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# Concurrent Structured Analysis SE Method applied to a solar irradiance monitor satellite


**Rodrigo Britto Maria**, INPE MSc. Student
**Gabriel G. Coronel M.**, INPE MSc. Student
**Halph Macedo Fraulob**, INPE MSc. Student
**Adair Rohling**, INPE Ph.D Student
**Adrielle Chiaki**, INPE MSc. Student
**Geilson Loureiro**, INPE Systems Engineering Professor


INPE

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# INPE AT A GLANCE

# Introduction: INPE at a glance



**INPE** is the Brazilian National Institute for Space Research
(Portuguese: **I**nstituto **N**acional de **P**esquisas **E**spaciais)

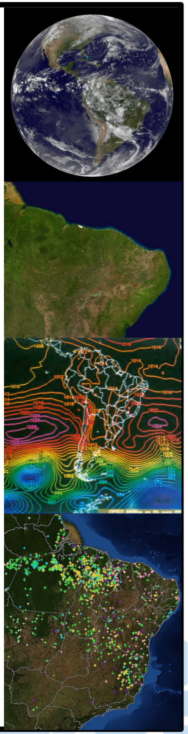

INPE was founded in **1961** and is a research unit of the Brazilian Ministry of Science and Technology

**SATELLITES**
Earth and Universe Observation Missions
Telecommunication Missions

**GROUND SYSTEMS**
Control, reception, processing and distribution of space data

**ANALYSIS AND MODELING**
Space Science and
Earth System Science

**ACCESS TO KNOWLEDGE**
Innovative products to society



# Introduction: INPE at a glance

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## Graduation courses (MSc and PhD)

- ✓ Astrophysics
- ✓ Space Engineering and Technology
- ✓ Space Geophysics
- ✓ Applied computing
- ✓ Meteorology
- ✓ Remote sensing
- ✓ Earth System Science


# CONCURRENT STRUCTURED ANALYSIS SE METHOD

# Concurrent Structured Analysis (CSA) Systems Engineering method

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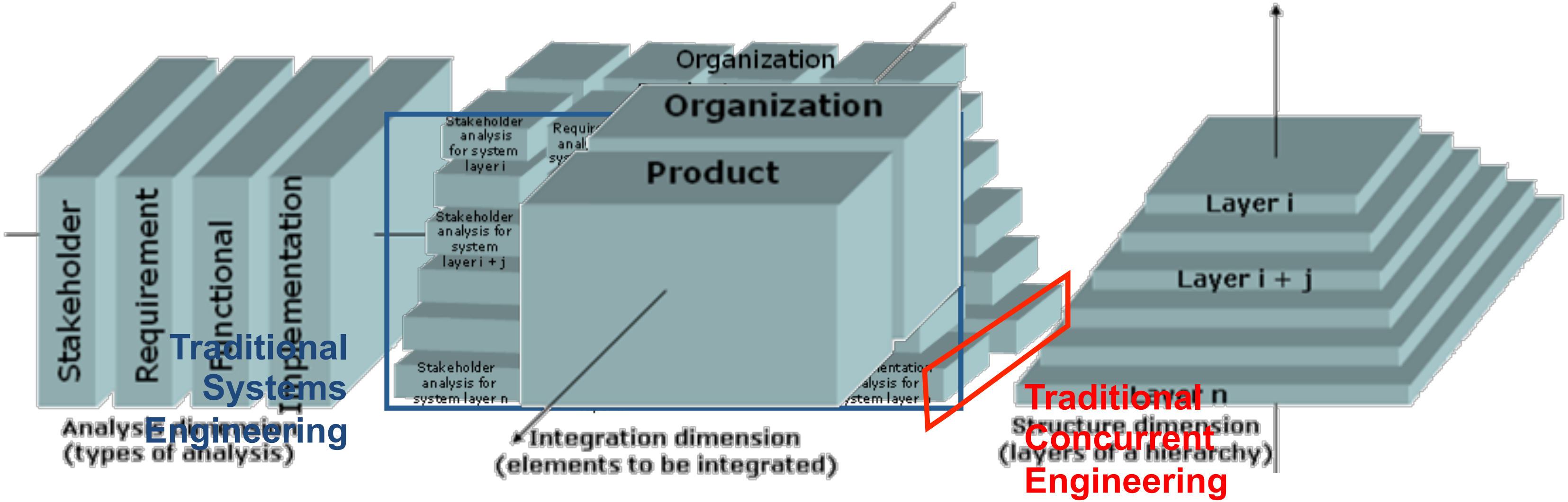
CSA combines different types of analysis (i.e. stakeholder, requirement, functional and implementation), with different elements to be integrated (i.e. product and organization) and with different layers of hierarchy (e.g. mission, system, subsystems) (Loureiro, 2015).



# Concurrent Structured Analysis (CSA) Systems Engineering method

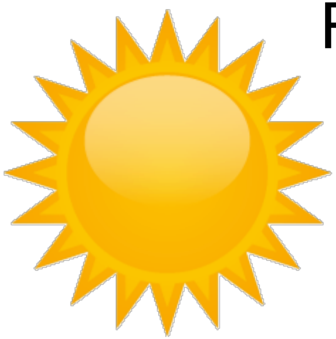


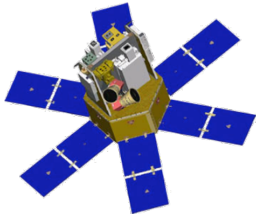
- The results of the CSA method application will have **synergy between the designed product and the performing organizations**.
- The CSA method can be thought of as comprised by six iterative phases:
  1) Mission identification;
  2) Life cycle processes;
  3) Stakeholder analysis;
  4) Requirements analysis;
  5) Functional analysis;
  6) Physical analysis.

# Solar Irradiance Monitor Satellite

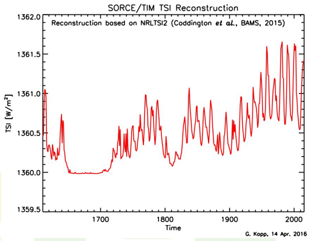
- Selected system for the application of the CSA method in the discipline "Systems Engineering for Space Systems" of the INPE Graduation Course;

Electromagnetic Radiation





TSI data ($W/m^2$)




# Solar Irradiance Monitor Satellite

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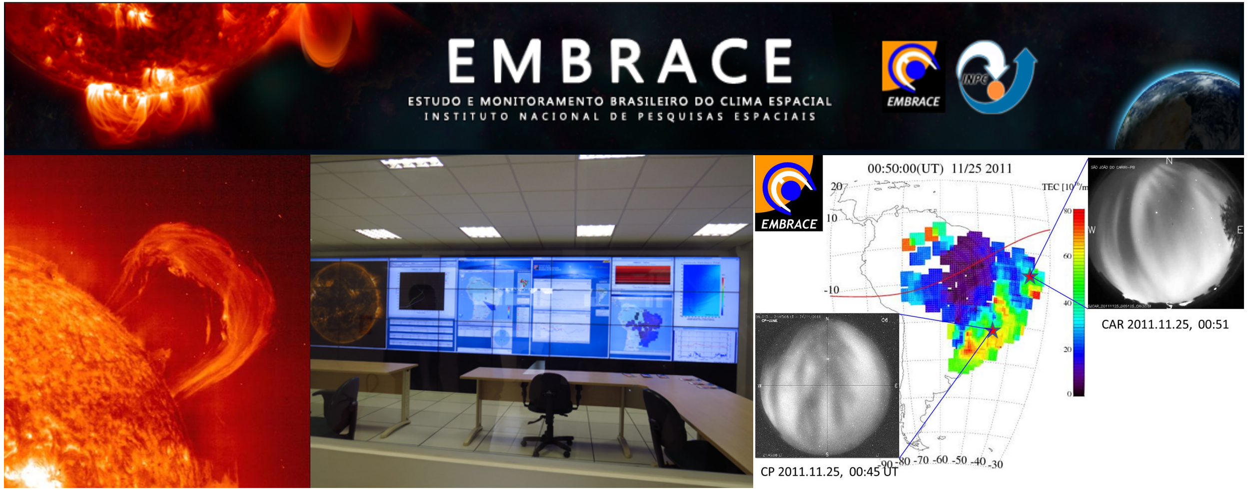
The selection of the system was based on a real need from the **EMBRACE** (Brazilian Study and Monitoring of Space Weather) research group, which became our main stakeholder.

**Why does EMBRACE need a solar irradiance monitor satellite?**

To be able to have proprietary high precision data of solar irradiance in order to understand the role of solar variability on Earth surface's temperature.



PHASE 1:

# MISSION IDENTIFICATION

# NEED STATEMENT

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- The **NEED STATEMENT** is a simple statement of proposal of the system to be developed, the environment in which it will operate and any other special operational consideration which may be important (Jackson, 1997).

- It translates the customer's expectation into the problem space of Systems Engineering (Larson at al, 2009).

- For this work, the need statement was "**EMBRACE needs to collect high precision data of solar irradiance in order to understand the role of solar variability on Earth surface's temperature**".

# INITIAL STAKEHOLDERS

- **Initial stakeholders** are the ones directly affected by the definition of the mission. Assuming that the system fulfills the need, the following questions were asked:
  1) Who are the sources of inputs?
  2) Who are the receivers of outputs?
  3) Who are the sources of control or the control themselves?
  4) Who are the sources of mechanisms or the mechanisms themselves?
- The answers are the stakeholders who affect or are affected by the product during that sub-process (Loureiro, 1999).
- Other stakeholders are discovered later, after individual analyses of all the scenarios.

# INITIAL STAKEHOLDERS

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| | |
|---|---|
| **Source of inputs** | EMBRACE researchers |
| **Receivers of outputs** | EMBRACE researchers, solar irradiance scientific community, Brazilian National Astrophysics Laboratory (LNA) team |
| **Control** | INPE, Brazilian Space Agency (AEB), National Telecommunications Agency (ANATEL), Project Manager, Sponsor agencies (CNPq, CAPES, FAPESP) |
| **Mechanisms** | Systems Engineering team, System Development team, Payload and Subsystems Development teams, Tracking and Control Center (CRC) team, LNA team, suppliers, EMBRACE team |

# GOALS AND OBJECTIVES

- EMBRACE was interviewed to articulate their expectations, which were reviewed and stated as GOALS with associated OBJECTIVES.

| | |
|---|---|
| Goal 1: Provide continuous measurements of high precision Total Solar Irradiation (TSI) in space with a low degradation rate | |
| Objective 1.1 | Absolute accuracy of 300 parts per million (ppm) in the Beginning of Life (BOL) (maximum value) |
| Objective 1.2 | Long-term relative accuracy (stability) of 10 ppm/year (maximum value) |
| Objective 1.3 | Solar irradiance measuring at least 4 hours/day |
| Goal 2: Release collected data to the scientific community | |
| Objective 2.1 | Send data to CRC in no more than 24 hours after measurement |
| Goal 3: Allow continuous climate records measurements, considering other space missions | |
| Objective 3.1 | Operate for at least 1 year, preferably 2 years |
| Goal 4: Take advantage of current resources (personnel, equipments, facilities) in order to reduce costs | |
| Objective 4.1 | Use existing INPE's facilities |

# ACCEPTANCE CRITERIA AND QUALIFICATION STRATEGY



- The acceptance criteria define, for each requirement, what would be a successful outcome from the qualification approach adopted.
- There is usually a one-to-one relationship between a requirement and its acceptance criterion.

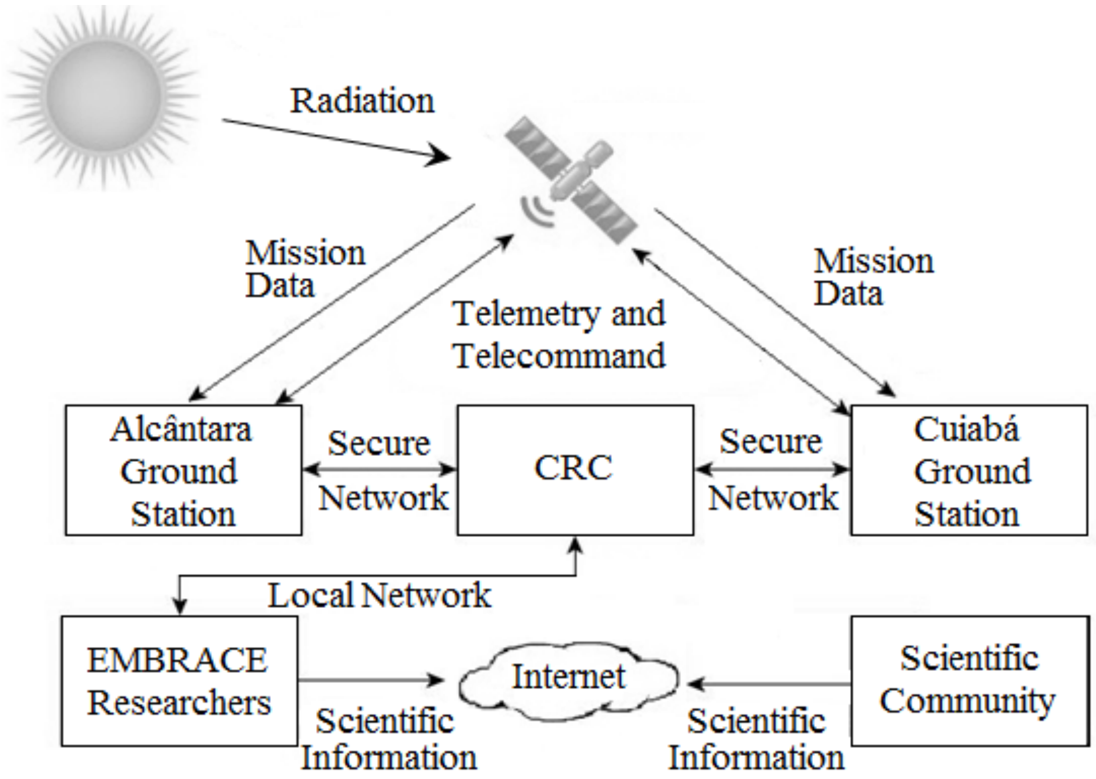
| Requirement | Acceptance criteria | Rationale | Qualification strategy |
|---|---|---|---|
| Accuracy | The system should measure the solar radiation with an accuracy of 300 ppm at BOL (maximum value). | EMBRACE considers that measures with accuracy greater than 300 ppm will not have the necessary quality to be used in mathematical models of temperature. | Test |
| Stability | The system must have a long-term relative accuracy (stability) of 10 ppm/year (maximum value). | EMBRACE determined that a loss in accuracy of 10 ppm/year will not affect the quality of measurements throughout the lifetime. | Analysis |
| Latency | The data collected by the system should be available to the public every two days. | EMBRACE determines that an update of the publications every two days is the best contribution to the scientific community. | Demonstration |

# AS-IS OPERATIONAL ENVIRONMENT



- INPE receives data from the University of Colorado who obtains it from the SOlar Radiation & Climate Experiment (SORCE) satellite.
- Other data available on the internet from other satellites (FY-3A, FY-3B, SOHO and ACRIMSAT).

# TO-BE OPERATIONAL ENVIRONMENT

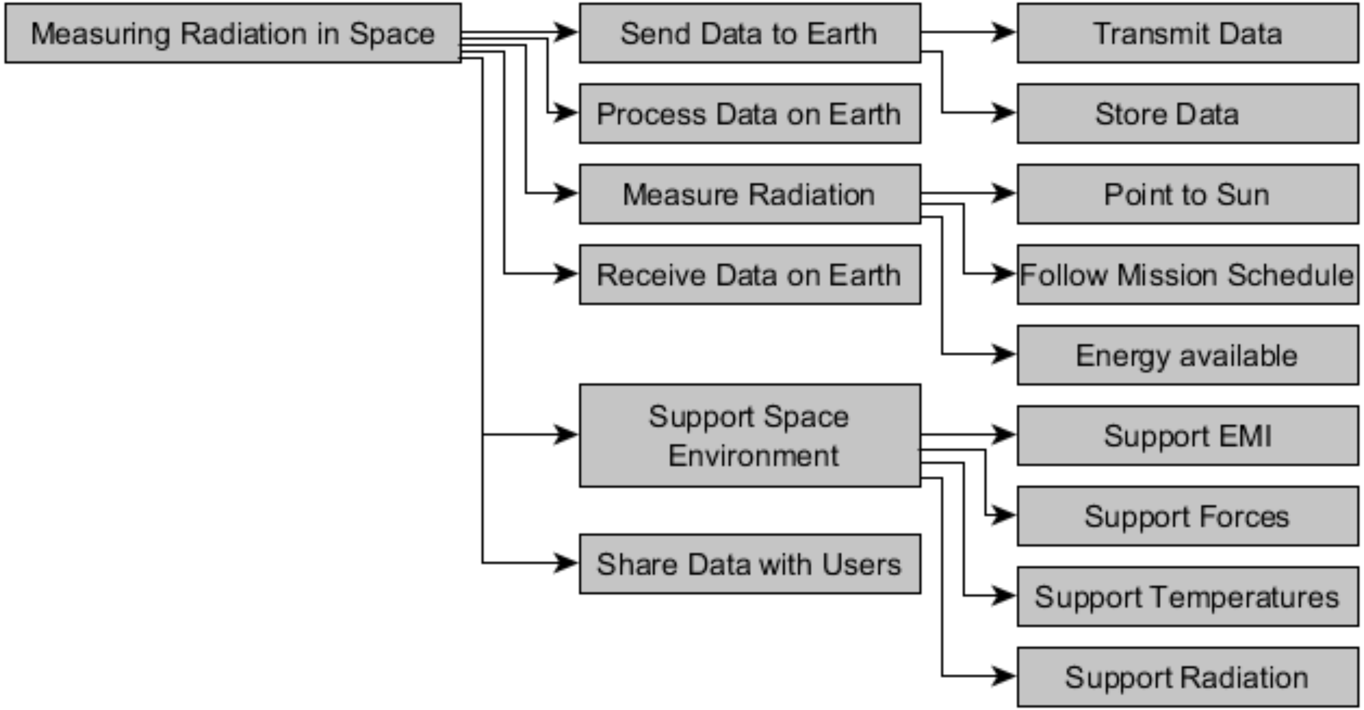


# CAPABILITY REQUIREMENTS



- Once the To-Be Operational Environment is defined, some **capabilities** that the system must comply with come to light.
- Further, those capabilities can be **unfolded** to identify more capabilities that are required in order to successfully attend the mission.
- Capabilities are later translated as **requirements**.

# CAPABILITY REQUIREMENTS

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# PRIMARY CONSTRAINTS



- Primary constraints are legacy operational and support resources, as well as systems and infrastructure and limits on performance (Larson et al, 2009).
- These are also translated later as **requirements**.

# PRIMARY CONSTRAINTS



| Constraint | Description |
|---|---|
| Infrastructure | Existing INPE facilities shall be used. |
| Standards | Existing manufacturing, assembly and testing standards from INPE shall be used. |
| Precision | Maximum measurement precision of 300 ppm shall be achieved. |
| Stability | Maximum measurement deviation of 10 ppm/year shall be achieved. |

# CONCEPTS OF OPERATIONS

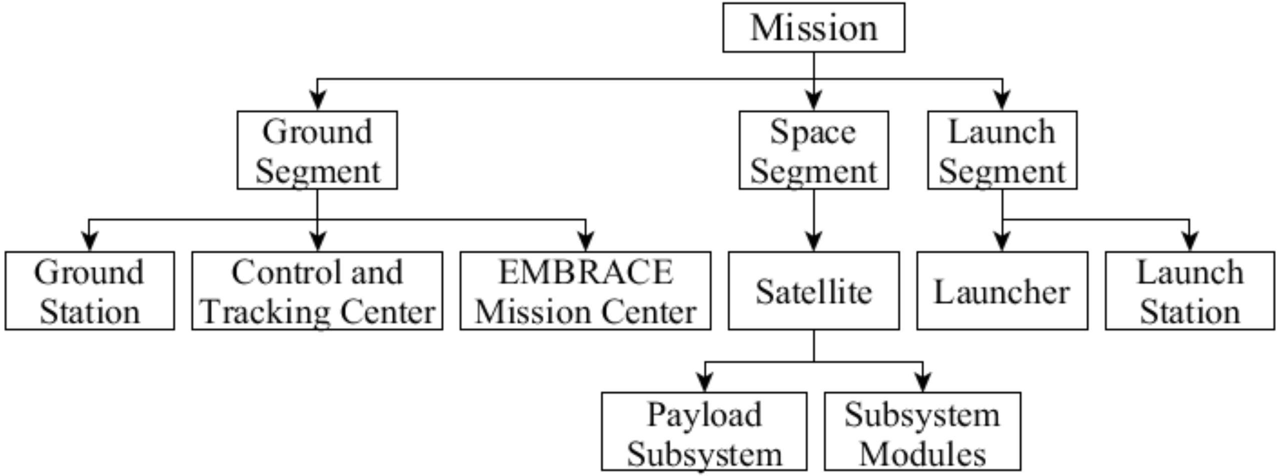


- Alternative concepts of operations for the space segment:
  - Low Earth Orbit (LEO)
  - Geostationary Orbit (GEO)
  - Sun-Synchronous Orbit (SSO), which is a kind of a LEO where the satellite orbital plane remains approximately fixed with respect to the Sun.
- After a trade-off considering the time that the satellite would have line of sight to the Sun, the lifetime and the launch cost, the **SSO was chosen**.

# SYSTEM OPERATIONAL ARCHITECTURE



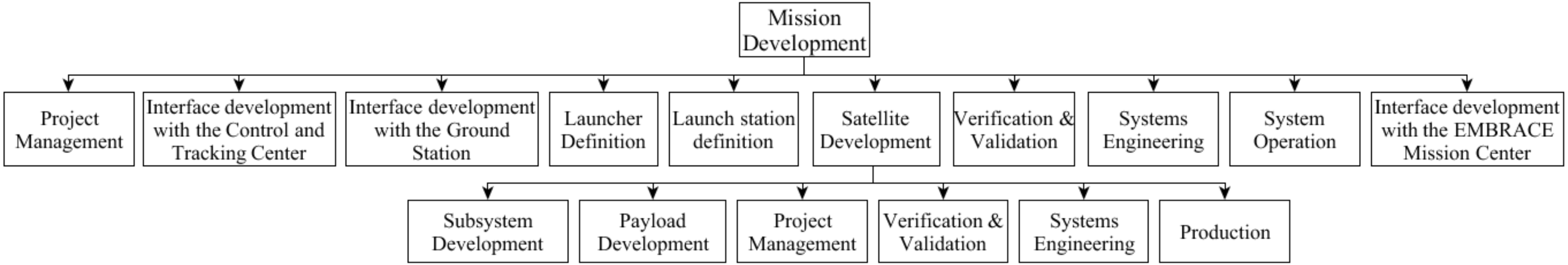
- **Product Breakdown Structure (PBS)** at MISSION level shows the elements of the mission):



# SYSTEM OPERATIONAL ARCHITECTURE



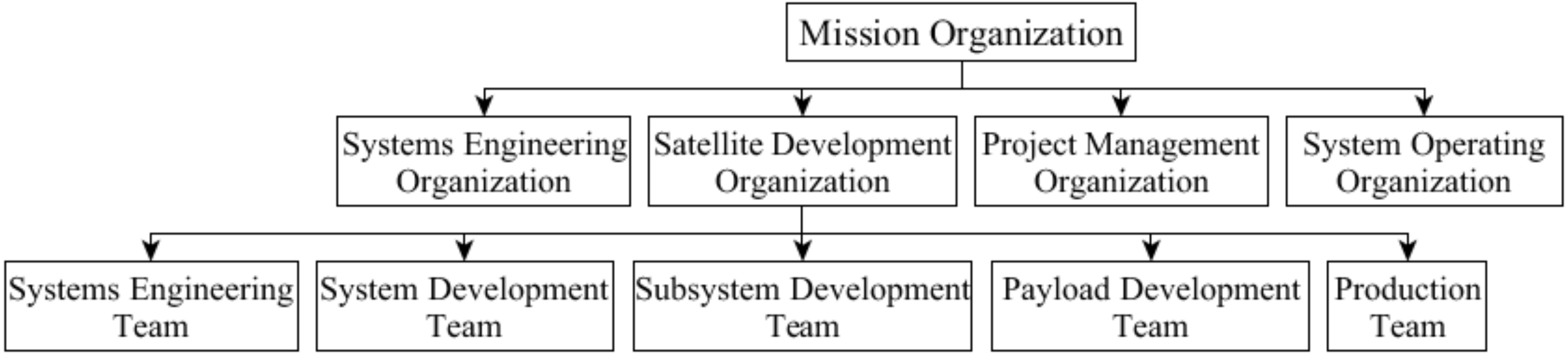
- **Work Breakdown Structure** (WBS) shows the work or activities that must be done to develop the mission:



# SYSTEM OPERATIONAL ARCHITECTURE



- **System Breakdown Structure** (SBS) shows how the organization developing the mission is divided in order to perform different tasks of the WBS:



# SYSTEM OPERATIONAL ARCHITECTURE

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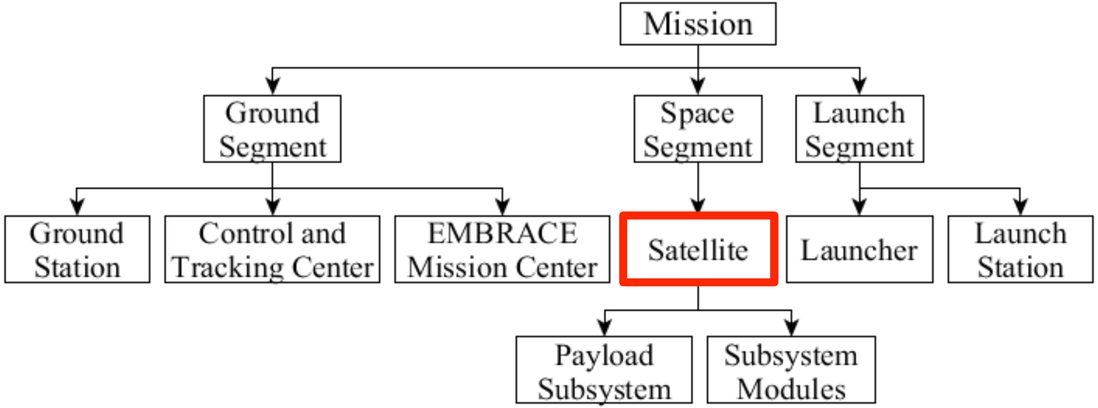
- Once the mission and its elements are clear, the **System of Interest** (SoI) should be chosen.
- The SoI represents the element that is object to development. In this case, the **SATELLITE** was chosen as SoI.



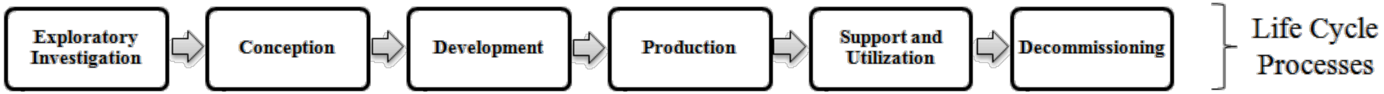
PHASE 2:

# LIFE CYCLE PROCESSES

# LIFE CYCLE PROCESSES



- The life cycle of a system is a description of all the characteristic stages of evolution experienced by the system during its "life".



# LIFE CYCLE PROCESSES



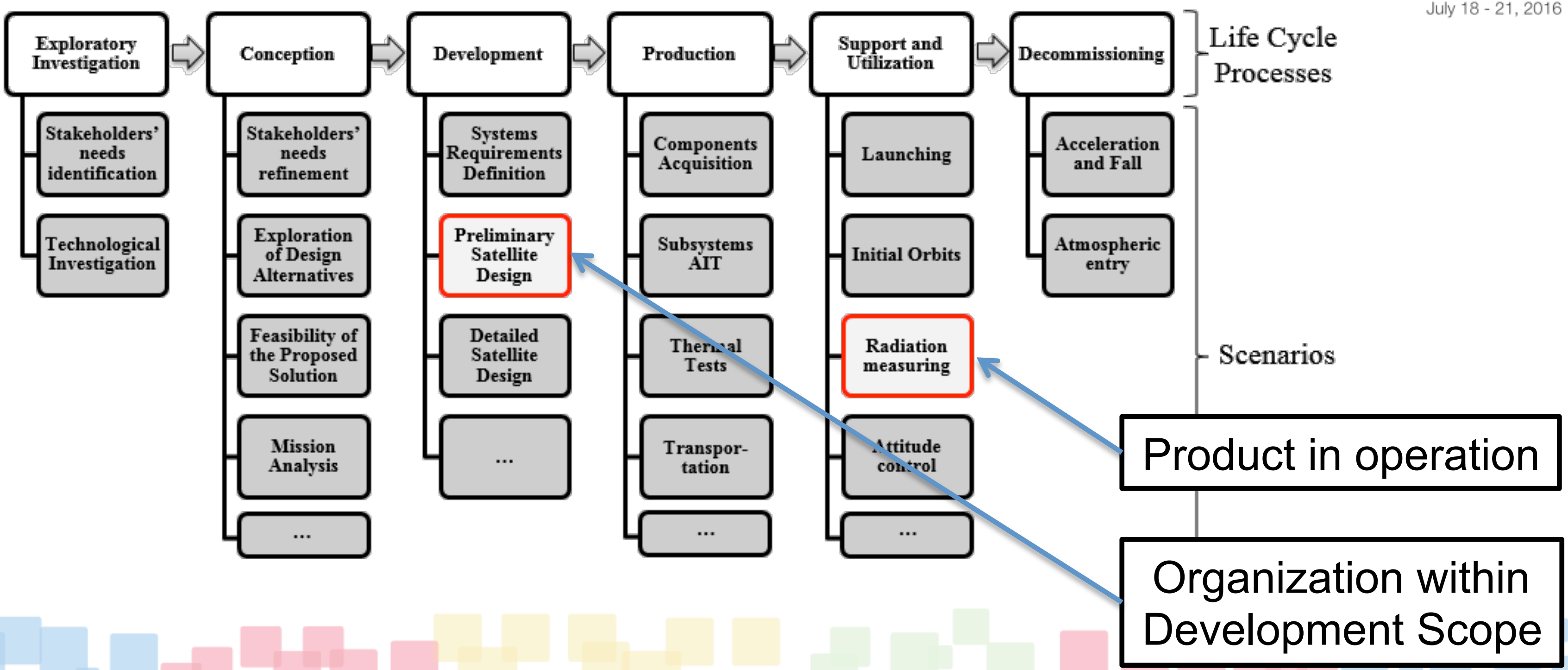
- Due to the parallel application of SE to the product and the organization, four types of scenarios exist:

| Product Scenarios | Organization Scenarios |
|---|---|
| Product in Operation | Organization within Development Scope |
| Product out of Operation | Organization out of Development Scope |

- Two particular scenarios were selected to illustrate the CSA SE method application in next phases.

# LIFE CYCLE PROCESSES

- Selected scenarios:



PHASE 3:

# STAKEHOLDER ANALYSIS

# IDENTIFICATION AND CONCERNS

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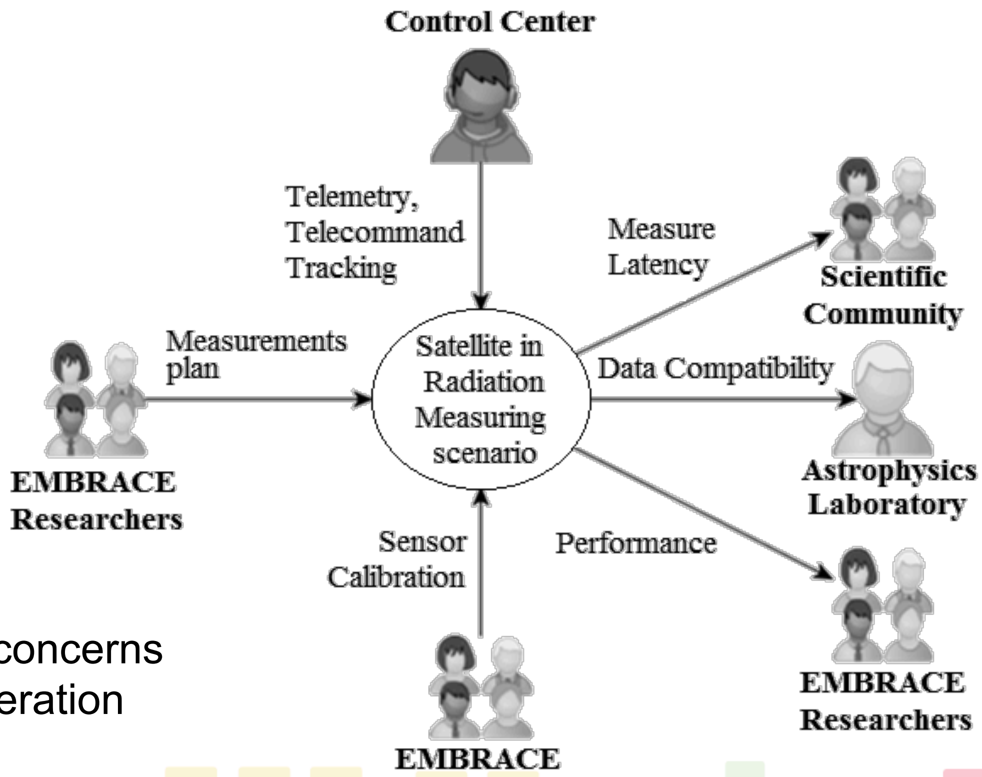
- Determination of the stakeholders of the SoI and its organization.
- The same questions used to discover the initial stakeholders are now asked for each selected scenario of the life cycle processes:
  1) Who are the sources of inputs?
  2) Who are the receivers of outputs?
  3) Who are the sources of control or the control themselves?
  4) Who are the sources of mechanisms or the mechanisms themselves?
- Stakeholder worries, wishes, desires, goals and wants are investigated and become stakeholder CONCERNS.

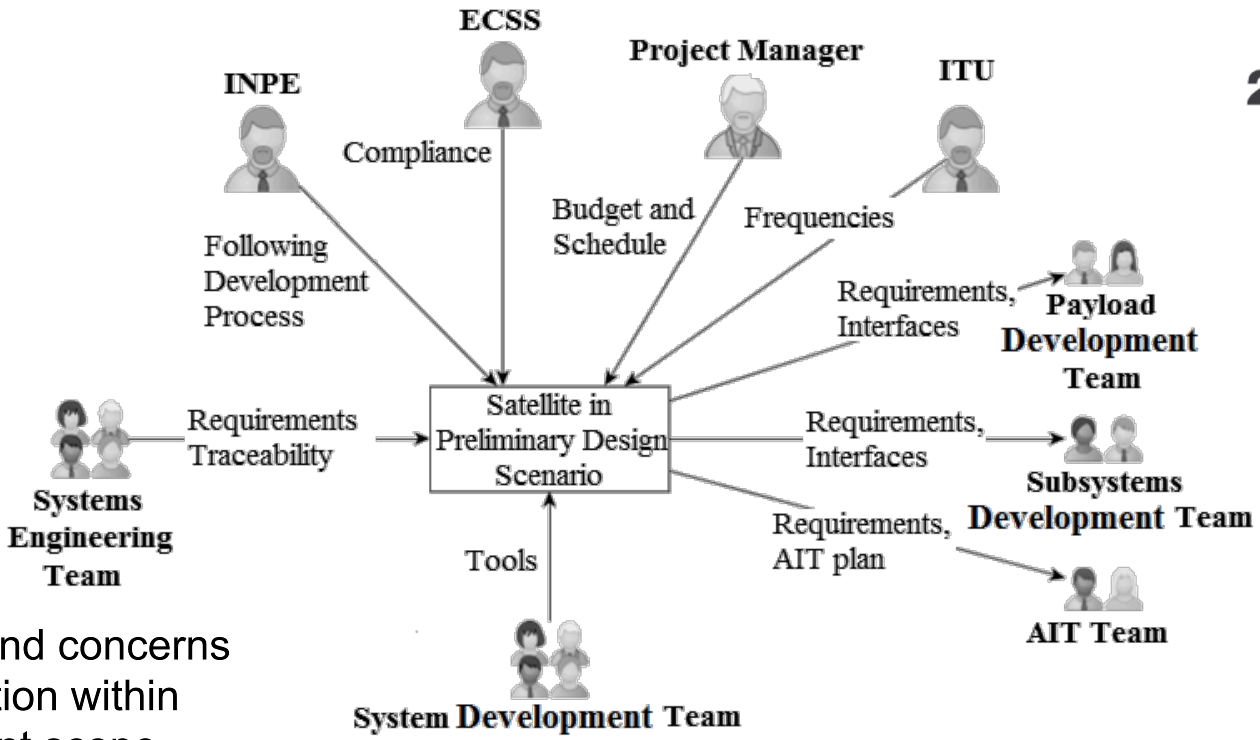
# IDENTIFICATION AND CONCERNS




Stakeholders and concerns for product in operation scenario

# IDENTIFICATION AND CONCERNS

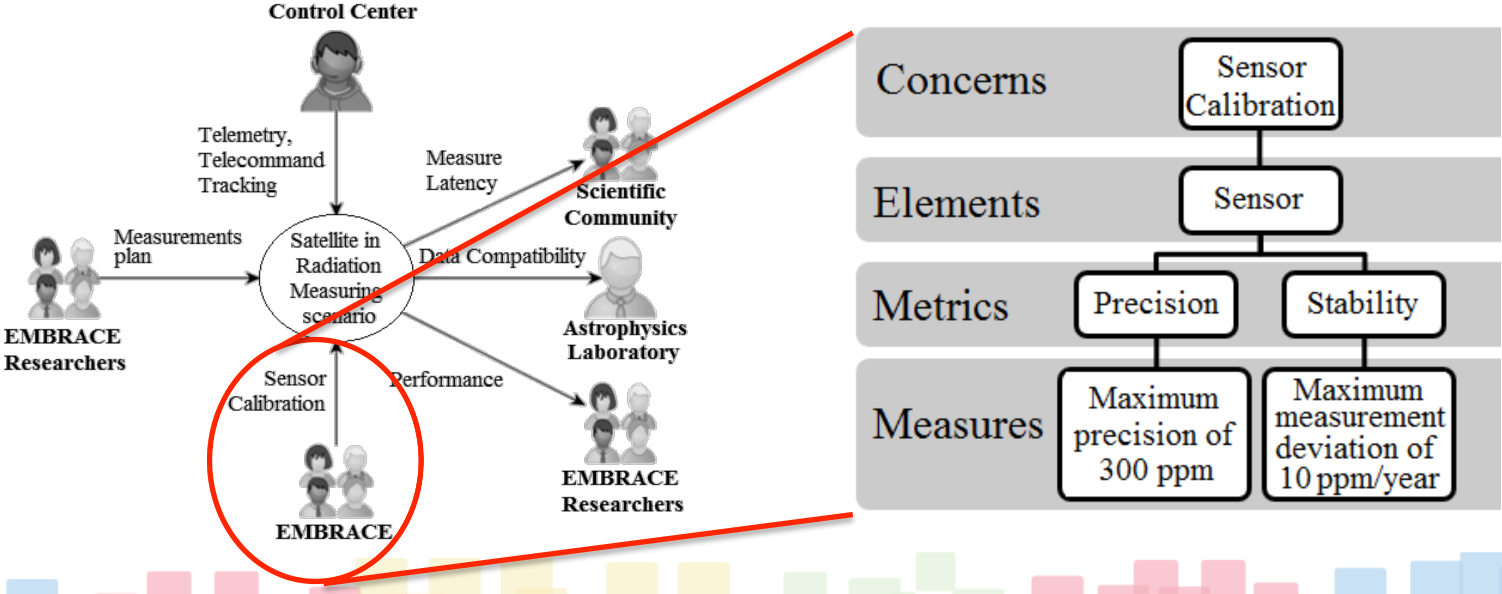





Stakeholders and concerns for organization within development scope scenario

# MEASURES OF EFFECTIVENESS

- The adapted GQM (Goal-Question-Metric) method was applied to the stakeholder concerns of the two selected scenarios, resulting in a list of Measures of Effectiveness (MoEs).



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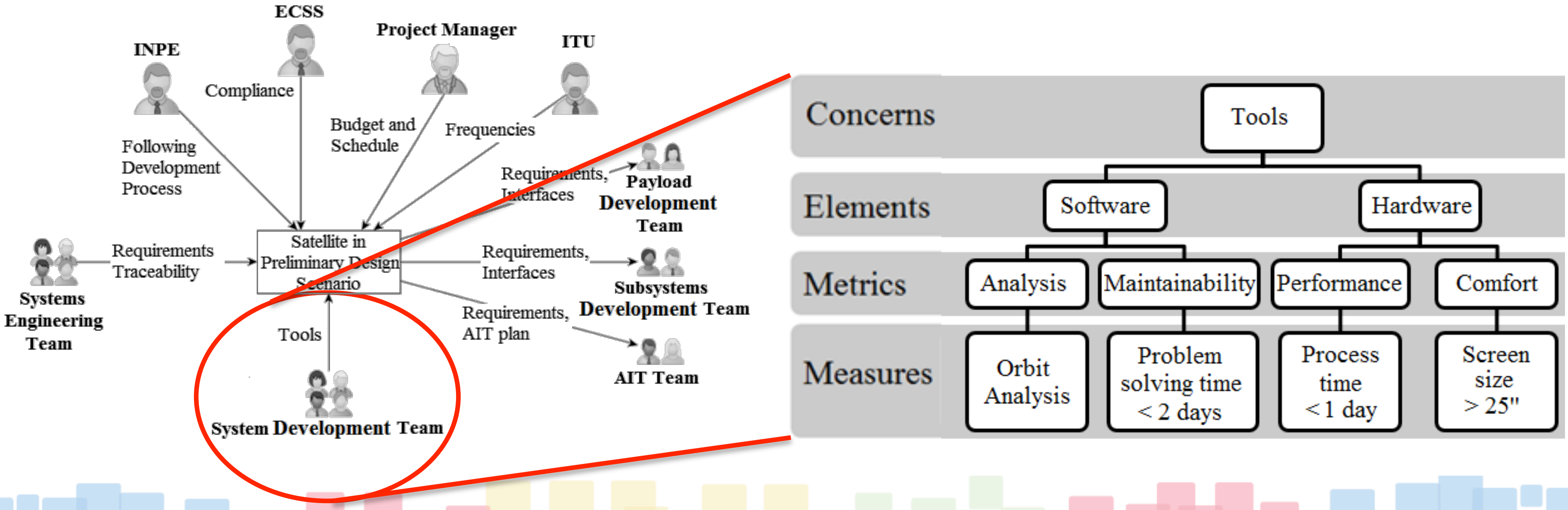

PHASE 4:

# REQUIREMENTS ANALYSIS

# REQUIREMENTS ANALYSIS

- Once the MoEs for the stakeholders' concerns are identified, the next step is to perform a **Requirements Analysis** to define the **Stakeholder and the System Requirements**.

- Stakeholder CONCERNS are translated into stakeholder REQUIREMENTS: what does the STAKEHOLDER (not the system) needs to accomplish?

| Stakeholder Requirement # | Stakeholder | Concern | Stakeholder Requirements |
|---|---|---|---|
| 01 | EMBRACE | Sensor calibration | EMBRACE shall be able to regulate the solar radiation measurement precision when the satellite is in normal operation mode. |
| | | | EMBRACE shall be able to regulate the solar radiation measurement stability when the satellite is in normal operation mode. |

| Stakeholder Requirement # | Stakeholder | Concern | Stakeholder Requirements |
|---|---|---|---|
| 02 | System Development Team | Tools ready for use | The System Development Team shall be able to develop the satellite with the software and hardware supplied by the organization responsible for the preliminary satellite design. |



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# REQUIREMENTS ANALYSIS

- STAKEHOLDER requirements are then translated into one or more SYSTEM requirements: functionalities of the system needed to satisfy the stakeholder requirements.

| System Req. # | System Requirements |
|---|---|
| 01.1 | The satellite shall be able to modify its internal parameters, through telecommands received from the ground stations, so that the solar radiation measurement has the required precision, when the satellite is in normal operation mode. |
| 01.2 | The satellite shall be able to modify its internal parameters, through telecommands received from the ground stations, so that the solar radiation measurement has the required stability, when the satellite is in normal operation mode. |

| Organiz. Req. # | Organization Requirements |
|---|---|
| 02.1 | The organization responsible for the Preliminary Satellite Design shall deliver to the System Development Team a hardware which is capable of simulating, in less than 1 day, all the satellite orbits traveled in 1 year. |
| 02.2 | The organization responsible for the Preliminary Satellite Design shall deliver to the System Development Team a hardware a with screen size not less than 25". |

PHASE 5:

# FUNCTIONAL ANALYSIS

# FUNCTIONAL ANALYSIS

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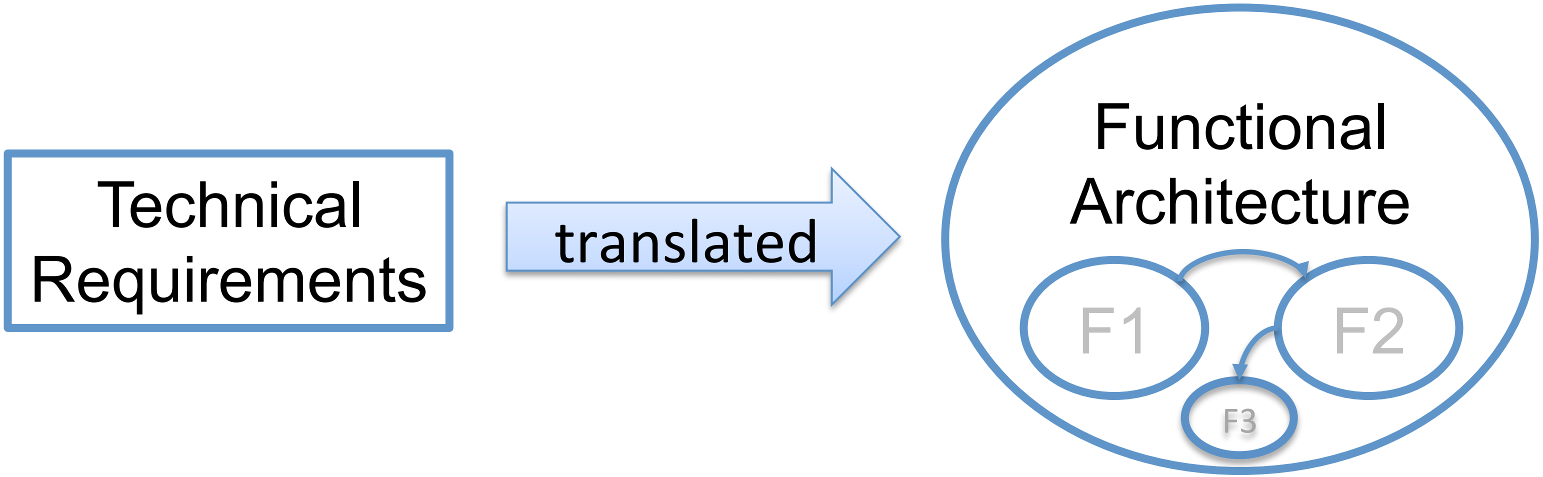
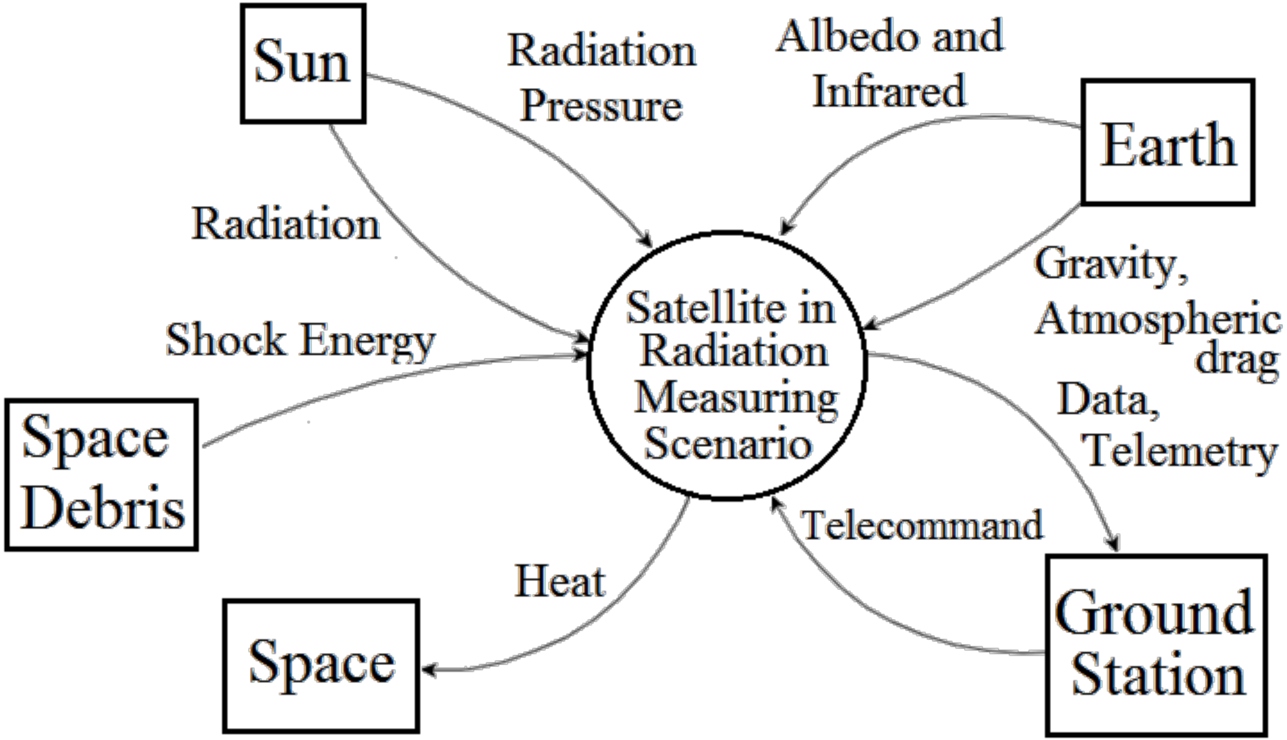
## Functional Analysis



# CONTEXT ANALYSIS

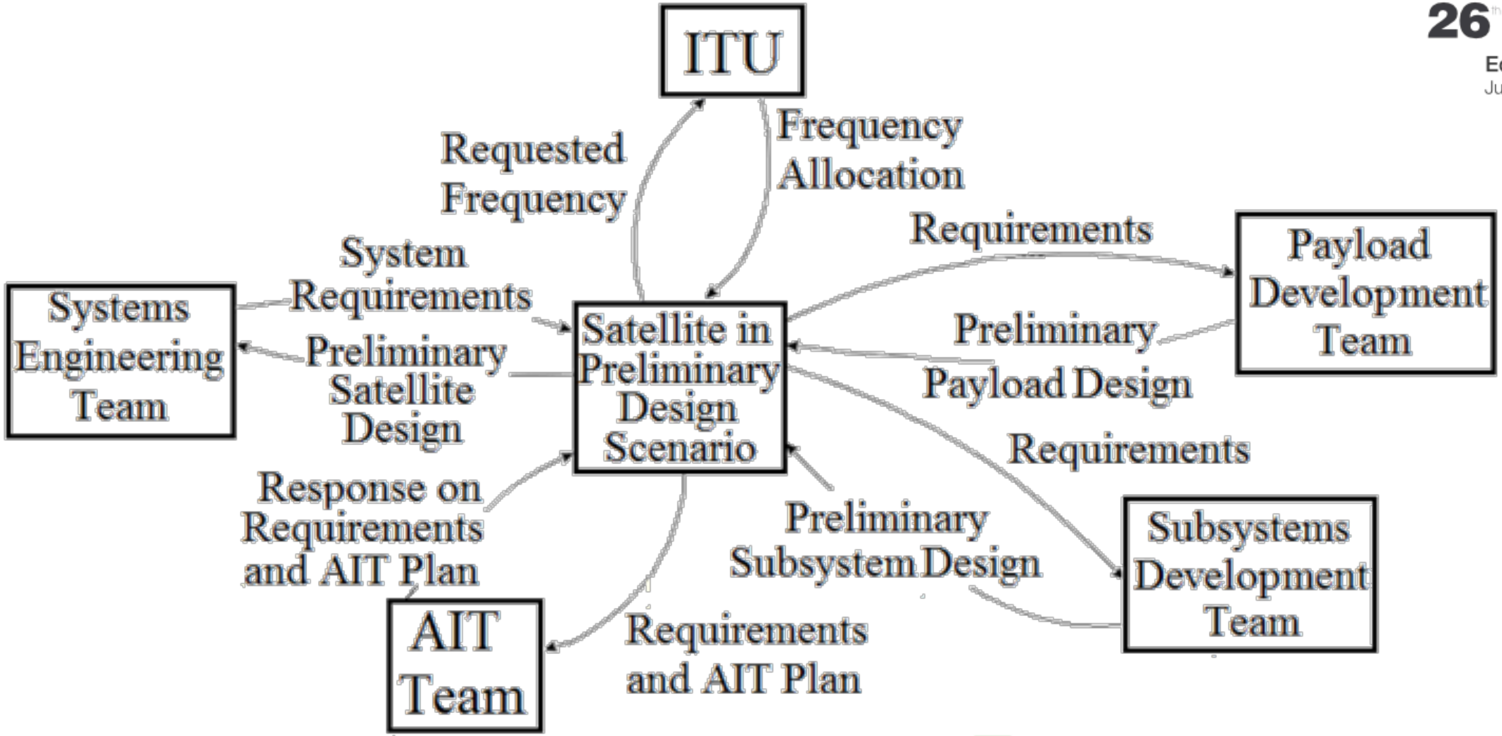
- Defines what is **within** the system and what is **outside**.
  - **Primary functions** of the system are stated.
  - **Elements in the environment** interacting with the system are identified.
- System **external functional interfaces** are identified.
- Functional interfaces are characterized by the **data, energy and material** crossing the boundaries of the system.

# CONTEXT ANALYSIS



# CONTEXT ANALYSIS



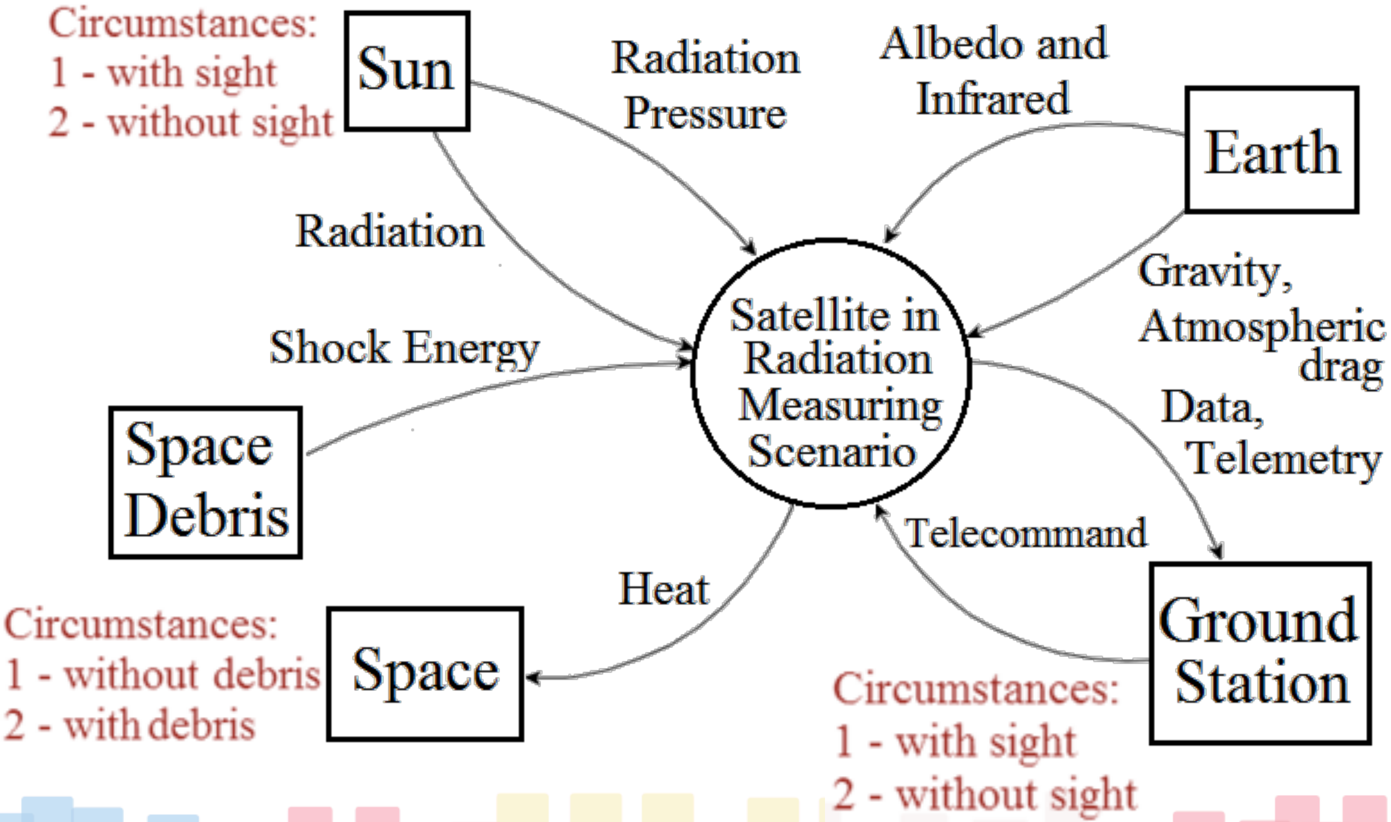


# CIRCUMSTANCES ANALYSIS



- CIRCUMSTANCES:
  - Combinations of the possible values of the attributes of the elements in the environment.
  - Flows in the context of the system.

# CIRCUMSTANCES ANALYSIS



# CIRCUMSTANCES ANALYSIS

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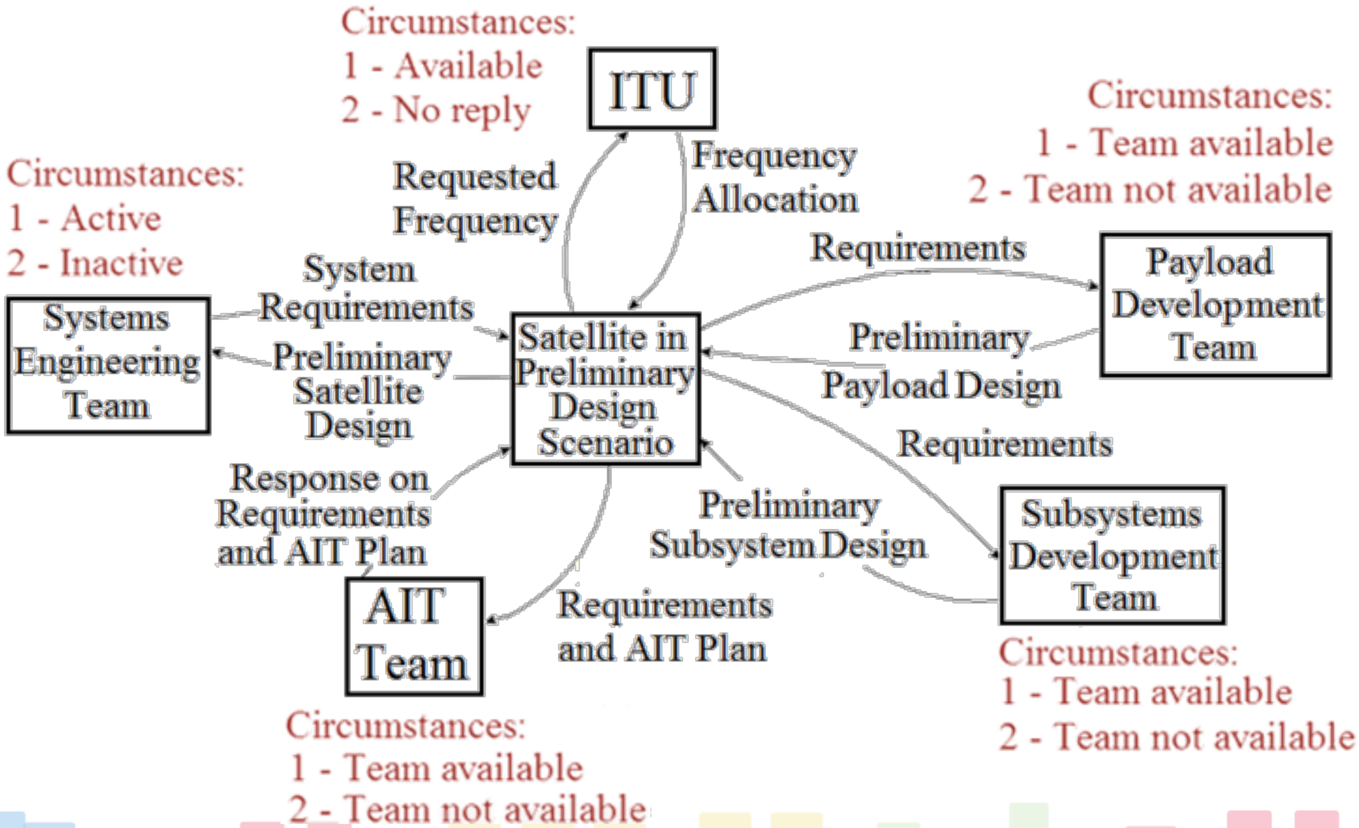

# MODES

- From the circumstances previously presented, some MODES of the system could be identified.
- Every mode represents a particular arrangement or condition.

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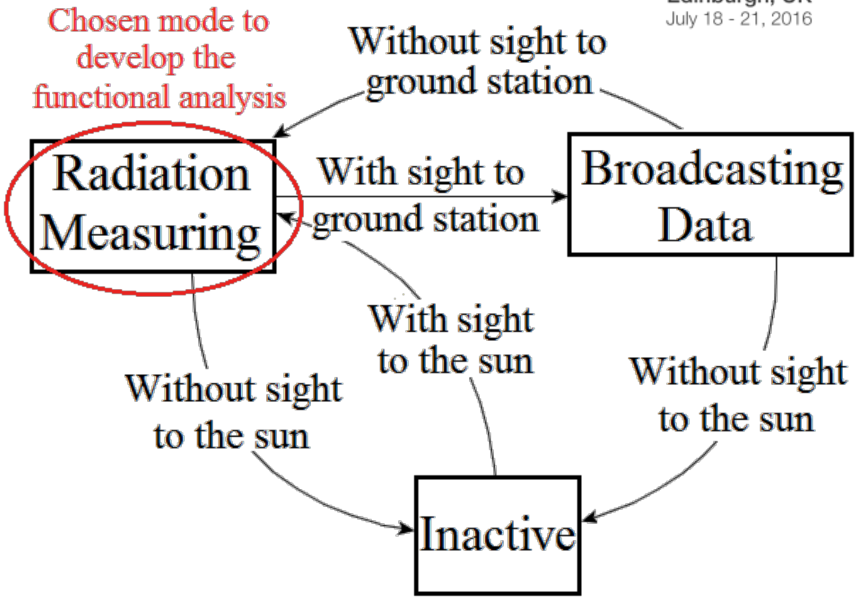
# MODES TRANSITION DIAGRAM

| **Modes** | **Circumstances** | |
|---|---|---|
| | *Sight with the Sun* | *Sight with ground stations* |
| Measuring | Yes | No |
| Broadcasting | Yes | Yes |
| Inactive | No | - |



# MODES OF THE ORGANIZATION



| Mode | Circumstances | | | | |
|---|---|---|---|---|---|
| | *SE team* | *AIT team* | *Subsystem development team* | *Payload development team* | *ITU* |
| Normal | Active | Available | Available | Available | Available |
| Delayed | Active | Any of them delayed (or without reply) | | | |
| Inactive | Inactive | - | | | |

# EVENTS AND ESSENTIAL FUNCTIONS



- From the **flows** between the **system** and the **organization** with their correspondent **environments**, several **events** can be identified.

- **Essential system functions** can be determined from the correlation between any **event in the environment** with **system functions**.

# EVENTS AND ESSENTIAL FUNCTIONS

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| X (environment) | Y (satellite) |
|---|---|
| The Sun emits energy (radiation) | Transforms the solar energy into energy usable by it |
| The Sun emits energy (radiation) | Measures the solar irradiation |
| The Earth emits albedo and IR energy | Measures the absorbed energy coming from the Earth |
| Space absorbs heat | Expels heat and measures it |

# EVENTS AND ESSENTIAL FUNCTIONS



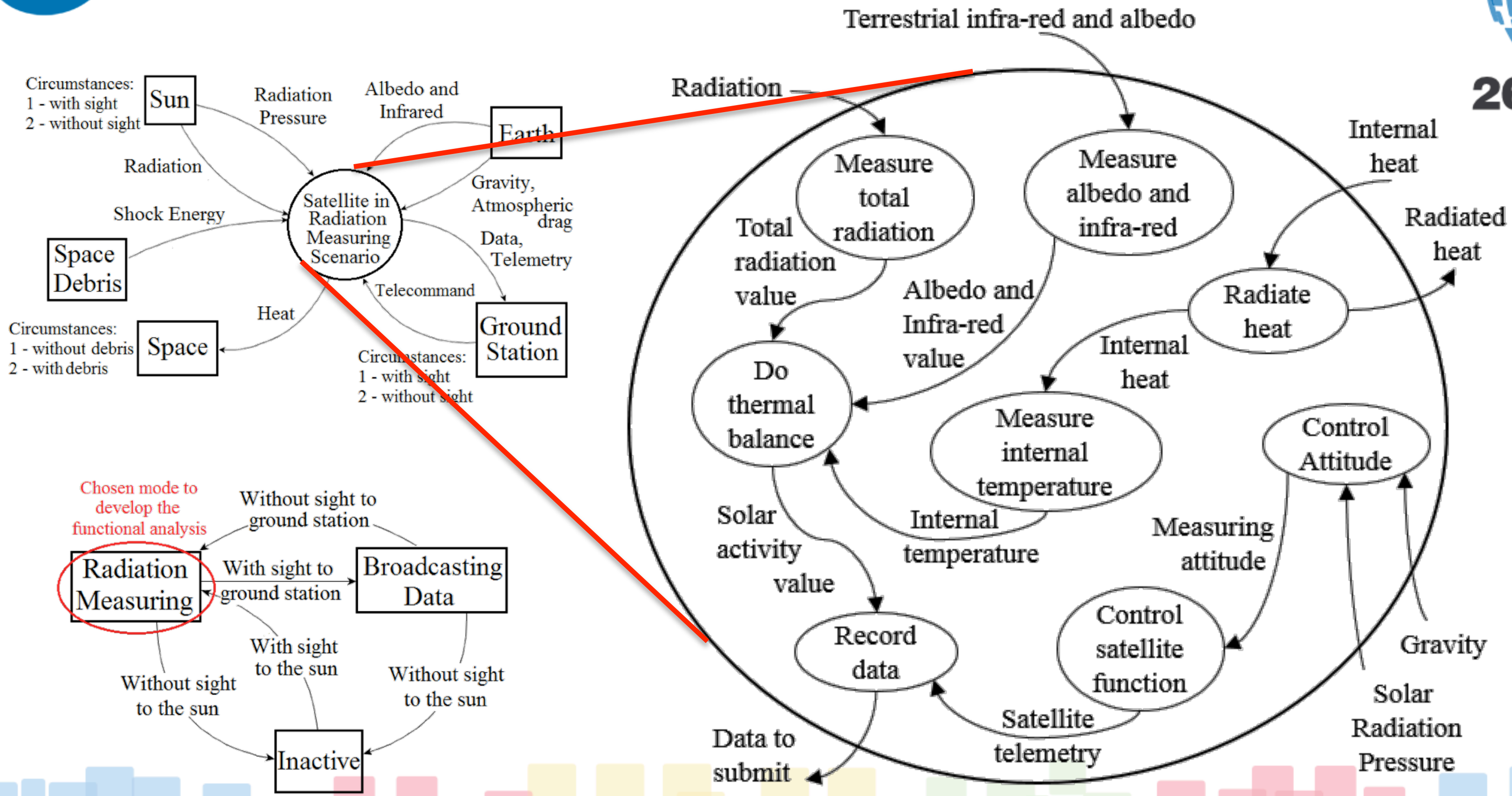
| X (environment) | Y (organization) |
|---|---|
| SE team delivers system requirements | Receives system requirements |
| ITU receives frequency request | Sends frequency request |
| ITU sends frequency allocation | Receives frequency allocation |
| AIT team receives AIT requirements and plan | Sends AIT requirements and plan |
| AIT team sends response of AIT requirements and plan | Receives response of AIT requirements and plan |
| Payload development team receives payload requirements | Sends payload requirements |
| Subsystems development team receives subsystems requirements | Sends subsystems requirements |
| Payload development team sends preliminary payload design | Receives preliminary payload design |
| Subsystems development team sends preliminary subsystems design | Receives preliminary subsystems design |
| SE team receives preliminary satellite design | Delivers preliminary satellite design |

# FUNCTIONAL STRUCTURE AND BEHAVIOR



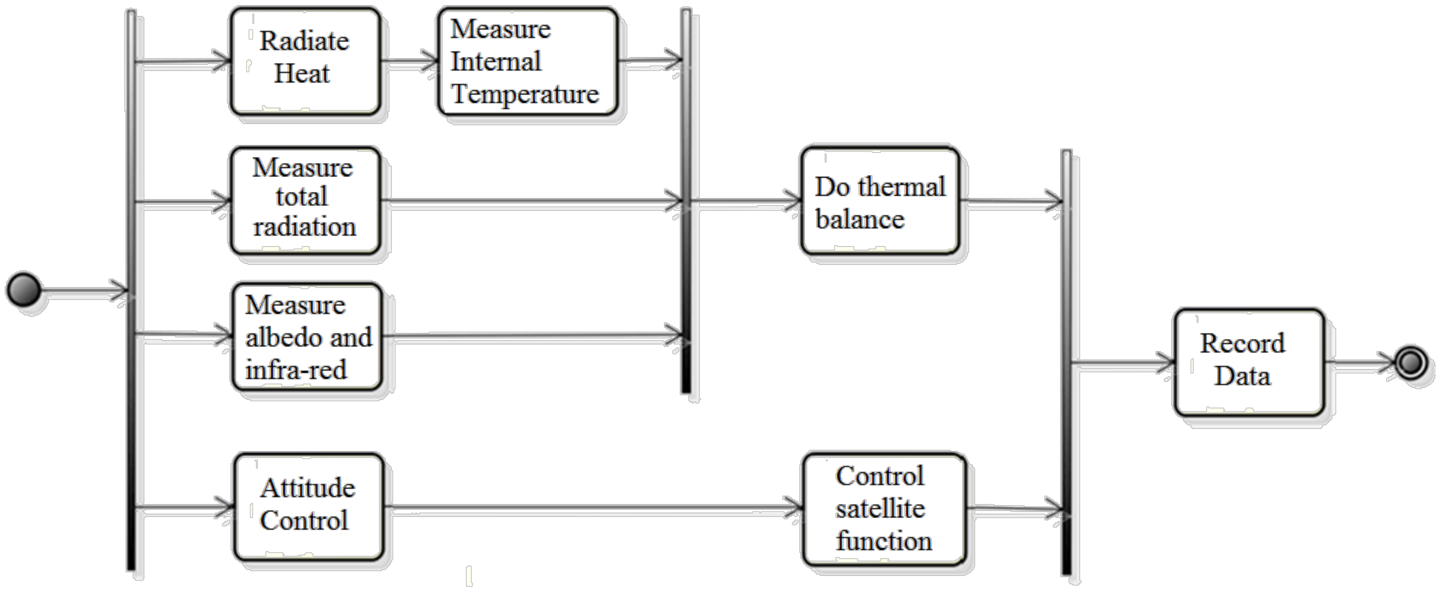
- From essential functions, other functions are added in order to provide the necessary inputs to the already identified functions.
- The relation within those functions is **structural** and **behavioral**:
  - STRUCTURAL relations are the energy, information and material that flow from one function to another.
  - BEHAVIORAL relations are the time relationships, the control flows, the transitions, modes, states, among others.

# PRODUCT FUNCTIONAL STRUCTURE

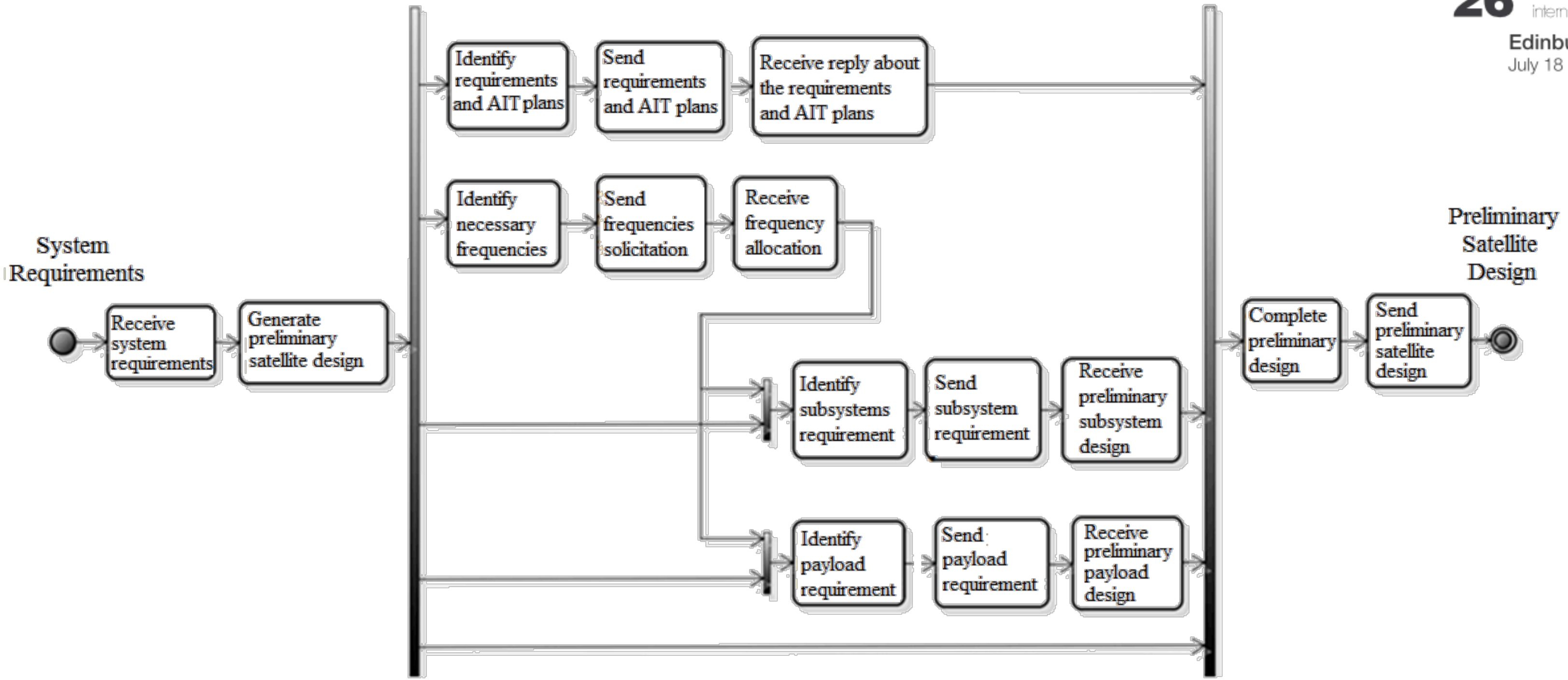


# PRODUCT FUNCTIONAL BEHAVIOR

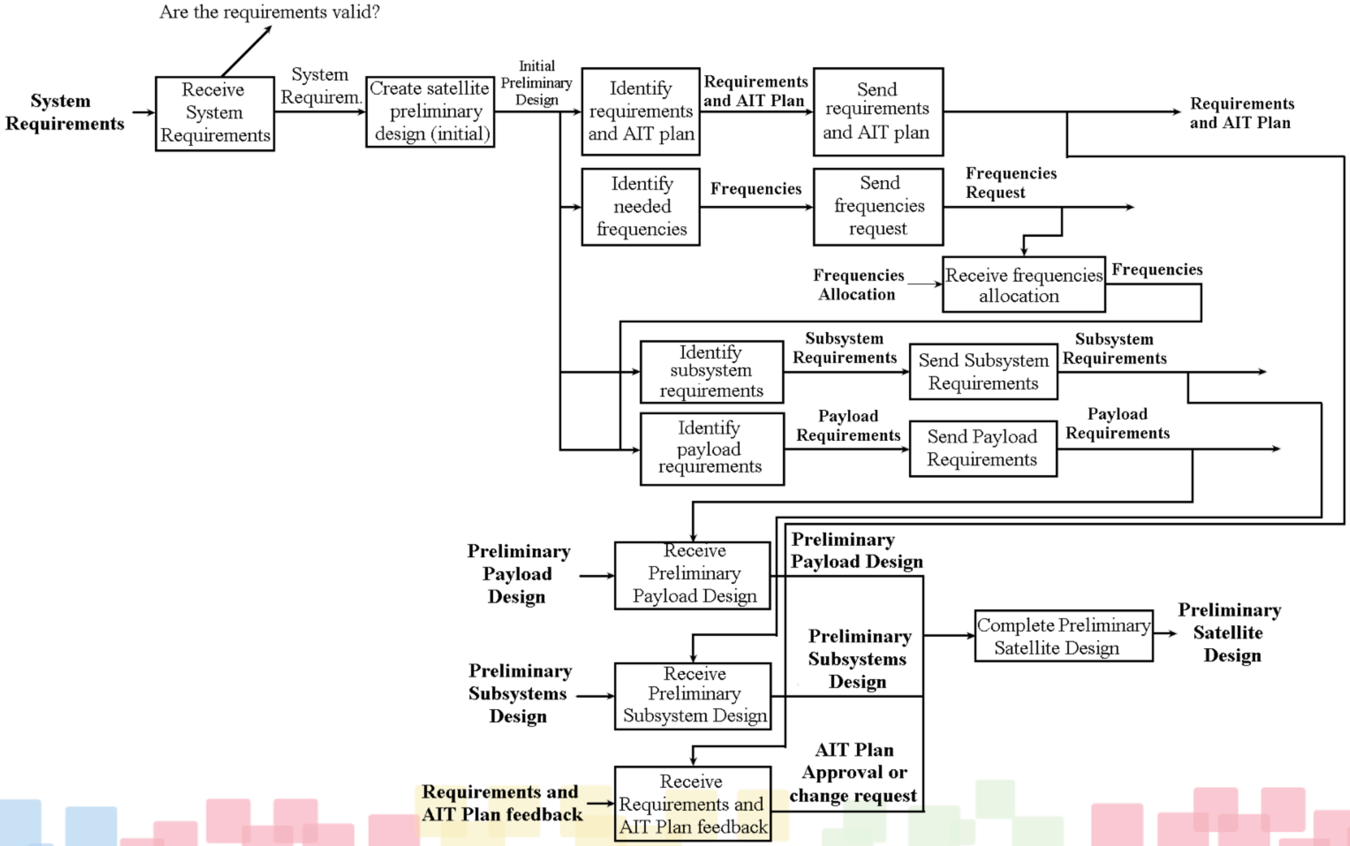




# ORGANIZATION FUNCTIONAL BEHAVIOR



# ORGANIZATION FUNCTIONAL STRUCTURE

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# HAZARD AND RISK ANALYSIS

- Finally, a hazard and risk analysis could be performed to identify additional detection, prevention, protection or correction functions.

PHASE 6:

# PHYSICAL ANALYSIS

# PHYSICAL ANALYSIS

- The physical analysis process identifies the **components** and their **interfaces** and defines the **physical architecture** of the product.

- In this work, the physical analysis process as proposed by Loureiro (1999) consists of describing the **product** and the **organization** in terms of physical constituents which can be later developed, reused or bought for creating the **whole system**.

# PHYSICAL ANALYSIS



- Physical analysis aims to identify the component elements of:
  - Physical architecture of the product.
  - Product life cycle processes.
  - Organizations deploying the life cycle processes.
  - Interactions among these elements.
  - Attributes that characterize each element and interaction.

# GENERIC ARCHITECTURE



- The generic architecture identifies the physical elements for a system without specifying the performance characteristics of the physical resources that compose each element.

- It’s a "Reference" or "Platform" architecture.

# GENERIC ARCHITECTURE

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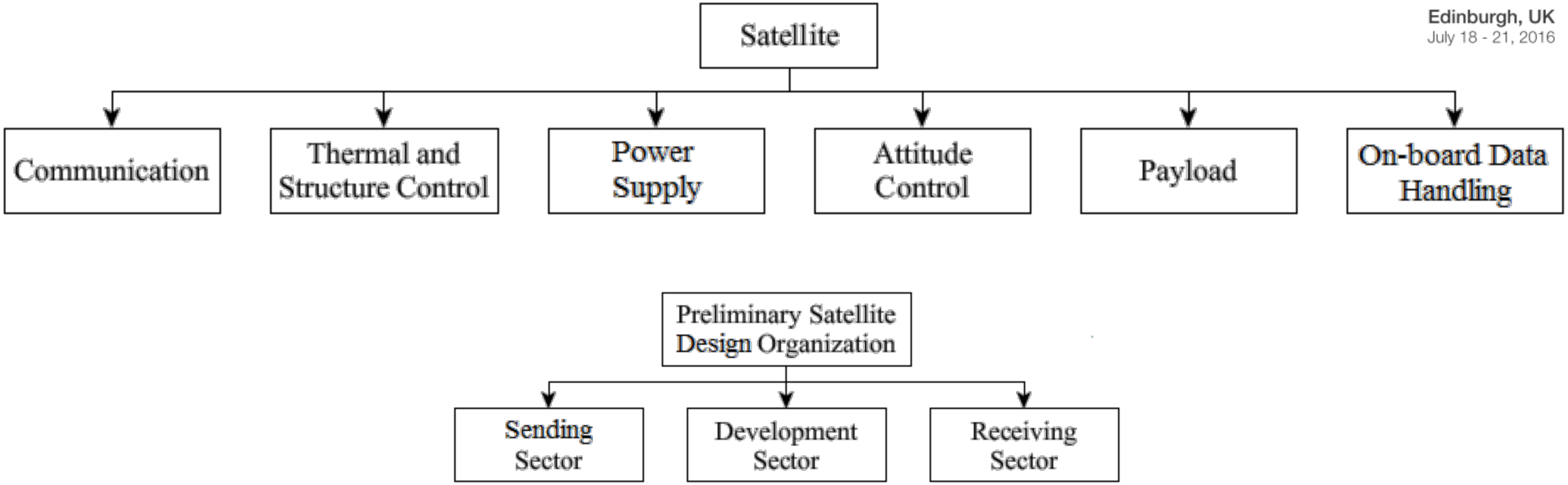

# FUNCTIONAL ALLOCATION



- Each function in the functional architecture must be allocated to the components in the physical architecture.
- Every function must be performed by only one component, while a component could perform one or more functions.

# PRODUCT FUNCTIONAL ALLOCATION



| | On-board data handling | Payload | Thermal and Structure Control | Power Supply | Commu-nication | Attitude Control |
|---|---|---|---|---|---|---|
| Measure total radiation | | x | | | | |
| Measure albedo and infrared | | x | | | | |
| Radiate heat | | | x | | | |
| Control attitude | | | | | | x |
| Control the satellite function | x | | | | | |
| Record Data | x | | | | | |
| Measure internal temperature | | | x | | | |
| Do Thermal Balance | x | | | | | |
| Supply power | | | | x | | |
| Data transmission | | | | | x | |

# ORGANIZATION FUNCTIONAL ALLOCATION



| | Receiving Sector | Development Sector | Sending Sector |
|---|---|---|---|
| Identify requirements of the subsystems | | x | |
| Send requirements of the subsystems | | | x |
| Receive preliminary design of subsystems | x | | |
| Identifying payload requirements | | x | |
| Send payload requirements | | | x |
| Receive preliminary payload design | x | | |
| Complete preliminary design | | x | |
| Send preliminary satellite design | | | x |

# SOLUTION IDENTIFICATION



- Several **generic components** were identified in the generic architecture of the product, so **alternatives** for those components were listed in a morphological chart.

| Power Supply | Thermal and structure control | Communication | On-board Data Handling | Payload | Attitude Control |
|---|---|---|---|---|---|
| Only Primary Battery | MLI (insulation) | UHF | Qualified on-board computer | 1 Sensor | Star Sensor |
| Photovoltaic | Painting | S-Band | Unqualified on-board computer | 2 Sensors (Primary and Secondary) | Sun Sensor |
| Photovoltaic + Battery | Radiator | X-Band | ARM Architecture | | Magnetometer |
| | Thermodynamic cycles | | | | Gravity Gradient Pendulum |

# SOLUTION IDENTIFICATION

- Alternatives for the SoI were generated from those components of the morphological chart.

| Elements | Alternative 1 | Alternative 2 | Alternative 3 |
|---|---|---|---|
| Power Supply | Only Primary Battery | Photovoltaic | Photovoltaic + Battery |
| Thermal and structure control | MLI (insulation) and aluminum structure | Painting on aluminum structure | Thermodynamic cycles + aluminum structure |
| Communication | S-Band | UHF | X-Band |
| On-board Data Handling | ARM Architecture | Unqualified on-board computer | Qualified on-board computer |
| Payload | 1 Sensor | 2 Sensors (Primary and Secondary) | 2 Sensors |
| Attitude Control | Sun Sensor | Gravity Gradient Pendulum | Star Sensor |

# SOLUTION IDENTIFICATION

- Next step: select a method to **evaluate alternatives**.
- An evaluation method based on the additive model of Philips (1984) was chosen.
- Parameters used: cost, development time, development ease, lifetime and availability.

| Objective | Score | Alternative 1 | Alternative 2 | Alternative 3 |
|---|---|---|---|---|
| Cost | 40% | 8,0 | 9,0 | 5,0 |
| Development Time | 10% | 9,0 | 7,5 | 7,0 |
| Development Facility | 10% | 8,5 | 8,5 | 6,0 |
| Lifetime | 30% | 5,0 | 7,5 | 8,0 |
| Availability | 10% | 8,0 | 7,5 | 9,0 |
| Sum | 100% | 72,5% | **82%** | 66% |

Selected Alternative



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# FINAL ARCHITECTURE BLOCK DIAGRAMS



- SE method allowed the decompositon of the mission into elements, where the satellite was selected as SoI.
- The satellite was decomposed into several subsystems and elements.
- These elements could be obtained in four different ways:
  - Internally developed.
  - Externally developed.
  - Reused from other missions.
  - Bought as Commercial-Off-The-Shelf (COTS) items.

# FINAL ARCHITECTURE BLOCK DIAGRAMS

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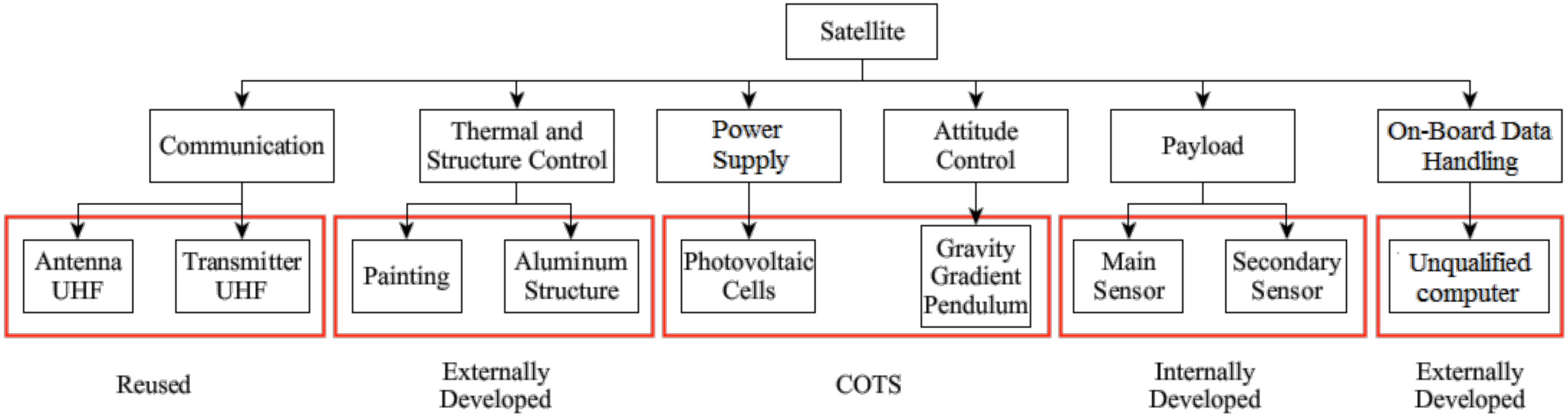

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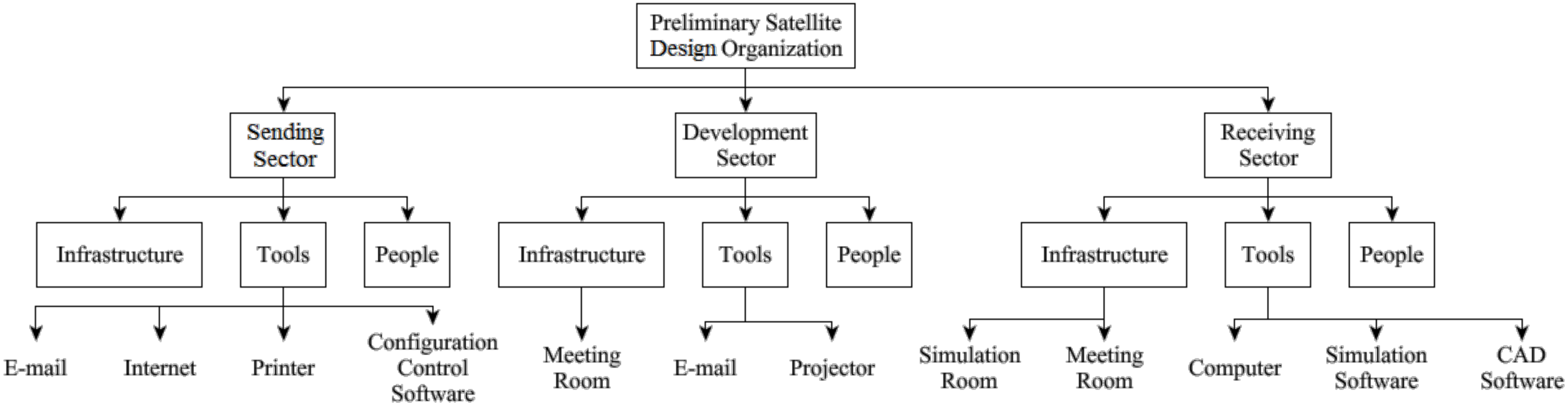

# CONCLUSIONS



- The application of CSA method enabled the **understanding of the real problem**, which was obtaining measures of solar activity and its relations to climate change on Earth.
- The application of the method allowed the development to **evolve from a real need** to a **product architecture** that would fulfill that need.
- It also allowed the **organization** to identify what would be its architecture and the activities that it must perform.

# CONCLUSIONS

- Even when only two scenarios were detailed described, the CSA method was understood and its concepts were successfully applied to those scenarios.

- For a real application, this method should be **applied to the remaining scenarios** in order to have a complete architecture of the satellite and of the organizations related to each life cycle process.

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# THANK YOU!

INPE