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Model-Based System Engineering (MBSE) applied to Ground Segment Development of Space Missions: New Challenges.

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Abstract

Solutions with optimized financial resources, design with reliability and reduced development time drives the new challenges of space missions. Consequently, ground segment has to be aligned with the requirements defined by space segment to improvement the synergy between these segments. Traditionally, a ground segment is a ready-to-run system; notwithstanding, during the mission development, new requirements can be requested. In this scenario, many questions are raised in order to meet cost and operability requirements and contribute to systemic solutions, such as document-centric designs, adoption of integration and testing procedures aimed at the ground segment, cultural inertia, information sharing policies and new project methods. Ground segment design has to demonstrate the concepts innovations that are required for the increase in data types and volume, and their processes, communications protocols, as well as modern development methods. These concepts are found in the recommendations of the Consultative Committee for Space Data Systems (CCSDS), for: a) the standardization of the managerial interfaces of the Tracking, Telemetry, and Command (TT&C) services, b) the Space Link Extension (SLE) Protocol services for the cross support and interoperability. In addition, these concepts collaborate with the goals of the Interagency Operations Advisory Group (IOAG), for achieving full interoperability among member space agencies. The guidelines of the European Cooperation for Space Standardization (ECSS) and National Aeronautics and Space Administration (NASA) on systems engineering area also cover such concepts for system development, not limited to these major entities. In this paper, we provide an overview from space segment requirements to the ground segment requirements on the point of view of Model-Based System Engineering method and the SysML modeling language to formally describe and specify a space system, notably for the Satellite Control Center and the Telemetry, Tracking and Command (TT&C) ground stations at the National Institute for Space Research (INPE). The aims of this work is to establish a process for optimization, management and implementation of the ground segment designs in a model-based approach, also considering an ontology. In such a way, we intend to improve and standardize the systems engineering practices and concurrent engineering procedures. The paper addresses the following topics: challenges for ground segment development, a space system overview, the INPE's ground segment evolution; concepts adopted as systems engineering, MBSE, ontology, language, and technologies; MBSE applications for space systems, and a process using MBSE.

Keywords: CCSDS, Ground Segment, Interoperability, Model-Based System Engineering MBSE, Ontology, Space Mission.

Acronyms

CBERS China-Brazil Earth Resources Satellite
CCSDS Consultative Committee for Space Data Systems
CNES Centre National d'Études Spatiales
DLR Deutsches Zentrum für Luft- und Raumfahrt e.V (German Space Agency)
ECSS European Cooperation for Space Standardization
EIA Electronics Industry Association
ESA European Space Agency
ESOC European Space Operations Centre
ESTRACK ESA Tracking Network
IEC International Electrotechnical Commission
INCOSE International Council on Systems Engineering
INPE National Institute for Space Research

IOAG Interagency Operations Advisory Group
ISO International Standards Organization
JAXA Japan Aerospace eXploration Agency
JPL Jet Propulsion Laboratory
MBSE Model-Based Systems Engineering
NASA National Aeronautics and Space Administration
OMG Object Management Group
OOSEM Object-Oriented Systems Engineering Method
OPD Object-Process Diagrams
OPL Object-Process Language
OPM Object-Process Methodology
RUP Rational Unified Process
SCC Satellite Control Centre
SLE Space Link Extension
SysML Systems Modeling Language
SYSMOD Systems Modeling Process
TC Telecommand
TM Telemetry
TT&C Telemetry, Tracking and Command
UML Unified Modeling Language

1. Introduction

Traditionally, a ground segment is considered a ready-to-run system and is closely aligned with the requirements defined by the space segment through a document-centric design approach. However, this approach presents inherent difficulties in updating the teams involved, and invariably the content is inconsistent or redundant; and on the course of mission development, new requirements may be requested from the ground segment and involve updating all dependent documents.

In document-centric designs, the systems engineering software tools operate stand-alone, each with its own database, and consequently, a lot of effort is required for the integration and maintenance of information.

Another consideration is related to the set of requirements, interfaces, integration and test, and ground segment's ability to handle changes and new requirements during project. Often this set is traceable only in the memory of the systems engineers and can therefore increase project time, hinder teamwork and knowledge building [1].

In addition, there are challenges that are not technical in nature. Cultural inertia, information-sharing policies are challenges to be faced in adopting modern development methods.

These new challenges make the system more complex and the ground segment lacks mechanisms to meet the requirements of cost, operability, time and contribute with systemic solutions to maintain the legacy of successful design development.

In order to improve system engineering procedures, establish guidelines to optimize the development, management, and implementation of ground segment designs and their interaction with the space segment, our work explore a process using MBSE, its modeling language, ontology, as well as methodologies and supporting tools for design development.

This paper is organized as follows: Section 2 overviews space systems, and shows two INPE's missions and its ground segment evolution; section 3 explains the concepts adopted in our work as systems engineering, Model-Based System Engineering, models, metamodels, ontology, language and methodologies. Section 4 addresses a literature review on MBSE applications and space systems. Section 5 presents a proposed process using MBSE, and section 6 presents the paper's conclusions.

2. Space System and its Segments

2.1. Space System

A generic space system comprises the space segment and the ground segment. The space segment is defined as everything beyond the Von Kármán ellipsoid [2], it can consist of a spacecraft or spacecraft set that provides, as a product, data to the ground segment. The ground segment is defined as everything before the ellipsoid.

A space segment, typically, consists of a service module and payloads follows ECCS [3,4] and NASA [5] guidelines and CCSDS [6,7] recommendations as presented in Fortescue et al. [8], and Larson and Wertz [9].

A ground segment comprises the entirety of hardware, software and human resources needed to manage and control a spacecraft, monitoring and analysing its operation in orbit, and data distribution to the user. Basically, the ground segment consists of (i) the Telemetry, Tracking and Command (TT&C) ground stations, (ii) the Satellite Control Centre (SCC), and (iii) the Application Segment.

According to reference [10], the TT&C ground stations are in charge of establishing communication between the ground segment and the spacecraft monitored, and the SCC is responsible for the plan and executes all activities related to the spacecraft's control.

The Application Segment comprises (i) the Reception and Recording Stations, (ii) the Mission Center that plans and coordinates the spacecraft image acquisition operations, and (iii) the Remote Sensing Data Center that processes and stores the images, and makes them available to users.

The ground segment designs follow ECSS [3] and NASA [5] guidelines for systems engineering and the CCSDS recommendations for Management Services for Data Transfer, Space Link Extension (SLE) Protocol Services for Cross Support and Interoperability [7].

An example of space system and its respective segments is shown in Figure 1, it refers to the CBERS-4A [10] mission, which is a partnership agreement involves the National Institute for Space Research

(INPE) and China Academy of Space Technology (CAST). The CBERS-4A was successfully launched in 2019 from Taiyuan Satellite Launch Base (TSL C).

Another example of a space mission and its segments is the Amazonia-1 [10] mission. The Amazonia-1 is the first remote sensing satellite completely designed, integrated, tested and operated by Brazil.

It is a development coordinated by the Ministry of Science, Technology and Innovations (MCTI) and conducted by the INPE/MCTI in partnership with the Brazilian Space Agency (AEB/MCTI). It was successfully launched in February 2021 from Satish Dhawan Space Centre SHAR, Sriharikota, India.

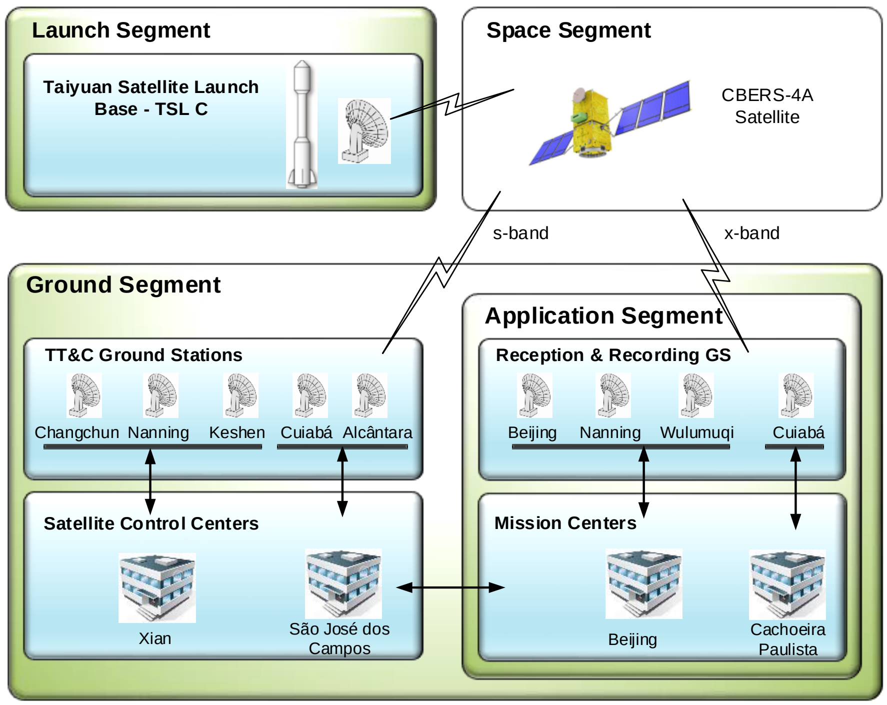

Fig. 1. Space System and its Segments [10]

2.2. *Ground Segment Evolution: A Brief history*

Space agencies have strived to optimize financial resources, design infrastructure, and reduce development time; in this scenario, several ground segment architectures have been proposed to meet interoperability and cross support requirements. Initially, for sending Telecommand (TC) and receiving Telemetry (TM). These ground segment architectures included the installation of specific hardware and the implementation of software-based bilateral interfaces.

In order to resolve the natural problems associated with the considerable number of hardware and software interfaces for exchanging services between the ground stations (called providers) and satellite control centres (called users), CCSDS, in a collaborative work with space agencies, recommended a set of standardized services for Telemetry and Telecommand.

This set of services, namely, Space Link Extension (SLE) Protocol Services [7,11] and their management activities enable cross support among space agencies. These SLE Protocol Services recommendations were adopted by many space agencies: ASI, CNES, DLR, ESA, ESOC, INPE, JAXA, and NASA, and by private sector companies.

An example of ground segment architecture, which provides the cross support, is the ESA Tracking Network (Estrack) which supplies the link between the spacecraft and the ESOC, according to ESA [12].

Another example of ground segment architecture, complying with interoperability and cross support requirements is proposed by Julio Filho [13,14] to the INPE ground segment. This approach aims to simplify access to ground stations and enable real-time detection of redundancy between stations, and consequently extend the spacecraft's tracking capability.

In addition, studies and applications of the cross support meet the goals of the Interagency Operations Advisory Group (IOAG) [15]. A specific IOAG goal is the achievement of full interoperability among member space agencies: ASI, CNES, CSA, DLR, ESA, JAXA, NASA, and UK Space Agency. In this direction, IOAG provides a forum for identifying common needs across multiple agencies related to mission operations, space communications, and interoperability.

3. Concepts and Technologies

This section presents the main concepts used in our work as systems engineering, Model-Based System Engineering (MBSE), models, metamodels, ontology, language and methodologies.

3.1. Systems Engineering

Systems engineering [2] can be described as a formalized and disciplined approach to the development, deployment, utilization, and disposal of a system that satisfies specific needs, formalized by a set of needs and technical requirements or specifications within the bounds of stringent constraints. The successful realization of systems engineering is a system that satisfies the stated needs and balances the technical requirements and constraints, with the latter often being cost, schedule, and risk.

According to [2], the broader field of systems engineering is being developed by organizations such as the Electronics Industry Association (EIA), the International Systems Engineering Council (INCOSE), the International Standards Organization (ISO) and the International Electrotechnical Commission (IEC).

On the other hand, ESA and NASA continue leading the development of space systems engineering practices through documented practices, training and standards.

3.2. Model-Based Systems Engineering

INCOSE [16] defines MBSE 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.

MBSE approach 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 [17]. This approach improves communications between development teams, the quality of specifications and design, and enables the reuse of specifications and artifacts [18]. MBSE collaborates to manage complexity by moving the practice of document-based systems engineering to a model-based approach.

In the following, we present some initiatives for adoption of MBSE in space systems.

NASA's Systems Engineering group [19] began evaluating the adoption of a digital or model-based systems engineering approach in 2011. Standards were evaluated, infrastructure requirements discussed, and NASA stakeholders were interviewed. In 2016, the MBSE Pathfinder was established to evaluate the application of MBSE to some of the most challenging aspects of real NASA's spaceflight systems.

ESA has selected the Euclid mission [1] as a use case to demonstrate the benefits of MBSE in the context of ground segment engineering. It is a science mission currently under development and is due to be launched in 2021 on a Soyuz-Fregat from Kourou, French Guiana.

ESA mission ground segment engineering follows a set of processes, mainly issued by ECSS. The most relevant standards are ECSS E70 - Ground Systems and Operations [4], and ECSS E10 - System Engineering General Requirements [20].

3.3. *Models, Metamodels and Ontology*

A model [21] is a physical, mathematical, or other logical representation of a system or entity, it is an abstraction of a system or entity that allows meaningful predictions or inferences to be made. A metamodel is a prescriptive model of a modeling language, explicitly defining the constructs and rules necessary for constructing specific models within a domain of interest. A model, therefore, conforms to its metamodel.

An ontology [21] is a formal and explicit specification of a conceptualization of a domain: its terminology, definitions, and relationships of the entities that exist for a domain.

The idea of an ontology is to define a common vocabulary [22] for researchers who need to share information. Ontologies facilitate good modeling and can be considered as reusable components, i.e. libraries, in knowledge-level system modeling as they enable knowledge sharing and reuse. Following this approach, ontologies are used as the backbone in MBSE and in software development.

According to reference [23], one initiative in the space area was the creation, by the INCOSE Space Systems Working Group (SSWG) in 2007, of the Space Systems MBSE Challenge team to consider ontologies as a component in engineering modeling activities. [23]; another initiative was from Jet Propulsion Laboratory (JPL), which in 2011, created the Model-Centric Integrated Engineering office. During the first years, this office started the task of developing an ontology for space systems engineering.

3.4. System Modeling Language

Object Management Group (OMG) defined Systems Modeling Language (SysML) as a semantic-based graphical modeling language to represent requirements, behavior, structure and properties of systems and their components [24,25]. It is a general-purpose modeling language used in automotive, medical, aerospace systems, and can support many different MBSE methodologies.

SysML diagrams are nine, organized in four major blocks known as the four pillars of SysML, and represent the system requirements, the structure, the behaviour, and the parametric relationships [18].

3.5. System Engineering Methodologies

System Engineering methodology [26] can be characterized as a collection of related processes, methods, and tools used to support the discipline of systems engineering in a "model-based" or "model-driven" context, where:

a) A Process is a logical sequence of tasks performed to achieve a particular objective. A process defines the "WHAT" is to be done, without specifying the "HOW" each task is to be performed.
b) A Method consists of techniques for performing a task, the "HOW" of each task. The terms "method," "technique," practice," and "procedure" can be used interchangeably in this context.
c) A Tool is an instrument that, when applied to a particular method, can enhance the efficiency of a task. The purpose of the tool should be to facilitate the accomplishment of the "HOWs".

An MBSE approach has three pillars, namely: (i) language, (ii) methodology, and (iii) tools. The most common MBSE approaches [27] adopt SysML, versatile, therefore requiring adaptations, and are associated with various methodologies [26] as OOSEM, OPM, Rational Unified Process (RUP), Systems Modeling Process (SYSMOD), etc., and implemented with several tools such as Cameo Systems Modeler, Enterprise Architect, Rhapsody, as illustrated in figure 2.

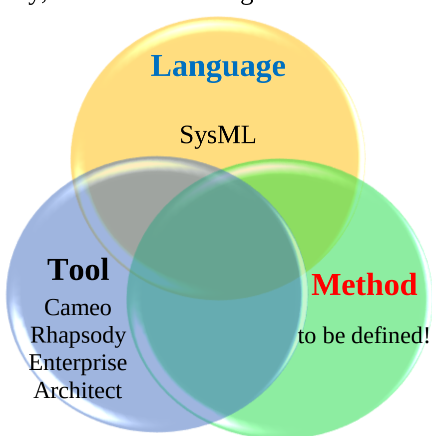

Fig. 2. Classic MBSE with SysML, adapted from [27].

Several methodologies support the MBSE approach and are presented in detail in the reference [26].

In this work, we present three methodologies, their languages, and tools, namely: (i) Object-Oriented Systems Engineering Methodology (OOSEM), (ii) Object-Oriented Process Methodology (OPM), and (iii) ARChitecture Analysis and Design Integrated Approach (ARCADIA).

i) 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 detail in the INCOSE Systems Engineering Handbook [16] and the Practical Guide to SysML [18].

OOSEM includes analyzing stakeholder needs, analyzing system requirements, defining the logical architecture, synthesizing candidate physical architectures, optimizing and evaluating alternatives, and validating and verifying the system.

The logical architecture is a decomposition of the system into logical components that interact to satisfy the system requirements. The logical components are abstractions of the physical components that perform the system functionality without imposing implementation constraints.

The physical architecture defines the physical components that interact to satisfy the system requirements. The physical components of the system include hardware, software, persistent data, and operational procedures. The associate tools for using SysML are COTS-based OMG SysML.

ii) Object-Process Methodology

OPM [26] 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 (what the system does or designed to do), structure (how the system is constructed), and behavior (how the system changes over time) of systems in an integrated, single model.

The premise of OPM is that everything in the universe is ultimately either an object or a process. At the modeling level, OPM is built on top of three types of entities: objects, processes, and states, with objects and processes being the higher-level building blocks, collectively called things.

Tool support for OPM is provided via OPCAT Software Solutions. This product suite supports the concepts related to the OPM metamodel for the system development process, including modeling support of the System Diagram. The System Diagram is the top-level specification of the OPM metamodel. It specifies Ontology, Notation, and the System Developing process as the major OPM features. Ontology includes the basic elements in OPM, their attributes, and the relations among them. The Notation represents the Ontology graphically (by OPDs) or textually (by OPL sentences).

iii) Arcadia

Arcadia [28] is a model-based engineering method for systems, hardware and software architectural design. It has been developed by Thales [29] between 2005 and

2010. It promotes [27] collaborative work among all key players, from the engineering (or definition) phase of the system and subsystems, until their Integration, Verification and Validation (IVV).

This method is supported by various kinds of diagrams inspired by UML and SysML. Arcadia method is supporting by the Capella Toll. This toll is provided as Open Source within the industry working-group PolarSys of the Eclipse Foundation, as part of the French collaborative Clarity project (www.clarity-se.org/).

Figure 3 shown a specialized system architecture approach comprising by the Arcadia (Language and Methodology) and the Capella tool.

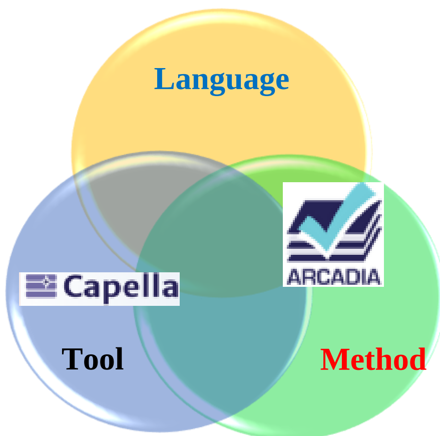

Fig. 3. MBSE with Arcadia/Capella, adapted from [27].

4. Literature Review: MBSE and Space Systems

With the objective of getting evidence in the literature on the current application of MBSE methodology in the space systems domain, we conducted an academic research on MBSE and space systems in 2021.

Two main research questions guided this study:

- RQ1. What are space systems development areas supported by MBSE methodology?
- RQ2. What are ground segment development areas approached by MBSE methodology?

The research considered the period between 2010 and 2020 and was done in six electronic databases that are considered the most relevant sources in the fields of space research, engineering and computer science, domains, namely: Scopus, IEEE Xplore, Compendex, Science Direct, Web of Science, and the National Institute for Space Research Online Library.

The search string was defined as [architecture and (space system or ground segment or mbse)] and also a set of relevant synonyms for the search keywords was identified. It was applied in three metadata fields: title, abstract and keywords.

Applying the search string, 842 papers were retrieved, and after applying the selection criteria, 80 papers remained.

The results, referring to question RQ1. "What are space systems development areas supported by MBSE methodology?", show that space segment has been leading research involving the MBSE methodology, 29 publications, 36.25%, of the primary papers. In Figure 4 only the Artificial Intelligence is based on System Engineering (SE), and others subclasses (subareas) (93.10%) are based on MBSE.

We can observe that the CubeSat development is responsible by 31.03% of the publications related with space segment, which according to the papers, show great interest of the academic, university and industrial communities.

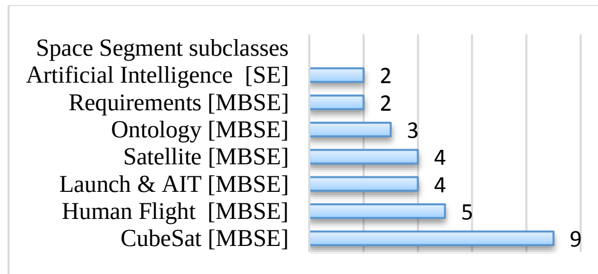

Fig. 4. Papers by space segment subclasses (subareas).

The results, referring to question RQ2. "What are ground segment development areas approached by MBSE methodology?", show the main evidences found in our research about ground segment.

The 20 publications, 25.00%, address Systems Engineering (SE) and the ground segment, which are related to the subclasses of data management, network, EGSE and avionics, Figure 5.

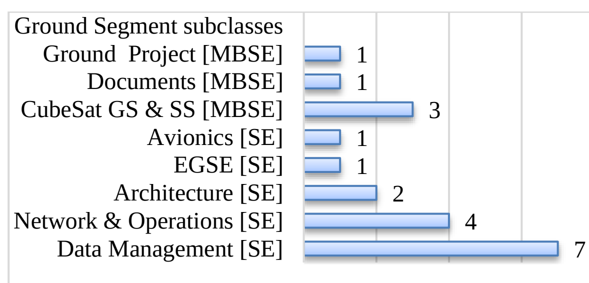

Fig. 5. Papers by ground segment subclasses (subareas).

Finally, among 20 publications, only 5 papers, 6.25%, of the 80 primary papers, address MBSE and the ground segment.

The academic research illustrates evidence on MBSE methodology that shows its maturity and establishment in the industrial, academic, and governmental domains and also indicates a wide distribution in subareas related to the space systems domain.

5. A Proposed Process using MBSE

With the main goal of applying an MBSE approach to ground segment of space missions we propose a process which considers the complexity of MBSE (language, method and tools). So, the process must be simple, intuitive, and allow the reduction of the learning curve, and without the need of specialized architects to translate the models.

In MBSE, the model serves as the single source of truth for the development team and is the primary artifact produced by systems engineering activities. Documentation becomes secondary and is generated from the system model.

5.1. Process

The proposed process consists of seven activities. These activities are applied iteratively throughout the system development. Following are presented the seven activities.

Activity 1 - Analyze the Mission Requirements.

The analysis of the mission requirements is a focus in the systems engineering, and it is fundamental to the beginning of the model development, as well as the considerations for meeting new requirements. In this activity, the space segment and ground segment requirements must be considered.

The requirement sets should allow the modeling, simulation and assessment of behaviour. References [30,31] discuss methods for developing a well-defined set of requirements.

Activity 2 - Analyze the Available Ontologies.

An analysis of the available ontology [32] or its elaboration is necessary to reduce time and allow reuse. Its adherence and standardization for space missions, especially for the ground segment, must be verified.

Ontologies facilitate good modeling and can be considered as reusable components, i.e. libraries, in knowledge-level system modeling.

The ontology [32] should be developed and modeled using tools to facilitate understanding, adoption and acceptance by the community and support decision processes using a language familiar to users. It should be noted that the proposed process allows for feedback on activities.

Activity 3 - Select the Language.

The language selection is directly related to the learning curve of the development team.

SysML is intended to facilitate the application of an MBSE approach to create a cohesive and consistent model of the system. It helps specify and architect systems and to specify components that can be designed using other domain-specific languages, such as UML for software design, VHDL for electrical design, and three-dimensional geometric modeling for mechanical design.

On the other hand, Arcadia (Language and Methodology) concepts are similar to the UML/SysML standard, and interoperability with SysML tools is possible using ad hoc import/export. Because of the focus on architectural design, some of the SysML concepts have been simplified or specialized in order to better match the concepts system engineering practitioners already use in their engineering documents and assets.

Activity 4 - Select the Methodology.

We highlight three methodologies presented in section 3 and discuss the basic justifications to be considered. The proposed process is not limited to these methodologies.

OOSEM methodology [18] is an example of how SysML is applied using MBSE. OOSEM leverages object-oriented concepts in conjunction with traditional top-down system engineering methods and other modeling techniques to help architect more flexible and extensible systems to accommodate evolving technology and changing requirements.

OPM [26] is a holistic systems paradigm, and it combines formal simple visual models and natural language. A major contribution of OPM to systems science and engineering is the precise semantics and syntax it ascribes to graphic symbols and the unambiguous association with natural language constructs.

Arcadia [33] enforces an approach structured on different engineering perspectives establishing a clear separation between system context and need modeling (operational need analysis and system need analysis) and solution modeling (logical and physical architectures).

Activity 5 - Select the Tool.

The choice of a tool plays an important role in the whole process and it is strictly linked to the methodology and language previously considered.

The ability of the tool to integrate all views of the model is essential, and the information contained in the model views is interrelated; a change in one view influences the others.

The most common SysML MBSE approaches are associated with various methodologies and implemented with several tools (not-exhaustive list) such as Cameo Systems Modeler, Enterprise Architect, Rhapsody, OPCloud, in other hand Capella is a toll for using with the Arcadia.

Activity 6 - Build the Models

This activity is based on reference [18], and comprising six sub-activities consistent with the systems engineering:

a) *Organize the Model* is a critical step prior to initiating a significant modeling effort to define the system. The complexity of the system model can quickly overwhelm the users of the model and become unmanageable.
b) *Analyze Stakeholder Needs* to understand the problem to be solved, the goals the system is intended to support, and the effectiveness measures needed to evaluate how well the system supports these goals and satisfies the stakeholder needs.
c) *Specify System Requirements* including the required system functionality, interfaces, physical and performance characteristics, and other quality characteristics to support the goals and effectiveness measures.
d) *Synthesize Alternative System Solutions* by partitioning the system design into components that can satisfy the system requirements.
e) *Perform Analysis* to evaluate and select a preferred system solution that satisfies the system requirements and maximizes the effectiveness measures.
f) *Maintain Requirements Traceability* to ensure the proposed solution satisfies the system requirements and associated stakeholder needs.

Activity 7 - Simulate and Assess

Simulation and assessment of behavior are necessary to make decisions and indicate possible solutions for design implementation in advance.

According to reference [18], relevant system modeling standards include Modelica, which is a simulation modeling language; the High Level Architecture (HLA), which is used to support the design and execution of distributed simulations; and the Mathematical Markup Language (MathML), which defines a language for describing mathematical equations using the Extensible Markup Language (XML). The Architecture Analysis & Design Language (AADL) standardized by the Society of Automotive Engineers (SAE).

Figure 6 shows the flow of the seven activities comprising the proposed process.

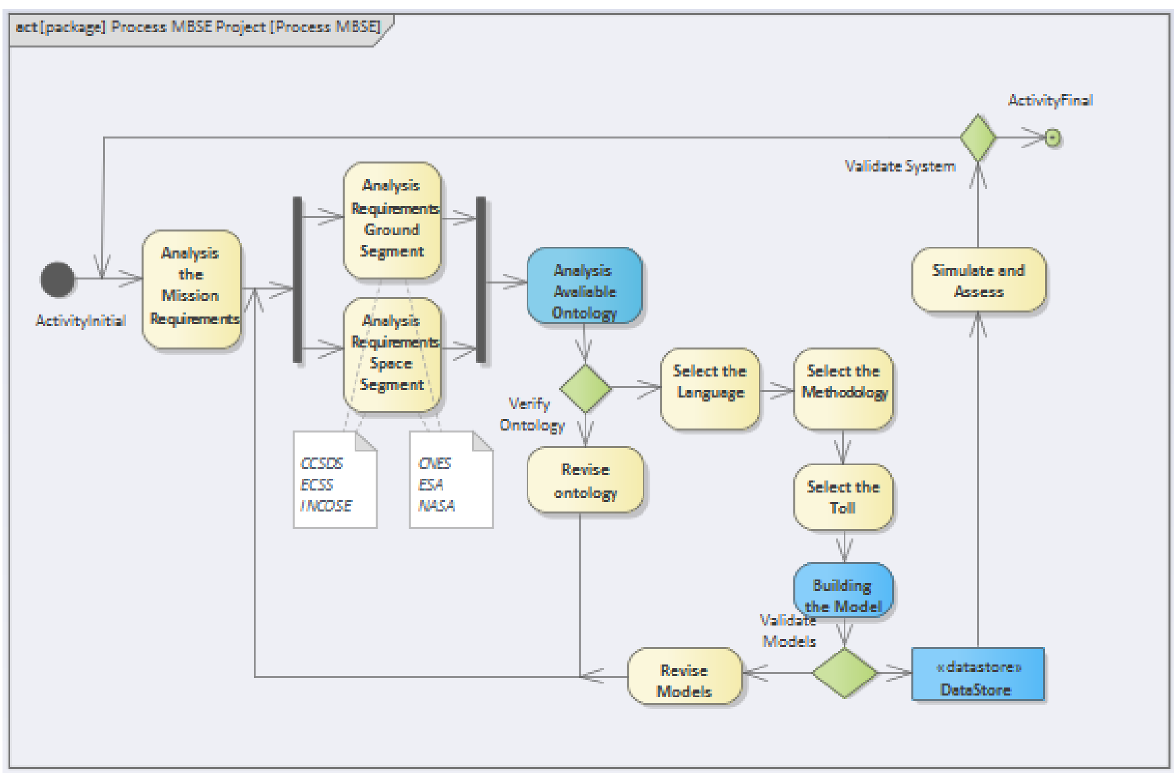

Fig. 6. The Proposed Process

5.2. Diagram Examples

Starting from the requirements of a space mission, we present some diagrams obtained when applying the process and illustrate the similarities and differences [33] between SysML and Arcadia/Capella.

Figure 7 shows the Block Definition Diagram in SysML, and it defines features of blocks and relationships between blocks such as generalizations, and dependencies. This Figure is a representation of a space mission and its segments. The figure evidences of the relationships between the segments and the mission, as well as the breakdown into major components.

It shows the result of 6 activities of the proposed process: Analyze the Mission Requirements, Analyze the Available Ontology, SysML selection, OOSEM Methodology, and selection the Enterprise Architect toll.

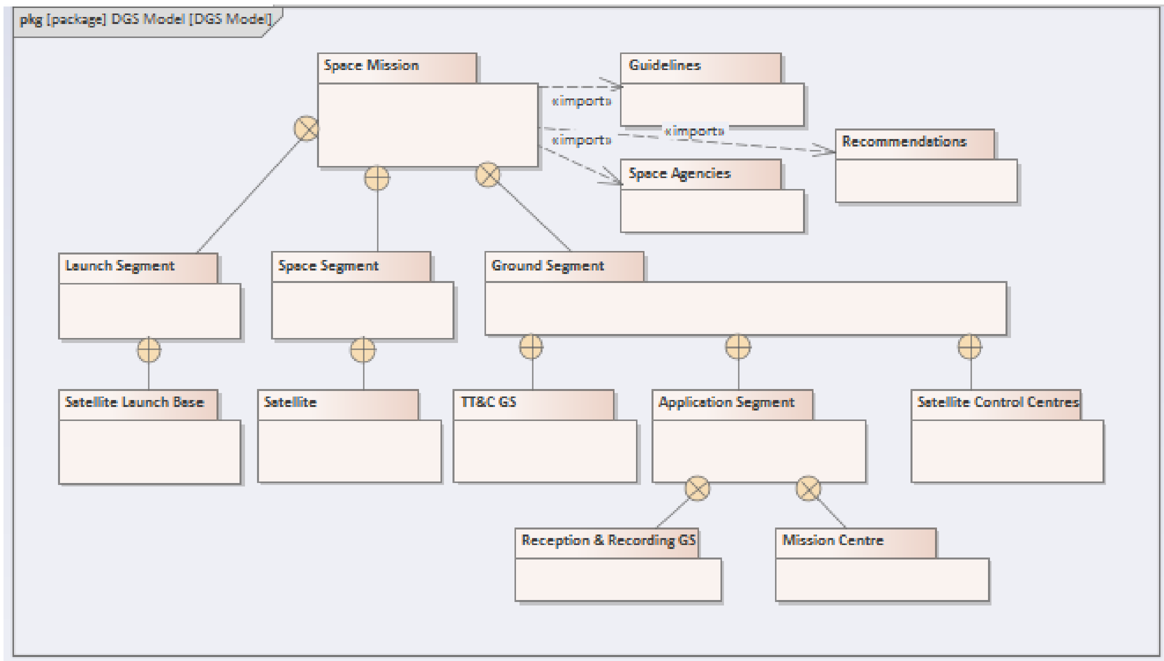

Fig. 7. Space System - Block Definition Diagram, in SysML.

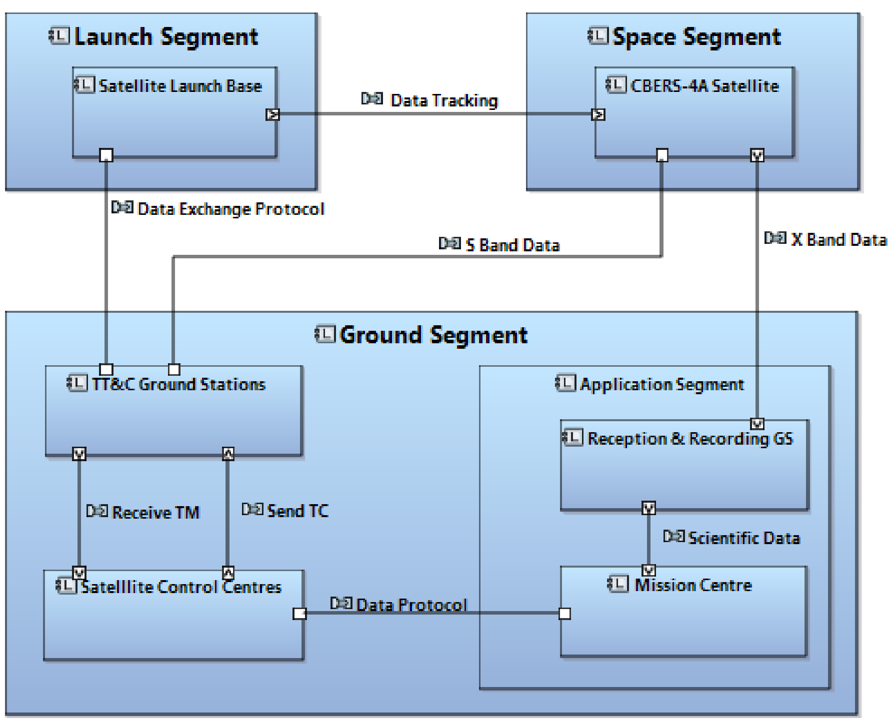

Fig. 8. Space System – Arcadia/Capella Architecture Diagram.

Figure 8 shows the same space mission depicted using Arcadia/Capella. The Arcadia architecture diagrams describe component assembly in terms of system hierarchy, internal breakdowns and connections.

The connections allow viewing the data exchange showing source and destination, as indicated by the arrow, for example, the flow called "Send TC" comes from Satellite Control Centres and goes to TT&C ground stations. The flow called "S Band Data" is bidirectional, between the TT&C grouns station and the satellite.

It shows 6 activities of the proposed process: Analyze the Mission Requirements, Analyze the Available Ontology, Arcadia selection, and Capella toll.

In these diagram examples, the similarities and differences between SysML and Arcadia are related to presentation, overview and data exchange, organization, and model goals.

SysML (language) provides very rich and advanced means of expression that cover a very broad spectrum of applications, ranging from high-level architecture modeling to detailed design at the simulation frontier [33].

Arcadia/Capella, inspired by SysML concepts, focuses on the design of system architectures. For the sake of an easier learning curve and because of the precise scope, the expression means are sometimes reduced compared to SysML.

6. Conclusions

Models can collaborate to assess the real impacts on ground segment development and anticipate the presentation of solutions early in development and continue through the later phases of the system life cycle.

The literature review illustrates evidences on the Model-Based Systems Engineering methodology that show its maturity and establishment in the industrial, academic, and government domains, and also a wide distribution in the space systems domain, however, there is a gap of applications in the ground segment.

MBSE offers a powerful alternative and can bring effectiveness to ground segment engineering. However, the broad adoption of MBSE implies necessary advances from organizational, methodological, and tools perspectives, requiring studies before being stablished.

In fact, the operational value added with an MBSE approach is based on several criteria, such as the definition of design modeling goals, the implementation of methods, the skills of the teams, the integration with the existing database system.

With respect to language, SysML provides a means of capturing the system modeling information without imposing a specific methodology, and Arcadia (language and methodology) provides a specialized system architecture approach.

The proposed process for the development and optimization of the ground segment of space missions considers that MBSE complexity (language, method, and tools) must be simplified, become intuitive, and allow the reduction of the learning curve, and without the need of specialized architects to translate the model.

Future work includes studying ontologies, building models for the ground segment, and continued evaluation of the proposed process.

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