High-level Developments in Space Systems Engineering of the RaioSat Project

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The RaioSat project envisages a 3-U CubeSat proposal by INPE-Brazil in order to detect intra-cloud and cloud-to-ground lightning flashes simultaneously, namely the total lightning detection for regions over Brazil. This information is usefull for predicting extreme weather phenomena which requires high-resolution numerical weather prediction (NWP) models and high amount of observational data. The RaioSat approach is based on previous bigger satellites projects like FORTE, OTD and LIS which have shown that detection of lightning events from space is feasible and can provided important datasets for lightning research and new space technology development. This project integrates Earth System Sciences research with some space technological development and uses an optical sensor and a VHF antenna onboard a cubeSat platform. This paper briefly covers high-level developments in space systems engineering the RaioSat project, namely: 1) Mission, 2) Life cycle process, 3) Stakeholder Analysis, 4) Requirements, 5) Functions, 6) Systems Architecture and 7) Detailed design. Two different sensor networks that detect and locate lightning flashes in Brazil, called RINDAT and BrasilDAT, will be used as reference data. The RaioSat mission is expected to be in a LEO orbit and it will use a 3U-CubeSat aluminum frame (10x10x30cm) to accommodate the main platform and its payload. The main platform shall have telemetry, commanding and housekeeping capabilities via an onboard computer, 3-axis attitude control and a GPS. The payload shall have a VHF passive antenna (range of 50 to 200MHz) and a spectral imaging camera (SIC) having a spectral range from 700 to 900nm using a band-pass optical filter. The RaioSat project is expected to be then an important starting point for future research and developments in the areas of Earth System Sciences and Space Engineering Technologies at INPE-Brazil. This joint project allows the technical development for remote sensing lightning events and their detection from space. These data can be then assimilated into the NWP models to improve the forecast of extreme weather events, which are one of the major features in climate change.

1. Introduction

Climate change and its impact on sustainability are one of the top agenda in academia and it has stimulated a number of studies on climate behavior. One of the main factors for climate change is the extreme weather phenomena caused by natural events and/or human activities. The prediction of these events must be made by precise mathematical models known as Numerical Weather Prediction (NWP) and the maximum amount of observable data available. A typical NWP accumulates observations of current climate states and processes these data with computer models to predict future status. These models analyze the radiation data generated by lightning, through sensors.

Optical detection of lightning has a long tradition of more than 10 years and it can be either ground or/and space-based. Ground based location of lightning over large areas is better performed in the lower frequency radio bands, since the detection range is limited to the line of sight and the Earth's curvature. A space based optical observation has the advantage of an obstructed view from above the clouds and potentially large field of views using only a single instrument.

In Brazil, lightning radiation can be detected by terrestrial sensors of different types, however, due to the size of the national territory the installation of sensors, becomes complicated and expensive. In this sense, the use of an optical sensor and a camera embedded in a satellite is attractive, since it reduces the amount of sensors and increases the field of view. Basically, the optical detection of lightning from space is measuring the radiation of light, which is emitted by the hot lightning channel and then propagates throughout the atmosphere and clouds (which mainly scatters the light), reaching finally the observer above the clouds [1].

This paper presents some high-level developments in space systems engineering a nanosatellite to detect lightning that happens between clouds and above the clouds, called Raiosat. The project is proposed to detect intra-cloud and cloud-to-ground lightning flashes simultaneously, expected to operate in a LEO orbit using a 3U-CubeSat (10x10x30cm) framework to accommodate an optical sensor with a spectral filter in the OI (777,4 nm) and NII (868,7 nm) bands [2].

This paper is organized as follows: Section 2 presents the RaioSat nanosatellite; Section 3 presents the method of approach of simultaneous engineering of systems; Section 4 presents the application of method to the RaioSat nanosatellite system and; Section 5 concludes this work.

2. The RaioSat Mission

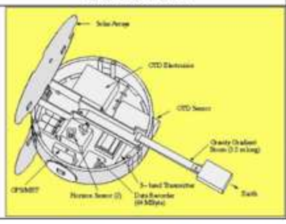
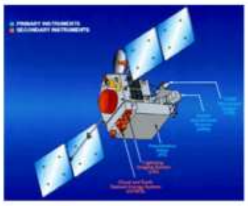
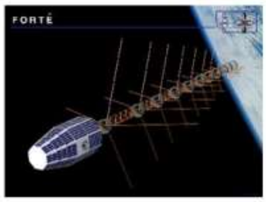
The RaioSat satellite mission goal is primarily to detect both intra-cloud and cloud-to-ground lightning flashes simultaneously the so-called total lightning data using an optical sensor and a VHF antenna. Hence it will only contain the experiment to acquire this data for a time-limited mission. It should be launched during a window that maximizes data collection in the lighting season over Brazil, which is expected to be from October to March. In this work, the systems engineering process is just applied in RaioSat system.

Previous space-based sensors for lightning detection were: the Oberview1/MicroLab, launched in 1995, the TRMM launched in 1997 and the FORTE launched in 1997 [3]. All those missions are big satellites whereas in 2014, this nanosatellite mission was first proposed, see Figure 1 for an overview.

Nanosatellites, by definition, are small satellites (SmallSats) with a mass ranging from 1-10 kg. For the Raiosat it is intended to use the class of nanosatellite called CubeSat that use a size and a standard format. The standard Cubesat size uses a "1U" as size unit. In this context, a "1U" block measures 10x10x10 cm.

Cubesats, as well as large satellites, accomplishes several high-level objectives in a simplified way. In other hand, its reduced size allows the development and manufacturing of a functional satellite at low cost, by using COTS and significant launch cost reduction with shared launch vehicles.

The Raiosat nanosat will have a 3U-Cubesat aluminum structure (10x10x30cm) that will be composed of a main platform, called a service module, and its payload, called the payload module [4]. The service module shall have telemetry, telecommand and maintenance capabilities via onboard computer, a GPS and a 3-axis attitude control.

Satellite	OrbView-1/ MicroLab	TRMM- Tropical Rainfall Measuring Mission	FORTE - Fast On-orbit Recording of Transient
Lightning Detecting Payload	OTD - Optical Transient Detector	LIS - Lightning Imaging Sensor	RF antenna OLS – Optical Lightning Sensor
Mass	74 kg	3620 kg	210 kg
Altitude	785 km	350 e 402 Km	800 Km
Inclination	70°	35°	70°
Launch Date	01/04/1995	27/11/1997	29/08/1997
End of Life	24/08/2015	08/04/2015	
Ilustration			

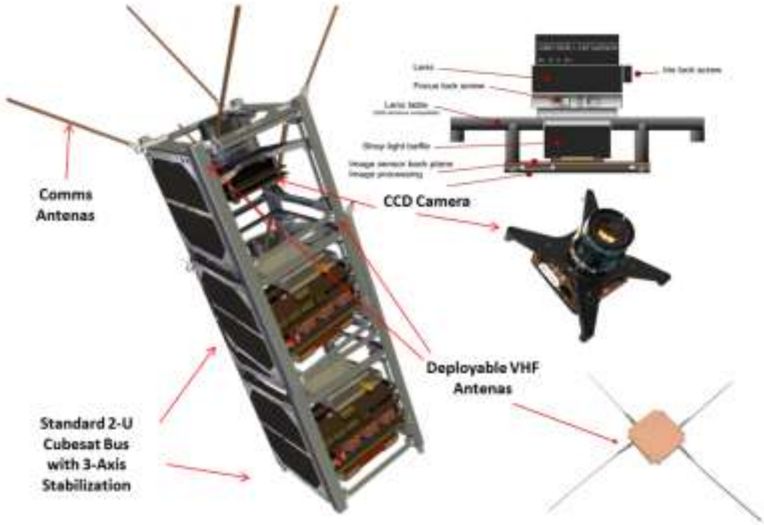


Figure 2: Previous lightning detection missions and the RaioSat system.

The payload module will feature a passive VHF antenna (50-200 MHz range) and a spectral image camera at 2.048 x 1536 pixel resolution, thus obtaining a surface image of 80 m / pixel. The camera should also have a spectral range from 700 to 900 nm using an optical band-pass filter. For this mission, the RaioSat will be in a prospectively LEO orbit at 650km altitude.

3. The High-level Space Systems Engineering Approach

Currently, two dominant methodologies for the development of new products are: System Engineering and Concurrent System Engineering. The high-level developments for the RaioSat mission are derived from a concurrent vision and will be further presented hereafter.

According to [5]: "*Concurrent engineering is a systematic approach to the integrated, concurrent design of products and their related processes, including manufacture and support. This approach is intended to cause the developers, from the outset, to consider all elements of the product lifecycle from concept through disposal, including quality, cost, schedule and user requirements*".

The high-level steps of the Concurrent System Engineering method are synthesized, consist of:

- Step 1: Definition and declaration of the mission of the product, identifying the needs and measures of effectiveness;
- Step 2: Identify the systems life cycle processes of interest, identify the scenarios of the life cycle process and scope of the development effort for product and organization.
- Step 3: Identify the stakeholders in the system and what their concerns are for each scenario of the system life cycle process.
- Step 4: Annotating and analyzing stakeholder requirements, deriving system requirements from stakeholder requirements
- Step 5: Identify the functional context of the product and organization for each scenario of the life cycle process and within the scope of the development effort, defining the modes from the analysis of circumstances
- Step 6: Identify the context of the product and organization deployment architecture for each life cycle process scenario and within the scope of the development effort.
- Step 7: Detail of the project, identification of the physical elements of the system through a decision matrix.

Applying these steps to the RaioSat for example will allow a transition between its operational scenarios as shown in Figure 3 which includes both ground and space-based sensor networks.

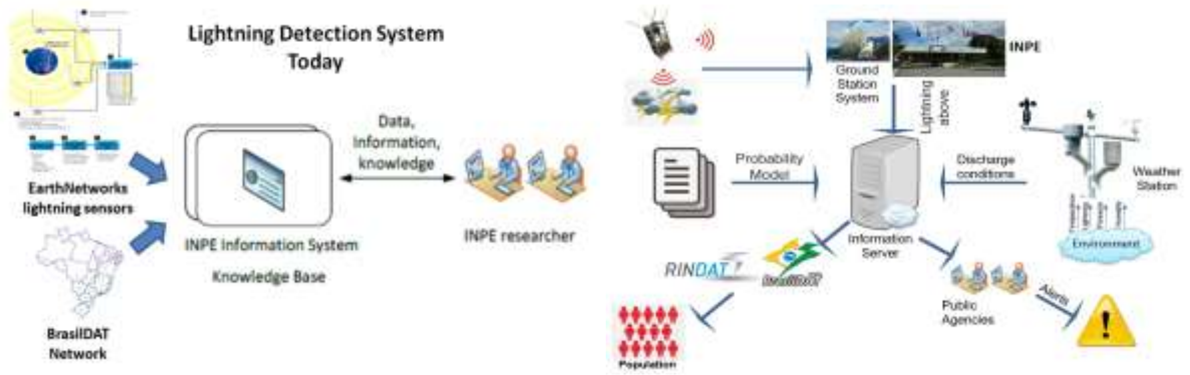


Figure 3: Transition of operational scenarios (a) to (b) with RaioSat addition.

4. Application of High-level Space Systems Engineering to RaioSat

Concurrent System Engineering derives system requirements from life cycle process scenarios which are identified from an operating system architecture. This intails a series of processes described in high level in this section.

4.1 Mission Definition, Measures of Effectiveness and Qualification Strategy

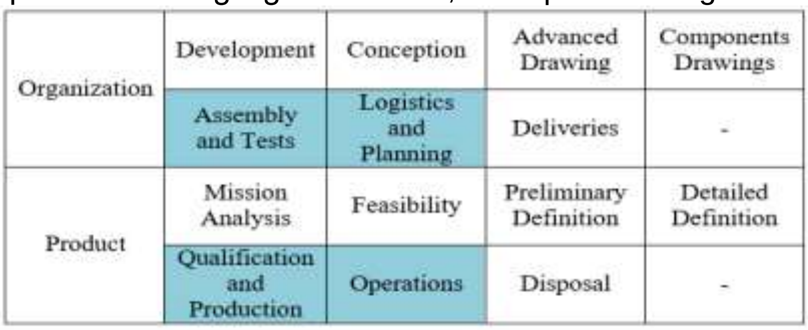
Researchers from CCST / INPE together with BrasilDat and RINDAT, wish to observe lightning through satellites (CubeSat), for important climatological studies and to develop a space lightning detection technology in Brazil, which will provide weather conditions for civilian agencies. Jointly with the project stakeholder analysis presented in [5], it is possible to derive a list, as shown in Table1, with measures of effectiveness (MOEs) and the qualification strategy.

Table 1: RaioSat goals, objectives, MoEs and qualification strategies.

Goals	Objectives	MoEs	Qualification Strategies
Collect data on lightning events.	Create database	Statistical calculations of the measurements collected by sampling rate.	Analysis
	Find events geographically	Correction of events according to geographic location.	
Provide the data collected for INPE scientists	Check and improve models	Reliability analysis	Analysis
	Detect covered and uncovered locations	Percentage of data available	
	Access control	Number of users accessing the data	Analysis
Allow a wide use of information collected for other institutions and companies	Provide data available on online public networks	Number of online access to data	Analysis
	Member registration / system users		
Correlate the total lightning data provided by CubeSat to the other lightning data sets available in the BrasilDAT, RINDAT and LMA networks.	Develop modeling tool	Correction of events / Correct data percentage after correlation	Analysis + Comparison
	Validate the data provided by the Raiosat.	Compare with real reliable data	
Developing new space technologies	Development of a network of LMA sensors in Brazil to compare the results of the Raiosat with the LMA data collected.	Compare and validate the datas obtained by Raiosat with the LMA datas.	Analysis + Comparison

4.2 Life Cycle Processes Analysis

This analysis illustrates the steps listed in Section 2. For product and organization, were performed analysis, for each life cycle process scenario simultaneously. The processes “Assembly and Test”, “Logistics and Planning”, Qualification and Production” and Operation are highlighted in blue, as depicted in Figure 4.



Organization	Development	Conception	Advanced Drawing	Components Drawings
	Assembly and Tests	Logistics and Planning	Deliveries	-
Product	Mission Analysis	Feasibility	Preliminary Definition	Detailed Definition
	Qualification and Production	Operations	Disposal	-

Figure 4: Raiosat Life Cycle Processes and product scenarios of interest.

These highlighted processes are the ones for which the stakeholder analysis, requirements analysis, functional analysis and implementation architecture analysis will be explained. In fact all the steps mentioned in Section 3 shall be run for all life cycle process scenarios.

4.3 Stakeholders and System Requirements Analysis

For the Raiosat product stakeholders analysis the following scenarios were considered: the Raiosat in nominal orbit and the Raiosat during integration. For the non-operational scenario, the input is the integration team, the control is performed by the product assurance, the mechanism is performed by the INPE/LIT and the output is test team (members of AIT).

Similarly, it was carried out the analysis of stakeholders for the organization in two scenarios: a non-development within transportation organization, the input is AIT Team, the mechanism is transport manager, the control is logistic manager and the output is the launch center.

Systems requirements are obtained from the identification, analysis and derivation of stakeholder requirements for each of the life cycle process scenarios. Requirement is a performance statement or design constraint to which the product must conform. In this way, the requirements must be verifiable. One way to achieve this verifiability is to group the requirements into categories, such as performance requirements and constraints.

A performance requirement is related to the ability of a system to perform its function. For demonstration purposes, 4 Stakeholders and 4 interests were chosen for 4 scenarios of the life cycle process. Table 2 presents the requirements of the stakeholders requirements and Table 3 presents the requirements of the systems. These are requirements that must be implemented for the product.

Table 2: RaioSat Stakeholder requirements.

ID	Type (F/C/P)	Description	Concern	Complice (M/D/O)	Type (Co/Ca)	Status (OK/TBD/TBC)	PPO	Verifiability	
								T/I/D	Procedure
REQ1	C	The integration should be done at INPE's	Logistics	M	Co	TBD	ORG	D	LIT Visits inspections
REQ2	F	RaioSat shall measure VHF signal and acquire CCD images time and geo-tags lightnings to ground	Research and Operation	M	Ca	TBD	PROD	T	Stimulate receivers with dummy radio signals and images
REQ3	C	After AIT, RaioSat shall be stored for future transportation.	Transport and launch campaign	M	Co	TBD	ORG	I	Check sealing at storage and temperature and humidity
REQ4	F	Development Team shall verify and analyze the test data available launchers	Development	M	Ca	TBD	PROD	T	Compare Raiosat's EMI / EMC levels with Launchers

Type (F/C/P): F-Functional / C-Condition / P-Performance. Complice (M/D/O): M-Mandatory, D-Desirable, O-Optional. Type (Co/ Ca): Co-Constrain / Ca-Capability. Status (OK/TBD/TBC): TBD-to be defined / TBC-to be confirmed. P/P/O: P-Process / P-Product / O-Organization. T/I/D: T-Test / I-Inspection / D-Demonstration.

Table 3: RaioSat System requirements.

ID	Text	F/D /C	P/O	Verifiability
01	After separation of the rocket, the CubeSat should be ejected from the P-POD with a speed and kept in orbit.	D	P	Test
02	The RaioSat should be in a LEO orbit at 650 km altitude.	C	P	Analysis / Test
03	The payload module must have a GPS to mark the location and time of any potential lighting event.	F	P	Analysis / Test
04	The payload module shall have a broad - spectrum radio antenna for detecting the electromagnetic emissions of the radioactive component from atmospheric discharges - passive VHF antenna, ranging from 50 to 200 MHz.	F	P	Analysis / Test
05	The payload module shall have a spectral image camera and an imaging device. The camera requires high performance image processing capability and large data storage memory and its resolution should be 2,048 x 1,536 pixels, leading to a surface image of 80 m / pixel at 650 km altitude and a spectral range of 700 to 900 nm using an optical bandpass filter.	F	P	Analysis / Test
06	The development organization shall design a CubeSat 3U with aluminum frame with the following measurements (10x10x30 cm) to accommodate the platform and payload.	C	O	Analysis / Test
07	The development organization must design the RaioSat System that can be produced in 07 months.	D	O	Analysis

4.4 RaioSat High-Level Risk Assessment

After the functional analysis, it is possible to derive the RaioSat high-level risk assessment listed in Table 4. This is made to identify potentially failures for the Raiosat operations, and provide specific actions to prevent, or at least minimize, the probability of identified failures to actually occur.

Table 4: Risk assessment for the Raiosat operations.

Source of Danger	Circumstance	Trigger Event	No-Function
Danger	Lightning or discharge not detected	Lightning or discharge not detected	Lightning or discharge not detected
Cause	Disabled ground station	EMI interference	Full back image
Probability	1	3	1
Failure	Power outage	Cumulus-nimbus cloud density too high	Sensor not initialized
Consequence	Telemetry not received	Bad telemetry data	Telemetry not generated
Impact	1	1	3
Hard to detect	1	1	5
Calculated Risk	1	3	15
Mitigation	Correction: acquire power generators	Detection: check local weather forecast	Preventive: verify captured image in EGSE
Qualification Strategies	Promote generator verification tests	Data verification and confirmation	Calibrate sensor using storm images

A risk assessment was made to identify potentially failures for the development organization, and provide specific actions to prevent, or at least minimize, the probability of identified failures to actually occur and this analysis is listed in Table 5.

Table 5: Risk assessment for the RaioSat development organization.

Source of Danger	Circumstance	Trigger Event	No-Function
Danger	Override the vibration test	Satellite detached from MGSE	Delay in OR
Cause	Loose component damaged battery	Adapter cylinder has not been locked	Component purchased incompatible
Probability	1	2	3
Failure	Battery leakage	Operator unaware of adapter lock	Component specified incorrectly
Consequence	Emission of toxic gases in the laboratory	Structure of the satellite compromised by the fall	AIT not completed
Impact	5	3	4
Hard to detect	4	2	1
Calculated Risk	20	12	8
Mitigation	Protection: isolate the satellite to contain the gases	Preventive: use of checklists in the handling	Preventive: detailed design review
Qualification Strategies	Enable the use of battery protection	Encourage greater use of checklists in development	Diversify staff for FDR

4.5 RaioSat Architecture Analysis

The architecture analysis were done for the RaioSat product and organization. An instantiated physical architecture is defined to the generic physical architecture, detailing the performance characteristics and resource requirements for physical elements. For the creation of the instanced physical architecture, it was necessary to allocate functions to the generic architecture, assigning the interfaces between the physical components and derived the requirements for those components of the system requirements [6]. For instance, in instantiated physical architecture, as shown in Figure 5, the reaction wheels (quantity and capacity), sensors (type and quantity) and magnetometers (quantity and capacity) were specified. The instantiated physical architecture of RaioSat.

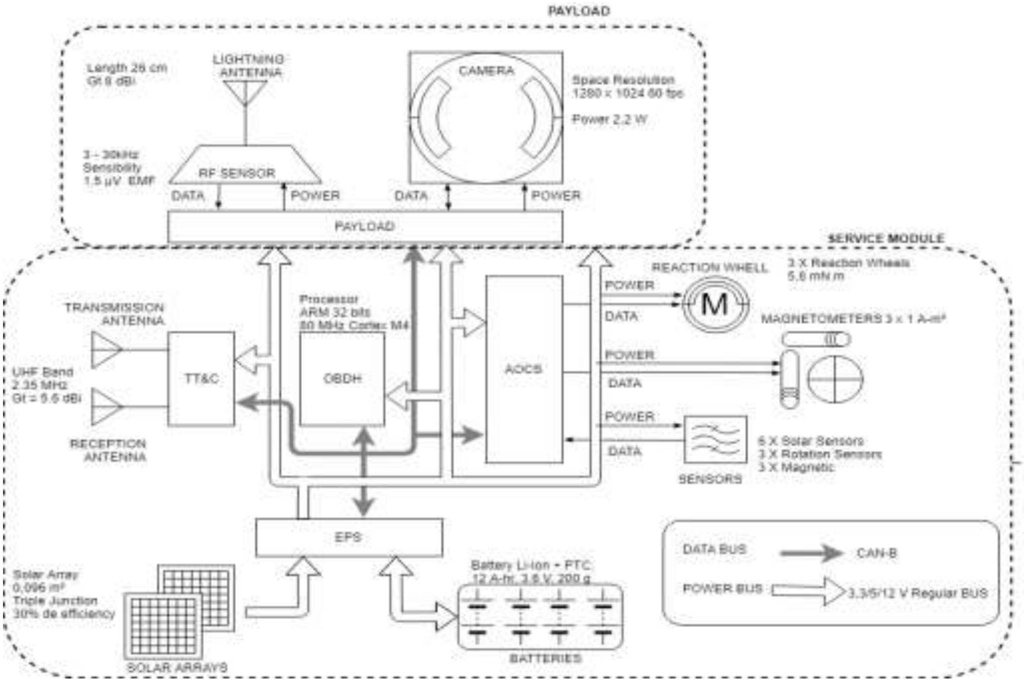


Figure 5: An instantiated physical architecture for Raiosat.

4.6 RaioSat High-Level Design

In a high-level design each of the physical elements of the system must be carefully specified and the design decisions concerning the elements that make up the system, Therefore, considerations on wether developed internally, developed externally, reused or purchased from an external supplier for satellite parts. Each step of the process within this part of the method will be shown using the RaioSat system as a basis. Using a Make-or-Buy matrix for decision making, the generation of the RaioSat Product Breakdown Structure (PBS) is shown in Figure 6.

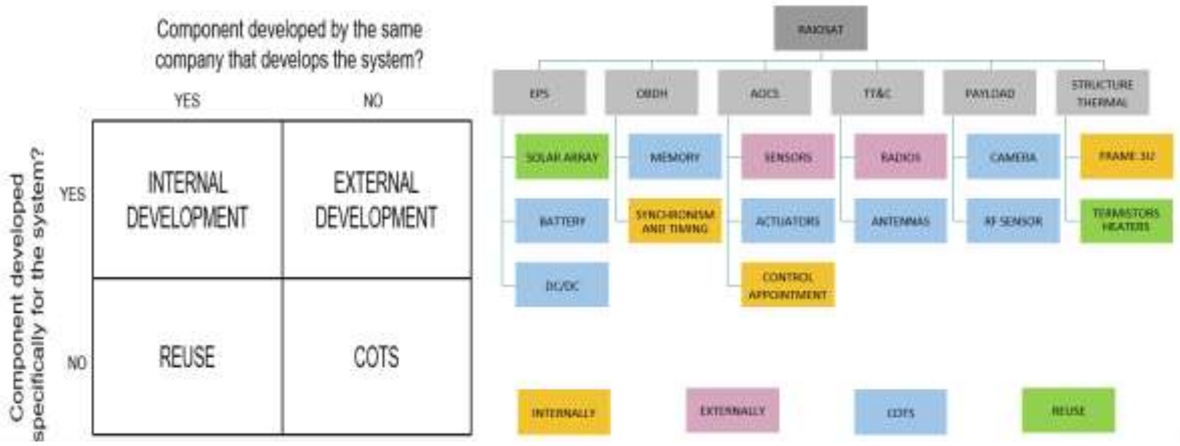


Figure 6: RaioSat Make-or-Buy decision matrix.

5. Conclusions

Nowadays, in Brazil, there are different ground networks composed by different types of sensors that provide earth system measurements, including lightning sensors. However, observations from space can provide a more spatially uniform and time-continuous coverage, which is very important to any study of the earth system processes. Three previous big satellite missions were successful to detect lightning from space which makes quite challenging using nanosatellites for similar purposes.

This paper briefly described a high-level concurrent system engineering method for RaioSat project, which integrates Earth System Sciences research targeting the total lightning detection over Brazil.

The work broadly described mission analysis, stakeholder analysis, requirements analysis, life cycle process identification, physical analysis, functional analysis as well as physical and functional architecture analysis simultaneously for RaioSat development. This approach helps in the design since it anticipates a broad and complex view of the whole life cycle process, avoiding unnecessary costs and increasing stakeholder satisfaction.

Presently, a RaioSat prototype is being initiated at INPE with expected launch by the end of 2020.

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