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Methodologies for Model-Based Systems Engineering to Leverage Ground Segment Development.

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Abstract. *A ground segment is considered a ready-to-operate system; however, during space mission development, new requirements may be requested, and new questions are raised about cost reduction, interoperability, and modern development methods such as Model-Based System Engineering and related methodologies. In this paper, we present some fundamental concepts about space systems and a description of the leading Model-Based System Engineering methodologies applied in industrial, aerospace, and academic domains. This paper also presents criteria to establish a methodology and identifies a set of candidate methodologies to leverage ground segment development of the space missions.*

Keywords: CCSDS; Ground Segment; Interoperability; Methodologies; Model-Based System Engineering - MBSE.

1. Introduction

The ground segment is closely aligned with the requirements defined by the space segment to improve the synergy between these segments. During the mission development, new requirements may be requested. In this context, many questions are raised in order to meet the requirements for cost reduction, increased efficiency and interoperability, as well as adopt modern development methods as model-centric designs, verification and validation of the ground segment.

A modern development method is Model-Based System Engineering (MBSE). This method 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 (FRIEDENTHAL et al., (2009).

The objectives of this research, based on a literature study, are to provide a description of the leading MBSE methodologies that have been employed in industrial, aerospace, and academic domains; moreover, to define criteria and to identify a set of candidate methodologies to leverage ground segment development of the space missions.

The criteria used to establish such a set of candidate methodologies are: (i) the degree of acceptance and application in industrial, aerospace, and academic domains in light of the key players such as NASA, ESA, Thales; (ii) the growth of teaching disciplines involving MBSE and methodologies; (iii) the learning curve reduction, and (iv) the availability of open-source tools or academic licenses.

This paper describes the segments of a space system, the currently ground segment architecture and initiatives for adoption for MBSE in space systems, the fundamental concepts such as System Engineering, MBSE, Ontology, Modeling Language, leading methodologies. It provides a set of candidate methodologies to leverage ground segment development.

2. The Segments of a Space System

A space system is made up of a space segment and a ground segment. A space segment consists of a configured spacecraft or spacecraft set, and its service and payload modules, which follows ECCS (2003, 2008); NASA (2013) guidelines and CCSDS (2003, 2006, 2007) recommendations, according to Fortescue et al. (2003); Larson and Wertz (1999).

A ground segment comprises the totality of hardware, software, and human resources needed to manage and control a spacecraft or spacecraft set, monitoring and analyzing their operation in orbit, and the data distribution to the end user, according to ECCS (2008); NASA (2013); recommendations of CCSDS (2003, 2006); and Larson and Wertz (1999). A typical ground segment comprises:

a) Telemetry, Tracking and Command (TT&C) ground stations for receiving telemetry, tracking, and sending commands to spacecraft;

b) Satellite Control Centre which is responsible for planning and executing all activities related to the spacecraft control;

c) Application Segment that includes data receiving and recording stations, the Mission Centre to plan and coordinate the operation of data acquisition by the payload, and the Remote Sensing Data Center, which collects, processes, stores, and makes the data available to users.

Figure 1 shows an example of a space system and its segments, referring to the CBERS-4A mission, successfully launched in 2019, a partnership between the National Institute for Space Research (INPE) and the China Academy of Space Technology (CAST). In this figure, the segments of a space system were drawn according to Arcadia/Capella adapted from Julio Filho (2019).

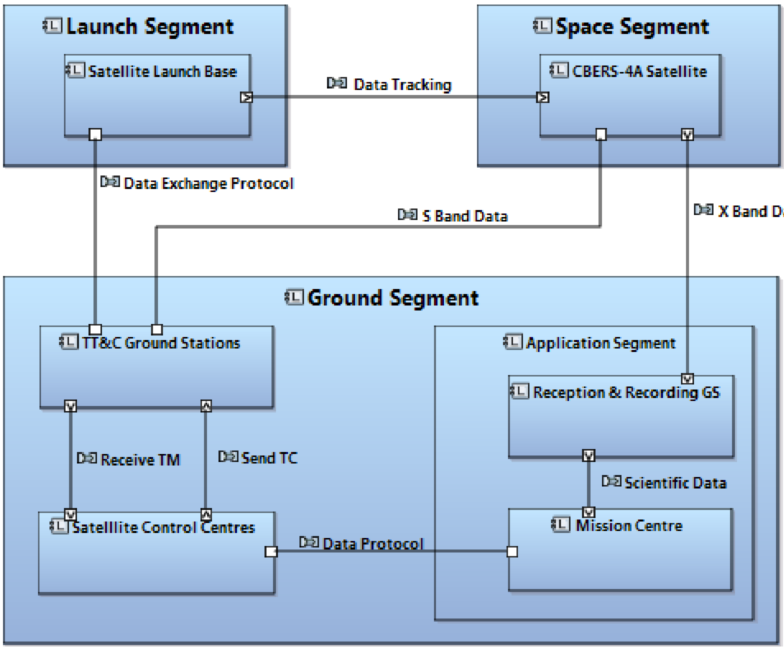

Fig. 1. The segments of the CBERS-4A mission space system drew according to Arcadia/Capella adapted from Julio Filho (2019)

Currently, the ground segment architecture is based on the Space Link Extension (SLE) Protocol Services that are part of recommendations for Cross Support and Interoperability between space agencies (CCSDS, 2005, 2006, 2007). An example of ground segment architecture complying with Cross Support and Interoperability requirements is proposed by Julio Filho (2015, 2019) to the INPE ground segment. The standardizations of SLE service management activities (BARKLEY et al., 2006; PIETRAS et al., 2010] are presented in the recommendations CCSDS (2009, 2011).

The evolution of the ground segment architecture created new challenges for development of a space mission. These challenges include cost reduction, increased efficiency and interoperability, and the ground segment's ability to handle design changes and the inclusion of new requirements during the project. In addition, there are challenges that are not technical in nature as cultural inertia, and information-sharing policies.

In order to address these challenges, many agencies have adopted the MBSE approach. As an example, we cite two initiatives for adopting MBSE in space systems, one from NASA and one from ESA.

NASA's Systems Engineering group (HOLLADAY, 2019) began evaluating the adoption of a digital or MBSE approach in 2011. 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 (FISCHER et al., 2018) 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.

3. Fundamental Concepts

Systems engineering (MACDONALD et al., 2014) is 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.

Model-Based Systems Engineering 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).

An *ontology* (BERMEJO-ALONSO et al., 2016) 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 to share information, and facilitate good modeling. Following this approach, ontologies are used as the backbone in software and MBSE development.

A standardized and robust *Modeling Language* is considered an enabler for MBSE, according to Friedenthal et al. (2009). Systems Modeling Language (SysML) is a semantic-based graphical modeling language to represent requirements, behavior, structure and properties of systems and their components (SPANGELO et al., 2012; JON et al., 2013). It is a general-purpose modeling language used in automotive, medical, and aerospace systems, and can support many different MBSE methodologies.

The word *Methodology* is often erroneously considered synonymous with the word process. For purposes of this work, the following definitions from Estevan (2009) are used to distinguish *methodology* from *process, methods, and tools*:

a) A *Process* (P) 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* (M) 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* (T) 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". In a broader sense, a tool enhances the "WHAT" and the "HOW.

Based on these definitions, a *methodology* can be defined as a collection of related processes, methods, and tools used to support the discipline of systems engineering in a "model-based" context (ESTEVAN, 2009).

According to Estevan (2009), in addition to the above definitions there is the concept of *environment*. An Environment (E) consists of the surrounding, the external objects, conditions (social, cultural, personal, and organizational) that influence the actions of an object, person or group. The purpose of a project environment should be to integrate and support the use of the tools and methods. An environment thus enables (or disables) the "WHAT" and the "HOW".

4. Leading MBSE Methodologies

We have analyzed the features, fundaments, tasks, and tools of the following leading MBSE methodologies:

a) Object-Oriented Systems Engineering Methodology (OOSEM);

b) IBM Rational Telelogic Harmony-SE;

c) IBM Rational Unified Process for Systems Engineering (RUP-SE);

d) Vitech MBSE Methodology;

e) JPL State Analysis (SA);

f) Object-Oriented Process Methodology (OPM);

g) Systems Modeling Process (SYSMOD);

h) Alstom methodology: Advanced System Architect Program (ASAP);

i) Pattern-Based Systems Engineering (PBSE) Methodology;

j) ARChitecture Analysis and Design Integrated Approach (Arcadia).

More details may be found in references Estevan (2009); Roques (2017).

The criteria used to select the candidate methodologies to leverage ground segment development are:

(i) the degree of acceptance and application in industrial, aerospace, and academic domains in light of the key players NASA (HOLLADAY, 2019, ESA (FISCHER et al., 2018), Thales (ROQUES, 2017);

(ii) the growth of teaching disciplines involving MBSE and methodologies (DORI et al., 2014);

(iii) the learning curve reduction;

(iv) the availability of open-source tools or academic licenses.

Table 1 summarizes the main characteristics of the methodologies in terms of features, fundaments, tasks and tools. .Table 1 also shows the score of each criterion for each methodology. The values were arbitrated between 0 and 10 points, where <u>0 means no adherence</u> and <u>10 means full adherence</u> to criteria (i), (ii), (iii), and (iv). The total score is the sum of the points obtained in each criterion.

Table 1. MBSE Methodologies, main characteristics, criteria and score.

Methodology	Features	Fundaments	Tasks	Tolls	i	ii	iii	iv	total
OOSEM	Provides a foundation for describing the composition of systems and their parts..	It leverages object-oriented: uses OMGSysML and ease integration with object-oriented software and hardware development, and test.	Analyze stakeholder needs & system requirements, define the logical architecture, synthese candidate physical architectures, optimize and evaluate alternatives, and validate and verify the system.	SysML are COTS-based OMG SysML. Cameo Systems Modeler, Enterprise Architect, Rhapsody.	8	7	10	5	30
IBM Rational Harmony-SE	Service Request-Driven Approach, that described by means of SysML diagrams.	It is a subset of a larger integrated systems and software development process, known as Harmony.	Analyze Requirements; Analyze System Functions; Architectural Design.	IBM Rational/Telelogic via Rhapsody.	5	5	5	5	20
IBM RUP-SE	Extends RUP style of concurrent design and iterative development	It emphasis on business modeling, business actors and flow of events.	Requirements, analysis, modeling, design, and construction. New roles and new artifacts & disciplines, (security, training, logistics).	IBM through its Rational® suite of tool.	5	5	5	5	20
Vitech MBSE	Concurrent SE activities linked system design repository.	It uses incremental process “Onion Model”: Allows complete interim solutions at increasing levels.	Process, Requirements, Behavior, verification & validation, Architecture. Strong adherence to agreed upon ontology to manage syntax and semantics.	Vitech CORE® product.	5	5	5	5	20
JPL SA	It leverages model and state based control architecture with iterative process.	SA process helps bridge gap between requirements on software specified by systems engineers.	Develop, manage, inspect, and validate system and software requirements.	SQL relational database management system such as Oracle®.	8	5	7	5	25

(i) application in industrial, aerospace, and academic, (ii) growth of teaching, (iii) learning curve reduction; (iv) open-source tolls or academic licenses.

Table 1 continuation - MBSE Methodologies, main characteristics, criteria and score.

Methodology	Features	Fundaments	Tasks	Tolls	i	ii	iii	iv	total
OPM	It combines formal simple visual models Object-Process Diagrams and natural language sentences Object Process Language.	OPM is built on top of three types of entities: objects, processes, and states.	Build higher-level blocks, called things, to express the function, structure, and behavior of systems in an integrated way. It specifies Ontology, Notation, and the System.	Tool support for OPM is provided via OPCAT Software Solutions, OPCloud.	10	10	10	5	35
SYSMOD	User-oriented approach for requirements engineering and system architectures.	It allows different levels of modeling intensities and a guidelines provided for each process activity.	Identify stakeholder; elicit requirements; analyze requirements with use cases; define system architecture (functional, logical, physical).	A free tool SYSMOD profile for use with the MagicDraw SysML Plugin.	8	5	5	10	28
ASAP	This approach is mandatory top-down, used in train and its subsystems.	It solution permits also to easily manage the change.	Analyze System operations, the System and Subsystem architecture: Operational, Functional, Constructional vision modelling.	Tool-free because no specific language stereotypes	5	5	5	10	25
PBSE	It based in S*Metamodel, S*Models and S*Patterns.	It creates the smallest (simplest) verifiable model to describe systems, re-usable.	S*Models and S*Patterns contain Features, Interactions, Roles, States, Components, Interfaces, Requirements.	SysML, IDEF, DOORS Siemens, ENOVIA Sparx Enterprise Architect, IBM Rhapsody.	5	10	5	5	25
Arcadia	It is a MBSE for systems, hardware and software architectural design. It is inspired by UML and SysML.	It promotes collaborative work among all key players, from the engineering phase of the system and subsystems.	Identify requirements, logical and physical architectures, optimize and evaluate alternatives, and validate and verify.	Capella, open-source.	10	10	8	10	38

(i) application in industrial, aerospace, and academic, (ii) growth of teaching, (iii) learning curve reduction; (iv) open-source tolls or academic licenses.

5. Methodologies for MBSE to Leverage Ground Segment Development

Among the methodologies presented, we highlight three potential candidates to leverage the development of the ground segment according to the total score: Arcadia, OOSEM, and OPM.

In this way, *Arcadia* promotes collaborative work among all stakeholders involved in the engineering phase of the system and subsystems. It enforces an approach structured on different engineering perspectives establishing a clear separation between system context and need modeling (operational and system need analysis) and solution modeling (logical and physical architectures). *Arcadia* is inspired by UML and SysML diagrams. It is supported by the Capella Toll, which is provided as open-source by the industry working-group PolarSys of the Eclipse Foundation (ROQUES, 2017).

OOSEM is an example of how SysML is applied in MBSE. *OOSEM* leverages object-oriented concepts in conjunction with traditional top-down systems engineering methods and other modeling techniques to help architect more flexible and extensible systems to accommodate evolving technology and changing requirements. *OOSEM* is supported by many tools such as Cameo Systems Modeler, Enterprise Architect, Rhapsody (FRIEDENTHAL et al., (2009).

OPM is a holistic systems paradigm, it combines simple and formal visual models with natural language sentences to express: (i) the function (what the system does or designed to do), (ii) structure (how the system is constructed), and (iii) behavior (how the system changes over time) of systems. *OPM* uses Object-Process Diagrams (OPDs) to represent the visual models and Object-Process Language (OPL) to describe sentences in 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. Tool support for OPM is provided via OPCAT Software Solutions (DORI, 2014; ESTEVAN, 2009).

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6. Conclusions

The study of existing development methodologies in the three domains: industrial, aerospace, and academic highlighted the maturity and indicated the Arcadia, OOSEM, and OPM methodologies for Model-Based Systems Engineering as those more adhering to the established criteria and able to leverage ground segment development of space missions.

The indicated methodologies to leverage ground segment development acomplished the criteria of (i) the degree of acceptance and application in industrial, aerospace, and academic domains; (ii) the growth of teaching disciplines involving MBSE and methodologies; (iii) the learning curve reduction, and (iv) the availability of open-source tools or academic licenses.

Although the methodologies were chosen based in a criteria and the MBSE is a powerful alternative to ground segment engineering as indicated by adoption in the industrial, aerospace, and academic domains, the widespread adoption of MBSE entails advances from an organizational and methodological standpoint, requiring studies prior to its establishment.

Future work includes studying ontologies, building models for the ground segment development, and continued evaluation of the MBSE methodologies.

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References

BARKLEY, E., et al. (2006). CCSDS SLE service management: real-world use cases. In: International Conference on Space Operations, Rome, Italy. Proceeding Available <http://hdl.handle.net/2014/39898>. Accessed feb. 2019.

BERMEJO-ALONSO, J., HERNANDEZ, C., SANZ, R. (2016). Model-based engineering of autonomous systems using ontologies and metamodels. In: ISSE 2016 - International Symposium on Systems Engineering - Proceedings Papers.

CONSULTATIVE COMMITTEE FOR SPACE DATA SYSTEMS (CCSDS) TM space data link protocol - CCSDS 132.0-B-1. Reston: Consultative Committee for Space Data Systems, 2003.

________. Cross support reference model - Part 1: space link extension services - CCSDS 910.4-B-2. Reston: Consultative Committee for Space Data Systems, 2005.

________. Cross support concept - Part 1: space link extension services - CCSDS 910.3-G-3. Reston: Consultative Committee for Space Data Systems, 2006.

________. CCSDS File Delivery Protocol (CFDP) - Part 1: Introduction and Overview CCSDS 720.1-G-3. Green Book. Issue 3. Reston: Consultative Committee for Space Data Systems, 2007.

________. Space communication cross support - service management-service specification - CCSDS 910.11-B-1. Reston: Consultative Committee for Space Data Systems, 2009.

________. Space communication cross support - service management - operations concept - CCSDS 910.14-G-1. Reston: Consultative Committee for Space Data Systems, 2011.

DORI D., WENGROWICZ N., DORI Y. J. A Comparative Study of Languages for Model-Based Systems-of-Systems Engineering (MBSSE), Israel Institute of Technology Haifa, Israel; Massachusetts Institute of Technology, Cambridge, MA, USA. 2014.

ESTEVAN, J. A., Survey of Model-Based Systems Engineering (MBSE) Methodologies. Jet Propulsion Laboratory California Institute of Technology. Pasadena, California, U.S.A

EUROPEAN COOPERATION FOR SPACE STANDARDIZATION ECSS-E-70-41A. Space engineering - ground systems and operations telemetry and telecommand packet utilization, 2003.

________. ECSS-E-ST-70C. Space engineering - ground systems and operation, 2008.

EUROPEAN SPACE AGENCY (ESA) Estrack Ground Stations. Available <https://www.esa.int/Enabling_Support/Operations/Estrack/Estrack_ground_stations> Accessed may 2020.

FISCHER, D., KECK, F.,WALLUM, M.,SPADA, M., STOITSEV, T. (2018). Leveraging MBSE for ESA ground segment engineering: Starting with the euclid mission. In: International Conference on Space Operations, 15th, Marseille, France.

FORTESCUE, P.; STARK, J.; SWINERD, G. (2003) Spacecraft systems engineering 3. Chichester, UK : John Wiley. ISBN: 678 ISBN 0-471-61951-5.

FRIEDENTHAL, S.; MOORE, A.; STEINER, R. (2009). Practical guide to SysML: the systems Modeling Language. Amsterdam, The Netherlands: Morgan Kaufmann. ISBN 978-0-12-378607-4.

HOLLADAY, J. B.,KNIZHNIK, J., WEILAND, K. J., STEIN, A., SANDERS, T., SCHWINDT, P., MBSE Infusion and Modernization Initiative (MIAMI): "Hot" Benefits for Real NASA Applications. In IEEE Aerospace Conference Proceedings, 2019.

INTERNATIONAL COUNCIL ON SYSTEMS ENGINEERING (INCOSE) (2020). Systems Engineering Vision 2020, version 2.03. Seattle, WA: International Council on Systems Engineering, Seattle, WA, INCOSE-TP-2004-004-02.

JON, H., SIMON, P., SysML for Systems Engineering 2nd Edition: A model-based approach. ISBN-13:978-1849196512, Institution of Engineering and Technology, London, United Kingdom, 2013.

JULIO FILHO, A. C. (2015). An Architecture for Dynamic Management of the Space Link Extension Protocol Services. Dissertation (Master's degree in Space Systems Engineering and Management) - Instituto Nacional de Pesquisas Espaciais, São José dos Campos, São Paulo, Brazil. URL:http://urlib.net/8JMKD3MGP3W34P/3HP2P7P (Accessed Aug. 2020).

JULIO FILHO, A. C.; AMBROSIO, A. M.; FERREIRA, M. G. V.; LOUREIRO, G. (2019). The China-Brazil Earth Resources Satellite - CBERS-4A: a proposal for ground segment based on the space link extension protocol services. In: International Astronautical Congress 70º, Washington, DC.

LARSON, W.J.; WERTZ, J. R. (Ed). (1999). Space mission analysis and design 3. Dordrecht, Netherlands: Kluwer Academic, 1999. ISBN: 969306936 ISBN 1-881883-10-8.

MACDONALD, M., BADESCU, V. The International Handbook of Space Technology. ISBN 978-3-642-41101-4, Springer Heidelberg New York Dordrecht London, 2014.

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION (NASA). (2013). NASA Procedural Requirements - NPR 7123.1B. Systems Engineering Processes and Requirements. Washington, DC.

PIETRAS, J. V.; BARKLEY, E.J.; CROWSON, A. (2010) CCSDS space communication cross support service management. In: International Conference on Space Operations, Huntsville, Alabama, EUA.

ROQUES, P., Systems Architecture Modeling with the Arcadia Method: A Practical Guide to Capella, ISBN-13: 978-1785481680, Elsevier Ltd, Kidlignton, Oxford, United Kingdom, 2017.

SMITH, R.R., SCHIMMELS, K. A., LOCK, P.D., VALERIO, C.P. (2014). A Model-Based Approach to Developing Your Mission Operation System. In: Proceedings International Conference on Space Operations, Pasadena, CA. Proceeding…URL: http://arc.aiaa.org/doi/pdf/10.2514/6.2014-1793.

SPANGELO, S. C., KASLOW, D., DELP, C., COLE, B., ANDERSON, L., FOSSE, E. (2012). Applying model based systems engineering (MBSE) to a standard CubeSat. In: IEEE Aerospace Conference Proceedings.