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# Model-Based Systems Engineering Methodology to the Concept of Operations in Space Systems.

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***Abstract.*** *The Concept of Operations (ConOps) is a fundamental activity performed during the space system development. Currently, an elaboration process on the Concept of Operations captures the system's functioning in a document-based approach. This approach presents limitations such as difficulty assessing completeness, verifying consistency, and tracking and understanding the impacts of changes that affect multiple elements. Model-Based Systems Engineering (MBSE) can address these limitations for ConOps development and enable communication with stakeholders in a formal and unambiguous way, while also leveraging product quality and reducing cost, risk, and development time. This paper introduces fundamental concepts about the System Engineering, MBSE, Project Lifecycle, and System Design Processes. It also presents considerations for establishing the ConOps associated with the MBSE methodology. In addition, the paper provides the possible contributions of the MBSE and a study case.*

**Keywords:** Concept of Operations; Ground Segment; Model-Based System Engineering; MBSE; Space System.

## 1. Introduction

The conventional systems engineering practices emphasize a document-based approach focused producing documentation of such items as requirements, scenarios, interface specifications, and ConOps. The document-based approach presents limitations including: (i) difficulty in assessing completeness, consistency, and relationships between systems engineering products such as requirements, analyses, design and test information; (ii) difficulty in tracing and understanding the impacts of changes that affect multiple elements; (iii) Systems engineering requirements and design information is laborious to maintain and has restricted reusability (BINDSCHADLER et al., 2020).

Model-Based Systems Engineering can address these limitations for ConOps development and enable communication with stakeholders in a formal and unambiguous way. Applying MBSE to the development of ConOps enables communication with all 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 via a single source of truth, a shared understanding of the operational expectations of the system (ANYANHUM et al., 2020).

The goal of this research is to introduce MBSE methodology to ConOps development. The paper is structured as follows: section 2 presents the five fundamental concepts; section 3 explains the considerations for applyng MBSE to the ConOps and a study case of ConOps for the CBERS-4A mission, and finally section 4 the conclusions.

## 2. Fundamental Concepts

This section presents a summary of the main concepts applied in this work, such as Systems Engineering, Model-Based Systems Engineering, Concept of Operations, Project Life Cycle Process, and System Design Processes.

### 2.1. Systems Engineering

Systems engineering (SE) (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. For space system engineering the recommendations are presented by Fortescue et al. (2003), Larson (1999), NASA (2013).

According to SEBoK, the definition of SE is: transdisciplinary and integrative approach to enable the successful realization, use and withdrawal of engineering systems, utilizing systems principles and concepts, scientific, technological and management methods (SEBOK, 2021).

The SE usually plays the key role in leading the development of the concept of operations and resulting system architecture, defining boundaries, defining and allocating requirements, evaluating design tradeoffs, balancing technical risk between systems, defining and assessing interfaces, and providing oversight of verification and validation activities (NASA, 2016a).

### 2.2. Model-Based Systems Engineering

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).

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 often involves combining several activities from the systems SE engine processes concurrently and iteratively, namely system behavior description, requirements analysis, system architecture, and test (V&V) approach. At this higher level, models may take the form of stand-alone or combined system behavior descriptions, requirements models, functional flow block diagram models, concept of operations models, programmatic work breakdown models, etc. (NASA, 2016a). More details may be found in literature review by Estevan (2009), and in the summary by Julio Filho (2021).

MBSE does not affect process but will enable the opportunity for overall better quality, lower cost, and lower risk. These benefits 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;

f) Models themselves can help to reveal hidden flaws of the models.

## 2.3. Concept of Operations

The ConOps is a description of the system's characteristics from an operational perspective. It describes how the system will operate to meet stakeholder expectations (INCOSE, 2006). In short, ConOps describes how a system will work from the user's perspective.

The development of ConOps is initiated at the early stage of development, describing the overall high-level concept of how the system will be used to meet stakeholder expectations usually in a time-sequenced manner. ConOps stimulates the development of the requirements and architecture related to the user elements of the system, and it serves as the basis for subsequent definition documents and provides the foundation for the long-range operational planning activities (NASA, 2020).

Typical information contained in the ConOps, during integration, test, and launch through disposal, includes a description of the major phases; operation timelines; operational scenarios; fault management strategies, description of human interaction and required training, end-to-end communications strategy; command and data architecture; power and data-budgets analysis, and operational facilities (NASA, 2016a).

After the initial stakeholder expectations have been established, the development of a ConOps will further ensure that the technical team fully understands the expectations and how they may be satisfied by the product. The scenarios and concepts of how the system will behave provide an implementation-free understanding of the stakeholders' expectations by defining what is expected without addressing how to satisfy the need NASA, 2016a).

Thinking through the ConOps and use cases often reveals requirements and design functions that might otherwise be overlooked. For example, adding system requirements to allow for communication during a particular phase of a mission may require an additional antenna in a specific location that may not be required during the nominal mission.

## 2.4. Project Life Cycle Process

NASA Project Life Cycle Process (NASA, 2016a), Figure 1, conceptually illustrates how the SE engine is used during each phase of a project (Pre- Phase A through Phase F). The life cycle phases are briefly described below.

In **Pre-Phase A,** the SE is used to develop the initial concepts; define the roles of humans, hardware, and software; establish the system functional and performance boundaries; identify a draft set of key high-level requirements, define one or more initial ConOps scenarios.

During **Phase A**, the recursive use of the SE engine is continued, this time taking the concepts and draft key requirements that were developed and validated during Pre-Phase A and fleshing them out to become the set of baseline system requirements and ConOps.

During **Phase B**, the SE is applied recursively to further mature requirements and designs for all products in the developing product tree and perform verification and validation of concepts to ensure that the designs are able to meet their requirements.

**Phase C** again uses the SE engine to finalize all requirement updates, finalize the ConOps validation, develop the final designs to the lowest level of the product tree, and begin fabrication.

**Phase D** uses the SE to recursively perform the final implementation, integration, verification, and validation of the end product, and at the final pass, transition the end product to the user.

The technical management processes of the SE engine are used in **Phases E and F** to monitor performance; control configuration; and make decisions; and closeout the system.

| Formulation | | | Implamantation | | | |
|---|---|---|---|---|---|---|
| **Pre_Phase A**<br>Concept Studies | **Phase A**<br>Concept & Tecnology Development | **Phase B**<br>Preliminary Design Tecnology Completion | **Phase C**<br>Final Design & Fabrication | **Phase D**<br>System Assembly AIT, Launch | **Phase E**<br>Operation & Sustainment | **Phase F**<br>Closeout |

Figure 1 - Project Life Cycle Process for Flight and Ground Segment (NASA, 2016a).

## 2.5. System Design Process

The system design processes are interdependent, highly iterative and recursive processes resulting in a validated set of requirements and a design solution that satisfies a set of stakeholder expectations. There are four system design processes: **developing stakeholder expectations**, **technical requirements**, **logical decompositions**, and **design solutions (**NASA, 2016a).

Figure 2 illustrates the recursive relationship among the four system design processes. These processes start with a study team collecting and clarifying the stakeholder expectations, including the mission objectives, constraints, design drivers, operational objectives, and criteria for defining mission success (NASA, 2016a).

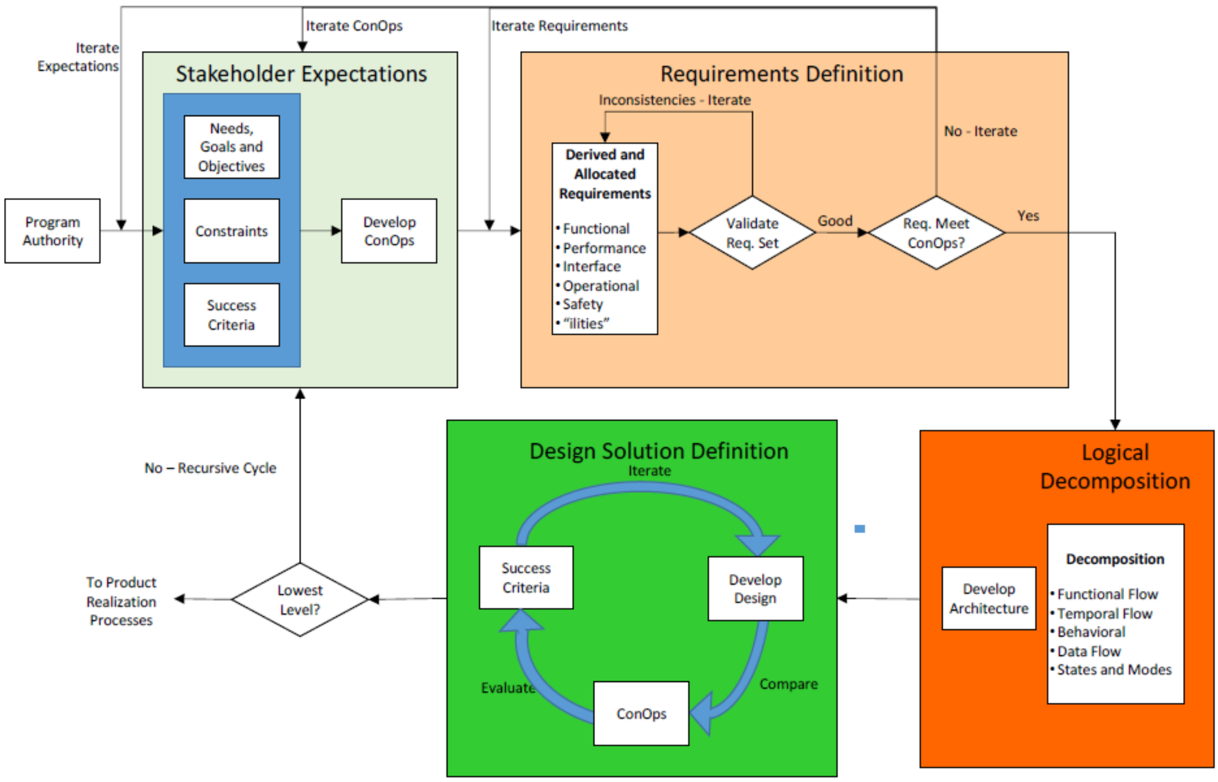


Figure 2 - Interrelationships among the System Design Processes (NASA, 2016a).

This set of stakeholder expectations and high-level requirements is used to drive an iterative design loop where an **architecture/design**, the **concept of operations**, and **derived requirements** are developed. These three products should be consistent with each other and will require iterations and design decisions to achieve this consistency. Once consistency is achieved, analyses allow the project team to validate the proposed design against the stakeholder expectations. A simplified validation asks the questions:

1) Will the system work as expected?
2) Is the system achievable within budget and schedule constraints?

3) Does the system provide the functionality and fulfill the operational needs that drove the project's funding approval?

If the answer to any of these questions is no, then changes to the design or stakeholder expectations will be required, and the process starts again. This process continues until the system architecture, ConOps, and requirements meet the stakeholder expectations. This is a simplified description intended to demonstrate the recursive relationship among the system design processes. For full details, refer to NASA System Enginnering Handbook (NASA, 2016a).

## 3. Applyng MBSE to the ConOps

A model-based ConOps exploits the use of a system model to capture the ConOps of a proposed system. An MBSE ConOPs model specifies the end-to-end system operation from the stakeholder's perspective.

Model-based ConOps development should consider (i) the project lifecycle process, and (ii) the system design process. In addition, it involves the application of MBSE best practices to assist in identifying key features and assumptions of the proposed system, thus helping to define the required functionalities and performance expectations of the system. Table 1 summarizes the MBSE contributions.

MBSE ConOps collaborates to articulate the problem space while also serving as a guide for designing and implementing system operations.

Table 1 - MBSE Contributions (NASA, 2016b).

| **SE Engine**<br>**System Design Processes** | **MBSE Contributions** |
|---|---|
| Stakeholder Expectations Definition. | Needs, goals, and objectives are kept within the model and form the top tier of eventual requirements flowdown. ConOPs is modeled showing interconnections. |
| Technical Requirements Definition. | Requirements are kept within the model allowing bi-directional traceability. |
| Logical Decomposition. | Requirements can be categorized into functional, behavioral, performance. These can be used to develop functional block diagrams, behavior diagrams, and other representations within the model. |
| Design Solution Definition. | Allows integration of information and designs from different engineering domains providing consistency and traceability of the supporting analyses, and a single source of truth. |

A model-based approach helps address the problem of inconsistencies that may exist among various documents and spreadsheets and diagrams in a project. In the case of requirements, model elements representing requirements are related to model elements representing system components, functions, interfaces, and design analyses (FISCHER et al., 2018); NASA, 2016b).

We propose a language and methodology to support MBSE ConOps. It is a model-based engineering language and methodology for the architectural design of systems, hardware, and software, called ARCHitecture Analysis and Design Integrated Approach (ARCADIA), which is inspired by UML and SysML (SPANGELO et al., 2012; JON et al., 2013) diagrams and supported by the Capella Tool (ROQUES, 2017).

ARCADIA focuses on designing systems architectures and offers an easier learning curve by having a more precise scope. ARCADIA promotes collaborative work among all stakeholders involved in the engineering phase of the system and subsystems. It enforces an approach structured on and need modeling (operational and system need analysis) and solution modeling (logical and physical architectures).

### 3.1. Study case to the ConOps

We selected the CBERS 4-A mission to illustrate the development of a ConOps. This mission aims to provide remote sensing images, with high revisit rate, to observe and monitor vegetation, especially deforestation in the Amazon region, monitoring of water resources, agriculture, urban growth, and land use (JULIO FILHO, 2019).

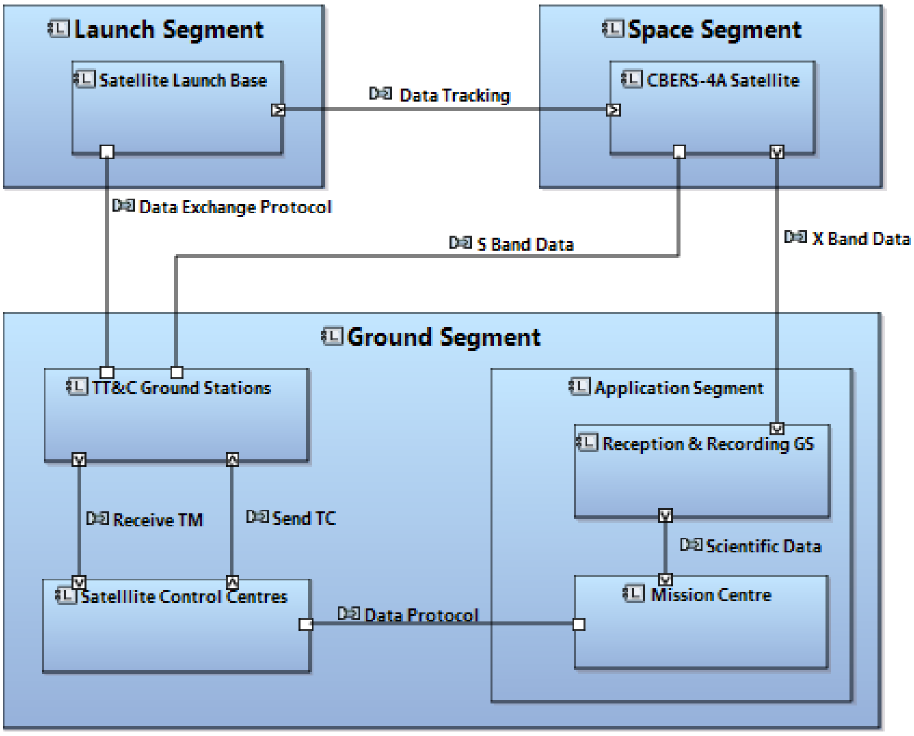


Figure 3 - Space System represented in Arcadia/Capella.

Consider a use case for initial acquisition of the spacecraft, as shown in Figure 3. This scenario begins with separation of the spacecraft from the launch vehicle. After launch, the satellite must communicate with the Cuiabá Ground Station, which is remotely connected to the Satellite Control Center (SCC) at INPE in São José dos Campos, for satellite control purposes. Commands scheduled into the flight plan are uploaded during satellite visibility over that ground station through an S-band link.

The mission data is sent from the satellite to the ground segment. The application Segment is comprised of the Reception and Recording Station, located in Cuiabá, Mato Grosso, and the Mission Centre, located in Cachoeira Paulista, São Paulo. The application Segment coordinates the operation of the satellite imaging acquisitions by the payload, processes, and stores the data received, making them available to the users.

Figure 3 presents an overview of ConOps, however for a complete description, it is necessary to elaborate its modes of operation and scenarios, and other characteristics of the system in the design phase. The complete description can be carried out using several diagrams with different points of view and a large volume of information.

## 4. Conclusions

MBSE has been adopted in several areas, such as industrial, aerospace, and academic domains to leverage the development of research, processes, products and management.

The application of Model-Based ConOPs that require a certain degree of formality both in way thinking and approach, surely Model-Based ConOPs approach benefits from the application of MBSE best practices to aid in identifying key capabilities and assumptions of the proposed system.

Early adoption of the model-based ConOPs approach shows significant promise that design formulation, testing, and integration efforts are mission-to-mission reusable and that produce high-quality requirements while reducing time, cost, and risk.

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## References

ESTEVAN, J. A., Survey of Model-Based Systems Engineering (MBSE) Methodologies. Jet Propulsion Laboratory California Institute of Technology. Pasadena, California, U.S.A, 2009.

FISCHER, D. et al. Leveraging MBSE for ESA ground segment engineering: Starting with the euclid mission. 15th International Conference on Space Operations, 2018, Proceedings... [s. l.], n. June, p. 1–17, 2018. Disponível em: https://doi.org/10.2514/6.2018-2572.

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.

INTERNATIONAL COUNCIL ON SYSTEMS ENGINEERING (INCOSE) SYSTEMS ENGINEERING HANDBOOK, V.3, INCOSE -TP-2003-002-03, 2006

______. Systems Engineering Vision 2020, version 2.03. 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.; AMBROSIO, A. M.; FERREIRA, M. G. V.; LOUREIRO, G. 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, 2019, Washington D.C., United States. 2019. Available in:<http://urlib.net/ibi/8JMKD3MGP3W34P/3UHRLHL>.

JULIO FILHO, A. C.; AMBROSIO, A. M.; FERREIRA, M. G. V. Methodologies for Model-Based Systems Engineering to Leverage Ground Segment Development: In: Workshop em Engenharia e Tecnologia Espaciais, 2021, São José dos Campos. WETE 2021, 2021.

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.

______ NASA SYSTEMS ENGINEERING HANDBOOK (2016). NASA SP-2016-6105.

______ NASA ENGINEERING ELEGANT SYSTEMS: THE PRACTICE OF SYSTEMS ENGINEERING SYSTEMS ENGINEERING HANDBOOK (2020). NASA/TP–20205003646.

______ NASA Expanded Guidance for NASA Systems Engineering (2016b) Volume 2: Crosscutting Topics, Special Topics, and Appendices.

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.

BINDSCHADLER D. L, SMITH R. R.,VALERIO C. P., AND KATHRYN A. S "**A Structured, Model-Based Systems Engineering Methodology for Operations System Design**" Jet Propulsion Laboratory, 2020.

ANYANHUM A. I., ANZAGIRA A. AND EDMONSON W. W. **Intersatellite Communication: An MBSE Operational Concept for a Multiorbit Disaggregated System.** IEEE JOURNAL ON MINIATURIZATION FOR AIR AND SPACE SYSTEMS, VOL. 1, NO. 1, JUNE 2020

LARSON, W.J.; WERTZ, J. R. (Ed). **"Space mission analysis and design 3"**. Dordrecht, Netherlands: Kluwer Academic, 1999.

SEBOK. Editorial Board. 2021**. The Guide to the Systems Engineering Body of Knowledge (SEBoK), v. 2.5,** R.J. Cloutier (Editor in Chief). Hoboken, NJ: The Trustees of the Stevens Institute of Technology. BKCASE is managed and maintained by the Stevens Institute of Technology Systems Engineering Research Center, the International Council on Systems Engineering, and the Institute of Electrical and Electronics Engineers Systems Council.: [*s. n.*], 2021. Disponível em: www.sebokwiki.org.

SPANGELO, S. C. et al. Applying model based systems engineering (MBSE) to a standard CubeSat. IEEE Aerospace Conference **Proceedings**, [s. l.], p. 1–20, 2012. Disponível em: https://doi.org/10.1109/AERO.2012.6187339.