13º WETE
16, 17 e 18 de novembro de 2022
13º Workshop em Engenharia e Tecnologia Espaciais

Systems Concurrent Engineering Approach into the Concept Design of an Optical Relay Satellite

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Abstract. *This document proposes a methodology for developing space systems, demonstrated by application in an LCRS (Laser Communication Relay Satellite) system as a study case. It consists of modeling product and organization elements and their interactions early in the development process by use of concurrent engineering and systems engineering in an integrated manner. In this sense, it is necessary to conduct an analysis of the stakeholders, requirements, functions, and implementation of the architecture, simultaneously, for the elements of the product and of the organization to the processes of the life cycle at all levels of the hierarchical structure of the LCRS system. The conceptual design in this approach comprises 6 phases: mission analysis, life cycle process, stakeholder analysis, requirements, functional analysis, and physical architecture. Uses for the results include an initial feasibility assessment, cost analysis, and energy and data balance simulations, besides constituting a basis for the detailed design.*

Keywords: Optical Communication; Concurrent Engineering; Systems Engineering; Concept Design

1. Introduction

Satellites have seen increasing data generation onboard with improvements of sensors and cameras (GOLKAR; CRUZ, 2015) at the same time transmission capabilities of radio frequency transmitters cannot further increase data rates without higher mass or power budgets, which are limited by launch costs and solar panel dimensions.

Optical communications, despite their many difficulties, have shown potential for much higher data rates than an RF system with the same mass and energy budgets. Many developments in the field can be found in the last decade, including several in-orbit tests, such as the Lunar Laser Communication Demonstration (KHATRI et al., 2015), and mitigation techniques addressing low link availability and reliability (KAUSHAL; KADDOUM, 2016). Furthermore, an optical link in space suffices to overcome the majority of the possible problems with this system, making an optical communication relay satellite a promising idea to bring the beginning of widespread use of the technology for regular satellites closer (YASSINE; BRAHA, 2003; CHAN, 2006).

The development of complex systems, such as the relay satellite studied, requires an interdisciplinary approach that accounts for both technological and external factors, such as socio-economic and environmental (YASSINE; BRAHA, 2003). While traditional systems engineering practices focus on the development of the operational product, concurrent engineering is a methodology that anticipates life cycle process requirements to early stages, seeking to optimize the product design considering its context during the whole development (LOUREIRO et al., 2010).

This paper has as its main objective to present the conceptual design of a laser communication relay satellite developed through a concurrent systems engineering methodology, considering some of its life cycle processes. The development process is presented to demonstrate how to apply the methodology and the main advantages of CE, as well as a viable approach to the design of an optical relay system.

2. Methodology

The method used for the development of the project concept is based on concurrent engineering and system engineering practices, following the same approach taken on (LOUREIRO et al., 2010), where the author analyzes different life cycle scenarios for the project, bringing forward information and requirements usually obtained only in later steps, while also incorporating a systemic view with functional and physical analysis.

The method approached in (LOUREIRO et al., 2010) is summarised in Figure 1, where the mission, life cycle processes and scenarios, and the scope of development efforts are used as the input for the structured approach that focuses on requirements elicitation and identification of both system's and organization's functions and initial architecture.

Furthermore, the development is supported by the following four principles of CE observed in (YASSINE; BRAHA, 2003). The iteration principle means that, in this phase of the project, where changes will save more money and time later on than the cost of implementing them in the project, designers should always be testing the design against the requirements and new information to identify necessary modifications. The parallelism principle seeks to shorten the development process, identifying tasks that can be performed simultaneously. This is achieved in this work by separating the life cycle analysis, but should be planned as well for the next steps of the project. The decomposition principle, naturally present in most engineering methodologies, seeks to split the system into relatively independent subsystems, helping with the planning of parallel execution. The stability principle means the project shall focus on accelerating the convergence of the design. Therefore, strategies are adopted to reduce the number of problems created, or design changes, when compared with the capacity of solving these problems and converging the design to an acceptable solution.

The Design Structure Matrix (YASSINE; BRAHA, 2003; BROWNING, 2001) is used at the beginning of the project as a tool to assist in the identification of the parallel tasks and the iteration and dependency between each step of the project. Furthermore, the DSM is a powerful tool to represent the project and manage its complexity, and its use should be extended to the next phases of the project.

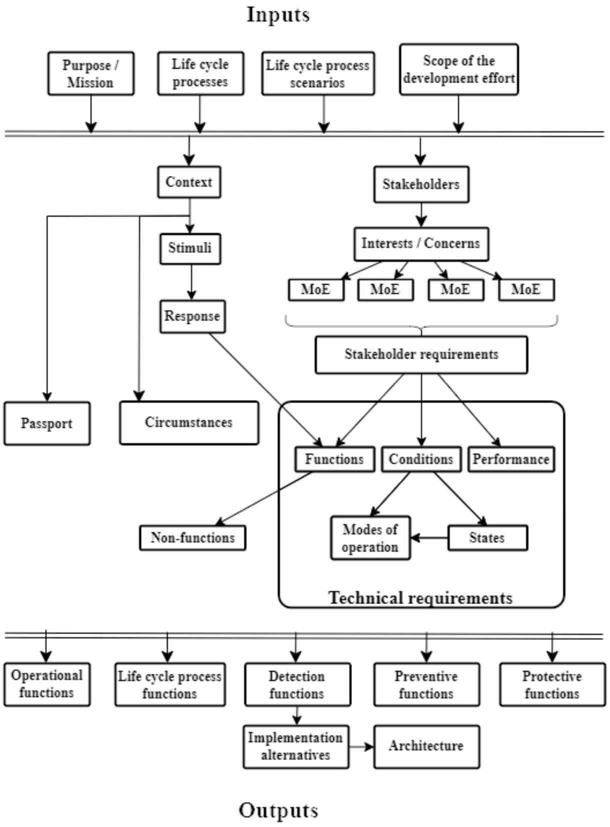

Figure 1. Systems Concurrent Engineering Method. [Source: Based on diagram from (LOUREIRO et al., 2010)

3. Systems concurrent engineering approach for LCRS

3.1. Mission analysis

The initial approach in the project itself was to define its scope by performing the mission analysis. A clear need statement was defined, from which the initial stakeholders were defined with their respective roles. This is represented in Figure 2.

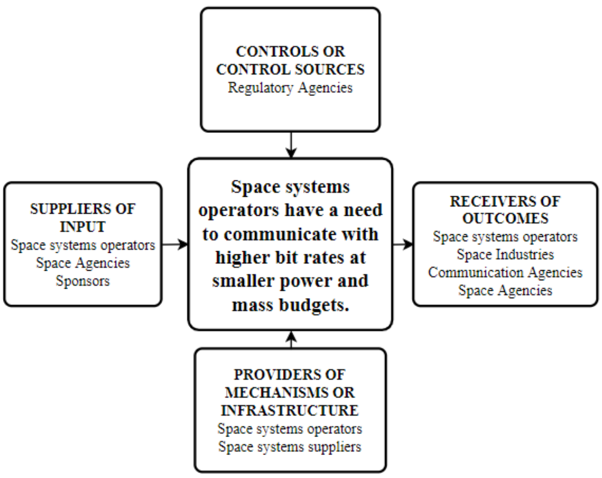

Figure 2. Need statement and initial stakeholders of the project.

The need statement and initial stakeholders definition are important in the definition of the initial goals, objectives, and MoEs of the project, from where the main functional and performance requirements and the qualification strategy will derive.

The goal should represent a function or constraint of the project, while the objectives are a refinement of the goal with target and minimum performance parameters. The MoEs represent a measurable quantity or characteristic that will define if the goal and objectives were achieved. The designer should derive these definitions together with the main stakeholders.

For the LCRS, the following example illustrates the procedure. The goal "The system shall provide relay for optical communication between satellites and ground stations" is translated into three different objectives: Two optical links capable of providing 500 Mbit/s (Threshold) or 1000 Mbit/s (goal) for interplanetary missions on a distance up to mars, eighteen optical links capable of providing 1000 Mbit/s (Threshold) or 2000 Mbit/s (goal) for missions on an LEO orbit, and Provide data latency transmission value of 100 ms (objective), 150 ms (threshold). From where the measures of effectiveness of transmission and simultaneous users can later be written as requirements for the system and used to define the qualification strategy.

Having at hand the initial capabilities and constraints of the system, a concept of operations of the system is derived to provide a further view of the interacting parts and their role in the project life cycle. This is represented in Figure 3.

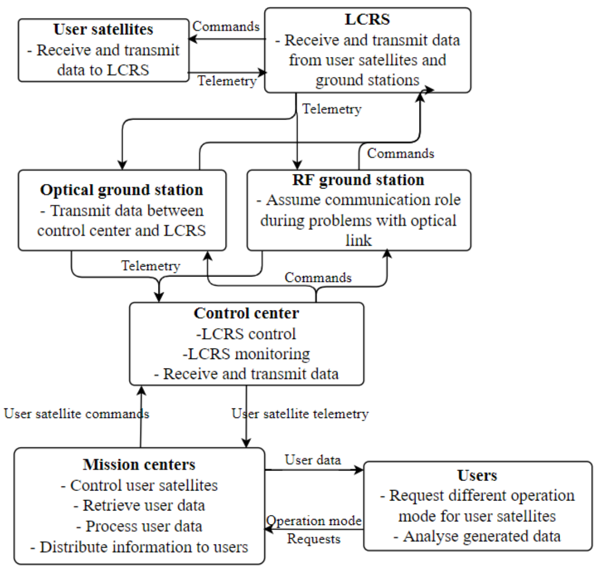

Figure 3. LCRS concept of operation with actors' roles.

3.2. Life cycle processes

Finally, the life cycle processes of the satellite are identified, which will allow for a CE approach in most of the processes in a parallel manner. All the main processes during the life cycle of the LCRS project are represented in Figure 4.

This study's aim is to develop the systems concurrent engineering approach rather than the full conceptual design of a laser relay satellite. Therefore, the four following life cycle scenarios were chosen for further analysis: The LCRS in operation, the LCRS in the AIT stage, the company in development effort, and the company in launch effort. For the illustration of the method, only part of the development for each scenario is represented in the work, due to most

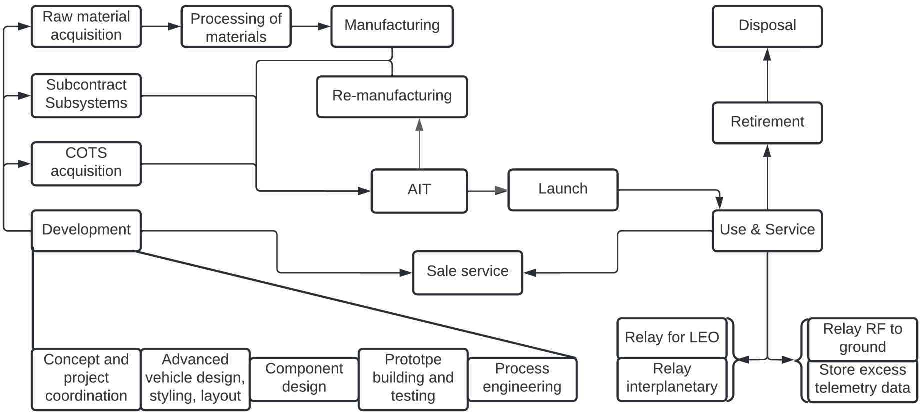

Figure 4. Life cycle processes for the LCRS project.

of the approach being the same in all scenarios. The focus will be given to the development of the product in operation scenario, since it requires the most complex and complete modeling.

For each life cycle, new stakeholders were again identified with their main concerns. Some of them are represented in Figure 5.

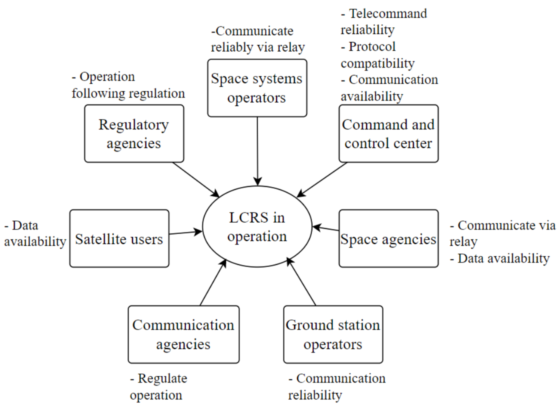

Figure 5. Product in operation stakeholders and concerns.

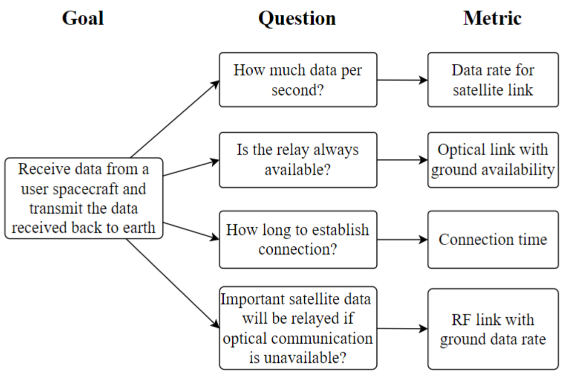

Figure 6. Example of goal question metric

With the definition of new stakeholders, the goal/question/metric method was employed to elicit new requirements for each of the identified scenarios. An example of the method exploited is presented in Figure 6.

3.3. Stakeholder and system requirements

The gathering of all the information collected in the previous steps allows for the formulation of a stakeholder requirements document. It is one of the most important documents of the project since it will be the common ground where the stakeholders' needs will be transformed into what the system must achieve. Mistakes in this document can result in a system that does not satisfy what the user wants and the need for major changes or even in the complete failure of the project.

According to (STEVENS, 1998), the stakeholder requirements document has some key elements that should be present, namely, a general description of the product, with capabilities and constraints, stakeholder characteristics, the operational environment, and assumptions and dependencies. The second part of the document should contain the specific capabilities and constraints for the scenarios. During the current project, it was noted that further separation of the general description section, or even the creation of different documents for scenarios very independent from one another, can be beneficial to maintain document coherence and understandability.

From the stakeholder requirements, the system requirements are derived, outlining what it must perform to satisfy what the stakeholder wants. It is important in this step to avoid directed design since it could prevent engineers from following better solutions that were not considered in this document. A requirements analysis is also necessary for both steps to ensure their consistency and to increment with pertinent additional information, such as the type of requirement, if it is mandatory, rationale, and verification and validation means.

An example of system requirement analysis is present for each scenario in Table 1. Additionally, columns with comments, rationale and verification means should be added for a complete analysis.

Table 1. System requirement analysis.

Scenario	Requirement	Type	Compliance	Constraint
Product in operation	The system shall be able to receive and demodulate signals with Differential Phase Shift Keying modulation at no less than 1000 Mbits/s from an emitting source of no more than 10W at any LEO orbit	P	M	N
Product in AIT	The system mechanical and electrical interfaces shall be in accordance with the ICD.	F	M	Y
Org. in development effort	The system shall be able to perform based on the standard defined by the regulatory agencies	F	M	Y
Org. in launch effort	The organization shall transport the satellite from the integration room through the different environments to low earth orbit reliably, and without compromising the mission.	P	M	N

P - Performance, F - Functional, M - Mandatory

3.4. Functional analysis

The functional analysis begins with the outline of the functional context (Figure 7), which allows us to identify every element of the environment that interacts with the system of interest and the exchanged information, material, or energy.

Two other diagrams, with the same elements, are important to represent other information on the system. The interconnect diagram represents the physical means through which the information, material, or energy are exchanged. For each environment element, it is important to represent their possible states, which will interfere with the operation mode of the system of interest. Furthermore, a risk analysis can be performed considering problems in the defined flows or environmental states that can be detrimental to the operation, as represented in Table 2.

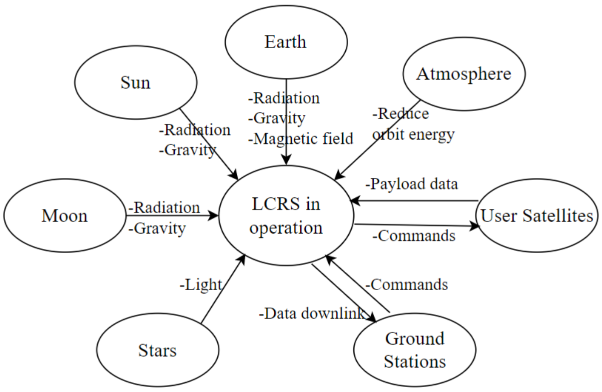

Figure 7. Functional context for product in operation.

Based on possible circumstances, operating modes and states are defined, as well as mode and state transition analysis for each. For each operation mode, the definition of events lists and data flow diagram allows for a better understanding of the behavior of the system, risk analysis on the possibility of functions not being performed, and identification of problems in the functional design.

The events list for LCRS in operation in nominal mode is depicted in Table 3. The corresponding data flow diagram is presented in Figure 8. The same procedure can be applied for the other scenarios, observing exceptions where a diagram might not be ideal to represent a system, like a data flow diagram for the product in integration steps.

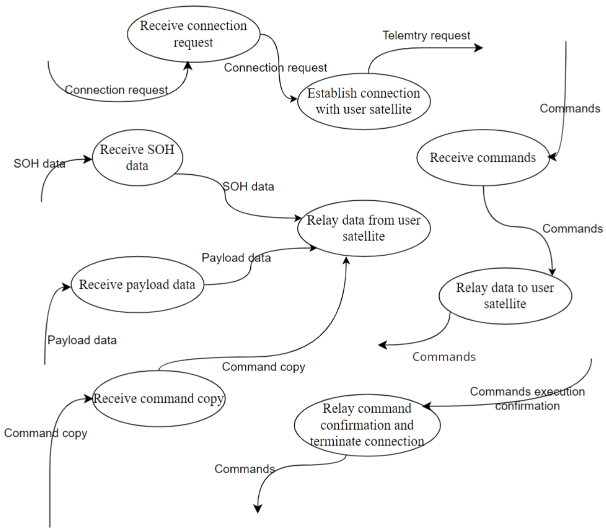

Figure 8. Data flow diagram for product in operation in nominal mode.

3.5. Physical architecture

For the physical architecture, an initial PBS was built with the main components, represented in Figure 9, with the interaction between them depicted in Figure 10, for the payload module.

An architecture interconnect diagram is also important to represent the physical connections that allow for the data flow represented in the architecture flow diagram.

With the main functions and components defined, an allocation matrix was built to make sure

Table 2. Risk analysis from a flow failure.

Cause	Turbulence Signal blocked by clouds or objects Radiation single event effect
Hazard	Error in telecommand signal
Consequence	Sent signal not executed
Means of detection	Hamming code detection Parity check
Severity (1-5)	3
Probability (1-5)	5
Risk	Very High
Risk mitigation	Higher telescope diameter Aperture averaging Adaptive optics Modulation and coding Multiple receivers Feedback to ground station to resend command
Verification	Testing with simulated conditions Analysis of correction and detection codes

Table 3. Events list for nominal operation mode

Environment element stimulus	**System response**
User satellite sends signal requesting connection	LCRS identifies request and establishes connection
User satellite sends state of health data	LCRS relays state of health data to ground stations
User satellite sends payload data	LCRS relays payload data to ground stations
Ground station sends confirmation data was received, verified and valid	LCRS informs user satellite no data will need to be sent again
Ground station sends commands to user satellite	LCRS relays commands to user satellite
User satellite informs LCRS commands were correctly received and returns a copy of commands	LCRS relays copy of commands to ground station
Ground station verifies that received commands are equal to the sent commands and informs LCRS	LCRS informs user satellite that commands are to be executed LCRS terminates connection with user satellite

all functions had a corresponding component. A morphological chart was also defined for the main components, combined with a decision matrix to define what solutions better satisfy what the system needs.

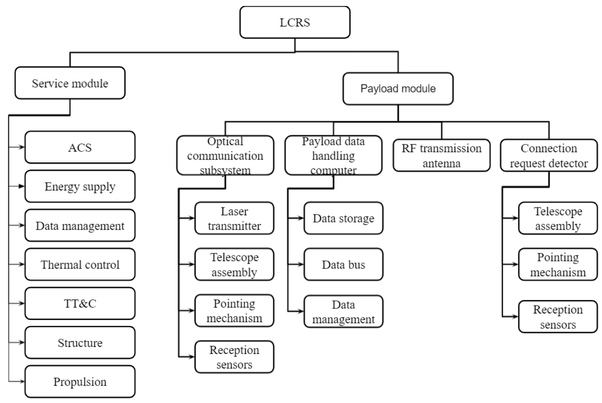

Figure 9. PBS for LCRS.

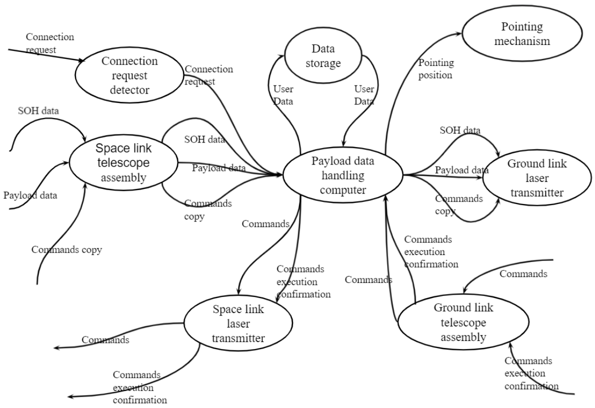

Figure 10. Architecture flow diagram.

An internal block diagram (Figure 11) can be used to represent the internal flows through the components and, in this case, was also used to represent which components are developed internally, externally, or COTS.

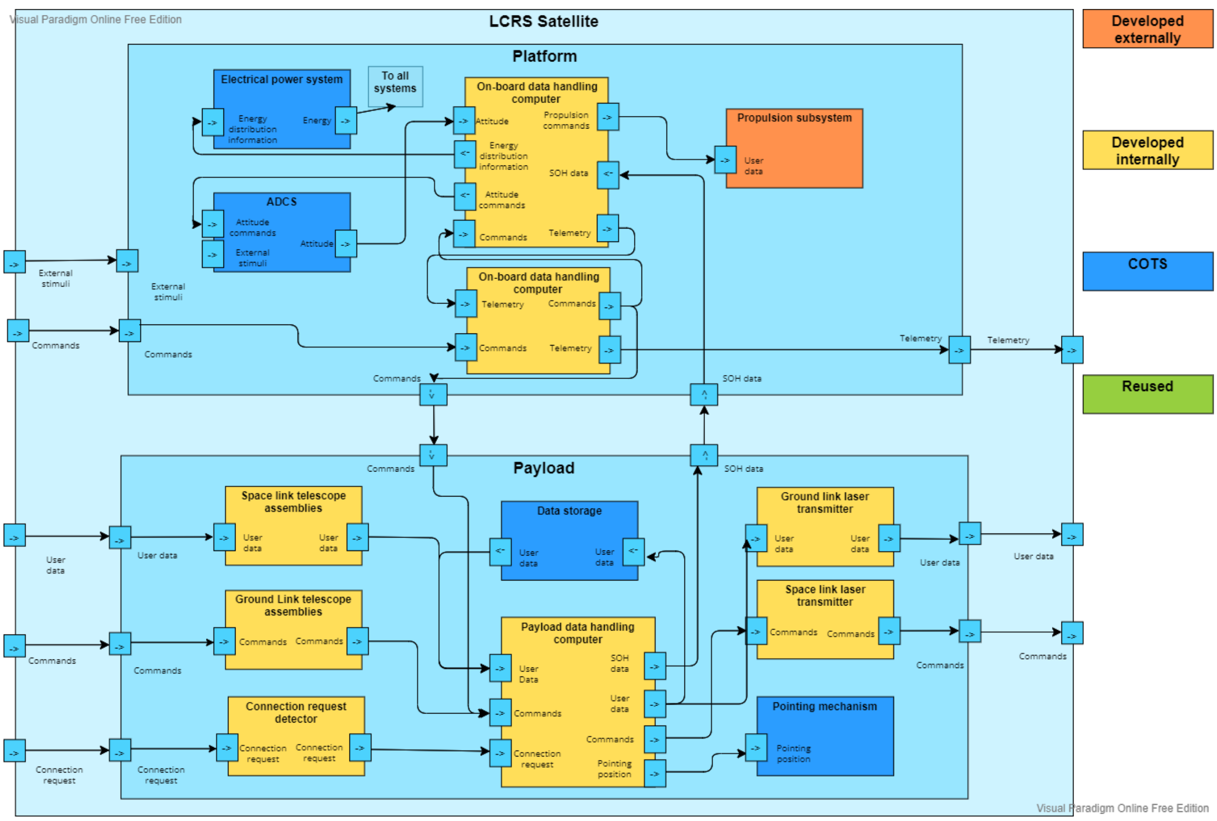

Figure 11. Internal block diagram for LCRS

To finalize the concept design, some early documents can also be outlined to help the view of the future steps, such as an interface control document for the higher level of abstraction achieved, requirement allocation documents, and some component specifications.

4. Conclusion

This paper shows the systems engineering processes to develop a relay satellite communication system via laser. In the development of the work, four life cycle processes were chosen for further analysis, where the product is studied in its operation (providing relay for multiple users) and AIT effort, and the organization in the development and launch efforts.

The stepwise systems engineering process was successfully used on the scenarios, with stakeholder identification, derivation of requirements and analysis, the study of functional aspects, and implementation architecture, simultaneously, for the product and organization elements of a system at each layer of the system decomposition structure.

The proposed approach allows us to anticipate the requirements of the entire product life cycle until the first stages of the architecture process of a system. Stakeholder requirements, features, performance, conditions, circumstances, modes, and exception functions are captured for the entire product life cycle process. External and internal physical and logical interfaces are also identified throughout the life cycle.

Those procedures during the first phase of the project are necessary to avoid future changes from mistakes, as well as improve future project steps, reducing development costs and time and improving the reliability of the system, increasing the satisfaction of the stakeholders during the life cycle of the product.

Acknowledgments:*We thank CAPES and INPE for the resources offered.*

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