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Research Article

ENERGY BALANCING AND ANALYSIS OF POWER SYSTEM FOR BCCSAT-1 SATELLITE

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ABSTRACT:
This paper presents the energy balance and the analysis of the power system of BCCSAT-1 in the BCC Space Program, a high school aerospace engineering program created by Bangkok Christian Collage in unison with King Mongkut's University of technology North Bangkok. BCCSAT-1 is a 1U CubeSat satellite, which heritage the design of KNACKSAT. The power system which has been adapted from the design of KNACKSAT power system to accommodate the mission to capture multispectral images using four cameras with different filters. The power system has been designed for continuous operation with high efficiency. It consists of four parts, power generation, power storage, power distribution and power management. The energy balance consists of determining the energy generation, which is determined by the altitude of the satellite, and the energy usage of the satellite. The analysis is performed by analysing the design of the power functionality in space, this is determined by testing the power system in space-like condition in test such as Vibration, Thermal Vacuum and Thermal Cycle testing.

Keywords: *1U CubeSat, Power system, Energy balance, Space environment testing*

1. INTRODUCTION

In recent years, more and more organizations and institutions became engaged in space technologies. Including the idea of creating CubeSats, which are square-shaped satellites that come with many sizes. For examples, 1U CubeSats which have the dimension of 10x10x10 cm on all sides, 2U CubeSats which have the dimensions of 20x10x10 cm and so on. With its miniature size gives many advantages including the time it takes to build it which can be as low as one to two years. It also costs enormously less compared to conventional satellites, which gives intuitions around the world with the access to build their very own CubeSats with their limitless imagination and ideas [1].

Bangkok Christian College is an institution in Thailand which the school's principle became engaged in space technologies and formed the BCC Space Program in 2018. The BCC Space Program is a program that brings a group of high school students who are also interested in engineering and especially space technologies. The purpose of the program is to build a 1U CubeSat called BCCSAT-1 and launch it on the Soyuz 2 rocket before the third quarter of 2020.

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BCCSAT-1 heritage the power system of KNACKSAT [2, 3]. And although the power system of KNACKSAT is quite capable, the payload requires additional power consumption due to the increased number of Cameras and increased volume of photographs to be downlinked.

There is an importance in analysing the budget of a power system to determine its capabilities, as the power system needs to deliver the necessary amount of power to the rest CubeSat. There were also many cases of CubeSat failures due to the failures of the power system. As such it is necessary to the budget of the power system. [4]

This document will mostly focus on the power system section of the BCCSAT-1. The power system must deliver all the output currents as efficiently as possible due to the limited resources of energy from the solar panels. Moreover, reliability and durability are the most important features of the power system. So, it must be tested several times and in critical situations to make sure all the functions of the power system will work well in the space environment.

2. MISSION OVERVIEW

BCCSAT-1 CubeSat is designed to take multispectral images via specific filters mounted on different cameras in order to combined of the wavelength to create multispectral images, which can be analyzed. After which these images are downlinked. However, in order to capture these images, and downlink them, the power system need to provide the system with enough power at all time. This will be discussed more in “the design of the power system”, and the way in which the space conditioned affected the system in “Space Environment Testing”. But lastly the most important thing is the energy balance, which is a method to confirm that the power used during the environmental testing is sufficient for the CubeSat to be able to operate once it is in orbit, even in the worst case scenario that the only one of the solar panel is able to capture the energy from the sun.

2.1 Mission Requirement

2.1.1 Orbital Period

The orbital period depends on the altitude of the satellite (Table 1) measured from the center of the Earth. The total orbit time can be calculated as follows:

$$T_{total} = 2\pi\sqrt{\frac{a^3}{\mu}} \quad (1)$$

, where T_{total} is the total orbit time, a is the semi major axis, and μ is the standard gravitation of the Earth [5]. The time spent in the eclipse can be calculated as follows:

$$T_{eclipse} = 4\pi \sin^{-1}(\frac{R}{2a}) \sqrt{\frac{a^3}{\mu}} \quad (2)$$

, where T_{umbra} is the time spent in umbra, a is the semi major axis, and μ is the standard gravitation of the Earth and R is the radius of the earth [6].

Table 1: Altitude and orbital period profile of BCCSAT-1 at 575km

Total Time	Time (s)	Time (minute)
Per Orbit	5,759.00	95.9
In Sunlight	3,630.64	60.5
In Eclipse	2,128.36	35.4

2.1.2 Power Requirement

In Table 2, the power consumptions of the BCCSAT-1 are summarized the mean power consumption of each boost converter line, depending on the mode it is in. It also shows when the power line is used. The peak power consumption is 5,161.06 mW on the ELEC line, which powers the payload, but the main power consumption is from TX(FM), which operates around 10 minutes at a time, whereas the payload operates only a few minutes at the peak. The values from Table 2 are measured during the Thermal Vacuum Testing, except for TX(FM) or downlink, which were measured separately.

Table 2: The power consumption of the BCCSAT-1

Boost Converter	Stand by Power consumption (mW)	Operation Power consumption (mW)	Operating time
ELEC	326.86	5,161.06	Payload Operation
TX(CW)	153.36	583.12	CW on
TX(FM)	3,509		GFSK on
RX	144.7		All time
EPS	253.4		All time

3. DESIGN OF THE POWER SYSTEM

Since BCCSAT-1 inherits the power system from KNACKSAT [4, 5], the design may have many familiarities, with some changes to suit the 4 cameras payload. The design can be summarized in Fig. 1.

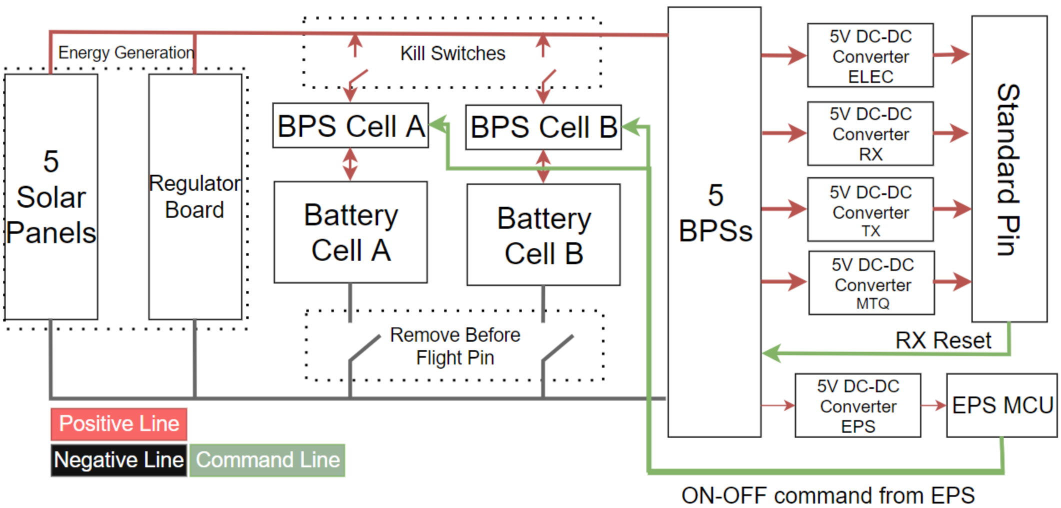

Fig. 1. EPS block system diagram

3.1 Energy Generation

On BCCSAT-1, the power is generated with 5 Gallium Arsenide (GaAs) solar panels connected in parallel and each panel contains 2 solar cells which is connected in series. In total the solar panels give an output approximately 4.8V. But, due to the battery limits, the regulator board regulates the 4.8V into 3.7V. Each of the solar panel generates 2,400mW, assuming the efficiency of the regulators to be 70%, the energy gained for the system during daytime is 1680mW per solar panel. Assuming the worst-case scenario that only one of the solar panel can generate energy at a time, due to the orientation of the CubeSat that only enable the sunrays to hit one solar panel, instead of hitting multiple solar panel at an angle, the rate that entire CubeSat generates then should be 1680mW in this scenario.

3.2 Energy Storage

The Batteries used in the BCCSAT-1 are two NCR18650B lithium-ion battery made by Panasonic batteries which is connected in parallel. As shown in Fig. 1, each battery cells have its own battery protection circuit which is controlled by power system's microcontroller. Additionally, the positive power line and the negative power line are connected to the Kill Switches and the Remove Before Flight Pin respectively.

3.3 Power Distribution

As shown in Fig. 1, the power system of the BCCSAT-1 deliver the power to 5 separated powerlines of which one is the power the power system microcontroller. The others powerline that will receive the energy are ELEC, RX, TX and MTQ which powers the payload, the receiver board, the transceiver board and the heater respectively. The MTQ line used to power magnetorquer, but due to space constraint BCCSAT-1 only have passive altitude control in the form of permanent magnet.

3.4 Power Management

For long-term use, BCCSAT-1's batteries must be highly optimized. And, the depth of discharge for the worst-case scenario which is when the BCCSAT-1 is operating in an umbra with the FM activated is 322.2546 mAh which is 4.8% DOD (Depth of Discharge) (Show how to calculate DOD as equation). Therefore, the setting of 15% depth of discharge will covers all the scenario including the worst case. The battery is kept at 50% of its maximum capacity and charged up to 65% via the power system microcontroller. The microcontroller also measures the current and the voltages of various parts of the system from analog sensors.

4. SPACE ENVIRONMENT TESTING

4.1 Thermal Cycle Testing

According to the orbital period at 575 km, the daytime is approximately 60.4 minutes and the eclipse time is approximately 35.5 minutes. Meaning, the battery charging time and discharging time are 60.4 minutes and 35.5 minutes, respectively. The Thermal Cycle Chamber uses heater and liquid nitrogen to heat up and cool down air. In the chamber, the temperature rapidly goes up and down from -5ºC and 45ºC to imitate the satellite orbiting the Earth. The Thermal Cycle Test Profile used in this Testing consists of 2 cycles in total and lasts approximately 3 and a half hours as shown in Fig. 2 and Fig. 3.

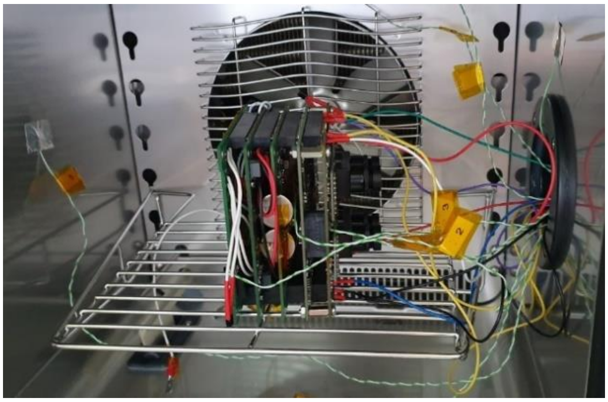

Fig. 2. BCCSAT-1 inside the Thermal Cycle Chamber

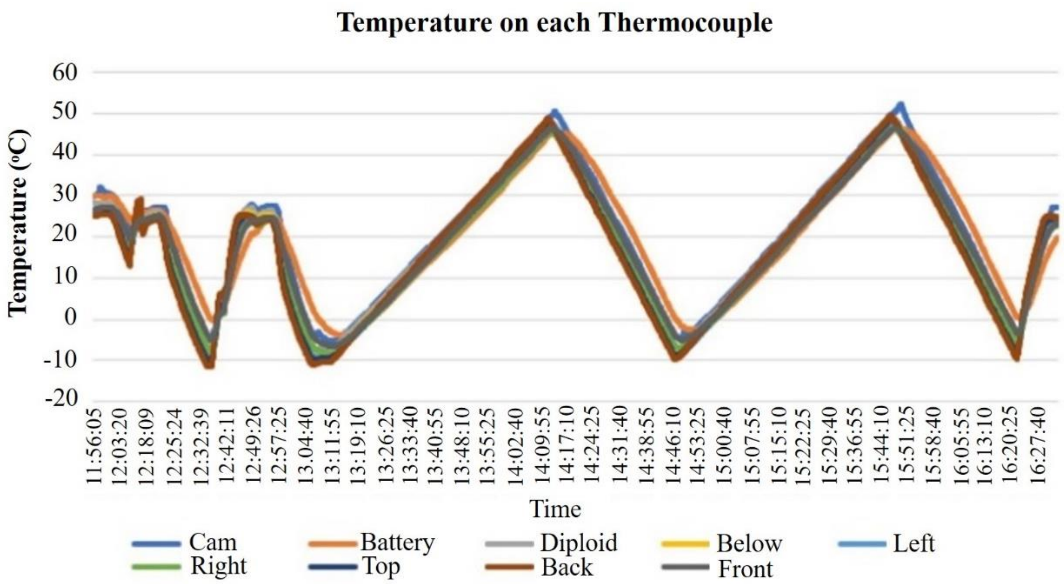

Fig. 3. Thermal Cycle Testing Profile with Time started and ended

4.2 Thermal Vacuum Testing

In order to simulate the real condition in space, in which the satellite is in a vacuum orbiting the earth, of which the satellite will directly get hit by sunlight during day, during which it has a hot temperature, and also the satellite resides in the shadow of the earth during eclipse time. The temperature profile during these phases range from -25C to 55C to simulate the condition while orbiting the earth. A thermal vacuum test consists of 7 cycles as shown in Fig. 4 and Fig. 5. During the testing the power system measures the power consumption in space-like environment. Also, the critical temperature of the system is 0 to 40 in the internal structure of the CubeSat because that is the functional temperature for the battery.

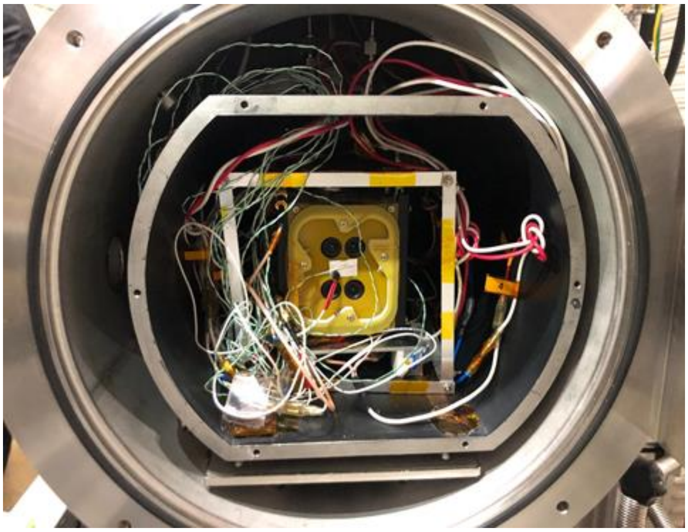

Fig. 4. BCCSAT-1 Inside the Thermal Vacuum Chamber

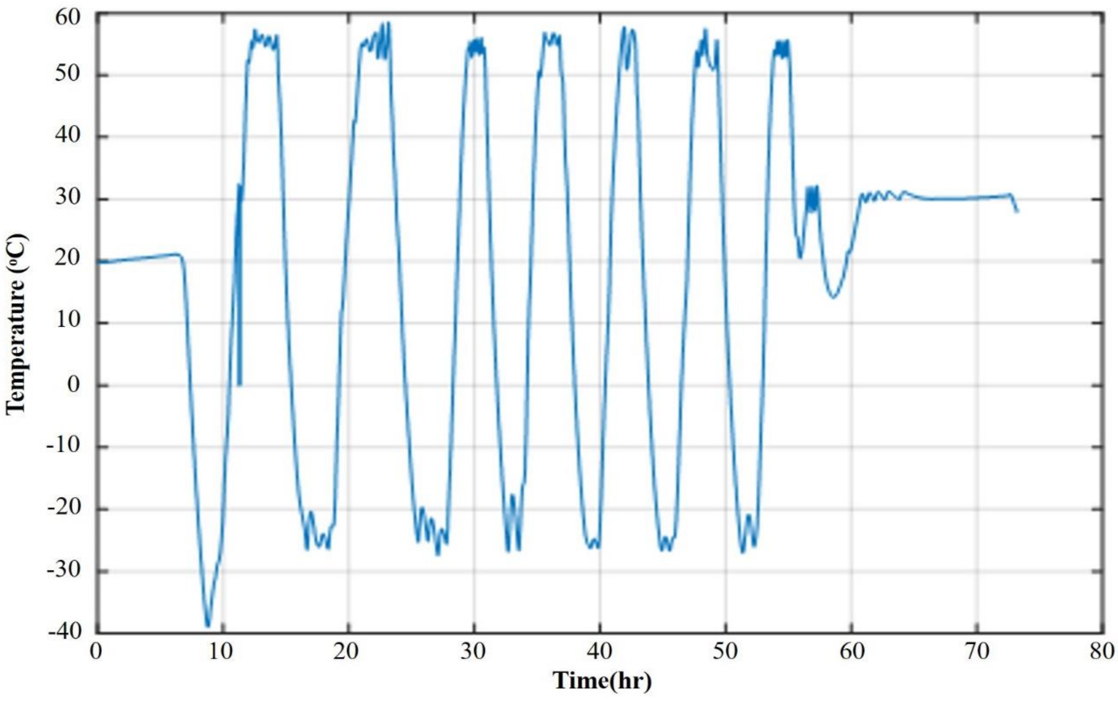

Fig. 5. Thermal Vacuum Tesing Profile

During the Thermal Vacuum Testing, the power system measures the power consumption from each of the power line, there are 4 major power lines that contribute to the overall power consumption of the system, namely ELEC line, which powers the payload (camera board and C&DH board), EPS line that powers the power system, RX line that power the receiver board and, TX line that power the transceiver board, which can be modulated in CW(Continuous Wave) and FM(Frequency Modulation) both are used to communicate with the ground station. While CW mode is for sending small amount of information to inform the ground station that the CubeSat is still alive, while FM mode is for downlinking the vast amount of data toward the ground station. The TX line during the Thermal Vacuum Testing operates in CW. Fig. 6, Fig. 7, Fig. 8, and Fig. 9 shows the power consumption over time during the 7 cycle from each of the major power line respectively.

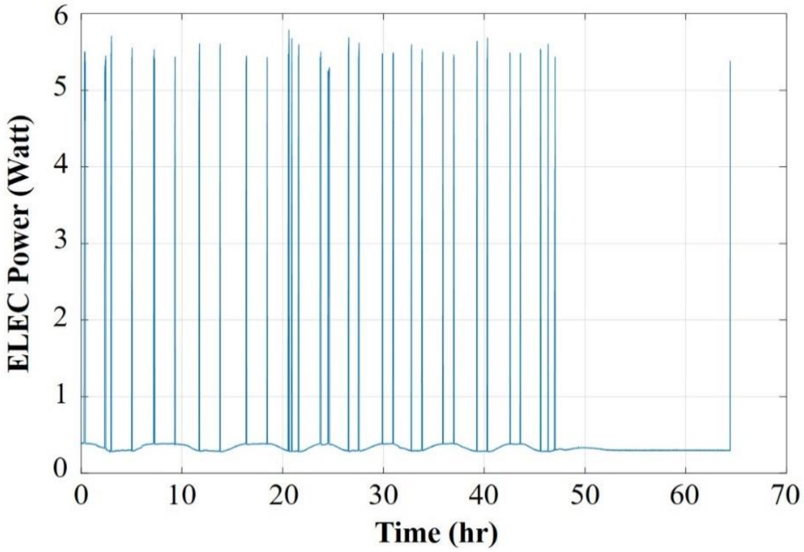

Fig. 6. ELEC Power over Time graph

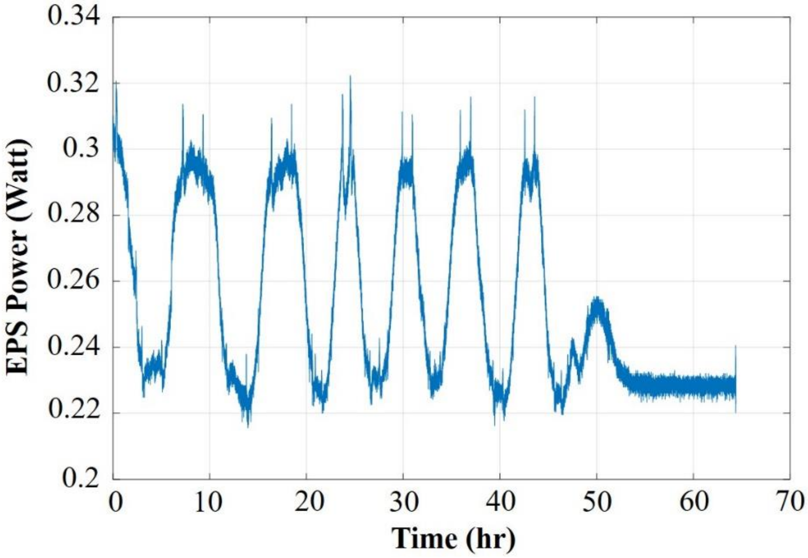

Fig. 7. EPS Power over Time graph

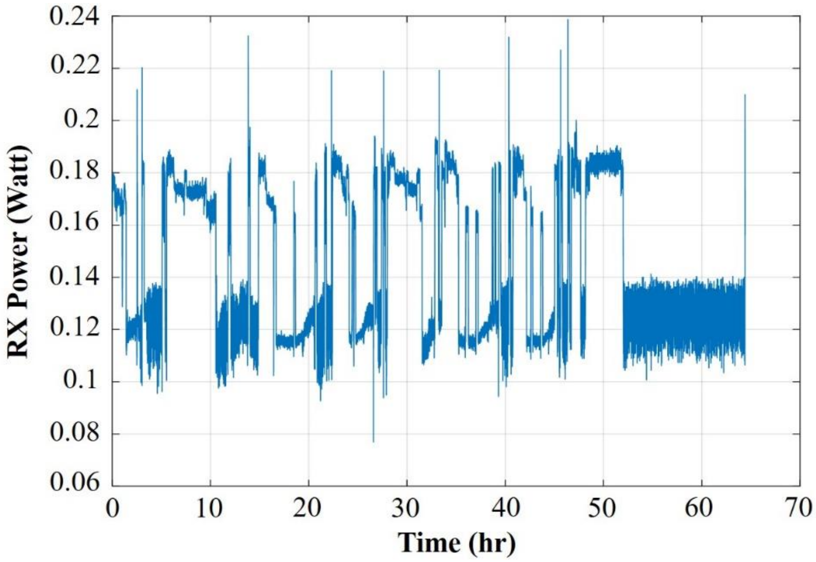

Fig. 8. RX Power over Time graph

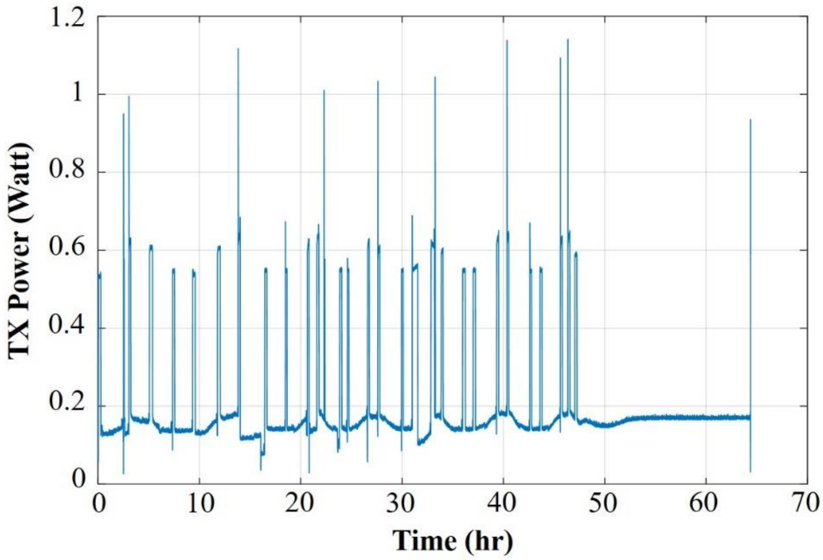

Fig. 9. TX Power over Time graph

The power consumption of all these power line, can be summed up in Table 3, and when each of the power line operates. Table 3 shows the average power consumption rate of EPS and RX line. While the ELEC and TX line have two modes, which is to standby or operates the function of their respective system.

Table 3: Thermal Vacuum Testing Power Consumption Measurement Table

Boost Converter	Stand by Power consumption (mW)	Operation Power consumption (mW)	Operating time
ELEC	326.86	5,161.06	Payload Operation
TX(CW)	153.36	583.12	CW on
RX	144.7		All time
EPS	253.4		All time

5. ENERGY BALANCE

The concept of energy balance revolves around the 1st law of thermodynamics, which states that the energy within the system cannot be created or destroyed. The system generates the energy from sunlight using solar panels and uses the energy to power the CubeSat.

$$\Delta E = E_{in} - E_{out} \tag{3}$$

However, in order to calculates the energy balance, the entire energy of the CubeSat at one point must be calculated, Table 4 represents the total energy used in each mode.

Table 4: CubeSat Power Consumption in each mode

Sub-System	Beacon Mode CW – ON (mW)	Beacon Mode CW – OFF (mW)	Downlink FM (mW)	Capturing image (mW)
RX	144.698	144.698	144.698	144.698
TX(CW)	583.117	153.360	153.360	153.360
TX(FM)	-	-	3,509.000	-
EPS	253.400	253.400	253.400	253.400
C&DH/PAY	328.859	328.859	328.859	5,161.062
Total	1,310.074	880.317	4,389.317	5,712.52

The Beacon Mode consists of turning CW on and off at an interval of 1 minute on and 3 minutes off. The graph consists of the energy gained and the energy used, as shown in Fig. 10.

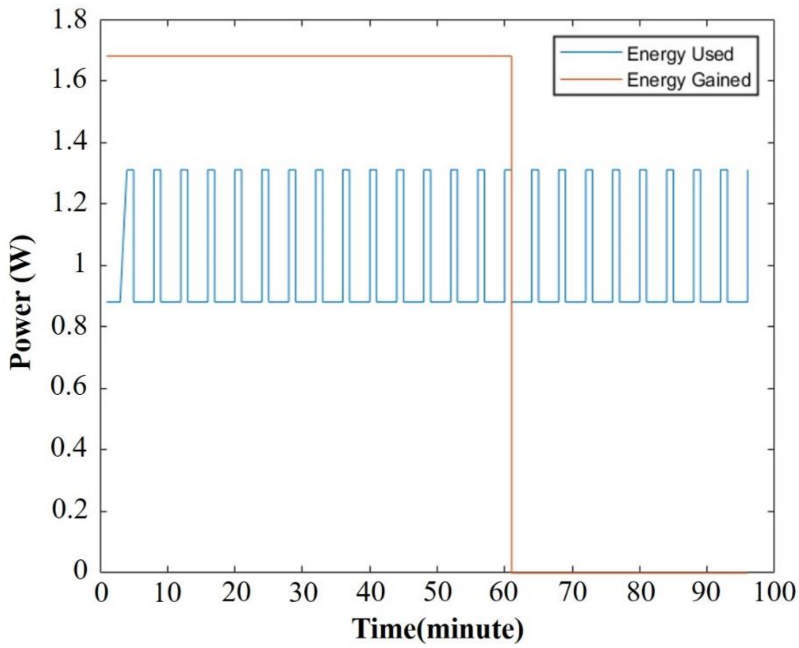

Fig. 10. Energy Gained and Used in Beacon Mode

The area under the graph can be calculated to find the energy balance. Table 5 shows the energy gained and energy used separately and summed to find the energy balance.

Table 5: Energy Gained, Used and Energy Balance per Orbit.

Energy	Energy Consumed (mWh)
Gained	+1,691.20
Used	-1,578.76
Balance	+1,12.436

The energy balance is positive, so for each time the CubeSat orbited the earth, it will generate 112.436 mWh per orbit around the earth, which at this rate can be calculated to find the time it takes for the CubeSat to operates the payload for 5minutes or downlinks for 10mininutes. The value can be seen in Table 6.

Since there are two batteries with 3350mAh and 3.7V with a depth of discharge at 15%, the CubeSat then can store up to 3718.5 mWh. Which takes a total of 33 orbits around the earth (2.2 days) in Beacon mode to fully recharged from depletion.

Table 6: Energy required to Operates Payload & Downlink

Operation	Operation Period	Energy Consumed	Orbit Frequency
Payload	5 minutes	476.04 mWh	4.2 times
Downlink	10 minutes	731.55 mWh	6.5 times

6. CONCLUSION

The BCCSAT-1 successfully provide the power to the whole system for the BCCSAT-1 missions, which is 4 cameras. The analysis of the satellite proved that the power system can theoretically generate enough energy for the CubeSat to operate in Beacon Mode, and the theoretical energy gained from each orbit around the earth gained significant enough energy to power the entire system's mission without the power system being the least effective system to function in the system, which holds of the effectiveness of the mission. The Satellite can theoretically downlink up to two time per day normally, and with the energy generated it can do so continuously, which helps the mission's ability to downlink as many images as possible.

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