Feasibility Analysis of an Optical Payload in a Lightning Detection Cubesat

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1st IAA Latin American Symposium on Small Satellites, Buenos Aires, 7th – 10th March, 2017

03/2017

Agenda

- Introduction
- Previous Missions for Lightning Detection
- Methodology Adopted for Feasibility Analysis
- Feasibility Analysis for an Optical Payload in CubeSats
- Conclusions and Research Outlook

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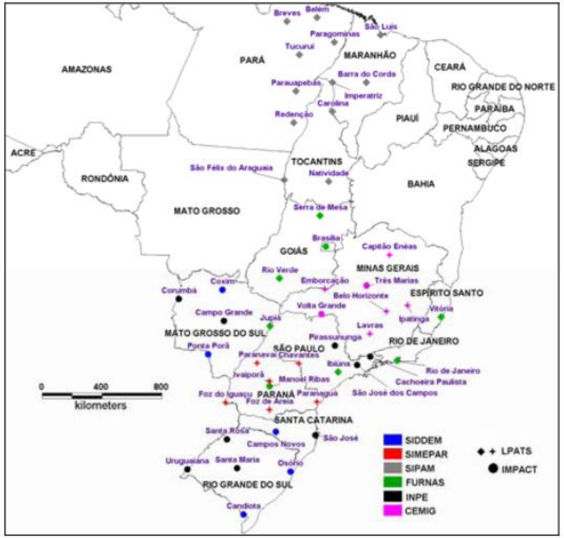
Motivations

- The Brazilian territory has a high incidence of lightning and does not yet have a monitoring system using satellites to complement its terrestrial lightning monitoring network (BrasilDAT).
- Space lightning monitoring systems using big satellites with specific payloads were built abroad.
- Missions of this size and specificity are expensive.



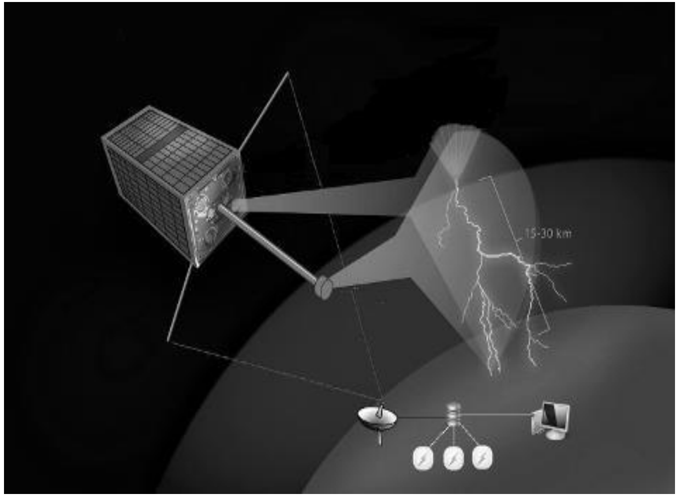
CCST - 1st IAA Latin America Cubesat Workshop

December 08-11, 2014, Brasilia, Brazil

Detection of total lightning flashes onboard of a CubeSat satellite

Carretero, Miguel A.e Naccarato, Kleber P.

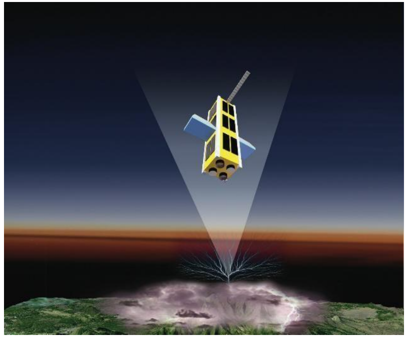
Simplified diagram of mission

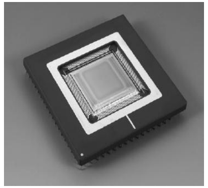


Camera CCD pointing to the surface

Challenges

- Investigate the feasibility of an alternative solution using Nanosatellites for lightning monitoring.
- Have an optical payload with two spectral bands filter that capture lightning signature.
- Use a VHF passive antenna, (50 to 200MHz) for discrimination of Cloud-Cloud and Cloud-Ground lightnings.





This Work Objectives

To verify the feasibility and implications for an optical mission for lightning monitoring on a Nanosatellite platform, from a Space Systems Engineering point of view

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Lightning Detection on Previous Missions

There are three Technology in Lightning Detection from Space:

- Photodiode-Photometer
- CCD- CMOS Imagers
- Radio Frequency

Photodiode-Photometer

Characteristics

- Provide Optical waveforms resolved in time of lightning events
- Waveforms reveal important information about the characteristics and phenomenology of individual ray pulses and the dispersion effects of the surrounding clouds
- Excellent temporal resolution (10-100 / µs)
- Generally low spatial resolution (100-1000 km)

CCD- CMOS Imagers

Characteristics:

- Provide accurate geolocation and two-dimensional images of lightning
- Provide global and regional rates of lightning and,
- Diurnal, seasonal and geographic variations in lightning and storms
- Excellent spatial resolution (1-10 km for LEO platforms)
- Low temporal resolution (1-10 ms)
- Lack of waveform information

Table 1. Lightning Experiments from Space

Satellite/Spacecraft	Launch Date	Sensor	Altitude (km)	Period	Lightning Power Sensitivity (Watts)	Footprint
Optical						
OSO 2,5	1965, 1969	Photometers	600	Moonless Night	$\sim 10^8$	
VELA V	1970	Photodiodes	1.1×10^5	Day-Night	$10^{11} - 10^{13}$	Very Wide Field of View
DMSP	1970	Scanning Radiometer	830	Local Midnight	Sensitive	100 km
DMSP-SSL	1974	12 Photodiodes	830	Local Midnight	$10^8 - 10^{10}$	700 km
DMSP-PBE 2,3	1977	2.5 mm Photodiode	830	Dawn/Dusk	$4 \times 10^9 - 10^{13}$	1360 km
S81-1 (SEEP)	1982	Particle Spectrometer Airglow Photometers (391.4, 390.8, 630.3 nm)	230	Night	10 R	100 km
Space Shuttle-NOSL	1981-1983	Photocell Plus Film	150	Shuttle Flights STS-2, 4, 6	NA	Variable
Space Shuttle-MLE	1988-1990	Payload Bay Video Cameras	150	STS-26, 30, 32, 34	NA	Variable
RF						
ARIEL-3	1967	HF Radio Receivers 5, 10, 15 MHz	600	Day/Night	RF	"Iris" Effect
RAE-1	1968	HF Radio Receivers 0.2 - 9.18 MHz	5850	Day/Night	RF	Ionosphere Structure Dependence
ISS-b	1978	HF Radio Receivers 2.5, 5, 10, 25 MHz	1100	Day/Night	RF	Several Hundreds of Kilometers
Goes-Next Lightning Mapper Sensor (Proposed)	Late 1990's	CCD Array	Geostationary	Continuous Coverage	$10^8 - 10^{11}$	10 km
EOS-A Lightning Imaging Sensor (Proposed)	Late 1990's	CCD Array	Low Earth Orbit	Continuous Coverage Within Field of View	$10^8 - 10^{11}$	1000 km x 1000 km Field of View with 10 km Pixel Resolution

Hugh J. Christian, Richard J. Blakeslee, and Steven J. Goodman. *Lightning Image Sensor (LIS) For the Earth Observation System*. **NASA Technical Memorandum 4350**, February 1992.

Limitations on Previous Lightning Experiments in Space

- Unable to provide detailed information on lightning characteristics, spatial extent and discharge frequency.

- Weak accuracy location (ie, hundreds of km) due to the low spatial resolution of the detectors.

- System detection efficiency was less than 2%.

NASA's Solution => U2 Mission

- Using a U2 high altitude aircraft and several devices established the baseline for lightning detection from a GEO orbit to be implemented in a future GOES mission.

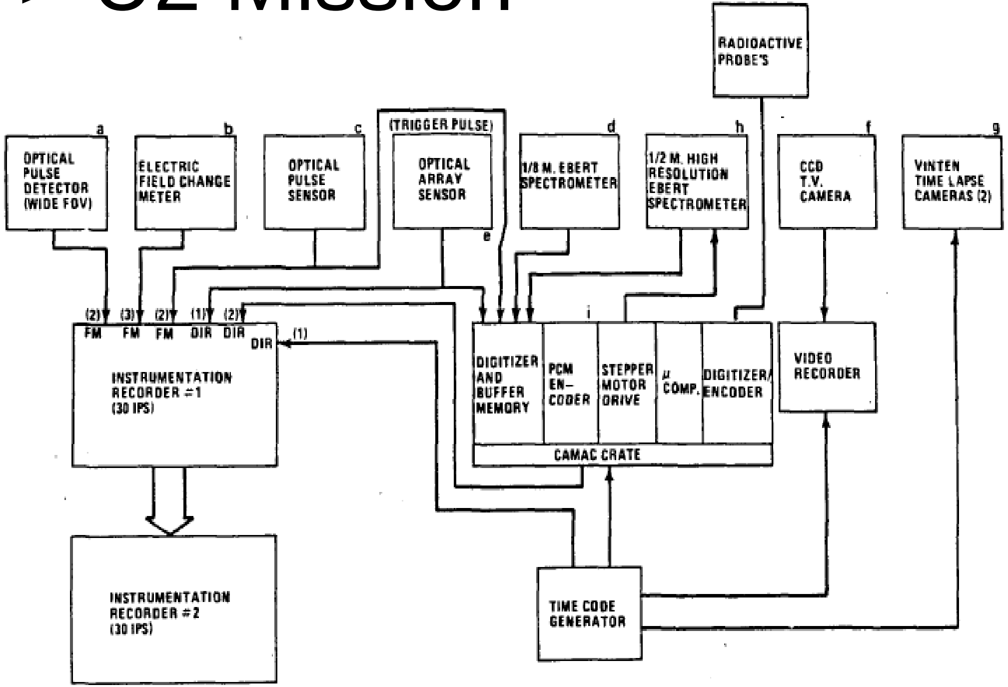
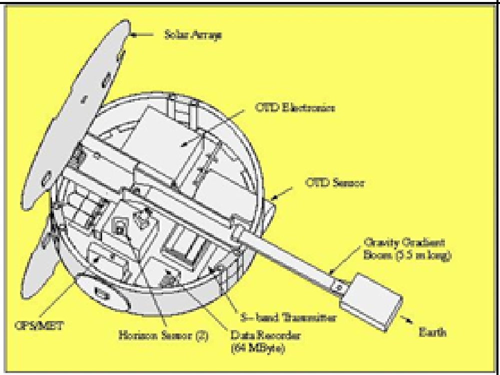
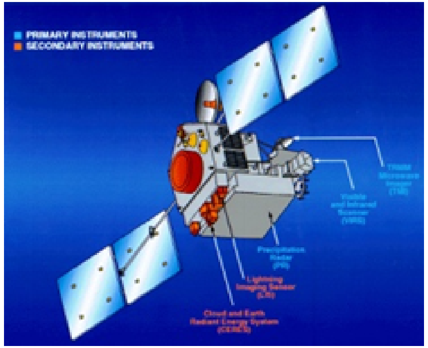
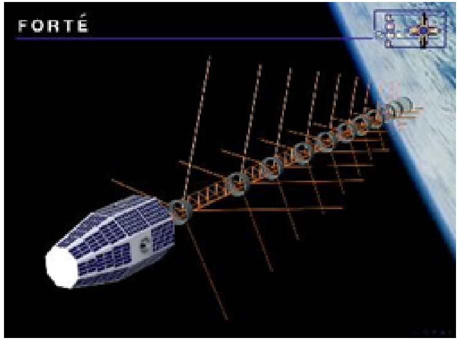


FIG. 1. Block diagram of U-2 aircraft lightning instrumentation.

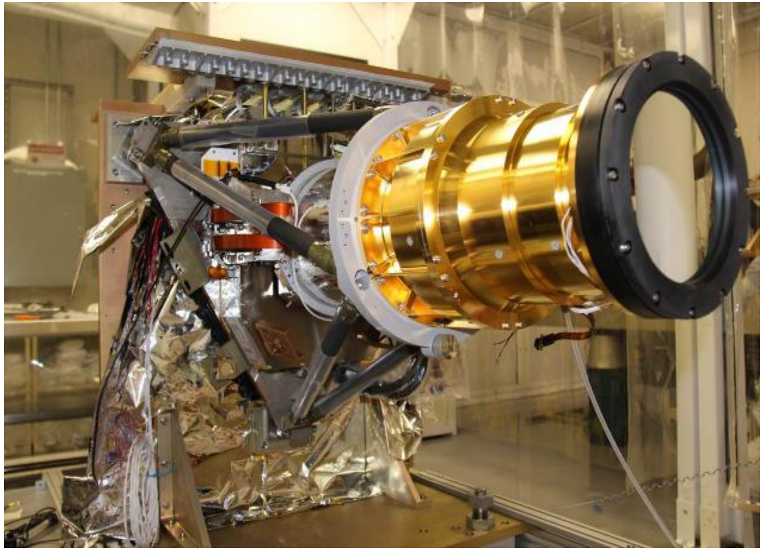
H. J. Cristian and S. J. Goodman. *Optical Observations from a High-Altitude Airplane*. **Journal of Atmospheric and Oceanic Technology**. VOL 4 Pages 701-7011, December 1987**.**

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	
llustration			

State of Art: GOES-R and the Geostationary Lightning Mapper (GLM)

- GLM-Geostationary Lightning Mapper payload, launched in the end 2016 at GOES-R, by NOAA/NASA consortium, which is an optical transient detector capable of measuring the occurrence of total lightning, in the Americas and nearby oceanic regions [8], with spatial resolution of 10 km.



GOES-R - http://www.goes-r.gov/mission/mission.html

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Methodology Adopted for Feasibility Analysis

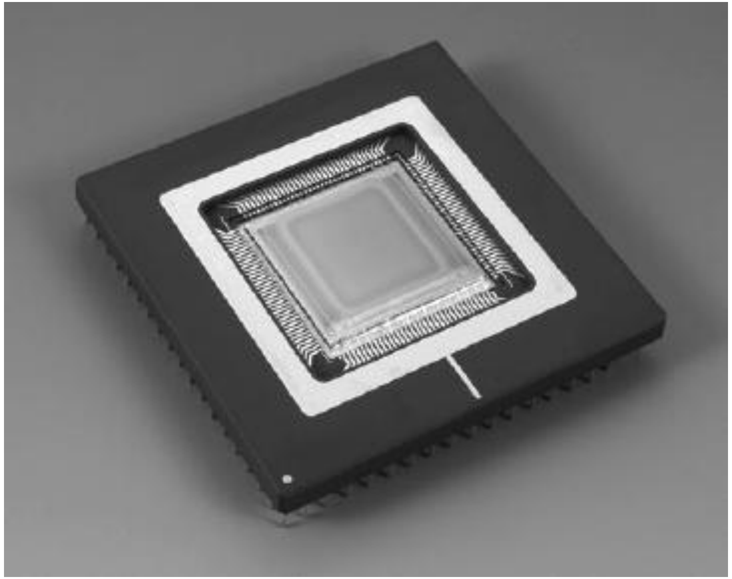
Steps
01. Define the Mission Requirements and Objectives
02. Determine the Mission Geometry and Orbit Parameters
03. Define Payload Requirements
04. Define the Payload Operational Concept
05. Determine the Spatial Sampling
06. Determine On-board Signal Processing needs
07. Determine Radiometric Sensitivity Performance
08. Estimate Payload Size, Mass and, Power
09. Determine Payload MOE´s
10. Document and iterate this process

Prospective optical payloads:

1st Try

NanoCam C1U [11]

2nd Try



•PB MV 13 Sensor [10]

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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.

4.1 Optical Mission Requirements and Objectives

RaioSat	FORTE
Camera 777.4 nm and 883,3 nm	Camera 777.4 nm
Without Photodiode	Photodiode PPD
RF Antenna	RF Antenna

4.2 Mission Geometry and Orbit Parameters

As Suggested By Naccarato et al. :

- LEO in the ISS orbit at 400 km of altitude or an alternative a Polar orbit possibly with launch in a DNEPR launch.
- The crucial orbital parameter for sizing of the imager is the altitude.
- For the mission, a more elaborate study of the most suitable orbit(s) is suggested.

4.3 Optical Payload Requirements

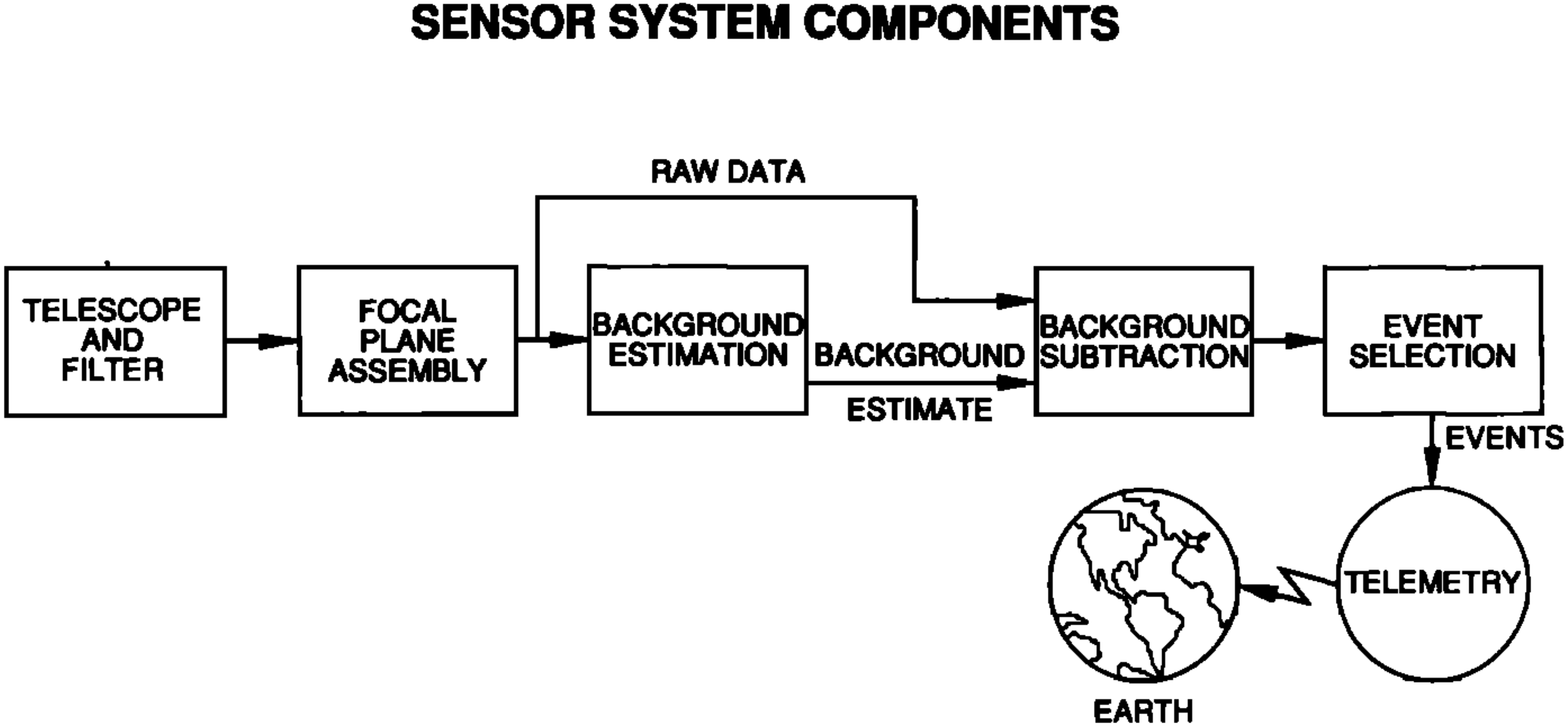
Optical sensor

- 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 777.4nm (atomic oxygen) or 863.3nm (atomic nitrogen) with a 1 nm bandwidth

Signal processing

- background signal estimator,
- a background subtractor,
- a lightning threshold detector,
- an event selector, and
- a signal identifier.

Optical Payload Requirements



HUGH J. CHRISTIAN, RICHARD J. BLAKESLEE, AND STEVEN J. GOODMAN.
The Detection of Lightning from Geostationary Orbit **Journal of Geophysical Research,** Vol. 94, no. Dll, pg. 13,329-13,337, September 30, 1989

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.

4.4 The Payload Operational Concept

- 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

(1) a background signal estimator,

(2) a background subtractor,

(3) a lightning threshold detector,

(4) an event selector and

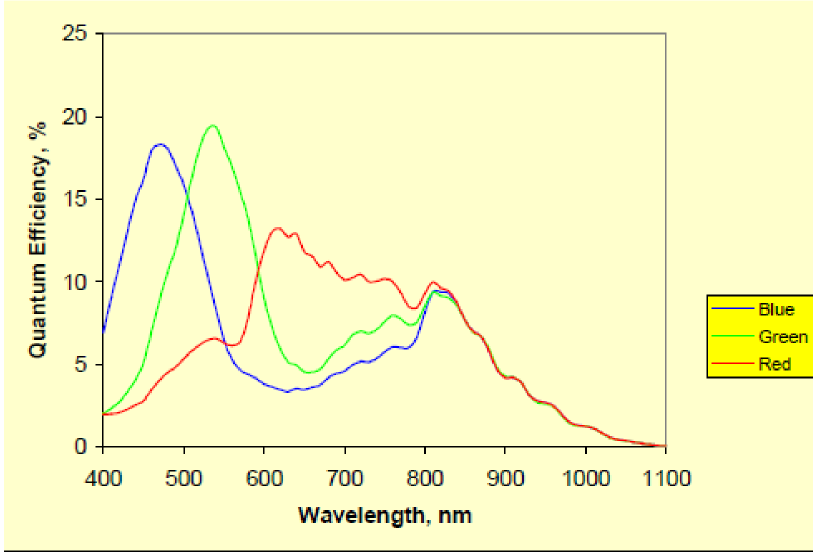
(5) a signal identifier.

- 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.

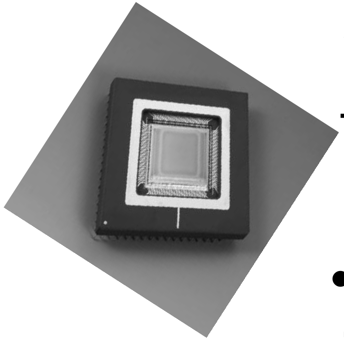
Quantum efficiency of Photobit PB MV 13 sensor



4.8 Payload Size, Mass and Power Estimations

- Wertz proposed three methods for evaluating a payload:

(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.

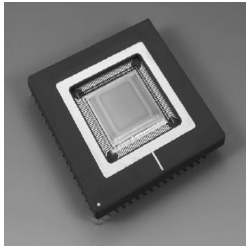
4.8 Payload Size, Mass and Power Estimations

- 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.
- Three MOEs are considered suitable for this purpose:
  - – Signal noise ratio at zero spatial frequency (SNR),
  - – Modulation Transfer Function (MTF) at the detector's Nyquist frequency and
  - – Ground Sampling Distance (GSD).

- A **Relative Quality Index (RQI)** is defined to allow quantitative comparisons with a reference instrument

RQI = (SNR/SNR Ref) x (MTF/ SNR Ref) x (GSD Ref / GSD)

RQI of Payloads OTD, LIS (ref) and LLS vs 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

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

GomSpace Camera NanoCam C1U - https://gomspace.com/Shop/payloads/earth-observation.aspx

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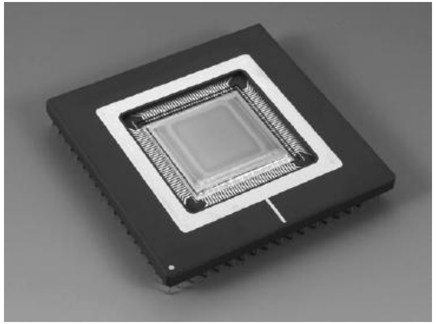
Conclusions and Research Outlook

NanoCam C1U - GomSpace

- Top rated candidate
- Full Imager
- Flight heritage
- Needs only a 777.4 nm filter
- Integration time less than 5 times the acceptable makes it unsuitable



Sensor PB MV 13 - Photobit

- 2ms integration time
- Flight heritage in cubesats.
- Lenses needes
- Additional electronics HW

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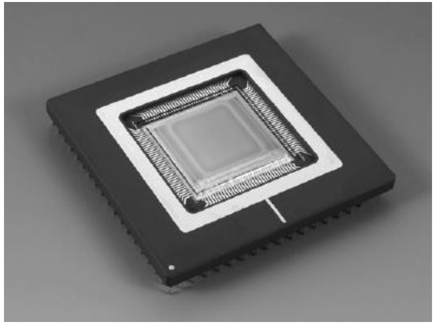

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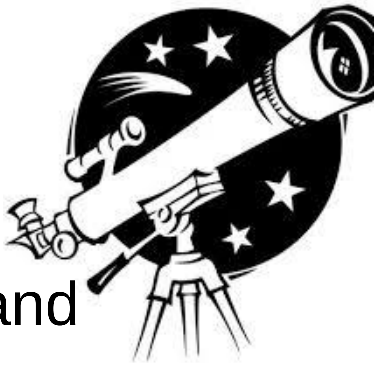

- Cost-benefit of lightning detection in both the oxygen and nitrogen bands
  - U2 had this feature.
  - All subsequent missions, Microlab, TRMM and FORTE, detected only the 777.4nm band.
- Future research will consider whether it is more interesting to:
  - Monitor lightning in two bands using one camera or
  - Look into one band with a camera adding a photometer.

attractive for new features.