardware Description Language Standards

[AD15] http://www.ivoa.net/documents/TAP/

[AD16] http://www.ivoa.net/documents/latest/SIA.html

[AD17] http://www.ivoa.net/documents/DataLink/

[AD18] http://www.ivoa.net/documents/SSA/

[AD19] Memorandum of Understanding between the SKA organisation and National Radio Astronomy Observatory relating to a work package for the study and design of a new data model for the CASA software package

[AD20] MeasurementSet definition version 3.0. MSv3 team, eds. 2018. http://casacore.github.io/casacore-notes/264

[AD22] Shibboleth Authentication Service from Interenet2 https://www.internet2.edu/products-services/trust-identity/shibboleth/

[AD23] COmanage Authorization Service from Interenet2 https://www.internet2.edu/products-services/trust-identity/comanage/

[AD24] SKA-TEL-SKO-0000990 SKA Software Verification and Testing Plan