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On-board images to characterize a CubeSat's ADCS

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ABSTRACT

ADCS for nanosatellites in the New Space sector are frequently offered as Commercial-Off-The-Shelves (COTS) systems. However, when the COTS datasheet and the actual performance in flight differ dramatically, there are few means to assess the discrepancies. Here, we update on the current operations with a flying nanosatellite to assess the attitude stability during inertial pointing mode, based on the analysis of on-board images of the sky. The satellite is OPS-SAT, a 3-unit CubeSat owned and operated by ESA. The imager is directed to the -Z longitudinal axis and the star tracker and a Sun sensor are oriented in the transversal (X,Y) plane. After a trial and error process, a complex processing revealed many stars in the captured images, that could also be identified. It demonstrates that the inertial pointing did not reach the expected performance and, moreover, it provides a fine assessment of the actual pointing and its jitter and drift. This information was fundamental in assessing the possible improvements in terms of sensors' alignments, operations and on-board systems. The latest results are presented, as the operations are still on-going. Such assessments were possible with low-sensitivity sensors and poor stability, demonstrating that a commissioning process of the ADCS in flight is needed and feasible.

OPS-SAT CONTEXT AND EXPERIMENT

OPS-SAT Hardware and Mission

OPS-SAT (Fig. 1), also called by ESA "the flying software lab", is a 3-Unit CubeSat (main body within 30 cm × 10 cm × 10 cm) and the first nanosatellite directly owned by ESA and controlled by ESA/ESOC in Darmstadt, Germany.[1,2] It flies in low Earth orbit, on a polar 6:00-18:00 Sun-synchronous orbit. It is equipped with a full set of sensors and actuators, in particular the imager IMS-100 by Berlin Space Technologies GmbH (BST) and two Attitude Determination and Control Systems (ADCS), the "cADCS" as a corse-pointing system using a fine sun sensor, photo diodes, gyros and magnetometers, but no star tracker, and the "iADCS-100" by BST as a fine-guidance ADCS that includes a star tracker. The bus is based on the NanoMind on-board computers by GOMSPACE running flight software developed by GMV Poland. The system prime and integrator is TU Graz of Austria. The main solar panels, once deployed, consist of five strings of 30 cm × 10 cm normal to -X axis. OPS-SAT offers a high datalink in S-band and X-band to download and check on ground the results of the on-board experiments.

OPS-SAT allows an experimenter to fly algorithms directly written for Linux shell, in JAVA, Python or C++. To this aim, the Institute of Communication Networks and Satellite Communications, from Graz University of Technology, Austria, developed a system on module called the Satellite Experimental Processing Platform (SEPP), with a library of high-level functions to interface with various OPS-SAT systems, like the imager and the iADCS. Hence, the experimenter's code can use functions of SEPP only rather than any functions of the sensors' and actuators' interfaces directly. SEPP is of great help for the experimenter who, nevertheless, still needs to understand and care of the correct chronology in the activation of OPS-SAT's systems and of their detailed status before proceeding from one step to the next. A full framework in Eclipse IDE was prepared to cross-compile the experiment code from the experimenter's environment (Intel, AMD) to the target environment, namely OPS-SAT with an ARM processor.

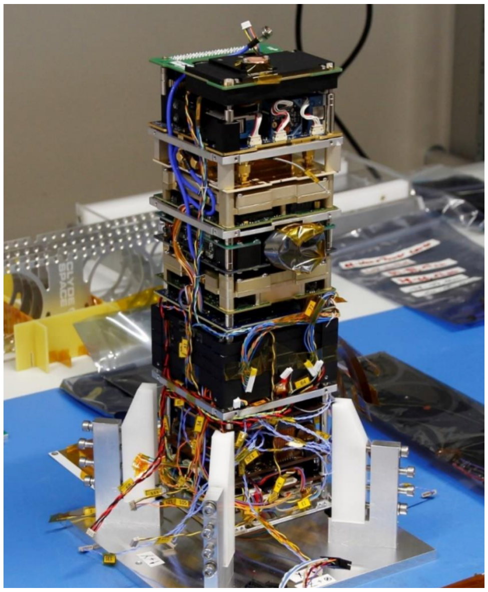

Figure 1: OPS-SAT (launched on 18-Dec-2019). "iADCS-100" with star tracker is visible in the middle of the stack. Credit ESA.

Astrometry Experiment

We prepared an astrometry experiment whose goal is to measure, on board with COTS hardware, the absolute direction of a beacon in a captured image, based on the identification of background stars, as a algorithm called "AbC" (Angle-based Correlation[3]). Due to a known issue with the inertial pointing of OPS-SAT, the experiment was turned into an image-based expertise of the ADCS, whose latest results are presented here.

The experiment is to capture images of the sky with a requested quaternion and, on ground, to reconstruct the actual pointing quaternion of the images by identifying the stars in the field of view. The operations have followed a trial and error process between CENSUS (experimenter team at Paris Observatory) and OPS-SAT (ESA operators). CENSUS computes a quaternion, for the weeks to come, that targets an area in the anti-solar hemisphere with multiple bright stars and allowing the -X panel to be illuminated by the Sun. The rotation about the wanted bore-sight is decided to avoid the illumination of the star tracker by the Sun. Then, the best periods along the orbit to perform pictures are indicated to make sure that the imager and the star tracker are not occulted by the Earth or illuminated by its dayside. Computations are checked in displays provided by VTS,[4] a free software that is specialized for space operations, developed by the French space agency CNES. Then, the OPS-SAT team plans the inertial pointing and the capture of images with the provided quaternion in the best way possible, along with all experiments to be run. The inertial pointing operations consist of a sequence of commands to initialize iADCS, enable telemetry, send magnetometer and sun state vectors to iADCS, start the pointing operation with desired quaternions as input. After the first characterizations of stars, we decided to capture series of 5 images in a row, that we call a "burst", each image with a 500-ms exposure time, covering 2.5 s per burst. One image weighs 7.8-MB in raw format. The images are timestamped with the on-board clock, whose drift from the CPU time is reset daily and kept lower than ~ 1 s. The images are downloaded to the ground station, then deposited in a folder shared with CENSUS. The images are processed by CENSUS with manual validations at various steps of the process. First, the cosmic rays above the brightest star signal are removed and cataloged for every image. The cleaned images are saved as a compressed PNG image (between 500 and 1500 KB in size). Then, each area with a candidate star is displayed and a manual decision is made whether or not it is classified as a star. For a burst of 5 successfully processed images, the cleaned images are re-aligned on the two brightest stars identified and stacked. The resulting image is submitted to the open-source Internet free service "Astrometry.net",[5] which returns a full characterization of the field of view if successful, that is, then, translated into an equivalent OPS-SAT quaternion. The telemetry of the ADCS and the photo diodes are also retrieved from OPS-SAT server. The whole data is formatted to get displayed in VTS and to compare the requested, the reached and the on-board estimated orientations. The example given in Figure 2 was obtained on March 23, 2022 and shows less than $0.5°$ between the 3 orientations.

The imager IMS-100 is aligned with the satellite's longitudinal axis, directed to -Z (Fig. 3). The start tracker's Attitude Knowledge Error (AKE) is expected to be within 15 arcsec transversely to its line of sight and it likely increases by a factor of 5 to 6 for the axis rotation error, i.e. up to 90 arcsec for OPS-SAT's imager that is aligned perpendicularly to the star tracker (not considering estimation filters that are embedded in the iADCS-100).

The IMS-100 is a converted COTS star tracker that was modified to image the Earth surface. Hence, the calibration and acceptance tests for this device addressed rather the risk of image distortion

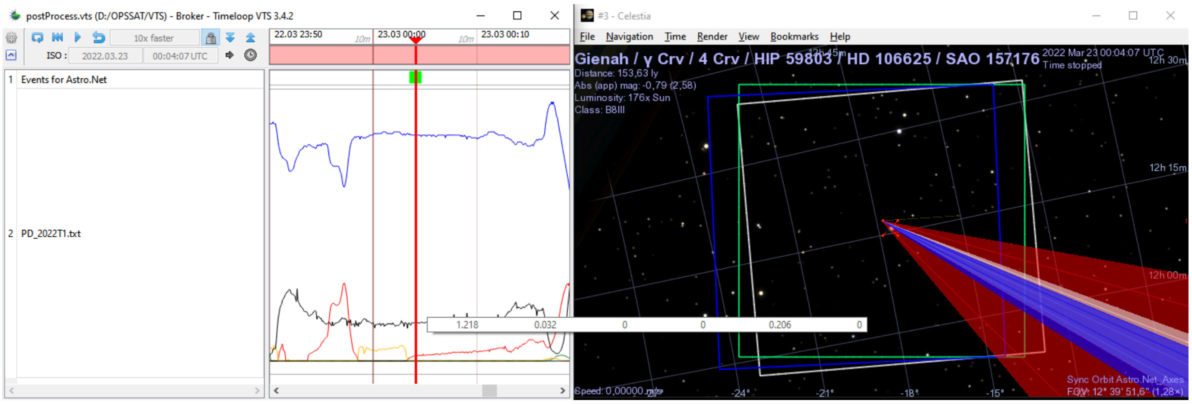

Figure 2: Trial on March 23, 2022. Actual field of view as reconstructed from the pictures (green square), with the requested (white) and the on-board estimated (blue) orientations. Star tracker is orientated to the bottom right. Chronograms of the photodiodes are displayed on the left panel

and not explicitly the sensitivity. As a result, the properties at imaging stars were unknown at the start of our experiment. The raw images are coded in the IMS-100 on 12 bits per pixel, using an RGGB Bayer pattern, on a 2048×1944 matrix of pixels covering approximately a $10° \times 10°$ field of view, with pixels of ~ 18 arcsec.

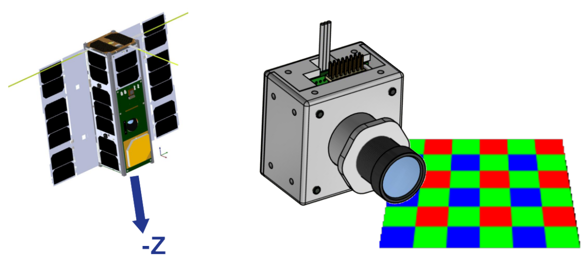

Figure 3: IMS-100 with an RGGB Bayer pattern, directed to OPS-SAT's -Z axis.

RESULTS

This paper is an update of results initially presented at the 4S Symposium 2022. We remind here the initial results briefly, as they are extensively presented, along with the image post-processing, in Segret et al. 2022.[6] Then, the latest results are presented in more details.

Star detection and ADCS characterization

The first images were captured in October 2021 and it took about 3 weeks to successfully detect stars after increasing exposure times from 2 ms to 800 ms and, eventually, adopting a constant expoure time of 500 ms and a cleaning process of the received images. Three main lessons were learned in this initial period:

- the signal of stars is well below the level of several hundreds of pixels (typically from 1 500 to 2 000, over a total of 4 millions of pixels of the sensor) impacted by cosmic rays, whose more than 1 000 pixels have become "hot pixels", i.e. always bright on all images; this latter number can be taken as a rough expression of need for the shielding of a sensor after 2 years of operations in Low Earth Orbit;
- in areas where stars can be seen, the light is spread over areas of 7×7 to 10×10 pixels, meaning that only a small fraction of the star light (typically $1/50^{th}$) is captured by one single pixel (the Point Spread Function is expected smaller than a pixel); this loss of sensitivity results from the instability of the platform, partially as a drift and likely as a jitter at high frequency (reaction wheels' vibrations and B-dot magnetorquer strategies could be an explanation);
- when straylight enters in the field of view, it reveals a strongly distorted focal plane with a permanent pattern, that was not reported in the acceptance tests of the sensor; the pattern would bias any photometric analysis, unless an updated PRNU (Photon Response Non Uniformity) is estimated in flight and can compensate the bias.

The image-based ADCS charaterization confirmed and quantified the issue at pointing the satellite in an inertial pointing mode. Not all images could be successfully processed and the bad images were discarded from the study, as the estimated attitude provided by the telemetry cannot be compared with ground truth measurement. With successful processing, there are two categories of results: either the image shows a pointing out of the requested field of view (more than 10° off-pointing) and results most likely of a pointing that was still not stabilized when the image was captured; or the image falls within the requested field of view, with a fairly stabilized pointing. The first category of results was a driver to improve the pointing operations. The second category is used to assess a possible bias in the alignment of the sensors, with 14 sets of successful measurements gathered from January to March 2022 (Table 1).

Table 1: List of first successful bursts.[6] Offsets are reported for the central direction, based on Astrometry.net processing (rotations not reported, for clarity).

#	Timestamp	Target (Long,Lat)$_{\text{ICRF}}$	Offset (°)
A	2022-01-13T11:49:20	(101.29, −16.72)	7.4
B	2022-01-20T13:08:55	"	5.3
C	2022-01-21T14:28:04	"	5.2
D	2022-03-10T14:22:17	(47.27, +49.61)	2.3
E	2022-03-22T08:15:11	(183.95, −17.54)	3.3
F	2022-03-22T20:54:22	"	2.0
G	2022-03-23T00:04:08	"	0.4
H	2022-03-23T20:37:50	"	3.3
J	2022-03-23T23:47:39	"	3.3
K	2022-03-24T21:56:14	"	0.6
L	2022-03-25T02:40:53	"	4.4
M	2022-03-26T00:49:27	"	1.7
N	2022-03-27T00:32:52	"	4.5
P	2022-03-27T11:37:10	"	2.0

During the first period of the experiment, it was possible to assess the needed magnitude of stars to be used, in association with the stability of the platform, and to build a database of several hundreds of individual star images. It was possible to improve the pointing operations, to provide ground truth of the achieved pointing and to compare them with their on-board estimates. Unfortunately, only few estimates provided by the star tracker were available. Then, it is difficult to assess possible misalignment of each of the optical sensors (star tracker, sun sensor and imager) that are oriented in different directions: their possible biases would be coupled and would require specific measurements.

Nevertheless, an initial attempt to re-assess the alignments of the star tracker and the imager was performed, noticing that the on-board quaternions produced by the iADCS seemed to converge to stable values, close to the pointing request, but different. These values were assumed to be the result of a successful tracking by the star tracker, meaning that the star tracker were able to recognize the pointing request on the sky from its own alignment and, hence, the pointing residual should reveal the misalignment of the star tracker itself. Only the most stable datasets were considered, namely datasets #D, F, G, J, K, L and M from Table 1 and the weighted average of the on-board estimates was compared with the request (the weights were taken from the number of reported telemetry estimates). It yielded to a new assessment of the star tracker, corresponding to a shift by $\sim 1.22°$:

- Theoretical alignment quaternion of the star tracker wrt the satellite body frame

$$q_{\text{ST}} = s(0.683) + \vec{v}\,[0.183, 0.683, -0.183] \tag{1}$$

- New assessment of alignment

$$q'_{\text{ST}} = s(0.673) + \vec{v}\,[0.196, 0.686, -0.196] \tag{2}$$

With this new assessment, the on-board estimate of the field of view quaternions were interpolated at the exact timestamp of the captured images and compared with the reconstructed quaternion of the actual field of view (matched by Astrometry.net). It yielded to a new assessment of the imager, corresponding to a shift by $\sim 0.85°$:

- Theoretical alignment quaternion of the imager wrt the satellite body frame

$$q_{\text{IMS}} = s(0) + \vec{v}\,[1, 0, 0] \tag{3}$$

- New assessment of alignment

$$\begin{aligned} q'_{\text{IMS}} = {} & s(-0.00762) \\ & + \vec{v}\,[0.999, -0.0432, 0.00134] \end{aligned} \tag{4}$$

Work-plan, Latest Results

A campaign was performed in May 2022 taking into account the new assessed alignments in Eq. 2 and 4 for star tracker and imager. The strategy for image capture was modified to use every single image as input for alignment assessment. It yielded a second set of 18 successful images during 4 new dedicated runs (Table 2).

Previously, the strategy for the first set of Table 1 was to produce "bursts" of 5 stacked consecutive images ($5 \times 500\,\text{ms}$), in order to secure a sufficient number of visible stars. As a drawback, the sensors' alignment was assessed on less inputs with lower accuracy, because one burst of stacked images counts for a single measurement to be compared with on-board telemetry. With the improvement in the stability of the pointing, the sensitivity for star imaging was expected better. Hence, in the May 2022 campaign, we decided to use every single image as a measurement to be compared with on-board telemetry. To this aim, images were captured at intervals of several tens of seconds, within sequences of 4 to 5 captures. Telemetry for on-board estimates was monitored every 10 seconds or better during the sequences.

Table 2: Images after a re-assessment of star tracker's and imager's alignment.

#	Timestamp	Target (Long,Lat)$_{\text{ICRF}}$	Offset (°)
Q1	2022-05-08T19:45:06	(233.79, −41.17)	8.3
Q2	2022-05-08T19:45:32	"	8.7
Q3	2022-05-08T19:45:58	"	8.6
Q4	2022-05-08T19:46:24	"	9.2
R1	2022-05-24T21:23:03	"	5.5
R2	2022-05-24T21:23:29	"	6.1
R3	2022-05-24T21:23:55	"	7.1
R4	2022-05-24T21:24:21	"	8.3
S1	2022-05-25T22:40:05	"	6.5
S2	2022-05-25T22:40:31	"	6.2
S3	2022-05-25T22:40:57	"	5.9
S4	2022-05-25T22:41:23	"	5.3
S5	2022-05-25T22:41:49	"	4.9
T1	2022-05-26T01:49:41	"	6.7
T2	2022-05-26T01:50:07	"	6.3
T3	2022-05-26T01:50:33	"	5.8
T4	2022-05-26T01:50:59	"	5.4
T5	2022-05-26T01:51:25	"	5.0

Although the absolute pointing error was not improved in the new campaign, it can be noted that 7 to 13 stars were distinctively detected in every single image, as a result of a greater stability of the platform. All images had a match with Astrometry.net and, inside each sequence, the offsets continuously increased for the sequences #Q{i} and #R{i}, or decreased for #S{i} and #T{i}, suggesting an evolving bias during each sequence, rather than a random error.

Then, a new diagnostic is being investigated. It is believed that the star tracker does not work and the iADCS relies on the Sun's state vector provided by the Sun sensor on $-X$ panel as the main sensor. It could explain the approximate pointing and its stability during the captures. In addition, the fairly constant reported attitude, while the matched images show a drift, could result from the reflection of the Sun from the Earth's limb. Figure 4 illustrates the situation: if the face with the Sun sensor "sees" the Sun and not the limb (face $\vec{n}_1$), the state vector is a measurement of the Sun's actual direction; if the face "sees" both the Sun and the Earth's limb (face $\vec{n}_2$), the measurement is biased by the reflection of the Sun. The reflection angle evolves along the trajectory at a rate that could explain the drift over $\sim 2\,\text{mn}$, but the quantification of α and the direction of the bias strongly depend on the reflecting area and are not trivial to estimate.

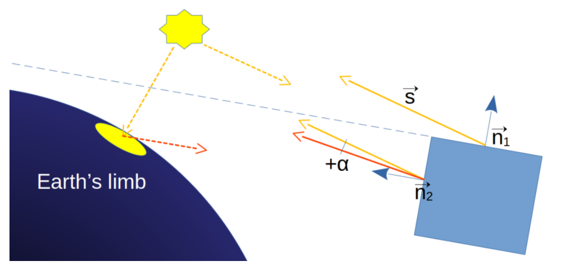

Figure 4: Sun sensor can be biased by the reflection of the Sun on the Earth's limb.

At the time of writing, the telemetry was not fully available and the investigation was still ongoing. The future work-plan is to reconstruct the elongation of the Earth's limb wrt the Sun, in order to search for a correlation with the telemetry and the measured drifts. In parallel, a new campaign of images is considered by adding in the constraints that the $-X$ panel would see the Sun only and not the limb. This is theoretically achievable by rotating about the Z axis but it puts more constraints in the planning of operations.

CONCLUSION

The paper is a state of progress of an astrometry experiment on board a 3-unit CubeSat, that was still running at the time of writing. It was already demonstrated that CubeSat hardware can be used to quantify the behavior of the ADCS and the on-board imager in terms of pointing error, stability, sensitivity and radiation shielding, provided a thorough post-processing of images of the dark sky. Then, we showed that optical sensors' alignment can be different from their expected value. We attempted to re-assess these alignments and the results are still under study. The stability was improved but a strong pointing error remains and a continuous drift is reported over the $\sim 2\,\mathrm{mn}$ capture sequences. We suggested that the star tracker is dysfunctional and that the Sun reflection on the Earth's limb introduces a bias in the estimate of the Sun direction. Beyond the particular case of OPS-SAT, the experiment shows that a CubeSat's ADCS and its imager can be, and shall be, investigated in details, provided a ground preparation as part of a commissioning process or, a posteriori, to diagnostic and hopefully troubleshoot an unexpected behavior.

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Fig. 2 was possible using CNES' free software VTS.[4] This work has also made use of Astrometry.net[5] and of the SIMBAD database, operated at CDS, Strasbourg, France.[7]

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