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"The RaioSat project: detecting total lightning flashes from a CubeSat"

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Extreme weather events are one of the major character in climate change. Predicting these complex meteorological phenomena requires high-resolution numerical weather prediction (NWP) models and the maximum amount of observational data available. Nowadays, in Brazil, several networks composed by different types of sensors provide these measurements, including electromagnetic passive sensors which are capable of detecting the lightning-producing radiation. Advanced processing units collect these data, locate the lightning discharges, integrate all the information, and store them in high-capacity and high-performance databases. These data are then assimilated into the NWP models to improve the forecast of extreme weather events. The RaioSat project intends to detect, for the first time, intra-cloud and cloud-to-ground lightning flashes simultaneously, the so-called total lightning data, using an optical sensor and a VHF antenna onboard a CubeSat platform. A dense network of surface sensors that detect and locate total lightning data in Brazil, named the BrasilDAT dataset, will be used to validate the RaioSat data as a ground-truth reference. The RaioSat mission is expected to be in a LEO orbit at 650km and it will use a 3U-CubeSat aluminum frame (10x10x30cm) to accommodate the main platform and its payload. The main platform shall be solar and battery powered, have telemetry, commanding and housekeeping capabilities via an on-board computer, 3-axis attitude control and a GPS. The payload shall have a VHF passive antenna, ranging from 50 to 200MHz, and a spectral imaging camera (SIC) with high-performance image processing capacity and large data storage memory. SIC resolution shall be 2,048 x 1,536 pixels leading to a surface imaging of 80 m/pixel at 650km altitude. Also SIC shall have a spectral range from 700 to 900nm using a band-pass optical filter. Additionally, this paper also analyses upfront the stages of the space mission over the system life-cycle which consists basically of: (a) mission analysis, (b) life cycle analysis, (c) functional analysis, (d) design architecture analysis and, (e) concept of operations among others.

Introduction

Lightning observation from satellites provides a globally uniform coverage, which is very important for climatological studies. Optical detection of lightning has a long tradition of more than 10 years. On the other hand, 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. 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].

The main sources of optical radiation produced by lightning are the return stroke in cloud-to-ground flashes and the recoil streamers in intra-cloud discharges [2]. The optical spectrum of lightning in the visible and near infrared range is made of spectral lines of the excited and ionized gases of the air. Based on studies of lightning spectroscopy [3][4][5], one of the most strong lines is the atomic oxygen OI(1) triplet line found at 777.4 nm. This line is being used for space based optical detection of lightning, since it contains about 6% of the total energy of the optical spectrum [3]. According to Guo and Krider [6], based on high resolution optical measurements, the mean duration of the optical pulse is 158 μs, which is determined by the cooling processes in the lightning channel. The mean rise time is 15 μs, which is determined by the propagation speed of the luminous phase od the channel, i.e. the upward velocity of the return stroke. The optical power produced by lightning varies strongly between individual flashes and different types of lightning. For first strokes of cloud-to-ground flashes, the time averaged power is 1.3×10^6 W/m in the range of 400-1000 nm [6]. The peak power for the whole channel were about 2×10^9 W [6]. In terms of optical energy, which is defined as integrated power over the pulse duration, the mean value of 3.7×10^5 J was found [6].

The concept of a dedicated lightning location sensor on board of satellites with the aim of geostationary detection has been developed since the 80s [7]. As a result, in April 1995, the first NASA lightning detector was launched into space: the OTD (Optical Transient Detector) on board of the MicroLab-1 satellite and operates until March 2000. Its circular orbit had an inclination of 70° with an altitude of 735 km and an orbital period of about 100 min. The projected field of view of the CCD onto the Earth surface was 1,250 x 1,250 km [8]. The LIS (Lightning Imaging Sensor) is part of the Tropical Rainfall Measuring Mission (TRMM) satellite, which was launched in November 1997 [9]. The observation area is limited to the latitudes ±35º. The altitude of 350km and orbital period of 92 min were changed in Aug 2001 to 402km and 93 min (TRMM boost) [8]. Due to the lower altitude, the projected field of view of the LIS CCD onto Earth surface is 670 x 670 km. The OTD and LIS data sets have been broadly used by the scientific community in atmospheric sciences and lightning research. Main applications were in climatology and inter-comparisons between instruments and case studies on storm cloud scale. Intensive tests and validations on these sensors data have been performed with the aim to develop algorithms and methods for future sensors in space. For more information on OTD and LIS sensors, see Finke [1].

In 1997, a joint Los Alamos National Laboratory (LANL) and Sandia National Laboratories project launched the FORTE (Fast On-Orbit Recording of Transient Events) satellite in a circular, 825-km altitude with 70º inclination. Besides an optical lightning detection sensor of the same design as OTD and LIS, it carries a broad band photo diode and VHF receivers which allows for a combined optical and radio frequency lighting observations [10]. According to the large literature published about the project [11][12][13][14], FORTE's large RF antenna structure was supported by a 10-m long nadir-pointing antenna boom. Along the boom were mounted two passive orthogonal log-periodic antenna arrays designed to point the 25–50 MHz beam-lobe maximum at nadir with the first null of the electric-field-plane lobe at the limb of the Earth. In addition to its RF instruments, FORTE also had an Optical Lightning Sensor (OLS) on board. This included a broadband (0.4 – 1.1 μm) silicon photodiode detector (PDD) of 15 μs time resolution and a charge-coupled device imager, called the Lightning Location System (LLS). OLS data were Global Positioning System (GPS) time-stamped to a precision of 1 μs. The OLS field-of-view was 80º, providing a 1200-km diameter footprint on the Earth below. The LLS offered complementary information, in that it geo-located events to within 10 km and provided two-dimensional imagery, but only sampled the light at 2.5 ms intervals. The LLS front-end operated autonomously and included a narrow band 777.4 nm spectral filter. For a comprehensive description of FORTE satellite instrumentation and all its lightning observation capabilities and results, refer to Hamlin et al. [10].

Based on the FORTE, OTD and LIS projects previously described, it is now well stablished that detection of lightning events from space is feasible and can provided important datasets for lightning research and new space technology development. Based on those previous experiences, in this work, a new total lightning (CG and IC discharges) dataset provided by CubeSat satellite is proposed. This experiment intends to use: (1) a broad spectrum VHF radio antenna, (2) an imaging device (CCD) and, (3) a lightning detection system (LDS) to assess location and timing of the lightning event.

Since 2011, INPE operates an ENTLS (Earth Networks Total Lighning System) in Brazil, which is called the Brazilian Total Lighting Network (BrasilDAT). The main goal of this network is to introduce a new lightning detection technology in Brazil in the same way that has been done in USA and Europe, where two or more lightning detection networks operate simultaneously. The idea is to provide distinct lightning data (that come from different sources) in order to improve the lightning research and to allow a wider use of the information for several other institutions and companies. Figure 1 show the status of the present network, which is now composed of 56 operational sensors. The conclusion of the network deployment is expected by the second half of 2016, reaching more than 70 sensors and thus covering almost all Brazilian regions, including the Amazon area.

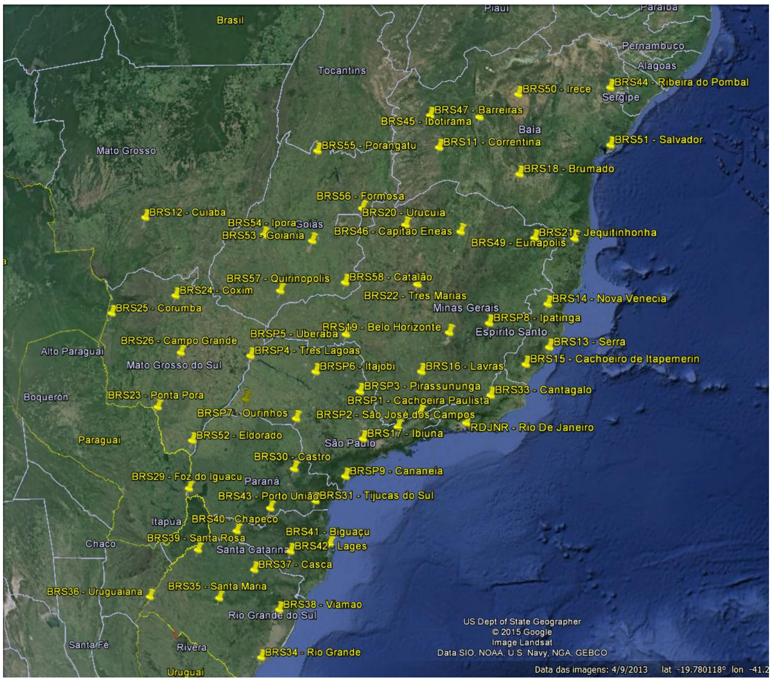


Figure 1. Present status of the BrasilDAT total lightning detection system with 56 installed sensors.

The BrasilDAT dataset will be used to the first validation the RaioSat dataset in terms of detection efficiency (DE), location accuracy (LA) and lightning type discrimination (LTD). Due to BrasilDAT network limitations (DE of 70-85%, LA of 400-900 m and LTD ~ 60%) [15][16], other lightning observation techniques can also be used to validate the RaioSat datasets: high-speed video cameras observations with fast electric-field measurements [17][18], and lightning mapper array (LMA) datasets [19][20], which is nowadays the most advanced lightning detection system available. The LMA is capable of detecting total lightning with very high detection efficiency (> 95%) and great location accuracy (< 100 m), providing also 3D images of the lightning propagation channel within the cloud and/or from the cloud towards the ground. However, the use of LMA dataset for the RaioSat dataset validation will require the deployment of a LMA sensor network in Brazil, an additional cost of about $ 250,000.

In the next sections, the RaioSat mission is described in details. A significant progress was made from the last work published previously in the 1st IAA-LACW [21]. Since the conceptual model is still under construction, many information presented in this paper is subject to change as a result of the future refinement of the model towards a feasible CubeSat mission.

The RaioSat Mission Analysis

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.

The current satellite prototype intends to use a 3-U cubesat platform in a circular orbit an inclination of about 25 degrees and 650km of altitude approximately. This result in a complete orbit is 98 minutes with a footprint over Brazil of approximately 15 to 20 minutes depending on the orbit. Since the satellite itself is not the main mission objective, it should be low cost and based on the open standard called CubeSat [22] [23].

Typically, in all space missions there are distinct groups with their own goals. Table 1 identifies these groups (key stakeholders) for RaioSat mission and their objectives. These stakeholders will interact and influence the overall outcome of this project

Table 1: Initial Key stakeholders for the RaioSat Mission

Stakeholder	**Objectives**
AEB	Coordinate space activities in Brazil
INPE	Implement innovative space missions and improve technology maturity levels as well as its readiness
CNPQ / FINEP/ FAPESP	Finance scientific projects with effective return-on-investments
CRC-INPE	Tracking, control and mission data operations
Brazilian Federal/Civil Agencies	Use lighting data for prevention, planning that maximizes benefits for the Brazilian society
Scientists from CCST-INPE	The Earth Science Research Center (CCST) - INPE, Brazil may improve the lightning research and to allow a wider use of the information

In order to define our Measures of Effectiveness (MoEs), we first list the expectations of key stakeholders that need to be captured and stated into the goals. The MoEs, acceptance criteria and qualification strategy for verification of those requirements will be defined from the objectives for each goal. Table 2 shows some of the identified goals and their respective MoEs.

Table 2: RaioSat Mission Goal and Preliminary MoEs

RaioSat Mission Goals	**Preliminary MoEs**
Collect data relative to lightning events	• Sampling rate of collected measurements • Correctness of geo-located events
Make the data collected available for INPE's scientists	• Coverage of datasets available • Percentage of scientists accessing datasets
Allow a wider use of the information for several other institutions and companies	• Number of access to public online datasets • Number of members in the download catalogue.
Correlate of the total lightning data provided by the CubeSat to the other available lightning datasets (BrasilDAT, high-speed cameras, LMA)	• Percentage of correlated hits • Correctness of events via modeling tools, if any

Following MoEs' definitions, we develop the operation concept description (OCD) of the RaioSat and the lightning detection system, that describes what operators and users want and how the conceived system and its elements will meet their needs [22]. The OCD, as shown in Figure 2 in a "as-is" and "to-be" way, is used to validate previously-defined goals, objectives, MoEs and qualification strategies. The OCD also works as a communication bridge of the Lightning Detection System among the various stakeholders associated as well as to develop and compare the current approach to the envisioned environment.

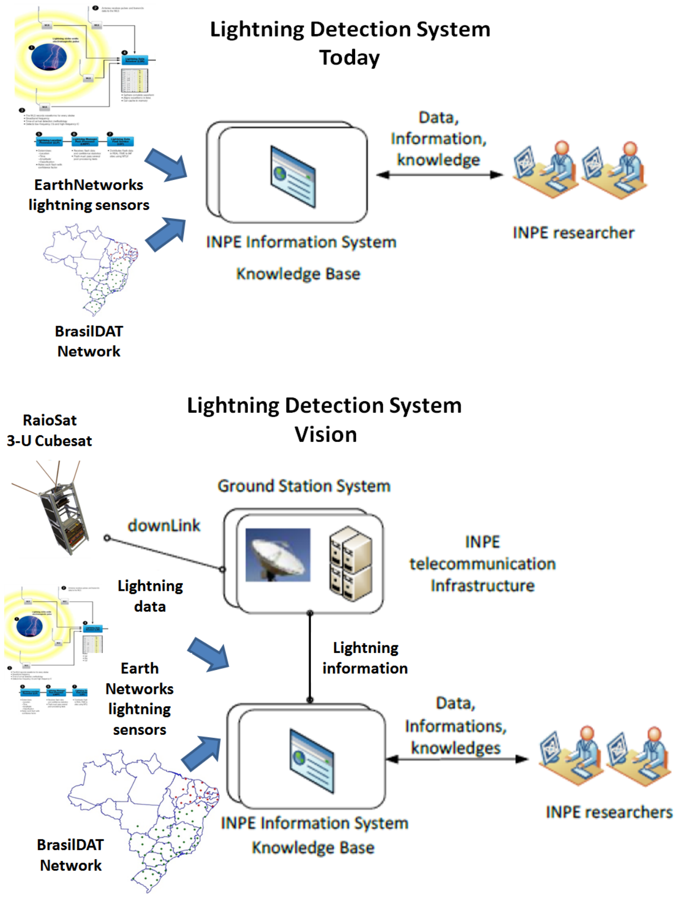


Figure 2. Operation Concept of the Lightning Detection System

The mission analysis is concluded when the function analysis is developed and the operation, or physical, architectures are delineated. Afterwards, detailed RaioSat stakeholders and systems requirements are defined. Therefore, the System Operational Architecture or Concept of Operations (ConOps) of the Lightning Detection System is depicted in Figure 3 where the main functions are listed as follows: (1) Launch System launches the RaioSat into an appropriate intermediate orbit inside the Poly-Picosatellite Orbital Deployer (P-POD); (2) P-POD ejects RaioSat to operational orbit; (3) RaioSat determines its orbit and attitude to ensure the conditions for operation and signals the Ground Station to start mission operations; (4) RaioSat performs systems checks; (5) RaioSat, in nominal operation, measures the VHF signal as well as captures CCD images and geo-location of prospective lightning activities and sends them to Ground Station; (6) Ground Station receives the detections and processes data into information; (7) Ground Station distributes lightning information to researchers via INPE´s portal networked system; (8) Researchers access lightning information and cross-check with BrasiDAT logs; (9) Researchers studies how lightning may affect the systems on earth; (10) Ground Station operator upload commands for the Cubesat provide a controlled re-entry through the Earth's atmosphere.

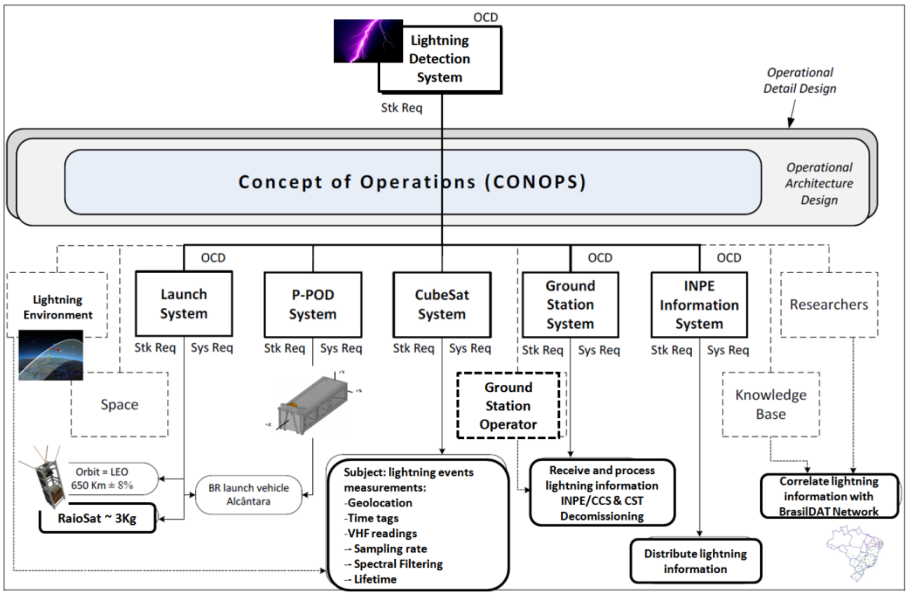


Figure 3. Concept of Operation (ConOps) of the Lightning Detection System

The RaioSat Life Cycle Analysis

All project phases from its inception to its end are described in the project life-cycle. The analysis commences with a high level description of the system life-cycle and breaks down each process life-cycle into the key scenarios through which the system undergoes throughout its lifetime. Relevant scenarios are defined basically as those that either will imply in different elements in the interacting in-situ environment of the system or in different stakeholders affected or affecting the system in that scenario.

A typical CubeSat life-cycle can be divided in the following stages [24]:

- CubeSat development - identify stakeholders' needs, propose viable

solutions, define system requirements, create solution description, build system, verify and validate system;
- CubeSat Manufacturing;
- CubeSat logistics - storage, handle, transport and launch provision;
- CubeSat operation - launching, P-POD ejection, orbit acquisition, operational test, nominal operation, and
- Re-entry through the Earth's atmosphere.

The system engineering method is applied for product and organization where for every scenario defined in the systems life-cycle analysis it should be concurrently performed. In order to exemplify the systems engineering process for the RaioSat using this method, this work covers only RaioSat nominal operation scenario. In this scenario the RaioSat measures the VHF signal, captures CCD images and geo-tags all prospective lightning activities and sends them to Ground Station. Therefore, the RaioSat basically switches modes during a nominal operation scenario as envisaged in Figure 4.

The collected total lightning data will be decoded, validated and stored in a database and the final products will be distributed, both via real-time and historical data series, by web applications running in a dedicated desktop.

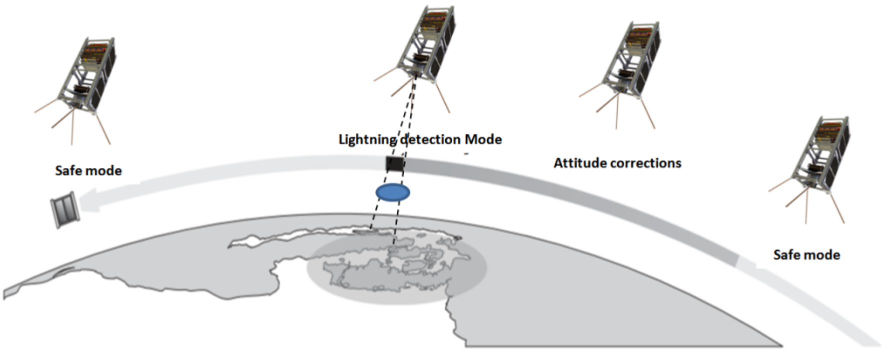


Fig. 4 - Envisaged RaioSat mode switchings during a nominal operation scenario

RaioSat System Stakeholder Analysis

The main input for the stakeholder analysis is the life-cycle decomposition in scenarios where a breakdown of each sub-process or scenario corresponds to a product during that sub-process. The technique employed for the stakeholder analysis is the same used in Arnaut et al. [24] where this is performed by casually asking questions for each scenario considered in this work.

Afterwards, for each stakeholder identified in this method, it is asked basically what are their desires, goals, worries, wishes, and needs. The answers are the stakeholder concerns, summarized in Figure 5 for both product and organization´s point of view.

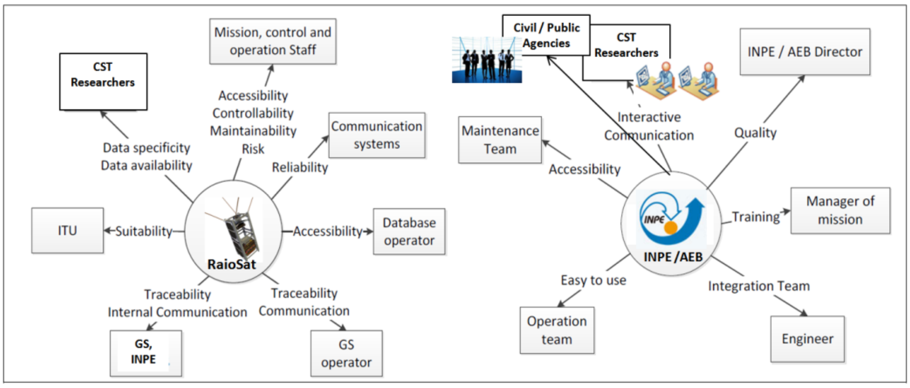


Fig. 5 - RaioSat stakeholders concerns for nominal operation scenario, adapted from Arnaut et al. [24].

The aspects, metrics and measures of effectiveness (MoEs) are got from each stakeholder's concerns using the Goal, Question, Metric technique. For instance, availability and easy to use feature are identified for CST Researchers and operation team concerns from RaioSat (product) and INPE (organization) points of view respectively. The following aspects are analyzed and metrics are defined. From the concerns and MoEs, the stakeholders' needs are derived, and then translated into stakeholders' requirements, for example, ease of access demands: (a) training – annual training for operators; (b) planning – time work; and (c) manuals – clarity, online procedures.

RaioSat System Functional Analysis

The first step in the Functional Analysis consists in creating a context diagram for each decomposed life-cycle scenario, and identifying the elements in the system environment and the flows of energy, material or information between them, as described in Figure 6. This type of analysis is part of the eliciting requirements process but it is restricted just to a functional point of view.

The data context diagram and the control context diagram are developed from the context diagram and they allow visualizing the connections between the system and the environment elements as well as extracting the system essential functions.

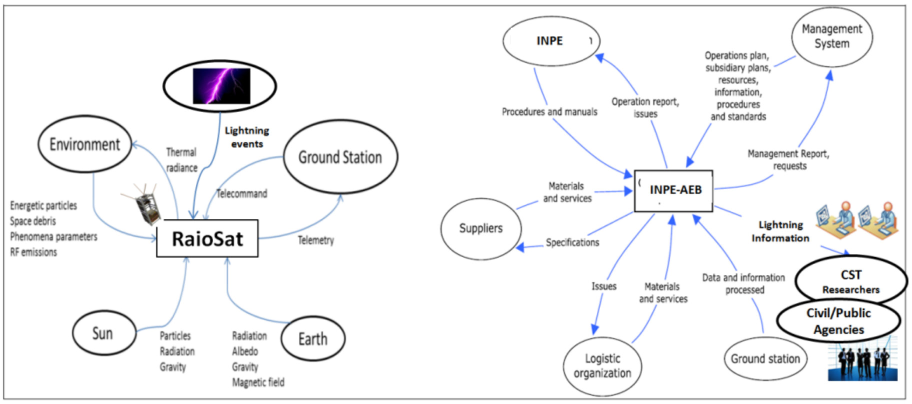
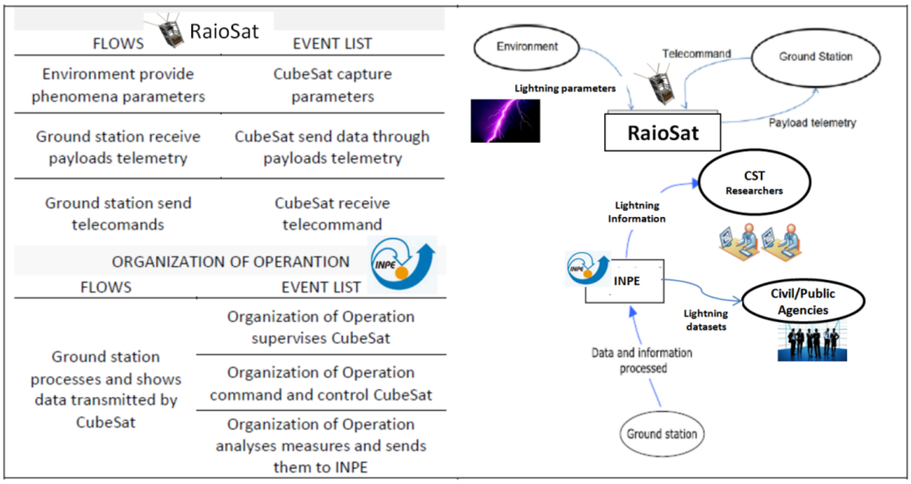


Fig. 6 - RaioSat functional context diagram in nominal operation scenario, adapted from Arnaut et al. [24]

Afterwards, it is recommended the development of circumstances analyses, which are typically combinations of the possible elements' attributes values in the environment and system context flows. The essential function diagram and the event list mode are developed based on the presented context and modes analysis. The event function diagram shown in Figure 7 represents the basic RaioSat (Product) and INPE (Organization) functions that justify its existence. The essential function diagram can be expanded and other secondary functions added to the system as a break-down to the essential functions. Figure 8 illustrates an example for CubeSat Product data flow diagram whereas Figure 9 depicts an example for the underlying organization data and control flow diagram.

Finally, a physical concept and an interface diagram can be developed from the previous analyses and an initial system architecture representation can be displayed as shows Figures 10 and 11 for the physical concept and an interface diagram for the RaioSat (product) and its underlying organization. At this stage, hazard and risk analyses can be performed for the system level, considering the breakdown of functions during the process. This topic is now out of the scope of this work.



RaioSat

FLOWS	EVENT LIST
Environment provide phenomena parameters	CubeSat capture parameters
Ground station receive payloads telemetry	CubeSat send data through payloads telemetry
Ground station send telecomands	CubeSat receive telecommand

ORGANIZATION OF OPERANTION

FLOWS	EVENT LIST
Ground station processes and shows data transmitted by CubeSat	Organization of Operation supervises CubeSat
	Organization of Operation command and control CubeSat
	Organization of Operation analyses measures and sends them to INPE

Fig. 7 - RaioSat event list with essential function and context diagram, adapted from Arnaut et al. [24]

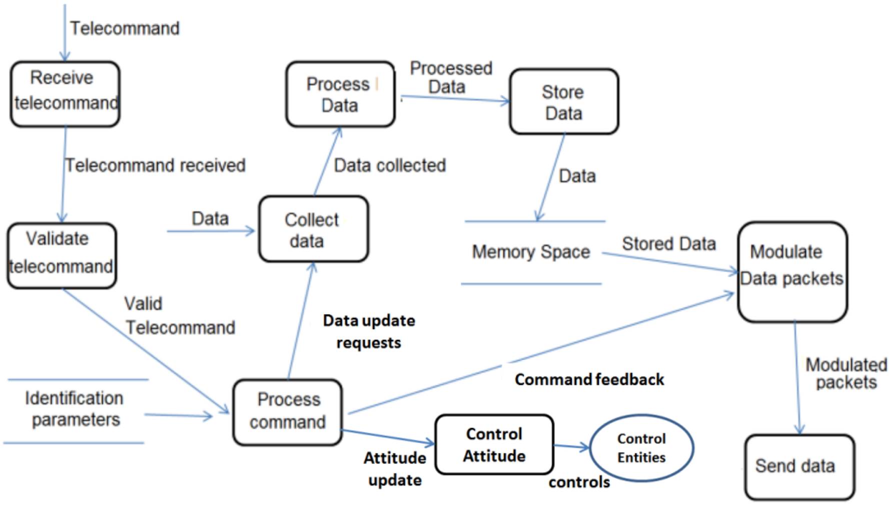


Fig. 8 - RaioSat event list with essential function and context diagram, adapted from Arnaut et al. [24]

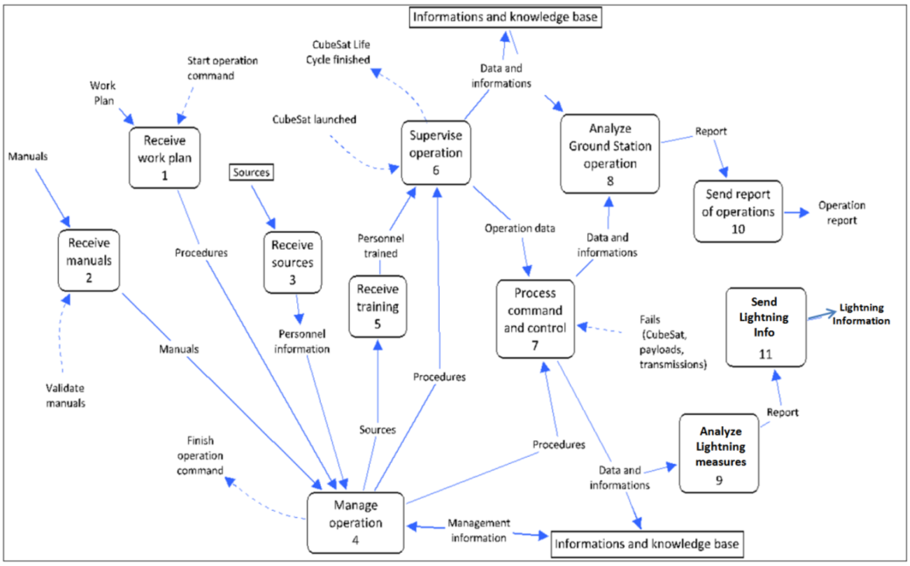


Fig. 9 - RaioSat operation organization data and control flow diagram, adapted from Arnaut et al. [24]

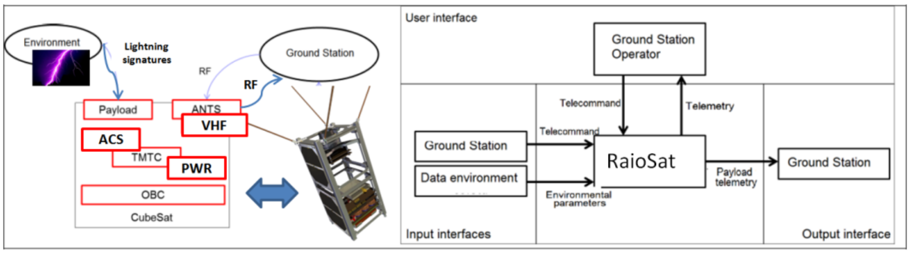


Fig. 10 - RaioSat architecture (physical / interface diagram), adapted from Arnaut et al. [24]

Behavior analysis is performed through state identification and transition diagram. The states identified for the CubeSat are simple, for example: a payload exposed or not exposed to space environment could be two different states. For the operation organization, the states are identified to start, operate and finish the mission. Figure 12 shows the state transition machine. The functional analysis results are synthesized in the system requirements.

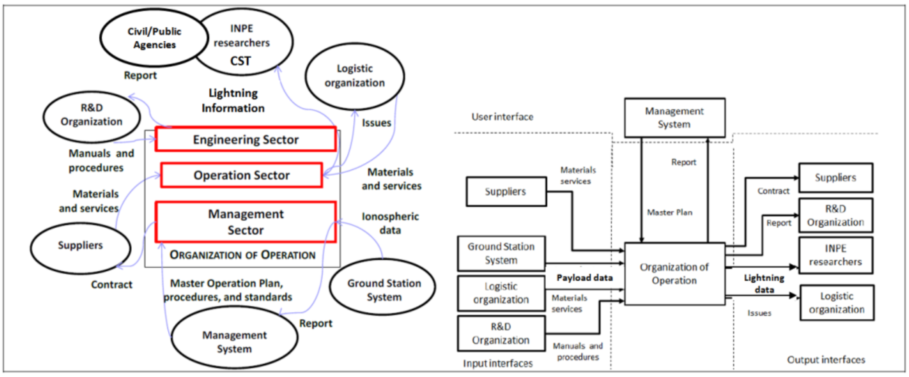


Fig. 11 - RaioSat operation organization architecture (physical and interface diagram), adapted from Arnaut et al. [24]

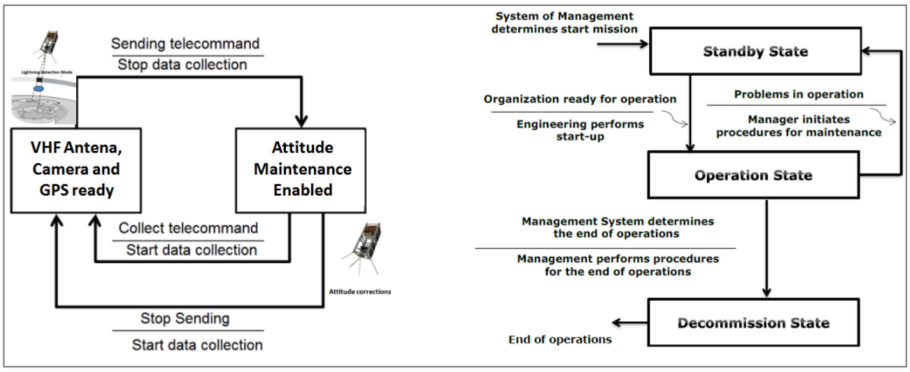


Fig. 12 - RaioSat state transitions machine (product and organization operation), adapted from Arnaut et al. [24]

Preliminary RaioSat System Architecture and Testing

In order to highlight the interfaces between the RaioSat subsystems as well as its organizational counterpart, the analysis results are then synthesized in specific physical architectures: architecture flow diagram and architecture interconnect diagram which are sketched in Figure 13 for both product and organization perspectives.

The allocation of functions to architecture physical elements makes the derived system requirements to be realized into the physical component directly. Once the requirements are set for each component (subsystem), this allows systems engineers to estimate some technology implementation alternatives and further elaborate a trade-off analysis.

In this project these considerations have been partially taken and decisions on whether to make-it or buy-it indicates that, for prototyping and mission demonstration, using COTS (Commercial off-the-shelf) in both 3-U platforms and payloads is the way to proceed. As a result, the envisaged RaioSat satellite structure and elements for integration is preliminarily shown in Figure 14.

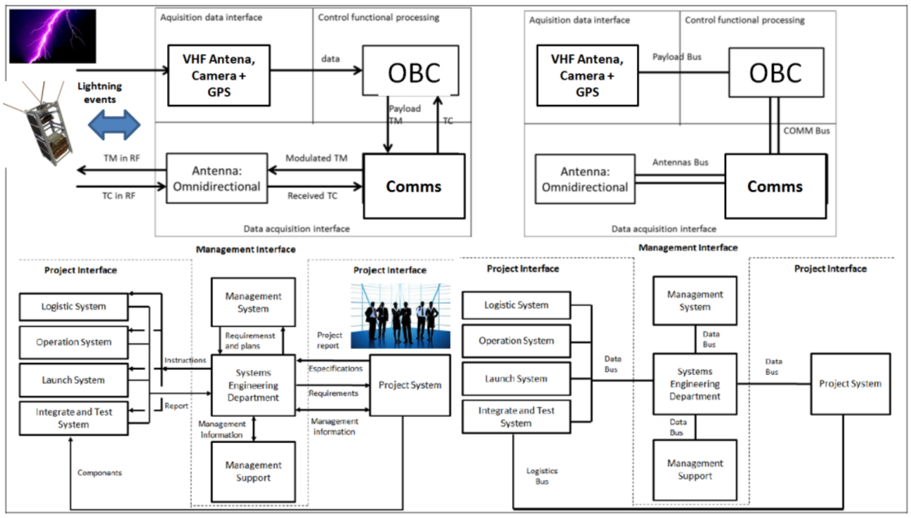


Fig. 13 - RaioSat Physical architecture interfaces for product and organization, adapted from Arnaut et al. [24]

For the RaioSat System, a new total lightning dataset (cloud-to-ground and intra-cloud discharges) provided by the onboard system is being prototyped and it intends to use:

- A broad spectrum radio antenna (in the range of tens of kHz to hundreds of MHz) to detect the electromagnetic emissions of the radioactive component of the lightning discharges. Therefore, the RaioSat shall have a VHF passive antenna, ranging from 50 to 200MHz.
- The spectral imaging camera (SIC), an imaging device (CDD), since the visible emission of the lightning flashes can be detected from space, as previously discussed. The SIC demands high-performance image processing capacity and large data storage memory and its resolution shall be 2,048 x 1,536 pixels leading to a surface imaging of 80 m/pixel at

650km altitude. Also SIC shall have a spectral range from 700 to 900nm using a band-pass optical filter

- Finally, a GPS is required to tag location and timing of any prospective lightning event.

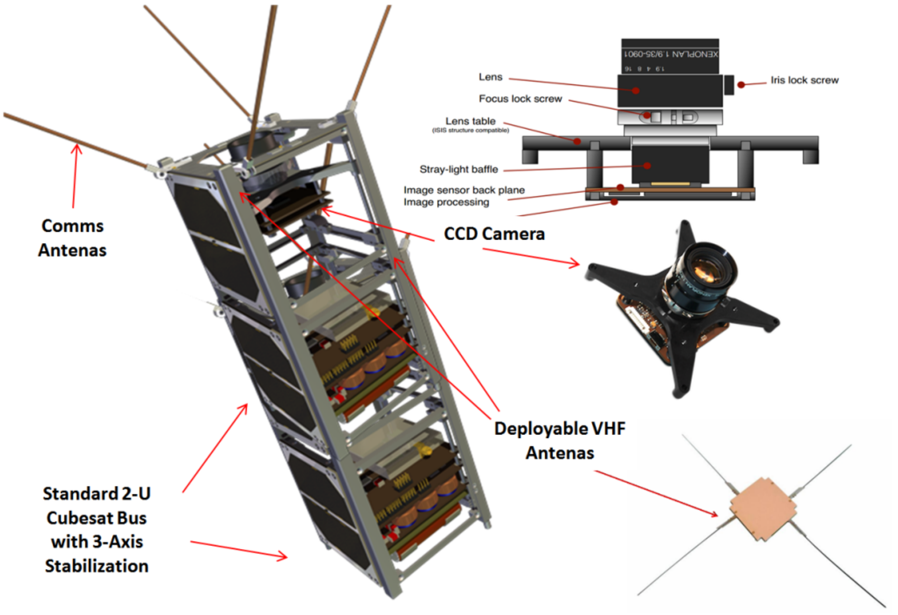


Fig. 14 - Preliminary structure and payload elements for the RaioSat system.

Major developments are going to concentrate in the on-board software, detection algorithms and components integration efforts. Major challenges envisaged will be related to: (1) Integration of a suitable VHF Antenna; (2) Spectral Filtering from CCD-Camera and, (3) Prospective on-board algorithms for discarding false-positive lightning events in advance.

Concerning the test requirements for the RaioSat system, the CubeSat Design Specification (CDS) [25] will be used as a guideline. Therefore, testing will be performed to meet all launch provider requirements as well as any additional testing requirements deemed necessary to ensure the safety of the RaioSat, P-POD, and the primary mission.

Since at this stage the launch vehicle environment is unknown, the documents suggested, The General Environmental Verification Standard (GEVS, GSFC-

STD-7000) and MIL-STD-1540, can be used to derive testing requirements. As a good practice the CDS says that test requirements and levels that are not generated by the launch provider or P-POD Integrator are considered to be unofficial. Hence, the launch provider testing requirements will supersede testing environments from any other source. Furthermore, the P-POD will be tested in a similar fashion to ensure the safety and workmanship before integration with the RaioSat. At the very minimum, RaioSat will undergo the suggested test schedule as shown in Figure 15.

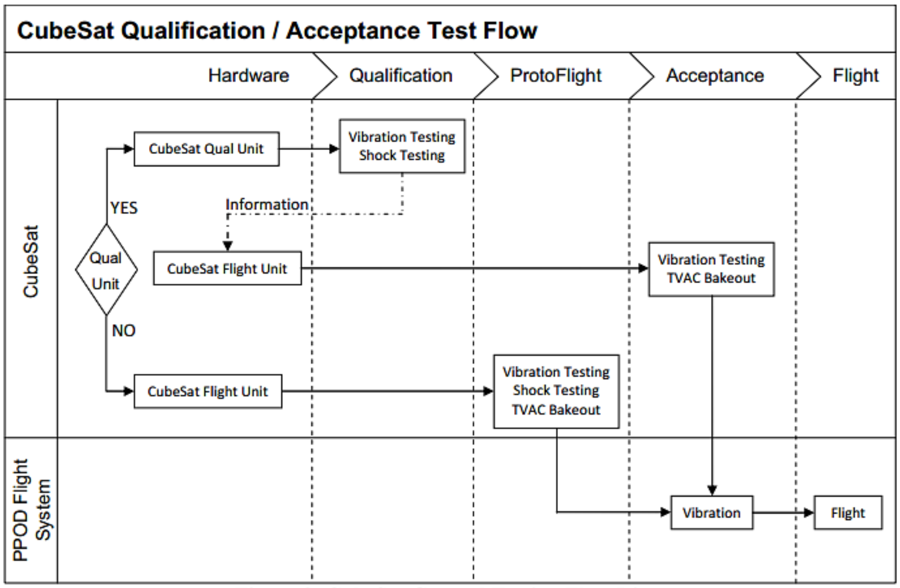


Fig. 15 - Suggested test planning for the RadioSat system, adapted from PolyCal [25].

Conclusions

This paper briefly described The RaioSat project, a 3-U CubeSat-based project which integrates Earth System Sciences research, namely the total lightning detection for regions over Brazil, with some space technological development.

Based on the FORTE, OTD and LIS projects previously described, it is now well stablished that detection of lightning events from space is feasible and can provided important datasets for lightning research and new space technology development. The RaioSat project is expected to be then an important starting point for future researches and developments in the areas of

Earth System Sciences and Space Engineering Technologies at INPE-Brazil.

Predicting extreme weather phenomena requires high-resolution numerical weather prediction (NWP) models and high amount of observational data, including lightning datasets. This joint project allows, for the first time in Brazil, the developing of national technology for environmental remote sensing for lightning 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 character in climate change.

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