Ground Testing of a Chip-Scale Atomic Clock for MAXWELL CubeSat Flight Experiment

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ABSTRACT

This paper provides an overview of a flight experiment to observe the performance of a chip-scale atomic clock (CSAC) on a LEO cubesat. The results of this experiment will provide the basis for a realistic evaluation of the utility of the CSAC to support onboard position, navigation, and timing (PNT) applications for small satellites. The paper focuses on the goals and outcomes of ground testing performed on a CSAC in preparation for flight onboard the UNP-9 cubesat mission MAXWELL. The ground testing includes live sky testing, RF/GNSS simulator testing, and electromagnetic field testing.

INTRODUCTION

Most near-Earth satellites rely on GPS for precise position and timing information. The specialized satellites in the GPS constellation produce their own timing from highly accurate atomic clocks, monitored by the control segment using the transmitted navigation signals.[1] These atomic clocks provide excellent reference signals; however, they are large, heavy, and expensive, rendering them impractical for use on small satellites. Chip-scale atomic clocks (CSACs) are miniature versions of these clocks and can be used as an external reference to the GPS receiver.[2] However, CSACs have yet to be extensively tested and characterized in spaceborne applications. The potential benefits of using CSACs in satellite timing systems include enhancing position, navigation, and timing.[3]

The use of accurate and stable clocks onboard spacecraft opens up realities of only requiring one-way signal transmission for deep space missions.[4] Using a CSAC to augment GPS-based timing potentially enables onboard positioning, navigation, and timing as opposed to relying on multiple signal relays to ground stations for the average satellite orbiting earth.

The Colorado Nanosat Atomic Clock Testbed (CONTACT) team is working with the MAXWELL project at the University of Colorado, Boulder to develop an experiment to characterize a CSAC onboard a cubesat. For the flight experiment, the CSAC will be used as an unsteered, external reference to the GPS receiver. The clock bias and frequency values that the receiver estimates are indicative of the CSAC performance. The experiment is planned to run for five days during which the flight computer will record pseudorange, phase, clock bias, and position from the GPS receiver.[5] Data from the CSAC, including the temperature and status data are of particular interest. The temperature data will be obtained in orbit to determine how varying thermal environments affect CSAC operation. These data will be downlinked and used to evaluate the accuracy and sensitivity of the CSAC to environmental changes in low Earth orbit.

This paper focuses on the ground testing for the CSAC experiment. Performing sufficient ground testing ensures that the design will operate as anticipated and provides a baseline expectation for the CSAC performance.

MAXWELL CUBESAT OVERVIEW

The MAXWELL cubesat is a 6U cubesat mission being designed, built, and tested by a graduate student project group at the University of Colorado Boulder.[6] The main objective of the MAXWELL mission is to demonstrate communication technologies for future cubesat applications. These technologies include advanced RF communications for X-band downlink and S-band uplink. The CSAC experiment is one of six mission objectives for the MAXWELL project. The CONTACT team is working closely with the MAXWELL group, as success of the CSAC experiment is dependent on the success of the MAXWELL mission. A block diagram of the CSAC experiment flight configuration is shown in Figure 1.

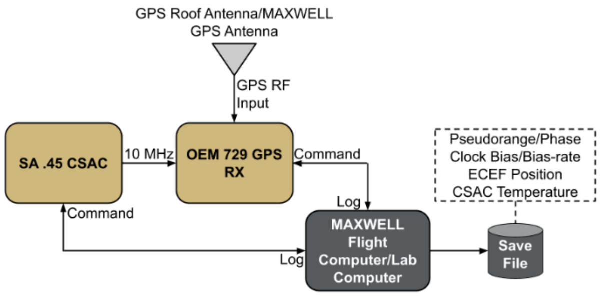

Figure 1: Block Diagram of the Flight Configuration and Live Sky Testing Setup for the CSAC Experiment

A key mission objective on MAXWELL is to test and characterize new communications technology, which include the X band antenna. One advantage to MAXWELL's multiple mission objectives is the potential use of this antenna for data relay. This antenna can downlink data at a rate of 10Mbps.[6] The CSAC experiment is currently designed to relay data via a UHF antenna. However, if the MAXWELL cubesat is able to demonstrate high performance using X-band, then we will be able to utilize X-band to relay the CSAC experiment data.

CSAC FLIGHT EXPERIMENT DESCRIPTION

The CSAC flight experiment utilizes a NovAtel OEM729 GPS receiver to observe the bias and drift of the clock. The CSAC is connected to the receiver as an unsteered external oscillator. The experiment will collect log messages from the GPS receiver to record the clock bias, bias-rate, ECEF position, pseudorange, and phase data at varying intervals. The clock bias will allow the team to characterize the performance of the CSAC on orbit. The OEM729 receiver uses a Kalman filter to estimate the bias; this bias is what is reported in the clock message from the receiver.[2] While not explicitly required for clock characterization, the pseudorange and phase data will allow us to consider other methods for reconstructing the actual clock behavior.

There are four main phases of the CSAC experiment which are displayed in Figure 2. The preliminary data collection is used to ensure that the CSAC and receiver are operating correctly and to verify that valid data are being recorded. The preliminary stage collects the BestXYZ, ClockModel, and temperature messages at an interval of 30 seconds for a total of 3 hours. After the preliminary stage is complete, the data from this section are relayed back to Earth via the UHF antenna. Stage 1 collects the same messages as the preliminary stage at a higher rate for approximately 2 orbits (3 hours). Stage 2 collects data every 10 seconds for 90 hours or approximately 60 orbits. The bulk of the data collected for the CSAC experiment will occur during this stage. The final stage reduces the frequency to collect data every 30 seconds and includes range messages as well. This stage will operate for approximately 2 orbits. After stages 1-3 are completed, the files from each section are transmitted to the ground station via the UHF antenna.

Table 1: CSAC Experiment Log Messages

Log Message	Data Collected
BestXYZ	Position in ECEF coordinates
ClockModel	Clock bias & bias-rate
Range	Pseudorange, phase, & C/N_0
CSAC Telemetry	Temperature, clock status

GROUND TESTING

As the MAXWELL team prepares to deliver hardware, the CONTACT team is performing ground testing on the NovAtel OEM729 receiver and CSAC. Ground testing is essential for the success of the MAXWELL project and the CSAC experiment as it ensures that the hardware and software interface properly. Characterizing the CSAC behavior on the ground provides a baseline for how we expect the CSAC to perform on-orbit. We will compare the results of the flight experiment to the baseline results to understand how the space environment affects the CSAC performance.

The ground testing includes live sky testing, RF/GNSS simulation testing, thermal chamber testing, and electromagnetic field testing. Live sky testing uses the GPS receiver and a roof antenna and yields the baseline performance of the CSACs on Earth. The RF simulator test sends artificial GPS signals to the receiver to replicate space-like scenarios. The thermal chamber experiments characterize the CSAC performance under varying temperature profiles. The electromagnetic (EM) field testing provides an understanding of how an increased EM field affects the CSAC performance.

LIVE SKY TESTING

Live sky tests were performed with the CONTACT team's three CSACs, nicknamed *Ralphie*, *Chip*, and *SpaceBuff*, to understand the performance of each clock. All are mounted on custom breakout boards that were designed by the CONTACT team in Fall 2020.[7] Some initial tests were conducted with *Chip* mounted on the Microsemi development board, however, it has been moved over to a CSAC breakout board for further testing.

The live sky tests were performed using the COMPASS lab's roof antenna drop (roof drop) atop the Smead Aerospace Engineering Sciences building at the

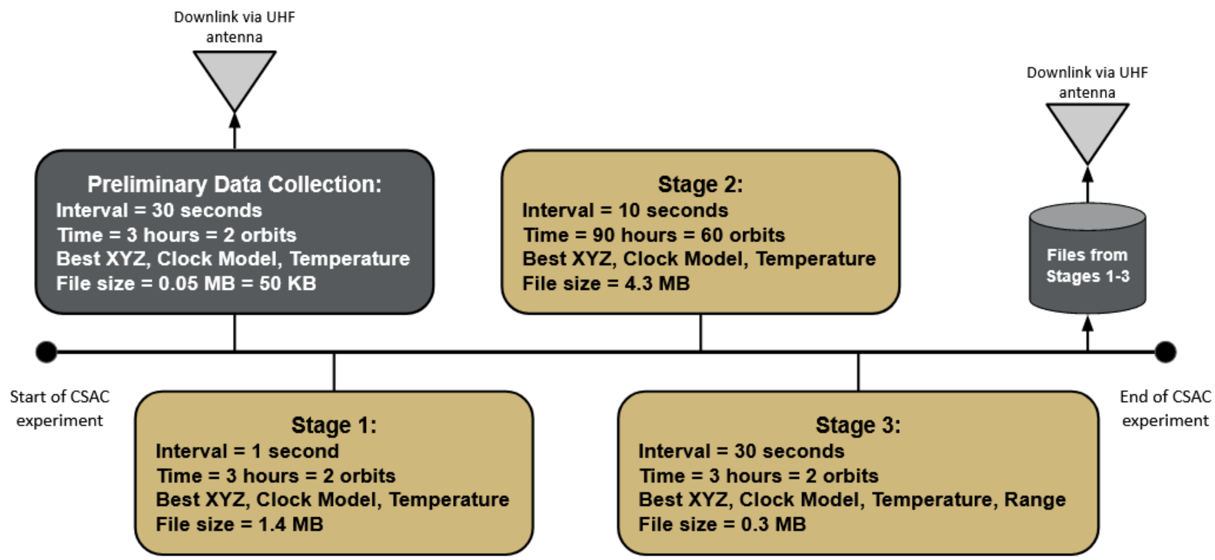

Figure 2: Concept of Operations for the CSAC Flight Experiment

University of Colorado Boulder. The roof drop was connected to a NovAtel OEM729 GPS receiver and the CSAC board was connected to the receiver as an unsteered external clock as shown in Figure 1. Pseudorange, phase, clock bias, and clock bias-rate were collected from the GPS receiver at a frequency of 1 Hz and temperature data was collected from the CSAC physics package at the same frequency. The duration of the live sky tests varied from one to four days. The Satellite Technology Integration (STIg) lab at the University of Colorado Boulder has a roof antenna drop where a few live sky tests were also conducted with a similar set up. Live sky tests were conducted using *Chip*, *Ralphie*, *SpaceBuff* and a PRS10 rubidium frequency standard (Rb) to get a baseline for each clock's performance on the ground as displayed in Figure 3.

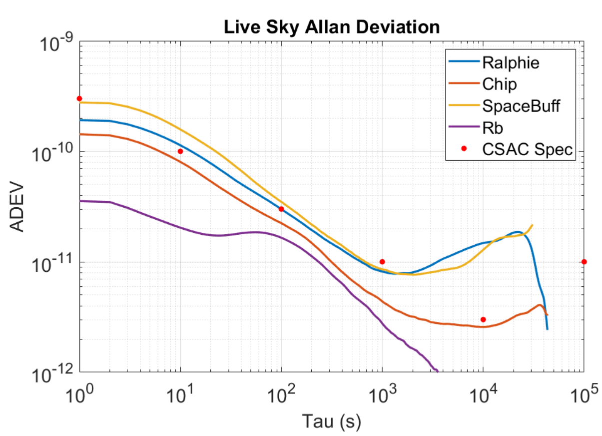

Figure 3: Allan Deviation Using Receiver Estimated Clock Bias from CSAC and Rb Live Sky Tests

In order to verify the clock performance on the custom breakout boards, live sky tests were conducted with *Chip* on a Microsemi development board and a custom breakout board. The ADEV plot is shown in Figure 4. The *Chip 2-9* yellow line represents the live sky test with *Chip* on the breakout board. This ADEV is very similar to the other two Chip tests which were completed with *Chip* on the Microsemi board. Figure 4 verifies that the custom breakout boards have comparable functionality to the Microsemi development board.

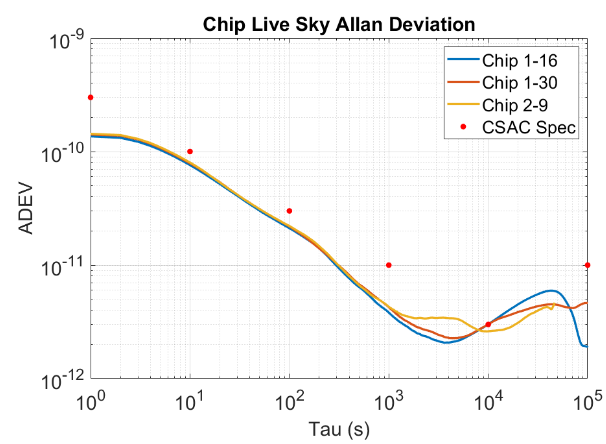

Figure 4: Allan Deviation Using Receiver Estimated Clock Bias: Comparing *Chip* Live Sky Tests

RF/GNSS SIMULATOR TESTING

Locked-Clock Testing

The purpose of the locked-clock tests is to determine whether the simulator is able to lock to an external reference. For the RF/GNSS simulator locked-clock test, a Spirent STR4500 simulator was connected to the MAXWELL engineering development (EDU) receiver through the antenna port on a NovAtel development board. The MAXWELL EDU receiver is a single frequency NovAtel OEM729 receiver. The *SpaceBuff* CSAC was connected to the receiver as an unsteered external oscillator via the development board. *SpaceBuff* was also connected to the Spirent simulator as an external reference. The test setup is shown in Figure 5. In this test, since the reference clock for both the simulator and the receiver are the same, the clock bias should be zero.

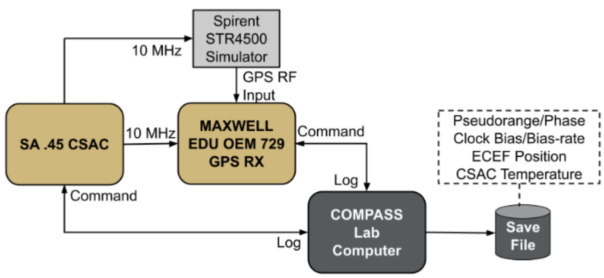

Figure 5: Locked-Clock Testing Setup Using CSAC as External Reference to GPS Receiver and Spirent Simulator

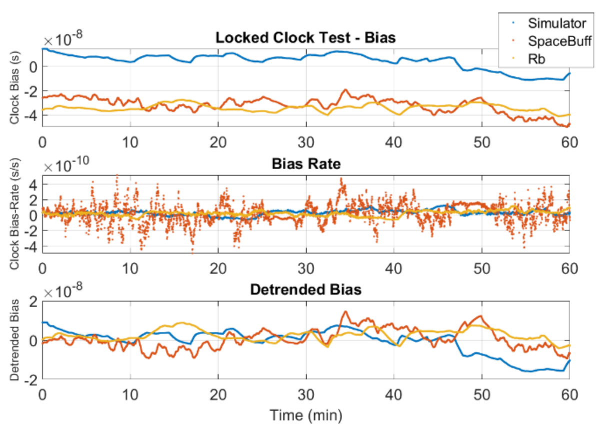

Figure 6: Three Separate RF/GNSS Simulator Locked-Clock Tests Using a CSAC, Rb, and Spirent Simulator as External References

The results of the locked-clock tests verified that the simulator is able to lock to the CSAC and rubidium as external references. Figure 6 shows a time series of the bias, bias-rate, and detrended bias from three separate tests in which the simulator, CSAC, and Rb were used to drive the simulator and GPS clocks. The CSAC appears to wander more than the Rb and simulator clocks. Since the magnitudes of the bias and bias rate are still very small, we can conclude that the simulator is properly locking to the external reference.

Flight Mode Testing

The purpose of the flight mode test is to simulate the on-orbit experiment configuration on the ground. In flight mode testing, the Spirent simulator is connected to the EDU receiver through the antenna port on the NovAtel development board. The Rb is used as an external reference to the Spirent simulator while the CSAC is the unsteered external reference to the EDU receiver. This setup is labeled flight mode because it is comparable to the setup that will be used on-orbit. Figure 7 shows the block diagram of the flight mode test.

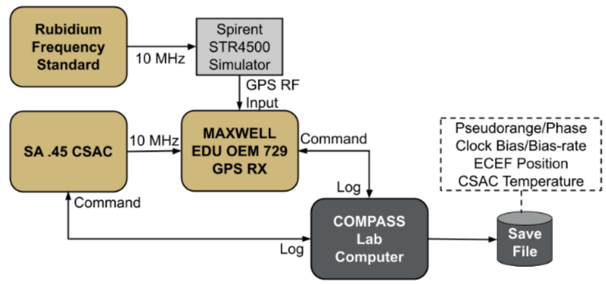

Figure 7: Flight Mode Testing Setup

A flight mode test was conducted using the Ralphie CSAC and the same orbit profile that was used for the locked-clock testing. The simulation was a LEO which ran for approximately 3.5 hours. The flight mode and locked-clock Allan Deviations are both shown in Figure 8. The flight mode ADEV is very different from what we observed in the live sky tests using the CSACs and the Rb. However, this behavior is similar to the ADEV plots from the locked-clock tests. The locked-clock and flight mode tests used the same LEO simulation.

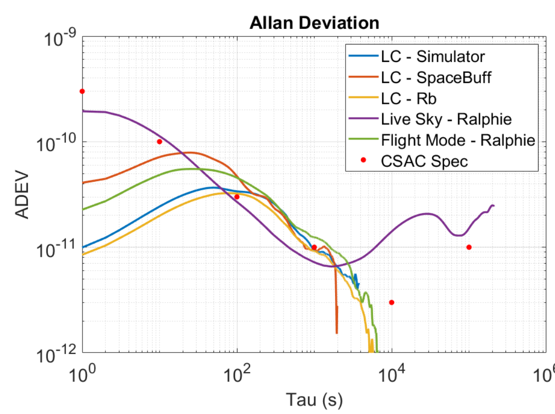

Figure 8: Allan Deviation Using Receiver Estimated Clock Bias from Locked-Clock, Flight Mode, and Live Sky Tests

One candidate hypothesis for the cause of the large periodic effect on the clock bias, is an unmodeled or mismodeled, simulated relativistic effect on the receiver clock. Looking at the simulation parameters, we found that the orbital eccentricity is set to zero, so there should be no periodic change in frequency due to variations in orbital speed. An offset in the frequency due to the combined effects of special and general relativity for the simulated orbit should be present. However, in live sky tests, this effect would be indistinguishable from a simple oscillator frequency offset. In fact, both represent actual frequency errors of the clock, so this effect is not one to be removed.

THERMAL TESTING

An important part of the CSAC flight experiment is determining a relationship between the environmental temperature and the performance of the CSAC. The clock performance is affected by temperature ramp time, dwell time, and the number of cycles.[8] We can conduct testing on the ground with a thermal chamber to get a better understanding of this relationship prior to launch.

The thermal test configuration is similar to the live sky tests, however, for this setup, the CSAC and breakout board are placed inside the thermal chamber. Pseudorange, phase, clock bias, and clock bias-rate were collected from the GPS receiver and the temperature was collected from the CSAC. The data rate was 1 Hz from both the GPS receiver and the CSAC. Three types of tests were conducted using the thermal chamber: a constant temperature hot test, a constant temperature cold test, and an orbital temperature profile test.

Figure 9: CSAC Breakout Board Inside Thermal Chamber

Constant Temperature Hot Test

For the constant temperature hot test, the thermal chamber was set to a constant 35C and data were collected for 20 hours. The purpose of this test was to get an understanding of how the CSAC is affected by warm temperatures and gain experience using the chamber. The CSAC did not demonstrate any loss of performance when soaked at an increased temperature. In fact, *Ralphie* performed slightly better than expected during the thermal test. The Allan Deviation plot can be seen in Figure 10. The *Ralphie - Thermal*, red line represents the thermal test using *Ralphie* in the STIg lab. This ADEV behaves very close to the CSAC spec. It is unclear as to why *Ralphie* performed better than expected in the thermal chamber hot test.

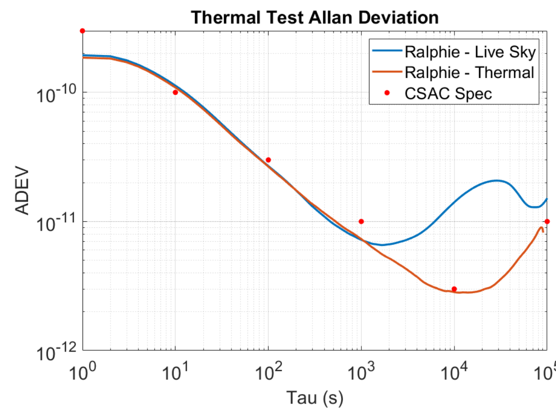

Figure 10: Allan Deviation Using Receiver Estimated Clock Bias of *Ralphie* in Constant Temperature Hot Test

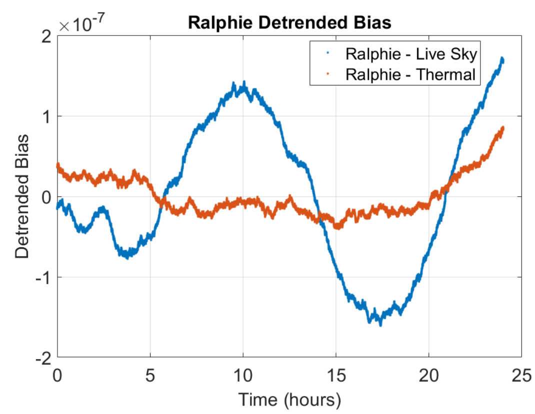

Figure 11: Receiver Estimated Detrended Clock Bias of *Ralphie* Comparing Live Sky and Constant Temperature Hot Tests

In addition to the ADEV plot, the receiver estimated clock biases were detrended and plotted versus time in Figure 11. The plot shows that the STIg live sky test has a slow, 12-hour sinusoidal trend over time while the thermal test stays fairly constant. This difference in the bias over time is likely the reason why we see the difference in the Allan Deviation plot. However, it is still unclear why the thermal test was less noisy than the live sky test.

Constant Temperature Cold Test

In order to prepare for the orbital thermal profile test, we also conducted a constant temperature cold experiment in the thermal chamber. The purpose of this test was to determine whether condensation developed at the minimum on-orbit internal temperature for MAXWELL. MAXWELL has a heater that turns on when the battery reaches 4C; this is the minimum internal temperature for the cubesat. For this test, no hardware was used; instead, a metal plate was placed inside the chamber during the test. The thermal chamber was set to a constant 4C. After approximately 20 hours, the thermal chamber and metal plate were examined for signs of condensation. No condensation appeared in the chamber or on the metal plate. A paper towel was used to wipe the inside of the chamber and both sides of the plate to determine whether any condensation was present.

Orbital Temperature Profile Test

The purpose of the orbital temperature profile test is to enhance our understanding of the CSAC's ability to compensate for periodic temperature changes. The thermal profile used for ground testing is motivated by a MAXWELL simulation study conducted by Rybak et al.[9] The study suggests that the external temperature on MAXWELL could vary 8C on-orbit. The MAXWELL orbital period is approximately 90 minutes. The profile is designed to begin at -4C and increase to 4C in 0.5 hours. Once the temperature in the chamber reaches 4C, the temperature will begin decreasing to -4C in one hour. The duration of the test is approximately 20 hours.

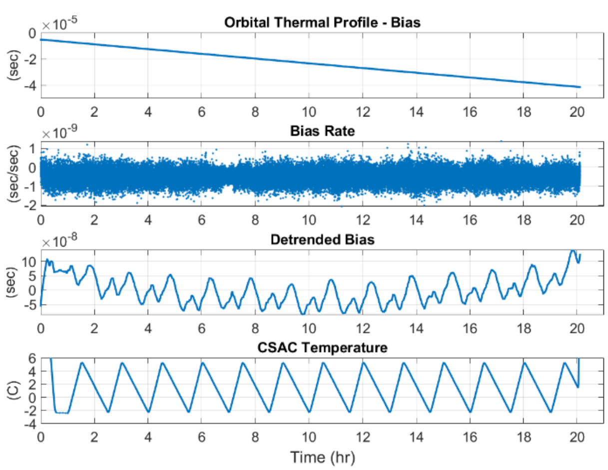

Figure 12: Time series of bias, bias-rate, detrended bias, and temperature for CSAC orbital temperature profile test

Figure 12 shows the bias, bias-rate, detrended bias, and temperature versus time for the orbital temperature profile test. The detrended bias is on the order of 10^{-8} seconds which tells us that the CSAC is compensating for some of the temperature variations. However, the periodic peaks in the detrended bias show that the CSAC is directly affect by temperature changes. Further analysis and testing are required to understand the relationship between the environmental temperature and the CSAC performance.

ELECTROMAGNETIC FIELD TESTING

Since the CSAC is sensitive to magnetic fields, it is also important that it is tested in the presence of them so the effect on the CSAC clock can be understood and characterized before the flight experiment. In magnetic fields under 2 Gauss, the CSAC has a magnetic sensitivity of $\pm 9\times10^{11}$/Gauss.[10] During the flight experiment, the CSAC will experience magnetic fields due to the torque rod used onboard MAXWELL for attitude control. The CSAC is particularly susceptible to the x-axis torque rod since it is to be placed about 10 cm away from this torque rod. One method of testing the CSAC in a magnetic field is utilizing a Helmholtz cage. The Helmholtz cage is operated using a serial port monitor, an arduino sketch, and a MATLAB function. Additionally, a power supply provides the electric current that is run through the three axes of the cage thus creating the magnetic field. The cage itself is about a square meter and provides a 10 cm cube directly in the middle of it that has a uniform magnetic field.[11]

The Helmholtz cage requires a manual calibration process. This process is based on the equation:

$$\boldsymbol{I_i} = \frac{\boldsymbol{B_i}}{[\boldsymbol{HC_i}]\boldsymbol{\mu_0}} \tag{1}$$

where the *i* denotes which axis the equation is applied to. This equation indicates that the current through the axis is proportional to the magnetic field it produces. This proportionality depends on the magnetic permeability of free space as well as HC_i which is a constant that needs to be determined via the manual calibration process. The HC constant is computed empirically for each axis via the equation:

$$\boldsymbol{HC_{empirical}} = \frac{\boldsymbol{B_{2,i} - B_{1,i}}}{\boldsymbol{\mu_0}[\boldsymbol{I_{2,i} - I_{1,i}}]} \tag{2}$$

This means that for each axis, two different currents must be run through the cage and the generated magnetic field must be measured. However, when actually conducting the calibration process one of the magnetic field measurements for each axis can be collected while there is no current flowing through the Helmholtz cage. This means that only four separate measurements need to be conducted for a proper manual calibration. It is important to note that the axis have to be separated during this process. For example, it would not be valid to have current running through both the x and y axes if the HC value for the x axis was being determined. After this process is completed the proper current can be applied to create the desired B field in the Helmholtz cage.

While this process should be valid in theory, the Helmholtz cage has some issues concerning practical use in testing the CSAC. The first issue is that it is limited to 8 V and 1 A in each axis which results in a total field of up to 1.3 Gauss. It is desired that the CSAC be tested in fields between 1 and 5 Gauss since the CSAC could experience greater magnetic fields from the torque rods.

A second way to potentially test the CSAC under the influence of magnetic fields is to use the actual torque rods. In order to conduct this experiment, the torque rod would be fired and the magnetic field at various distances away from the torque rods would be measured by a magnetometer. Then, the CSAC would be placed at the distance where the magnetic field was measured at 2 Gauss (or another desired magnetic field value), since 2 Gauss is the upper limit of magnetic field in the CSAC specifications[10]. Another test would be to measure the magnetic field at the set distance where the CSAC is to be placed away for the torque rod. Then, depending on how strong the field was, the CSAC would be placed at the distance, then the resulting clock behavior would be characterized. Ideally, the field at this distance would be under 2 Gauss. The magnetic field testing is an important area of current and future work.

FUTURE WORK

The CONTACT and MAXWELL graduate projects will continue into Fall 2021. Ground testing will continue to be the focus for the CSAC flight experiment. Environmental tests such as the orbital thermal profile and electromagnetic field tests will take priority. To ensure the success of the experiment on-orbit, it is important that we test and understand how both thermal and electromagnetic fields affect the clock. Testing to measure the magnetic field of the torque rods and additional orbital thermal profile tests are set to begin soon.

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