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# ATTITUDE CONTROL BACK-UP MODULE FOR LOW EARTH ORBIT SATELLITES

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**Abstract**—A satellite in orbit uses the Attitude Determination and Control Subsystem (ADCS) to perform orientation maneuvers for specific mission purposes such as imaging Earth targets. The ADCS is designed with fully redundant components, hence doubling the power, volume, mass and cost of the satellite. During emergencies, a satellite is sent to a safe-hold mode where the attitude is regulated to ensure that power and ground communications with the satellite are still operational. The satellite Attitude Control Back-up Module (ACBM was developed to address the need for a simple system to regulate the satellite's attitude during safe-hold mode. It is a complimentary ADCS subsystem that can be interfaced to small Low Earth Orbit (LEO) satellites in the 200kg range. The ACBM is modular, weighting only 3kg and occupying an envelope of $10 \times 10 \times 30$ cm$^3$. A command from the Mission Control Ground Station activates the ACBM and maneuvers the satellite's solar panels to the sun to ensure maximum power generation using a new sun tracking algorithm with three magnetic coils and one pitch reaction wheel. The ACBM is designed with a Flight Control software (FCS) distributed between two low powered microprocessors. Each microprocessor resides on individual boards, one to handle Attitude Determination and sensor measurements and the other to handle the Attitude Control and driver actuation. The ACBM performance has been verified in simulation, where solar panel normal to the Sun vector is less than 15°, hence ensuring the feasibility of the system to be used on future small LEO satellites.

**Keywords:** Attitude Determination, Attitude Control, Distributed Microprocessors.

## 1. INTRODUCTION

A satellite orbiting the Earth is required to orientate and point specific instruments such as an optical camera towards the Earth or part of its body such as non-articulated solar panels towards the Sun. This is achieved by the Satellite Attitude Determination and Control Subsystem (ADCS). The ADCs estimates the rotational kinematics and controls the rotational dynamics in a close loop system. As with any digital control system, the ADCS consist of sensors, actuators, estimators and controllers running on a dedicated microprocessor. The sensors sense the variation in physical space and using estimation methods, determine the orientation, i.e. attitude, of the satellite's body with respect to a reference frame. The actuators use the conservation of momentum principle to execute rotational maneuvers driven by commands computed by control algorithms to reduce the attitude error between the reference attitude and the estimated attitude.

Satellites are designed to carry out their specific missions, such as communications or remote sensing during their designed lifetime without having any access to maintenance or servicing. Hence satellites are designed to be highly reliable when operating in the harsh space environment. Unfortunately, history has shown that satellites can fail, even with all the necessary reliability efforts in place. Hence all satellites are designed with a safe-hold mode, a state in which the satellite enters, to ensure that communication with the ground station is maintained and power is continuously generated. This mode allows the satellite operators time to figure out a recovery plan which can span from hours to days. Since nearly all conventional Low Earth Orbit (LEO) satellites rely on the Sun for power generation using solar panels and rechargeable batteries, the optimum way to maintain power is to point and regulate the solar panels towards the sun with a normal cosine angle of nearly 15° or less. Without panels that articulate, this can only be achieved by changing the attitude of the entire satellite body.

Robertson and Stoneking [1] reported that from 1990 to 2001, 12 out of the total 121 reported LEO satellite anomalies were attributed to the satellite's ADCS. Hence, as with any subsystems, the ADCS are designed with redundant ADCS components to avoid any single point failures. This however introduces additional mass, power consumption and complexity to the satellite and reduces the satellite's efficiency. Several simplified ADCS solutions on paper have been proposed, such as a fault tolerant ADCS for zero momentum spacecrafts [2] and low power magnetic torque rods to stabilize the spacecraft [3]. The former solution requires a set of momentum wheels for actuation which adds additional mass and power consumption, whereas the latter stabilizes the satellite to a local vertical orientation and does not guarantee that the solar panels will face the sun continuously during safe-hold modes.

This paper presents a new ADCS solution, called the Satellite Attitude Determination and Control Back-up Module (ACBM) to address the need for a non-redundant but efficient ADCS system that is able to ensure the satellite maintains a power efficient safe-hold mode.

## 2. SYSTEM OVERVIEW

### 2.1. ACBM Description

The Attitude Control System Backup Module (ACBM) is designed to be compatible with any small LEO satellite in the 100kg to 200kg range. The ACBM is small, i.e. occupying not more than $10 \times 10 \times 30$ cm$^3$ in volume and with a mass not more than 3kg. A size comparison of the module with respect to a typical 200kg mass LEO satellite with a cylindrical dimension of 1.2m in height and 1.1m in diameter is shown in Figure 1.

The main function of this ADCS Backup Module is to ensure stabilization and tracking of the Sun by fixed body mounted or deployed solar panels for optimized power generation. The ACBM is not a complete ADCS subsystem but has the capability to provide a 15° Sun vector to solar panel normal angle pointing accuracy using low powered actuators, i.e. 3 axes magnetic torque coils, a single pitch reaction wheel and a low powered Inertial Measurement sensor. Thus, the ACBM only compliments the primary satellite ADCS and only operates during emergencies. The ACBM is designed to interface with the satellite Onboard Computer (OBC) and other primary ADCS subsystem components, depending on the configuration of the host satellite. For example the primary satellite magnetic torque rods are integrated to the ACBM due to the extra capability of the rods that are optimally sized to actuate the satellite, rather than the inbuilt ACBM actuators.

### 2.2. Concept of Operations

In the event that the small LEO satellite encounters an anomaly at any point during its operational lifetime, the ACBM is activated by the satellite operator from the Mission Control Ground Station as shown in Figure 2. When the satellite enters the safe-hold mode state, the ACBM will determine the

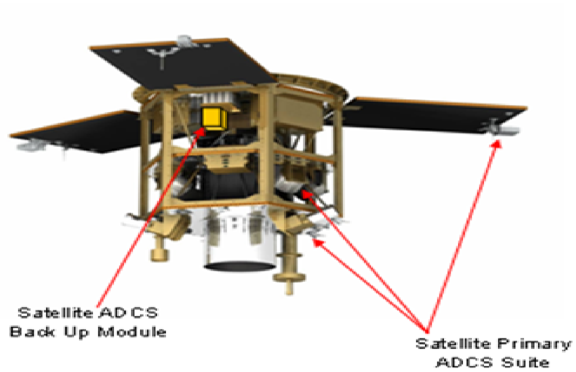


Figure 1: ACBM interface to a LEO Satellite platform

coarse orientation of the satellite, compute the attitude error and actuate the satellite to maneuver the solar panels towards the sun.

Within the mode, Whole Orbit Data (WOD) will be downloaded from the satellite and problems will be resolved by the satellite operators. Any correction and updates are sent to the satellite from the ground to fix the anomaly. This duration can range from hours to days and hence the importance of the satellite to maintain a continuous power generation scheme. Once the issues are resolved, the recovery commands are uploaded to the satellite and the ACBM will be commanded to return to standby mode. The primary ADCS will then return the satellite to its nominal operational mode.

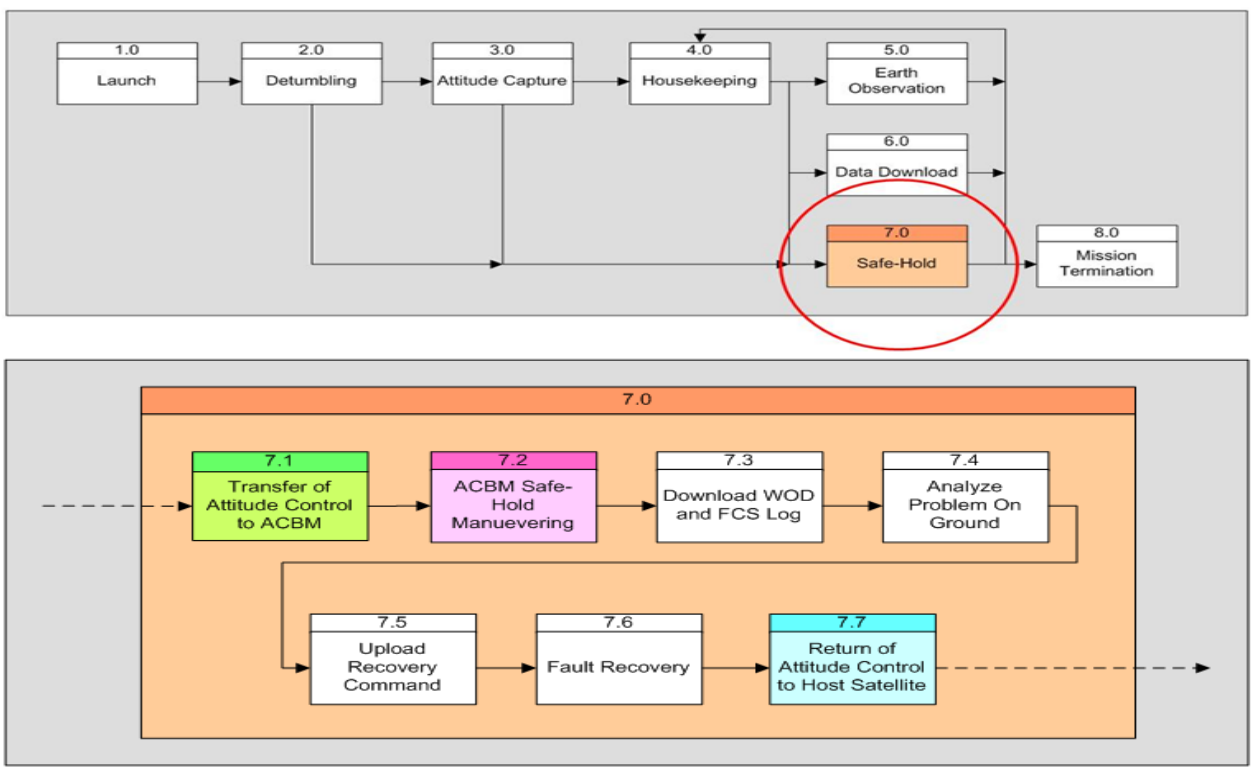


Figure 2: ACBM Concept of Operations

### 2.3. Regulating Sun Tracking Solar Panels

For verification of the ACBM performance, the case study satellite is a small LEO satellite with deployed solar panels, where the panel's normal vector is in the negative Z direction (ZO) of the satellite's body reference frame. Pointing of the satellite body Solar Panels to the sun vector using the ACBM is achieved by a new Sun Tracking 3-axis control algorithm presented in reference [4]. By using a set of 3 axis magnetic torque coils and a pitch reaction wheel, the controller aligns the body axes (XB, YB, ZB) to the sun vector using an Orbit reference frame (XO, YO, ZO). The resultant is a positive Sun Azimuth angle of 90° and negative Elevation angle of 90° as shown in Figure 3.

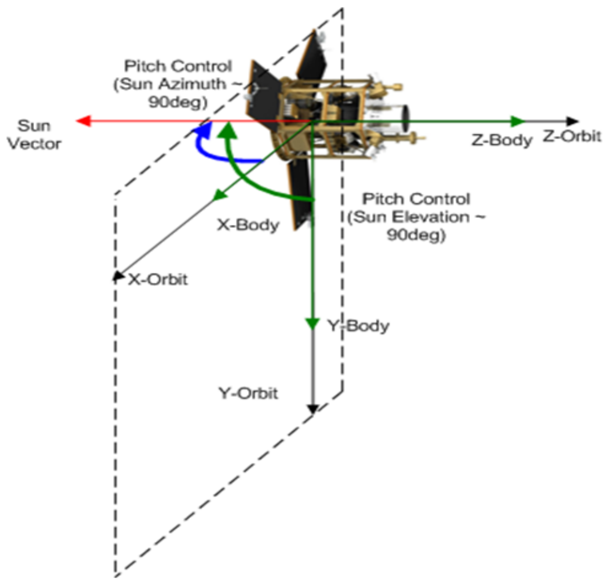


Figure 3: Alignment of satellite body axis to Sun Vector with respect to the Orbit Reference Frame

The controller will regulate the alignment of the body axes to the Sun Vector over the satellite orbit period. As shown in Figure 4, even though the orbit reference frame rotates with respect to the Sun Vector, the body axis is following this vector, maintaining the required azimuth and elevation angles.

## 3. SYSTEM ARCHITECTURE

### 3.1. Overview

The ACBM consist of two stacked microprocessor boards, i.e. MicroP1 and MicroP2 each with footprints less than $10 \times 10$ cm$^2$ and the core of each board is an 8-bit microprocessor. The ACBM Flight Control Software is distributed and handled by both microprocessors. The concept is to maximize onboard processing capabilities using low powered and flight heritage microprocessors that are bridged to each other, similar to a duo core concept. MicroP1 is dedicated to attitude estimation and sensors sampling, i.e. an Inertial Measurement Unit. MicroP2 handles the Attitude Control of the Magnetic Torque Coils, the pitch Reaction Wheel and Data storage. Both microprocessors convey telemetry and telecommand between each other and to the Onboard Computer.

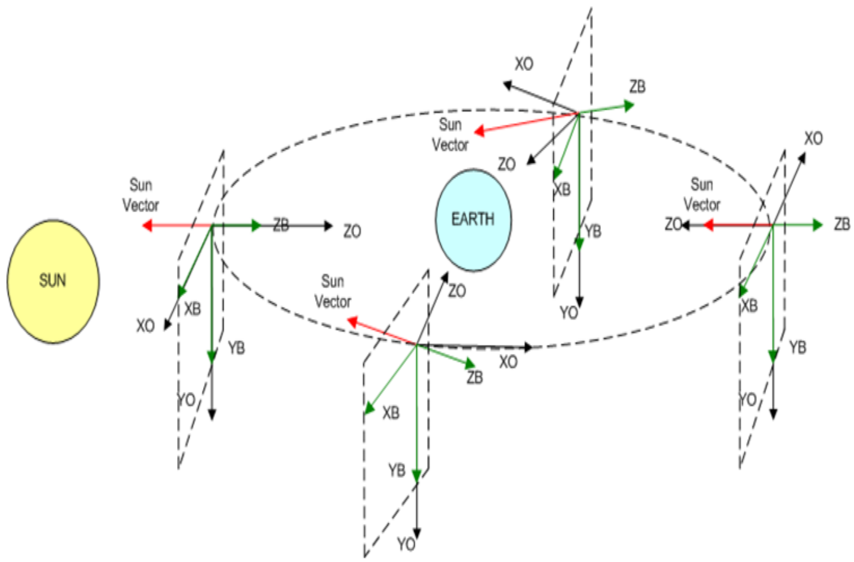


Figure 4: Sun Vector alignment regulation over one orbit duration

The ACBM is debugged and tested using a Simulator test PC that handles the space environment, satellite kinematics and dynamics. Simulated telemetry and telecommand data are exchanged between the prototype and PC via RS232, as shown in Figure 5, *ala* Hardware-in-the-Loop test bench.

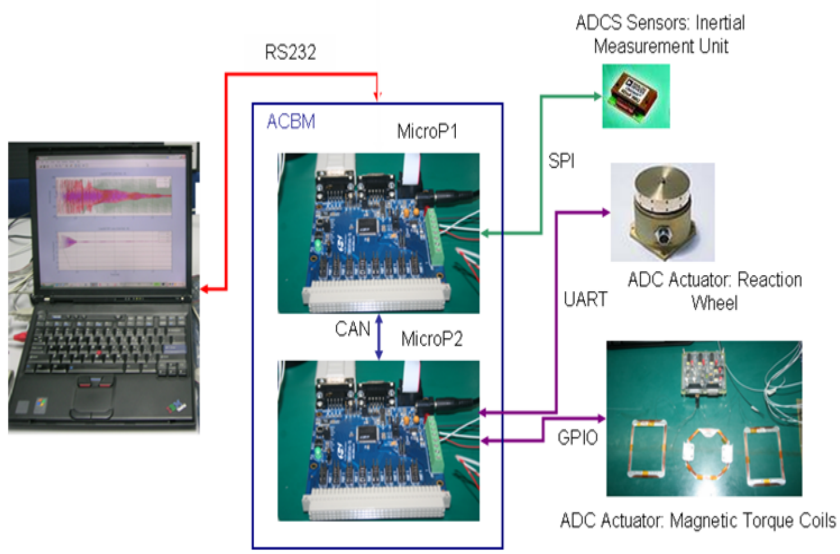


Figure 5: ACBM Architecture

### 3.2. Software Architecture

The ACBM Flight Control Software consists of two major segments, the Flight Control and the Microprocessor drivers. The Flight Control consists of attitude determination and attitude control functions whereas the microprocessor drivers contain the configuration, initialization, timing and communication codes. The attitude determination algorithm is made up of mathematical and celestial libraries required to perform attitude determination using sampled and logged telemetry data from the Inertial Measurement Unit. This is housed in MicroP1. The attitude control contains the new Sun Tracking 3-axis control algorithm and driver actuation for the magnetic torque coils and pitch reaction wheel. This is housed in MicroP2. Both MicroP's use the same drivers and operate in a *foreground / background (Super-Loop)* technique for real-time preemptive multitasking (See Figure 6).

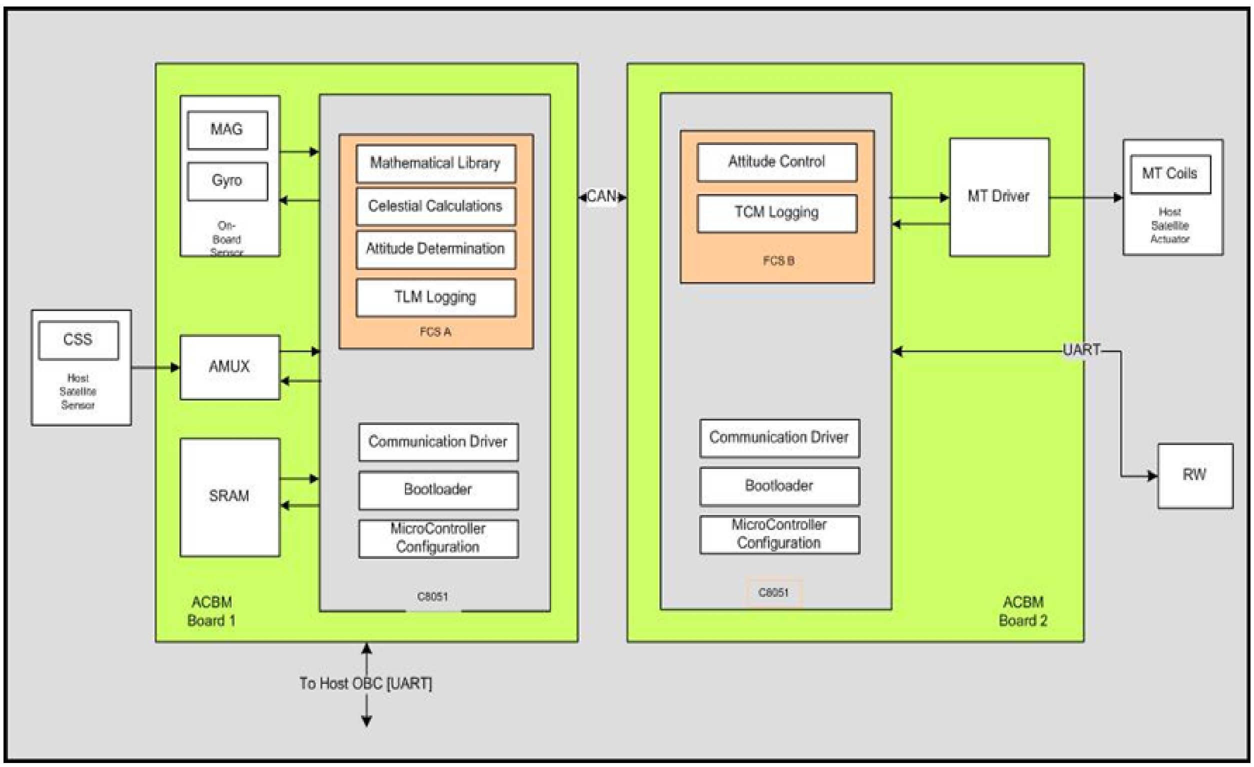


Figure 6: ACBM Software Architecture

### 3.3. Hardware Architecture

MicroP1 and MicroP2 are both similar in design. Each board has the same embedded microprocessor and power circuit. Both boards are bridged for power and grounding. Communications between both boards are implemented using a Controller Area Network (CAN) architecture.

MicroP1 has an integrated Micro Electrical Mechanical System (MEMS) IMU and is controlled by the microprocessor via a Serial Peripheral Interface (SPI). An analogue multiplexer circuit is incorporated to handle all external sensor telemetry sampled from the primary satellite ADCS, most importantly the solar sensors. Interface to these external sensors shall be handled by the Analogue Digital Sampling in the microprocessor. MicroP2 contains the analogue driving circuit required to handle the current distributed to the external magnetic torque coils. The board also controls the external reaction wheel with its own in-built electronics and wheel control circuit. MicroP2 shall also contain a SRAM to store and log all telemetry.

Both boards are stacked and placed in a single mechanical housing interfaced to the external magnetic torque coils and pitch reaction wheel, resulting in a height of less than 30cm and a footprint of $10 \times 10$ cm$^2$.

## 4. VALIDATION METHOD

### 4.1. Simulation

Performance of the ACBM, specifically regulating solar panel sun tracking was conducted using a space simulator, actual control algorithms and a satellite model. The simulation was conducted for 3 orbits for a LEO satellite, where 66% of the orbit period is in daylight.

As shown in Figure 7, the satellite pitches from $-90°$ to $+90°$ at a rate of 0.06deg/s. This corresponds to the orbital rate of the satellite in anti orbit normal and is achieved by the controller driving the pitch reaction wheel and magnetic torque rods. Hence the body axis maintains alignment with the Sun Vector as discussed in Section 2.3. In Figure 8, the Sun Vector elevation is maintained at $-90°$, while the Sun Vector azimuth is maintained at 105° which is within the tolerance of 15° sun cone angle during daylight. Hence the deployed solar panels are tracking the Sun and generating power as expected. During eclipse the controller returns and aligns the body axes to the orbital frame.

In the first orbit, the controller was initiated early in the sunlight period. Hence the ACBM control system is able to maneuver the satellite to the desired sun tracking state at any point of the orbit as depicted in the concept of operations.

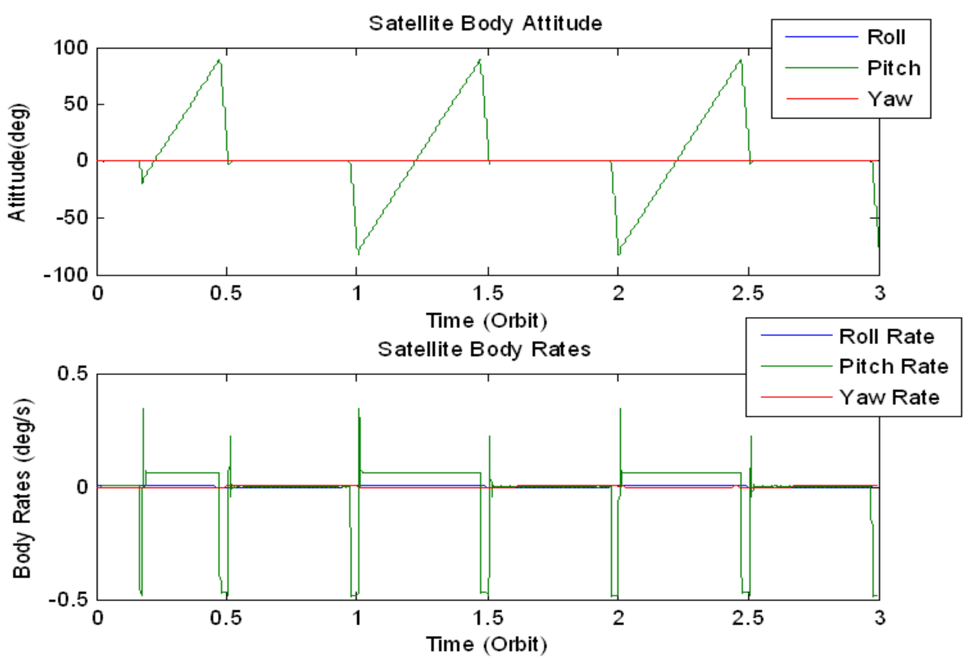


Figure 7: Satellite Attitude and Body Rates in Safe-Hold Mode using ACBM

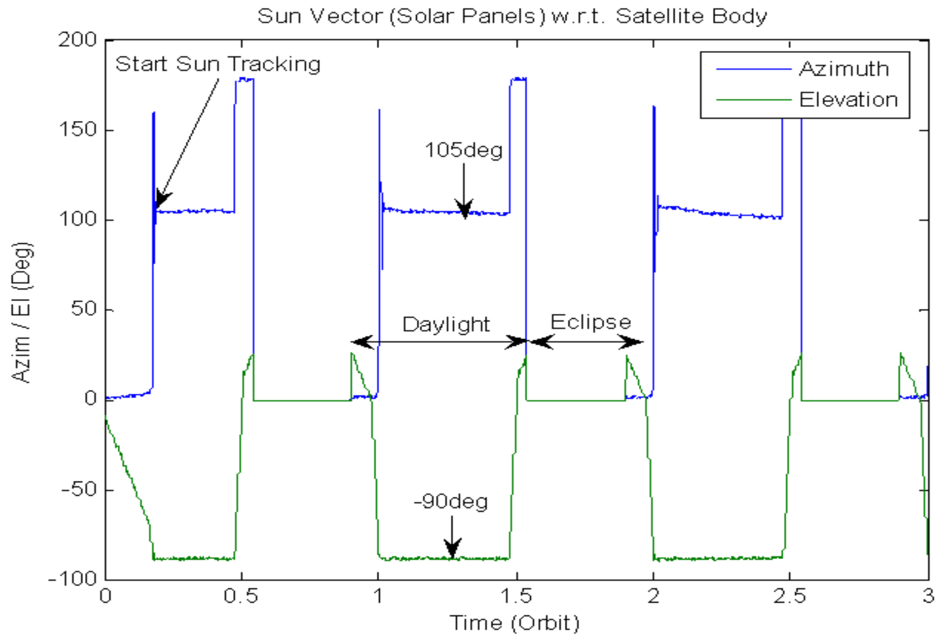


Figure 8: Sun Vector Azimuth and Elevation with respect to Satellite Body Frame during Safe-Hold Mode using ACBM

## 5. CONCLUSION

The system simulation of the modelled ACBM in operations has validated that the system controller together with the modelled actuators are able to maintain a 3-axis sun tracking attitude during the satellite's safe-hold mode. The deployed solar panel normal is nearly aligned with the Sun vector with an angle error of 15°, hence the cosine efficiency is almost 96%, allowing the satellite to generate power continuously without having the need to use the satellite Attitude Determination and Control primary subsystem. The design of a dual power efficient stacked microprocessor with a dedicated but simple attitude determination and attitude control demonstrated that a compact system ADCs back-up system can be built for a LEO satellite platform for safe-hold mode purposes. Further development is required to ensure that the ACBM is a viable system for future small LEO satellites.

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