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Agile Design and Development of the Mission Operations Segment for HiVE Constellation of Microsatellites

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Abstract

HiVE is a constellation of microsatellites to deliver daily sub-field Land Surface Temperature (LST) imagery optimized for precision agriculture at global level. The technology is based on the successfully validated LisR (Longwave Infrared Sensing demonstratoR) payload, launched to the International Space Station in February 2022 and successfully operated onboard for several month. The satellite architecture enables rapid scaling to achieve global coverage, daily revisit times, high spatial and spectral accuracy. The constellation deployment will start in 2023 with the launch of the IOD, followed to subsequent flight models in 2024, enabling global daily revisit.

HiVE faces a challenging and ambitious launch plan, requiring agile development practices in both space and ground segments. Mission Operations Segment (MOS) development follows the same agility requirement. HiVE MOS includes three major element, Mission Control, Mission Planning and Flight Dynamics, orchestrated to plan the observations, task the satellites, and monitor the constellation automatically. With gradual launch of the constellation satellites, MOS, each of its elements, and the overall ground operations, should be scalable. MOS benefits from the cloud-enabled services in the "New Space" sector to reduce development and maintenance costs of the ground software and facilities. The architecture is therefore composed of commercial solutions and in-house developed software systems.

The paper introduces the constellation and the mission operations segment architecture and its interfaces to the rest of the constellation elements. Constraints driving the development process are introduced. It describes the overall agile development process for the first two satellites of the HiVE constellation, focusing on the activities performed in early design phases, and explains the complexities involved in the process. Lastly, status of the system and future to scale it up to include the next satellites are presented.

Keywords: Mission Operations, Mission Control, Mission Planning, Agile development, Earth Observation, Constellation

Acronyms/Abbreviations

COTS	Component off-the-shelf
FDS	Flight Dynamics System
GSaaS	Ground station as a service
GSMS	Ground Station Management System
HIVE	High-precision Versatile Ecosphere monitoring mission
LisR	Longwave Infrared Sensing Demonstrator
LSE	Land surface emissivity
LST	Land surface temperature
MCS	Mission Control System
MOS	Mission operations segment
MPS	Mission Planning System
PDS	Payload data segment
TIR	Thermal infrared
VNIR	Visual near-infrared

1. Introduction

Two of the most pressing challenges of our time, a growing population and a changing climate, are contributing to a third potential threat to our planet and humanity; that is, how to secure a sustainable, equitable food supply. The global food production system is exposed to significant uncertainty and instability; current crop monitoring systems are non-scalable, costly, imprecise or too coarse, meaning actionable data for optimisation is unavailable, insufficient or inconsistent between areas. New, affordable data sources, available globally and at a precision that enables action, are required to support the stabilization of the food supply chain.

Constellr is a space data and services company leading the way in delivering daily, global land surface temperature (LST) data for smart farming. Using its swarm of infrared monitoring satellites, Constellr precisely measures the actual temperature of crops at a sub-field level daily and across the full globe. Unlike traditional space-based systems that rely on plant colour for stress monitoring, Constellr rather observes plant transpiration, enabling the robust detection of vegetative stress earlier than ever before, from space. This advanced warning means the risk of crop failure or damage is significantly reduced, allowing more accurate crop yield forecasting and thus better stability and management across supply chains. LST is especially critical for agricultural customers since it provides highly precise data on crop health change to support practices such as crop irrigation and other forms of yield optimisation. Constellr's customers, which include major agribusiness corporations, agri-tech firms and policy and research organisations, use the data to create more accurate and effective precision farming solutions, manage scarce water resources more effectively and boost agricultural production without harming the environment. Constellr's data platform offers fully secure API access to a range of temperature data and value-added services in industry standard formats and using delivery methods ready for integration into operational precision farming applications.

The Longwave Infrared Sensing demonstratoR (LisR) mission was the precursor of the HiVE constellation mission and included a longwave infrared camera which flew outside the ISS on the *Nanoracks* Experimental Platform. With the LisR instrument launched in February 2022, Constellr developed its first thermal infrared camera that has allowed de-risking critical technologies of the remote sensing chain and, as well, on-boarding early customers and starting pilots with early users.

The demonstrator mainly consists of a cryo-cooled thermal infrared frame camera, a free form optical assembly and an on-board data processing unit (Fig. 1- left). It images the earth's surface in two longwave infrared bands which allows the derivation of highly accurate Land Surface Temperature information with high spatial resolution. Early results of LisR orthorectified Land Surface Temperature (LST) products are presented in Brunn, 2022 [1] of which a sample is presented in Fig. 1-rigth.

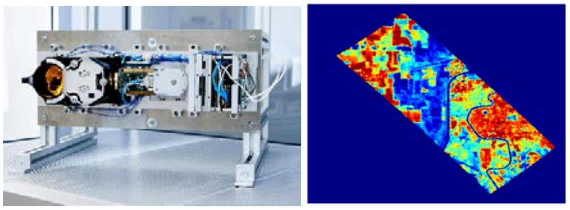

Fig. 1. LisR in clean room (left), LisR temperature image from ISS Apr-22 (right) [1]

1.1 HiVE

HiVE (High-precision Versatile Ecosphere monitoring mission) is going to be the world's first microsatellite constellation for thermal infrared land surface temperature monitoring. The mission is developed by Constellr GmbH, together with OHB System, NanoAvionics and Fraunhofer EMI, using a blend of standard techniques and newspace approaches. The primary goal is to provide global land surface temperature (LST) imagery optimised for high-precision agriculture, water management, temperature-derived crop health management, yield forecasting and sustainable resource management. Sub-field crop monitoring calls for high resolution imagery, day-to-day planning requires high revisit frequencies and operational use demand low latencies for data and analytics delivery.

A high-level schematic of the mission architecture is reported in Fig. 2: it follows the classical divisions of space segment, composed of multiple microsatellites, and ground segment. Each satellite is equipped with a multispectral

TIR cryocooled sensor, delivering the main mission data, and a multispectral VNIR to enable precise geolocation, atmospheric correction and cloud detection. The ground segment is in turn divided into a mission operations segment (mission planning & control incl. simulator and flight dynamics) and payload data segment. The ground segment directly interfaces with the user segment platform delivering L2 LST data in 6 to 12 hours from observation in space to user delivery. The ground segment receives users' requests and space and ground assets availability, optimize the mission plan and task both the constellation and the data processing system accordingly. The overall availability of the end-to-end system is targeted to be above 95% and a response time from user request to image delivery of 1 day. External interfaces with 3rd party data providers and missions are foreseen for data processing and mission planning purposes as well as ground stations services.

Due to its commercial nature, the constellation aims to be cost-efficient via the use of commercial-off-the-shelves components, while providing all key capabilities. HiVE is targeting a launch as soon as Q2/2024 using a Falcon9 ride-share mission: up to 4 satellites can fit a single 24''. This configuration will provide a precise and cost-efficient way of inserting multiple satellites into the same orbit.

The mission architecture comprises multiple operational concepts including virtual calibration for payload miniaturization and dynamic (on-demand) tasking/targeting, serving more users/payloads. By introducing novel operational concepts, the required payload satellite mass and volume can be minimised, thereby reducing space segment costs to a fraction of current systems whilst ensuring high radiometric precision.

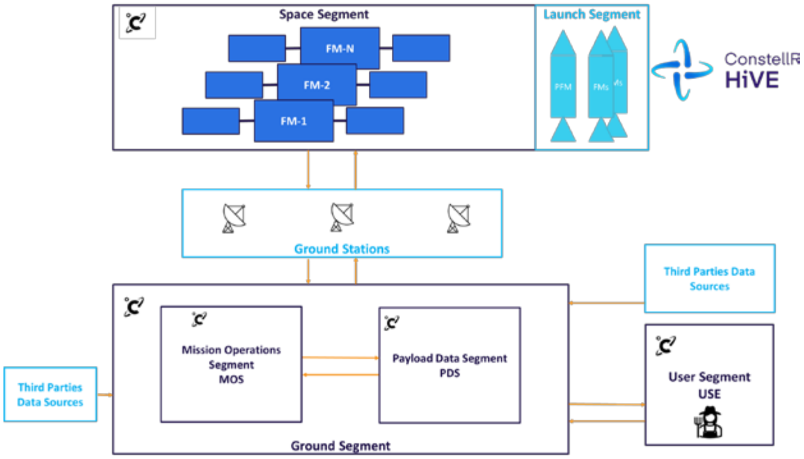

Fig. 2. HiVE high-level mission architecture [2]

2. Mission and concept of operations

HiVE is a constellation of microsatellites in the 80kg class, flying in formation in the same sun-synchronous orbital plane at an altitude between 520km and 560km. Precise phasing between the satellites is maintained by an electric propulsion system. The satellites are designed to safely de-orbit in less than 12 years from the end of the 5 years mission (full compliance with applicable debris mitigation standards will be guaranteed and the satellite has enough propellant to perform end of life manoeuvres to further decrease the re-entry time).

Driving user requirements for the constellation have been:

- spatial resolution
- revisit time
- radiometric uncertainty
- latency time between data recording and delivery.

The first generation of the satellites will deliver <50m ground resolution in LWIR/TIR and <15m in VNIR with up to 1.4 Mkm² imaging capacity per satellite per day (daylight, land). Five assets will be able to deliver 1-day global temporal resolution in selected areas, with a goal lifetime of 5 years.

The concept of operations foresee primary mission phases, durations and functions are reported in Fig. 3.

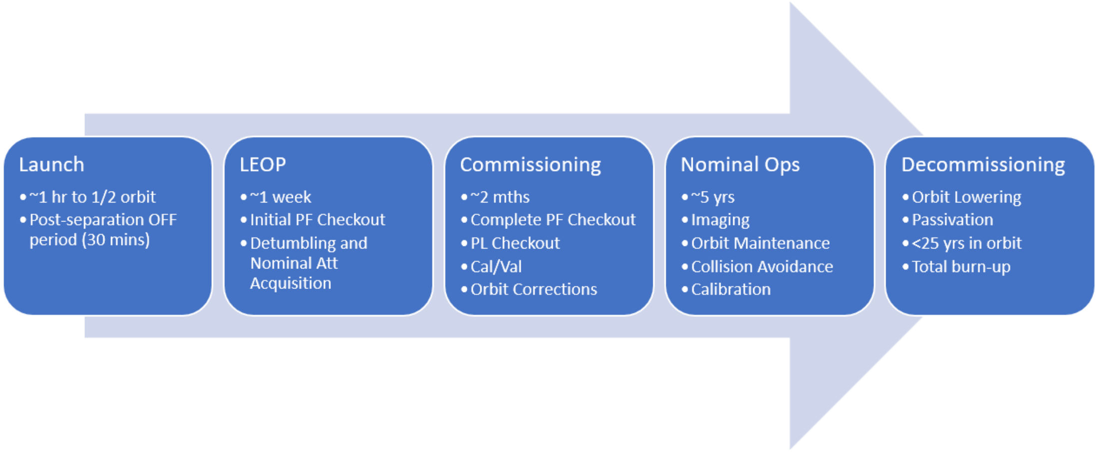

Fig. 3. Primary mission phases [2]

During nominal operations, payload data will be downlinked via 2 baselines ground stations (Fig. 4): 8 to 12 passes per day are sufficient to downlink a 13% average duty cycle with the required maximum latency. Contacts with ground stations are performed as much as possible out of the observation windows.

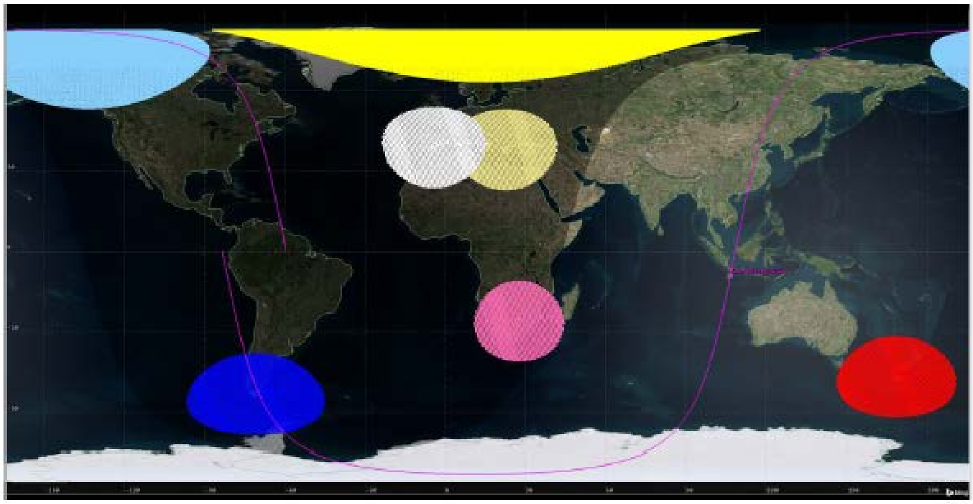

Fig. 4. Ground station pass opportunities using KSat network [2]

To read more on the HiVE mission design, satellite platform and payload please refer to Benvenuto [2].

3.1. MOS architecture

The Mission Operation Segment (MOS) consists of 3 major components and several smaller tools. It partly leverages the tools available on the market, integrating them with mission-specific custom software. All components are designed considering automation and scalability requirements. To improve availability and scalability and reduce operations costs, all components would be deployed on cloud. An orchestrator integrates all the elements to fully automate the operations.

At the core of MOS, the Mission Planning System (MPS) is responsible for providing a conflict free plan for observations. Both on-demand and opportunity observations, maximizing coverage of specific target areas, are considered in the planning logic. MPS exchanges information with user segment and payload data segment on the status of observation requests. Mission Control System(MCS) is responsible for telemetry and telecommand chains and monitoring of the constellation. To provide enough downlink capacity, MOS would use one or more ground station as a service (GSaaS) provider. The Ground Station Management System (GSMS) block would wrap the APIs from different providers to harmonize the interfaces for the Mission Planning System. The last major element of MOS is the flight dynamics tool. In addition to the usual tasks of the flight dynamics, orbit determination and orbital events generation, this system is also responsible for manoeuvre plans for different satellites.

A high-level MOS architecture is depicted in Fig. 5. This is a preliminary functional architecture, and its main objective is at this stage to encapsulate requirements to building blocks for later tool selection or development. This breakdown does not explicitly reflect for example the orchestration needed to automate the processes. It is noteworthy that the boundaries of these building blocks can also change. It is for example possible that MCS to some extent covers the functionalities of GSMS. These uncertainties emphasize the need for agile development.

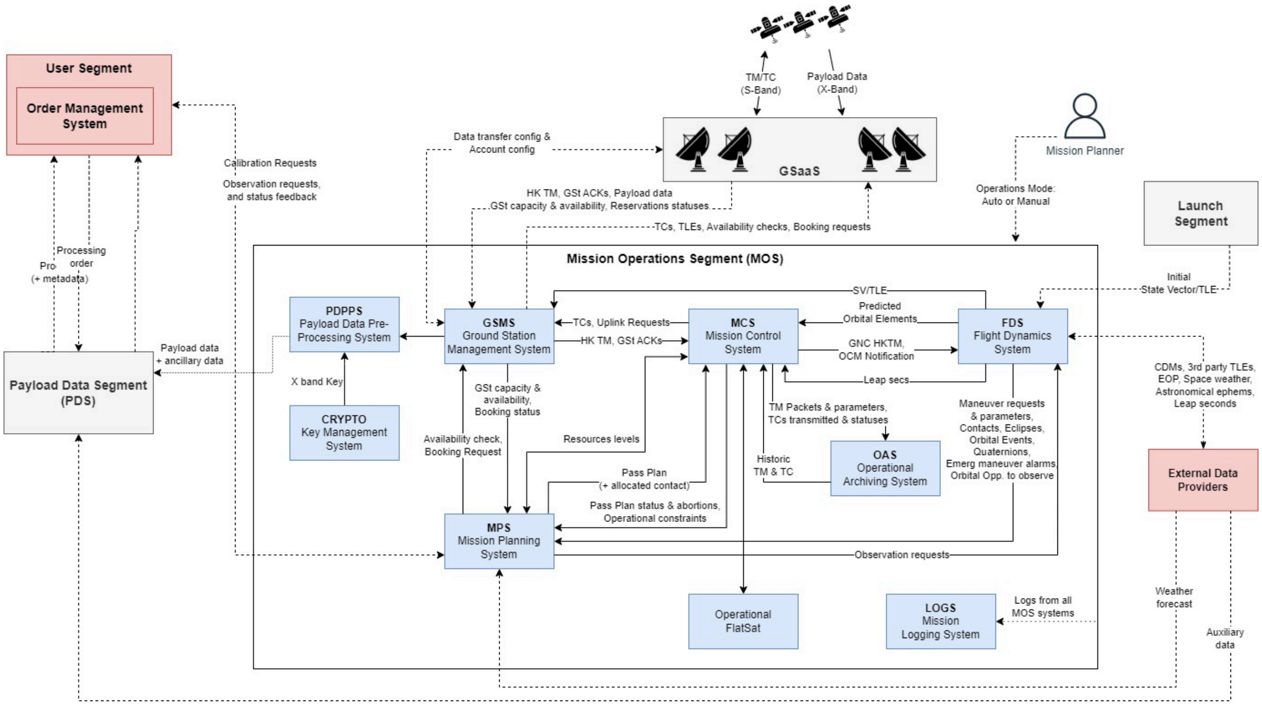

Fig. 5. MOS building blocks

MOS interfaces all major components of the constellation. Ground Segment as a whole is deployed on cloud, and interfaces are mostly web-based. This of course puts an emphasis on security of operations and availability.

3.2. Integrated Operations Concept

MOS is part of the overall operations of the constellation. Fig. 6 shows the high-level integrated operations concept of the constellation, including customer, user segment, MOS, satellites and PDS. As shown in the picture, MOS and PDS are connected to the commercial operations through user segment (automatically) or client support (manually). These blocks are all developed in parallel, and each play a significant role in responding to client needs.

This not only implies the need for a collaborative development with frequent discussions on the system level consistency, but also necessitates an agile approach to be able to better manage the changes in interfacing systems.

There are frequent collaborative workshops to update the interface definitions or define new features in different segments based on the changes in other segments or needs identified elsewhere. End to end verification and validation activities have to be performed before launch to ensure observation requests are handled as expected

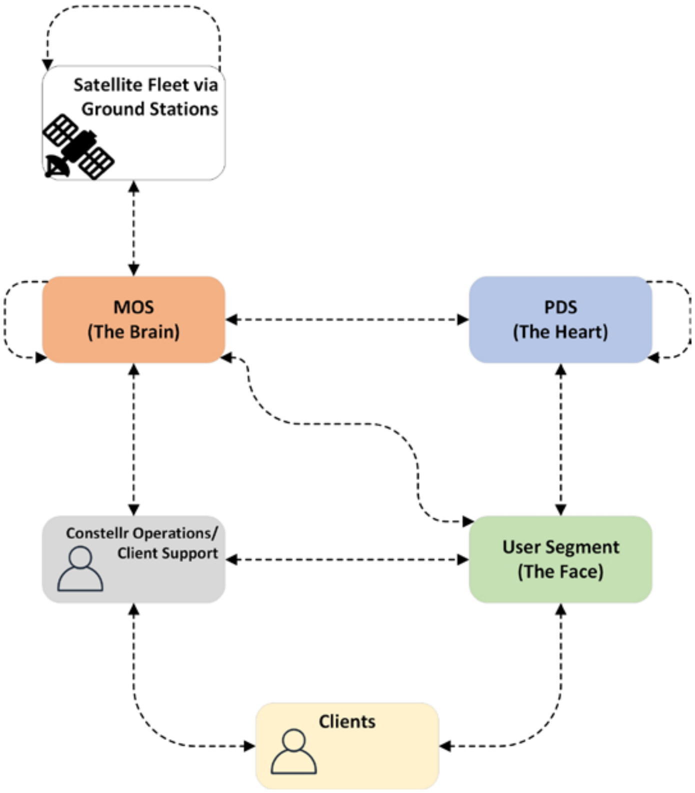

Fig. 6. Integrated operations concept

The integrated operations concept is one of the main inputs for the development of mission planning system. Planning logic is designed in accordance with the end to end operations concept, At the same time mission planning constraints contribute to the overall end to end process.

4. MOS Development Process

This section describes the approach to MOS development. Major requirements for MOS development, development and procurement process, and complexities in assessment of proposals is explained in detail. With the purpose-driven, newspace approach used in development of the space segment, development of operations and operational tools should partly adapt itself to space segment specifications. Staying in line with the newspace environment, operations development leverages the tools on the market to reach the operational phase faster.

4.1. Process Driving Requirements

MOS should comply with the constraints imposed on it by the rest of the system. These constraints are technical and non-technical and strongly influence the choice of tools and services. The main constraints are:

- **Time to launch:** The main driving factor in MOS development is time to launch. The first two satellites in the constellation are set to be launched in 2024, and nominal business operations is expected soon after, along with scale up of the operations to 5 satellites in 2025.
- **Cloud-based Infrastructure:** The second major driving factor in MOS development is the decision for cloud-based operations, rather than on-premises infrastructure. This facilitates distributed operations and removes the need for a dedicated operations room in the long run. On the other hand, this limits the tools that can be used in operations.
- **Constellation-compatibility and heterogenous growth:** Another factor is to develop multi-satellite tools. This decision is to keep the MOS small and develop lean operations, minimizing maintenance efforts and infrastructure needs. This as well facilitates integrating new satellites in operations. It should as well be taken in to account that the end constellation may vary in terms of instruments and .
- **Satellite platform procurements**: As the satellite platform is procured, operations is partly driven by the selection of the platform. This impacts the protocols and procedures. Part of the requirements is derived from the platform operations. This of course has an obvious advantage, that existing operational experience exists with the procured platform, and tool configurations for the mission can be performed faster.
- **Parallel developments**: Last but not least, MOS has interfaces with other segment, which are being developed in parallel, and their specifications may change during design and development phases.

The above mentioned imply that a flexible design is required, particularly with respect to interfaces, and necessitate an agile mindset in approaching the MOS development. What is meant here by agile is the acceptance of change and incremental development of features. Updates during operations is expected, and therefore operational processes shall also define MOS maintenance concept as well.

4.2. Incremental Development

With the time to launch restriction, MOS development leverages the tools on the market. Mission-specific tools, with less generic functionalities, are developed in-house. Nevertheless, there are several tools providing part of the generic functionalities needed within MOS.

All tools must comply with the constrained mentioned above. In addition, with the vision that MOS would be a mosaic segment with several tools, custom needs and numerous dataflows. all tools essentially need to be extensible, and interfacing should be facilitated.

Incremental development process is applied to both in-house developed tools and procured tools, as shown in Fig. 7. The input to the development process is the set of features to be developed. Most COTS tools would require complementary mission-specific development, interface development and configurations. A detailed coverage study is performed in the beginning to define the coverage of features that are essential to the mission. This coverage study can include demonstrations and pilot projects whenever necessary.

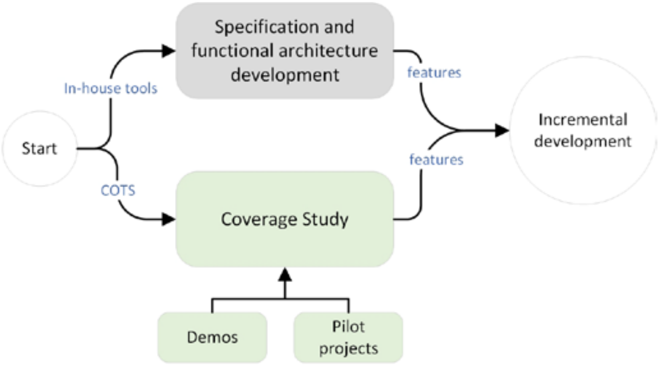

Fig. 7. Feature detection for tools

4.3. Complexities in component selection in newspace market

There are numerous COTS tools in newspace market, with different approaches and scope. In creating the final architecture of the MOS for HiVE constellation, two major topics are to be answered:

- The use of as-a-Service solutions or cloud-deployable licensed software. The approach shall consider not only the break-even point, where the service costs grow higher than license costs, but also consider efforts to guarantee service levels, security and similar aspects.

- The advantages and disadvantages of a heterogenous mission operations segment, in which tools are provided by different suppliers, and umbrella solutions whose functionalities extend across the mission operations segment components. While umbrella solutions are cost-effective and reduce the development effort for interfaces among components, they may provide less coverage of the requirements for each component, demanding more complementary development.

Agile mindset in all the teams and suppliers involved in the development of tools are essential. Changes in requirements are expected in newspace missions and all development activities have to include enough flexibility to handle the possible changes.

4.4. Feature Ranking

After coverage analysis and at the start of incremental development, given the tight timeline to launch, features will be ranked to focus on mission-critical ones. Automation-related features are considered secondary, as manual operations during the first few months of the orbital lifetime is considered advantageous for better understanding of platform and payload.

4.5. Development of Mission Base and Operational Procedures

In parallel to procurement activities in early design faces, two development activities are followed.

As part of MOS development, a mission database shall be specified and developed as well. This database integrates the definitions for telemetry and telecommand packets for both platform and payload. HiVE satellites also use file-based operations, and therefore file definitions should as well be included in the database.

This mission database is the backbone to mission control. It is therefore ideal to define the interfaces in a collaborative manner. However, tool selection can impose constraints on the database design (Fig. 8)

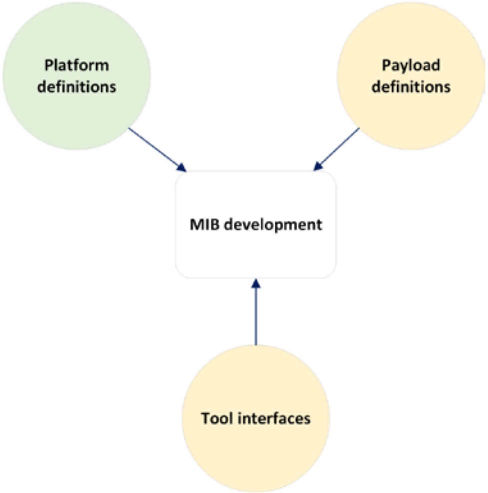

Fig. 8. MIB inputs and dependencies

The databases are all version-controlled and deployed on cloud infrastructure.

In addition to database development, early design activities also include procedure development. Procedure development as well depends on platform and payload definitions. Procedures are version controlled and maintained as well.

4. Current Status

At the time of writing this manuscript, PDR activities are closed. It is envisioned that by project CDR, the tools are selected, and features to be developed are selected and ranked for priority.

With the first two satellites planned for launch in Q2-2024, the objective for MOS development is to deploy a reliable, however minimal, version by Launch Readiness Review. Operations will start mostly manually, for two reasons: first is to better understand the platform and payload as the satellite is not manufactured or integrated in-house, and second due to the tight schedule to launch, automation is not the top priority. As the main tools are all multi-satellite capable, system scale up activities will follow to include 3 more satellites in 2025. However, the architecture of the system will stay almost the same. Scale up is ideally a configuration issue for the operational tools.

References

[1] A. Brunn et al., Towards High-Revisit, High-Resolution Thermal Monitoring: LisR - data, calibration and processing of thermal infrared data from the LisR ISS mission, The 4S Symposium,Vilamoura, Portugal, 2022,16-20 May.

[2] R.Benvenuto, et al., HiVE, an agile microsatellite constellation for thermal infrared Earth observation enabling "more crop per drop", IAC-22-B1.2.10, 73rd International Astronautical Congress, Paris, France, 2022, 18-22 September.