F4GSA:
A Framework for Ground Segment Architectures Development of Space Missions.

CAPELLA DAYS 2025

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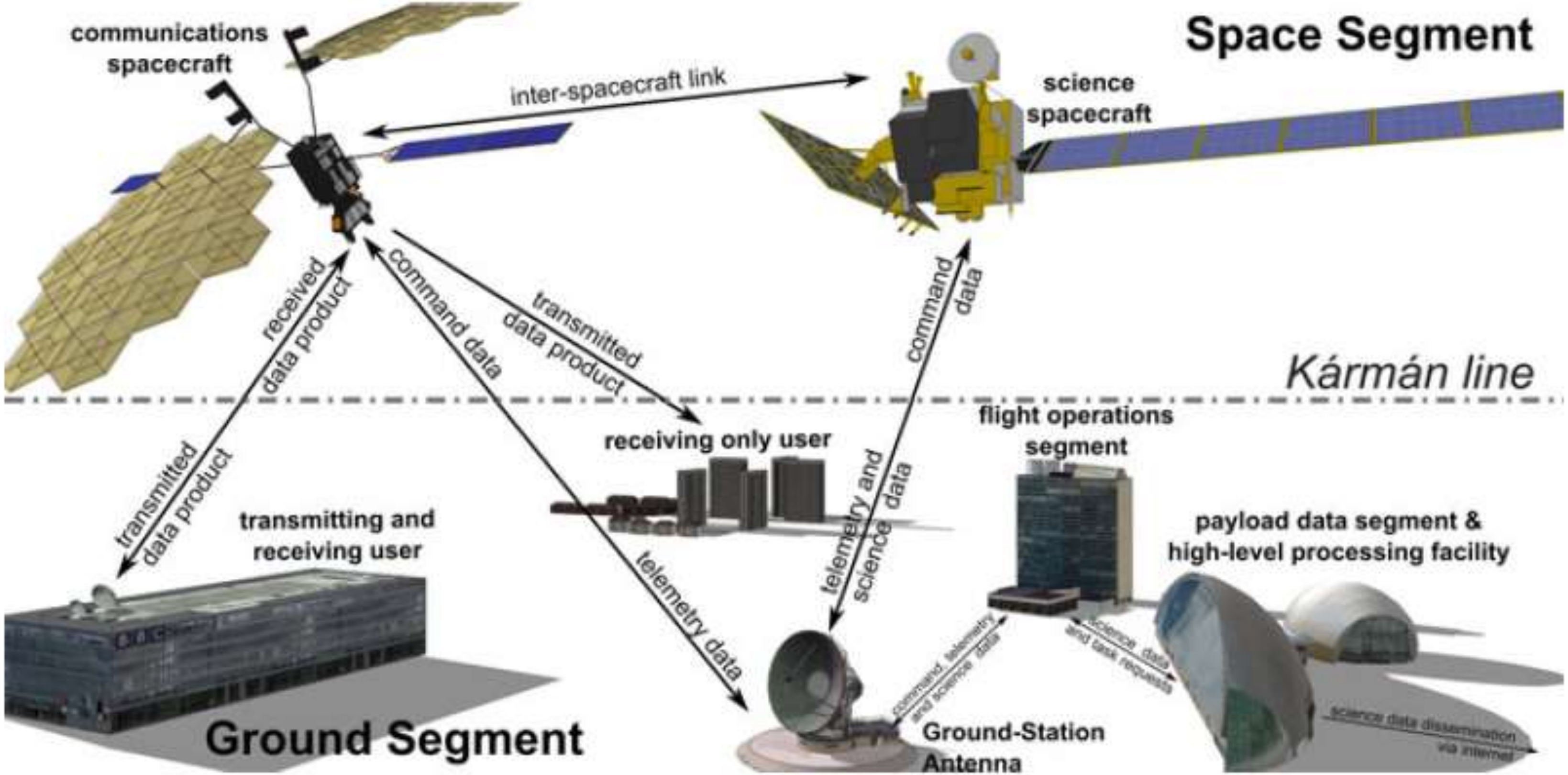
2025/11/19

Brazilian National Institute for Space Research - INPE.

Agenda

1. Introduction
2. Motivation
3. Problem
4. Goal
5. Concepts
6. F4GSA
7. Case Studies
8. Conclusions

Introduction



Generic Space System, Source: Macdonald (2014).

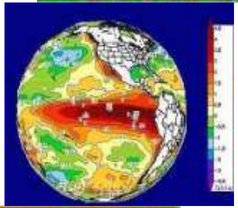
INPE: CONVERTING DATA INTO KNOWLEDGE

SATELLITES

Earth Observation, Scientifics and Data Collection.

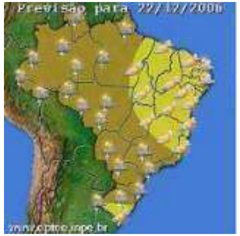
GROUND SEGMENT

Satellite Controlling, Reception, Processing and Distribution Data Satellites.



ANALYSIS and MODELING

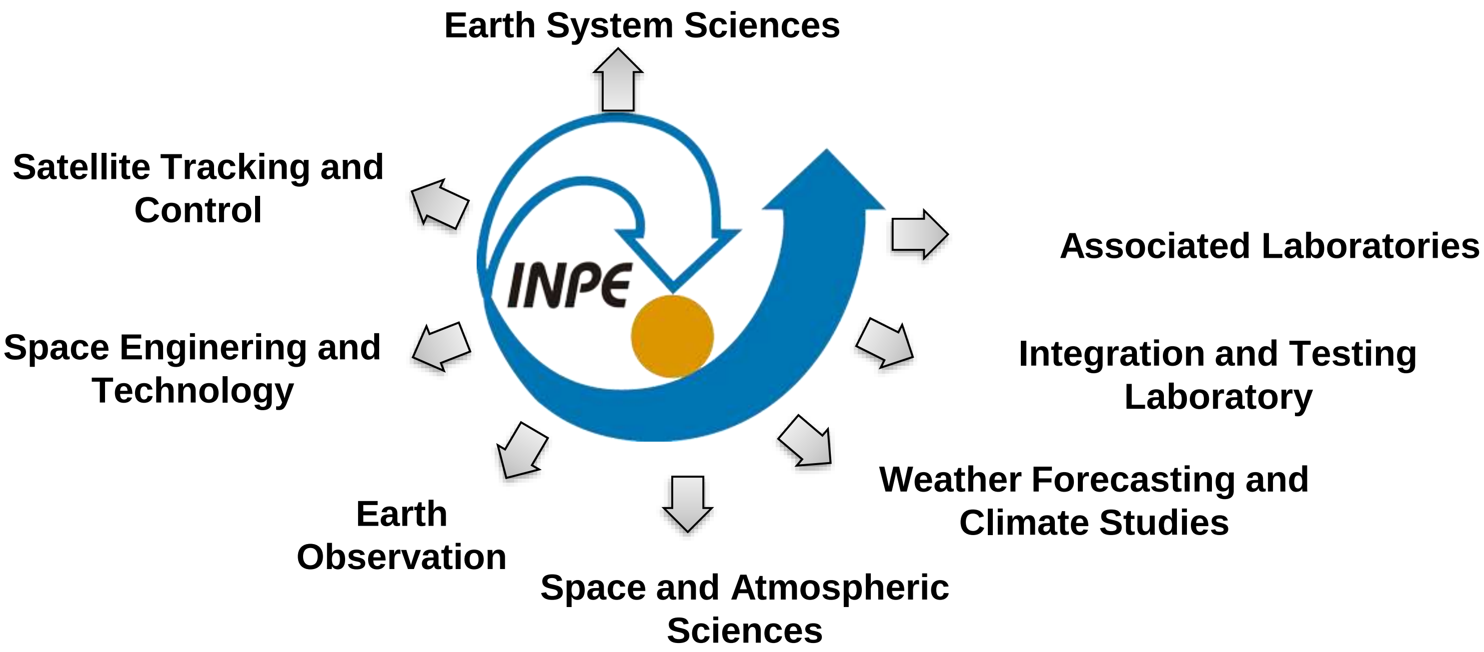
Space Weather, Forecasting and Earth System Science.



SOCIAL BENEFITS

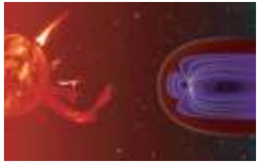
Innovative Products to meet Brazil’s needs.

INPE Areas


Earth System Sciences
Satellite Tracking and Control
Associated Laboratories
INPE
Space Enginering and Technology
Integration and Testing Laboratory
Weather Forecasting and Climate Studies
Earth Observation
Space and Atmospheric Sciences

Postgraduate studies at INPE

Astrophysics



Space Geophysics

Space Engineering and Technologies

Applied Computing

Meteorology

Remote Sensing

Earth System Sciences

Areas of Concentration

The program aims to provide scientific training in critical disciplines within the space sector, including:

Space Mechanics and Control (CMC)

Materials Science and Technology and Sensors (CMS)

Space Systems Engineering and Management (CSE)

Combustion and Propulsion (PCP)

INPE Satellite Missions

Satellites in operation:

SCD-1, SCD-2
1993, 1998

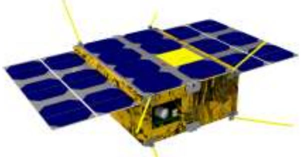
CBERS-4, CBERS-4A
2014, 2019

Amazonia-1
2021

SPORT
2022 - 2023*

Satellites operations forecast:

EDC UFSC
2025



BiomeSat
2027/2028

Amazonia-1B
2027

CBERS 5
2030

EQUARS
2030

Cross Support by INPE

- Corot (2006), France;

- Chandrayaan-1 (2008), Chandrayaan-2 (2019), India;
- Mars Orbiter Mission (2013), India;
- Astrosat (2015), PSLV-C29 (2015), India;

- Shenzhou-8 (2008), Shenzhou-9 (2009), China;

- Megha-Tropiques (2011), India/France;

- Van Allen Probes (2015), USA.

F4GSA

A Framework for Ground Segment Architectures Development of Space Missions.

Motivation

Articles that motivated:

A Model-Based Approach to Developing Your **Mission Operations** System.

Smith et al., 2014 (JPL)

→ Traditional methods for developing space systems can lead to integrity and traceability problems → **MBSE**.

Leveraging MBSE for ESA **Ground Segment Engineering**: Starting with the Euclid Mission.
Fischer et al., 2018 (ESA)

→ Space projects suffer from redundancies and inconsistencies as system development progresses.→ **MBSE**.

Developing a CubeSat Model-Based System Engineering Reference Model.

Kaslow et al., 2018 (INCOSE)

→ Investigate the applicability of **MBSE** in space projects.

Mission of the National Institute for Space Research
Master Plan 2022-2026..

→ Strategic Objective 10:
“Fortify INPE's capacity and maintain its leading role in the design and execution of space missions."

Analyzing causes and actions in the Ground Segment context

Problem:
The growing number of space missions and the consideration that the ground segment is a "Ready-to-Run System."

Objective:
To propose a framework that guides the creation of Ground Segment Architectures with processes integrated with MBSE.

Causes

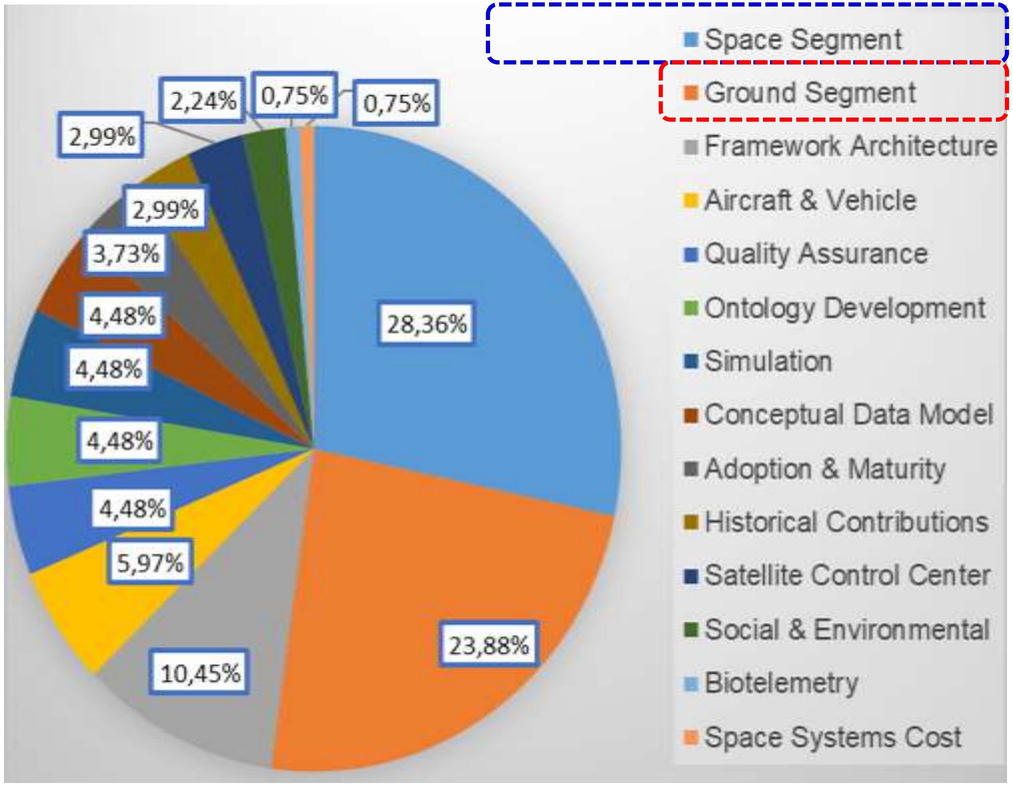
1. Neglect of the development challenges of the Ground Segment.
2. Difficulty evaluating existing solutions for a given mission and multi-missions.
3. Lack of a comprehensive view of solutions for Ground Systems.
4. Inconsistent information.

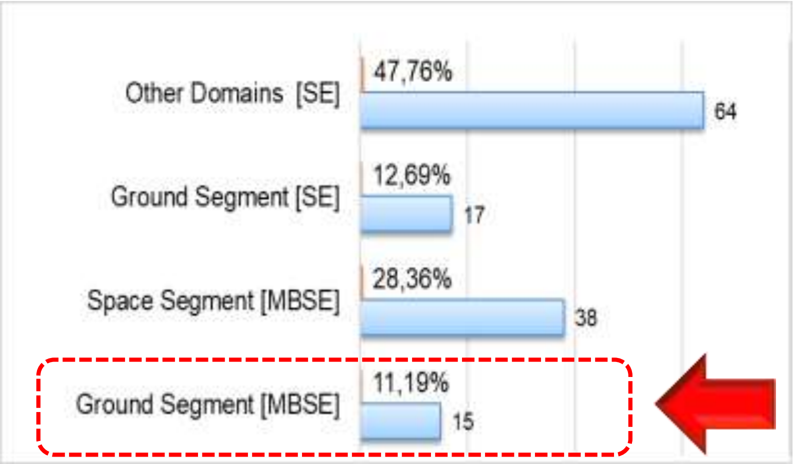
Actions

1. Anticipate the development of the ground segment.
2. Assess available capabilities.
3. Propose candidate architectures.
4. Facilitate change management.

Framework for Ground Segment Architetures - F4GSA

Rationale, 134 articles found in System Literature Review





Articles

Authors	Objective	Main Features
Smith et al., 2014	MBSE for Mission Operation Preparation (JPL).	SysML, BPMN.
Fischer et al., 2018	MBSE for ground segment in synergy with space and science segments (ESA).	SysML, MySQL
Coicev, 2019	Using MBSE for EGSE in AIT (INPE).	SysML
Almeida, 2021	Application of MBSE in ConOps for CubeSat (INPE).	ARCADIA/Capella.
Fernandez, 2024	ECCS documentation and MBSE application (ESA).	SysML.
Pierce et al. 2024	Mission Conduct, MBSE Leadership Team (NASA).	SysML.
Ramirez et al. 2024	MBSE, Digital Twins and Machine Learning Projects (Airbus).	SysML.
Julio Filho, 2025	A Framework for Development of Space Missions Ground Segment Architectures (INPE).	ARCADIA/Capella.

Concepts

MBSE

Formalized application of modeling to support the requirements, design, analysis, V&V of activities initiated in the conceptual design phase and throughout the SLC.

Thales Alenia, 2005.
Boeing, 2016.

NASA, 2011; 2024.
ESA, 2014; 2024.

Model

Physical, mathematical or logical representation of a system, entity, phenomenon.

System

Combination of elements (hw, sw, facilities, personnel) that work together to serve a purpose.

Architecture

High-level structure that defines a system.

Covering: the concepts, properties, and characteristics of the system;

Represented by: functions, flows, interfaces, relationships, and elements.

Process

Set of activities applied to convert inputs into desired outputs and generate expected results.

More Concepts

Framework

Real or conceptual structure consisting of a set of integrated strategies and actions, designed to assist in the construction of a specific objective.

Knowledge base

Repository that describes domains and establishes a hierarchy between concepts, vocabulary, and information: Models, metamodels, ontology, taxonomy.

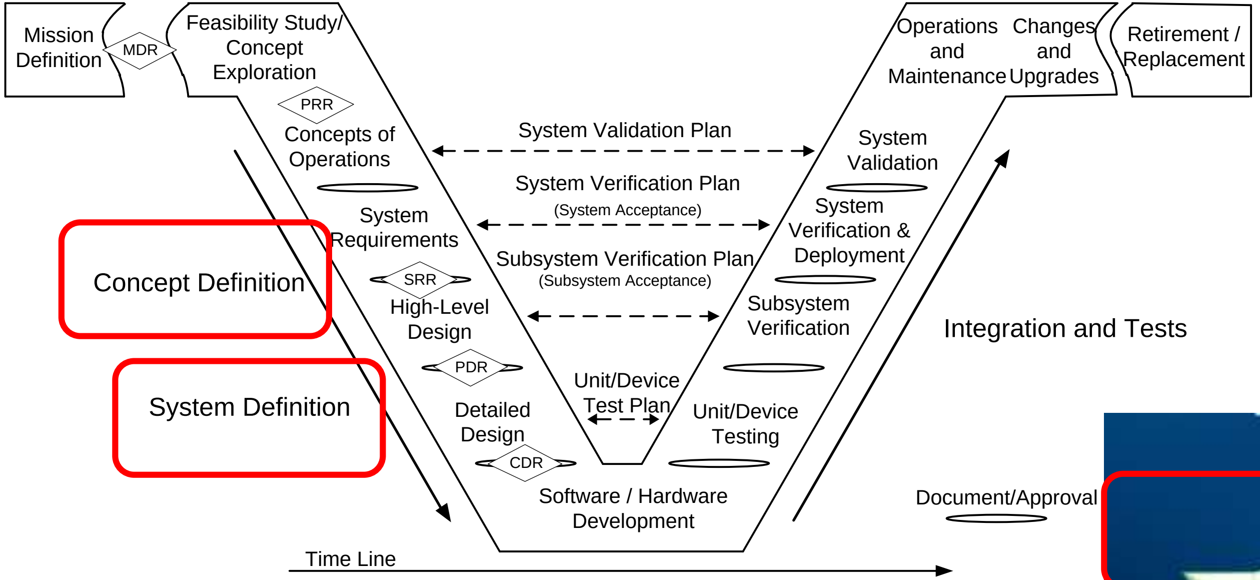
Implementation methods

Processes for evolving models throughout life cycles (modeling standards, data exchange).

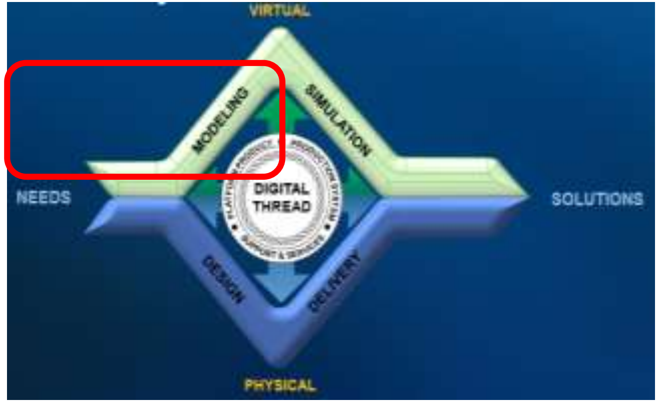
Supportive environment

Consisting of an integrated set of software tools that support models and processes.

Transforming Systems Engineering (SE) into Model-Based Engineering (MBE).



1990s SE V



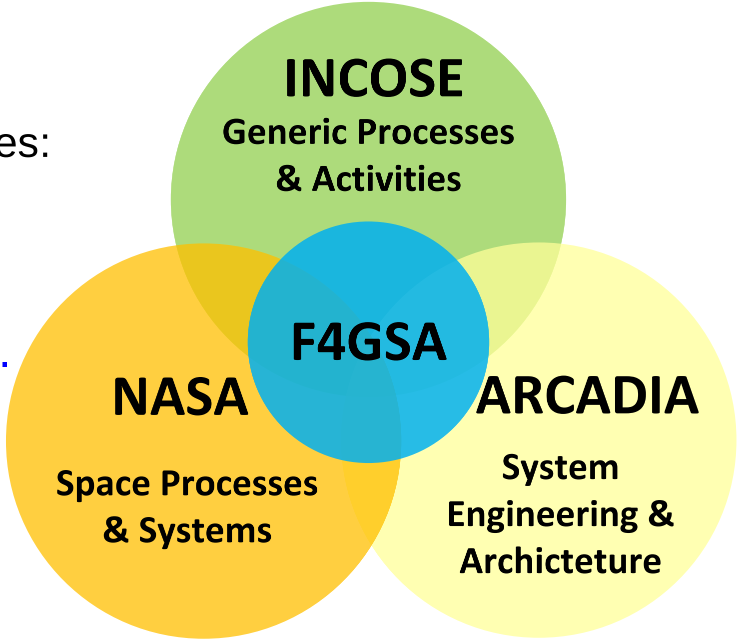
2020 MBE Diamond

Source: Boeing

Premises for elaborating the Framework

- The Framework is based on the macroprocesses:

  1) Definition of Concepts and
  2) Definition of Systems in System Life Cycle.



- It is a **Tailoring** of the processes:
  - INCOSE Generic Processes and Activities (WALDEN et al., 2014);
  - NASA Space Processes & Systems Design (NASA, 2016a);
  - Activities proposed by the ARCADIA Methodology (VOIRIN, 2023).

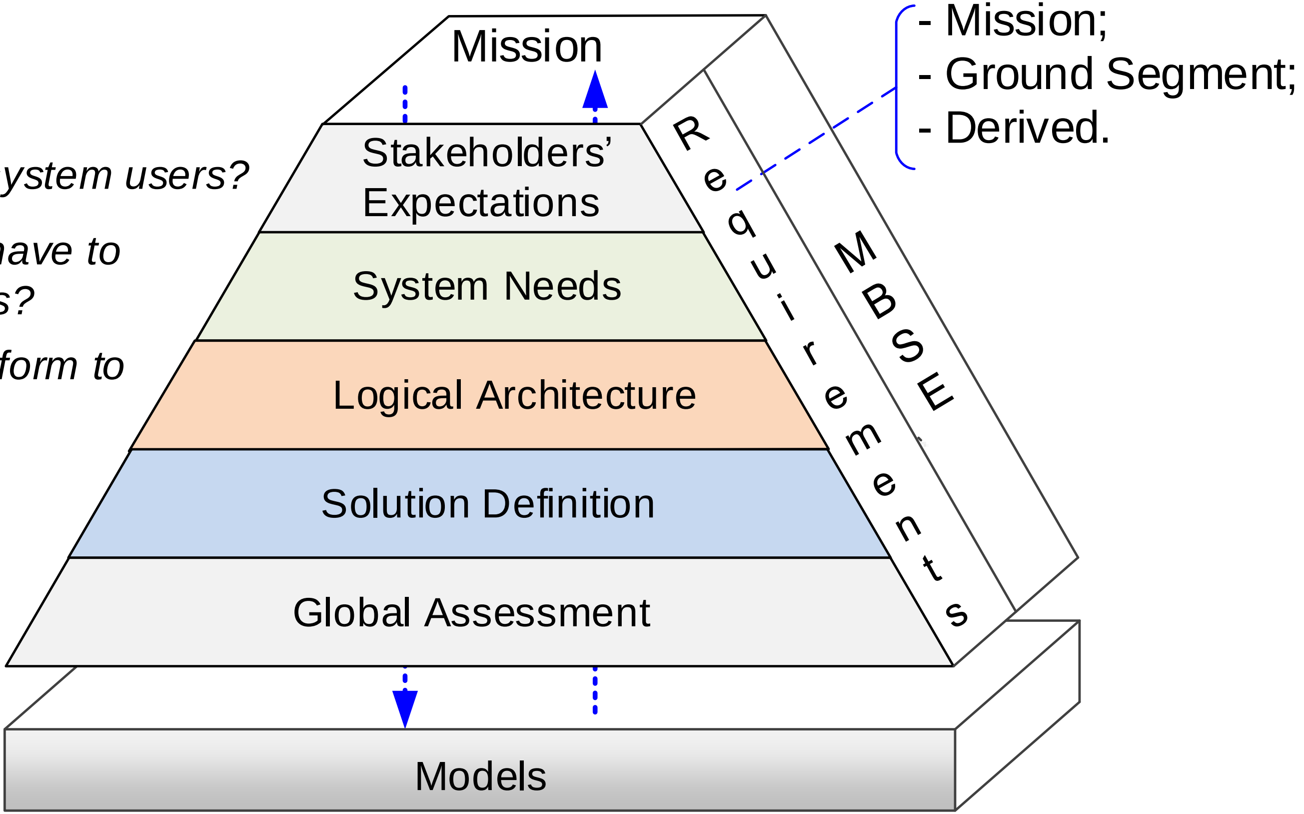
What are the needs of system users?

What does the system have to accomplish for the users?

How will the system perform to meet expectations?

How wil the system be developed and built?

How will the system be assessed?



Context Diagram

F4GSA

Controls
CCSDS, ECSS,
SEBoK,
Space Agencies.

Inputs
Mission Objectives,
Requirements &
Constraints.

Processes
[1] Stakeholders' Expectations Analysis.

[2] System Needs Analysis.

[3] Logical Architecture Conception.

[4] Design Solution Definition.

[5] Carry out a Global Assessment.

Outputs
Candidate
Architectures
for Ground Segment.

Enablers
Model Based System
Engineering - MBSE,
Language & Tool.

F4GSA Processes

What are the users' needs?

Contribute to a proper understanding of expectations.

What should the ground system accomplish?

Requirements feasibility and operational use.

How will the system work?

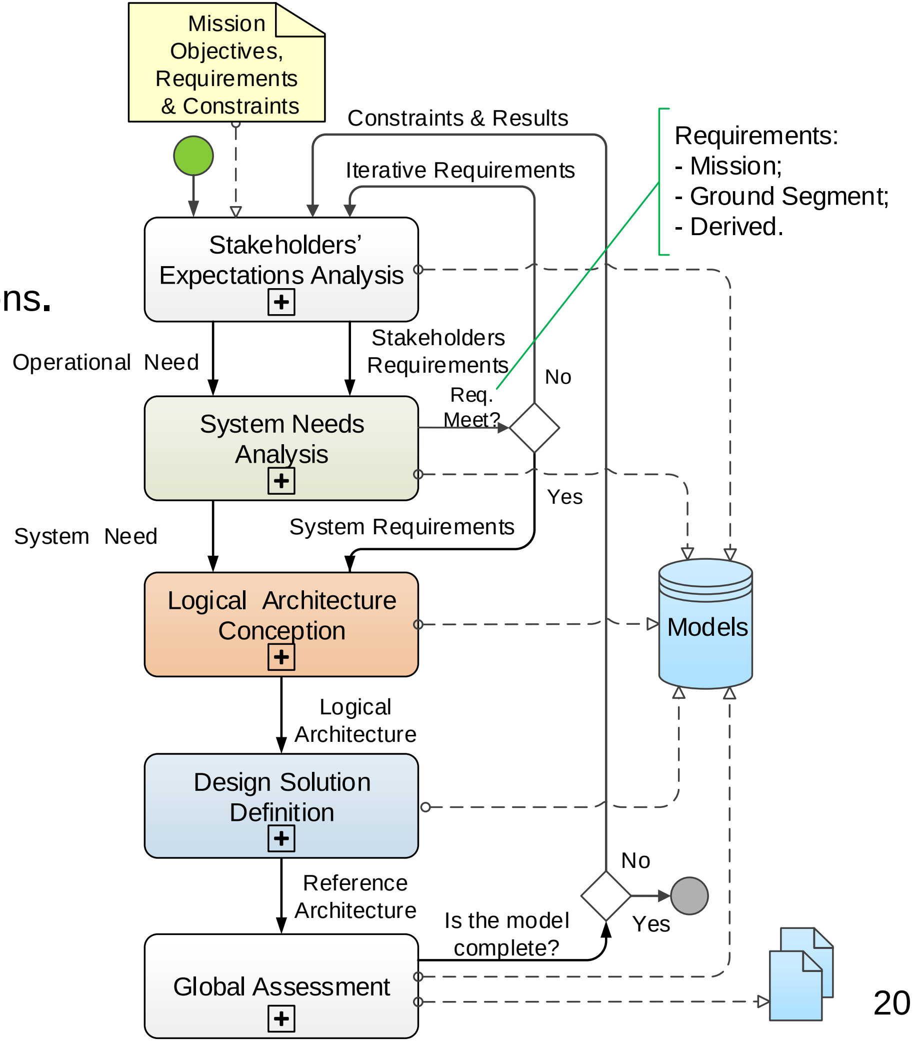
Solution-oriented system decomposition.

How will the system be developed and built?

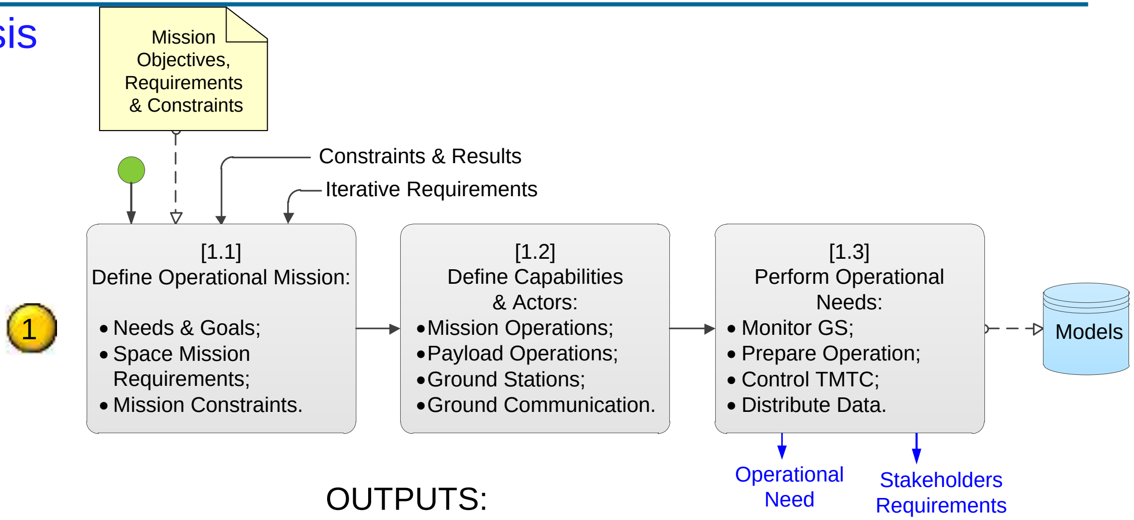
Define the Reference Architecture.

How will the system be evaluated?

Approval criteria with expert support.

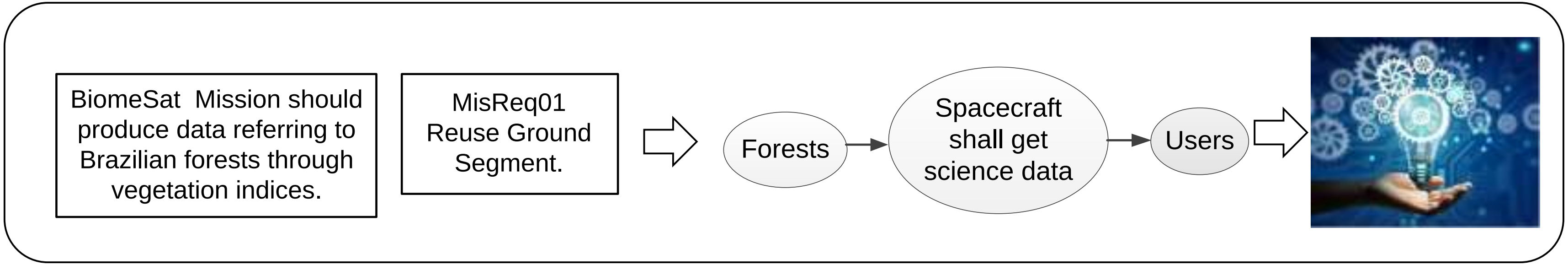


Stakeholders Expectation Analysis Process [1]

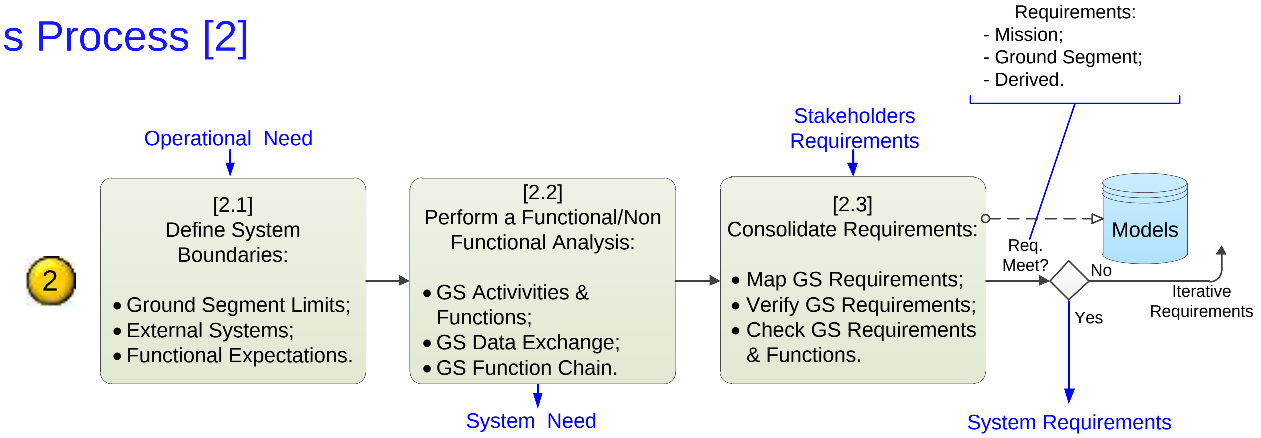


INPUTS:
- Initial Stakeholder Expectations;
- Needs, Goals, Objectives(NGO);
- Requirements & Constraints;
- * Iterative Data.

OUTPUTS:
- Stakeholder Requirements;
- Operational Needs.



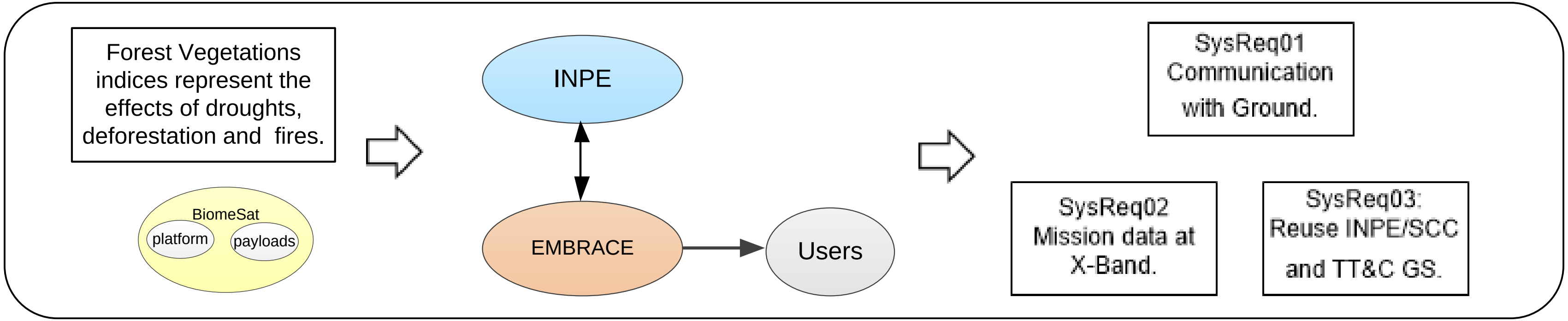
System Needs Analysis Process [2]



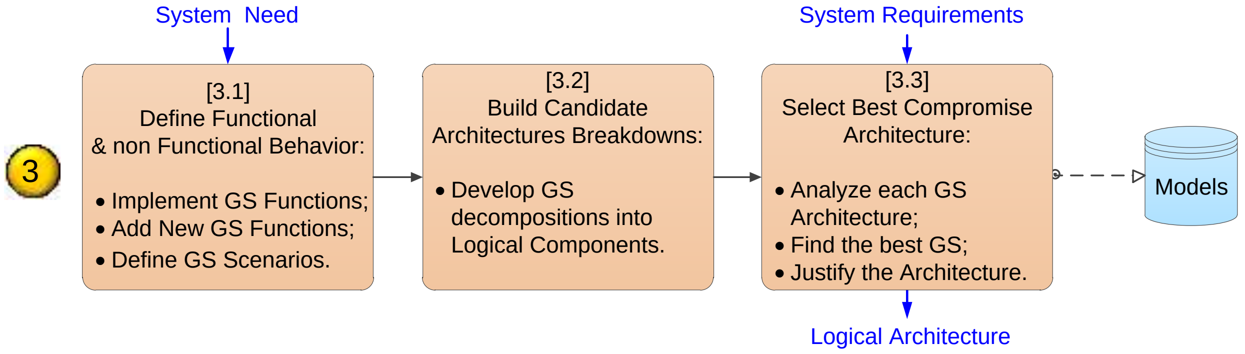
INPUTS:
- Stakeholder Requirements;
- Operational Need.

OUTPUTS:
- Validated System Requirements;
- System Needs;

Iteration with Process [1].

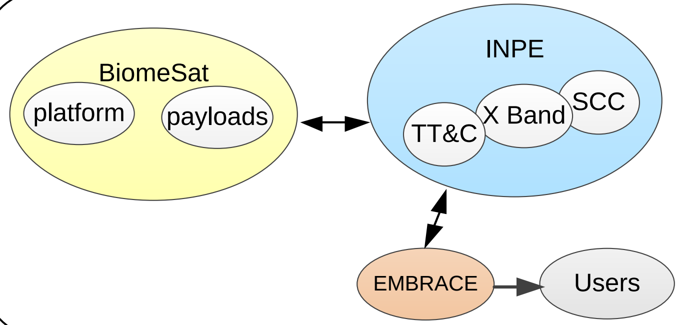


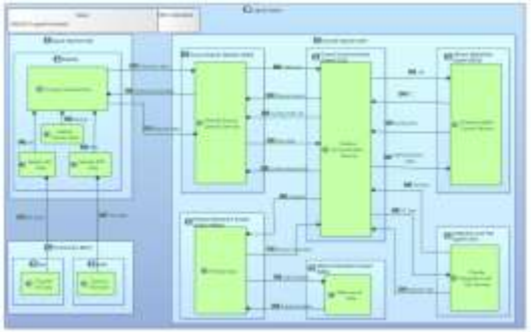
Logical Architecture Design Process [3]



INPUTS:
- Validated System Requirements;
- System Needs.

OUTPUTS:
- **Selected Logical Architecture;**
- Decomposition Models;
- Derived Requirements.





Design Solution Definition Process [4]

Logical Architecture

4

[4.1]
Define Architectural Principles:

- Generic HW for GS;
- Legacy SW for GS;
- Data Server.

[4.2]
Define finalized Functional/Non Functional Behavior:

- Fix ambiguities;
- Add New Functions GS;
- Check the behavior.

[4.3]
Build Detailed Candidate Architecture:

- Decompose the LA in components;
- Consolidate the Reference Arquitecture.

Models

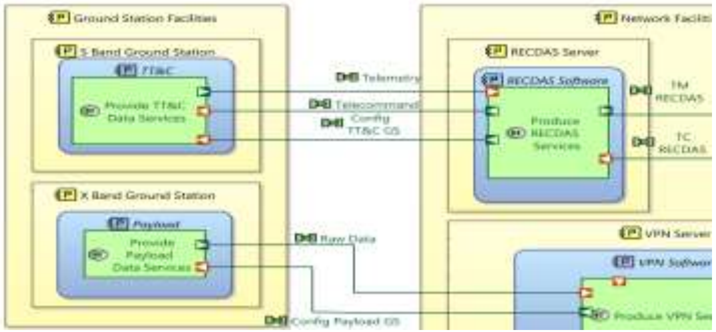
Reference Architecture

INPUTS:

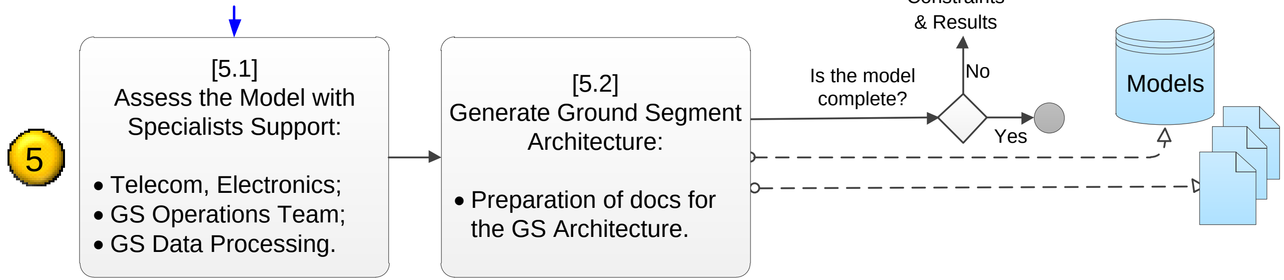
- Selected Logical Architecture
- Decomposition Models;
- Derived Requirements.

OUTPUTS:

- **Reference Arquitecture;**
- System Specifications;
- Initial Subsystem Specifications;
- External Interface Specifications.



Global Assessment Process [5]



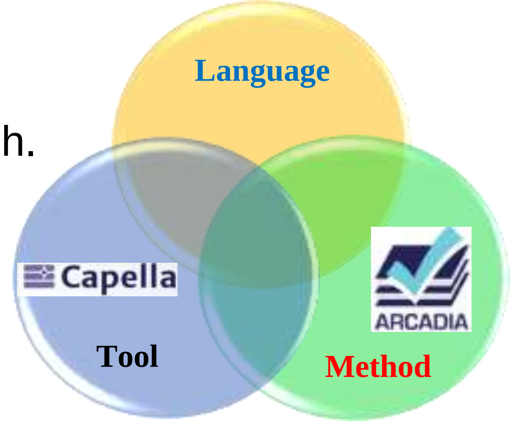
INPUTS:
- Reference Arquitecture;
- System Specifications;
- External Interface Specifications;
- Initial Subsystem Specifications.

OUTPUTS:
- **Ground Segment Architecture**
- Assessment Reports;
- Initial Verification & Validation Plan;
- Iteration with Process [1].

Case Studies

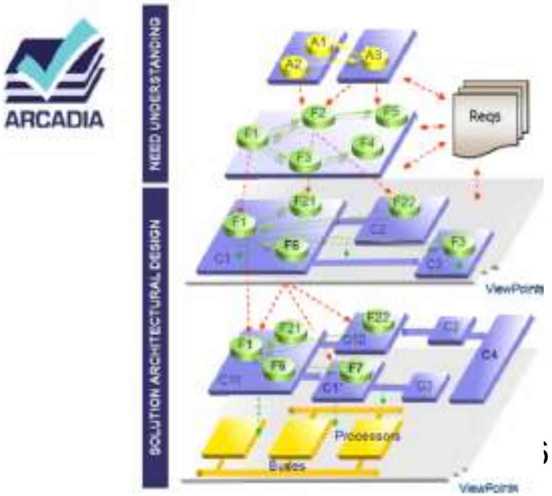
ARCADIA: **ARC**hitecture **A**nalysis and **D**esign **I**ntegrated **A**pproach.

It is a model-based engineering language and methodology for architectural design systems, hardware, and software.



ARCADIA is supported by diagrams inspired by UML/SysML, it and uses the **Capella Tool**.

- *Architecture diagrams;*
- *Dataflows diagrams;*
- *Functional chains diagrams;*
- *Sequence diagrams;*
- *Tree diagrams;*
- *Mode and States diagrams;*
- *Classes and Interfaces diagrams.*



BiomeSat Mission

A remote sensing satellite to support the planning, monitoring, and management of Brazilian biomes: Amazon, Atlantic Forest, Caatinga, Cerrado, Pantanal, and Pampa.

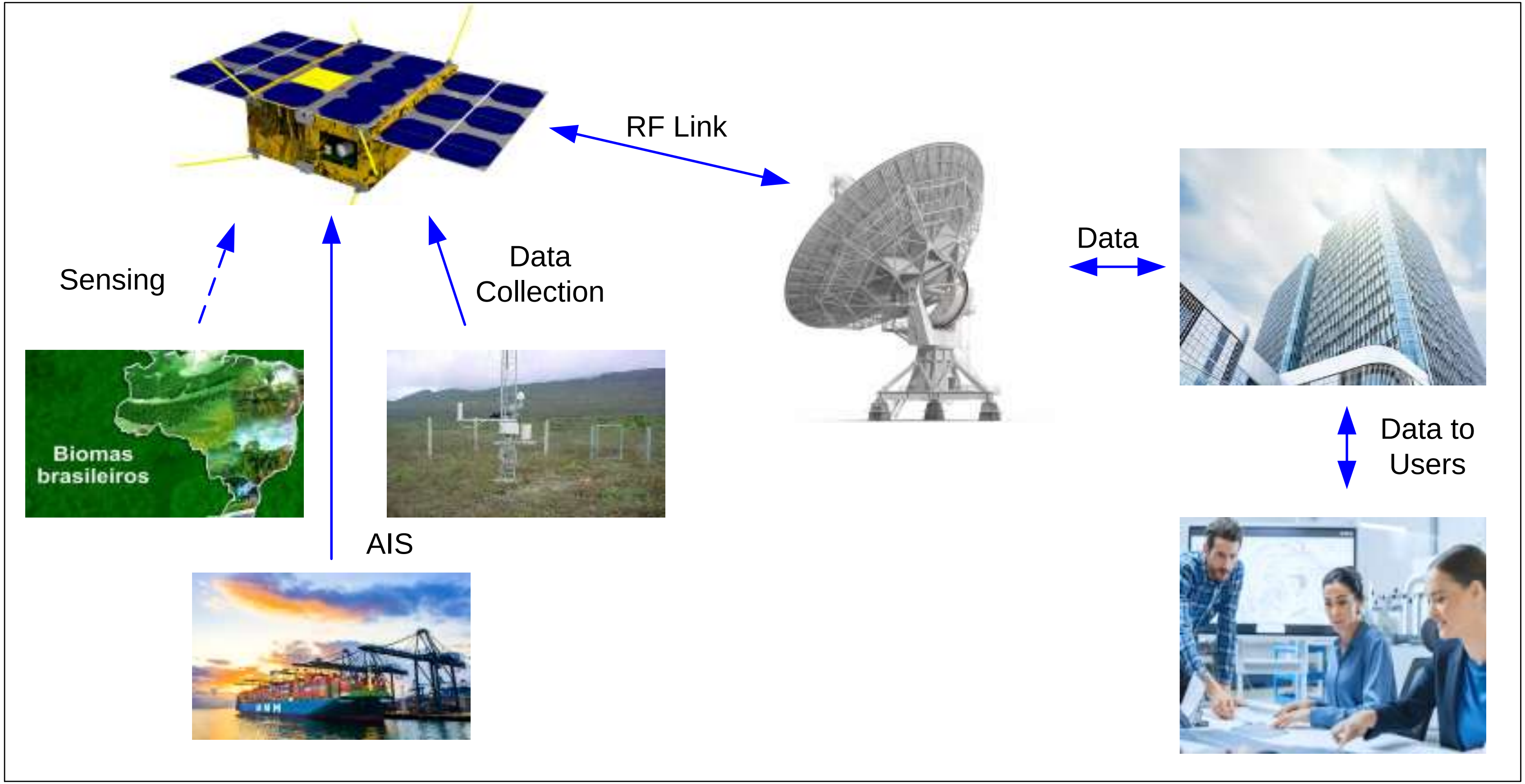
Capable of collecting radiometric data in the visible and near-infrared spectral ranges, influenced by pigments such as chlorophyll and the cellular structure of leaf surfaces.

Small satellite equipped with an Environmental Data Collector (EDC) payload that receives data from Data Collection Platforms (DCPs).

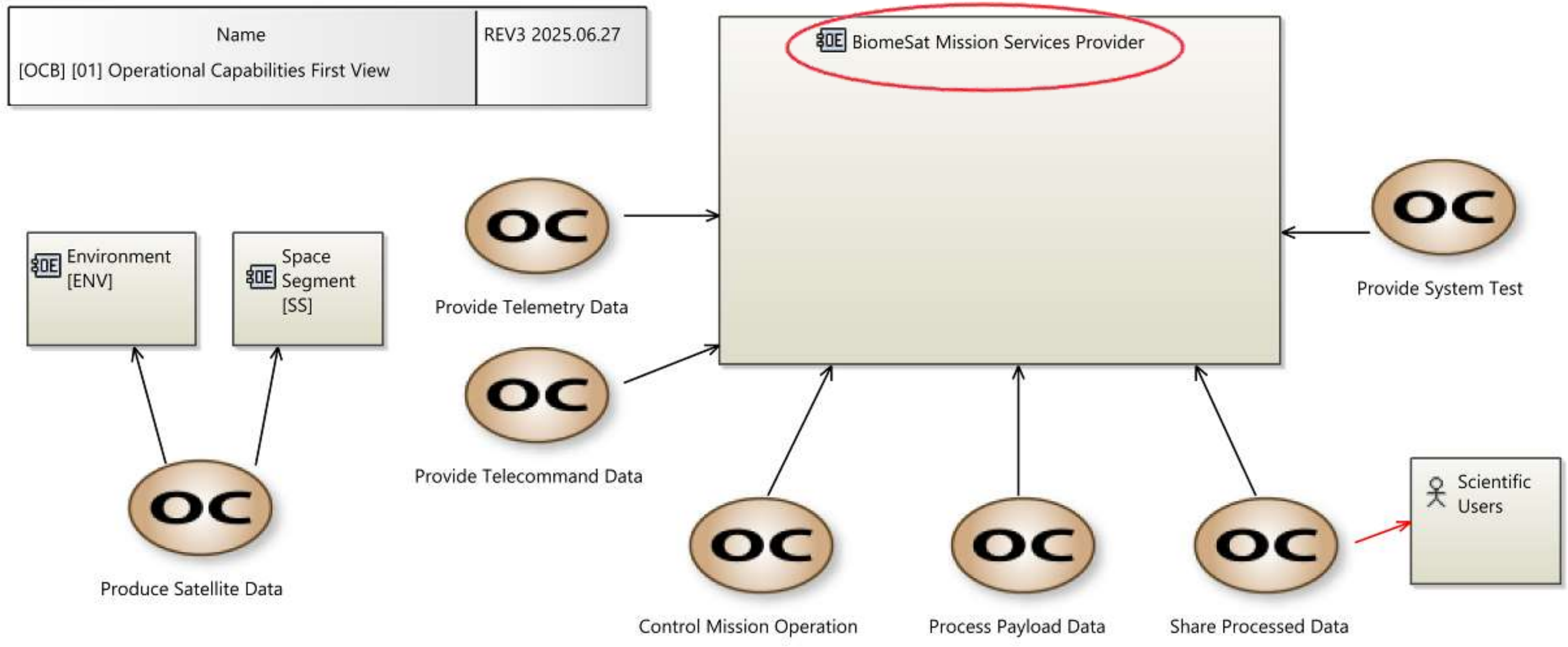
Integrates an Automatic Identification System (AIS) for vessels along the coast and rivers of Brazil.

The mission is complementary to the CBERS and Amazonia series satellites.

BiomeSat Mission

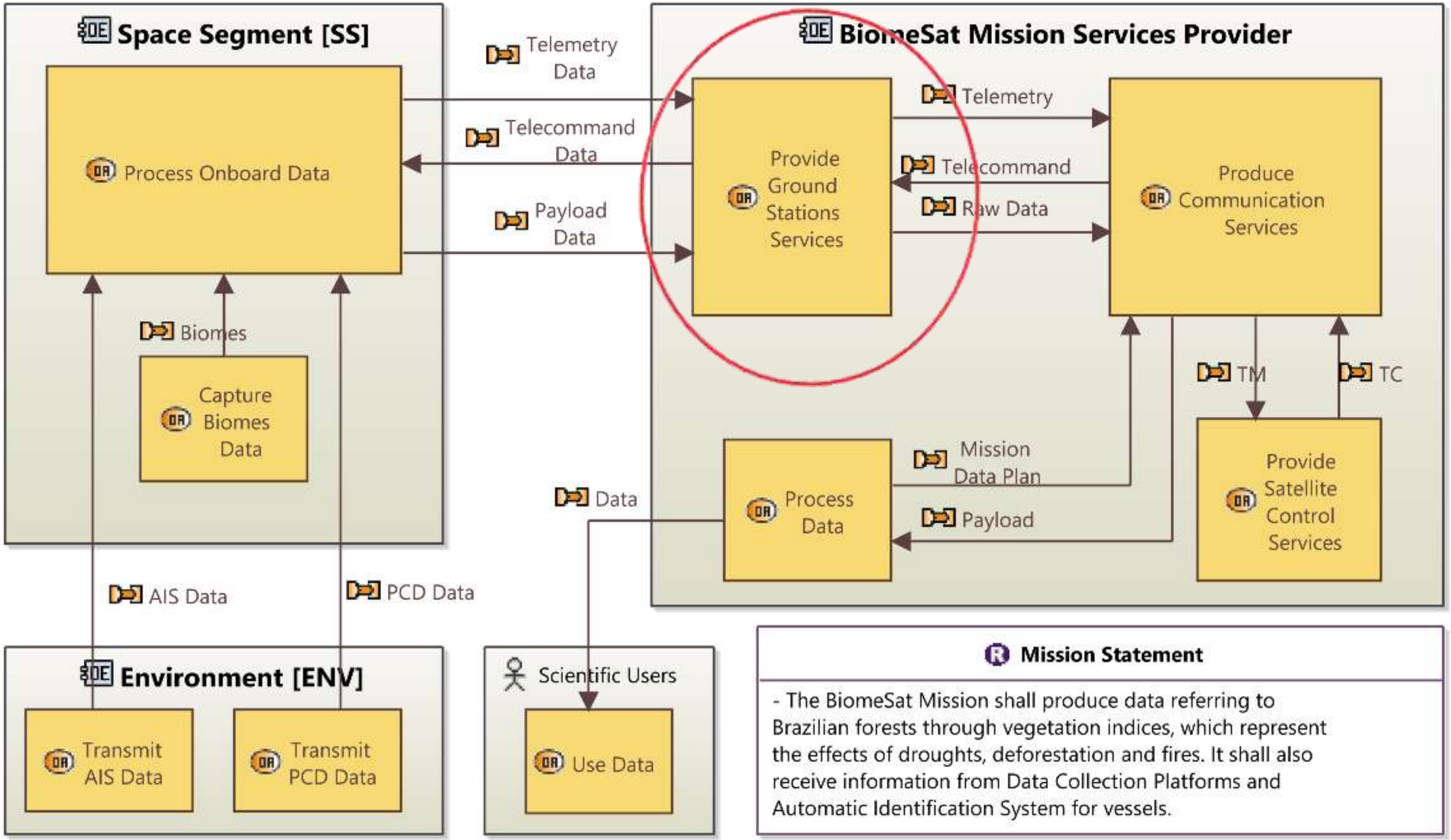


P1 Operational Capabilities



P1

Operational Entities

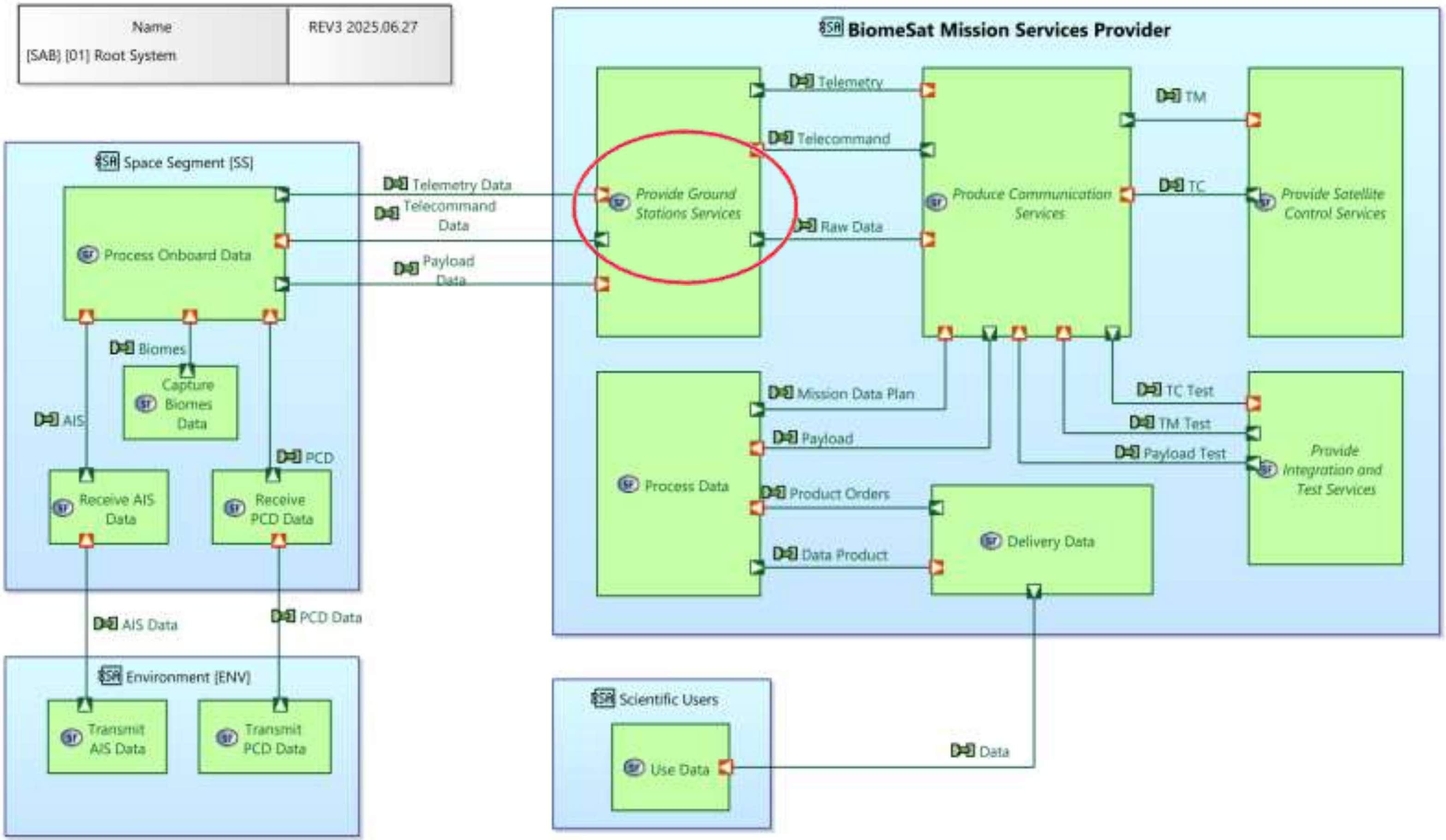


Mission Statement

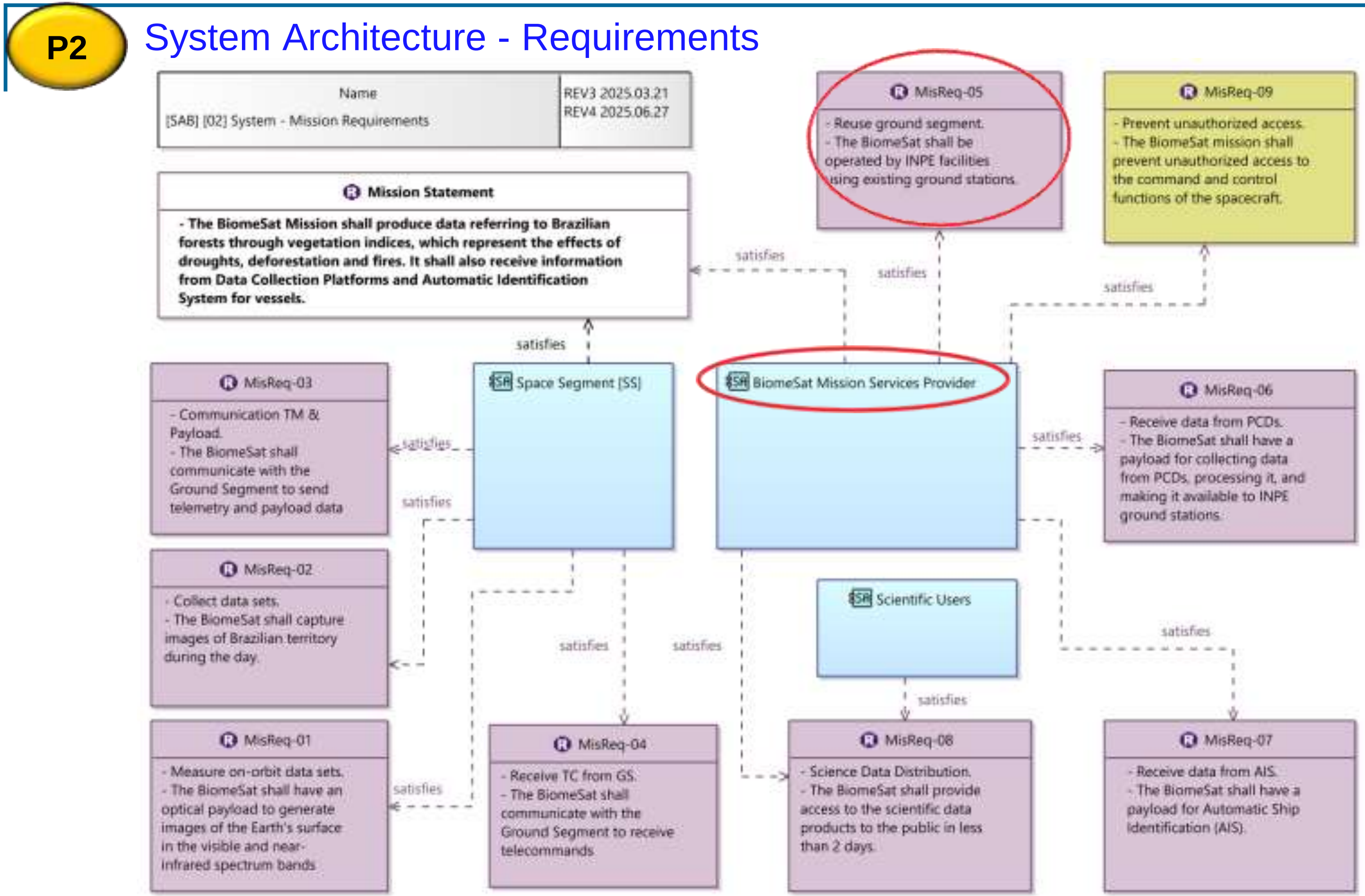
- The BiomeSat Mission shall produce data referring to Brazilian forests through vegetation indices, which represent the effects of droughts, deforestation and fires. It shall also receive information from Data Collection Platforms and Automatic Identification System for vessels.

P2

System Architecture

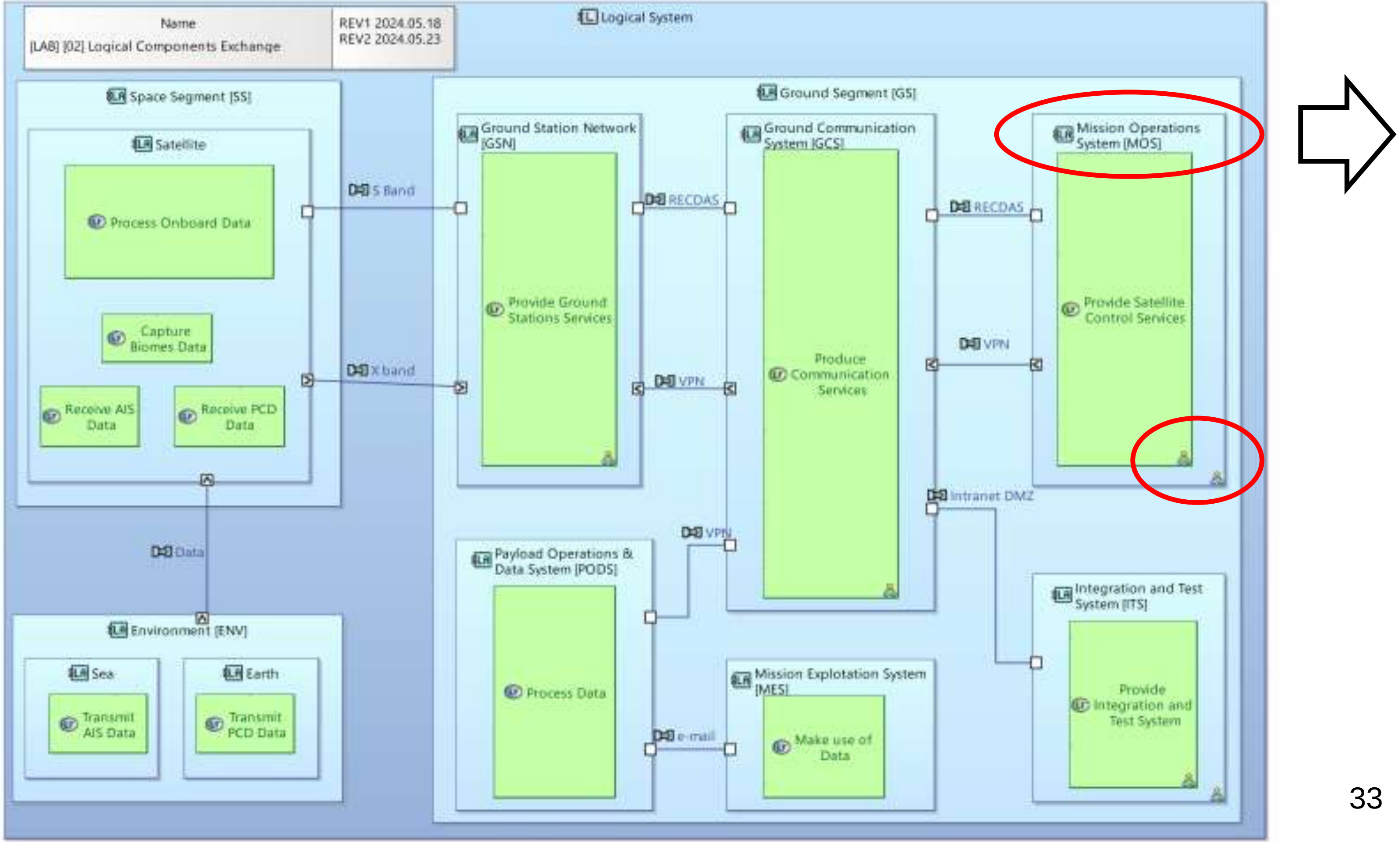


System Architecture - Requirements



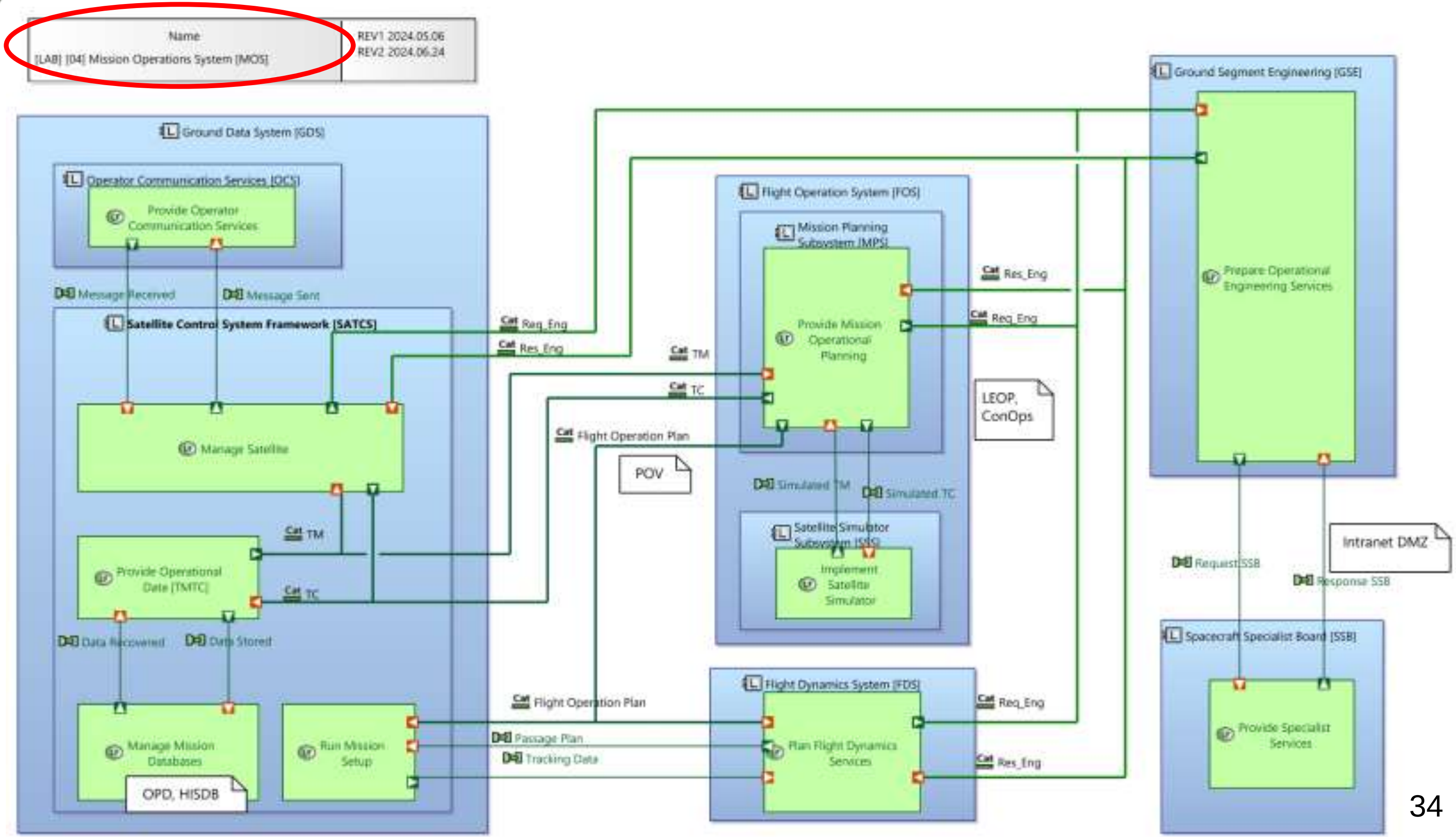
Logical Architecture

P3



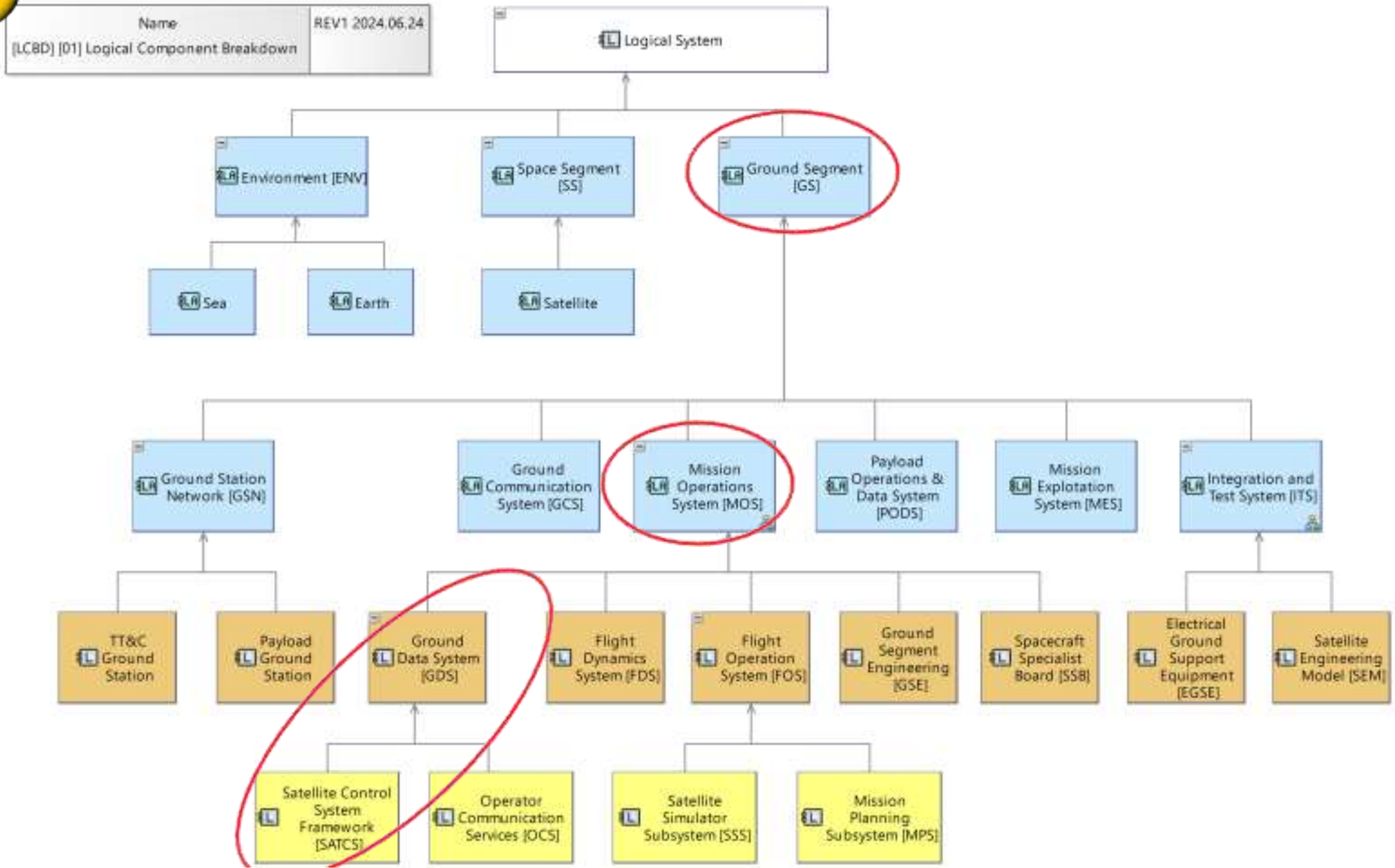
Logical Architecture [Zoom]

P3

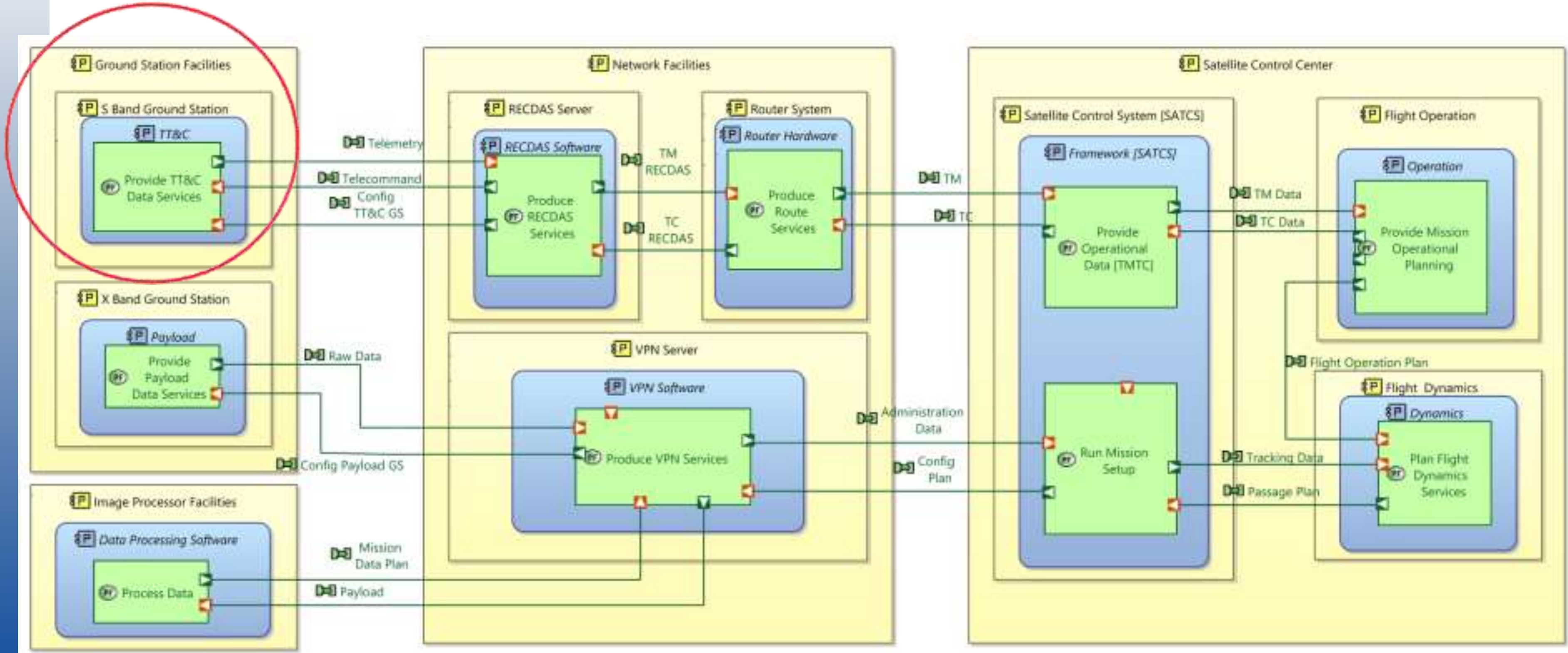


P3

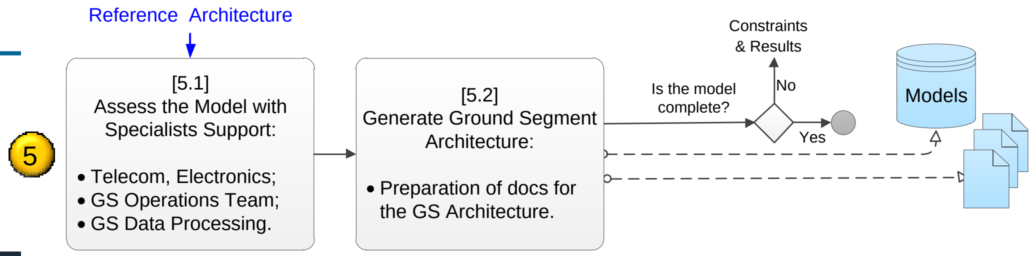
Logical Architecture



P4 Physical Architecture



P5



BiomeSat Ground Segment System

Criteria for evaluating the system:

- Does it provide functionalities for stakeholders?
- Does it meet operational needs?
- Will it function as expected?

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      - Capabilities
      - Interfaces
      - Data
      - Structure
      - Missions
    - Logical Architecture
    - Physical Architecture

BiomeSat Ground Segment System

SystemEngineering

BiomeSat Ground Segment System > BiomeSat Ground Segment System

Operational Analysis

Several stakeholders have relationships with the BiomeSat Ground Segment System, and with different goals.

The focus is put here on the operational needs the BiomeSat Ground Segment System.

The entities and their goals are presented in the operational capabilities diagram: [OCB] Operational Capabilities

Operational Architecture Diagrams provide a comprehensive view of the activities performed by the entities in order to reach their goals.

These diagrams are [OAB] Operational Entities and its refined version by [OAB] Operational Entities & Activities .

The names of space system elements are based on ECSS-E-ST-70C(31July2008), p21 and ECSS-E-ST-70-32C(31July2008). p14 (31 July 2008).

System Need Analysis

The focus here is put on the BiomeSat Ground Segment System itself. The objective is to set the boundaries and provide a clear vision of the need.

Four diagrams provide interesting entry points to the model:

- [SAB] Structure with components and its refined version [SAB] Structure with Functions are very good entry points to further navigate in the
- [SAB] Structure with Mission Requirements show the Mission Statement, the Mission Requirements and all Actors.
- [SAB] Structure with System Requirements show the System Requirements that are derived from [SAB] Structure with Mission Requirements.

Concept of Derived Architectures

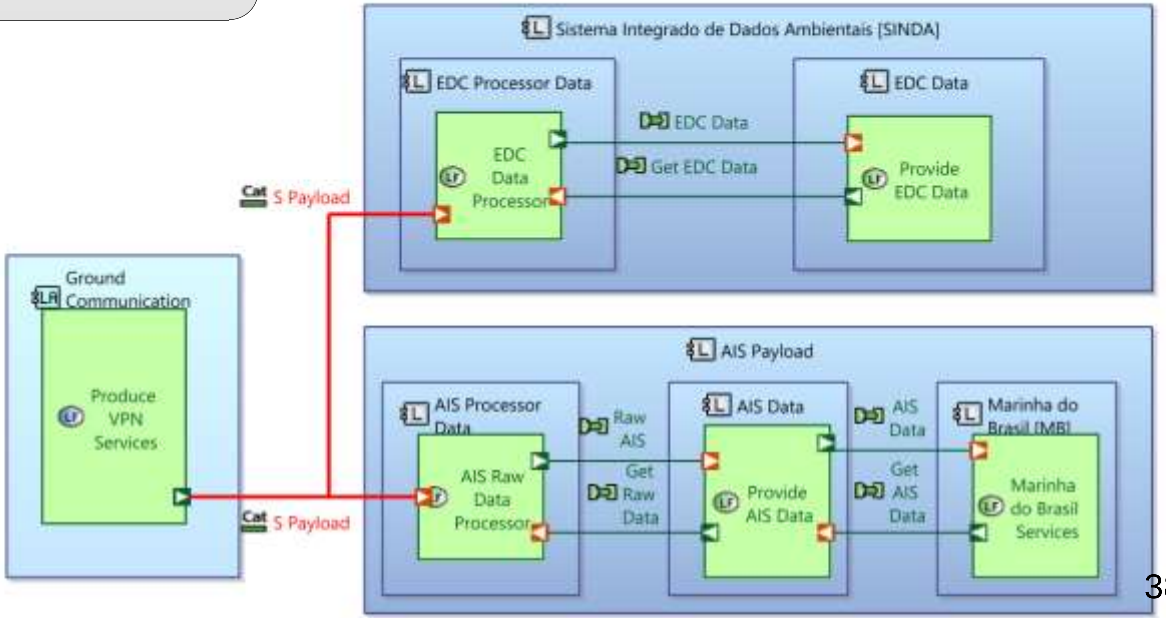
Input
Reference Architecture

Inputs
New Requirements

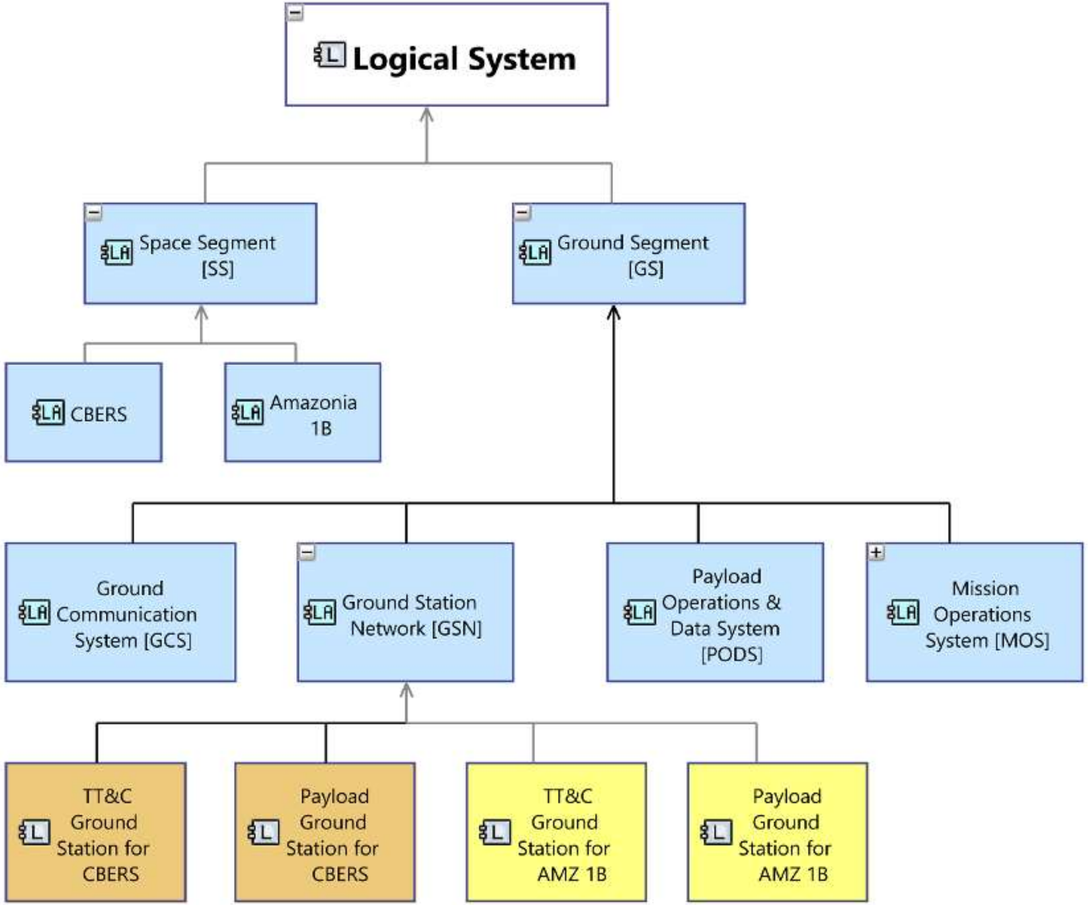
Framework for Ground Segment Architectures

F4GSA

Outputs
Candidate Architectures for Ground Segment.



CBERS and Amazonia Multimissions



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Comparison between processes

- INCOSE → ISO/IEC/IEEE 15288:2023, clear and comprehensive structure, diverse industrial and research sectors, the complexity of the processes may require a longer adaptation and implementation time;

- NASA → processes for all space products, ensuring alignment with standards such as AS9100. Requires control and coordination between teams.

- ARCADIA → ISO/IEC/IEEE 15288:2023, SE and architecture. Differentiating factor in defining complex architectures for different domains, according to the needs, constraints and know-how of the teams.

- F4GSA → Tailoring of Technical Processes, System Design and ARCADIA processes, focusing on the architecture of the ground segment of space missions.

Emerging characteristics of F4GSA

- Processes for the ground segment architectures in the development and System Life Cycle phases, allowing for the early identification of problems and the anticipation of solutions;
- Integrating processes into the MBSE methodology enables the handling of the complexity of space systems, promoting greater cohesion and clarity;
- Reference Architecture for a common basis for dedicated/multi-missions.

Lessons Learned

- Positive results with the participation of SE teams in modeling from the initial phases;
- There are challenges for migrating from a documentary approach to models;
- Development of architectures through successive iterations and in an incremental mode;
- ARCADIA/Capella is fundamental for these types of challenges.

Publications (14)

- III Brazilian Aerospace Congress - III CAB 2025;
- The International Council on Systems Engineering - INCOSE 2025 (preprint);
- International Astronautical Congress - IAC 2023, 2021, 2020;
- International Conference on Space Operations - SpaceOps 2021, 2018;
- Latin American Cubesat Workshop - LACW 2024, 2022;
- Journal Aerospace Technology and Management - JATM 2020;
- Workshop in Engineering and Space Technologies - WETE 2023, 2022, 2021, 2020.

F4GSA:
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CAPELLA DAYS 2025, Thank you!

Dr. Antonio Cassiano - cassiano.filho@inpe.br 2025/11/19

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