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Total Lightning Flash Detection from Space

A CubeSat Approach

Kleber P. Naccarato
Earth Science System Centre (CCST)
INPE
São José dos Campos, Brasil
kleber.naccarato@inpe.br

Walter A. Santos / Miguel A. Carretero
Candido Moura / Auro Tikami
Space Engineering and Technologies (ETE)
INPE
São José dos Campos, Brasil

Abstract—**The RaioSat project intends to detect 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. 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 at 650km 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 on-board 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) with resolution of 2,048 x 1,536 pixels leading to a surface imaging of 80 m/pixel. Also SIC shall have a spectral range from 700 to 900nm using a band-pass optical filter. Additionally, the paper briefly describes all the main stages of the space mission over the system life-cycle.**

Keywords—lightning; cubesat; detection; technology; space; VHF; optical; thunderstorms.

I. 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 (Finke, 2009).

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 (Rakov & Uman, 2003). 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 (Uman, 1969; Orville and Henderson, 1984; Luz, 2015), 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 (Orville and Henderson, 1984). According to Guo and Krider (1982), 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 of 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. The peak power for the whole channel were about 2×10^9 W. 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 (Guo & Krider, 1982).

The optical source pulse is transformed along its path through the atmosphere. While its spectrum remains almost unchanged, its main physical characteristics are strongly affected by the scattering of the cloud particles (Christian & Goodman, 1987). According to several theoretically and numerically (using Monte Carlo simulations) studies, the optical signal at the cloud upper surface is delayed and broadened according to the total optical path it propagates. Thus there is a function which describes the radiance of the optical pulse as function of space, time and direction. This function then is used as the input for a detection device on board of a satellite. Typically, the spatial pattern of the optical pulse is blurred by scattering to a size of about 5-10km

(Goodman et al. 1988). Moreover, the optical pulse is delayed and widened by the scattering process. Typically, the delay times are around 100 μs. Additionally, mean rise time values of about 150 μs and pulse width values of about 400-500 μs were reported by Christian & Goodman (1987). These authors also observed that the radiation energy density of the signal at the 777.4 nm line is of 3×10^{-6} J.m^{-2}.sr^{-1}. On the other hand, they also observed that 90% of the flashes have optical pulses with an energy density larger than 4.7×10^{-6} J.m^{-2}.sr^{-1} at 868.3 nm.

The concept of a dedicated lightning location sensor on board of satellites with the aim of geostationary detection has been developed since the 80s (Christian et al. 1989). 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 70º 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 (Christian et al. 2003). The LIS (Lightning Imaging Sensor) is part of the Tropical Rainfall Measuring Mission (TRMM) satellite, which was launched in November 1997 (Hummerow et al. 1998). 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) (Christian et al. 2003). 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 further information on OTD and LIS sensors, please refer to Finke (2009).

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 (Hamlin et al. 2009). According to the large literature published about the project (Jacobson et al. 2000; Suszcynsky et al. 2000; Light et al. 2001; Suszcynsky et al. 2001), 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 m) 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 1μs. 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. (2009).

According to the huge amount of studies based on data from the FORTE experiment (Hamlin et al. 2009), satellite-borne RF observations suffer from many constraints and complications to which ground-based systems are immune:

- The propagation path from the source (lightning flash) to the satellite crosses the ionosphere, leading to spectral dispersion of the VHF signal, particularly below 30 MHz. Moreover, 20 MHz is the practical limit below which signals from terrestrial lightning cannot be reliably studied by satellite;
- The satellite VHF detection is subject to a huge source of background noise, against which the lightning signals must compete. As a result, only lightning VHF signals of moderate to high power can be studied;
- Single-satellite VHF observations are not enough to locate lightning For interpretation of the VHF signals, source location assessed by alternate methods is highly encouraged. As examples, joint satellite VHF / ground-based array observations or joint both satellite VHF / optical observations;

On the other hand, satellite-borne VHF observations have some unique advantages over ground-based systems:

- Within the limitations of the orbit, satellites offer very large or global coverage;
- When an intracloud discharge is located by some other technique, the recorded RF signal contains information on the emission altitude;
- Since the satellite is moving and lightning source locations vary, the satellite obtains data from a variety of elevation angles. This diversity of elevation angles facilitates inference of the VHF emission lobe for different lightning processes

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.

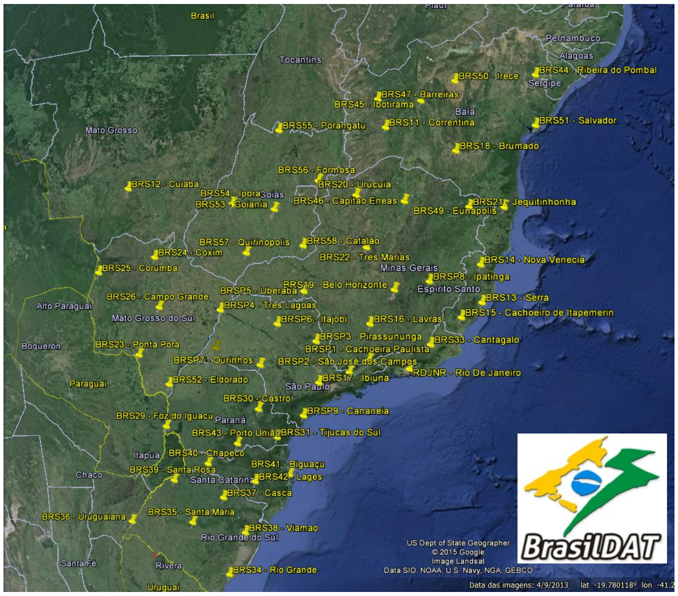

Fig. 1. Present sensor configuration of the BrasilDAT total lightning detection system with 56 installed sensors.

The RINDAT network (from Vaisala technology) was the first lightning location system (LLS) deployed in Brazil. It started its operation in 1988 by CEMIG with only 4 LPATS-III sensors in Minas Gerais State. Throughout the following years, SIMEPAR, FURNAS and INPE joint the RINDAT consortium to extend and upgrade the network. In 2001, the RINDAT network used to be composed of 16 sensors setting up a hybrid network of LPATS-III, LPATS-IV and IMPACT-141T/ES/ESP sensors. By 2010, RINDAT expanded to 35 sensors after the addition of SIDDEM sensors. In 2010, INPE added 2 LS-7000 to the network and in 2011/2012 added more 5 LS-7000, replacing old IMPACT 141-T/ES/ESP sensors. In 2011, FURNAS acquired 4 LS-8000 sensors and built the first total lightning network in Brazil using Vaisala's technology. SIMEPAR started to replace its LPATS-III sensors to LS-7001 and also purchased an additional LS-8000 sensor that was integrated to FURNAS VHF network. Right now, CEMIG and FURNAS are upgrading their old LPATS-III/IV sensors to LS-7002. Figure 2 and 3 shows, respectively, the present and the 2017-projection of the RINDAT sensor configuration.

Both BrasilDAT and RINDAT datasets will be used to the validation the RaioSat preliminary data in terms of detection efficiency (DE), location accuracy (LA) and lightning type discrimination (LTD). Due to both networks limitations (DE of 70-85%, LA of 400-900m and LTD ~ 60-80%) (Naccarato & Pinto Jr., 2008; Naccarato et al. 2008; Naccarato et al. 2014), other lightning observation techniques can also be used to validate the RaioSat datasets: high-speed video cameras observations with fast electric-field measurements (Saba et al., 2006, 2010), and lightning mapper array (LMA) datasets (Rison et al., 1999; Thomas et al. 2000), 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.

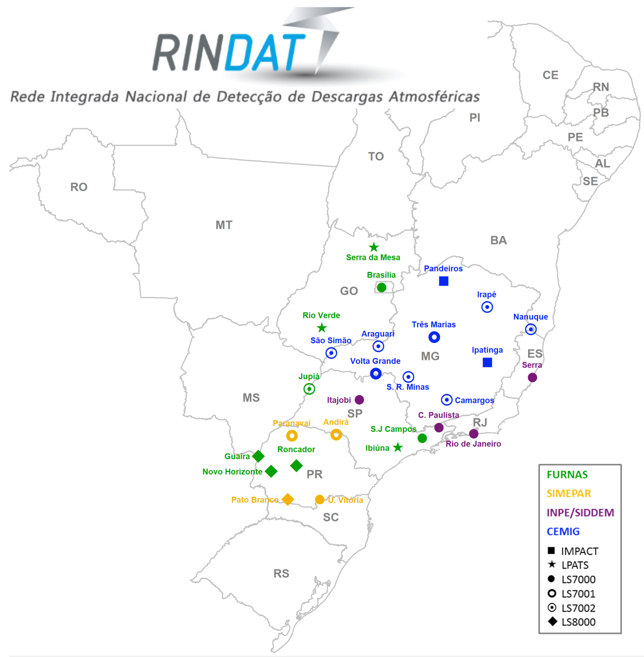

Fig. 2. Present sensor configuration of the RINDAT lightning detection system with 27 installed sensors.

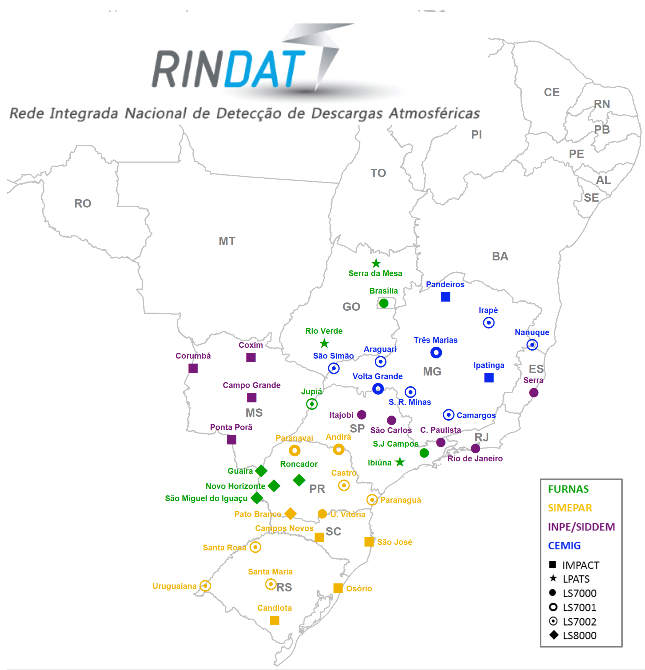

Fig. 3. Projected sensor configuration RINDAT for 2017 reaching 42 installed sensors.

In the next sections, the RaioSat mission is described. A more comprehensive discussion of all the steps of the mission analysis, please refer to Naccarato et al. (2016). In general, the current satellite prototype intends to use a 3-U cubesat platform in a circular orbit an inclination of about 25º and 650 km of altitude approximately. This result in a complete orbit is 98 min with a footprint over Brazil of approximately 15 to 20 min 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 (Larson et al., 2009; PolyCal, 2015).

The RaioSat satellite mission goal is primarily to detect both intra-cloud and cloud-to-ground lightning flashes simultaneously using a spectral imaging camera (SIC) 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.

II. System Engineering – The RaioSAT Project

A. Main Overview

System Engineering is an engineering technique applied to develop complex systems like a car, an airplane or a satellite. The first step in system engineering applied to a space mission is the mission analysis where we identified the principal players involved to the mission; the key stakeholders, theirs goals and establish the measures of effectiveness (MoEs) that will quantify how well the system will meet these goals; develop an operational concept description (OCD), that describes what operators and users want and how the conceived system and its elements will meet their needs and finally; we develop the function analysis and delineate the system physical architecture.

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 I. 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 II. 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

The operation concept description (OCD), as shown in Figure 4 in a "as-is" and "to-be" way, is used to validate previously-defined goals, objectives, MoEs and qualification strategies (Larson et al., 2009). The System Operational Architecture or Concept of Operations (ConOps) of the Lightning Detection System is depicted in Figure 5 where the main functions are listed.

B. The RaioSat Life Cycle Analysis

All project phases from its inception to its end are described in the project life-cycle. A typical CubeSat life-cycle can be divided in the following stages (Arnaut et al., 2013):

- 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.

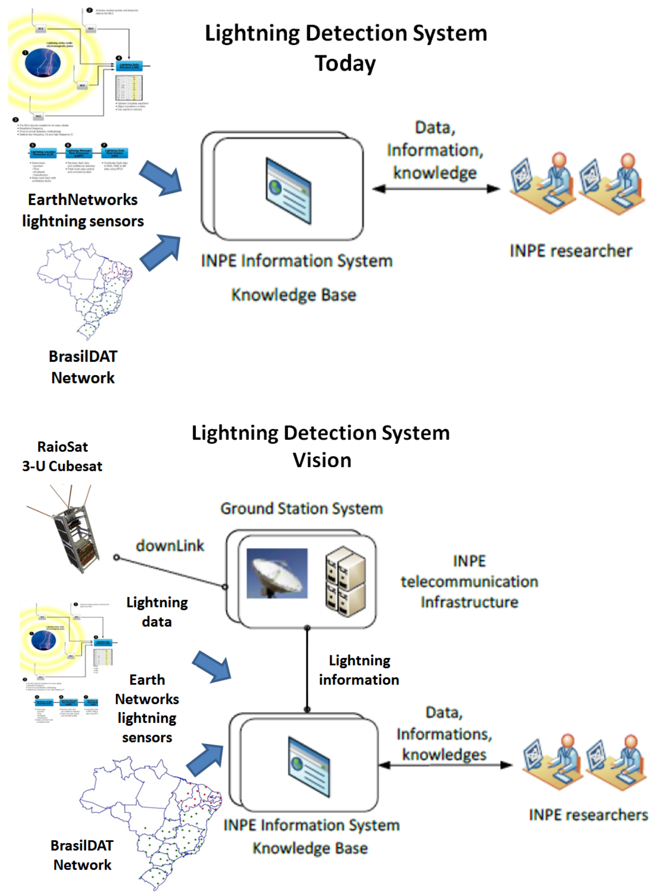

Fig. 4. Operation Concept of the Lightning Detection System.

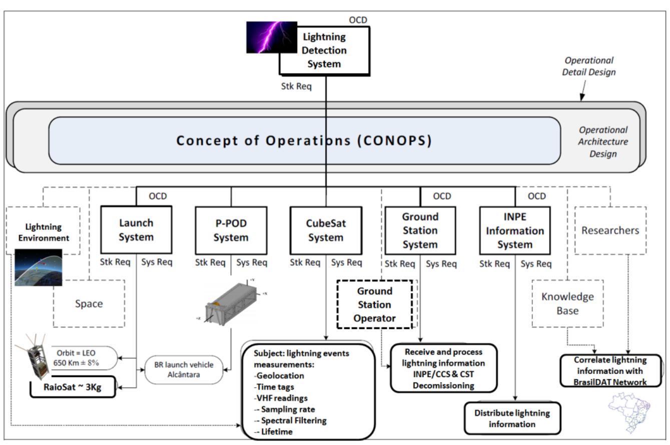

Fig. 5. Concept of Operation (ConOps) of the Lightning Detection System

C. 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.

In order to exemplify the systems engineering process for the RaioSat, 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.

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 6 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 7 illustrates an example for CubeSat Product data flow.

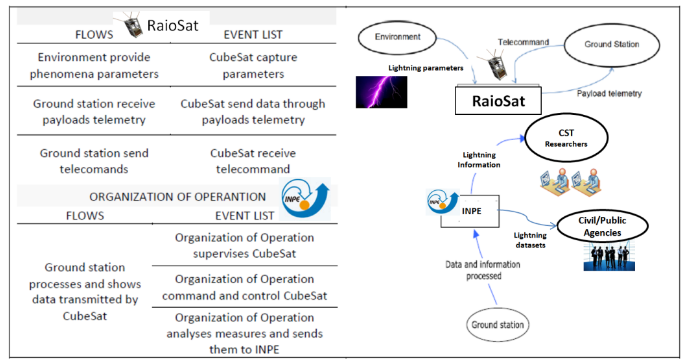

Fig. 6. RaioSat event list with essential function and context diagram

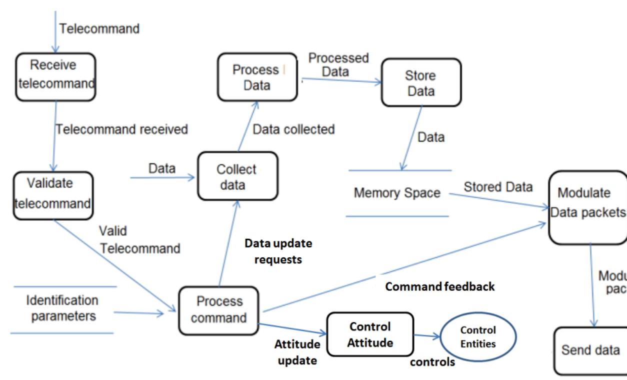

Fig. 7. RaioSat event list with essential function and context diagram

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 8 from where the physical concept and an interface diagram for the RaioSat (product) and its underlying organization can be derived.

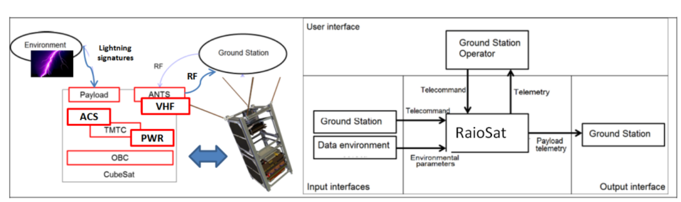

Fig. 8. RaioSat architecture (physical / interface diagram)

D. 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. The allocation of functions to architecture physical elements makes the derived system requirements to be realized into the physical component directly which 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 9.

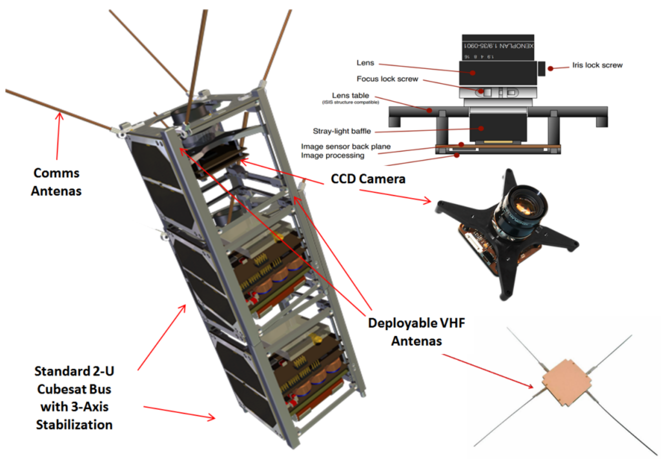

Fig. 9. Preliminary structure and payload elements for the RaioSat system.

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.

III. 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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