LESSON LEARNED ON IN-ORBIT OPERATION OF THE IRIS-A ATTITUDE DETERMINATION AND CONTROL SUBSYSTEM

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IRIS-A is a 2U CubeSat and it is the first of a three-satellite family being developed by National Cheng Kung University (NCKU) in Taiwan. The mission's name IRIS stands for Intelligent Remote Sensing and Internet Satellite, and it relies partly on the heritage of a previously successfully launched 2U CubeSat, named Phoenix, by the same institution. One of the biggest challenges when developing Space technology inside a university is the fact that most of the team members are students who eventually graduate, and it requires a lot of administrative strength to properly transfer the hands-on knowledge from generation to generation. The purpose of this paper is to catalogue a series of scenarios that could be encountered when commissioning the Attitude Determination and Control Subsystem (ADCS) of a CubeSat and to provide a proposed solution for the aforementioned scenarios.

IRIS-A has a small camera on one of its sides and one of the mission objectives is to manoeuvre its attitude to position that camera facing a desired object before taking a picture, *e.g.*, make the camera face directly zenith and take a picture of Taiwan. Even though the ADCS used in IRIS-A is a Commercial Off-The-Shelf (COTS) system, the module is not fully tested in the ground testing phase as the setup of the hardware and the operation of the software is not completely consistent. This error remained unnoticed until the CubeSat was already in Space and the system was turned on.

The transducers in IRIS-A are comprised of a set of six Coarse Sun Sensors (CSS), a 3-axis magnetometer, a gyroscope, and an Infrared Earth Horizon Sensor (IREHS), which is a is a non-scanning Earth limb detector designed to detect the Earth's limb by comparison of differential thermopile readings. The initial state had a three-axis Root-Sum-Squared (RSS) of approximately 15.5deg/s but with most of it along the ram-direction-axis at approximately 15deg/s, as measured by the transducers. Surprisingly, after the first attempt to stabilize the CubeSat, the RSS increased by almost 200% in a single orbit instead of decreasing; rotation was also no longer concentrated into a single axis.

The first step into understanding what was really happening was to double-check the consistency in the data by the different transducers. They all agreed independently in that the spinning rate was increased to approximately an RSS of 43deg/s. A simulation tool was then developed using the commercial software ANSYS and SIMULINK for the IRIS-A configuration which considered its physical properties (such as mass, center of mass, etc.), transducers input data, control law, and actuators employed for stabilization (three electromagnets and three reaction wheels). Special considerations were made for the electromagnets because their maximum duty cycle could not exceed 72%, or else, they would interfere with the magnetometer readings. Also, special considerations were made for the reaction wheels because they could not operate under 20RPM, so a torque compensation operation should be made with the magnetorquers if the desired torque was under that range.

Several scenarios and iterations were made in the simulation and, combined with the hands-on experience of previous missions, the main hypothesis formulated was that at least one of the dipoles of the magnetorquers was inversely configured into the flight software. The dipoles could be easily reconfigured, and their gains recalibrated but doing so without the proper analysis could worsen the problem and potentially lead to a complete mission failure. The simulations showed that turning on the system in a differently wrong configuration for about 30 minutes would generate an unstable scenario, whereas about 4 hours were needed in the right configuration to decrease the RSS to nearly zero from the current state. A consensus was finally reached for the hypothesis that all three dipoles were inverted, so it was decided to re-invert them in the flight software and to turn the system on for 20 minutes. After the data was downloaded and no significant change was observed, it was decided to repeat the procedure for 4 hours.

Throughout this process, it was clear for everyone involved that the simulation software developed had its flaws and limitations. However, the proposed solution of re-inverting the three dipoles of the magnetorquers successfully solved the problem and the final state was a near-zero RSS for IRIS-A. The hypothesis was proven right, and the simulation tool has proven to be a useful reference for in-orbit problem solving. The full set of simulated scenarios and proposed solutions can be found in a later section of this paper.

Key words: In-flight, Instrument Calibration, CubeSat, Attitude Determination, Control Loop

1. Overview

CubeSats are a relatively low-cost opportunity to learn lessons for operations in Space and performing in-situ technology demonstrations. The field is filled with surveys for subsystems like ADCS, their performance and their limitations [1] [2], one of which even includes a theoretical analysis of the ADCS used in the IRIS-A mission prior to their first flight [1]. The literature agrees in that coherence must be found amongst several sensors and that at least two are needed to be able to properly determine attitude in orbit [2] [3], which was taken into consideration when commissioning the ADCS for the IRIS-A mission.

In order to prevent system failures in orbit, extensive testing must be done before flight like the work done by Jonis [4], which included a full hardware-in-the-loop test in ground. However, despite all the testing, sometimes problems will arise during operations. Even though some ADCS systems are commercially available and widely used, some of the lessons learned reported in the literature also include troubleshooting. According to Aurandt *et al.* [5], CubeSats have failure rates of about 25%. Recently, Wu *et al.* [6] developed a constellation of three CubeSats to monitor glaciers, ships, and airplanes and one of them was carrying a CubeProp which wrongly fired and caused unwanted spinning which they later successfully detumbled.

IRIS-A (NORAD ID 51044) was placed in orbit on a SpaceX Falcon 9 rocket on January 3, 2022. Its orbit is described as follows:

- Perigee: 523.3km
- Apogee: 537.7km
- Inclination: 97.5
- Period: 95.1 minutes
- Semi major axis: 6901km

The following sections will describe the in-situ data acquired by IRIS-A and its analysis, the main problem encountered when commissioning the ADCS, and the troubleshooting process. Since CubeSats must compel to the same standards [7], it is possible that the results for these simulations may be useful for other 2U CubeSat missions that may encounter similar initial conditions as the ones stated here.

2. ADCS Commissioning

The first step for commissioning the ADCS was to turn it on passively in a read-only mode to gather data from the transducers and analyzing it. The idea is to find whether or not the data from different sets of transducers is consistent with each other. As stated before, the ADCS has a 3-axis gyroscope, IREHS, six CSS, and a magnetometer. Fig. 1 shows the location for all transducers in IRIS-A. The gyroscope and IREHS are placed in the ADCS case, CSSs are marked with yellow and black cross circles, and the magnetometer is placed 138mm away from the ADCS case as per the operation requirements; the exterior of the satellite has been hidden for the lower half to show its exact location. Note that the magnetometer frame of reference (blue) is the same as the body frame of reference (red).

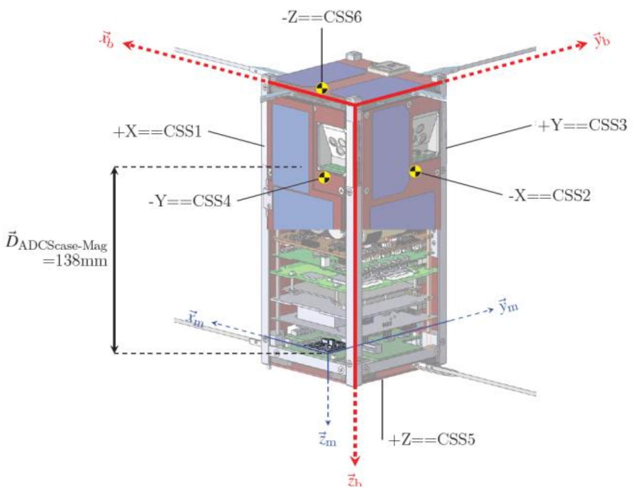

Fig. 1 Transducers map for IRIS-A.

The readings from the CCS are coupled in pairs for each axis as follows:

- X-Axis: CSS1, CSS2
- Y-Axis: CSS3, CSS4
- Z-Axis: CSS5, CSS6

According to the gyroscope data, the initial state of IRIS-A was highest about the body-frame-X-axis, slightly above 15°/s, as shown in Fig. 2. Then, as expected, it can be seen in Fig. 4 and Fig. 5 that CSS on opposite sides of the Y- and Z-axis show normalized peak readings only one at a time. In the case of CSS1 and CSS2, it seems like CSS2 is constantly facing the Sun while CSS1 is constantly facing Earth; therefore it is not incoherent that CSS2 shows a reading slightly about 30% of CSS1 because this can be explained by accounting for Earth's albedo in accordance with the literature [8] [9] [10]. Sample frequency for all transducers was 10 seconds over a whole orbit 90-minutes orbit. Eclipse periods can be observed in Fig. 3, but Fig. 4 and Fig. 5 only show a 10-minute period for clarity of their interlapping peaks. The data from the magnetometer was also validated by comparing it to IGRF [11] at it's given position.

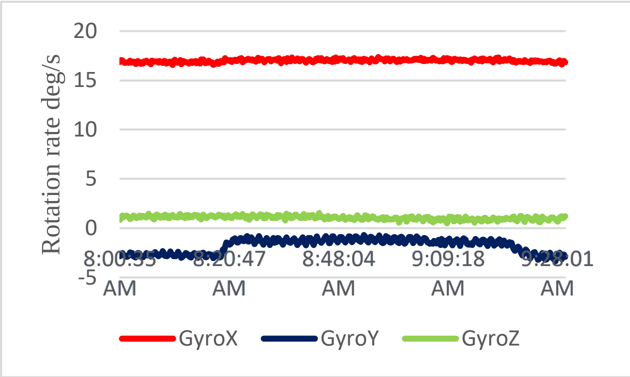

Fig. 2 Gyroscope readings for IRIS-A starting 2022/04/29 08:00:35UTC in deg/sec.

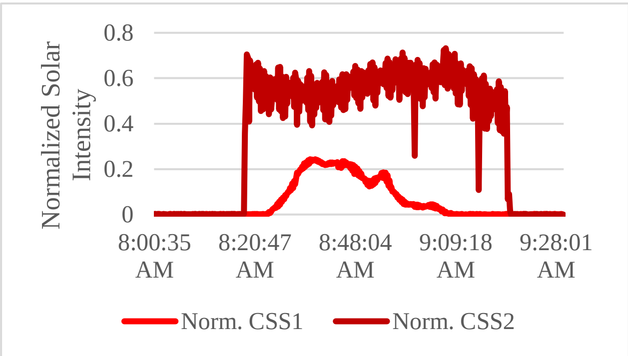

Fig. 3 Normalized X-Axis CSS readings starting 08:00:35UTC.

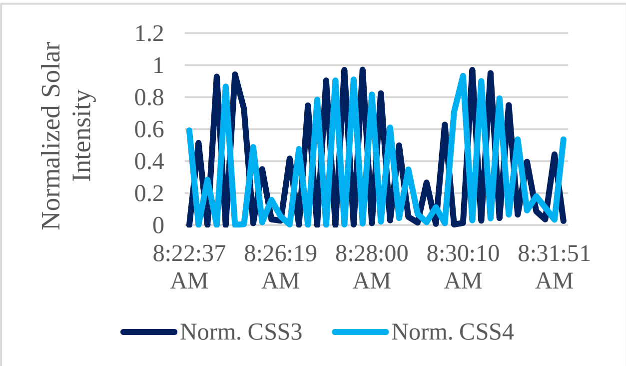

Fig. 4 Normalized Y-Axis CSS readings, starting 8:22:37UTC.

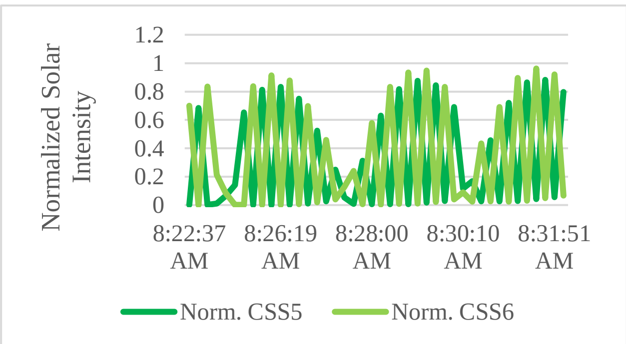

Fig. 5 Normalized Z-Axis CSS readings, starting 8:22:37UTC.

3. Initial Detumbling Failure and Troubleshooting

After the initial inspection and reading of the transducers, the ADCS was commanded into an operation mode that commands all wheels to zero torque and uses only the electromagnets as actuators to dampen the rotation by measuring the rate of change of the measured magnetic field according to [12]

$$Torque\ Commanded\ to\ Coils = K_{\dot{b}} \cdot B_d \cdot D_{gain}$$

Where $K_{\dot{b}}$ is the vector of $\dot{b}$ gains, B_d is the vector of the rate of magnetic field change in the body frame (Tesla/sec), and D_{gain} (A/m^2) is a vector of the dipole gains. Both the $K_{\dot{b}}$ and D_{gain} are values updatable by the user and they depend on the specific configuration of the CubeSat; however, there were some discrepancies between the software and hardware, so ground testing was not fully possible before launch.

Fig. 6 shows the results from this initial detumbling attempt, which lasted 6000s. As it can be clearly seen, the angular rate increased greatly instead of decreasing, and instead of being mostly concentrated in the single body-frame-X-axis, IRIS-A was now rotating in all three axes.

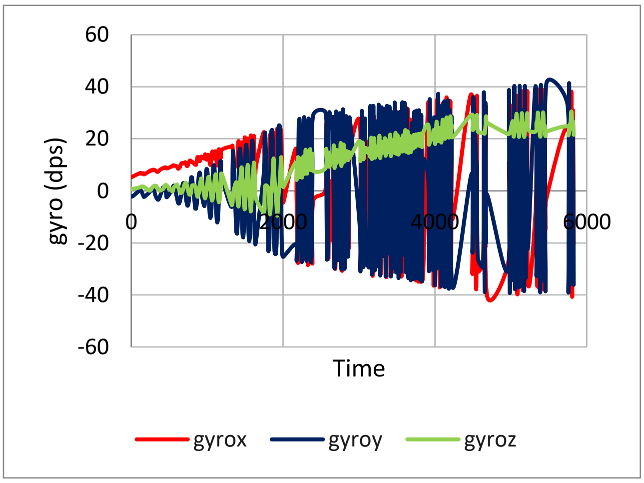

Fig. 6 Results from first detumbling attempt.

The three most obvious explanations for this behavior were that either the transducers, actuators, or the control law were working improperly, or a mixture of these. Since the transducers were properly tested and evaluated in ground and Space before the detumbling attempt, the attention was focused on the latter two explanations.

The hypothesis that at least one of the dipole gains was set in an inverted position during the setup phase of IRIS-A arose rapidly. In order to test this hypothesis, a simulation software was built using MATLAB and SIMULINK. This allowed to safely perform several scenarios and solutions without further risking the mission.

4. Results of Sims. for the Latin Hypercube of Scenarios

A Latin Hypercube of possible scenarios was built in order to explore and test different solutions for the unknown problem. The first step was to try to replicate the flight data obtained in Fig. 6, therefore the initial conditions for the simulations was defined by the initial state in that set of flight data. Also, report data from the ground tests and Flight Readiness Review was used to feed into the simulation software.

The following initial conditions were employed:

- Simulated rotation period before detumbling:
  t = 0 - 300s
- Active Detumbling period:
  t = 300 – 6100s
- $\omega_x = 8°/s \;\; \omega_y = -2°/s \;\; \omega_z = 1°/s$
- $I_x = 0.015 kg \cdot m^2 \; I_y = 0.016 kg \cdot m^2$
  $I_z = 0.007 kg \cdot m^2$

The results of the simulation can be seen in the following figures, which show the body-to-inertial frame angular rate in degrees per second and the horizontal axis shows time in seconds. Note that according to the first simulation in which all the dipoles are set properly, detumbling is successful after about 700s.

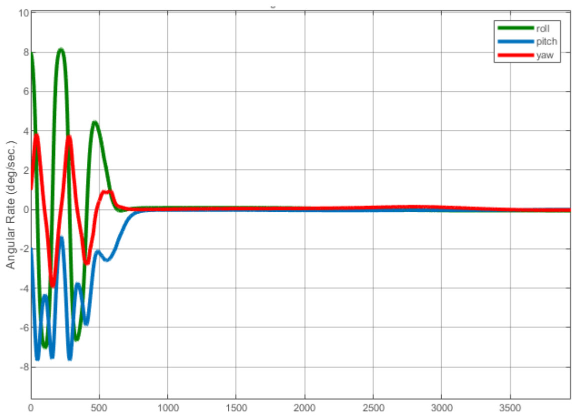

Fig. 7 Angular rate variations with all three dipoles set correctly in deg. per sec. over 3500s.

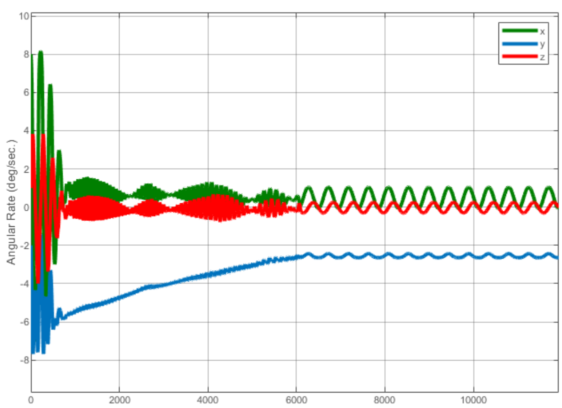

Fig. 8 Angular rate variations with X-dipole inverted in deg. per sec. over 10000s.

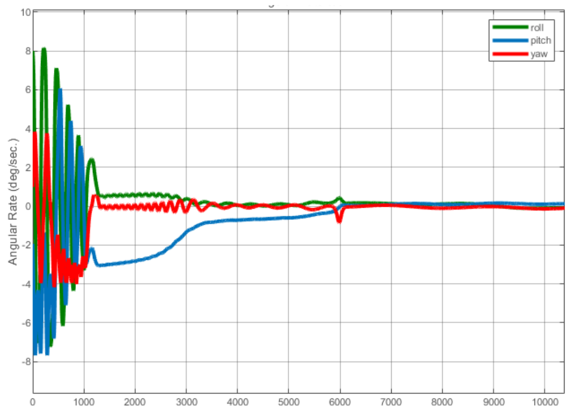

Fig. 9 Angular rate variations with the Y-dipole inverted inverted in deg. per sec. over 10000s.

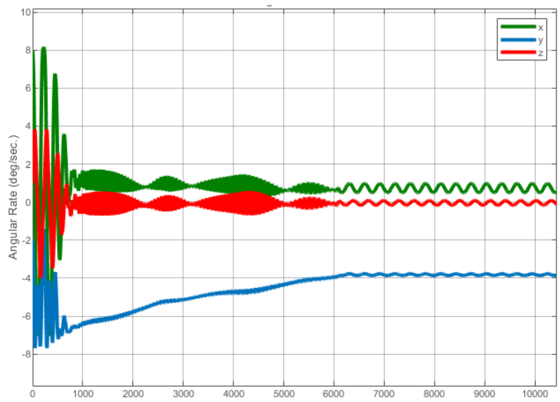

Fig. 10 Angular rate variations with the Z-dipole inverted inverted in deg. per sec. over 10000s.

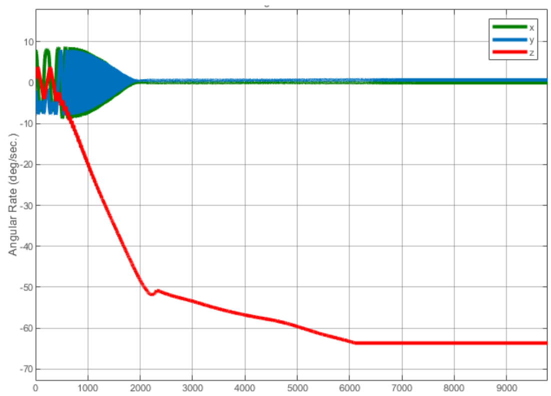

Fig. 11 Angular rate variations with a dual X- and Y-dipoles inverted inverted in deg. per sec. over 10000s.

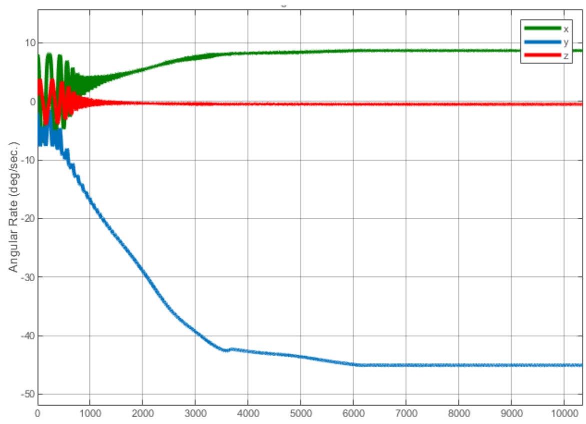

Fig. 12 Angular rate variations with a dual X- and Z- dipoles inverted inverted in deg. per sec. over 10000s.

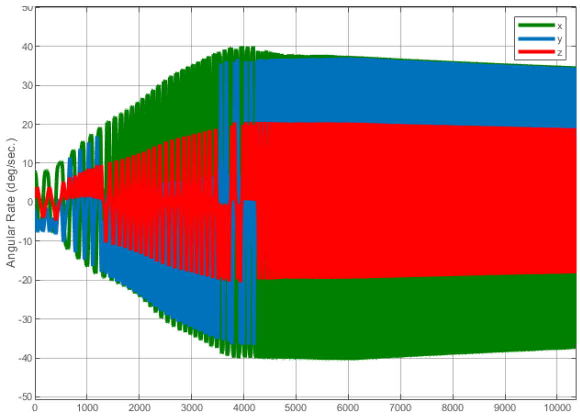

Fig. 13 Angular rate variations with a dual Y- and Z-dipoles inverted inverted in deg. per sec. over 10000s.

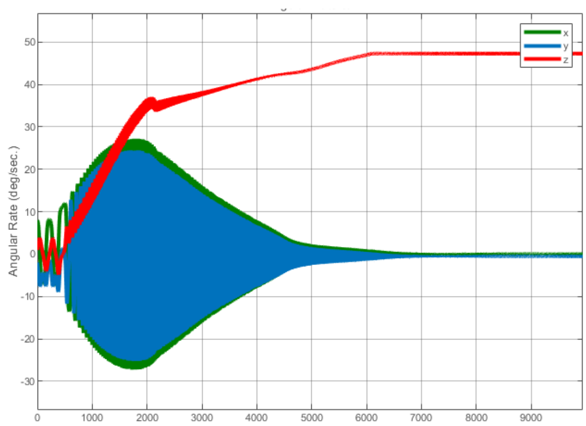

Fig. 14 Angular rate variations with all three dipoles inverted inverted in deg. per sec. over 10000s.

5. Discussion of Sims. Results and Detumbling Strategy

After running several iterations of simulations, a pattern started to emerge, and it was clear that at least two dipole gains had to be inversely configured to explain the observable behavior. The program was, however, far from perfect and its limitations were known to the developing team. After some small tweaks, like swapping the moment of inertia for X and Y, and also swapping the initial angular velocity of ω_x and ω_y, and with the three dipoles being inverted, the exact same result was obtained as the observations.

Then, a new set of simulations was made for another Latin Hypercube using the final state of Fig. 6 as an initial state and applying a solution. By this point, the main hypothesis was that all three dipoles were inverted. However, if this hypothesis was wrong, the second set of simulations showed that a second wrong configuration would further destabilize the satellite after about 20 minutes of operation. If the hypothesis was correct, it would take at least 4 hours to fully stabilize IRIS-A into a near-zero rotation rate.

It was then decided to manually invert the three dipoles for a period of 20 minutes and download the data of the process. By this time, if the hypothesis was wrong, a major change should be noticeable. However, the data showed no major change when downloaded and then it was decided to command a detumbling process of 4 hours. After this second process, the satellite showed a near-zero rotation rate, thus proving the hypothesis was correct.

Further operations of IRIS-A used this information and commanded for the dipoles to be inverted for any attitude determination and control process. Fig. 15 shows an example of an operation in which IRIS-A was successfully controlled into a desired attitude in which its body frame was perfectly aligned with the orbital frame. Here, quaternions are expressed as [i, j, k, R], so Qbo_4 is the real part of the quaternion and a value of 1 represents a perfect alignment with the reference frame (orbital) for the desired period of time.

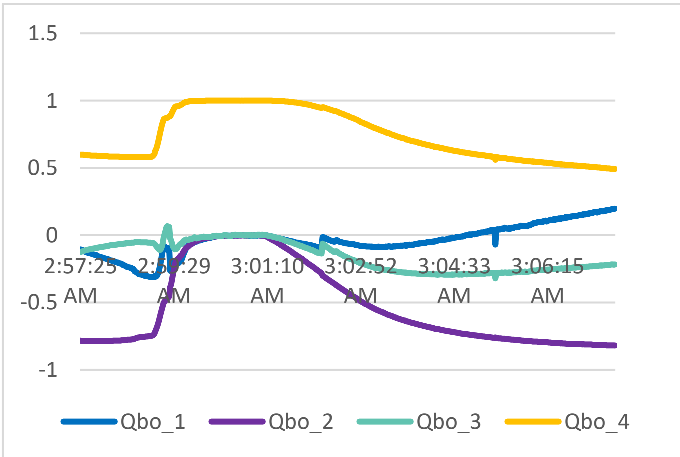

Fig. 15 Quaternion of successful attitude control of IRIS-A in orbit.

6. Conclusion

The problem encountered in orbit was successfully solved with the simulation tool developed for this purpose.

Acknowledgements

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