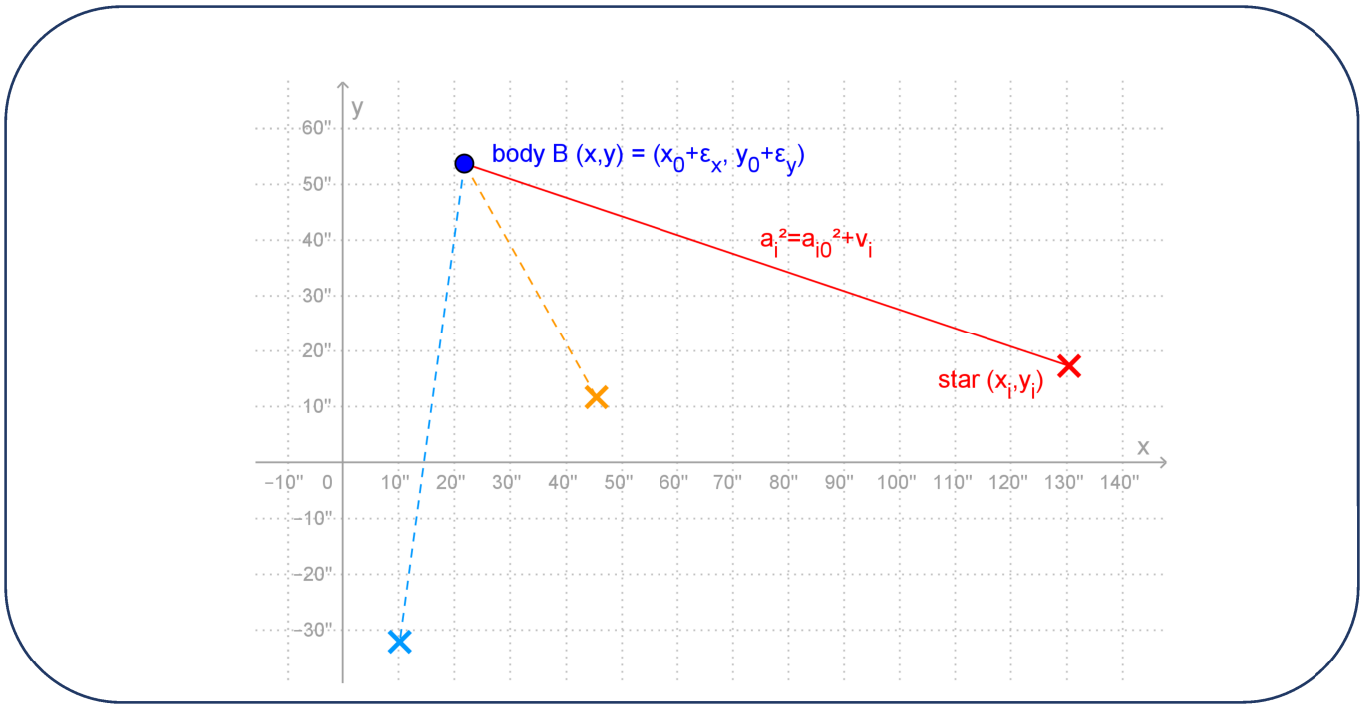
→ DISCOVERY



Angle-based Correlation (AbC), refined astrometry on board a CubeSat, Experiment 156 on OPS-SAT

Executive summary report

Study Activities

OSIP, "OPS-SAT Experiments" Campaign

Affiliation(s): CENSUS, pôle d'expertise nanosatellites à Observatoire de Paris - PSL

Activity summary:

AbC is a compact on-board algorithm, initially intended for CubeSats, to measure the absolute direction of a distant beacon with optimised accuracy. The AbC environment anticipates a ground pipeline that has been used with OPS-SAT images to diagnose the ADCS. It has been shown that a ground-truth assessment of the satellite's orientation can be made which, with sufficient data, could allow precise re-alignment of multiple sensors. The ESA contract funded the implementation of the on-board algorithm in C++ and its pipeline in Python. A database of flight images was created to demonstrate the performance of AbC, which is still ongoing.

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Angle-based Correlation (AbC)

refined astrometry on board a CubeSat, Experiment 156 on OPS-SAT

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Author : **Boris SEGRET**, Exp.156 “AbC” P.I.
CENSUS, pôle d’expertise nanosatellites, Observatoire de Paris - PSL

Revision	Date	Major Changes
1.0	11-Jul-2023	Creation of the document

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I. - Programmatic context

1. - Idea and achievements

"AbC" (Angle-based Correlation) is an astrometry experiment to highly improved image-based measurements of the absolute direction of a beacon, as diverse as a planet's moon, an asteroid or an artificial satellite. It aims to be compact and as autonomous as possible in order to be run on-board a nanosatellite, as a priority target but not limited to it. It was proposed for tests on OPS-SAT as Experiment #156. Then, AbC was also proposed as an OSIP idea in 2021 and received a 50k€ contract from ESA in 2022 (ref. [1]) to hire an engineer and implement the algorithm in C++ to run on OPS-SAT and its associated ground pipeline in python. Hence, M.Eng. Pedro da Fonseca could be hired for 13 months, from 11/2022 to 12/2023.

The initial interest for AbC was expressed as a need to feed an on-board Kalman filter with optical measurements of foreground beacon associated with accuracy better than the arcsec (ref. [2], [3]). As it appeared challenging with the current state of the art, an algorithm was developed (ref. [P1] in §II.4.a.) based on a highly compact quaternion algebra, making use of recognized stars in the image of the beacon of interest. In parallel, studies are on-going to assess the relevance of such precision with regard to other sources of errors (e.g. optical aberrations, sensor alignments…) but such additional errors are out of the perimeter of the current experiment.

The experiment was proposed, acknowledging a few risks and suggesting risk management accordingly. In particular, it was known that OPS-SAT has been exposed to instabilities during requests for inertial pointing (risk #2 in [1]). Nevertheless, at the end of the ESA contract period (mid-2023), the project has achieved its expectations, in the framework of the management of risk #2 for image acquisition:

- We have maintained two development branches for AbC, both branches share a common on-ground pipeline for mission preparation and post-processing:
  - one branch to support platform diagnostics and recommendations (up to v.0.9.3) based on those on-board images, where stars could be indetified;
  - one branch for the nominal on-board AbC algorithm (from v.1.0) with the goal to test on-board its process-reliability, and on-ground to test its performance based on available datasets.
- A database of more than 100 images from flight was produced, where stars could be detected and identified (with the on-ground pipeline and the use of the open-service Astrometry.net).
- We published a new peer-reviewed paper about the AbC experiment with OPS-SAT (ref. [P2] in §II.4.a.) as a proceedings paper for the international ESA 2022 4S Symposium, that shows an unexpected and efficient application of AbC to assess pointing biases and misalignments, as well as re-alignment solutions.
- The engineer position is still funded until the end of 2023. We will continue to propose image acquisitions and diagnostics from successful images, if possible, until the end of 2023.

As a whole, two scientific papers and three presentations in international conferences have been given. Five specifications or reports have already been produced. A private git repository is maintained on the servers of the Paris Observatory.

2. - References

[1] ESA OSIP Idea_I-2021-03628, granted ESA contract No. 4000137343/22/NL/GLC/ov (running as of 3/02/2023)

[2] 2019 French manuscript: “Algorithme embarqué de navigation optique autonome pour nanosatellites interplanétaires”, HAL Id tel-02889414 , version 1

[3] “Autonomous Orbit Determination for a CubeSat Cruising in Deep Space”, Segret, Mosser, 2021, arXiv:2104.09989v1

II. - Results

1. - Team & Tasks

- Youssoupha DIAW, M1 student (3.5 months FTE, 2021): initial framework and skeleton code
- Yannis Gougeat, L3 student (5 months FTE, 2022): database of received OPS-SAT images
- Mohamed Mansouri, M2 student (6 months FTE, 2022): framework and first in-flight version
- Pedro da Fonseca, engineer (13 months FTE, 11/2022-11/2023): framework and in-flight versions
- Boris Segret, senior engineer (10% FTE since 01/2021): AbC author, OPS-SAT mission preparation (for AbC) and image post-processing, Experiment’s supervisor.
- Scientific contributions from: Valery Lainey, D. Hestroffer, V. Robert, J. Desmars (IMCCE / Paris Observatory – PSL)

The database of the available images is ready. The framework to interface with OPS-SAT team is ready. An initial version of the AbC in C++ was successfully flown in 10/2022 (v0.8). The wanted embedded software engineer has been appointed since 11/2022 for 1 year. Three more versions of AbC were flown (v.0.9; v.0.9.2, v.0.9.3) to scope, as good as possible, with OPS-SAT’s attitude determination. A version with the full algorithm is being prepared as v.1+.

2. - List of requested pointing quaternions

#	Validity Period	Quaternion	AbC SW	Nb.o.Im.
15	8..27 / 07 / 2023	v(-0.3536 0.1238 0.1721) + s(0.9111)	0.9.3	(pending)
14	20/03 .. 30/04/2023	[v(-0.3977 -0.4542 -0.6986) + s(0.3840)]	0.9.2	0 / -
13	2..19 / 03 / 2023	[v(0.4610 -0.8004 0.3316) + s(0.1919)]	0.9.2	0 / -

12	30/01 .. 20/02/2023	v(0.2351 -0.8900 0.3535) + s(0.1664)	0.9	36 / 13
11	12/12/22 .. 30/01/23	v(-0.5121 -0.7193 0.1868) + s(-0.4307)	0.8	0 / -
10	14..31 / 10 /2022	v(0.0682 0.4982 0.1172) + s(-0.8564)	0.8	3 / 3
9	2..14 / 09 / 2022	v(-0.0631 0.4989 0.3349) + s(-0.7969)	- (no burst)	7 / 7+1
8	15..25 / 07 / 2022	v(0.2355, 0.2777, 0.1666) + s(-0.9163)	- (no burst)	0 / -
7	1..14 / 07 / 2022	v(-0.3659, 0.5991, 0.7119) + s(-0.0176)	- (no burst)	0 / -
6	28/04 .. 27/05/2022	v(-0.38456, -0.12756, -0.75594) + 0.51423	- (no burst)	18 / 18
5	18/03 .. 23/04/2022	v(0.5883, 0.0569, 0.8064) + 0.0221 v(0.0569, -0.5883, 0.0221) - 0.8064	- (burst)	50 / 50+10
4	14/02 .. 15/03/2022	v(-0.0514, 0.9575, 0.0039) + 0.2837	- (burst)	15 / 15+3
3	22/01 .. 14/02/2022	v(-0.2537, 0.6937, -0.6718) + 0.0557	- (burst)	65 / 65+10
2	7..20 / 01 / 2022	v(-0.3263, 0.4997, -0.7447) - 0.2987	- (burst)	84 / 76+10
1	24/12/21 .. 7/01/22	v(-0.5425, 0.2019, -0.4026) – 0.7091 v(+0.5425, -0.2019, +0.4026) + s(-0.7091)	-	28 / 6
	Until 24/12/2021	No quaternion provided => pointings by ESA	-	43 / 8

- "burst": set of 5 consecutive images of 500ms each, that allows a stacked image (with or without re-alignment), under the conditions that at least 2 same stars are visible.
- "Nb.o.Im.": Number of Images that were downloaded / that were processed successfully. The "+n" number means the number of successful stacked images that could be produced.

Summary:

During a first period from 12/2021 to 04/2022, many stable inertial pointing could be obtained, with some successes at assessing the achieved pointing and its stability. A "stacking" process was explored, allowing the detection of more stars than in single pictures, and deeper assessment of the stability. From stacked pictures, the webservice Astrometry.net could return absolute orientations of the camera in the sky.

From 05/2022, the pointing stability was getting worse and very few new pictures with stars were obtained. In particular in 02/2023, new attempts were performed and none of the taken pictures could reveal stars.

3. - Project's production (private or confidential)

- CENSUS 2021-119-YD, "OPS-SAT Framework install for MS-Windows" (outdated), v2.0, 19-Apr-2021
- CENSUS 2021-133-YD/BS, "Exp.156 / OPSSAT, Q&A follow-up", v0.4, 7-Oct-2021
- CENSUS 2021-136-BS, "Exp.156 / OPS-SAT, IMS-100 characterization", v0.1, 3-Dec-2021
- 2022-03-29 Meeting "Exp156: Discussion on Pointing and Quaternions", MoM / OPS-SAT

- CENSUS 2022-142-YG, “Exp.156 / OPS-SAT, Database Specification”, v1.4, 5-Jul-2022
- CENSUS 2022-141-MM, “Exp.156 / OPS-SAT, AbC Specification”, v2.1, 7-Oct-2022
- CENSUS 2023-147-BS, “AbC Progress Report”, v1.0, 3-Feb-2023
- AbC Database (2.72GB, 1390 files, as of 08/2022)
- GNU OCTAVE pipeline for OPS-SAT Mission Preparation
- GNU OCTAVE pipeline for OPS-SAT Image post-processing
- C++ framework and development branches (gitlab.obspm.fr, code and wiki)

The framework we setup before OPS-SAT OSIP contract was further improved. An early publication was possible [2] as soon as in 2022 that showed the potential to assess the pointing and its stability as ground-truth. With enough data, we showed that a re-alignment calibration can be performed. Unfortunately, we could not get enough data to demonstrate such a “troubleshooting” potential.

We developed an early version of the AbC architecture, to check for flight compatibilities (up to v.0.9.3). In parallel, we developed an initial full implementation of the AbC algorithm (beacon on-board measurement), as versions 1+. This version is still under development to date, and we hope to fly the code in 09/2023 and have some improvements (with or without platform stability) before end of 2023.

4. - Publications

II.4.a. Papers:

[P1] B. Segret, Y. Diaw, V. Lainey, “Refined Astrometry on Board a CubeSat”, 2022 IEEE Aerospace Conference, BigSky / Montana (USA).

[P2] B. Segret, S. Bammens, S. Bras, D. Marszk, V. Shiradonkar, V. Zelenevskiy, D. Evans, “ON-BOARD IMAGES TO SPECIFY AND COMMISSION THE ADCS,” 2022 4S Symposium, Vilamoura / Portugal.

II.4.b. Talks

Talks were given at:

- 2020 Open-Source CubeSat Workshop (on-line)
- 2022 IEEE Aerospace Conference, Big Sky, Montana / USA
- 2022 4S, Vilamoura, Portugal
- 2022, IAC, Paris, France

In the future, a poster “AbC: an ADCS Commissioning Service” will be presented during the ESA 6th CubeSat Industrial Days, from 12 to 14 September 2023, in Leiden, NL.

5. - Valorization

AbC appears to be an efficient solution to diagnose the behavior of an ADCS. This is particularly topical in the NewSpace for nanosatellites, whose ADCS performances are known to be poor and poorly tested. We decided to seek for valorization in two directions:

1. ADCS Commissioning services: the ground process is available and can be re-used for new hardware setup, to diagnose and calibrate the alignments post-launch. Then, it can become a "service" for end-users of nanosatellites to get the value from their money, for integrators to demonstrate their platforms' agility or for sensor producers who expect their sensor to be carefully aligned. Moreover, as "ground-truth", the service appears as an expertise independent from any industrial influence (from device manufacturer or integrator).
2. Navigation augmented sensor: using the full power of the AbC genuine algorithm, we consider that AbC can be a new feature in existing hardware like star trackers or navigation camera, to provide and enhanced measurement of foreground beacons.

Although OPS-SAT was not stable enough, we could gather a very valuable dataset in the first period that allows the demonstation of the AbC on the ground, against actual flight data.

In 2022:

- a call-to-tender was opened by CNES for new space services, that institutions were invited to apply for. We were later told that an industrial partner was missing and we did not get funded.
- At IAC2022/Paris, we could discuss with SIMERA for possible tests with a panchromatic optical solution.

In 2023:

- PSL University called for projects needing pre-maturation and valorization. AbC was presented. A support is now being discussed to identify the addressable markets.
- Within this OPS-SAT involvement, we could get in touch with CRAFT PROSPECT who is also a possible approach to keep involved in the next developments after OPS-SAT or in other projects.

III. - Conclusion

AbC is still under development, with a software engineer employed on the OSIP contract until the end of 2023, allowing the priority goal of implementing the AbC code in C++ to be achieved.

Initially, AbC was conceived as an "augmented sensor" for astrometry. Based on the very valuable experience with OPS-SAT, AbC also appears as a possible NewSpace service to commission ADCS, with ground-truth results independent of any vendor. It's a happy ending to find an economic application in this way. Unfortunately, there is still a lack of hardware capabilities and financial support to reach a validation milestone, both commercially and technically.

Therefore, we kindly request a letter of support from the ESA OPS-SAT project management to help us to valorise AbC as an independent service in NewSpace for the commissioning of ADCS.