AMICal Sat: A Sparse RGB Imager on Board a 2U CubeSat to Study the Aurora

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Abstract—AMICal sat, a dedicated 2U CubeSat, has been developed, in order to monitor the auroral emissions with a dedicated imager. It aims to help reconstructing the low-energy electron fluxes up to 30 keV in the Earth auroral regions. It includes an imager entirely designed in the Grenoble University Space Center. The imager uses a 1.3-Mpixels sparse RGB CMOS detector and a wide-field objective (f = 22.5 mm). The satellite platform has been built by the Polish company Satrevolution. Launched 3 September 2020 from Kuru (French Guyana) on board the Vega flight 16, it produced its first images in October 2020. The aim of this article is to describe the design of the payload, especially the optics and the proximity electronics, and to describe the use of the payload for space weather purpose. A preliminary analysis of a first image showing the relevance of such an instrument for auroral monitoring is performed. This analysis allowed us to reconstruct from one of the first images the local electron input flux at the top of the atmosphere during the exposure time.

Index Terms—Aurora, CubeSat, imager.

I. INTRODUCTION

SPACE weather is a system science in the sense that it includes a chain of complex phenomena coming from the Sun and going to the Earth mainly through the magnetosphere. Added to this, the effects on the Earth infrastructures and their vulnerability have to be taken into account. This chain is too poorly described to allow accurate nowcasting and forecasting of space weather events and of their effects on the Earth [1]. In this chain, the upper atmosphere as well as its interface with the magnetosphere require improvements in their description. Precipitations of auroral electrons along magnetic lines lead to auroras, which are one of the most striking manifestations of space weather. These phenomena characterize the relationship of the magnetosphere and the upper atmosphere, and their intensity and localization indicate the state of the near-Earth space. The energy release in the region of the auroral oval, associated with precipitation of auroral electrons, is controlled by the solar wind parameters and is one of the important reasons leading to changes in space weather in the polar magnetosphere and ionosphere.

It is, therefore, fundamental to observe, monitor, and model the energetic inputs in the relevant regions of the near-Earth space. Koskinen et al. [2] highlighted the strong importance of improving the accuracy of both measurements and numerical models. In this frame, one of the main gaps in both data and modeling is the monitoring of the precipitation of low-energy (0.02–30 keV) particles in the ionosphere and in the magnetosphere, especially electrons which are key contributors to ionospheric currents.

Ground-based networks of instruments for auroral monitoring have been used for several decades. Among those currently active, we can mention the MIRACLE network of all-sky cameras, the ALIS network [3], [4], or the ASK [5] instruments which can produce very fast images in several emission bands. However, although very useful, ground-based instruments are often blinded by cloud coverage and cannot be operated with daylight. For instance, weather conditions in Ny-Alesund on Svalbard are cloudy about 75% of the time [6]. These constraints, hence, drastically limit optical data availability for space weather applications.

Other ground-based instruments can provide complementary observations of upper atmospheric processes and magnetosphere–ionosphere couplings. We can mention, for example, incoherent scatter radars, such as EISCAT or magnetometers networks on the ground. However, these data are not fully suitable to monitor the low-energy particles coming into the atmosphere in auroral regions or they cover a limited part of the oval preventing large-scale monitoring. Optical data are thus mandatory. In this frame, space observations of auroral...
emissions can bring invaluable information, since they are not affected by cloud coverage, they allow us to monitor wavelengths absorbed by the atmosphere, and the geometry allows limb observations of aurora, which makes it possible to reconstruct the vertical profile of the emissions, a task which is rather difficult from the ground and impossible with a single instrument.

II. Space-Born Imager for Auroral Monitoring

Numerous satellites observed the polar lights both in the UV and visible range; however, AMICal Sat is the first CubeSat to be dedicated to the observation of the optical emissions of the auroras. Most of them are observing the auroras in the UV, especially in the far UV (FUV). For example, we can quote the following missions:

1) IMAGE satellite with FUV imaging instrument [7];
2) TIMED satellite with GUVI instrument [8];
3) Freja satellite with ultraviolet imager (UVI) [9];
4) Dynamic explorer satellite with spin scan auroral imager (SAI) instrument [10];
5) Viking satellite with V5 UV instrument [11];
6) Polar satellite with UVI instrument [12];
7) Feng Yun satellite with wide-field auroral imager (WAI) instrument [13] with a very wide field $2 \times 10^7 \times 68^\circ$;
8) DMSP satellite with the special sensor ultraviolet limb imager (SSULI) and special sensor ultraviolet spectrographic imager (SSUSI) [14], [15].

Far fewer satellites are observing auroras in the visible range. We can mention the following:

1) the Nadir-looking photometer system (NPS) on board DMSP;
2) the instrument visible imaging system (VIS) [16] on board polar satellite;
3) finally, Cassiopee small-satellite carries near-infrared and narrow-band visible imager with the fast auroral imager (FAI) instrument [17].

However, in the visible range, the Japanese satellite REIMEI is one of the most interesting.

REIMEI is a small satellite operated by the Institute of Space and Astronautical Science, Japan Exploration Agency (ISAS/JAXA) with the aim to understand interaction with high atmosphere and auroral electrons. It was launched on 23 August 2005 from Baikonour by Dnepr rocket on a polar synchronous orbit at 608 by 655 km of altitude and inclination of 98.17°. This small satellite has a mass of 72 kg and size of 70 cm $\times$ 62 cm $\times$ 62 (H) cm. It carries four instruments, as follows:

1) a multispectral monochromatic auroral imaging camera (MAC);
2) the electrons and ion energy spectrum analyzers (ESA/ISA);
3) the plasma current probes (CRM);
4) a three-axis geomagnetic field aspect sensor (GAS).

The GAS instrument allows the auroral camera MAC to capture the projected footprint of the REIMEI position along the local magnetic field line at an altitude of 110 km. The ESA/ISA instrument measures electrons and ions carried by the magnetic field line and is responsible for the auroral emissions captured by MAC. REIMEI is then able to measure auroral particle properties and simultaneous aurora images, called Mode-S. The MAC instrument has a field of view of $70 \times 70$ km in the local horizontal plane direction and a matrix of 1024 $\times$ 1024 pixels for three wavelength bands: 427.8, 557.7, and 670 nm. Temporal resolution is 120 ms. The ESA/ISA instrument allows us to obtain energy-pitch angle distribution function of auroral particles with the energies of 10 eV/q–12keV/q for ions and 12 eV–12 keV for electrons [18], [19]. Intensities observed by MAC must be corrected as explained in [20] due to parasitic light sources. They mentioned Moon light pollution and reflection of the aurora itself on the ground or clouds.

One of the remaining challenges in the frame of auroral particle quantification is to cover the full oval in order to reconstruct a larger part of the energetic inputs. Several ways could be allowed to achieve this: the first is to provide a very wide-field instrument, and the other is to build a constellation of satellites. To keep the cost at quite low levels, the most convenient way for this last option is to use CubeSats.

III. AMICal Sat Imager

AMICal Sat, a 2U demonstrator CubeSat, was launched on 3 September 2022 on board the Vega flight 16. It is on a Sun synchronous orbit with a mean altitude of 530 km with an inclination of 97.5°. The payload is an imager designed to take pictures of the aurora both at the limb and the Nadir. It aims allowing a short exposure time in the range of 1 s. The imager is equipped with a homemade objective with a focal length of 22.5 mm and an aperture of f/1.4. The imager fits in less than 1U.

The real originality of this imager is the detector with its sparse RGB CMOS detector using 10-$\mu$m pixels. As stated by Sharif and Jung [21], the black and white pixels are much more sensitive than colored ones. This can also been checked looking at the datasheet of the ONYX detector. Only one pixel over 16 is colored. This detector named ONYX contains 1.3 millions of pixels (1280 $\times$ 1024).

Since the launch, AMICal Sat is working and has been able after commissioning to begin the science mission in October 2020. However, a failure in the attitude determination control system (ADCS) perturbs the mission since the orientation control is thus lost. However, the images have been registered. They show both the aura and the ground on the night side.

A. Auroral Observations With Sparse RGB Detector

Auroral emissions have the particularity to be an emission line spectra and not a continuum. Main lines in the visible range in terms of intensity are the $O^1S$ green line at 557 nm, the $O^1D$ triplet at 630 nm, and the 0–1 band of the $N_2^+$ first negative system at 427 nm. In the very near UV, there also exists the 0–0 band at 391 nm of the same electronic transition of this ion, which shows a stronger intensity than the 427 band with a constant branching ratio. It is not visible with the AMICal Sat instrument.
TABLE I  
LINEAR COMBINATION OF EACH FILTER REGARDING MAIN AURORAL LINES

| Line | Wavelength (nm) | Blue Filter | Green Filter | Red Filter | Panchromatic pixels |
|------|-----------------|-------------|--------------|------------|--------------------|
| $O^+\Sigma_u^+$ | 537 | 0.084 | 0.066 | 0.0418 | 0.6618 |
| $O^1\Sigma_u^+$ | 630-639 | 0.12 | 0.085 | 0.663 | 0.663 |
| $N_2(A^3\Sigma_u^+ - B^3\Pi_g)(\Delta \nu = \frac{\lambda}{\lambda_0})$ | 680 | 0.14 | 0.11 | 0.65 | 0.653 |
| $N_2(A^3\Sigma_u^+ - B^3\Sigma_u^+)(\Delta \nu = \frac{\lambda}{\lambda_0})$ | 570-610 | 0.06 | 0.32 | 0.391 | 0.65 |
| $N_2(X^2\Sigma_u^+ - A^2\Sigma_u^+)(G - 1)$ | 427 | 0.425 | 0.038 | 0.0735 | 0.5113 |

$N_2$ first-positive bands also have significant intensity, especially when considering the integration over large spectral bands, especially between 600 and 700 nm.

The fact that in the blue and green filter bandpass, the intensity of these main lines represents the larger part of the intensity is interesting when using large band filters to monitor aurora. In the first approximation, the green line intensity will be equal to the intensity in the green pixels as well as the 427 lines in the blue filter. The situation is immediately more complicated in the red filter bandpass, where several bands are present, especially the first-positive band of $N_2$ and the oxygen red line.

In black and white pixels, the intensities of all lines will be mixed; however, those pixels are much more sensitive. The global sensitivity will then be much higher since they represent 15/16 of the total number of pixels. This will be useful for the shape reconstruction.

However, the sensitivity of the filters is not zero even far away from the central wavelength, meaning that a slight component of the other lines is also present. If we consider only the lines mentioned above, we can consider that each filter is a linear combination of the different lines. The coefficients are given in Table I.

In the AMICal Sat configuration, each pixel represents 240 m at the ground level considering a mean altitude of the satellite of 530 km. Since the pattern for red and blue pixels is 8 pixels in each direction, this means that we obtain red information only every 2 km. This is the same for the blue pixels. However, the $B&W$ pixel resolution stays close to 240 m.

It means that we keep the information on the geometrical structure of the aurora despite the lack of colored information.

The reconstruction of the colored image can be done via a color reconstruction via a switch to YCbCr representation. However, for scientific purpose, it is better to distinguish both $BW$ images from colored channels. We then perform an interpolation of each color using cubic functions and obtain four different images: one $B$ and $W$ and three colored ones.

### B. Optical Design

The central part of the imager is a compact, fast, and wide-field objective lens, suited for a CubeSat platform. These challenging characteristics were not met in any existing commercial solutions and have called for a specific development in the AMICal Sat mission.

The parameters achieved in the design of the imager are summarized in Table II. The choice of the parameters were driven as follows: first, a pixel size of 10 $\mu$m of the Onyx detector was chosen, which enables a compromise between a large optical étendue (faint targets) and small spatial resolution. Then, the size of the detector and the total field of view (40.8°) set the focal length of the design. From an initial $f$-number of $f/1.1$ (targeted), the requirement on the aperture was revised to $f/1.4$, once again to be compatible with the short exposure of faint targets. Finally, the total optical length (entrance pupil to detector) had to be smaller than 50 mm, in order to fit the 1U volume dedicated to the payload.

The design adopted here is of the kind of double Gauss objectives (Fig. 1), with a special emphasis put on the compactness of the design. The resulting solution includes six lenses, made of two glass materials (S-LAH65VS for lenses 1, 3, 4, and 5; S-TIH14 for lenses 2 and 6) in order to compensate for the chromatic dispersion, at the level of each air-spaced doublets. These doublets are intentionally not cemented, in order to be compatible with the void conditions in space.

The typical size of the point spread function (PSF), defined as the edge of the square that encircles 80% of the energy of the PSF, is 14.96 $\mu$m at the center of the field, 33.6 $\mu$m at half-diagonal, and 47.52 $\mu$m at the extreme edge of the diagonal (Fig. 2). The objective was also specifically designed to avoid vignetting. It is not rigorously telecentric, although an important constraint was put on the maximum incidence angle tolerated on each pixel, in the form of an image telecentric design. This maximum incidence angle is set by the design of the pixel itself and its embedded microlens.
For the sake of both compactness and image quality, the last lens of the design acts as a field lens, and was placed at close separation of the optical window of the detector. These features (close back-focus, close air-spaced doublets) called for a specific mechanical development, which were essential to reach the performances of the instrument.

C. Baffle and Mechanical Design

The Amical-SAT imager can be separated into three parts: 1) the optical baffle to remove the stray light; 2) the optical imager; and 3) the detector with its electronic board (Fig. 3). As stated above, six lenses are collecting the aurora light and focus it on the detector. There are positioned by spacers with an important accuracy (between 10 and 20 μm). The important thermal cycling between day time and night time forced us to choose a material with the same coefficient of thermal expansion as that of the lenses. Titanium alloy (Ta6V) is chosen for all the spacers.

To avoid important stress inside the lenses' glass, lenses and spacers are fixed with a group of springs. The spring load is determined with the total weight of the lenses and spacers and the maximum acceleration during the launch phase. A margin factor of 1.5 is applied. The distance between the lenses and the detector can be adjusted by a shim spacer. Spacers are machining with holes and grooves to remove air during the launch phase. To reduce the weight, the mechanical box is made with aluminum alloy (7075 T6). The material of all the screws is stainless steel 316 with class 8.8. All the aluminum parts are coated with standard black anodized. The titanium spacers are not coated. Due to the baffle and the pupil stop, there is no direct light on those spacers.

To avoid parasitic light out from the field of view, a baffle has been designed. It considers the following constraints:
1) available space;
2) field of view and optical properties;
3) structural constraints to avoid vibration of the objective since the baffle links the optical mount to the satellite structure;
4) thermal protection of the sensor;
5) manufacturing difficulties.

To maximize the efficiency of the baffle, custom vanes have been designed. Fig. 4 described the ray tracing method for building the vanes as explained in [22] or [23]. There is no coating on the mechanical parts, even on lenses spacers. The shape of vanes is difficult to machine. Grenoble Alpes University (S.M.ART resource platform) is exploiting an electron beam modeling (EBM) equipment. This process is depositing metallic powder, under vacuum, which is particularly compatible with the space environment. Added to this, 3-D printing allows us to get high roughness. In this case, it was larger than 3.2 μm, giving better optical properties.

The global design is summarized in Fig. 5.

We had decided to delegate the machining of the optical imager parts and the integration at the same company (OPA-Optical) than the lenses. The baffle and the electronic...
Vibration level for mechanical tests

| 3 Axes vibrations | 1 min at 0 dB | Global $G_{rms}$ |
|--------------------|------------|-----------------|
| Frequency range    |            |                 |
| 20-50 Hz           | 0.0071     |                 |
| 100 Hz             | 0.0142     |                 |
| 200-500 Hz         | 0.0355     | 5.89            |
| 1000 Hz            | 0.0142     |                 |
| 2000 Hz            | 0.0071     |                 |

Table III

Transmission of the objectives versus wavelength

| Lambda (nm) | Transmission lenses | Transmission coating | Total transmission |
|-------------|---------------------|----------------------|--------------------|
| 0.43583     | 0.9657              | 0.8                  | 0.7725             |
| 0.48613     | 0.9854              | 0.97                 | 0.9558             |
| 0.58756     | 0.9957              | 0.95                 | 0.9459             |
| 0.65627     | 0.9949              | 0.95                 | 0.9451             |

Table IV

Random vibration tests were done by Satrevolution SA (Poland). The vibration by the Air Liquid company (ALAT-France) and the thermal in the integrated nanosat. Random vibration tests were done (ISO 5).

The final integration of the imager was done at IPAG clean room (ISO 5).

Before launch, tests were done only at the acceptance level in the integrated nanosat. Random vibration tests were done by the Air Liquid company (ALAT-France) and the thermal tests were done by Satrevolution SA (Poland). The vibration random-level requirements specified are in Table III. The CubeSat withstands the random vibrations at acceptance level on $X$, $Y$, and $Z$.

Two different thermal tests were done: 1) thermal bake-out and 2) thermal cycling between $-35$ °C and $75$° during 700 min (Fig. 6). The CubeSat withstands at the both thermal tests at the acceptance level.

D. Optics Transmission

At this stage, due to a failure in the ADCS of AMICal Sat, it has been impossible to take any picture of the Moon. The sensitivity is thus the one calculated from ab-initio calculation using the specificity of the detector and optical front end elements. The simulation of the optical elements gives the transmission for the objective described in Table IV. The coating leads to a transmission of 0.98 in the green and 0.95 in the red. It has a significant effect in the blue since the transmission in then only 0.8.

We, thus, obtain a total transmission for the objective, varying from 0.77 to 0.96, then by multiplying by the quantum efficiency of each filter and each detector, we are able to calculate the sensitivity of the instrument.

E. Line Intensity Reconstruction

We express the intensity in the total flux for each pixel for each extracted image considering that each pixel has a field of view of $2.05 \times 10^{-3} \text{sr}$.

The full equation to reconstruct the intensity emitted in the auroral region is then for one line

$$I_g = S_{pix} \times \Omega_{pix} \times \left( QE_{557} \times Abs_g \times L_{557} + QE_{427} \times Abs_b \times L_{427} + QE_{630} \times Abs_r \times L_{630} + QE_{N2\Delta v=3} \times Abs \times L_{N2\Delta v=3} + QE_{N2\Delta v=4} \times Abs_r \times L_{N2\Delta v=4} \right)$$

$$I_r = S_{pix} \times \Omega_{pix} \times \left( QE_{557} \times Abs_g \times L_{557} + QE_{427} \times Abs_b \times L_{427} + QE_{630} \times Abs_r \times L_{630} + QE_{N2\Delta v=3} \times Abs \times L_{N2\Delta v=3} + QE_{N2\Delta v=4} \times Abs_r \times L_{N2\Delta v=4} \right)$$

$$I_b = S_{pix} \times \Omega_{pix} \times \left( QE_{557} \times Abs_g \times L_{557} + QE_{427} \times Abs_b \times L_{427} + QE_{630} \times Abs_r \times L_{630} + QE_{N2\Delta v=3} \times Abs \times L_{N2\Delta v=3} + QE_{N2\Delta v=4} \times Abs_r \times L_{N2\Delta v=4} \right)$$

$$I_{Pan} = S_{pix} \times \Omega_{pix} \times \left( QE_{Pan557} \times Abs_g \times L_{557} + QE_{Pan427} \times Abs_b \times L_{427} + QE_{Pan630} \times Abs_r \times L_{630} + QE_{PanN2\Delta v=3} \times Abs \times L_{N2\Delta v=3} + QE_{PanN2\Delta v=4} \times Abs_r \times L_{N2\Delta v=4} \right)$$

where $QE$ is the quantum efficiency at a given wavelength, Abs is the absorption due to the optical elements, and $L$ the received luminance for a given line. $S$ represents the surface of the pixel and $\Omega$ is the solid angle for one pixel.

As it is, the system is underdetermined since it contains five variables for only four equations. We can, however, consider a constant branching ratio between the $\Delta = 3$ branch and $\Delta = 4$ of the first-positive band. $[I(\Delta v = 4)/I(\Delta v = 3)] = 0.21$, reducing the number of variables. Based on laboratory spectra from [24], $\Delta v = 3$ and $\Delta v = 4$ represent more than 95% of the total intensity of $N_2$ first-positive band. We can then consider that these two bands represent the full first-positive band and we choose not to correct and consider the full intensity is included in these spectral features. Added to this, we considered the uncertainties due to the noise in the detector as described in the ONYX datasheet. It indicates at 25 °C:

1) readout noise ERS: $\leq 3$;
2) DSNU: 10;
3) PRNU: $\leq 1$;
4) dark signal: 2.
However, the temperature of the satellite is included between 0 °C and −10 °C, much lower than 25 °C. We then can consider that the noises are much lower probably less than five counts. To evaluate the effect of this noise, we propagate a noise of five counts coded in 12 bits in the processing pipe. Considering the bias described above and the noises described in the datasheet, the intensity reconstruction precision is then evaluated in the order of 10% for low signal, down to 2% for almost saturated signals. However, some variable lines not taken into account in the previous calculations could also degrade this precision. It is extremely difficult to estimate since they are variables but never higher than few percent, we then consider that we have 10% uncertainties for a high signal also.

F. Line of Sight

After intensity reconstruction, it is necessary, in order to compare with auroral emission intensity, to reconstruct the line of sight.

The luminance obtained on the instrument is

\[ L = \int_{0}^{\theta_{\text{max}}} \text{Em}_{\text{vol}} \Omega R^2 \frac{dz}{\cos(\theta)} \]

where \( \theta \) is the angle between the line of sight and the local vertical and \( \text{Em}_{\text{vol}} \) is the volume emission rate in the aurora which can be compared with auroral simulation outputs.

IV. ELECTRONICS DESIGN

A. Institutional Framework

The institutional framework in which the design and fabrication of the electronics took place, led to some nonoptimal technical solutions. It has to be briefly exposed in order to give a better understanding of these.

AMICal Sat payload electronics specification started about 20 months before the delivery date of the payload. Although the electronics team was directed by a single person throughout the whole project duration, several students were successively involved, mostly for a duration of 2–6 months. This turnover combined with the short duration of the project led us to prioritize the choices as follows.

1) Use of technologies already executed in labworks of the university, thus well known by staff and students.
2) Easier and faster prototyping solutions, immediately doable at the university labs.
3) Buying from common suppliers, hence limiting the possibilities of using space-qualified parts.

ONYX sensor part was an exception, because it came to the electronics team as an input of the project. Therefore, next sections also detail what the team was able to set up, in order to eventually design and build a fully functional payload, despite the team’s limited knowledge and lack of experience and support on this part.

B. Inputs of the Project

Nanosatellites common design constraints often include the following.

1) Limited volume allowed to the payload electronics.
2) Low-power design and advanced sleeping modes.

In the AMICal Sat case, the choice of allocating 1 full U (1 dm³) to the payload, combined with the size of the optics and its sensor, led to some comfortable room allocated to the printed circuit board (PCB). In the end, it is rather high-frequency considerations (differential serial outputs of the sensor, and fast Static RAM signals) that conducted us to miniaturize the PCB. Indeed, the power supply design was not room constrained at all, and no tradeoff had to be made between the PCB room and quality of the power supplies decoupling (capacity and max voltage values). Regarding the power consumption, the ONYX sensor rules a minimum working frequency, which defined the whole payload acquisition working frequency. When implementing sleeping modes on embedded systems, a balance has to be done between:

1) energy cost of the wake-up from sleep versus full boot-up and reconfiguration from poweroff state;
2) on/idle time ratio;
3) waking up periodicity.

In our case, the balance was clearly in favor of a full poweroff of the payload between two sets of acquisitions.

Other inputs that had to be dealt with were as follows.

1) High throughput of the ONYX sensor (total throughput cannot be set lower than 975 Mbits/s).
2) Low noise analog power supplies to the sensor.
3) The 12-bits digital camera media interface (DCMI) bus to the SatRevolution OBC, with a throughput limited to about 60 Mbits/s because of OBC limitations.
4) When possible, space-qualified design.

C. Digital Design in Space-Qualified Context

Basically, the payload electronics is an image frame grabber. Because of the great gap between sensor minimum throughput and OBC 12-bits DCMI input bus throughput (limited to 7 Mwords/s), the digital architecture detailed in Fig. 7 was chosen.

1) A small field-programmable gate array (FPGA) [actually, a big complex programmable logic device (CPLD)] to deserialize the sensor’s six serial outputs.
2) A 32-Mbits SRAM to bufferize a full frame.

When starting the digital design, we studied the European Space Components Coordination Qualified Parts List (ESCC QPL). We immediately noticed how very few complex digital components are qualified. This led us to consider using...
nonspace-qualified parts, but with extra care during the parts selection. Space-qualified FPGAs were eliminated from the choice list because of their overpriced IDE tools and the lack of experience of staff and students on it. The Altera mature MAX II CPLD family was chosen because of its compliance with the institutional framework described in Section IV-A, and also because of its availability in automotive-grade. One of the big concerns about FPGAs/CPLDs in space is the risk of alteration of their configuration memory. Anti-fuse memory technology is well suited, but as already said, no such part entered in our institutional framework. MAX II family is based on E2V, we chose to electrically protect it against single event latch-up (SEL). This point is detailed in the next section.

As previously explained, the SRAM and MAX II CPLD TID and SEE tolerances are rather good. On top of that, the choice was made to shield the whole payload PCB electronics in a 3-mm thick aluminum case, itself mounted inside the 1-mm aluminum external walls of the nanosatellite. CSUG ran aluminum thickness simulations with the OMERE tool, for the AMICal Sat main memory, has the best TID and SEE tolerance [27]. But in 2017, the only STT-MRAM available technology did not meet the 12-ns write cycle requirement.

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1) Active parts were chosen among automotive AEC-Q200 certified parts when available, or at least in the industrial temperature range version.
2) Passive parts are easily available in AEC-Q200, and were all chosen accordingly.
3) Capacitor voltage rating was systematically doubled.
4) The main risk for ceramic capacitors is a mechanical break of their structure, due to launch vibrations. This usually leads to fatal short circuit of the corresponding power line. Cascaded electrode technologies, such as the AVX Flexisafe product line lowers drastically this risk. We were not able to provision such parts, and had to settle for more standard AEC-Q200 parts.
5) A trick to limit the latter risk, consists in splitting the decoupling capacitor in two equal capacitors, serial mounted, with the drawback of doubling the room occupied on PCB. When we realized we could not get hold of cascaded electrodes capacitors, it was too late to modify the PCB.

The flying model PCB was manufactured in the N35 space-qualified material with ENEPIG plating. Prototyping and flying model PCB assembly was conducted at CEDMS, a UGA university lab, part of the IUT1 Electrical Engineering department.

1) Soldering material was a standard SnPb solder.
2) Soldering process of the SRAM small-pitch BGA package was elaborated through several tests, thanks to the great experience of the lab technician.1
3) In order to absolutely avoid the risk of a weak intermetallic soldering, any form of hand soldering was ruled out, except for the PGA ONYX package.
4) Critical soldering zones such as BGA interballs spaces were visually checked with dedicated optical instruments, and full X-ray imaging checking was conducted.

F. Sharing of Operation Experience

At the time of writing, analysis of the first datasets we got from operating AMICal Sat shows the following,

1) Payload electronics is successful at powering and controlling the ONYX image sensor.
2) Payload digital design is successful at grabbing, buffering, and preprocessing a frame.
3) Lack of some random pixels in images is not related to payload electronics, but to S-band communication considerations.
4) Payload SEL feedback signals are ineffective, that matter is analyzed as follows.

We can thus conclude that the overall precautions taken during the design of AMICal Sat electronics were adequate to reach as close as possible to a space-qualified design, despite our institutional context constraints.

After the launch and first payload power-up, examining the telemetry information immediately showed evidence of a minor error in the electronics design: IC TPS2553-1 fault output signal is open-collector, active low. Resistors pulling-up to the 3.3-V line supply were implemented on the payload PCB. When the platform OBC powers down the payload, this 3.3-V line becomes floating, and so does the fault signal, generating spurious faults to the OBC. Pull-up resistors should have been implemented on the OBC PCB, above the 3.3-V payload line switch. Also, onboard OBC software is inefficient at memorizing pertinent SEL faults which could happen during payload ON state: it needed to be processed as an interrupt, with timestamp storage of the event. This part of the software, which could not be provided directly within the payload application programmer interface (API) to SatRevolution OBC subcontractor, should have been subject to a specific software interface document, instead of just an oral recommendation. Since this minor malfunction could have been partly corrected during the final tests after assembly and integration, it demonstrates the importance of very comprehensive test specifications, even on noncritical features.

Another interesting experience feedback is the CPLD choice. It proved at first to be technically pertinent during the prototyping phases A and B of the project, but began to show poor digital electronics behavior in late phase C, when testing the design’s full performance. A misinterpretation of the ONYX sensor documentation (not yet stabilized at that time), about how the deserialization should be carried out in the CPLD or FPGA, led to instability in the frame grabbing process. At that point, switching to a more appropriate FPGA, would have required a large redesign of the PCB. It would have unacceptably delayed the payload electronics delivery. Thankfully, this problem was smartly circumvented in the last months, by tricking the HDL design and performing extensive signal stability testing. Today, that very difficult choice of standing for a design on which the team already had strong skills, proved to be successful.

V. IMAGES

Despite the problem in the ADCS, it has been possible to take some images. Several of them can be exploitable for auroral monitoring. We will focus on one of them quoted in the following pictures 46R2 (Table V).

A. Timestamp

During the commissioning phase of the satellite mission, we experienced a shift in the master clock of the satellite. This shift has been measured and quantified. We thus give as a timestamp for each picture the corrected one.
B. Ground-Based Reflection

Two sources of light can perturb significantly the auroral emission measurement. First one is the Moon, second one is the aurora itself both reflected on the clouds or snow cover. Estimation of the Moon intensity can be done since the Moon is a very stable photometric standard and a quasi punctual source.

The intensity of the Moon depends of the phase of the Moon. As a reference, we can consider the following calculations have been done based on [29] and considering the following hypotheses.

1) Date of the Data: November 30, 2012, 11:40:43. Almost full Moon, 96%.
2) Flux at the Top of the Atmosphere: 2.633 μW.m⁻².nm⁻¹ at 550 nm (Uncertainty 0.45%).
3) Cloud/Snow Albedo: 0.7, no specular reflexion, reflexion in 2π sr (Lambertian).
4) Nadir sighting.

The intensity on each filter is then

\[ L_{\text{Moon Filter}} = \int_{\lambda_{\text{min}}}^{\lambda_{\text{max}}} F_{\text{Top QE}}(\lambda) \times A \times \frac{\lambda}{hc} \times \frac{1}{2\pi} d\lambda, \]

where \( A \) is the albedo and the other parameters are the usual ones. The integral of the Moon spectra between 400 and 700 nm represents 290.2 kR most of the time, much larger than the auroral emission. At the time and location of picture 46R snap, the Moon elevation was 17.65° at the ground altitude and the phase was 37%. We then can count on a small Moon contribution in the image if clouds or snow are present. We neglected them in the following calculations. In further developments, the ROLO and POLO codes to calculate the Moon intensity at the top of the atmosphere will be used. However, hypotheses will have to be done on the snow and cloud coverage except if coordinated measurements in the infrared are not available. Since our calculation are based on the hypothesis of the absence of cloud or snow, we also neglect the reflexion of the aura itself.

VI. AURORAL INTERPRETATION

The interpretation of the auroral intensities are made using the Transsolo code [30], a kinetic code which uses as input the electron flux and the solar EUV flux on the dayside. It calculates the transport of the suprathermal electrons along a line of sight or a vertical and the subsequent auroral emissions. Emission output is the volume emission rate at different altitude as mentioned in Section III-F. A schematic view of the Transsolo flow is given in [25].

A. Nadir Pointing

Image 46R pointed the terrestrial globe. Some parts of the image are close to direct nadir pointing. Fig. 9 shows the color reconstructed image. Intense colored points lack in the radio transmission. The left band should not be positioned like this but should be repositioned on the right. The black band is a reference.

As mentioned in Section III-B, the PSF varies along the diagonal from 14.96 μm at the center of the field to 47.52 μm at the extreme edge. To avoid dispersion of the light energy on the edge of the field, we choose to integrate the intensity on a much larger square field. Since the objective has been designed to fully avoid the vignetting, we then consider that the sensitivity is constant over the entire field. The sensitivity determination could have been much better using Moon calibration as planned. However, since the ACDS of the satellite is out of order, this method represents the only way to get absolute intensity.

Arbitrarily, we first chose to consider a 17 × 17 pixels region and reconstruct the input parameters, i.e., mean energy of the distribution and total flux at the top of the atmosphere. The hypothesis of a Maxwellian energy distribution is done. However, the unknown geometry is a difficulty in this frame, especially when the line of sight is strongly inclined. In this case, it crosses a wide panel of regions and it is then necessary to sample the line of sight and to run several times the Transsolo code.

We chose, in this article, to keep only line of sight close to the vertical with only one needed run of Transsolo. Further investigations will be driven to take into account the specific geometries accessible on each image. The topic here is to show in one example the principles of the electron flux reconstruction from the images.

Using picture 46R around pixel (1216, 644) which is close to nadir pointing, we found an intensity in the four channels equal to 2620 counts in the panchromatic channel, 2000 counts in the red channel, 1540 counts in the green one, and 1390 counts in the blue one. The reconstruction of the green and blue lines gives \( I_G = 1.92 \text{ kR} \) and \( I_{427} = 2.30 \text{ kR} \). The reconstruction of the bands in the red O 630 nm and N₂ first-positive band is too imprecise due to the fact that the panchromatic and the red channels show similar QE in this region. We cannot be confident in their extracted values. We, thus, only keep the green and 427-nm lines. Under the hypothesis of no parasitic light at the Nadir meaning no cloud or snow, we found by minimizing the differences between the measured intensities and simulated ones, an electron distribution supposed to be Maxwellian, with a mean energy of 3.02 keV and a total flux of 5.17 erg.cm⁻².s⁻¹. In case of high albedo, the total flux will be biased, however, the mean energy mainly based on \( I_G/I_{427} \) ratio will be almost unchanged.

If comparing with other auroral intensity simulation, especially the GLOW code [31], we can see that Transsolo needs
higher energy flux to get an equivalent green line intensity. In our case, the difference is around 50%. However, the codes are somehow different since GLOW is a two stream model and Transsolo a multistream model (8 in our calculations). On the other side, the chemistry simulation included in GLOW is more elaborate than in Transsolo. As stated in [32] for the Martian case, the uncertainty propagations of cross sections, especially in kinetic codes such as Transsolo, can drive to large uncertainties in the final results. Further investigations must be driven to explain these discrepancies.

VII. Conclusion

Since its launch, AMICal has been able to take some pictures of the aurora despite the failure of the ADCS. First rough interpretations of the data have been performed. They, however, remain uncertain due to several problems.

The first one and most important is the uncertainty on the geometry of the line of sight due to the failure of the ADCS.

The second one is the lack of different filters, which necessitates us to make some hypotheses on the intensity of the $N_2$ first-positive vibrational bands. It shows the importance of continuing to develop spectrometers and spectro-imager.

The third one is the absence of recalibration on the Moon which could give better photometric precision than the ab-initio calculation performed in this article.

The fourth is the calculation of the background intensities due to the Moon and the reflection of the aurora itself.

It is possible to reduce some of these biases by precise calculation of background intensities, but measuring the aurora in the visible range with such sparse RGB detectors needs hypotheses on the branching ratio on the $N_2$ emissions. More precise estimations need spectra and/or of course spectral images. The future ATISE [25] and wide-field auroral imager (WFAI) [33] will allow us to get the additional information.

However, we showed that it is possible with a sparse RGB detector to get the intensity of the green and $N_2$ 427-nm auroral lines and then reconstruct roughly the electron input fluxes under the calculation hypothesis. If the mean energy reconstruction is done with relative confidence, the total flux is very uncertain as shown by using comparisons with other simulations such as GLOW. As this stage, we are only able to get an order of magnitude with an uncertainty estimated around 50%.

The extraction of the N2 and Oxygen red line is still more difficult and, in most of the cases, impossible. Since it allows rough estimation of the electron fluxes but are very low cost, a large monitoring of the aurora with such imagers could be considered for further space missions. Considering they fit in less than 1U, it demonstrates the interest of CubeSats such as AMICal Sat for auroral space weather monitoring. However, the best way to reconstruct these electron fluxes is clearly to perform spectral measurements and best spectral imaging measurements such as the WFAI instrument mentioned in [33].

The development of AMICal also allowed us to test in real conditions a non-space-borne CMOS detector, the Teledyne E2V Onyx, with a specific electronics described here, and to design a very compact wide-field imager and its very robust packaging. As a last conclusion, it is also important to mention that more than 50 students worked on this project from bachelor’s to master’s degrees, as well as two Ph.D. students.

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References

[1] C. J. Schrijver et al., “Understanding space weather to shield society: A global road map for 2015–2025 commissioned by COSPAR and ILWS,” Adv. Space Res., vol. 55, no. 12, pp. 2745–2807, 2015.

[2] H. E. J. Koskinen et al., “Achievements and challenges in the science of space weather,” Space Sci. Rev., vol. 212, no. 3, pp. 1137–1157, 2017.

[3] K. Kauristie et al., “Ground-based and satellite observations of high-latitude auroral activity in the dusk sector of the auroral oval,” Ann. Geophys., vol. 19, nos. 10–12, pp. 1683–1696, 2001.

[4] B. U. E. Brändström et al., “Brief report on ALIS (auroral large imaging system), a new all-sky camera in Kiruna and auroral imaging using a mini-DV camcorder,” in Proc. Atmos. Stud. Opt. Methods, vol. 10, 2001, pp. 1–4.

[5] H. Dahlgren et al., “Energy and flux variations across thin auroral arcs,” Annales Geophysicae, vol. 29, no. 10, pp. 1699–1712, 2011.

[6] M. Cisek, P. Makuch, and T. Petelski, “Comparison of meteorological conditions in Svalbard fjords: Hornsund and Kongsfjorden,” Oceanologica Acta, vol. 59, no. 4, pp. 413–421, 2017.

[7] S. B. Menute et al., “Far ultraviolet imaging from the IMAGE spacecraft. 1. System design,” Space Sci. Rev., vol. 91, nos. 1–2, pp. 243–270, 2000.

[8] A. B. Christensen et al., “Initial observations with the global ultraviolet imager (GUVI) in the NASA TIMED satellite mission,” J. Geophys. Res. Space Phys., vol. 108, p. A12, Dec. 2003.

[9] R. Lundin, G. Haerland, and S. Grahn, Eds., “The Freja ultraviolet imager,” in The Freja Mission. Dordrecht, The Netherlands: Kluwer Acad. Publ., 1995, pp. 17–42.

[10] M. H. Rees et al., “Auroral energy deposition rate, characteristic electron energy, and ionospheric parameters derived from dynamics explorer 1 images,” J. Geophys. Res. Space Phys., vol. 93, no. A11, pp. 12841–12860, 1988.

[11] C. D. Anger, “An ultraviolet auroral imager for the Viking spacecraft,” Geophys. Res. Lett., vol. 14, no. 4, pp. 387–390, 1987.

[12] G. A. Germany et al., “Auroral observations from the POLAR ultraviolet imager (UVI),” in Geospace Mass and Energy Flow: Results From the International Solar-Terrestrial Physics Program, vol. 104. Washington, DC, USA: Amer. Geophys. Union, 1998, pp. 149–160.

[13] X. X. Zhang et al., “Wide-field auroral imager onboard the Fengyun satellite,” Light Sci. Appl., vol. 8, no. 1, pp. 1–12, 2019.

[14] R. P. McCoy et al., “Far-and extreme-ultraviolet limb imaging spectrograph for the DMSP satellites,” in Proc. Instrum. Planetary Terrestrial Atmosphere. Remote Sens., vol. 1745, 1992, pp. 310–321.

[15] L. J. Paxton et al., “Special sensor ultraviolet spectrographic imager: An instrument description,” in Proc. Instrum. Planetary Terrestrial Atmosphere. Remote Sens. vol. 1745, 1992, pp. 2–15.

[16] L. E. Frank et al., “The visible imaging system (VIS) for the Polar spacecraft,” Space Sci. Rev., vol. 71, nos. 1–4, pp. 297–328, 1995.

[17] L. Cogger et al., “Fast Auroral Imager (FAI) for the e-POP mission,” Space Sci. Rev., vol. 189, no. 1, pp. 15–25, 2015.

[18] H. Saito et al., “Small satellite REIMEI for auroral observations,” Acta Astronautica, vol. 69, nos. 7–8, pp. 499–513, 2011.

[19] Y. Ebihara, T. Sakanoi, K. Asamura, M. Hirahara, and M. F. Thomsen, “Reimei observation of highly structured auroras caused by nonaccelerated electrons,” J. Geophys. Res. Space Phys., vol. 115, no. A8, 2010, Art. no. A08320.

[20] D. K. Whiter, B. S. Lanchester, T. Sakanoi, and K. Asamura, “Estimating high-energy electron fluxes by intercalibrating Reimei optical and particle measurements using an ionospheric model,” J. Atmospheric. Solar-Terrestrial Phys., vol. 89, pp. 8–17, Nov. 2012.

[21] S. M. Sharif and Y. J. Jung, “Deep color reconstruction for a sparse color sensor,” Opt. Exp., vol. 27, no. 17, pp. 23661–23681, 2019.
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