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CRON-1 - The First Brazilian Private Cubesat

Otavio S. C. Durão, João Braga
INPE - National Institute for Space Research
Av. dos Astronautas, 1758; São José dos Campos, SP; 12227-010; phone: 55-12-3208-7118
otavio.durao@inpe.br

Valter R. Schad, Manuel Bernardo da Silva Neto, Maury Esper
Horuseye Tech Systems Engineering Ltd.
R. Professor Roberval Fróes, nº 390 ap. 202A; phone: 55-12-98112-8304
horuseye@horuseye.com.br

Gilberto Rigobello, Celso Benedito Ribeiro
CRON Systems and Technology Ltd
Av. Andrômeda, 693, sl. 708; São José dos Campos, SP; 12.230-000; phone: 55-12-98106-8000
gilberto.rigobello@gmail.com

ABSTRACT

Brazil has launched a few cubesats so far. Both through universities as well as through space research institutes and its Space Agency. There is a growing interest in the country for this type of satellite due to its low and feasible costs for these institutions, as well for the increasing number of possibilities with its use. The advantages of its use for science and educational purposes is not questioned any more in a changing scenario, as was the case in the world in general. However, so far, all these missions were developed with government funds. The challenge now is to transfer this technology and application to the private sector.

The mission here described is the first in the country developed by a private company in cooperation with the public R&D space sector for the payload. In the process it also creates a production chain with other companies for the development of part of its subsystems and software. A few of them (HorusEye, USIPED) are new in the space field although with large experience in other micro electronics and precision mechanics applications. These subsystems are the attitude determination and control, the EPS and the structure. All of these with advantages when compared with similar subsystems available in the international cubesat market. Software is also developed by a small company from former INPE graduate students (EMSISTI). The OBC and the transceiver will still have to be imported due to the larger development costs, and the limited budget for the project. The scientific payload of the mission is an experiment for the detection of hard X-ray and gamma ray radiation in space, possibly from cosmic explosions such as Gamma-Ray Bursts (GRBs). This experiment was initially conceived for a larger bus but it has never materialized due to its costs. The number of detectors in the payload array was significantly reduced but it will still produce significant results for the mission PI. One exciting possibility is the detection of electromagnetic counterparts of gravitational wave signals detected by the LIGO/Virgo consortium. This was not known when the larger bus was being considered for this mission. The cubesat is a 2U with 1U fully for the payload. CRON-1 was officially submitted to be launched in 2021 by the first launch of VLM (Microsatellite Launch Vehicle), the small launcher under development by the Brazilian Air Force, Brazilian industries and DLR (German Aerospace Center). However it will be ready to be launched by the end of 2020 and another earlier launch alternative may be selected if it can´t be launched by VLM. The project was selected to be funded by the São Paulo State Foundation for R&D (FAPESP) in a call from its Innovation Program for the Small Company (PIPE) for the development of the engineering model so far. The paper gives more information and details about the payload and the science motivation for the mission as well as for the subsystems developed for CRON-1.

INTRODUCTION

Cubesats are now a trend that came to stay in the space sector. The concept of a cheap, smaller, faster project finally has materialized after it was partially conceived at NASA many years before the cubesat standards were born through Bob Twiggs and Jordi Puig-Suari in California, through the "faster, better, cheaper" concept introduced in 1992 by the the Dan Goldin´s administration, with very controversial results. The difference is in the words "smaller" and "better" that are difficult to match. But this distance is in many cases decreasing as well. The R&D and academic community are achieving outstanding results with cubesats mission in different applications, including interplanetary. On the other hand there is also a trend that larger missions and space projects be conducted by the private sector. This is also happening in the cubesat world where due to low costs and faster developments more players can participate in these new space businesses. However this move, from the R&D, academic and generally public funded sector, to the private one, is not generally easy, despite the technical or scientific merits of the mission. Other variables play a role which are not always under the realm of the developer, as well as the business people don´t quite understand well what is going on with the project. However, one can say that this may be the ultimate challenge to the cubesat sector. That is, to be able to capture the interest of customer willing to pay for them and their applications. In order to be able to do this, not only the business variables have to be understood but also technical and R&D characteristics of the satellite have to be consistent in the long run in terms of reliability, life time and more demanding technical requirements.

Brazil has launched four cubesats so far. At the present time other four or five are scheduled to be launched until the end of next year. All of them however have been developed by the public sector and with public budgets. Although budgets are low when comparable to larger missions, still the bureaucracy exists to be able to raise the necessary amount and uncertainties are present that affect planned schedules. As public projects, this in many times can be accommodated by the stakeholders and their expectations. In the private sector this may not be true.

This paper describes the first cubesat mission developed by a private company in Brazil. It is in fact a scientific private-public partnership where the PI is from the National Institute for Space Research (INPE) and the platform is a combination of national developed subsystems with imported ones, also in a long standing partnership with ISIS Innovative Solutions in Space. The project aims also to create a production chain in the country that may be able to support future projects.

Budget is provided through a grant from the São Paulo State Foundation for R&D (FAPESP) that, although a state government agency and thus from public budget origin for its funding, is fully provided to the main contractor which is a private company that has fully control over it. The program within FAPESP is the Innovation Program for the Small Company (PIPE) where this project was selected among many other candidates.

THE SPACE MISSION

For many years, INPE has been tried to launch a scientific micro satellite in the order of 150 kg. to an astronomy X-ray mission. Difficulties to get the required funding along with an unstable yearly budget to the project have made it not to exist so far. This mission has been called MIRAX[1]. With the existence now of low cost cubesats this mission, in a reduced but useful version, will fly in a 2U cubesat thas is being called NanoMirax within INPE and CRON-1 elsewhere, due to the name of the Brazilian company building it in a cooperation approach. CRON-1/NanoMirax will be capable of detecting with an accuracy of a few degrees, explosive cosmic events that manifest mainly through the emission of hard x-rays. In particular, in the present age of multi-messenger astronomy, strongly stimulated by the first detections of gravitational waves from the coalescence of compact objects, it will be extremely auspicious that experiments capable of detecting and locating the electromagnetic counterparts of these events are "patrolling" the celestial sphere. The payload uses a subset of CdZnTe-type X-ray semiconductor detectors used for a MIRAX balloon prototype[2],. The configuration studied for the payload allows it to have sufficient sensitivity to detect and locate short gamma-ray bursts (GRB), associated or not with gravitational wave events.

The X-Ray Detector Payload

The X-ray detector consists of a small hard X-ray imaging camera (10 to 200 keV), composed, due to power limitation on board the 2U bus, of 4 CdZnTe detectors of 10mm x 10mm x 2mm (thickness) developed for the MIRAX prototype balloon project[2]- see Figure 1 - placed side-by-side in a 2x2 configuration (see Figure 2).

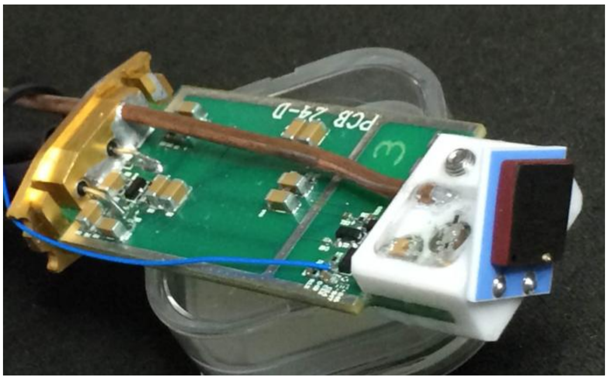

Fig. 1 - CdZnTe detector (CZT) - right hand insert - and its prototype electronic board of acquisition; final electronics developed in house at INPE

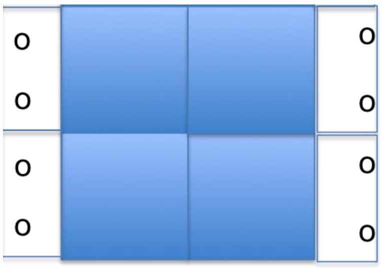

Fig. 2 - top view of the set of 4 CZT detectors that form the detector plane - small circles represent the electrical

contacts of the cathode and the anode (upper and lower planes - the wires are not shown for clarity).

Figure 3 shows an energy spectrum of one of the detectors obtained using a radioactive source of 241 Am. CZT detectors have excellent photoelectric efficiency up to hundreds of keV and very good energy resolution when compared to traditional scintillation detectors

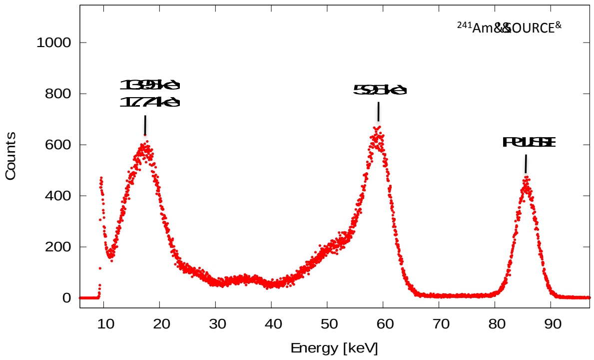

Fig. 3 - Energy spectrum of one of the LECX detectors. The line at 59.5 keV of the radioactive element 241Am is clearly identified, also showing a left wing originated by the incomplete collection of charge for a fraction of the events. The artificial line at ~ 85 keV comes from a pulse generator and aims to measure the intrinsic electronic resolution of the system.

The Acquisition Electronics

When a high-energy photon interacts within the detector material, a certain amount of electron-hole pairs is created, producing a charge cloud with a diameter of approximately 100 µm. A reverse voltage of 200 V causes the electrons to migrate to the cathode. The pulse produced is captured by a low noise charge preamplifier, which feeds an LNA of 60-70 dB and then a shaper. The pulse is then pulse-height analized by a 10-bit Wilkinson type ADC (1024 channels). A conversion and multiplexing electronics formats each photon detected in a digital word containing time (from a GPS receiver chip on board), the detector reached (which gives the xy position of the interaction) and the height of the pulse (proportional to the photon energy). Data files with the events are stored on board and transmitted to the ground at each satellite passage by the receiving station.

The localization system

With this detector plane of only 4 pixels and 4 cm2, we can determine the sizes of the X-ray shadows of the shielding walls projected on the 4 detectors by measuring the total counts in each detector for a given integration time. This allows the localization of point sources in the sky within certain limitations. Surprisingly (since this is a small cubesat experiment) as will be shown below, this configuration allows detection and localization with some degree of accuracy of cosmic explosions known as "short-hard gamma-ray bursts", which are believed to be electromagnetic counterparts of transient gravitational wave sources. These events occur when two compact objects (neutron stars or black holes) in a binary system agglutinate to form a single black hole. This hypothesis was confirmed by event GW 170817[3].

Figure 4 shows an exploded diagram of the mass model for the X-ray detector. The arrangement of detectors will be surrounded at the bottom and sides by a Pb-Sn-Cu gradual screening system (thicknesses of 1.0, 1.7 and 0.3 mm, respectively) to reduce background noise and determine the field of view. In the intended configuration, the "box" of shielding will have dimensions of 50mm x 30mm x 20mm (height) and a weight of 160g. Thus, the field of view will be 51.3° x 36.9° (FWHM) and 26.5° x 14.0° (maximum sensitivity). The aperture determined by the shield will have a central element, 10mm x 10mm, also Pb-Sn-Cu 3mm thick, which actually represents the "coded mask" that will allow the location of the detected cosmic explosions. The entire system represented by the detector plane and the shield will be mounted on a cubesat plate so that the top of the shield box is allocated in an aperture of an outer face of the satellite structure. The acquisition electronics will be mounted on the same board.

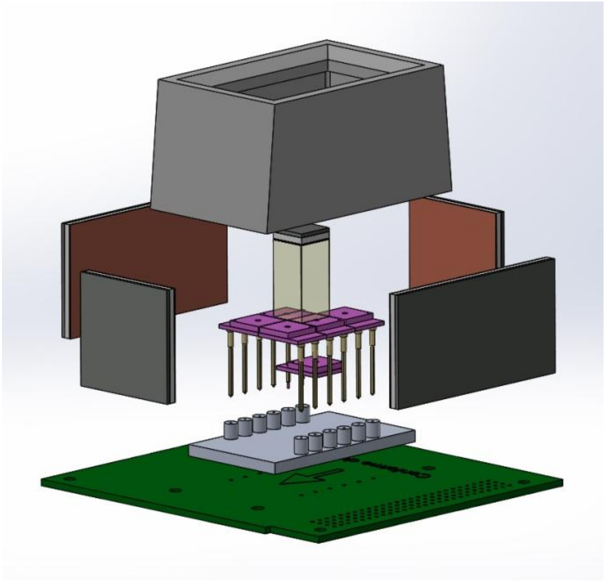

Fig. 4 - exploded diagram of the mass model for the camera of the X-ray detector.

A source positioning algorithm was developed that has been extensively demonstrated by Monte Carlo simulations. Essentially, it consists of the following steps from the "trigger" of a cosmic explosion (total counts above a certain threshold), (a) the counts for a given integration time, are measured, (b) based on the counts, the sizes of the shadows of the shielding walls are determined, (c) determine the peak of the correlation map, (d) the corresponding angles right ascension and declination are calculated based on the attitude knowledge of the spacecraft. For a typical short GRB, lasting one second, the simulations show that the position is retrieved with an accuracy of approximately 3°. 100 times more intense cosmic explosions, such as long-lasting intense GRBs, can be located with an accuracy of a fraction of a degree.

Sensitivity

In order to estimate the performance of the system described above in low orbit (550km, circular) equatorial, we performed Monte Carlo simulations using the GEANT4 package. As input parameters, the mass model of the experiment (Figure 4) and the radiation fields of the external environment are inserted. Figure 5 shows the background noise expected for the experiment from these simulations. It is noted that diffuse electromagnetic radiation penetrating the camera aperture is largely dominant, especially below 100 keV. With these background noise spectra, one can calculate the sensitivity of the experiment to point sources, for a given statistical reliability. Figure 6 shows the sensitivity for a 4-hour integration with a reliability level of 5σ. Surprisingly, this small cubesat experiment is able to detect the flow of a cosmic X-ray source such as the Crab Nebula (Crab) at least up to 100 keV.

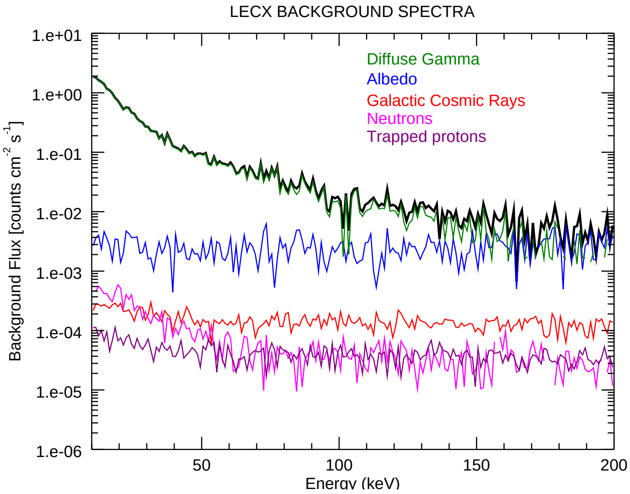

Fig. 5 - Background noise spectra expected for the X-ray detector (LECX) in low orbit (550 km, circular, equatorial) for the main radiation fields in this region.

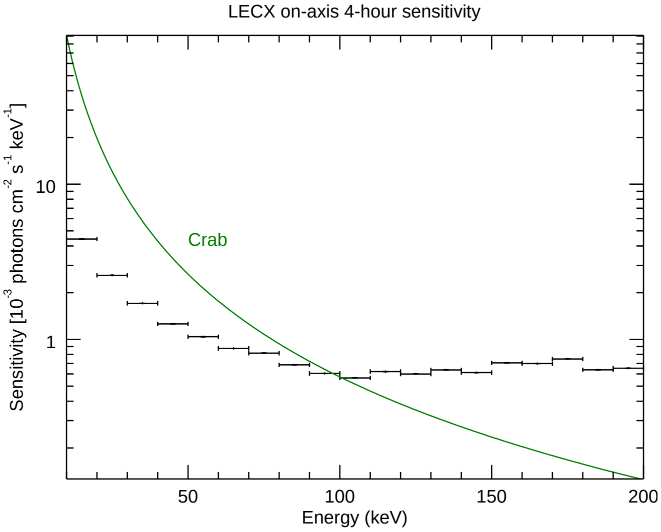

Fig. 6 - X-ray detector (LECX) sensitivity for 4 hours integration in low orbit (550 km, circular, equatorial) and a statistical reliability level of 5σ.

In the case of a short-term GRB-type cosmic explosion, the sensitivity calculated for 1 second of exposure (Figure 7) shows that the X-ray detector (LECX) can detect such an event at energies up to 150 keV.

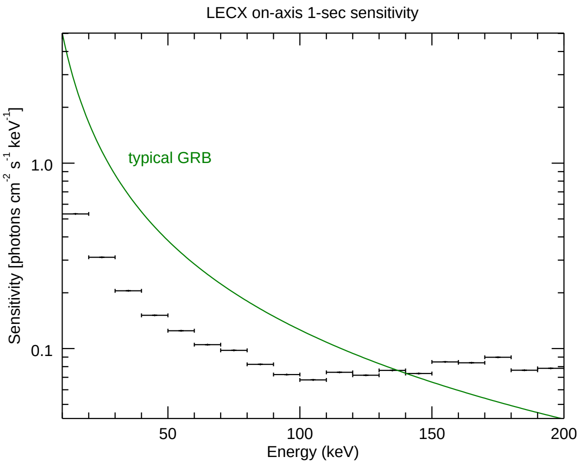

Fig. 7 - Sensitivity of the X-ray detector (LECX) to GRBs, with integration in low orbit (550 km, circular, equatorial) and a statistical reliability level of 5 sigma

In summary, the X-ray detector, also called LECX, is an extremely interesting, simple, low-cost, and rapid development payload for a nanosat based on a cubesat platform. A 2U platform is being designed to accommodate the experiment. Detectors, acquisition electronics and high voltage sources for detectors have already been developed under the balloon prototype MIRAX project. Developments were done to adapt the payload subsystems to a cubesat platform and to design the interfaces required with cubesat onboard computing and power supply subsystems.

Preliminarily, it is estimated that the amount of data created on board by the LECX experiment will be 630 bits / s under the normal regime. During the occurrence of a cosmic explosion, this rate can be multiplied typically by a factor of 10, but only for a few seconds. A trigger system should be developed to determine the occurrence of explosions. For a low orbit with a typical 90 min period, 4 MBits of onboard data storage and a 6 kbits / sec telemetry will be required for data transmission in 10 min passes by the receiving station (assuming only one a station - two stations may be available to the mission). The total mass of the LECX payload shall not exceed 1 kg. The power to be consumed by the experiment is limited to 0.8W always on.

THE CUBESAT BUS

Under the strategy to create a cubesat supply chain in the country, a few companies, not necessarily already working with space projects, were selected, and accepted, to develop part of the platform subsystems and the on board and ground software, and therefore enter the cubesat space market. Unfortunately the budget available was not sufficient to the development of all the subsystems. Thus the prime contractor will import the OBC and the transceiver from ISIS Innovative Solutions in Space. This company has a long history of cooperation in Brazil with the prime contractor since the first cubesat mission in Brazil[4]. It is also a spin off from TU Delft and DelfiC-3, in an analogous scenario that occurs with the institutions involved in the CRON-1/NanoMirax mission. For future projects it is intended that this cooperation continues into a commercial and technological exchange of opportunities and knowledge. These two subsystems (OBC and transceiver) are now object of two specific proposals to FAPESP for their developments, by two of the brazilian companies participating in the CRON-1/NanoMirax mission. If the proposals are granted, the whole set of subsystems may be developed locally for future missions, although the cooperation with ISIS is aimed to be kept.

Among the hardware and software being developed to the CRON-1/NanoMirax mission, two subsystems were selected to be described with more details.

Attitude Determination and Control Module (ADCM)

Although solar sensors in the cubesat panels are used in the project, and the ADCM has been designed with potential for pointing at a target, due to the limitations of the sensors used, this project only provides stabilization at angular velocity after release of the cubesat, using magnetic torque actuators, and attitude determination with magnetometers, solar sensors and gyrometers. The mission does not require pointing at a specific target but just attitude knwledge at the orbit point where measurements are made. The ADCM has an innovative design with redundant sensors for increased reliability, and redundancies may or may not be mounted on circuit boards, given the particularities of reliability requirements, cost and power available for experimentation for each mission. In the present version, the choice of the sensors to be used is determined by software, shortly after the acquisition of the measurements, and based on coherence tests.

After release, the cubesat will be stabilized using the measurements of a triad of MEMS gyros, which provide the angular velocity of the cubesat with respect to an inertial frame. The actuation will be done by magnetic torquers, which generate orthogonal proportional torques at the inertial angular velocity and magnetic field, expressed in the cubesat axes. If there is stability, the speeds will be reduced to the residual gyros biases. Velocity stabilization can also be done using a B-dot algorithm, in which the readings of the magnetometers are filtered and their derivatives obtained. These data are used to reduce these values to a minimum, acting proportionally on the magnetic torquers. If there is stability, the speeds are reduced to magnetometer residual error. In both cases, it should be noted that by the very nature of the actuation (the magnetic torque generated by the actuators is proportional to the vector product of the vector magnetic field measured by the magnetometers, by the local magnetic field vector of the Earth), when these fields are collinear, this actuation is zero. However, depending on the inclination of the orbit, the magnetic field varies in intensity and direction along it. The existence of residual angular velocity in the cubesat is considered tolerable for communication with the Earth, and also for the experiment, provided the attitude is determined.

$$\mathbf{L} = \mathbf{m} \times \mathbf{B}$$

Where L is the resulting magnetic moment in the cubesat, m is the moment generated by the magnetic torque and B is the earth's magnetic field, all expressed in the cubesat reference.

The applied moment, in the case of use of gyrometers and magnetometers, is:

$$\mathbf{m} = \frac{k_\omega}{|\mathbf{B}|}\, \boldsymbol{\omega} \times \mathbf{b}$$

In case of use of magnetometers only, the applied moment m is:

$$\mathbf{m} = \frac{k_B}{|\mathbf{B}|}\, \dot{\mathbf{B}}$$

Where $k\omega$ and k_B are fixed or variable gains that guarantee the stability and performance of the control. The electrical actuation itself can be done with PWM drive, for better energy efficiency, for the same performance.

The attitude determination phase starts after stabilization in angular speed,. The attitude is determined using the measurements of the triad of magnetometers and the solar sensors in the cubesat panels when there is no obscuration of the solar sensors. Therefore, if there is availability of components of two non-collinear vectors in the cubesat frame, a deterministic algorithm like TRIAD or QUEST can be used to determine the instantaneous attitude. During the unavailability of solar sensor information by obscuration by the Earth, the attitude is propagated with the help of the gyrometric triad and a stochastic Kalman Filter type estimator.

Forecasting the use of the ADCM in applications as a medium performance OBC, a 32 bits M7 ARM microcontroller of the SAM E70 family was chosen. This is a high performance microcontroller with moderate consumption, capable to operate until 300MHz of internal clock. For an application with an OBC present, the lowest allowable clock for the processing will be used aiming at the lowest possible consumption. Although this microcontroller internally has an RTC, it was chosen to use an external model in order to be able to completely switch off the microcontroller without losing an embedded time reference. This microcontroller already has a considerable memory capacity for code (internal flash with 2 Mbytes) and for work (internal RAM with 384 kbytes). However, taking advantage of an available feature to execute code in an external serial memory (QSPI interface), the option to forecast for a NOR type flash with capacity of 16 Mbytes was included. It is also envisaged two FRAM (SPI interface) memory units with a capacity of 512 kBytes each, totaling 1 Mbyte of resource.

For applications where it is necessary to record information during the operational period, a SDCard interface is available on this microcontroller. Although it is possible to record operational configuration parameters on the internal flash, the option was to use an external 8-KByte E2prom (I2C interface) for this purpose. For communication with the ADCM internal sensors, there is an SPI bus with several selector lines and an I2C Master bus. For communication with external devices or systems there is an I2C Slave bus (main communication with OBC), an SPI bus, two asynchronous serial interfaces, a USB interface and a CAN interface. The firmware load is made by the JTAG interface, accessed by the JTAG connector.

The hardware for the torquer actuation consists of three magnetic torquers and three digital temperature sensors, as well as proprietary connections and the CSKB bus. This hardware will be mounted on a standard PCI. Figure 8 shows the design of the board, where the torque X and Y are in red, mounted on the upper face of the PCI; the torque Z in blue, mounted on the underside and the ADCM fitted as a daughter plate (in lilac). In gold there are the fixings and the bus CSKB.

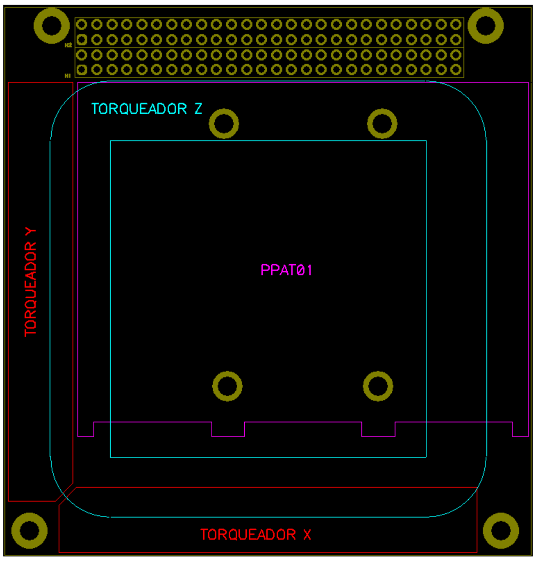

Figure 8 - ADCM design

Figure 9 shows the engineering model of the ADCM yet without the torquers assembled onto it.

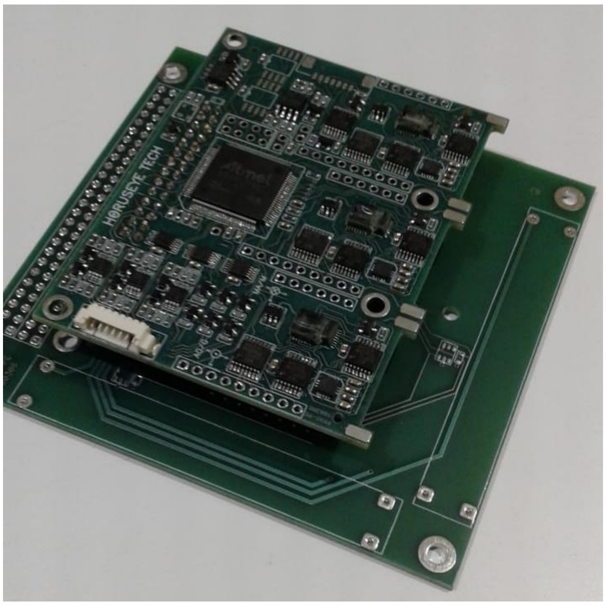

Figure 9 - ADCM EM without the torquers.

Figure 10 shows the prototype of the torquers before assembly onto the ADCM EM for CRON-1/NanoMirax.

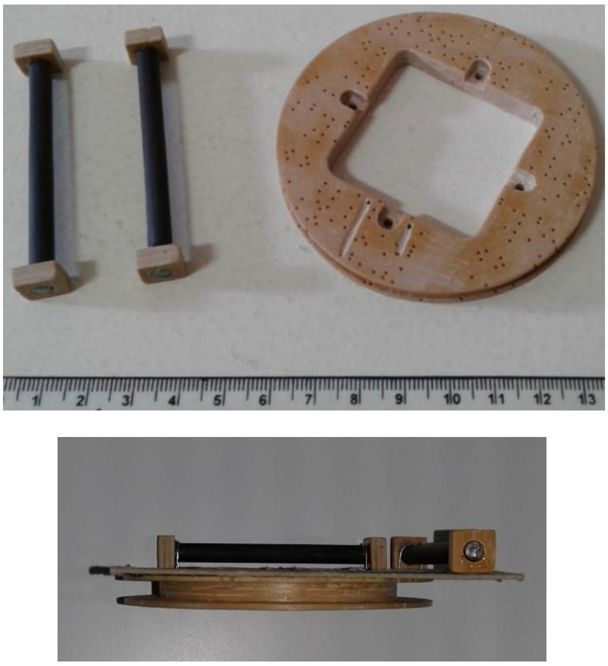

Figure 10 - Torquers and their ADCM board layout.

Power Generation and Management Module - PGMM

The prerogatives of MGGE are:

- Optimize the transfer of energy captured by solar panels;
- Control the distribution of power to the system;
- Manage the generation, storage and energy consumption by the system;
- Provide all information for processing by the mainboard system (MGPD);
- Perform protection of the batteries (voltage and current) by hardware and software;
- Allow configuration of parameters inherent to the charge of the batteries and the distribution of energy;
- Check the temperature of the batteries by hardware and software.

The power conversion of the solar panels is carried out by BOOST type converters using MPPT (Maximum Power Point Tracking) mode. Each converter has two inputs for solar panels. The MPPT operation seeks to maximize the utilization of the energy that the panels can generate and this is useful when the system needs to recharge the batteries and does not consume the full capacity of the panels. In this case, all excess consumption is directed to storage. The implemented circuit can operate in two MPPT modes:

- constant voltage
- maximum power

The constant voltage mode assumes an optimum working point of the solar panel, and keeps the voltage at its terminals close to a reference value associated with that point (it is the default mode of the hardware and independent of the microcontroller).

The maximum power mode monitors the voltage and current at the panel terminals and modifies the power draw (by varying the working voltage) so that the current product x voltage is maximum. The technique used in this case is D & O (Disturb and Observe). The refresh rate is around 1ms. This operating mode depends on the microcontroller.

The designed circuit allows changing the working voltage of the panel, around a default value, so that, according to previous configuration, it can operate in any mode. With this, it is also possible to change by software the value of the working voltage for constant voltage mode (dependent on the microcontroller). When there is no destination for the excess power that the panels can generate, the drive operates in constant voltage output mode, extracting only what the system needs from the panels.

The PGMM control center uses an 32 bits M4 ARM microcontroller of the SAM G55 family. This is a microcontroller of high performance with low consumption. Since the microcontroller always operates in the active mode, the operating frequency has been chosen around 24MHz so that the consumption of the board is as small as possible using an external crystal for clock stability, which allows the use of an internal RTC to " time stamping" of operational analyzes and providing a window of recent events with accuracy of occurrence. For these records there is an external flash memory with 128kbytes capacity, with SPI interface. Figure 11 shows the MGEE engineering module by itself and assembled with the ADCM.

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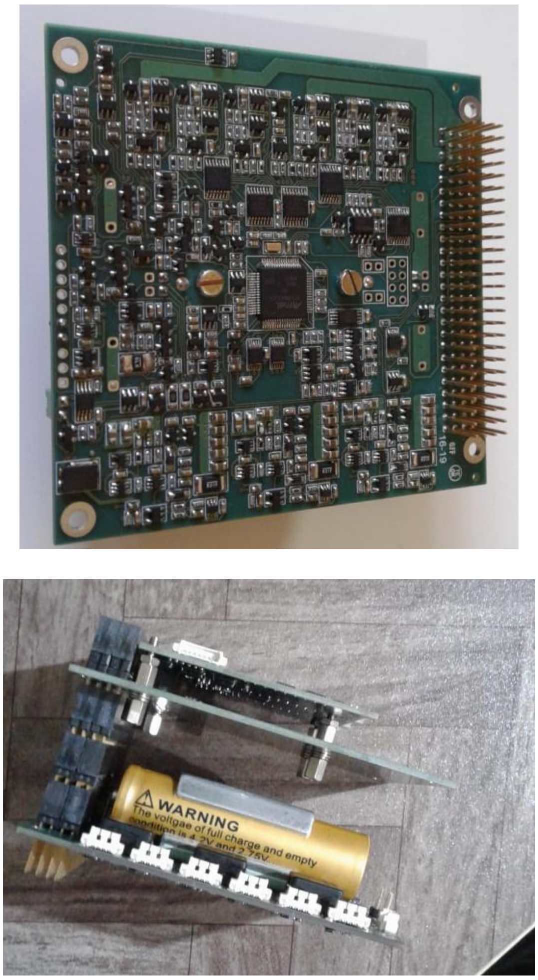

Figure 11 - PGMM EM itself and with ADCM

CONCLUSIONS

The engineering model of the CRON-1/NanoMirax 2U cubesat is scheduled to be finished by June 2020. Assembling, integration and testing will be done at the Integration and Testing Laboratory at INPE. Launch may be with the VLM - Microsatellite Launching Vehicle, being developed in Brazil. This launcher has its initial flight planned to 2021. The CRON-1/NanoMirax is already an official candidate as a payload for the first VLM flight.

References

1. Braga, J. 2006, “MIRAX Mission Overview and Status”, AIP Conference Proceedings, **840**, 3
2. Braga, J. et al. 2015, “The protoMIRAX hard X-ray imaging balloon experiment, Astronomy & Astrophysics, **580**, A108
3. Abbot, B. P. et al. 2017, “GW170817: Observation os Gravitational Waves form a

Binary Neutron Star Inspiral”, Physical Review Letters, **119**, 161101

4. Schuch, N.J., Durão, O.S.C, Silva, M.R. da Silva, Mattiello-Francisco, F., Martins, J.B.S, Legg, A.P, da Silva, A.L. and Burger, E.; "The NanosatC-Br Program - A Joint Cubesat Program Developed by UFSM and INPE/MCTI - Space Geophysics Mission Payloads and First Results"; The Brazilian Journal of Geophysics; vol. 1, no. 37; 2019.