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Advances in the RaioSAT project: detecting lightning from space using a nanosatellite

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Abstract*— 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. The prediction of extreme weather events (one of the major features of climate changes) requires high-resolution numerical weather prediction (NWP) models and the maximum amount of observational data available, greenhouse gases, wind and solar potential for energy generation, however the Brazilian scientific community now demands new types of measurements that can be provided by satellite solutions, like for example the nanosatellites. We are now working to develop the RaioSat project, which is a nanosatellite expected to operate in a 650 km LEO orbit using a 3U-CubeSat (10x10x30cm) aluminum structure to accommodate an optical camera with a spectral filter in the oxygen and nitrogen bands and a VHF antenna. In this work, we will present the feasibility study of an optical payload in order to detect total lightning from space. We investigate three possible COTS cameras available in the market. A set of optical requirements for detecting lightning phenomenon is used to perform the feasibility analysis that help us choose the optical sensor electronics, spectral filtering and the system engineering constraints to the camera payload. The paper also addresses the high-level requirements of the on-board processing unit, the ground communication links and the elimination of false-positive lightning occurrences. Finally, we present a list of future topics in continuing the RaioSat project.

Keywords — lightning detection; cubesats; optical payloads; feasibility analysis

I. INTRODUCTION

In many studies of sustainability and climate change, several types of measurements are required to understand earth system phenomena and/or environment variables. Nowadays, there is a significant amount of ground-based measurements of dozen types of environment variables. 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. As examples of the use of satellite measurements: (1) prediction of extreme weather events (one of the major features of climate changes) requires high-resolution numerical weather prediction (NWP) models and the maximum amount of observational data available; (2) remote observation of surface properties (both over land and sea) can be very useful for land use studies, deforestation impact assessment and interaction of the vegetation with the ground and sea (climatic conditions); (3) assessment of atmospheric gases from space (e.g. nitrogen and carbon dioxide) can provide biogeochemical traces to improve the studies of the greenhouse effect and global warming. Nowadays, in Brazil, there are several ground networks composed by different types of sensors that provide earth system measurements, including lightning and/or thunderstorm sensors, greenhouse gases, wind and solar potential for energy generation, however the Brazilian scientific community now demands new types of measurements that can be provided by satellite solutions, like for example the nanosatellites. Such data are important to expand the observational databases improving S&T studies towards sustainable driven problem-solving researches.

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.

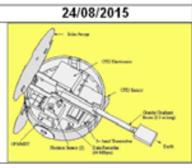
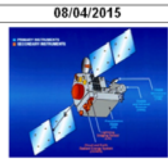
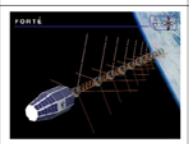
Three previous satellite missions are successful to detect lightning from space: the Oberview1/MicroLab, launched in 1995, the TRMM launched in 1997 and the FORTE launched in 1997. All those missions are big satellites. In 2014, a cubesat mission, named RaioSAT, was proposed to detect intra-cloud and cloud-to-ground lightning flashes simultaneously. It is mainly a nanosatellite expected to operate in a 650 km 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 (Carretero & Naccarato, 2014). The complete RaioSAT payload shall ideally 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 (Naccarato et al. 2016a,b).

This paper presents the feasibility analysis for an optical payload on-board the RaioSAT where resolution shall be 2,048 x 1,536 pixels having a spectral range from 700 to 900 nm using a band-pass optical filter (Moura, 2017; Moura et al., 2017).

II. Previous Missions for Lightning Detection

Nowadays there are three types of lightning detectors on-board satellites, two of them uses optical sensors which is the focus of this work and RF detectors. A summary of the main three major mission to optically detect lightning from space are shown in Table I: OrbView 1 / MicroLab, TRMM and FORTE and their respective payloads: OTD, LIS e LLS from which we derived the payload development requirements for the prospective RaioSAT mission.

TABLE I. Features of some missions for lightning detection

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			

A complete list of lightning experiments in space is described by Christian et al. (1992) with their missions, underlying technologies and their respective payloads. Key remarks must be drawn on some developments such as the Lightning Mapper Sensor – LMS in a GOES mission and the Lightning Imaging Sensor – LIS onboard TRMM in 1997.

Looking for lightning detection from space a study was carried out by NASA using a U2 high altitude aircraft (Christian & Goodman, 1987). This very important study used of several devices to stablish a baseline for lightning detection from GEO orbit. This was foreseen for a recent GOES mission originally planned for the mid-1990s (Christian et al. 1989) but ended up with the GOES-R launched recently [http://www.goes-r.gov/mission/mission.html].

III. Methodology Adopted for Feasibility Analysis

In order to analyze the feasibility proposed in this paper, the methodology chosen is based on Wertz et al. (2011) which proposes that the sizing of an observational payload is an interactive process. This involves negotiating and optimizing different payload alternatives often among a vast number of potential candidates. In the early stages of this process, it is important to be able to evaluate different options without going each one in detail.

The initial evaluation of alternative projects requires estimations on mass, size, power, data rate and pointing restrictions, satellite control and stability among other interface characteristics. This allows reducing the number of candidates for a more complete evaluation. This assessment flows from a detailed description and understanding of the mission to the concept of operation and the initial specifications of the payload of observation. The methodology was adapted from Wertz et al. (2011) and detailed hereafter.

Under the possible scenarios for a feasibility analysis, this work concentrates primarily in three possible devices shown in Figure 1. Main prospective analysis looks into the GomSpace Camera NanoCam C1U [https://gomspace.com/Shop/payloads/earth-observation.aspx] and then on Photobit PB-MV13 Sensor [http://www.alacron.com/clientuploads/PB-MV13_Product_Specification.pdf] and MT9M413 Sensor from Aptina Imaging [http://www.datasheetlib.com/datasheet/1220777/mt9m413c36stc_aptina-imaging-corporation.html].

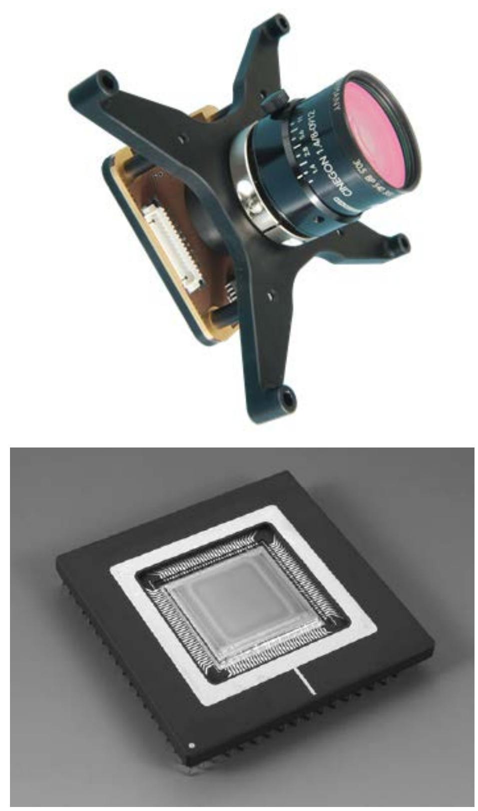


Fig. 1. Some prospective optical payloads: NanoCam C1U and Photobit PB-MV13 Sensor

IV. Feasibility Analysis for an Optical Payload in CubeSats

The feasibility analysis applies each step mentioned in the methodology proposed for sizing a prospective suitable for an optical payload on-board the RaioSAT CubeSat mission.

A. *Optical Mission Requirements and Objectives*

The development of an optical payload for detecting and geolocating lightning discharges from space onboard a LEO CubeSat was first proposed by Carretero & Naccarato (2014). The authors envisaged a mission with the optical payload with a filter in the OI band (777.4 nm) and in the N II band (868,3 nm), as well as an RF antenna.

From the literature analysis this proposal would be a CubeSat with functionalities similar to those of the FORTE satellite with the difference that this had also a photodiode named PPD that provided the optical waveform besides the LLS imager for detecting lightning flashes only in the OI band.

B. *Mission Geometry and Orbit Parameters*

Concerning the mission geometry and orbit parameters, the authors suggested launching in LEO from the ISS or alternatively an orbit of 650 km altitude and inclination of 25°. The crucial orbital parameter for sizing of the imager is the altitude. Hence the studies are being done taking into account these altitudes, namely 400 km and 650 km respectively. For the mission, a more elaborate study of the most suitable orbit is suggested, considering the requirements of coverage, revisiting, among others.

C. *Optical Payload Requirements*

From the literature review, we can infer that for obtaining a mapping of CG and IC lightning distribution, an optical payload, to detect space lightning and allow geolocation and timing tagging, will require an optical sensor capable of capturing the light emitted by lightning composed of:

- A CCD or CMOS matrix sensor with a maximum integration time of 2 ms, preferably 1 ms;
- Lenses that will conduct light to the sensor array;
- A narrow band filter adjusted for the wavelength of 777.4 nm (OI) and the 868.3 nm (N II) with a 1 nm bandwidth.

Additionally, it is required an on-board signal processing electronics and software for reducing the data transmission rate which demands: a background signal estimator, a background subtractor, a lightning threshold detector, an event selector, and a signal identifier. Analog/digital hybrid processing could be used instead of traditional digital techniques due to the high data rate and energy constraints of a lightning mapper.

D. *The Payload Operational Concept*

For the concept of operation of an observational payload, the mission must be understood end-to-end starting with the physics behind and all associated engineering, lightning phenomenology and its data interpretation. The payload operation approach, driven by users' data requirements needs, shall be cost-effective to meet mission goals.

The operational concept for a RaioSAT system should consider all aspects of the operational mission, including the different mission scenarios and alternative modes of operation. Hence this may include the following assumptions:

- Thunderstorm (and lightning) can start anywhere on Earth;
- The sensor field of view passes over the storm and collects lightning data;
- Lightning measurements are transmitted through a data stream;
- The data is processed on-board;
- Lightning detection algorithm determines its occurrence;
- If lightning is detected, the system generates a data set to the scientists that indicates its presence at a specific time and place.
- Scientists use data in their research and provide the results to end users.
- The system continues to monitor lightings jointly with the ground network called BrasilDAT (Naccarato et al. 2012).

E. *Determination of the Spatial Sampling*

A lightning seen from space has an average horizontal extension of 10 km. The technique used in the CCDs investigated by Moura (2017) tried to concentrate the lightning image into a single pixel or set of pixels mapped as a single pixel. Thus, the number of electrons produced during the 2ms image integration time gives a measure of the lightning intensity. For this reason, one of the candidate sensors has a set of 8x8 pixels mapped as a single pixel. The model of Figure 2 shows the displacement of the object light through the lens towards the photodetector with the parameters: (a) **10km** = spatial resolution (average lightning horizontal size), (b) **96µm** = image size in a single macro pixel, (c) ***h*** = Distance from the object to the lens and (d) ***f*** = Distance from the lens to the image.

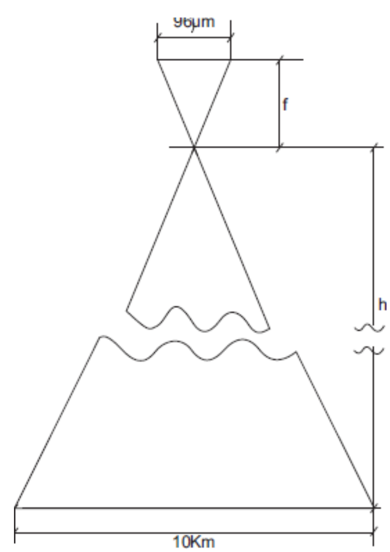


Fig. 2. Projection of a 10km object light up to its image

We then calculate the distance from the lens to the CCD (***f***):

$$\frac{f}{h} = \frac{96\mu}{10km} \quad (1)$$

For ***h*** = 650 km, then ***f*** = 6.24 mm.

The aperture angle is derived from Figure 3:

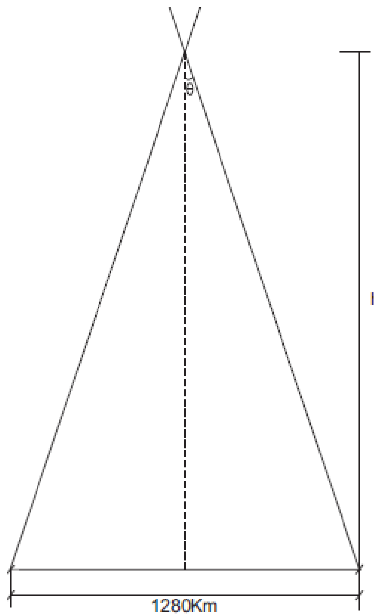


Fig. 3. Path of the object light up its image at 650 Km

Half of the aperture angle for r = 640 km and l = 650 km is tg θ = 0.9846 which means θ ~ 44.55°. Thus the aperture angle is 2 x θ, i.e., approximately 89.1°.

F. On-board Signal Processing Needs

The components required for the real-time signal processor are: (1) a background signal estimator, (2) a background subtractor, (3) a lightning threshold detector, (4) an event selector, and (5) a signal identifier. These are necessary since the sunlight reflection at the top of the clouds during the day is much more intense than the lightning signal itself. Without the signal processing, not could be detected under and the transmission of all data to be processed in the ground would increase dramatically the data rate from a few kbps to hundreds of Mbps which is unfeasible.

Currently a signal processing unit in the molds specified here is under development at INPE using the STM32F746ZG, mbed-Enabled Development Nucleo STM32F7 MCU 32-Bit ARM® Cortex®-M7 Embedded Evaluation Board.

G. Radiometric Sensitivity Performance

The radiometric performance of an instrument is determined by the signal-to-noise ratio (SNR) and the dynamic range. The SNR represents the image quality for a given set of measurement conditions, which includes the sensor aperture diameter, the instantaneous field of view, and the scene intensity. The quantum efficiency of the detector multiplied by the number of photons is equal to the number of electrons or electron/hole pairs. These charge-carriers are collected by the detector junction and correspond to the detector output signal. The quantum efficiency of Photobit PB MV 13 sensor as a function of wavelength are shown in Figure 4. More details can be found in Moura (2017).

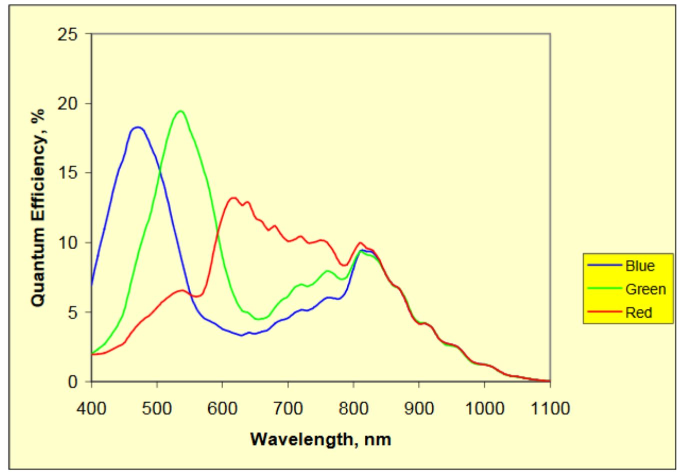


Fig. 4. Quantum efficiency of the sensor PB MV 13, Photobit PB-MV13

The number of electrons of the lightning optical signal $\boldsymbol{N_s}$ and background signal $\boldsymbol{N_B}$ that will be produced in the sensor can be calculated from basic radiometric equations (Slater, 1980):

$$N_S = \frac{(\pi D^2/4)}{R^2} A_S Q K \left(\frac{\lambda}{hc}\right) E_S \tag{2}$$

$$N_B = \frac{(\pi D^2/4)}{R^2} A_P Q K \left(\frac{\lambda}{hc}\right) I_B \alpha \Delta\lambda \tau \tag{3}$$

The results of the radiometric performance calculations and the baseline values used in the optical sensor prototype (OSP). Using baseline values for the current OSP, we calculated that the total number of signal electrons to be produced by a lightning discharge of intensity at the threshold level for 90% detection efficiency (NASA's U-2 mission) is $\boldsymbol{N_s}$ ~ 1.39 x 10^5 electrons.

We also calculate the worst-case background signal of $\boldsymbol{N_B}$ ~ 1.77 x 10^7 electrons. Thus, in this example, the background signal is 128 times greater than the lightning optical signal we are simulating. In the case of LMS (primary GOES sensor), for example, we had $\boldsymbol{Ns}$ ~ 4,550 electrons and $\boldsymbol{N_B}$ ~348,000, which gives us a background signal about 77 times greater than the lightning signal as well. This fact leads us either to decrease the number of background electrons, for example, using a 0.6 nm band pass filter, like the LMS, or require more processing for the image processing system.

H. Payload Size, Mass and, Power Estimations

The estimation of size, weight and power of the payload is a requirement of any mission, even more for CubeSAT missions which these factors are critical. Three methods for evaluating a payload are proposed in Wertz et al. (2011): (1) analogy with existing payloads; (2) dimensioning from existing payloads; (3) budget from components.

As the payloads in this category are for large satellites, the first two methods may not apply at first place; the remaining option is to inquire from the components which in any situation is the most reliable method. Currently in the project, the candidate with the highest probability of composing the desired payload is the Sensor MT9M413 da Aptina Imaging a CMOS image sensor that has an open architecture to provide access to its internal operations. A complete camera system can be built using the chip in conjunction with the following external devices such as: (1) A FPGA / CPLD / ASIC controller to manage the synchronization signals required for sensor operation; (2) A 20mm diagonal lens and, (3) Polarization circuits and by-pass capacitors.

In addition to the image processing, there is a study for using a NUCLEO-F746ZG from STMicroeetronics platform in hardware. A sensor of dimensions similar to those of the NanoCam C1U, using these components, is currently being developed at INPE.

I. Determination of Payload MOEs

This work uses performance indexes that combine MOEs to compare instruments with similar characteristics. In the case of high-resolution optical imagers, three MOEs are considered suitable for this purpose: signal noise ratio at zero spatial frequency, Modulation Transfer Function (MTF) at the detector's Nyquist frequency and the Ground Sampling Distance (GSD). From theses MOEs a Relative Quality Index (RQI) is defined to allow quantitative comparisons with a reference instrument:

$$RQI = (SNR / SNR_{Ref}) \,.\, (MTF / SNR_{Ref}) \,.\, (GSD_{Ref} \;/\; GSD) \qquad (4)$$

This method is applied to analyze the payloads OTD, LIS LLS, and the NanoCam C1U, an optical camera from GomSpace as shown in Table II. The NanoCam C1U with two versions 35 mm (GS35) e 70 mm (GS70), is a candidate as the development base component of the desired payload, adopting the LIS sensor as reference payload.

TABLE II. RQI OF OTD, LIS, LLS AND GOMSPACE (GS35 AND GS70) PAYLOADS

RQI	SNR/SNR_{LIS}	MTF/MTF_{LIS}	GDS_{LIS}/GDS	Payload
0,76	1,999	1	0,38	OTD
0,43	1	1	0,43	FORTE
208,33	1,50	1	138,92	GS35
416,65	1,50	1	277,83	GS70

The results show that this camera far exceeds the spatial sampling requirements of the reference sensor, which is explained by the fact that it was designed for imagery. This in fact is a disadvantage, since spatial sampling is used as one of the filters for detection on the sensor that we aim at, namely to make the soil sampling match the average size of a radius, 10 km, so that the energy of a lightning be integrated into a single pixel. Moreover, as indicated in Table III, its maximum integration time proved inadequate for the intended purpose.

TABLE III. STANDARD SENSOR RESOLUTION FOR MICRON MT9T031

Resolution	Frame Rate	Column_Size	Row_Size	Shutter Width
2048 x 1536 QXGA	12 fps	2047	1535	<1552
1600 x 1200 UXGA	20 fps	1599	1199	<1216
1280 x 1024 SXGA	27 fps	1279	1023	<1040
1024 x 768 XGA	43 fps	1023	767	<784
800 x 600 SVGA	65 fps	799	599	<616
640 x 480 VGA	93 fps	639	479	<496

J. Conclusions and Future Work

In the beginning of this project, the most probable candidate for the RaioSAT lightning detection payload was the GomSpace NanoCam C1U camera suggested earlier in a COTS system with flight heritage. However, as shown, NanoCam C1U has a limited frame rate as it does not meet the integration time requirement raised in studies carried out by NASA to develop a baseline equipment for optical lightning detection.

Today a payload based on the Photobit PB MV 13 sensor is being considered which has a frame rate of 500 frames per second including: (1) the chip control electronics and lens system being developed, (2) filter for the 777.4 nm band with bandwidth of 1 nm, (3) system for treatment of image for background subtraction of the diurnal photos, indispensable in a payload for this purpose.

An issue still to be discussed is the cost-benefit of lightning detection in both the OI and NII bands since only the work of Christian & Goodman (1987) has proposed dual band detection. All subsequent missions, Microlab, TRMM and FORTE, detected only in the 777.4 nm (OI) band. An additional detection system in the NII band can be designed by including a photodiode like the FORTE.

At present, the RaioSAT prototype is being developed at INPE and is expected to be launched by the end of 2019.

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