DEVELOPMENT OF A CUBESAT FOR TOTAL LIGHTNING FLASH DETECTION FROM SPACE: RAIOSAT MISSION - PRELIMINARY RESULTS.

Antonio Cassiano Julio Filho[(1)], Marcus Vinicius Cisotto[(2)], Auro Tikami[(3)], Ângelo José Augusto Florentino[(4)], Moara de Oliveira[(5)], Antonio Ferreira de Brito[(6)]

[(1,2,3,4,5,6)] National Institute for Space Research (INPE), São José dos Campos, São Paulo - Brasil, 55 12 32086615, [(1)]cassiano.filho, [(2)]marcus.cisotto, [(3)]auro.tikami, [(4)]angelo.florentino, [(5)]moara.oliveira, [(6)]antonio.brito [@inpe.br]

***Keywords**: CubeSat, RaioSat, Lightning flashes, detection, technology*

The National Institute for Space Research (INPE), within its competences, can promote means of technological and scientific development by meeting internal and external demands through project coordination, mission analysis, management and development, such as remote sensing satellites (CBERS family, Amazonia-1) and the small satellites for educational and technological applications, for example, Tancredo-1 and the mission RaioSat. The Tancredo-1 is a small satellite developed by Brazilian students with support from INPE and successfully placed in Low Earth Orbit, in 2017, from the International Space Station. The mission RaioSat is a joint work between Earth Science System Centre (CCST) and Space Engineering and Technology (ETE), and others INPE's areas to support the multidisciplinary activities. The RaioSat mission aims to detect the intra-cloud and cloud-to-ground lightning flashes simultaneously (total lightning data) over the Brazilian territory. The information collected from the lightning detection it is useful for predicting extreme weather phenomena, complementing the data for the high-resolution Numerical Weather Prediction models and the Brazilian meteorological networks, called BrasilDAT. The mission is being planned for a CubeSat 3U with a lifecycle of less than one year in a Low Earth Orbit about 650 km altitude with inclination between 70° and 98°. The RaioSat satellite consists of two modules, one for service, and the other for payload. The service module comprises an Onboard Computer, a Communications Subsystem, an Attitude Determination and Control System, and an Electric Power Subsystem. The Payload Module comprises a Spectral Mapping Camera with 2048 x 1536 pixels of resolution, a VHF Receptor with a Passive Antenna in a frequency from 80 to 200 MHz, and includes and a Global Position System. This paper presents an overview of the RaioSat Mission and its scientific objectives and describes the preliminary results obtained during the development of a prototype, with emphasis on communication subsystem, onboard computer subsystem and Global Position System; and in the implementation of communication protocol for uplink and downlink with the Ground Stations. Also it describes the integration of the prototype to the Brazilian Data Collection System Simulator, a system that allows testing and evaluation of the dynamic behavior of the elements that make up the data flow between satellites and Ground Stations. Finally, the contributions and limitations, design´s status, lessons learned and suggestions for future works are presented in this paper.

1. Introduction

The National Institute for Space Research (INPE), within its competences, can promote means of technological and scientific development by meeting internal and external demands through project coordination, mission analysis, management and development, such as remote sensing satellites (CBERS family, Amazonia-1) and the small satellites for educational and technological applications, for example, Tancredo-1 and the mission RaioSat. The Tancredo-1 is a small satellite developed by Brazilian students with support from INPE and successfully placed in Low Earth Orbit, in 2017, from the International Space Station.

The mission RaioSat is a joint work between Earth Science System Centre (CCST) and Space Engineering and Technology (ETE), and others INPE’s areas to support the multidisciplinary activities.

The detection and geolocation of lightning flashes are important for a wide variety of applications and in several areas of scientific research. Among the main ones, we can mention the very short-term forecasting systems for the occurrence of severe atmospheric events, identification of damage to structures and definition of protection standards, risk analysis of accidents involving deaths and fires, scientific research on atmospheric phenomena of the terrestrial system, determination of economic and social impacts through insurance claims, electricity interruptions and forensic data.

Typical users of lightning information include universities, research institutes, meteorological agencies and institutes, civil aviation companies, military agencies (air traffic control and space launch facilities), environmental and natural resource management agencies, electricity transmission and distribution operators [1].

The sensors on board satellites allow wider coverage, detecting lightning flashes with the same efficiency and temporal and spatial resolution that a detection system installed on the ground, called BrasilDAT [2].

This document is organized as follows: section 2 presents the RaioSat Mission, explaining its objective and the space segment; section 3 presents the Service Module; section 4 provides the Payload Module; section 5 explains about the Product Breakdown Structure and Physical Architecture; the section 6 presents the preliminary results for prototype and finally the conclusions.

2. The Mission RaioSat

The RaioSat mission aims to detect the intra-cloud and cloud-to-ground lightning flashes simultaneously (total lightning data) over the Brazilian territory. The information collected from the lightning detection it is useful for predicting extreme weather phenomena, complementing the data for the BrasilDAT high-resolution Numerical Weather Prediction models.

An atmospheric discharge is essentially an impulsive electric current of great proportions that occurs in the Earth's troposphere as a consequence of the electrification (separation of electrical charges) of the so-called storm clouds or cumulonimbus and radiate electromagnetic energy over a wide range of frequencies [3].

The RaioSat mission intends to integrate for the first time a sensor for detecting lightning in a CubeSat, with the development of national technology for detecting lightning from space and complementing the existing data from the Brazilian meteorological networks.

The figure 1 shows the main elements of RaioSat Mission: the Space Segment, the Launch Segment and the Ground Segment.

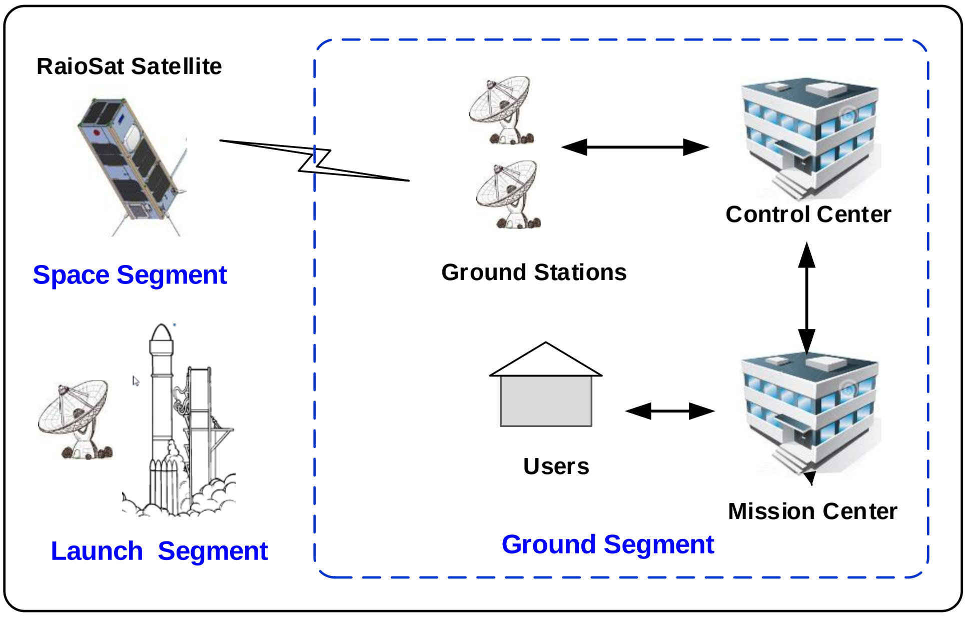

Figure 1: Elements of RaioSat Mission [1].

The RaioSat satellite is based on a CubeSat 3U structure (10 x 10 x 30 cm), it is being planned for a lifecycle of less than one year in a Low Earth Orbit (LEO) about 650 km altitude with inclination between 70° and 98°.

The RaioSat satellite consists of two modules, one for service, and another to payload. The service module comprises an Onboard Computer, a Communications Subsystem, an Attitude Determination and Control System, and an Electric Power Subsystem [4]. The Payload Module comprises a Spectral Mapping Camera [5], a VHF Receiver and a Global Position System Receiver.

3. Service Module

This section describes briefly the Onboard Computer, the Communications Subsystem, the Attitude Determination and Control Subsystem, and the Electric Power Subsystem.

The Onboard Computer of RaioSat will be performed by the RISC processor of the ARM9 family of 32 bits and 400 MHz on a dedicated printed circuit board and software based on Real-time Operating System - freeRTOS. The Onboard Computer will be responsible for performing the following tasks [1]:

- Supervision: ensure, in the event of failure, contingency actions are taken.
- Scheduling: Store and perform tasks previously scheduled by telecommands.
- Reception: Perform demodulation and data retrieval of telecommands.
- Housekeeping: Collect the diagnostic information of the satellite subsystems.
- Log: Generate a log of events.
- Deployment: Extend the moving parts of the system.
- Beacon: Enable transmission of beacon signal from RaioSat.
- Downlink: Transmitting telemetry.
- Payload: Manage payload activities.

The Communications Subsystem is responsible for the exchange of information between the satellite and the ground segment by uplink and downlink that will operate in UHF band. The International Telecommunications Union (ITU) will coordinate the frequency of operation of RaioSat.

In small satellites it is quite advantageous that the communication between satellite and the ground segment occurs within the UHF band of amateur radio, as the data of RaioSat may also be received by the radio amateur community. The International Amateur Radio Union (IARU) is responsible for frequency pre-coordination for a satellite operating in the aforementioned UHF band.

Communication must be carried out via a programmable half duplex transceiver in the 430 to 440 MHz UHF band of high performance and low consumption. The receiver must have high sensitivity (around -118 dBm @ 9600 bps) and the transmitter must allow data communication in narrowband channels with modulation to be defined between GFSK, FM and FSK, with the data rates will be 9600 bps using the AX.25 protocol.

The Attitude Determination and Control System (AOCS) is essential when pointing is necessary, such as when using cameras pointed towards Earth. It is also essential in the alignment of other devices such as solar panels and antennas in space vehicles in different missions. A detailed explanation is presented in ref. [1]. The aiming accuracy of the RaioSat camera will be up to 5 degrees with a spatial resolution of 80 meters per pixel and a field of view of 10 km in orbit. The attitude control system will be carried out using mainly torque magnetic coils in 3 axes and reaction wheels also in 3 axes.

The Electrical Power Subsystem (EPS) is responsible for generating, storing, conditioning and distributing the energy necessary for the operation of all subsystems during the mission and a detailed explanation is found in ref. [6].

4. Payload Module

This section describes the Spectral Mapping Camera, the VHF receiver and the GPS receiver.

The camera to be used should allow a surface image of 80 meters per pixel, in the spectral range of 700 to 900 nm using a sensor with optical pass-through filter for the OI (777,4 nm) and NII (868,7 nm) bands [7], and must meet the following characteristics: Resolution: 2048 x 1536 pixels; Image sensor: 10-bit RGB (Bayer).

The payload module should also feature a VHF receiver with a passive antenna [8], in the 80 MHz to 200 MHz band, to validate the events observed by the camera through a detector to be implemented using Software-Defined Radio (SDR) technology.

The GPS receiver is required on board the RaioSat for time information and georeferencing of events, an option for a GPS receiver is the piNAV-L1 model from SkyFox Labs [9]. The GPS module must meet the following characteristics: LEO operation (3600 km), 120 mW consumption, GPS: signal L1 C/A and 15 channels and 1Hz position rate.

5. Product Breakdown Structure and Physical Architecture

A Product Breakdown Structure of RaioSat is shown in Figure 2, analyzing how the components of the subsystems will be distributed. The physical architecture, Figure 3, is added to the generic physical architecture, detailing the performance characteristics and resource requirements for physical elements.

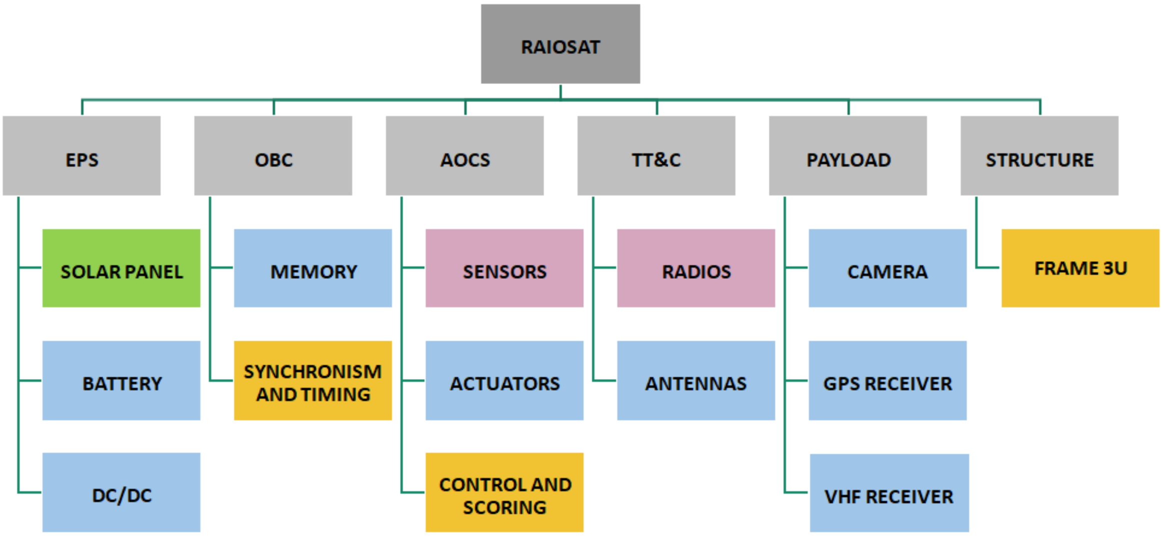

Figure 2: Analytical Structure of the RaioSat Product [1].

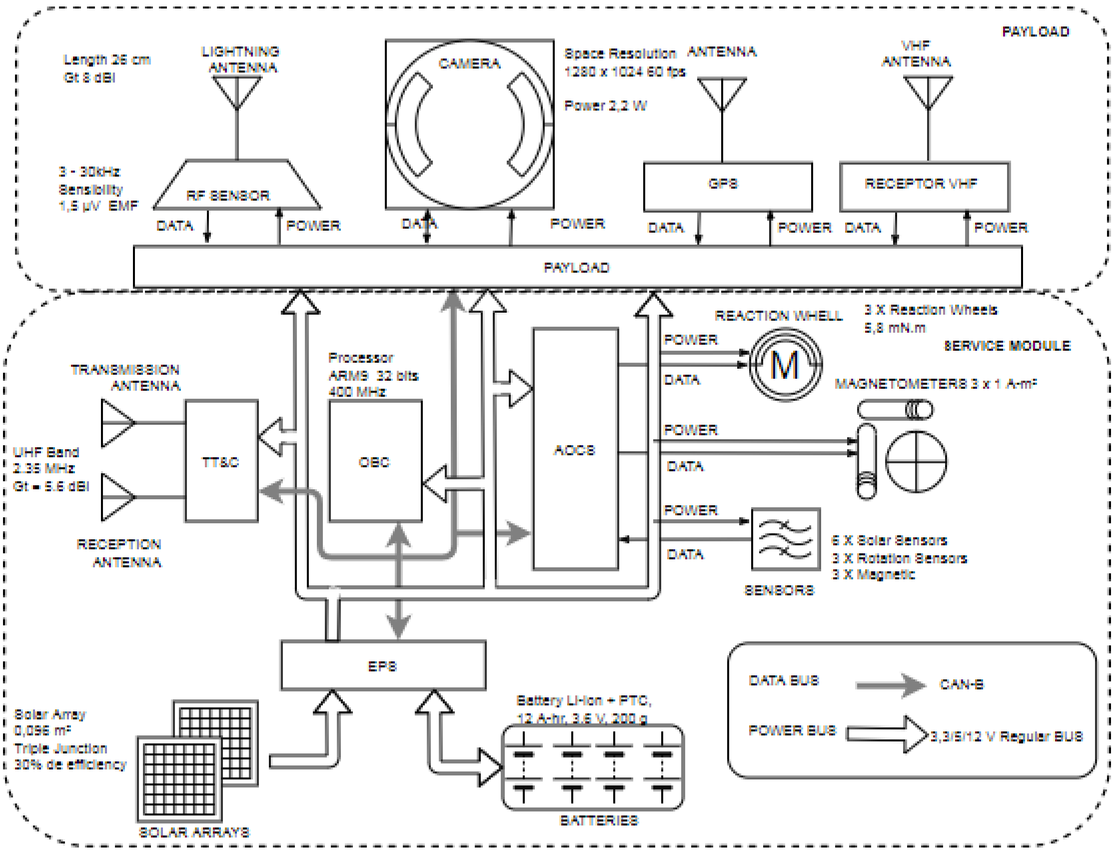

Figure 3: Physical Architecture of the RaioSat Satellite [1].

The instantiated physical architecture of RaioSat, Figure 3 is a reference model and driver to the full project and it includes all satellite elements.

For the creation of the physical architecture, it is necessary to allocate functions for the generic architecture, assigning the interfaces between the physical and derived components of the requirements to those components of the system requirements. For example, in the instantiated physical architecture, reaction wheels (quantity and capacity), sensors (type and quantity) must be specified.

6. Preliminary Results – Prototype

This section presents the preliminary results obtained during the development of a prototype, with emphasis on communication subsystem, onboard computer subsystem, Global Position System, and in the implementation of communication protocols for uplink and downlink with the ground station.

It, also, describes the integration of the prototype to the Brazilian Data Collection System Simulator, a system that allows testing and evaluation of the dynamic behavior of the elements that make up the data flow between satellites and ground stations.

The development of the prototype is based in commercial components and the free software platform. The prototype architecture, shown in figure 4, allows testing the proposed experiment. The main objective is the validation the solutions with reduced costs, time to implement and tests. The validation of the system will be through the launch of the hardware developed as a prototype in a stratospheric balloon that can reach 30 km of altitude and in this way; we evaluate the performance of the system in flight and the ground station.

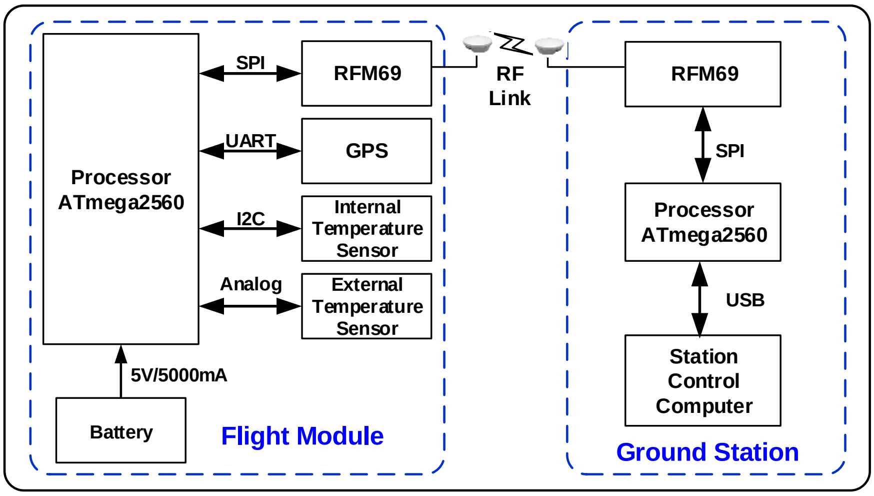

Figure 4: Block Diagram of the RaioSat – Prototype.

a) Communication Subsystem

The Communication Subsystem is responsible for the exchange of information between RaioSat and the Ground Station by uplink and downlink. The frequency used for tests is 430 MHz that guarantees RaioSat data can also be received by the radio amateur community. Communication Subsystem is based in the RFM69HCW, a transceiver module by HopeRF Electronic [10].

The RFM69HCW is a transceiver module capable of operation over a wide frequency range, including the 315,433,868 and 915 MHz license-free ISM (Industry Scientific and Medical) frequency bands. It is responsible by detection the preamble, frame synchronization and header (identification of satellite).The main features RFM69HCW are:

- Compliance ETSI and FCC regulations,
- +20 dBm - 100 mW Power Output Capability,
- High Sensitivity: down to -120 dBm at 1.2 kbps,
- High Selectivity: 16-tap FIR Channel Filter,
- Programmable Pout: -18 to +20 dBm in 1dB steps,
- FSK Bit rates up to 300 kb/s,

- FSK, GFSK, MSK, GMSK and OOK modulations,
- Built-in Bit Synchronizer performing Clock Recovery,
- Incoming Sync Word Recognition,
- Automatic RF Sense with ultra-fast AFC,
- Packet engine with CRC-16, AES-128, and built-in temperature sensor.

On the telecommand (uplink) and the telemetry (downlink) the data rate initially defined 9600 bps. The modulation type defined is the GFSK with a bandwidth of 19200 Hz and the Communication Protocol with the processor is through the SPI interface. Figure 5 shows the telemetry message format has 87 bytes of data size.

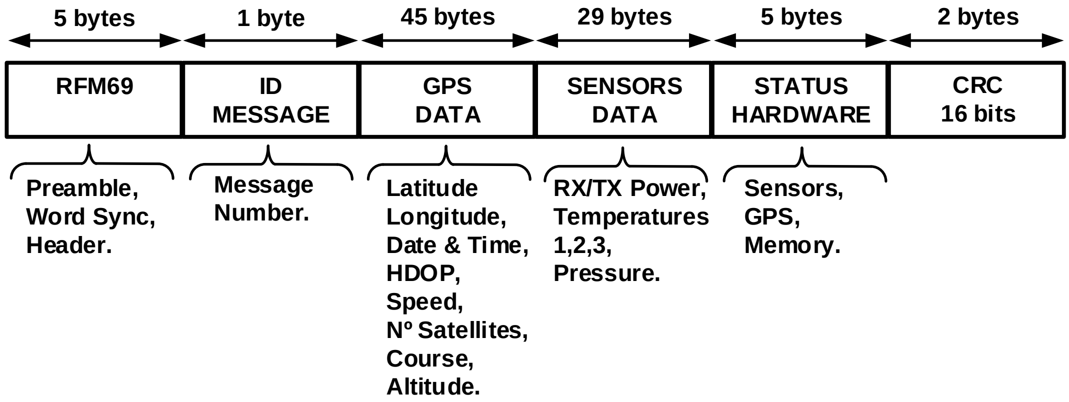

Figure 5: Telemetry Message Format for RaioSat – Prototype.

Figure 6 shows the telecommand message format with 19 bytes of data size. The prototype has two telecommands, one to setup the internal temperature limit and another to setup the transmitter power.

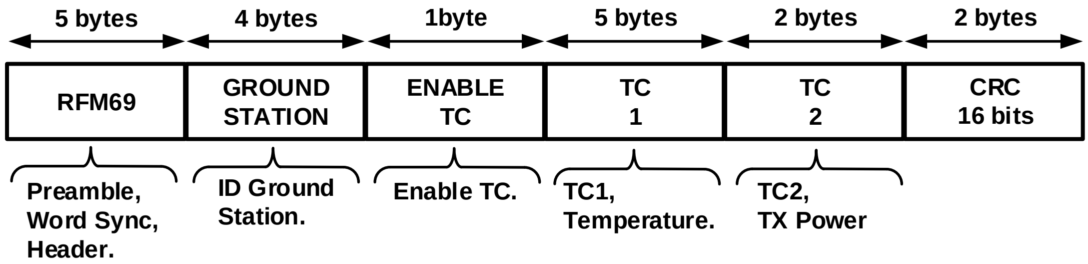

Figure 6: Telecommand Message Format for RaioSat – Prototype.

b) Onboard Computer

The onboard computer of the prototype is based Arduino Mega 2560 [11] and in C language, and it is responsible for performing the following software tasks:

- Supervision: ensure that, in the event of failure, contingency actions are taken.
- Scheduling: Store and perform tasks previously scheduled by telecommands.
- Reception: Perform demodulation and data retrieval of telecommands.
- Housekeeping: Collect the diagnostic information of the satellite subsystems.
- Downlink: Transmitting telemetry.
- Payload: Manage payload activities.

c) Global Position System

The Global Position System (GPS) is responsible for obtaining the dating information used to record all events that have been managed by the onboard computer, such as Telemetries or Telecommands.

The GPS is based in a CAM-M8 module by u-blox [12] that can utilize concurrent reception of up to three GNSS systems: GPS/Galileo together with BeiDou or GLONASS. The modules are designed to receive and track the L1 C/A signals provided at 1575,42 MHz by the GPS and it can use National Marine Electronics Association (NMEA) protocol and UBX protocol by u-blox. This project using the UART interface for communication with the onboard computer.

d) Ground Station

The Ground Station is based, also, in the RFM69HCW, a transceiver module, a processor AT Mega 2560 and a personal computer. It is in charge of establishing communication between the ground control system and the satellite monitored.

The ground station receives, during the visibility periods, a variety of satellite information that allows drivers keep themselves fully informed about the status of the satellite equipment and it sends the telecommand. Figure 7 illustrates the main activities performed by the flight module and the ground station (prototype).

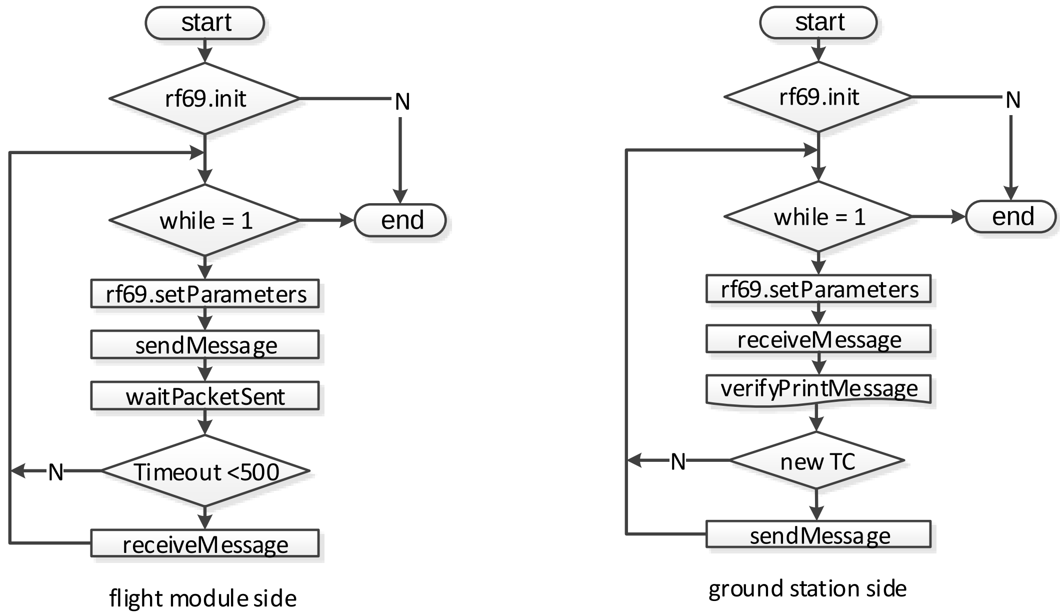

Figure 7: Main activities performed by prototype.

e) Integration of the RaioSat prototype to SSBCD

The modules obtained in the development of the RaioSat prototype are used as models for the implementation of the Brazilian Data Collection System Simulator (SSBCD) therefore, there is a great synergy in the methodology of product development.

The Simulator of the Brazilian Data Collection System [13] is a test system based on the Testing and Verification Unit (UTV) that consists of a hardware and software subsystem that generates signals applied to the Data Collection Processor (PROCOD) input. We are developing an SSBCD engineering model that is composed of the input and output interfaces and the control subsystem with UTV and PROCOD. The elaboration of the model must use the method of implementing programmable hardware in microcontrollers [14], and software modules in C/C++.

The resulting module of RaioSat project will be a subsystem that has the potential to assist in the management of the SSBCD, assessing the impact of inclusions of new data collection platforms, ground stations and satellites in the system.

Conclusions

The detection of lightning discharge data for the entire national territory in a uniform manner will be an important contribution to the improvement of the techniques for forecasting severe events in the very short term (up to 6 hours). The main result is the production of reliable data that will be useful in various areas of scientific research. In addition to the production of reliable data, the RaioSat project can promote means of technological and scientific development with synergy between national and international educational and research institutions.

The most important and innovative technical of the work (such as preliminary results: communication, on-board computer, GPS and Ground Station) that the presented methodology guarantees the integration of the prototype with reduced cost and reliable systems.

The stratospheric balloon, with the first flight model, is expected to be launched in the second half of 2020 to analyzing the results and determining the next steps for full implementation of the RaioSat project with the flight model development to will launch on space.

Acknowledgments

We thank the Brazilian National Institute for Space Research (INPE, acronym in Portuguese) by their support and the National Council of Scientific and Technological Development (CNPq, acronym in Portuguese) for the financial support afforded to Ms. Moara de Oliveira and Mr. Ângelo José Augusto Florentino.

Acronyms

AES	Advanced Encryption Standard
AFC	Automatic Frequency Correction
BrasilDAT	Atmospheric Discharges Brazilian System
CCST	Earth Science System Centre
CNPq	National Council of Scientific and Technological Development
CRC	Cyclic Redundancy Check
dBm	decibel miliwatt
DDC	Display Data Channel
EPS	Electrical Power Subsystem
ETE	Space Engineering and Technology
ETSI	European Telecommunications Standards Institute
FCC	Federal Communications Commission
FIR	Finite Impulse Response
FM	Frequency Modulation
FSK	Frequency Shift Keying
GFSK	Gaussian Frequency Shift Keying
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
I2C	Inter-Integrated Circuit
IARU	International Amateur Radio Union
INPE	National Institute for Space Research
ISM	Industry Scientific and Medical
ITU	International Telecommunications Union
LEO	Low Earth Orbit
MSK	Minimum Shift Keying
NII	Ionizable Nitrogen
NMEA	National Marine Electronics Association
OI	Ionizable Oxygen
OOK	On-off Keying
PROCOD	Data Collection Processor

RF	Radio Frequency
RGB	Additive Color System Red, Green and Blue
RISC	Reduced Instruction Set Computer
SDR	Software-Defined Radio Technology
SPI	Serial Peripheral Interface
SSBCD	Simulator of the Brazilian Data Collection System
UART	Universal Asynchronous Receiver/Transmitter
UBX	Binary Protocol U-blox
UHF	Ultra High Frequency
UTV	Testing and Verification Unit
VHF	Very High Frequency

References

[1] Julio Filho, A. C. et al.. DEVELOPMENT OF A CUBESAT FOR DETECTION OF ATMOSPHERIC DISCHARGES: RAIOSAT PROJECT.. In: Proceedings of the 2nd Brazilian Aerospace Congress. Anais...Santa Maria (RS) Federal University of Santa Maria, 2019. URL: https//www.even3.com.br/anais/2cab2019/224875-DESENVOLVIMENTO-DE-UM-CUBESAT-PARA-DETECCAO-DE-DESCARGAS-ATMOSFERICAS--PROJETO-RAIOSAT (accessed February 2020).

[2] Naccarato K. P., Pinto O., Sllop C. D., Heckman S., Liu. C. "Evaluation of BrasilDAT relative detection efficiency based on LIS observations and a numeric model". International Conference on Lightning Protection (ICLP), pp. 1814-18, 2014.

[3] Naccarato K. P., "Lightning characteristics in southeastern Brazil", 362 p. (INPE-14083-TDI/1069). Doctoral Thesis in Space Geophysics, Instituto Nacional de Pesquisas Espaciais, São José dos Campos, São Paulo, Brazil, 2005. URL: http://urlib.net/6qtX3pFwXQZGivnJSY/HB8iH (accessed February 2020).

[4] Naccarato K.P., Tikami A., Dos Santos W. A., Carretero M.A., "The RaioSat project: detecting total lightning flashes from a CubeSat". 2nd IAA Latin American CubeSat Workshop (LACW), Florianopolis, 2016.

[5] Moura, C.O., "Feasibility analysis of an optical payload in nanosatellites for lightning detection". IBI: <8JMKD3MGP3W34P/3PA5A98>. Master Dissertation in Engineering and Management of Space Systems, Instituto Nacional de Pesquisas Espaciais, São José dos Campos, São Paulo, Brazil, 2017.

[6] Mahdi, M. C.; Jaafer, J. S.; Shehab, A.-A.-R. Design and Implementation of an Effective Electrical Power System for Nano-Satellite. International Journal of Scientific & Engineering Research, [S.l.], v.Volume 5, n.Issue 5„ p.29–, May 2014.

[7] Luz, E. S. A. M. "Case study of atmospheric discharges by slitless spectroscopy" 2015. 198 p. IBI: <8JMKD3MGP3W34P/3KMAELH>. (sid.inpe.br/mtc-m21b/2015/11.30.02.40-TDI). Dissertation (Master in Space Geophysics/Atmospheric Sciences) – Instituto Nacional de Pesquisas Espaciais, São José dos Campos, São Paulo, Brazil, 2015. URL: http://urlib.net/rep/8JMKD3MGP3W34P/3KMAELH (accessed February 2020).

[8] Hamlin, T., Wiens, K.C., Jacobson, A.R., Light, T.E.L., Eack, K.B., "Space- and ground-based studies of lightning signatures". In: Lightning: principles, instruments and applications – Review of modern lightning research, Ed.: H. D. Betz, U. Schumann, P. Laroche, Springer, 641 pp., 2009.

[9] Kovář, P., "piNAV L1 - GPS receiver for small satellites". Gyroscopy Navig. 8, pp. 159-164, 2017.

[10] RFM69 HopeRF [Online]. Available: https://www.hoperf.com/. [Accessed February 2020].

[11] ATmega2560 [Online]. Available: https://www.microchip.com/wwwproducts/en/ATmega2560. [Accessed February 2020].

[12] CAM-M8 https://www.u-blox.com/sites/default/files/CAM-M8-FW3_DataSheet_%28UBX-15031574%29.pdf. (Accessed February 2020).

[13] Cisotto M. V., "Proposal of a system for testing and evaluation of the Brazilian data collection system processors". Master Dissertation in Space Systems Engineering and Management, Instituto Nacional de Pesquisas Espaciais, São José dos Campos, São Paulo, Brazil, 2012.URL: http://urlib.net/8JMKD3MGP7W/3C9E2G2 (accessed February 2020).

[14] Raspberry Pi [Online]. Available: https://www.raspberrypi.org/. (Accessed February 2020).