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Since the 1970s several satellites were launched with the mission to detect lightning from space such as OSO 2, OSO 5 and Defense Meteorological Satellite Program (DMSP) observing lightning with various optical sensors. Other missions used radio frequency (RF) sensors where the lightning detection rate was generally less than 2%. In the 1980s, NASA conducted an extensive study using a high-altitude U-2 aircraft inspiring later a Lightning Mapper Sensor (LMS) project to be boarded in a future GOES geostationary mission. The LMS project gave rise to three optical payloads in low Earth orbit: OTD, LIS and LLS, this last one launched in 1997. This previous research established an optical payload to detect lightning from space and allow its geolocation and timing in order to allow the construction of distribution maps of cloud-ground and intra-cloud. These maps would be provided by a CCD/CMOS matrix with a narrowband filter adjusted for the wavelength of the atomic oxygen 777.4 nm or the atomic nitrogen 863.3 nm with a bandwidth of 1 nm. In addition it should contain the electronics and software for on-board signal processing in order to decrease the data rate consisting of: a background signal estimator, a background subtractor, a radius event threshold detector, an event selector and a signal identifier. Recently, it was proposed the development of an optical payload for detection and geolocation of intra-cloud and cloud-ground lightning from the space to be shipped in a cubesat. This paper applies a recommended methodology for evaluating the feasibility for the development of the payload as suggested. We define performance indexes that combine measures of effectiveness (MOEs) to compare instruments with similar characteristics. In the case of high-resolution optical imagers, three MOEs are considered suitable for this purpose: signal-to-noise ratio at zero spatial frequency, MTF of an instrument at the detector's Nyquist frequency and, GDS ground sampling distance. Thus, we defined the Relative Quality Index (RQI) to allow quantitative comparisons with a reference instrument. We apply this method to analyze the OTD, LIS and LLS payloads as well as a COTS cubesat camera candidate to serve as the basis for the development of the intended payload and using the LIS as reference payload. The first results show that this camera may meet some the optical requirements to serve as the basis for the development of the desired payload whereas some features of Photobit PB MV 13 Sensor are also attractive. Future steps will be the development of a 1nm-narrow band filter for the 777.4 μm wavelength as well as planning the algorithms and associated electronics for onboard signal processing to reduce the data rate to values compatible with its transmission to the ground.

Keywords: *Lightning Detection. Cubesats. Optical Payloads. Feasibility Analysis.*

1. Introduction

Climate changes have motivated the study of extreme weather events since the prediction of complex meteorological phenomena requires accurate numerical weather prediction (NWP) models and the maximum amount of observational data available. This work looks into lightning-producing radiation data in Brazil, which since 2010 is provided by Earth Networks Lightning Sensor (ENTLS) by different types of sensors that helps detecting them. Nevertheless terrestrial sensor coverage has some drawbacks taking into account the vast Brazilian territory, which makes the concept of a dedicated lightning location sensor on board of satellites attractive.

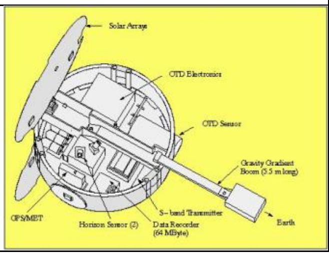
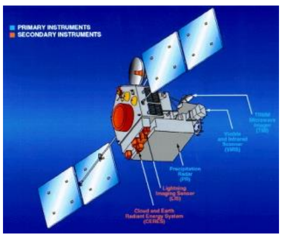
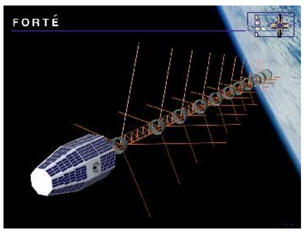
Many previous missions detected lightning from orbit, specially three of them were very successful: The Oberview1/ MicroLab, launched in 1995, the TRMM launched in 1997 and the FORTE launched in 1997, all missions range from micro to large satellites. In 2014, a cubesat mission, named now RaioSat, was proposed to detect intra-cloud and cloud-to-ground lightning flashes simultaneously, using an optical sensor and a VHF antenna onboard [1]. 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. This paper presents the feasibility analysis for an optical payload on-board the RaioSat having a spectral range from 700 to 900nm using a band-pass optical filter [2].

The work is organized as follows. Section 2 analyses previous missions with the same goal from which the main optical payload requirements are derived. In section 3 the applied methodology is discussed whereas in section 4 the candidates for a proposed optical payload are presented and their feasibility analysis performed. Finally, section 5 concludes and points out to future works.

2. 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 highlight on some missions is summarized into Table 1 such as OrbView 1/ MicroLab, TRMM and FORTE and their respective payloads OTD, LIS e LLS from where we derived the payload development requirements for the prospective Raiosat mission.

Table 1: 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	
Illustration			

A list of various lightning experiments in space is described in [3] with their missions, underlying technologies and their respective payloads. Key remarks must be drawn on some developments such as the LMS - Lightning Mapper Sensor in a GOES mission and LIS - Lightning Imaging Sensor on-board TRMM in 1997.

In the search for lightning detection from space a study was carried out by NASA using a U2 high altitude aircraft [4]. This very important study used of several devices to stablish a baseline for lightning detection from GEO orbit. This will be implemented in a future GOES mission originally planned for the mid-1990s but it could only end up with the GOES-R launched at the end of 2016.

3. Methodology Adopted for Feasibility Analysis

In order to analyze the feasibility proposed in this paper, the methodology chosen is based on Wertz et al [9] 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 [9] and detailed hereafter.

Under the possible scenarios for this feasibility analysis, this work had started primarily only with the GomSpace Camera NanoCam C1U [11]. Later on, a new prospective optical device was considered, the Photobit PB MV 13 Sensor [10], since some requirements were not satisfied by the camera. The two possible devices options are shown in Figure 1.

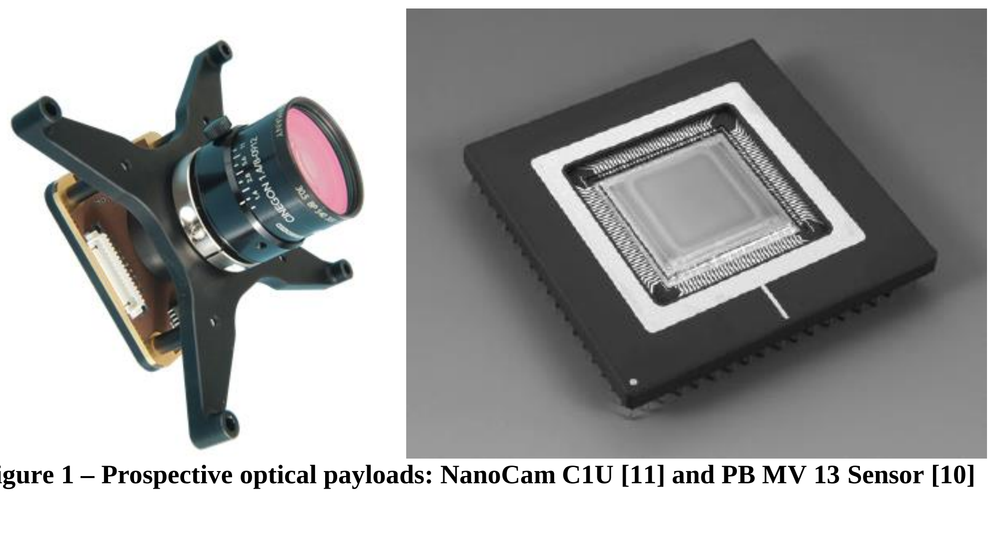


Figure 1 – Prospective optical payloads: NanoCam C1U [11] and PB MV 13 Sensor [10]

4. 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.

4.1 Optical Mission Requirements and Objectives

The development of an optical payload for detection and geolocation of cloud-cloud and cloud-ground lightnings from space shipped in a LEO cubesatat was proposed by Nacaratto et al. [1] [2]. The authors envisaged a mission with the optical payload with a filter in the oxygen band 777.4 nm and in the band of the nitrogen 883,3 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 lightning waveform besides the LLS imager for detecting rays only in the oxygen spectrum.

4.2 Mission Geometry and Orbit Parameters

Concerning the mission geometry and orbit parameters, the authors in [1] [2] suggest the launch in LEO in the ISS orbit or an alternative polar orbit possibly with launch in a DNEPR launch. 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 future steps on this prospective mission, a more elaborate study of the most suitable orbit(s) is suggested which considers the requirements on coverage, revisit time among others.

4.3. Optical Payload Requirements

From the literature review undertaken, one can infer that for obtaining a mapping of cloud-ground and intra-cloud 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 consisting of:

- A CCD or CMOS matrix sensor with a maximum integration time of 2 ms, preferably 1 ms in fact;
- Lenses that will conduct light to the sensor array;
- A narrow band filter adjusted for the wavelength of 777.4nm (atomic oxygen) or the 863.3nm (atomic nitrogen) with a 1 nm bandwidth

Additionally, it is necessary an on-board signal processing electronics and software for reducing the data transmission rate which demands the following: a background signal estimator, a background subtractor, a lightning threshold detector, an event selector, and a signal identifier.

Analog/digital hybrid processing shall be used instead of traditional digital techniques due to the high data rate and energy constraints of a lightning mapper.

4.4 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:

- Storms with lightning may start anywhere on the earth.
- The sensor field of view passes over the storm and collects its data
- Lightning measurements are transmitted through a data stream
- The data is analyzed at the mission control center or processed on-board.
- Lightning detection algorithm determines its occurrence probability at the analyzed locality.
- If lightning is detected, the system generates a data set to the researchers that indicates its presence at a specific time and place.
- Researchers use data in their research and provide the results to end users.
- The system continues to monitor lightings jointly with the terrestrial network named Brasildat.

4.5 . Determination of the Spatial Sampling

A lightning seen from space has an average size of 10 Km, the technique used in the imagers being investigated tries to concentrate the lightning image into a single pixel or set of pixels mapped work as a single pixel. Thus the amount of electrons produced during the 2ms image integration time gives a measure of the lightning intensity. For this reason, one of the candidate sensors being studied has a set of 8x8 pixels mapped as a single pixel and the calculations of the focal length and the instant field of view are being revised.

4.6 On-board Signal Processing Needs

The components required for the real-time signal processor includes: (1) a background signal estimator, (2) a background subtractor, (3) a lightning threshold detector, (4) an event selector and (5) a signal identifier. This is 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, nothing would be detected under these circumstances and the transmission of all data to be processed to the ground would raise the data rate from a few kbps to hundreds of Mbps which would be impractical.

4.7 Radiometric Sensitivity Performance

The radiometric performance of an instrument is determined by the signal-to-noise ratio (SNR) and dynamic range. The SNR describes the image quality for a given set of measurement conditions, including sensor aperture diameter and the instantaneous field of view and 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. For details such the quantum efficiency of Photobit PB MV 13 sensor as a function of wavelength can be found in [10].

4.8 Payload Size, Mass and, Power Estimations

The estimation of size, weight and power, even before a detailed design is available is a need in any mission, even more for cubesat missions where these factors are critical. Three methods for evaluating a payload are proposed in [9]: (1) Analogy with existing payloads; (2) Dimensioning from existing payloads; (3) Budget from components.

As the payloads in this category are from micro to 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 are the most reliable method. Currently in the project, the candidate with the highest probability of composing the desired payload is the PB-MV13 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 an Arduino platform in hardware. All these components and subsystems have already been used in other cubesat missions which assures its feasibility.

4.9 Determination of Payload MOE´s

This work uses performance indexes that combine MOE´s 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 MOE´s a Relative Quality Index (RQI) is defined to allow quantitative comparisons with a reference instrument indicated by subscript “**ref**”.

$$\boldsymbol{RQI = (SNR/SNR_{Ref}) \,.\, (MTF/SNR_{Ref}) \,.\, (GSD_{Ref} /GSD)} \qquad (1)$$

This method suggest by [9] is applied to analyze the payloads OTD, LIS and LLS, and the NanoCam C1U, an optical camera from GomSpace (https://gomspace.com/) as shown in Table 4. The NanoCam C1U, in its two versions 35mm (GS35) e 70 mm (GS70), is a candidate as a basis for the development of the desired payload and adopting the LIS sensor as reference payload.

Table 4 – RQI of Payloads OTD, LIS (**ref**) and LLS and GomSpace (GS35 and GS70)

RQI	SNR/SNR_{LIS}	MTF/MTF_{LIS}	GDS_{LIS}/GDS	Paylod
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 obtained show that NanoCam C1U meets the optical requirements to serve as the basis for the development of the desired payload, however its maximum integration time proved to be inappropriate for the intended purpose as indicated in Table 5.

Table 5: Standard sensor resolution for Micron MT9T031 [11].

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

5. Conclusions and Research Outlook

This paper initiated a feasibility analysis considering the GomSpace NanoCam C1U camera as a prospective RaioSat lightning detection payload. This was suggested earlier since the camera is a COTS system with flight heritage. However, the NanoCam C1U has a limited frame rate as it does not meet the suitable integration time requirement suggested by NASA in an earlier study.

Today a camera payload based on the Photobit PB MV 13 sensor is being considered which has a frame rate of 500 frames per second. Therefore, items still to be developed are: (1) the chip interfacing electronics and lens system, (2) a filter for the 777.4 nm band with bandwidth of 1nm and, (3) a system for image processing for background subtraction of the diurnal photos indispensable in this application.

Payloads based on photodiodes and photometers are mainly used to provide optical waveforms acquired at the lightning event time. These waveforms reveal important information about the characteristics and phenomenology of individual pulses and lightning pulses as well as the scattering effects of the surrounding clouds. Additionally, photodiode / photometer are characterized by a good temporal resolution (e.g. 10-100µs) and generally have a low spatial resolution (100-1000 km).

On the other hand, CCD and CMOS imagers are used mainly for providing accurate geolocation and two-dimensional images of lightning events in time periods of a flash and are ideal for studying global and regional lightning rates and daytime, seasonal and geographic variations in lightning and storm activities.

An issue still to be discussed is the cost-benefit of lightning detection in both the oxygen and nitrogen bands since only the study in [4] had this feature. All subsequent missions, Microlab, TRMM and FORTE, detected only the 777.4nm band.

Future research will consider whether it is more interesting to monitor lightning in two bands using cameras as previously proposed or just in one band with a camera with the addition of a photometer. This last option might be attractive for replacing the detection in a second band since photodiodes add new features.

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