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Model-Based Systems Engineering to Develop Space Missions Ground Segment Architecture

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Abstract*. The ground segment of space missions is often considered a ready-run system, however during the missions evolution, new requirements may be requested, which become new functions and challenges for the ground segment. In this scenario, it is necessary to address new issues and apply additional analysis to meet the cost requirements, product quality, reduction of risk, and development time, as well as contribute to systemic solutions with modern development methods. One modern development method is the Model-Based Systems Engineering (MBSE), which is applied to aeronautical, automotive, and space systems. The method's relevance is evidenced by the adoption of MBSE in the programs and missions of major space agencies such as the European Space Agency (ESA) and the National Aeronautics and Space Administration (NASA). This paper presents the method concepts and explores the development of space mission ground segment architecture by applying MBSE, it also presents the contributions of this approach.*

Keywords: Architecture, Ground Segment, Model-Based System Engineering - MBSE, Space Mission.

1. Introduction

The document-based approach to SE presents challenges such as: (i) difficulty in assessing the integrity and consistency between SE products (requirements, analysis, design and testing) and (ii) difficulty in tracking and understanding the impacts of changes that occur in various elements.

MBSE can address these challenges for development and enable communication with stakeholders in a formal and unambiguous way. Moreover, the model-based method overcomes the drawbacks of traditional text-based methods by effectively communicating to both stakeholders and system developers.

In order to optimize ground segment architecture development and interaction with the space segment, this work explains a process using MBSE, based on the ARChitecture Analysis and Design Integrated Approach (ARCADIA) method and the Capella tool.

2. Fundamental Concepts

This section presents a summary of the main concepts applied in this work, such as Model-Based Systems Engineering and Modeling Methodologies.

2.1. Model-Based Systems Engineering

MBSE often involves combining several activities from the Systems Engineering (SE) engine processes concurrently and iteratively, namely system behavior description, requirements analysis, system architecture, and test (V&V) approach.

According to Friedenthal et al., (2009), MBSE defines formal semantics for technical information and allows constructing patterns defining element relationships and facilitating auditing and completeness checking, and it ensures consistency across all generated products through single-source-of-truth.

MBSE is defined as the formal application of modeling to support the requirements of systems, design, analysis, verification and validation of activities initiated in the conceptual design phase and continuing throughout the development of the later stages of the life cycle (INCOSE, 2020). MBSE collaborates to manage complexity by moving the practice of document-based systems engineering to a model-based approach (SMITH et al., 2014).

Some initiatives for adopting MBSE in the area of space systems: MBSE Pathfinder was established, in 2016, to evaluate the application of MBSE to some of the most challenging aspects of real NASA's spaceflight systems (HOLLADAY et al., 2019). The ESA has selected the Euclid Mission (FISCHER et al., 2018) to demonstrate the benefits of MBSE in the context of ground segment engineering.

2.2. Modeling Methodologies

Several methodologies support the MBSE. This paper presents a summary of three methodologies their languages:

1. **Object-Process Methodology** (OPM) (ESTEVAN, 2009) is defined as a formal paradigm to systems development, lifecycle support, and evolution. It combines formal yet simple visual models known as Object-Process Diagrams (OPDs) with constrained natural language sentences known as Object-Process Language (OPL) to express the function, structure, and behavior of systems.
2. **Object-Oriented Systems Engineering Method** (OOSEM) provides a foundation for describing the composition of systems and their parts in a particular domain. The OOSEM is covered in the INCOSE Systems Engineering (INCOSE, 2020) and the Practical Guide to SysML (FRIEDENTAL et al., (2009). The associate tools for using SysML are COTS-based OMG SysML.
3. **ARChitecture Analysis and Design Integrated Approach** (ARCADIA) (ROQUES, 2017), developed by Thales, is a model-based engineering method for systems, hardware and software architectural design.

Arcadia method, supporting by the Capella tool, promotes collaborative work among all key players, from the engineering phase of the system and subsystems, until their Integration, Verification and Validation. It supported by various kinds of diagrams inspired by UML and SysML.

3. BiomeSat Mission

The BiomeSat main mission intends to continue monitoring environmental changes, deforestation and forest degradation. The imagery acquired will support applications in areas of vegetation, environment and education. BiomeSat, a 6U small satellite platform, will contribute complementary to the existing bigger observation satellites available to INPE (ABRAHÃO DOS SANTOS et al., 2022).

The initial conception is planned to carry a set of payloads, namely: (i) a Remote Sensing Camera for forest health monitoring which is the primary mission, (ii) a Environmental Collecting Transponder which was developed by INPE´s Northeast site, (iii) an Automatic Identification System Transponder (AIS) for monitoring vessels by Brazilian maritime authorities.

3.1. INPE's Ground Segment for BiomeSat Mission

The BiomeSat mission imposed new challenges for the implementation of the ground segment. The ground segment must allow higher rate revisits, associated with the control and reception of data from several satellites, such as CBERS 4A and Amazonia-1, in addition to support and interoperability for all ground facilities, which requires an architecture to support them.

The contributions to overcoming the challenges associated with the development of the ground segment for small satellites and ensure the mission accomplishment are: (i) the integration and tests of the ground segment; (ii) the planning for control and operation of the BiomeSat satellite, (iii) the Data storage and dissemination by the Brazilian Space Weather Monitoring and Study (EMBRACE) at INPE.

BiomeSat shall be use a ground segment, which comprises by INPE TT&C ground stations located at Natal and Cuiabá, under control of Satellite Control Center (SCC), located in São José dos Campos. For scientific data downlink, the BiomeSat shall be use two X-band antennas located at Cuiabá and Cachoeira Paulista.

The SCC at INPE headquarters (ECCS, 2008) in São José dos Campos remotely operates TT&C ground stations using SATellite Control System for BiomeSat and communication private links. The mission operations at INPE involve the support and operational teams, ground system infrastructure (hardware and software), and facilities.

The data center at EMBRACE receives the data and distributes decommutated instrument and engineering data to the instrument teams (Mission PIs) for data reduction.

4. Proposed solution for system modeling

The proposed approach considers the complexity of modeling (language, methods, and tools) and aims to apply MBSE to the ground segment architecture development of space missions. To achieve this goal, the modeling process was carried out based on the Arcadia method and the Capella tool (ROQUES, 2017) e (VOIRIN, 2017).

The modeling process is premised on being simple, intuitive and allowing for a reduction in the learning curve, without the need for specialized architects to translate the models. In MBSE, the model serves as the single source of truth for the development team and is the main artifact produced by SE activities (JULIO FILHO et al., 2023).

4.1. Arcadia Architecture Phases

Arcadia defines core-engineering phases, represented by activities, to analyze need and define solution architecture (VOIRIN, 2017), these phases are:

1. **Operational Analysis (OA):** *"What the users of the system need to accomplish"*.
2. **System Need Analysis (SA):** *"What the system has to accomplish for the users"*.
3. **Logical Architecture Design (LA)**: *"How the system will work to fulfill expectations"*.
4. **Physical Architecture Design (PA):** "*How the system will be developed and built"*.
5. **Building Strategy Definition (BS) (End Product Breakdown Structure):** *"What is expected from the provider of each component"*.

4.2. BiomeSat Modeling results

The mission's Stakeholders provide the inputs: the requirements of the system to be modeled, mission objectives.

The BiomeSat mission modeling process emphasized the **Ground Segment Architecture**, following the phases: **Operational Analysis (OA), System Analysis (SA), and Logical Architecture (LA)**.

Each phase receives the appropriate inputs and produces, through the modeler, the outputs. The Physical Architecture (PA) is not a scope of this work.

4.2.1. Operational Analysis (OA)

The first perspective on systems engineering brought by Arcadia is related to the analysis of the needs and objectives of stakeholders, their missions and expected activities (VOIRIN, 2017).

In this perspective, the engineering main goals are: (i) understand the real customer need, in terms of tasks to be completed by users; (ii) check the need consistency, completeness; (iii) collect material for future technical trade-offs, and negotiations with customer.

Typical inputs are stakeholder requirements, textual description; documents, such as, use cases, scenarios, capabilities analysis, operational and first system models; and previous generation systems.

Outputs of this engineering activity mainly consist of an "operational architecture" which describes and structures the stakeholder's need in terms of actors/users, their operational capabilities, and activities.

The model produced is the Operational Architecture Blank (OAB), called [OAB] Operational Entities, Figure 1. It comprises by Space Segment [SS], Ground Station System [GSS], Mission Operations System [MOS], Mission Explotation System [MES], Payload Operations & Data System [PODS], Electrical Ground Support Equipment [EGSE] and Satellite Engineering Model [EM].

Figure 1. Operational Architecture Blank [OAB] - Operational Entities.

Another perspective of the model is [OAB] Operational Entities and Activities, Figure 2, which shows all associated entities and activities.

For example, the GSS entity associated with two activities *"Provide TT&C Ground Stations Services"* and *"Provide Payload Data Services"*, and the GDS entity, associated with the activity *"Implement Ground Data Services"*.

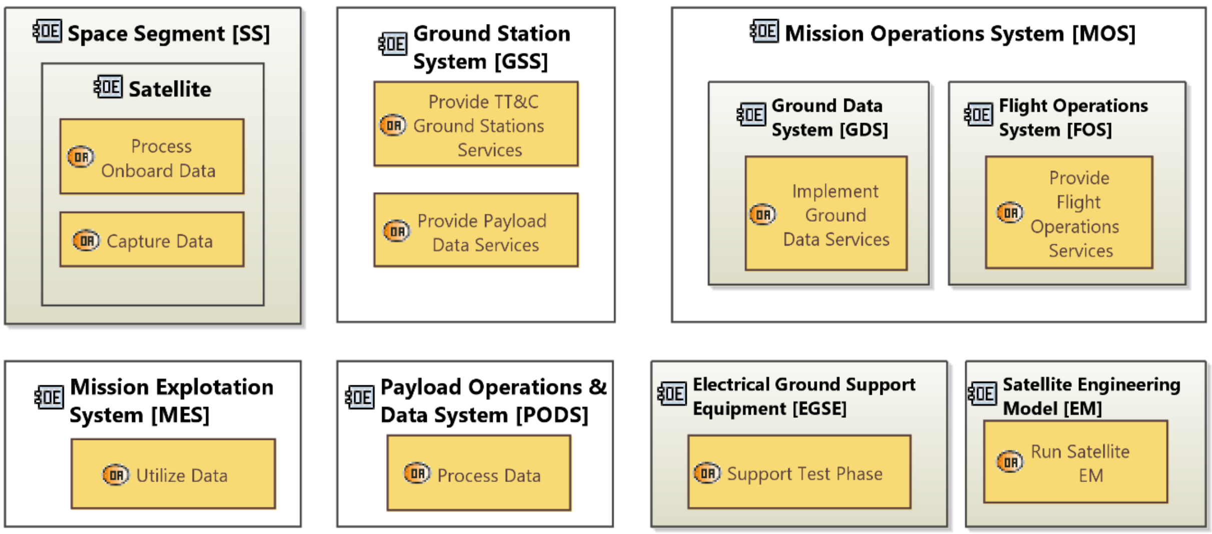

Figure 2. Operational Architecture Blank - [OAB] Operational Entities & Activities.

4.2.2. System Need Analysis (SA)

The System Needs Analysis perspective focuses on the system itself, in order to define its contribution to the satisfaction of previous operational needs, together with its behavior and expected qualities. The main objective at this point is to verify the feasibility of stakeholder requirements such as cost, schedule, technological readiness, etc..

The information entered for this level is “operational architecture” produced by the previous level Operational Analysis. The outputs of this engineering activity mainly consist of descriptions of system functional needs (system capabilities, functional chains and scenarios), interoperability and interaction with users and external systems (functions, exchanges plus non-functional constraints) (JULIO FILHO et al., 2023).

The model produced is the System Architecture Blank (SAB), called [SAB] System - Functional & Components Exchange comprises by System Components: [SS], [GSS], [MOS], [MES], [PODS], [EGSE] and [EM], Figure 3.

This perspective of the model illustrates all components and functions of the system. For each system component indicated by blue boxes, the functions indicated by green boxes are associated.

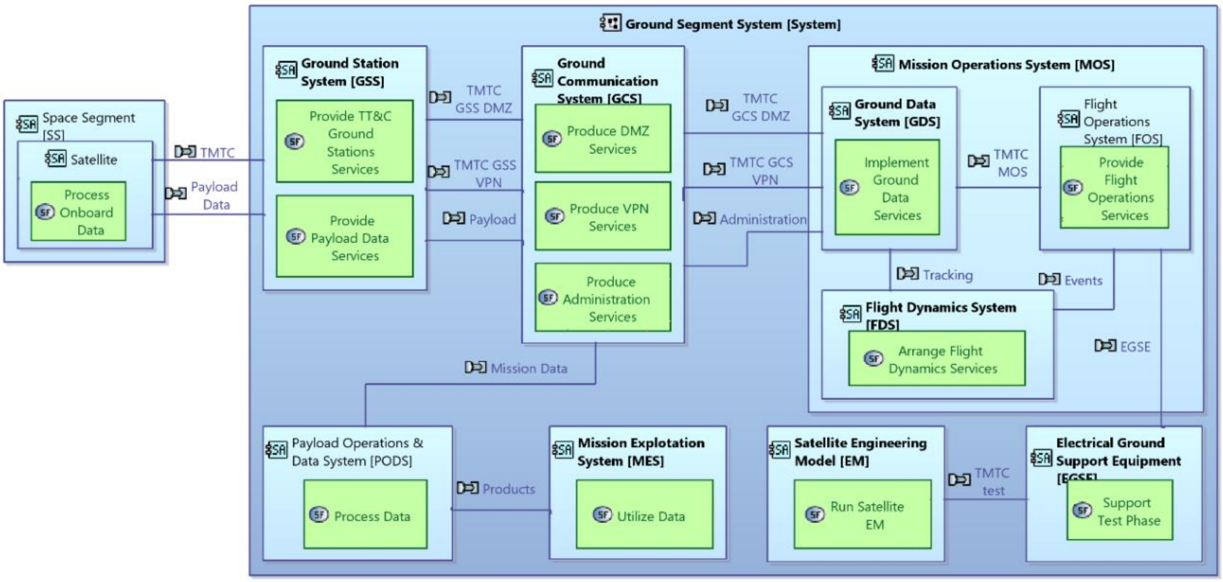

Figure 3. System Architecture Blank - [SAB] System - Functional & Components.

4.2.2.1. System Need Analysis - Requirements

At this level, mission and system requirements are associated with the previous components and functions, to implement data exchanges, non-functional constraints and complement the requirements originated by customers. These associations maintain bidirectional traceability between system requirements and needs functions, data flows, interfaces, and scenarios (VOIRIN, 2017).

The model produced is the System Architecture Blank (SAB), called [SAB] System - Mission & System Requirements, figure 4, comprises by System Components, Mission and System Requirements and their relationship.

Mission Requirements, indicated by pink boxes, are related to one or more components indicated by **blue boxes**. These mission requirements are derived for system requirements, which in turn are associated with one or more components.

For instance, the MisReq 05 "Ground Segment Reuse" is associated with **the system requirements, (green boxes)**, SysReq 01, SysReq 03, SysReq 04, and SysReq 05.

These associations are illustrated by the "satisfies" connection coming from one or more components, and the "deriveReqt" connection indicates the relationship between mission and systems requirements, and components.

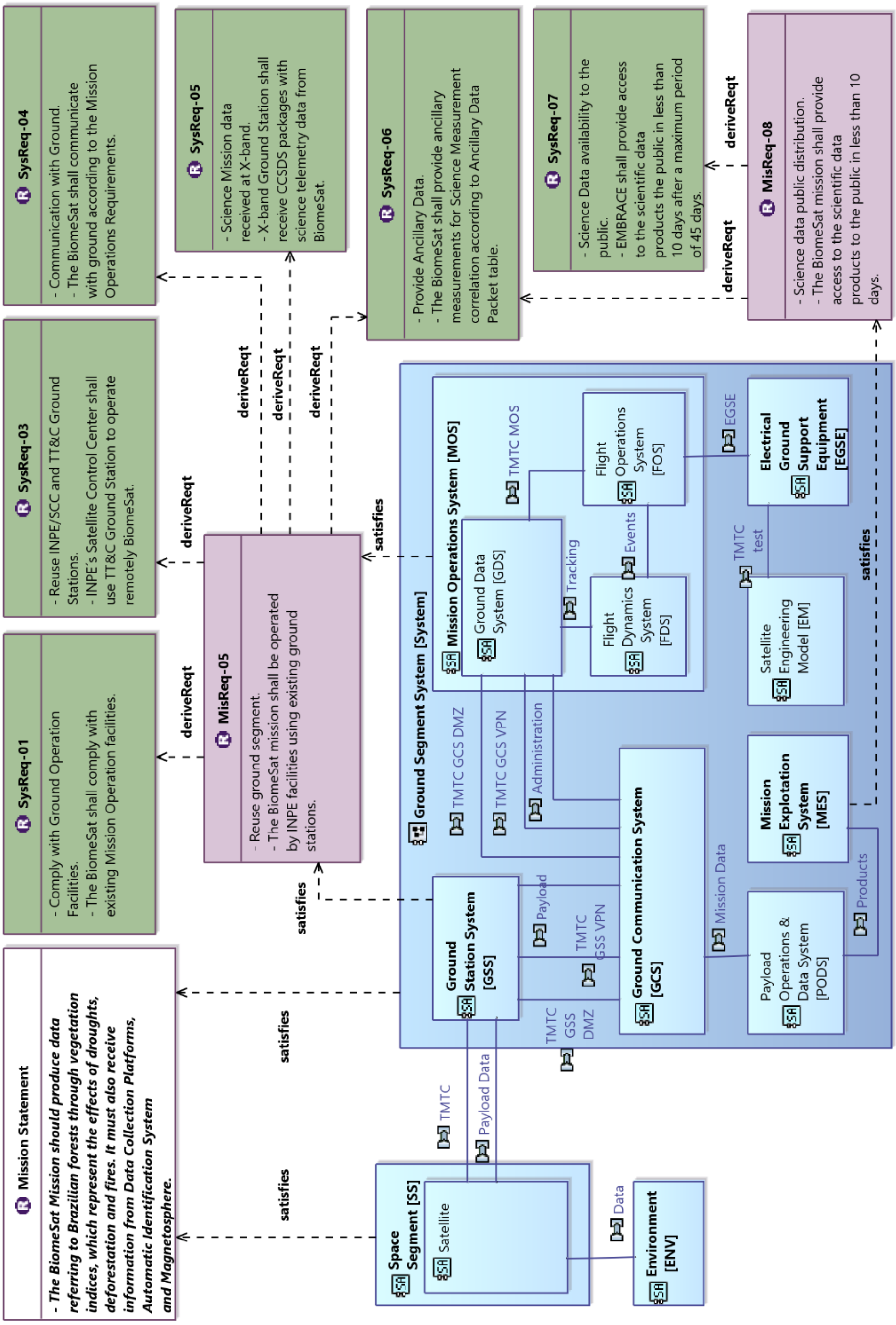

Figure 4. System Architecture Blank - [SAB] System - Mission & System Requirements.

4.2.3. Logical Architecture Design (LA)

This perspective aims at building a component breakdown of the system into logical components. It is based on functional and non-functional analysis describing the designed behavior (functions, interfaces, capabilities, functional chains & scenarios, modes & states) (VOIRIN, 2017). Its limited complexity level helps in exploring the solution alternatives. **The Logical Components those are independent from any technological choice.**

Starting from previous functional & non-functional analysis results (functions, interfaces, data flows, behaviours), build one or several decompositions of the system/software into logical components.

Logical Architecture Candidate outputs consist of the best-selected "Compromise Architecture", which is described by the definition of justified components and interfaces, functional behavior, scenarios, modes and states, formalization of all points of view and the way they are taken into account in component design.

The model produced is the Logical Architecture Blank (LAB), called [LAB] Logical Architecture - Components & Components Exchange, in this example, comprises by System Components, Logical Functions, Functional Exchange, and Components Exchange, Figure 5. For instance, the logical *Components [GSS] and [GCS]* exchange data (information or matter) such as components exchange *TMTC GSS DMZ, and Payload.*

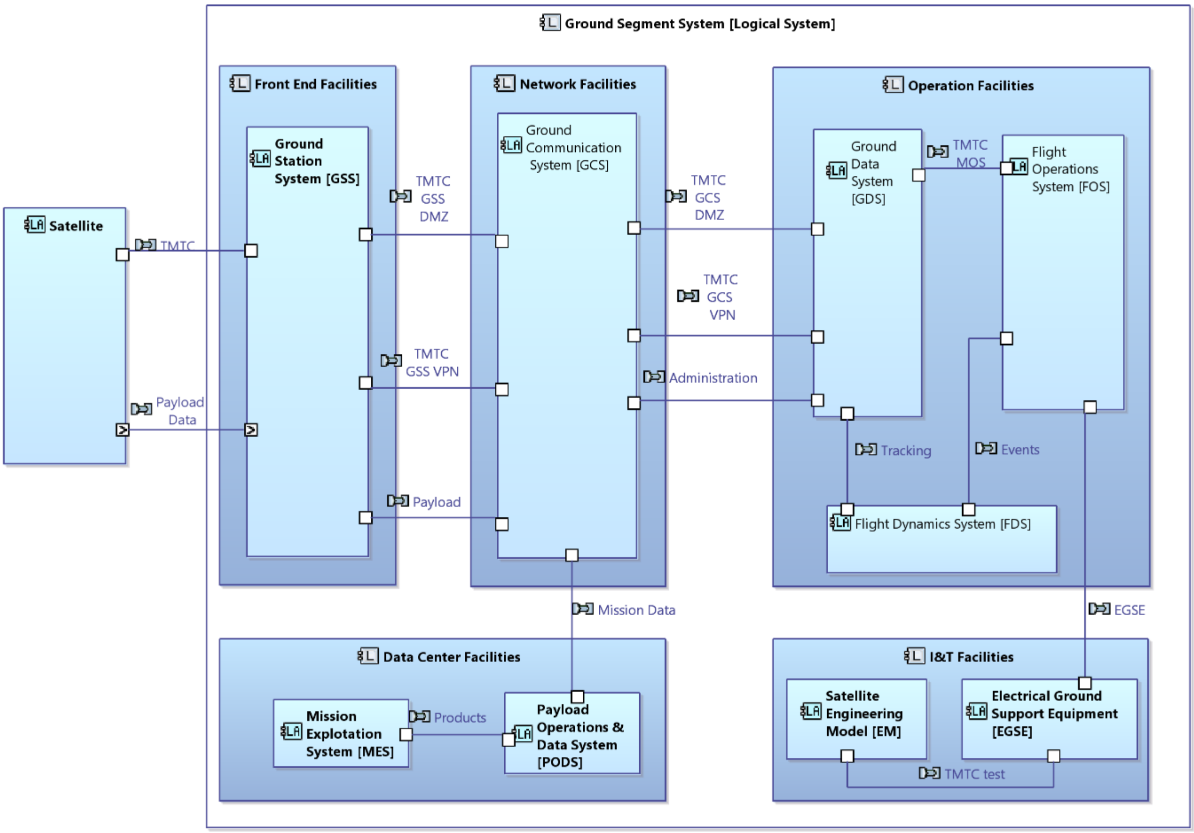

Figure 5. Logical Architecture Blank - [LAB] Logical Architecture - Components & Components Exchange.

5. MBSE Contributions

MBSE utilizes the essence of SE processes, and allows the opportunity for better overall quality, lower cost and lower risk. These contributions come about because:

a) There can be greater consistency of all products;

b) There can be better visibility into the salient characteristics of a system;

c) There can be greater congruence between documentation and reality, the artifacts can be generated automatically;

d) Navigation, traceability, and interrogation of information are facilitated in the model-based approach;

e) Models used for verification can have higher quality, and provide greater confidence.

6. Conclusions

The BiomeSat mission modeling process emphasized the **Ground Segment Architecture**, following the phases: Operational Analysis (OA), System Analysis (SA), and Logical Architecture (LA).

Early adoption of the model-based approach shows a promise that project formulation, testing and integration efforts are reusable from mission to mission and that they produce high-quality requirements, reducing time, cost and risk.

Applying the model-based approach requires a degree of formality in both thinking and approach. Certainly, ground segment architecture benefits from the application of MBSE best practices to help identify the key features and assumptions of the proposed system.

MBSE offers a powerful alternative and can bring efficiency to architecture development. However, the widespread adoption of MBSE implies advances from an organizational perspective.

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