



Applying the LISA Science Ground Segment Model to the Lunar Gravitational-wave Antenna

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Ground Segment: Operations + Science

Ground segment

The system set up on Earth to manage and control a space mission, and to receive and process the data produced by a spacecraft's instruments, and to send out and archive mission data products. Typically split into an **operations part** and a **science part**.

Operations Ground segment (OGS)

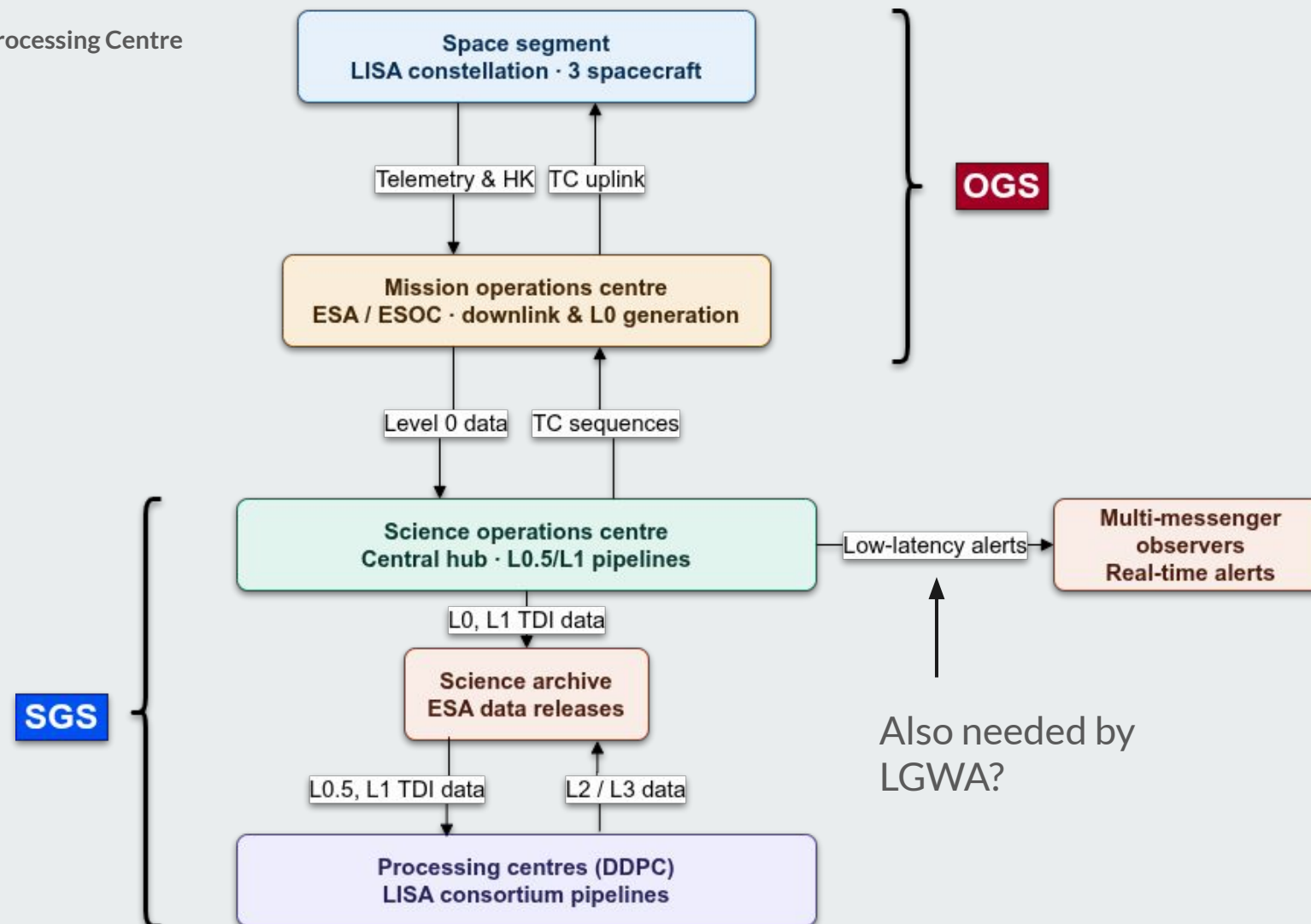
Managed entirely by ESA, it includes the **Mission Operations Centre (MOC)** at ESOC, the ground stations, and the communications network.

Science Ground segment (SGS)

It refers to the infrastructure, systems, and operations that support the collection, processing, and distribution of scientific data from space missions or satellite systems. It is composed of the **Science Operations Center (SOC)** operated by ESA and a number of **Science Data Centers (SDCs)** in charge of data processing, provided by a Consortium. It usually includes the **Instrument Operations Team (IOT)** during nominal operations.

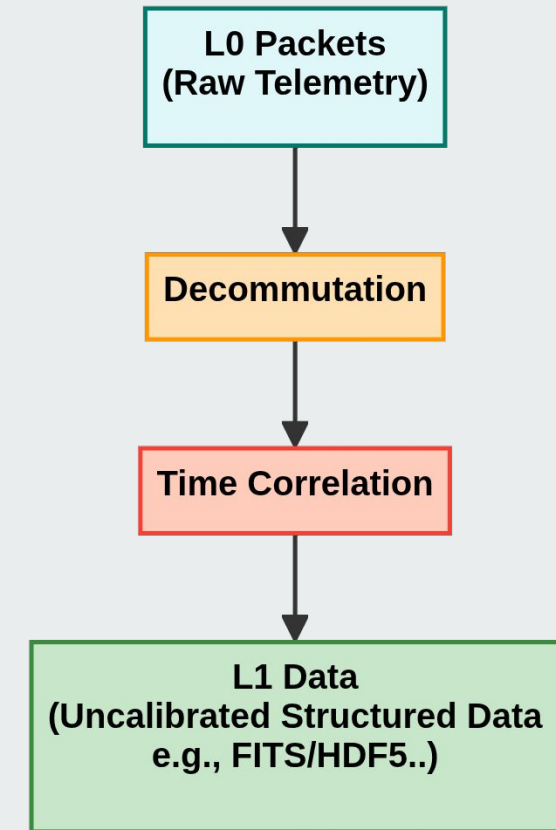
LISA: MOC vs SOC vs DDPC

DDPC = Distributed Data Processing Centre

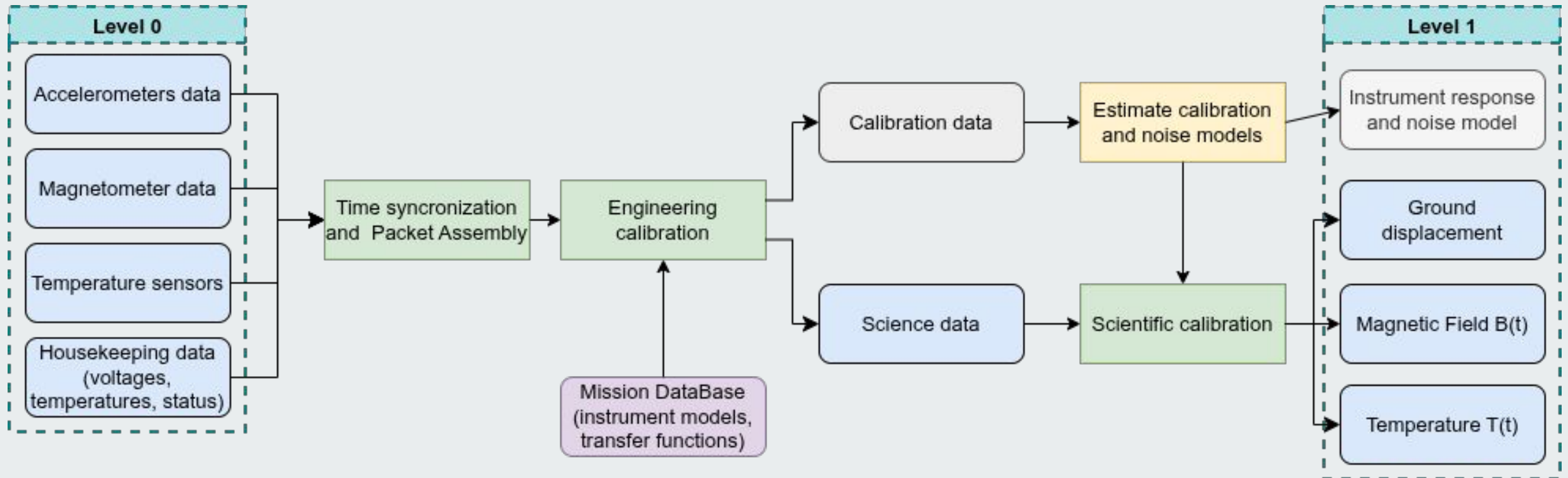


Data processing: processing levels definition in LISA

- ❖ **Level 0**
 - science telemetry data (TM) + housekeeping TM (CCSDS Space Packet protocol) + auxiliary data
 - TM is De-multiplexed, de-duplicated, error-corrected, etc.
- ❖ **Level 0.5**
 - De-packetized, de-compressed (if applicable)
 - Reformatted in official exchange format
 - common astronomical timescale
 - ADU to physical units (if applicable)
- ❖ **Level 1**
 - Fully calibrated TDI (Time-Delay Interferometer) data streams
 - augmented with spacecraft ephemerides
- ❖ **Level 2**
 - consists of the model parameters and their posterior probability density function (PDF) (where applicable) of identified GW sources or other identifiable events
- ❖ **Level 3**
 - consists of a catalogue of sources, their physical and astrophysical parameters



From Level 0 to Level 1 for Soundcheck (Example)



Main SGS infrastructure components

Common Data Model

Formal, **schema-based definition** of all mission products and their relationships. Foundation for the entire processing chain.



Metadata archive

Centralised **mission metadata store**, shared by SOC and all SDCs. Enables product discovery and traceability across processing levels.



Distributed storage

Scalable **distributed data storage** across multiple science data centres, with files centrally **referenced via the metadata archive**.



Software deployment

Containerised **packaging of pipeline software** for consistent delivery. Ensures reproducibility from development to production.



Workflow management

DAG orchestration for L0.5→L2 pipelines. Abstracts underlying compute infrastructure for portability.



The SGS Teams (other than MOC, SOC and SDC teams)

IOT – Instrument Operations Team

Consortium

Responsible for payload operations and the interface with the SOC (while the Istr. Dev. team interfaces with the MOC up to commissioning). Its activities include: defining and implementing **payload commanding procedures**, **monitoring instrument health** and performance from housekeeping and telemetry data, **supporting real-time and near-real-time operations** (including quick-look product assessment), and contributing to **anomaly detection**, diagnosis and resolution. Involved in the **L0.5 and L1 pipeline** development.

SPT – Science Pipelines Team

Consortium

Manages the **entire data processing chain**, from raw telemetry to science-ready products. It designs and develops the overall **data processing architecture** in the SDC environment.

The SPT is also responsible for the **data quality assessment**, and delivers the **pre-integrated L0.5, L1 and LLA pipelines** to the SOC.

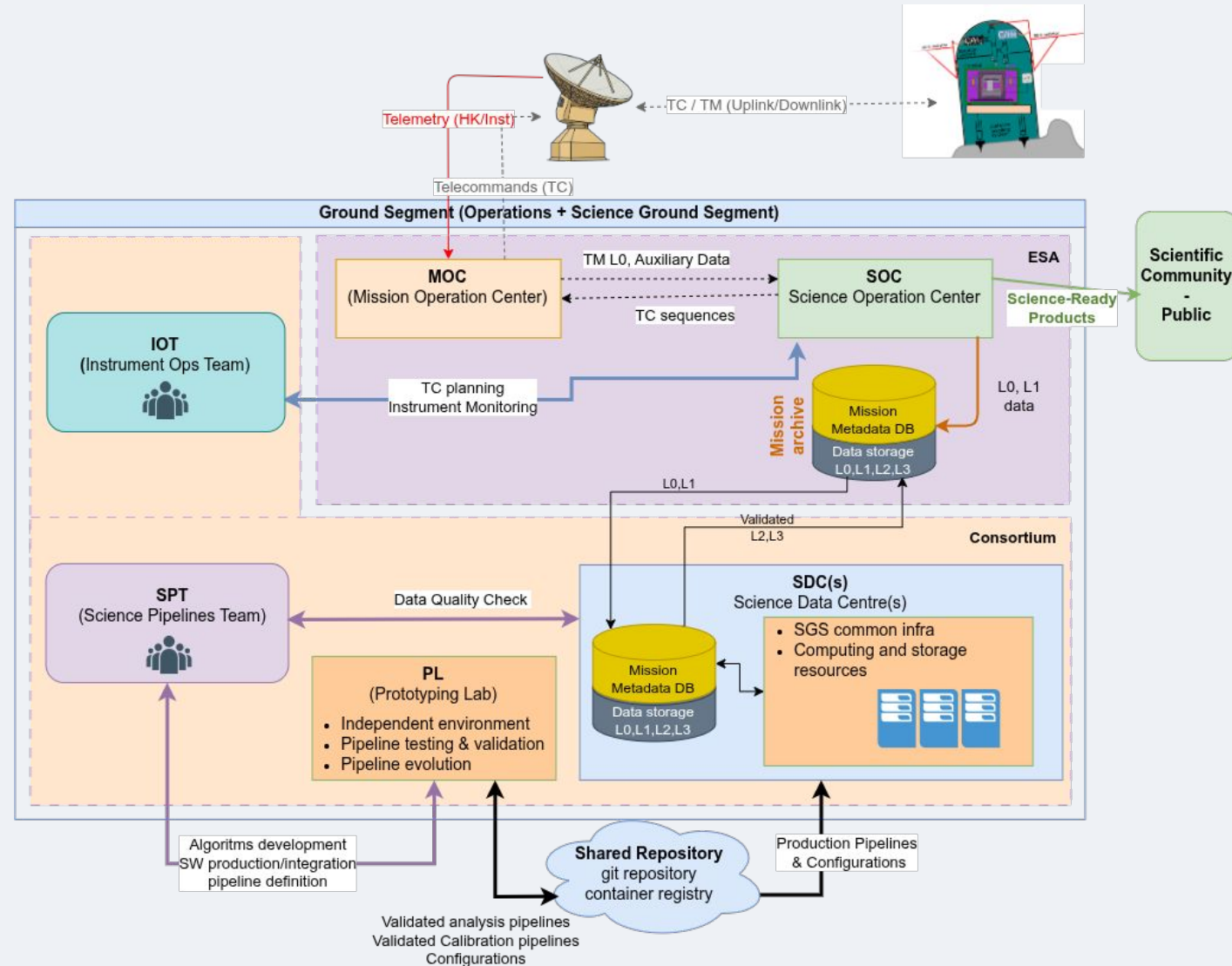
ST - System Team

Consortium

ESA

Defines the architecture of the SGS **common infrastructure and services**, the overall SGS technology stack and the common software engineering guidelines. It plans and **monitors the provision of computing and storage resources** by the involved SDCs. It also includes the **operations team**, which runs the production pipelines in the SDC infrastructure.

Example of Ground Segment architecture



Lessons learned from past missions (Planck, Euclid)

Previous ESA science missions (Planck, Euclid) each had to implement their own versions of the same SGS components (lack of mature, open source alternatives):

- ❖ **Data model definition** — Custom schemas redesigned per mission
- ❖ **Metadata archive services** — Separate implementations with overlapping functionality
- ❖ **Distributed data storage** — Proprietary or custom-built files stores
- ❖ **Pipeline orchestration** — Mission-specific workflow managers from scratch
- ❖ **Software deployment** — Fixed reference platform or centralized and slow building and deployment

Costs



Long implementation timelines

Custom toolchains require years to design, develop, test and commission



Significant FTE investment

Large teams dedicated to infrastructure rather than science — repeated each mission



Knowledge not fully reusable

Lessons learned rarely transfer directly due to different technology choices per mission



Maintenance burden

Proprietary systems lock missions into specific expertise and long maintenance period

Science Ground Segment: cloud-native technology stack

SDC cloud-based technology stack (compatible or shared with the SOC infrastucture)

Metadata Archive & Data Model

Separate prod/dev instances. JSON-schema model for algorithm evolution.

Document-oriented DB

Distributed Object Storage

S3-compatible, fault tolerant. Common archive view (SOC & SDC).

CEPH

MinIO

Container Deployment

Reproducible pipeline packaging for consistent deployment.

OCI - Open Container Initiative

OCI containers

Processing orchestration

Abstracts data centre infrastructure: scalable pipeline scheduling and execution.

K8s cluster

Workflow Management

Cloud-friendly DAG orchestration for L0.5→L1→L2 pipelines.

Argo Workflows

Software CI and repository

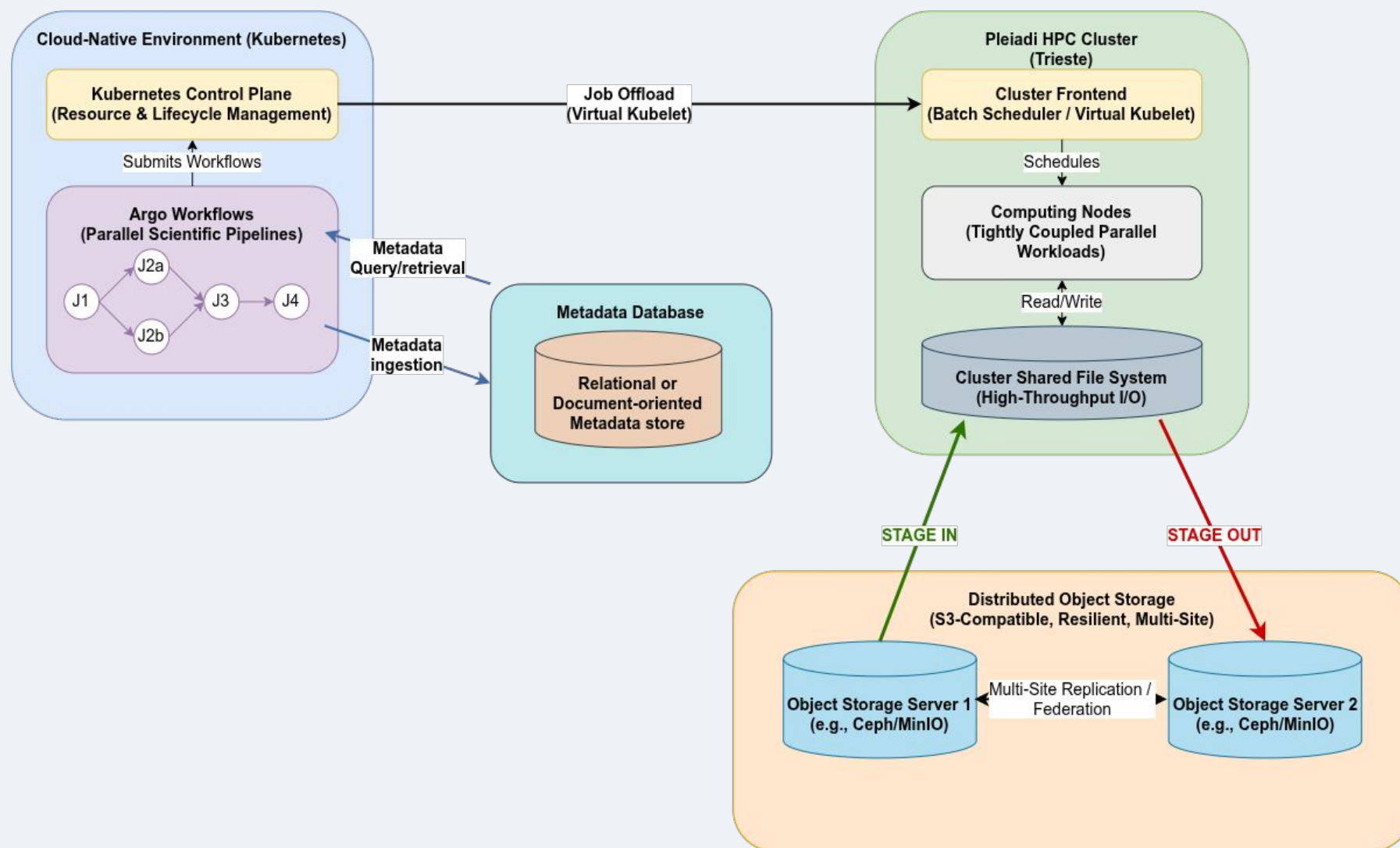
Central repository for version control, Continuous Integration (CI), and container distribution.

GitLab

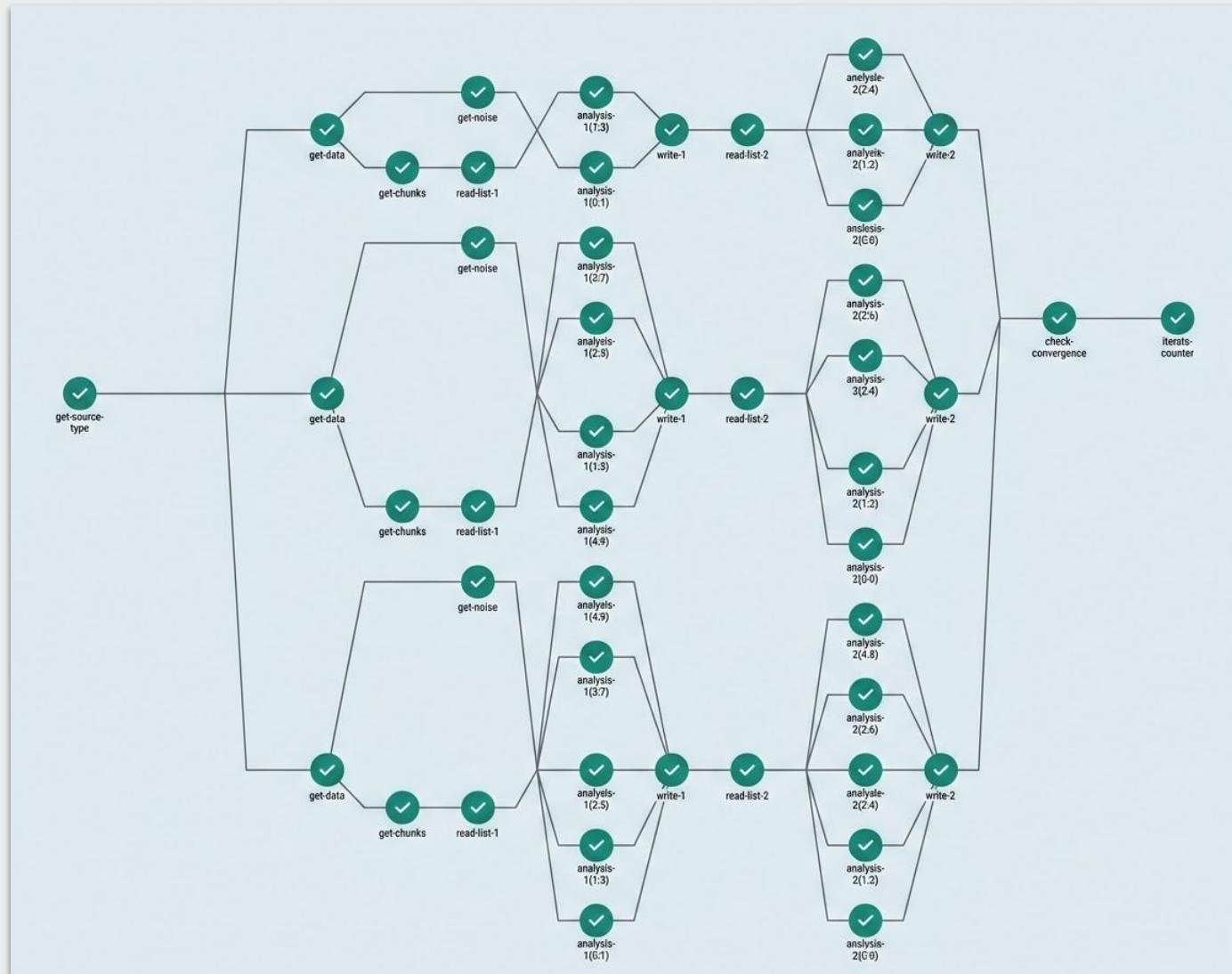
Argo Workflows

SonarQube

Processing pipelines: workflow management (HPC cluster case)



LISA: first tests with a GlobalFit prototype (Argo Workflow)



SGS: checklist for phase A

- ❖ **Preliminary SGS architecture document**
 - Data model (for simulations) and metadata archive architecture
 - Mission DataBase (as designed first, then as built)
 - Main algorithms, processing chains and constraints
- ❖ **Interfaces outline (in the Management Document)**
 - SOC - Consortium SGS
 - IOT - SOC/MOC
 - SPT - ST (Science Pipelines Team - System Team)
- ❖ **Telemetry budget**
- ❖ **Schedule and activities budgeting**

Thank you for your attention

Ground Segment centres

MOC — Mission Operation Centre

ESA

The central node for spacecraft operations: **telemetry acquisition, telecommand uplink, orbit and attitude control, and instrument health monitoring.**

SOC — Science Operation Center

ESA

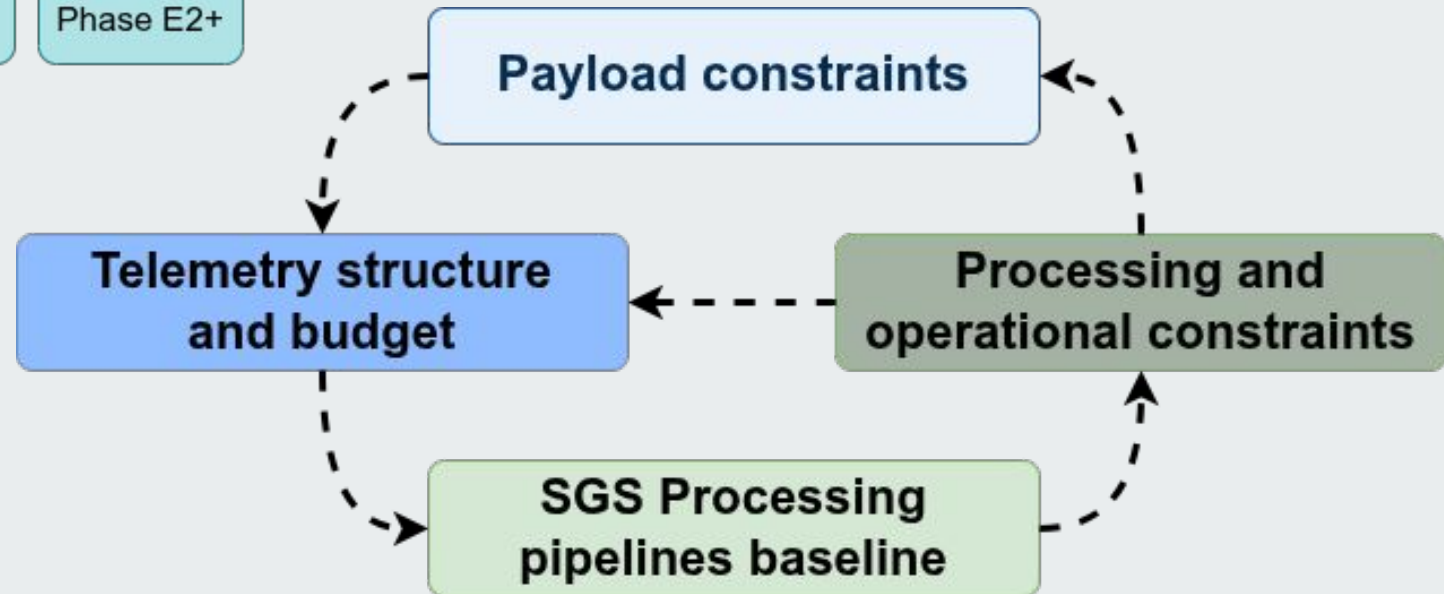
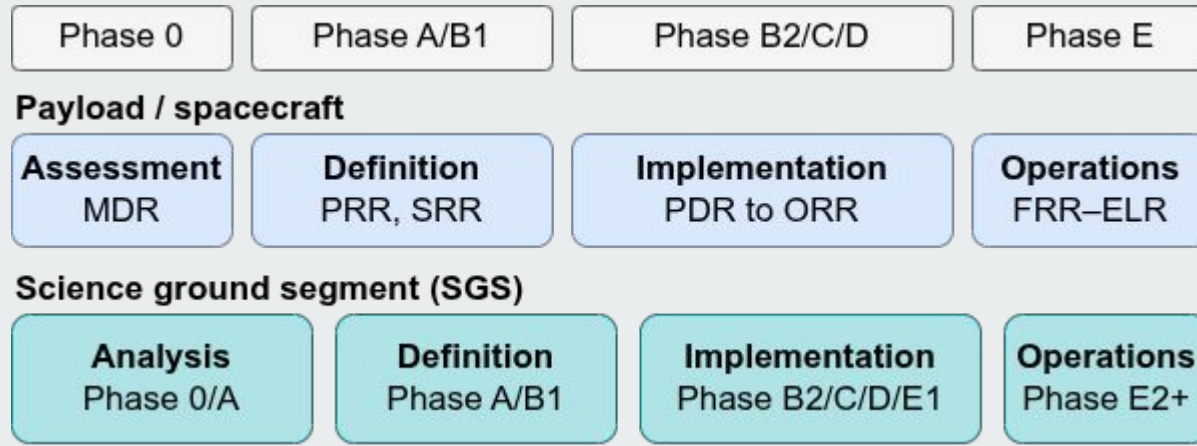
Raw **Level 0** telemetry and auxiliary data are routed from the MOC to the SOC, where they undergo pre-processing (**L1**). It executes the QLA (**quick look analysis**) and prepares payload telecommands sequences for the MOC. The SOC also maintains the **mission metadata archive**.

SDC — Science Data Centre(s)

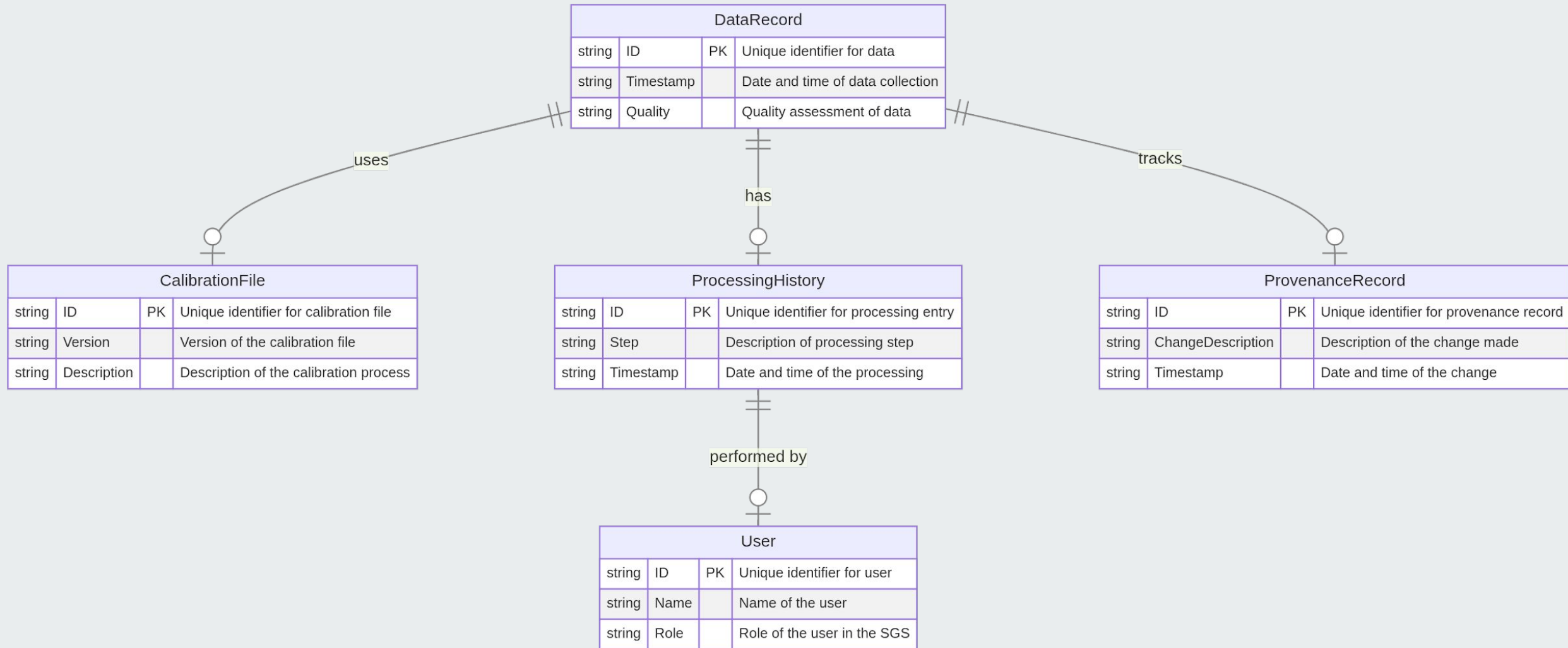
Consortium

An independent consortium environment for **pipeline development, testing, validation and production** through E2E simulation campaigns using synthetic data generated by the instrument simulator. Validated pipelines and configurations are tagged into a shared source **repository and deployed** to enter the production environment of the SDC (**L2, L3**).

Why Early SGS Co-Design Is Critical



Metadata archive: query, quality, provenance, reproducibility



More on the SGS infrastructure

- ❖ **Common Data Model** definition (using a formal language, e.g. JSON Schema)
- ❖ **Mission DataBase**: common database with **payloads** and spacecraft models (as designed, as built, etc) and **preliminary/ground calibration products**, constants, etc.
- ❖ **Mission metadata and data archive**: a single, shared, metadata database for all mission products. Data can be distributed between two or more Science Data Centres (e.g. using Object Storage solutions)
- ❖ **Common workflow management system**: it abstracts from a specific computing and storage infrastructure, parallelizing and distributing scientific workflow tasks
 - For distributed memory parallel tasks, just an offload to the HPC batch system
- ❖ Common software deployment system: automatic deployment and distribution of new pipeline releases, with additional checks (unit tests success and coverage, sw quality metrics)
- ❖ **Common Software Engineering Guide**: necessary to enable the PA/QA checks
- ❖ **Definition of interfaces** with MOC, SOC and IOT
- ❖ **Definition of a Technical Processing budget**: it starts with a definition of all the processing levels (including simulations), the data volume and the expected computing and storage resources