LAUNCH ENVIRONMENT DATA LOGGER DESIGN AND IMPLEMENTATION FOR CUBESATS

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Abstract

Designing to the CubeSat standard has allowed many universities the ability to launch satellites missions to space. These small satellites are secondary, or even tertiary, payloads on launch vehicles. In fact, these ride-share payloads are frequently used as ballast for weight and balance of the launch vehicle and are often mounted near the engines. The environment experienced by these CubeSats is not well known. The Launch Environment Data Logger was designed to measure temperature and vibrations of the launch vehicle to better understand what kind of environment these small satellites must survive on their ride to space. Through this thesis the requirements of the Launch Environment Data Logger system are established and the initial design developed.

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Dedication

This work is dedicated to my mother. She has forever been my cheerleader telling me to reach for the stars. Ever since I was a small kid she would always let me know when Nova would be airing a show on space or on the Hubble space telescope so that I could come watch it. She has been my inspiration, showing me that you can do anything if you put your mind to it. I hope that one day I can have the same effect on others, that I can inspire others as she inspired me.

Acknowledgements

I would like to thank my team with the Alaska Space Grant Program for their continuous support. Specifically I would like to thank Jesse Frey for his wonderful mentorship and guidance to help me to understand the microcontroller hardware and software we use for our satellite. I want to thank Jordan O'Dell for his help with design, build, and testing of the Solar Panel Boards that house many of the sensors that are used for my project. I want to thank Patrick Wade and Matt Pacheco for designing the mechanical structures that the piezo electric sensors mount to. I would like to thank Logan Graves for testing of the piezo electric sensors to help get a base line of the electronics needed for the final design of the system. Last, I would like to thank my advisor Dr. Denise Thorsen for her endless support in getting me to finish my degree and supporting my graduate degree program, I wouldn't have been able to do this without her. This research was supported in part by the Alaska Space Grant Program.

Chapter 1 Introduction

1.1 Before There Were CubeSats

In the beginning, the only satellites that made it to space cost millions of dollars to create and then cost millions of dollars more to launch. This meant that only large companies that had deep pockets, or the government, were able to design, build, and launch satellites. With the primary satellite installed, typically in the nose cone of the launch vehicle, the rocket is balanced with ballast weights to ensure that it flies in the correct path. After the satellite is delivered to orbit, the rocket, including the ballast weight, returns to earth and burns up on reentry. The initial concept of CubeSats was created from the idea that instead of using dead weight that burns up; ride-share payloads could act as the ballast. The launch provider would market spots on the rocket for a price and small payloads could get a ride into space. These additional payloads became the original CubeSats, creating a beneficial relationship between the launch service provider, the primary payload, and the research group that would like to design a small satellite.

The safety of the primary satellite and the launch vehicle is the number one priority for the launch service provider. The ride-share small satellites have to follow strict rules and regulations to be manifested. Any damage to either the primary payload or the launch vehicle would reduce the chances for future missions of small payloads to acquire a ride to space. The Poly PicoSat Orbital Deployer (P-POD) was designed by University of California Polytechnic as a way to reduce the risk to the primary satellite [1]. The P-POD fully contains the ride-share small satellites; mounts the payloads to the launch vehicle; and will only launch the payloads once it is safe to do so.

The CubeSat Design Specifications Rev. 13 defines the standard which must be met by all CubeSats [1]. The CubeSat Design Specifications lists General, Structural, and Mechanical requirements which have to be met to ensure the safety of the primary satellite, launch vehicle, and other CubeSats. If any requirement is not met, strict rules apply for receiving a wavier to ensure that the violation will not adversely affect the primary mission or launch vehicle.

1.2 Poly PicoSat Orbital Deployer and CubeSats

The P-POD payloads received their name CubeSats due to their cubed shape designed to fit inside the Poly Picosat Orbital Deployer (P-POD). The CubeSat Design specifications define the size and dimensions allowable so that the CubeSat can be launched in the P-POD (Figure 1.1). CubeSats, sometimes called PicoSatellites, range in weight from 1 kg to 3 kg and in size from 1 U to 3 U. The 1 U CubeSat is approximately $(10\ cm)^3$. Each unit size larger is 1.5, 2, or 3 times the length of a 1 U CubeSat. The maximum 3 U is 10 cm x 10 cm x 30 cm and takes up the entire space in the P-POD. As the satellites are placed inside the P-POD a spring is compressed to the rear of the box and the face of the Z+ axis can be closed to contain the CubeSats.

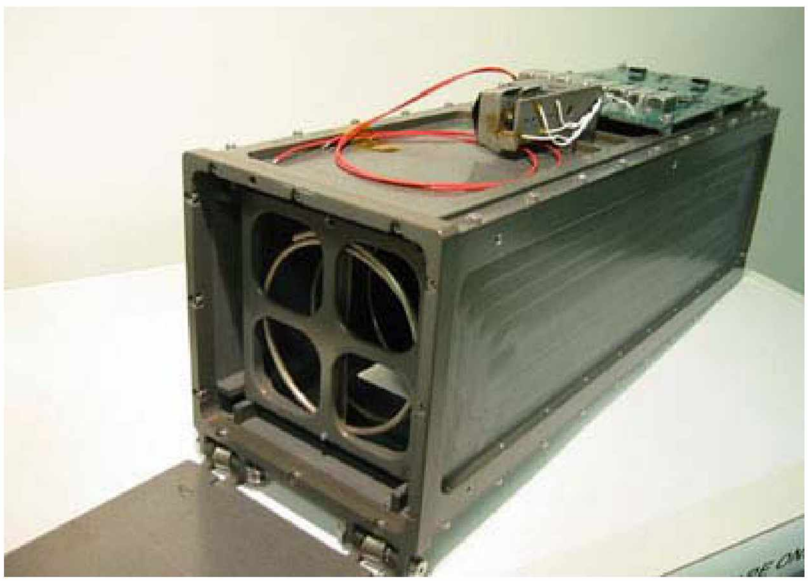


Figure 1.1: Poly-Picosat Orbital Deployer [1] .

The P-POD was designed to help keep the main payload and the launch vehicle safe during launch and orbital deployment as well as act as ballast for the launch vehicle. This means the P-POD frequently gets bolted near the engines of the launch vehicle. The difference between the CubeSats environment versus the primary payloads environment inside the launch vehicle is not well known. Current environmental data given to CubeSat designers from the CubeSat Design Specifications, references NASA's General Environmental Verification Specifications (GEVS) [2] and gives a range of expected vibration and thermal profiles. Testing to these specifications provides some confidence that the satellite will survive the ride to space and be operational when placed into orbit. However, these specifications were written for the environment of the primary payload typically located in the nose cone of the launch vehicle, not the ride-share payloads typically located by the rocket engines. The location of the CubeSats on the launch vehicle means that the launch environment that they experience could be hotter and sustain greater vibrations. As of the writing of this thesis, there have not been any successful attempts to measure the launch environment experienced by CubeSats inside the P-POD. NASA is interested in this data, as it would be valuable to anyone building a CubeSat.

1.3 Background of Alaska Research CubeSat

The University of Alaska Fairbanks (UAF) and Alaska Space Grant Program (ASGP) came together and designed a class to teach space system engineering. UAF's first satellite initial concept was started as a project in this class in the fall of 2009. The Alaska Research CubeSat (ARC) was designed as a technology demonstration mission to increase the technology readiness level of the ARC systems and to provide NASA with relevant data of the launch environment. The first satellite was named ARC1 which is shown in Figure 1.2. Its missions are to measure the environment of a launch vehicle, validate a novel low power attitude determination system and create a communication system capable of high bandwidth data transfer.

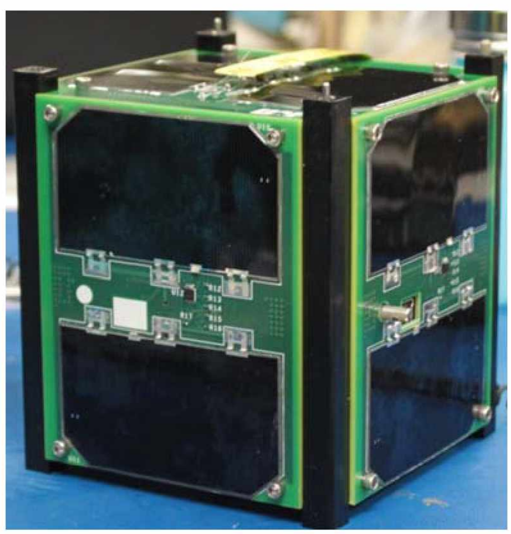


Figure 1.2: Finished satellite.

1.4 ARC1 Mission Objectives

The ARC1 project has one education objective and three scientific objectives:

Education Mission Objective 1 (EMO1): Provide authentic, interdisciplinary, hands-on student experience in science and engineering through the design, development and operation of a student small satellite mission.

Science Mission Objective 1 (SMO1): Characterize thermal and vibration environment inside the launch vehicle from ignition to orbit insertion,

Science Mission Object 2 (SMO2): Validate a novel low power Attitude Control and Determination System (ACDS), and

Science Mission Objective 3 (SMO3): Validate a high bandwidth communication system by obtaining images of changing snow/ice coverage in arctic regions.

All four missions are important to the CubeSat community from development of the next generation workforce to increasing the TRL level of CubeSat systems. SMO1 focuses on the environment that the satellite must survive within the launch vehicle and is the focus of this thesis. Understanding this environment would help the design process for all small satellites. SMO2 and SMO3 explore designs of basic systems required by any satellite and are constrained by the limited resources of small satellites such energy available from the sun. The limited power available to the satellite requires that the attitude control and communication system must optimize their capabilities.

The ARC1 missions can be summed up in the concept of operations shown in Figure 1.3. SMO1 will be validated in the ascent phase; the data logger will detect launch, turn on, verify launch and then begin to log data until the satellite is placed into orbital insertion. Once inserted, the attitude control system will turn on and detumble the satellite so that the antenna and the camera are facing Earth. After the satellite detumbles, the satellite will begin its daily operation and the system will send down its beacons every 10 seconds to verify health. When commanded from the ground station, the satellite will take photos and send down data as it passes over. When the mission is over, the satellite will be turned off by command and the satellite will deorbit and burn up on reentry.

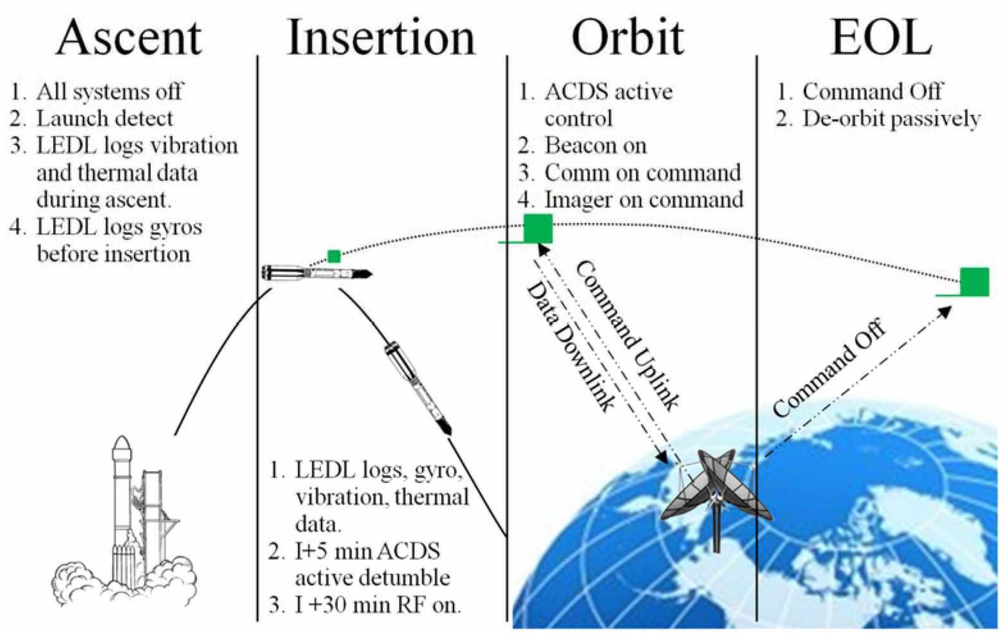


Figure 1.3: ARC1 concept of operation.

1.5 ARC1 Mission Objective 1 and the Creation of LEDL

The Launch Environment Data Logger (LEDL) was designed to meet Science Mission Objective 1 (SMO1) and will provide support functions for Science Mission 2 (SMO2). This thesis develops the requirements and initial design of the LEDL system which enables ARC1 to measure the launch environment.

Chapter 2 will discuss the nature of the mission, the LEDL system requirements and their relationship to the ARC1 mission requirements, and introduce the critical components (power management system, launch detection, sensors, and the software system) that need to be designed to meet those requirements.

Chapter 3 will examine the design of the LEDL power management system. The need for the LEDL to be operational during launch is in direct violation of the CubeSat Design Specifications and therefore requires an official waiver [1]. In order to obtain the waiver, the LEDL electrical power system (EPS) must be carefully designed to ensure the safety of the primary satellite and launch vehicle. The launch service provider ensures the safety of the primary satellite and launch vehicle by requiring that LEDL subsystem pass special electro-magnetic interference (EMI) testing.

Chapter 4 discusses the design of the launch detection system. This system must detect and verify launch has taken place without over burdening the power system.

Chapter 5 describes the sensors selection made to meet the LEDL system requirements.

Chapter 6 looks at the control modes and operation of the LEDL system. In this chapter the software state machine is developed, as is the data processing and logging protocols. This chapter discusses the software needed to operate the whole system from the beginning of its mission to end of life.

Chapter 7 examines the finished flight hardware of the LEDL system with the final selected components. This chapter ends with what could be continued with this project with a future work section.

Chapter 2 Launch Environment Data Logger

The Launch Environment Data Logger is a subsystem within the Alaska Research CubeSat Satellite. Chapter 2 defines the LEDL's subsystem requirements which flow down from the satellite's main mission requirements. The satellite requirements set the LEDL's requirements needed to accomplish the mission objective. The LEDL's requirements define the parameters that must be met in order to satisfy the need to measure the temperature and vibration during the vehicle's launch.

2.1 LEDL Overview

The Launch Environment Data Logger is the subsystem designed to meet Science Mission Objective 1 (SMO1) by measuring the vibration and temperature inside the launch vehicle from launch to orbital insertion, and to support Science Mission Objective 2 (SMO2) by taking needed telemetry to verify the satellite's attitude. These mission objectives flow down to the LEDL subsystem through two satellite mission requirements that constrain what telemetry must be acquired and the manner in which the telemetry must be acquired.

MR 011: The ARC1 System shall record the thermal and vibration environment from start of launch vehicle powered flight (T-0 seconds) through CubeSat ejection +60 seconds from P-POD. (SMO1)

MR 012: The ARC1 system shall be able to validate attitude within 5° via telemetry. (SMO2)

These satellite mission requirements establish that there needs to be a system which measures vibration and temperature from launch to orbital insertion plus 60 seconds after ejection from the P-POD. In addition, the second satellite mission objective requires the system to take telemetry data from which the satellites attitude may be determined.

LEDL's subsystem requirements are derived from the satellite mission requirements and the constraints imposed by the launch service provider. These subsystem requirements further define the four critical components of the LEDL subsystem: power system, launch detection, sensors, and the microcontroller and control modes of operation.

2.2 Power System

LEDL-001 LEDL shall request and receive a waiver from launch provider to allow active electronics during launch.

LEDL-002 LEDL shall provide its own power supply to operate during the launch phase.

LEDL-003 LEDL shall switch over to the satellite's main power supply after orbital insertion.

LEDL-004 LEDL shall be able to log launch data after remaining quiescent (on the shelf) for a maximum of 6 months prior to launch.

SMO1 requires LEDL to take data during launch. To do this the LEDL subsystem will have to be powered. Having any system powered during the launch phase is prohibited by the launch service provider. The CubeSat Design Specification [1] specifies that university payloads must be electrically inert during the vehicle's launch phase until the CubeSat is placed into orbit. Since the launch provider typically prohibits CubeSats from being electrically active during launch, the Alaska Research CubeSat (ARC1) requires a waiver to be electrically active. In order to acquire the necessary waiver the Alaska Research CubeSat must show that it is not a risk to the launch vehicle or the primary payload. The risk is minimized in part by requiring that LEDL have its own power system so that the rest of the satellite is off. The LEDL power system will need to have enough power to satisfy a 6 month waiting period, detect launch and log data for a 2 hour launch window. Once the satellite reaches orbit, LEDL will need to switch over to the main satellite power supply and discontinue using the LEDL power system.

2.3 Launch Detection

LEDL-005 LEDL shall detect initiation of launch within 120 seconds of ignition.

LEDL-006 LEDL shall verify that it has received positive launch detection.

Since the satellite is expected to sit on the launch pad for six months, LEDL will have to be able to identify when launch is happening. If the LEDL cannot determine when launch has happened it will not be able to log the data. To ensure that LEDL will begin logging data, LEDL will be required to detect launch within 120 seconds of ignition. With launch detected, LEDL must verify that there is actually a launch. This is to avoid false launch detections or accidental engagements so that LEDL will only record the environment during an actual launch. At confirmation of a positive launch LEDL will begin logging the sensor data.

2.4 Sensors

LEDL-007 The LEDL system shall operate and record acceleration in 3 mutual orthogonal axes in the measurable frequency range of 20-2,000 Hz during launch. A minimum data acquisition sample rate of 4,000 Hz, minimum 8-bit resolution with having a measurement in the range of ±14 G and the second set having a usable range of ±70 G. (SMO1)

LEDL-008 The LEDL shall operate and record thermal measurement in a manner that captures the flight thermal environments to the best practical extent. LEDL will operate and record temperature in a range -40 to +105 C with a minimum sample rate of 1 Hz.

LEDL-009 LEDL shall store all data collected during launch for later use.

LEDL-010 The LEDL system shall provide sensor data to other ARC1 systems after orbit insertion for mission support

The sensors utilized on the Launch Environment Data Logger are needed to meet Science Mission Objective 1 and to help with Science Mission Objective 2. The General Environmental Verification Standard (GEVS) provides expected vibration data for spacecraft under 50 kg [2]. Section 2.4.2.3 of GEVS states that the expected frequency range to test the satellite is from 20-2000 Hz and Table 2.4.4 from GEVS shows that the maximum acceptance level for acceleration is 10 G_{rms} for qualification testing. Therefore LEDL must be able to measure at least 10 G_{rms}. For sinusoidal forcing this would require that LEDL be able to measure a peak acceleration of approximately 14 G The maximum frequency expected for the launch vehicle is 2000 Hz; so based on Nyquist frequency theorem, the data will have to be sampled at least 4000 Hz to prevent aliasing. In addition, data needs to be taken at a high enough resolution to allow useful data to be analyzed. The specific accelerometer chosen can measure up to 18 G with a 12-bit resolution ADC gives 0.009 G resolution. In addition a 70 G accelerometer was included to measure shocks that might be in excess of 18 G. The resolution of the 70 G accelerometer given a 12-bit ADC is 0.034 G.

As part of the LEDL system determining the launch vehicle's temperature is its second priority after measuring the acceleration. Current NASA metals with Teflon coating experience touch temperature of 120 C to -129 C in space, but the actual temperature range measured by commercial sensors will be more limited by the components themselves. Most commercial off-the-shelf electronic components tend to have upper and lower bonds of +105 C to -40 C. A temperature sensor that can at least measure within these bounds will be needed.

With LEDL being the only system active during launch; LEDL will have to store all data for a later transmission. The amount of data that will be stored for a 2-hour launch window is mostly dependent on the rate the acceleration data needs to be logged; at least 4000 samples per second. The memory used will have to be large enough to store all data from the initiation of launch to orbital insertion.

LEDL will also perform any sensor readings necessary for other systems located on the satellite to support SMO2. Since the LEDL system will be connected to many boards on the satellite, it serves as a mission support for the needs of other systems within the satellite.

2.5 Microcontroller and Control Modes of Operation

LEDL-011 LEDL will maintain data in a format for easy transmission though the communication system.

LEDL-012 LEDL shall attach a time stamp every second during vehicle accent to keep track of sensor data.

LEDL-013 LEDL will maintain satellite health packets for beacon data during orbit.

All data that is stored on the LEDL system has to be downlinked to the ground station at a later time after the satellite has made it into orbit. To understand the data, the data will have to be in a known format to allow for analysis of the launch. The data will have to be formatted for easy transmission and for storage (LEDL-009). To make things easier for software development, these will be the same format. To analyze the data, the time of the sensor readings is required to separate out the events. A time stamp will be utilized to associate data with periods of time during a launch. Once the satellite is in orbit and the LEDL will begin its secondary functions to support Science Mission Objective 2, LEDL will gather all data during orbit passes and create heath packets to let the ground station know of the system's current status.

2.6 General System Hardware and Operation of System

The Science Mission Objectives are met by the LEDL requirements which outline the hardware and software necessary for the LEDL subsystem to succeed in its mission. The hardware and software become the main critical components that make up the LEDL subsystem. The entire LEDL subsystem can be summarized in the following block diagram (see Figure 2.1). The red blocks, indicate power devices, the blue blocks indicate any hardware, the microcontroller is the light blue box in the middle, the green blocks are the peripheral ports of the microcontroller and the yellow blocks are the software code blocks that need to be written. The arrows indicate communication and power which comes from the satellite bus, the red lines indicate power paths, the blue lines are hardware data paths, and the green are command/data paths.

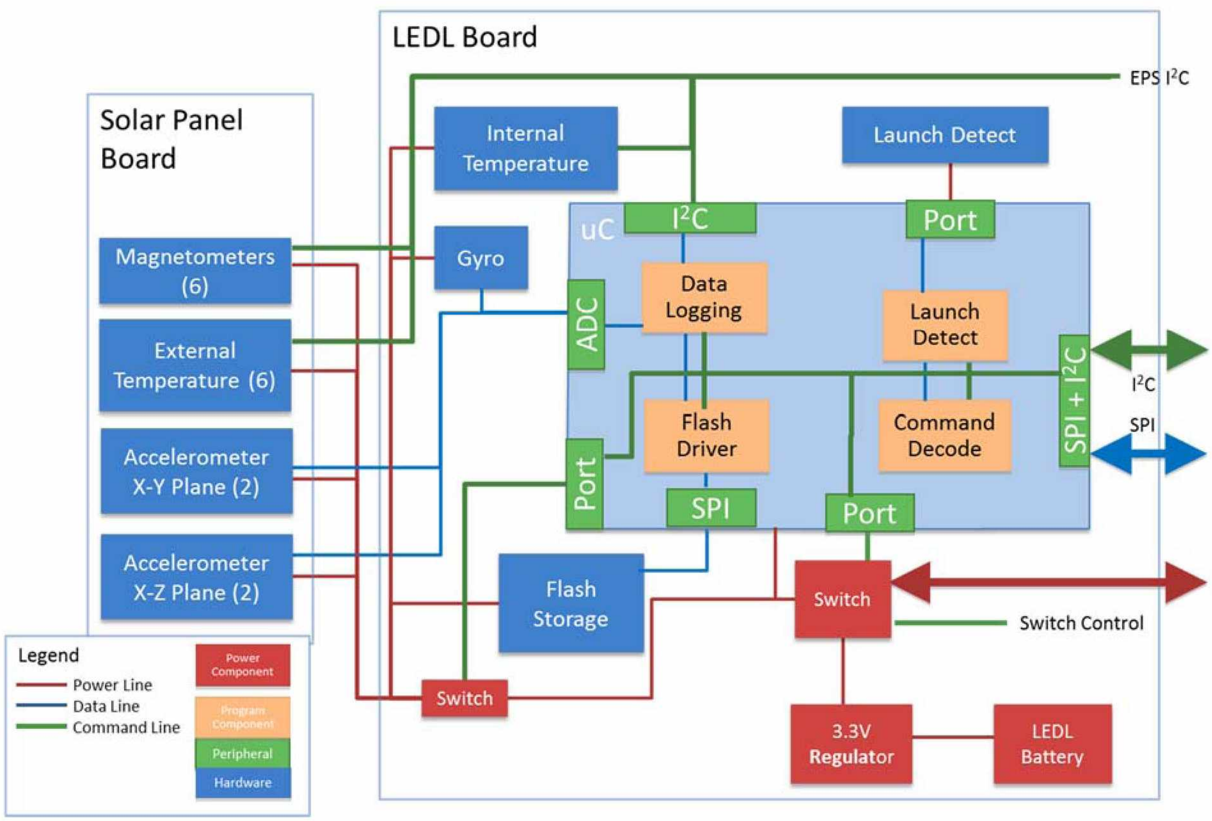


Figure 2.1: Basic LEDL block diagram.

The satellite as a whole is designed to be modular. Every subsystem uses the same microcontroller and the same memory. This allows for rapid prototyping and testing to determine the feasibility of the design. The microcontroller used in ARC1 is the MSP430F2618 [3]. The memory used for each subsystem is a 4 GB microSD card.

The four main critical components of the LEDL subsystem are the power system, the launch detect, the sensors, and the microcontroller and control modes of operation. The internal power system includes a switch to allow the system to change power supplies once in orbit. The launch detect sensor informs the microcontroller when launch has been detected and the microcontroller can respond accordingly. The sensors measure the acceleration and the temperature inside the launch vehicle and the mission support sensors are located externally on the solar panel boards as well as on the LEDL board. The last critical component, the operation of the system is within the microcontroller. The control modes of operations are software based which is represented by the user code block within the microcontroller. The following chapters will discuss the development of each critical component specified in the block diagram in which each section went through its own design process to become finished hardware.

Chapter 3 Critical Component – Power System Design

This chapter addresses the first critical component of the Launch Environment Data Logger (LEDL): the power distribution and management system. LEDL-002 specifies that LEDL will utilize its own power supply during launch while the rest of the satellite is off. In this chapter a strawman power analysis is performed to constrain the choices for the power system critical components.

3.1 Requirement Overview

The first consideration is that LEDL has to be operational during launch, which violates CubeSat Electrical Requirement 3.3.1 that all CubeSats have to be off during the launch. The requirement specifies that zero current can be flowing and the batteries are physically disconnected from the power bus to remove any possibility current [1]. Since the LEDL subsystem violates a CubeSat requirement, the ARC1 satellite requires a waiver for the subsystem to be on (LEDL-001). This waiver will allow the LEDL to be connected to a power supply and allow the system to be operational during the launch. When the satellite is integrated into the P-POD on the launch vehicle, the main electrical power system (EPS) batteries are physically disconnected, which removes power from the bus. With no satellite power on the bus, the LEDL subsystem must have its own power supply to be operation during launch (LEDL-002).

When the satellite is handed off to be integrated into the P-POD, the satellite is no longer accessible. The LEDL subsystem's lifetime from when it is handed off to be integrated has to be incorporated into the timeline of the power supply. The average time from satellite integration to launch is approximately 6 months. Once the satellite is handed off, the system will need to have enough energy to sit on a shelf for 6 months, go through integration, and still have enough energy to complete the mission (LEDL-003). When the satellite reaches orbit, the satellite will be ejected from the P-POD and the satellite's main power supply will connect to the satellite bus. At this time the LEDL subsystem will need to switch over to the satellite bus. If LEDL does not successfully switch over eventually it will no longer be able to read from the sensors in support of mission operations. Additionally, if the satellite malfunctions and has to have a hard reset, LEDL will not cycle with the rest of the satellite (LEDL-004).

To summarize the requirements, the subsystem must have a waiver to be active, it must be able to sit on the shelf for 6 months, it must have its own power supply and it must be able to switch over to the main power supply. The implementation of these requirements is now the question. The process to get a waiver was coordinated through the launch service provider. To retrieve the waiver the LEDL subsystem is required to pass a special electro-magnetic interference (EMI) testing to make sure that the LEDL does not radiate energy in certain frequency bands. The rest of the requirements provide design parameters. These parameters led to different trade studies that will be expanded upon next. The trade studies led to considerations about how much energy is needed to support the mission, how to switch over from the internal power system to the satellite power system, what are the best batteries to use in the design and what voltage regulator to use. The power analysis also provided constraints on the maximum current draw for the sensors.

3.2 System Power Analysis

One of the first considerations with the power system is how much energy is needed to satisfy the subsystem requirements. When thinking about how much energy the LEDL subsystem needs, the full lifetime of the satellite has to be considered. The full lifetime includes in-house vibration verification, handing off to integration, sitting on a shelf for six months, rocket integration, detection of launch, logging of launch data, and then switching over the power supply. Each stage of the lifetime impacts the design and the power usage for the LEDL subsystem and each one will be discussed in detail.

Before the satellite can be delivered to the launch service provider, the satellite has to go through in-house vibration testing to verify that the satellite does not come apart and create loose debris while in the launch vehicle. After the satellite goes though the vibration testing, the hardware is not allowed to be changed and the design is fixed. Therefore the batteries placed on the LEDL board before testing begins will be the final batteries upon delivery. When the satellite is handed off for integration, the satellite will undergo a second set of vibration testing to again verify that the stack of satellites within the P-POD will not create any debris in the launch vehicle. During vibration testing for both in-house and integration it is assumed that the system will wake up from a low power mode to determine if this vibration is caused by launch. After determining that launch is not happening it will shut back down and resume its lower power mode. After 6 months of waiting the LEDL subsystem will experience launch. The LEDL subsystem will wake up, evaluate that there is launch, and complete its mission by logging the data from the beginning of launch to the satellite's orbital insertion.

3.3 Strawman Energy Analysis

The necessary energy needed for the lifetime of the LEDL subsystem, and therefore the required battery capacity, can be calculated through the energy equation. Energy is defined by Equation 3.1

$$E = P \times T, \tag{3.1}$$

where E is energy, P is power and T is time. LEDL's electronics are represented by the power parameter. The microcontroller, the microSD card, and any other electronics chosen use a finite amount of power while in operation. The lifetime of the LEDL subsystem is the time component to the energy equation. The total energy (E) used by the system is based upon different modes of operation of the LEDL subsystem. LEDL has three distinct modes of energy use over its lifetime, (i) energy consumed during low power mode operation while waiting for launch E_1, (ii) energy consumed while detecting launch E2, and (iii) energy consumed during launch E_3.

$$E = E_1 + E_2 + E_3 \tag{3.2}$$

In Equation 3.2, the energy E_1 represents the energy used while sitting on a shelf for 6 months when the system's microcontroller is assumed to be in a low power mode and everything that can be shutdown is turned off. When the LEDL subsystem is detecting launch, during vibration testing and for launch detection, the energy used E_2 will be dependent on how long the vibrational tests last and the launch detection time. During this time period the subsystem will be in a semi-active mode, where only the microcontroller and the accelerometers will be on, while the system tries to determine if there is launch. The amount of time the LEDL subsystem spends detecting launch is an unknown that has to be accounted for. In-house vibration testing takes 5 min per axis. Total handling time of the satellite is about 2 hours. Assuming that the integration vibration is similar, a 4 hour time allowance is given for vibrational testing. This leaves an unknown amount of time allowed for launch detect. To give a safe time frame, a margin of 4 will be assumed in the time given for launch detect. While in data logging mode, E_3, the subsystem will assume a 2 hour time window (actual launch was at 5:49 am, CubeSats deployed at 9:00 am, 3+ hour time window) to measure data. During launch the microcontroller will be in a full active mode, all launch sensors will be active, and the SD card will be on continuously. The only other unknown to be considered is the efficiency losses of the power regulation circuit and current consumption from other components like the sensors.

Table 3.1: Current consumption and efficiency of electronics.

Electronics	**Low Power Mode (E_1)**	**Launch Detect (E_2)**	**Data Logging (E_3)**
MSP (I_M)	5 uA	9 mA	9 mA
SD card (I_S)	off	off	100 mA
Regulator Efficiency (η)	50-90%	50-90%	50-90%
Electronics estimate allotted for load (I_L)	off	10-50 mA	10-50 mA

Table 3.1shows the current consumption for different electronics chosen for the system. The different electronics listed are the microcontroller, the SD card, the expected range of the regulator's efficiency, and extra electronics estimated additional current. The MSP uses only 5 uA in low power mode and uses 9 mA in active mode. The SD card is only on while in the Data Logging mode and it uses 100 mA. The additional electronics associated with the sensors are only assumed to be on while in Launch Detect Mode and in Data Logging mode, in these modes the amount of current expected is varied from 10 to 50 mA. Last, the efficiency is varied from 50% to 90%. Using the data from Table 3.1, the total energy needed for the system under different assumptions can be investigated. The equation to determine the total energy used can be seen in Equation 3.3,

$$E = \frac{1}{\eta}((T_w - T_{ld}) \times \ I_{M_l} + T_{ld} \times \left(I_{M_a} + I_L\right) + T_l \times \left(I_{M_a} + I_L + I_S\right)), \qquad (3.3)$$

where E is the total storage energy of the battery in Amp-hour (Ah), η is the voltage regulator efficiency, T_w is the 6 month launch wait time, T_{ld} is the time spent in launch detect mode, T_L is the time spent during launch in active data collection mode, I_{ML} and I_{MA} are the microcontroller current draw in low power and active modes, I_{IL} is the current draw of any electronic load (i.e. sensors), and I_S is the current draw of the SD card.

Even though energy is defined as Power x Time, and Power is Voltage x Current, the energy being analyzed is in Ah. Ah is a common energy unit when looking at the energy for a system using batteries, as most energy rating for batteries are marketed as Ah for the unit.

Figure 3.1 shows the needed energy for different efficiency regulators and for different currents over the span of 15 hours of testing the satellite and a 2 hour launch window, as well as looking at different values of the expected extra electronics currents, in order it shows 10 mA, 25 mA, and 50 mA of current.

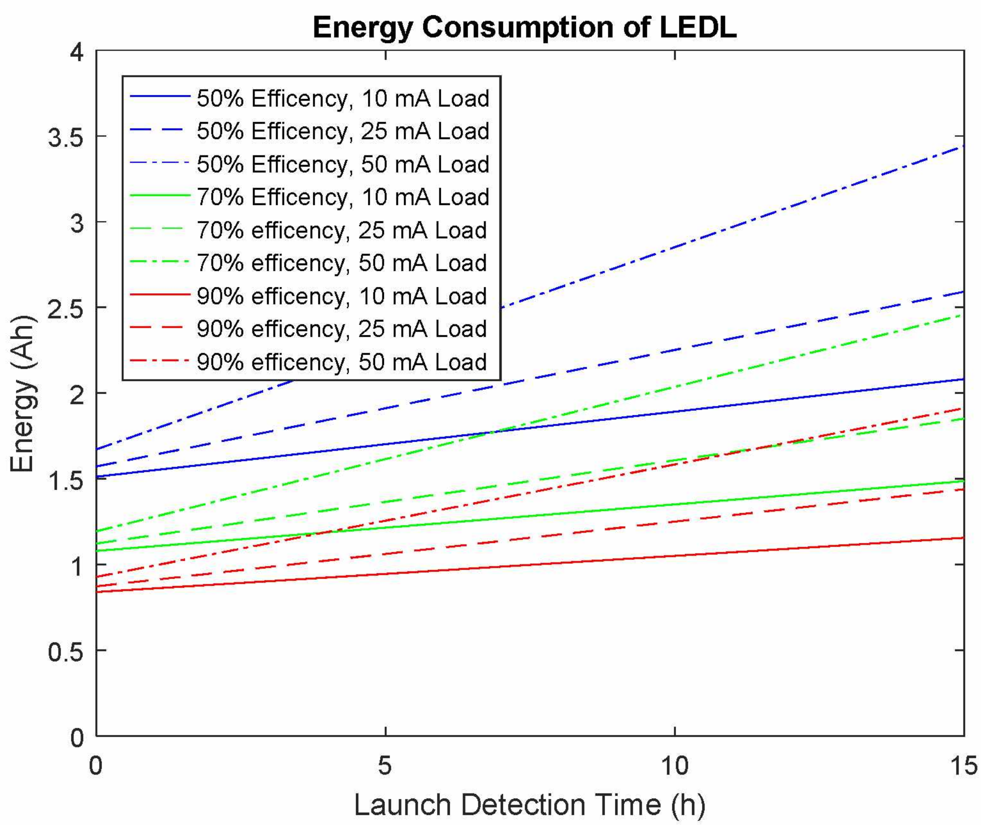


Figure 3.1: Estimated power budget for the Launch Environment Data Logger.

The analysis assumes a constant efficiency for the lifetime of the battery used for this system. The worst case scenario pushes the energy consumption to over 3.5 Ah, and the best case scenario is around 1 Ah. This analysis shows that the system could be expected to use anywhere from 1 Ah to 3.5 Ah depending on the design choices for regulation efficiency and the current consumed from sensors. The minimum required battery capacity is therefore between 1Ah and

3.5 Ah depending of other design choices. Alternatively, if the available battery capacity is 1.5 Ah, then the regulator efficiency would need to be greater than 50%. As a note, for actual operation the efficiency of the regulator will not be a fixed constant. The efficiency of the voltage regulator will change based on the difference from the input (battery) voltage and the output voltage. The efficiency changes over time as the energy is consumed from the battery. Also the current delivered from the battery will also effect the lifetime of the battery [4]. This analysis provides guidance for evaluating and selecting the LEDL power system components.

3.3.1 Batteries

LEDL-002 specifies that the LEDL subsystem has to have its own power supply for launch detection and data logging. The LEDL subsystem, based on estimated current calculations, has to be able to supply a fair amount of energy. The space available for batteries is constrained by the size of the satellite. The height allotted for batteries is only 12 mm, which limits the battery size to AAA batteries. When choosing an AAA battery there are two options, chargeable and non-chargeable (single use batteries), Table 3.2 shows a comparison of the two types of batteries. The first shown is a rechargeable AAA Energizer Nickel-Metal Hydride (NiMH) [5] batteries, which has 850 mAh of battery capacity, and the second is a non-rechargeable Duracell Quantum [6] which has 1500 mAh capacity. The single use batteries have a higher energy capacity for their size. Additionally, the launch service provider does not provide access to the satellite after it has been integrated onto the launch vehicle making the rechargeable option unavailable. Based on these two facts, the single use battery is a better choice to make for the LEDL system.

Table 3.2: Comparison of rechargeable verses single use batteries.

	Energizer Nickel-Metal Hydride (NiMH) [5]	**Duracell Quantum** [6]
Power Capacity	850 mAh	1500 mAh
Rechargeable/Single Use	Rechargeable	Single Use

Typical AAA batteries are 1.5 V, and the LEDL subsystem electronics are expected to be powered with a 3.3 V rail. The voltage will have to be regulated using a boost regulator. Additionally the constant current chart for the Quantum battery in Figure 3.2 shows that the battery's voltage varies for different current loads and service hours. Based on the figure, the batteries are not guaranteed to operate after the voltage on the cell reaches 0.8 V. The current draw profile shows that the battery is capable of providing the needed 100 mA current for the SD card for a maximum of 10 hours. At different current draw rates the batteries have different service hours. At a large current load at 500 mA the battery only lasts only 1 hour and gives 500 mAh. At low loads at 50 mA the battery is expected to last 23 hours giving 1150 mAh. For most of the time the current draw from the battery is expected to be approximately 50 uA. Although not shown in Figure 3.2, it is hoped that the battery capacity at 50 uA is closer to the 1500 mAh rating of the battery.

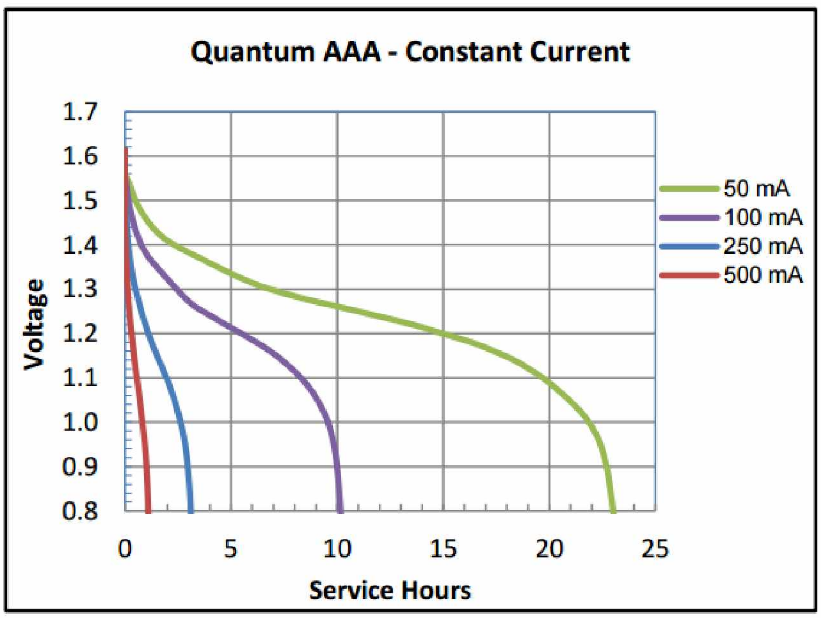


Figure 3.2: Constant current draw from Duracell Quantum AAA battery [6].

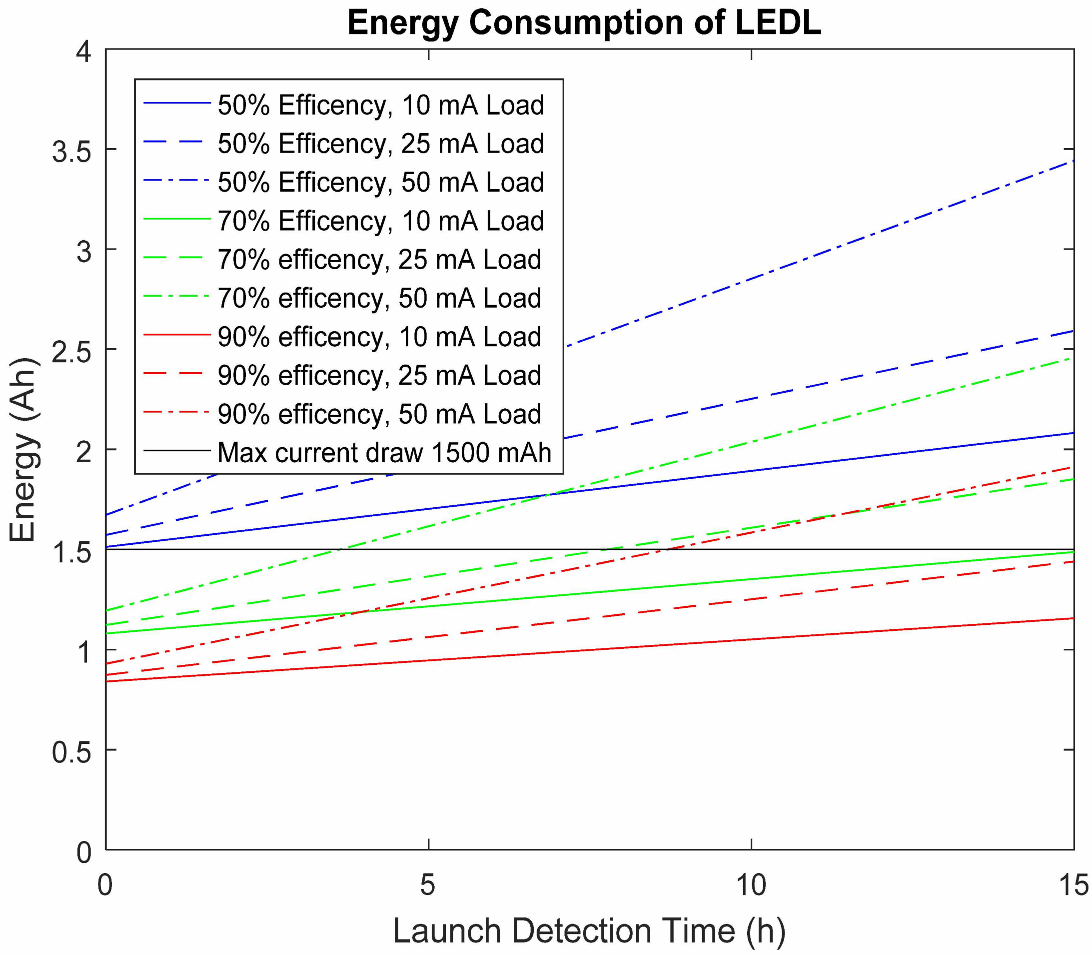


Figure 3.3: Maximum energy budget with projected energy usage for LEDL.

The maximum energy capacity for the LEDL system shown is expected to be about 1500 mAh. This shows that the power system will have to aim for a 90% efficient regulator to be able to make the time margin for the launch detect.

3.3.2 Voltage Regulator

In deciding what voltage regulator to use the three main requirements are to be operational with the battery discharged to 0.8 V, provide between 0-100 mA, and have a high efficiency. As mentioned in the previous section, a boost voltage regulator is required to increase the input voltage from the battery to the desired output voltage to 3.3 V. There are several alternatives on how to configure the batteries and voltage regulator. The first alternative is to use a single battery and require the regulator to boost the voltage from 1.5 V to 3.3 V.

Using a single battery would save space on the LEDL board. The second alternative is to use two batteries in parallel. The voltage regulator would still be required to boost the voltage from 1.5 V to 3.3 V, however this would double the lifetime of the batteries providing 3000 Ah instead of 1500 Ah. The third alternative is to place two batteries in series. The voltage regulator would only have to boost the voltage from 3.0 V to 3.3 V, the batteries would still only supply 1500 Ah.

A trade study was performed comparing three voltage regulators that provide 3.3 V output voltage. The TPS60310 [7] from Texas Instruments, the TPS63001 [8] from Texas Instruments, and the LTC1610 [9] from Linear Technologies, provide the required 3.3 V output, and have efficiencies between 50% - 90% (see Table 3.3).

Table 3.3: Comparison of different voltage regulators.

Regulator	**TPS60310 [7]**	**TPS63001 [8]**	**LTC1610 [9]**
Company	Texas Instruments	Texas Instruments	Linear Technologies
Voltage Output	3.3 V	3.3 V	3.3 V
Voltage Boost Capability	0.9 V – 1.8 V	2.4 V-4.2 V	1.5 V-3 V
Quiescent Current Consumption	2 uA	0.1 uA	0.01 uA
Efficiency	55-80%	65%-80%	65%-84%
Current Output Range	0-50 mA	0-1000 mA	0-120 mA

3.3.2.1 TPS60310 Voltage Regulator

The TPS60310 provides regulated output of 3.3 V given an input voltage from 0.9 V to1.8 V. The device has decent efficiency as seen from its plot in its datasheet [7]. Figure 3.4 shows that for a low power mode, the regulator can be placed into a sleep like mode that will increase the efficiency of the regulator for smaller current. When the system is drawing small currents the efficiency shows about 50%, and for higher currents the device is above 80% efficient. This choice would only require 1 battery and allow for necessary voltage regulation.

Figure 3.3 shows the current cutting off at 50 mA, which implies that this regulator might not be the best choice due to the uncertainty of how the regulator would perform under the high currents expected when writing to the SD card.

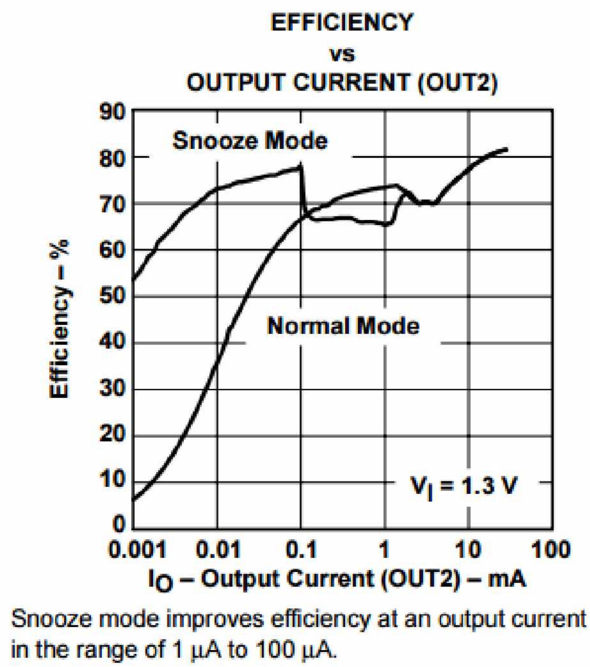


Figure 3.4: Efficiency of regulator TPS60310 [7].

3.3.2.2 TPS63001 Voltage Regulator

A second option for consideration is a buck boost TPS63001 also from Texas Instruments. For small currents the regulator is around 65% and for larger currents 120-150 mA the efficiency goes up to around 80%. One consideration to make here is that the input voltage is specified for 2.4 V-4.2 V. This would imply that the system will need two batteries in series to get the input voltage up to 3 V. A note of concern for this regulator is at the end of the battery life the total voltage is $2 \times 0.8 = 1.6$ V. The voltage regulator may not be able to utilize the energy from the battery between 2.4 V to 1.6 V. Based on the battery's constant current draw Figure 3.2 the lifetime of the battery would be dropped from 10 hours to 5 hours, effectively making this battery a 750 mAh battery.

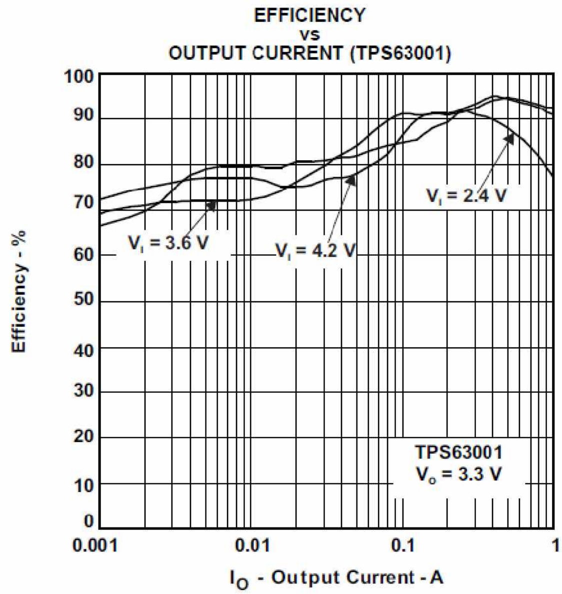


Figure 3.5: Regulator efficiency for TPS63001 [8].

3.3.2.3 LTC1610 Voltage Regulator

The last regulator looked at was an option from Linear Technologies LTC1610. Figure 3.6 shows that this voltage regulator has 60% efficiency for low currents and 80-85% for currents between 100-120 mA. In addition, the system could utilize one or two batteries by operating over a wider range of voltages. The minimum voltage that is represented by the graph is 1.5 V, and the lowest operating voltage specified by the batteries is 0.8 V. If the system uses two cells in series, the lowest voltage expected is 1.6 V. The voltage regulator will work with two cells in series. One flaw in this regulator is that the efficiency for the higher currents is not as good as the Texas Instruments TPS63001. This regulator is about 8-10% less efficient, but the regulator is guaranteed to work over all possible voltage ranges of the battery. The efficiency plot shown in Figure 3.6, shows this regulator has poor efficiency at low currents. However, this regulator can be turned off and will pass the battery raw voltage if desired. This increases the usability of the regulator.

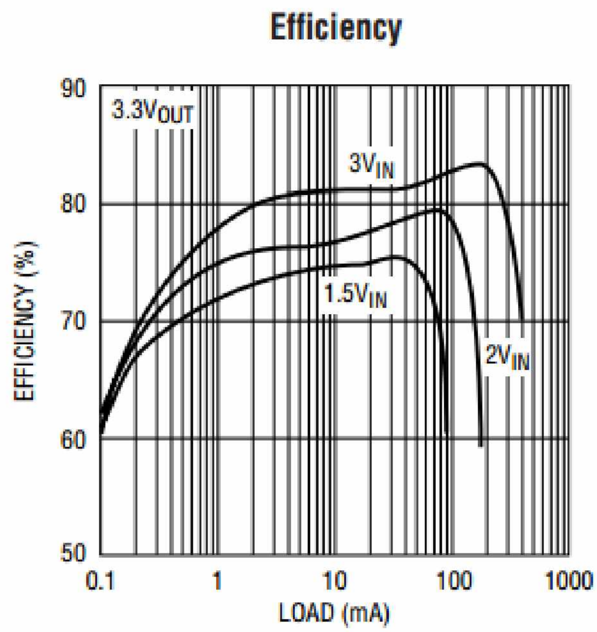


Figure 3.6: Efficiency of regulator LTC1610 [9].

As seen in Figure 3.6, the efficiency of the regulator is affected by the input voltage of the battery. As the battery is drained the battery voltage will drop. At the end of the battery lifetime the voltage regulator efficiency drops to 75%.

3.3.2.4 Regulator Decision with Power Analysis

The Texas Instruments TPS60310 satisfied the minimum power efficiency and could operate from a very low voltage, but was unreliable at high current draws. The Texas Instruments TPS63001 required two cells to operate and had a decent efficiency, but when the voltage drops below 2.4 V, the output was uncertain. The last regulator LTC1610 also utilizes two cells and can supply the necessary current. The efficiency for this regulator is not the best out of the three choices, but it can be shut off and not used at low currents where the efficiency is poorest.

Two analyses were done on the regulator, one leaving the regulator turned on for the entire time LEDL is on, and one with the regulator turned off while the LEDL is in a low power mode. The first analysis of this regulator has two efficiencies to consider, at low currents in low power mode the efficiency is 60% and for active mode during launch detect and launch the efficiency is 85%. This analysis was done to look at the expected energy utilized by the system with this regulator. The modified equation to represent the two efficiencies is shown in Equation 3.4, the only difference is the breaking up the equation with two efficiency components. η_1 as 60% and η_2 as 85%, the result of this analysis is shown in Figure 3.7.

$$E = \frac{1}{\eta_1}((T_w - T_{ld}) \times I_{M_l}) + \frac{1}{\eta_2}(T_{ld} \times (I_{M_l} + I_L) + T_l \times (I_{M_a} + I_L + I_S)) \qquad (3.4)$$

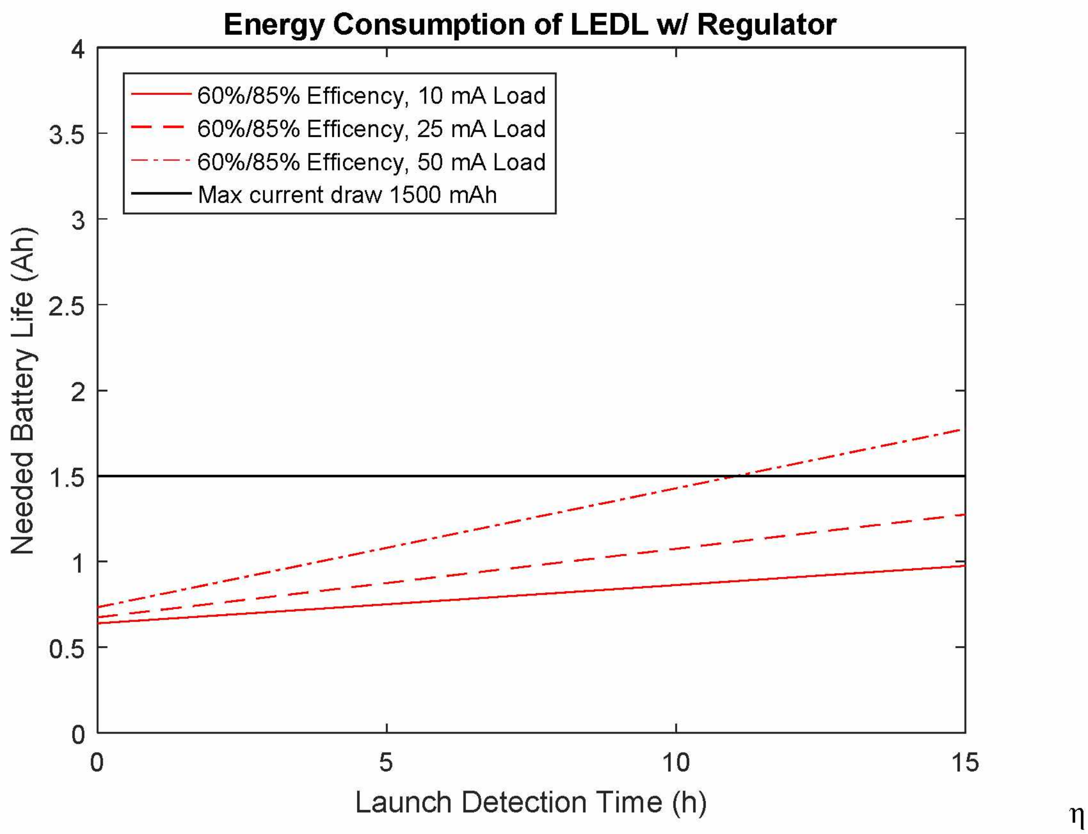


Figure 3.7: Battery life versus launch detection time.

In this analysis, the LEDL can support maximum of 35 mA of electronics if the system is to meet the requirement for 15 hours of testing time. Otherwise LEDL can operate with 50 mA of extra electronics and only get approximately 10 hours of testing time.

The microcontroller can operate from 1.8 V to 3.3 V. When the microcontroller is in low power mode the regulator can be turned off and the microcontroller can be powered from the raw battery voltage. If we re-analyze the current consumption without the efficiency while in low power mode and only have the 85% efficiency in the active mode a new analysis of the energy consumption of the system can be done. The new power equation is shown in Equation 3.5 with η_2 85%.

$$E = (T_w - T_{ld}) \times I_{M_l} + \frac{1}{\eta_2}(T_{ld} \times (I_{M_l} + I_L) + T_l \times (I_{M_a} + I_L + I_S)) \qquad 3.5$$

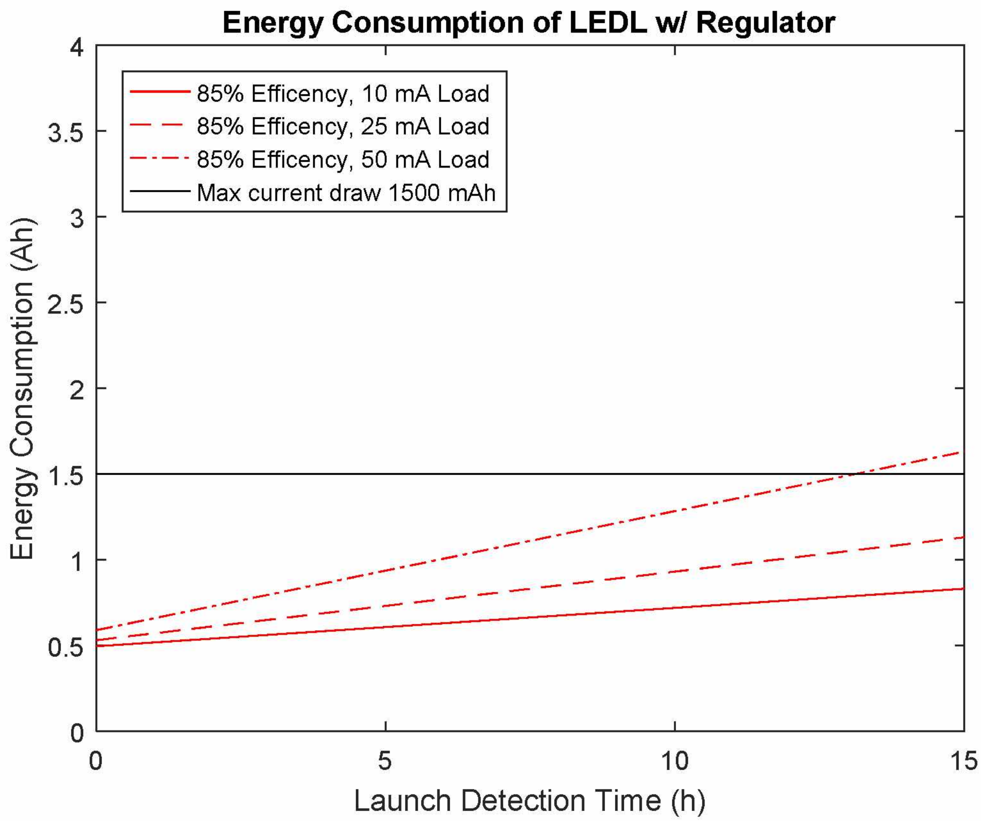


Figure 3.8: Battery life versus launch detection with regulator in sleep mode.

By taking into account that this regulator can be shut off, the system can save some power and can support a maximum of 50 mA load of electronics for up to 13 hours of testing time. By being able to shut off the regulator the system can get additional qualification testing time at the higher extra electronics. This regulator will be the choice for the Launch Environment Data Logger, it meets all the needs for the power system, it has 85% efficiency, can utilize two batteries in series, operate at the lowest battery voltage, and source the current needed during the data acquisition time. This analysis does not take into account the change in the batteries voltage as it affects the regulators efficiency, the efficiency is assumed to be held constant the lifetime of the battery.

3.3.3 Switch

The LEDL subsystem requires a switch to control where LEDL receives power. Prior to orbital insertion, LEDL is powered by its own power system. During this time the switch isolates LEDL from the rest of the satellite so that only LEDL is on. After orbital insertion, LEDL is powered by the satellite power system. At the time of orbital insertion the switch needs to disconnect the LEDL power system and connect LEDL to the main satellite power system. Two commercial switches were evaluated (see Table 3.4).

Table 3.4: Switch trade study.

Switch Name	**TPS2115A [10]**	**LTC4412 [11]**
Manufacture	Texas Instrument	Linear Technologies
Current Consumption	55 uA	29 uA

3.3.3.1 Switch TPS2115A

The TPS2115A from Texas Instrument [10] is an auto-switching power multiplexer which allows seamless transition between two power supplies. The power switch can be programed to either automatically switch to the higher power source, or manually change the source with the LEDL microcontroller. This switch utilizes a maximum current of 55 uA to operate. Equation 3.6 has been modified to include the constant current draw of the switch I_{Sw}.

$$E = (T_w - T_{ld}) \times I_{M_l} + I_{Sw}) + \frac{1}{\eta_2}(T_{ld} \times (I_{M_l} + I_L + I_{Sw}) + T_l \times (I_{M_a} + I_L + I_S + I_{Sw})) \quad (3.6)$$

Figure 3.9 shows the energy consumption of the LEDL with the previously defined regulator and the TPS2115A switch. What is immediately evident is that the 55 uA quiescent current over the month period utilizes more energy than the energy capacity of the selected battery (1500 mAh).

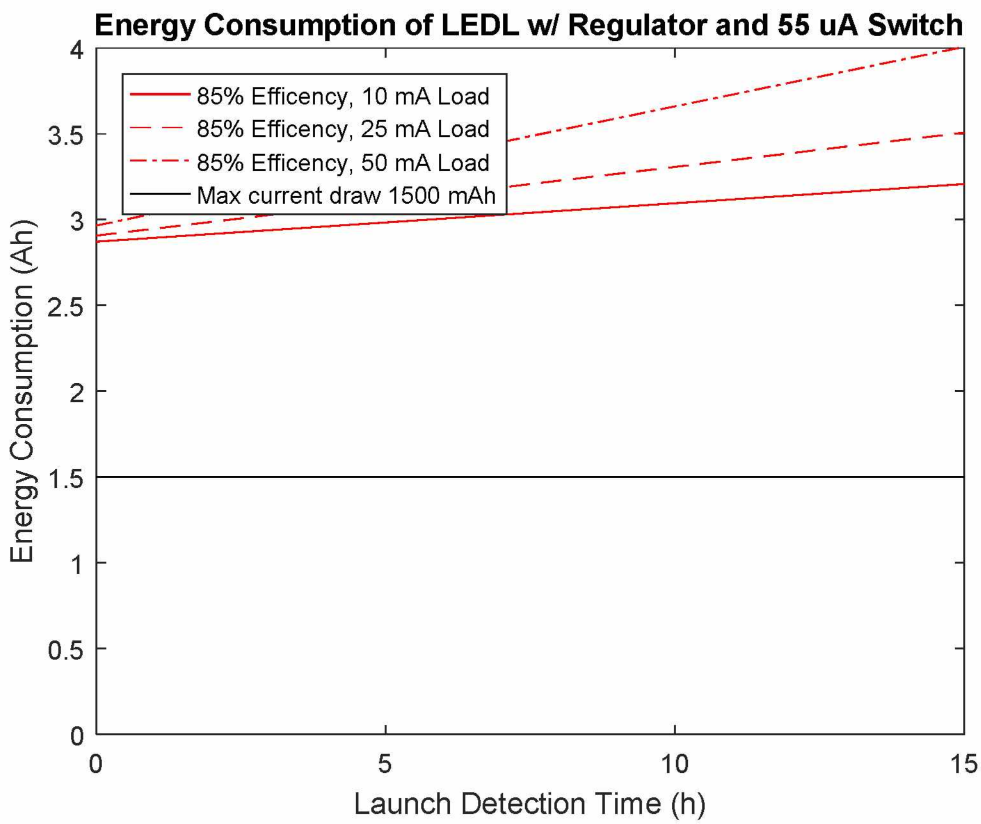


Figure 3.9: Battery life versus launch detection time with 55 uA switch.

3.3.3.2 Switch LTC4412

The LTC4412 [11] is a low-loss power path controller normally used in cell phone applications. It will automatically switch between a battery and a DC power supply which can then be used to charge the battery. This device uses a maximum current of 29 uA to operate. Figure 3.10 shows the energy consumption of the LEDL with the previously defined regulator and the LTC4412 switch. Again it is immediately evident that the 29 uA quiescent current over the 6 month period utilizes more energy than the energy capacity of the selected battery.

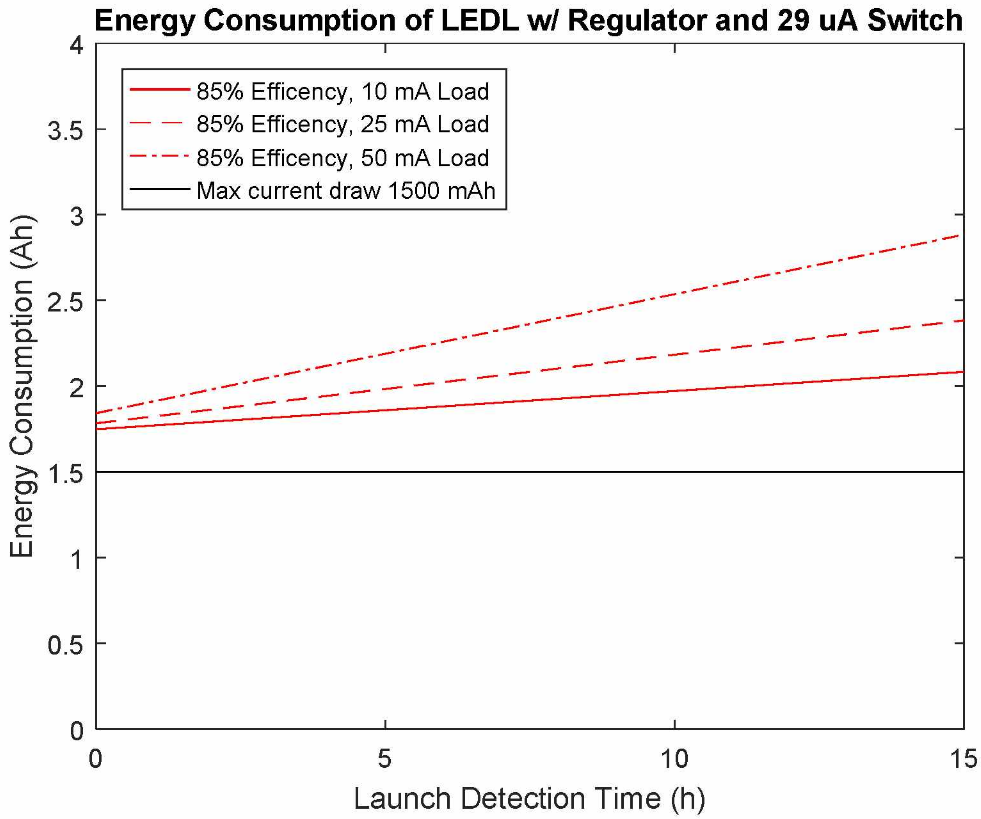


Figure 3.10: Current consumption comparison with 29 uA switch.

3.3.3.3 Potential Switch Energy Analysis

The switches chosen in the trade study use little current, but analysis shows the energy consumed by the switches is above the selected battery energy capacity. To provide the LEDL subsystem enough time to detect launch the current consumption of the switch has to be reduced substantially. An analysis to determine a minimum current range for a switch was examined to get a baseline of how little current should be used in a switch. After examining the current draw, the maximum current allowed into the system is about 10 uA. Anything more than that over the 6 month limit causes a large drain on the energy supply of the batteries (see Figure 3.11).

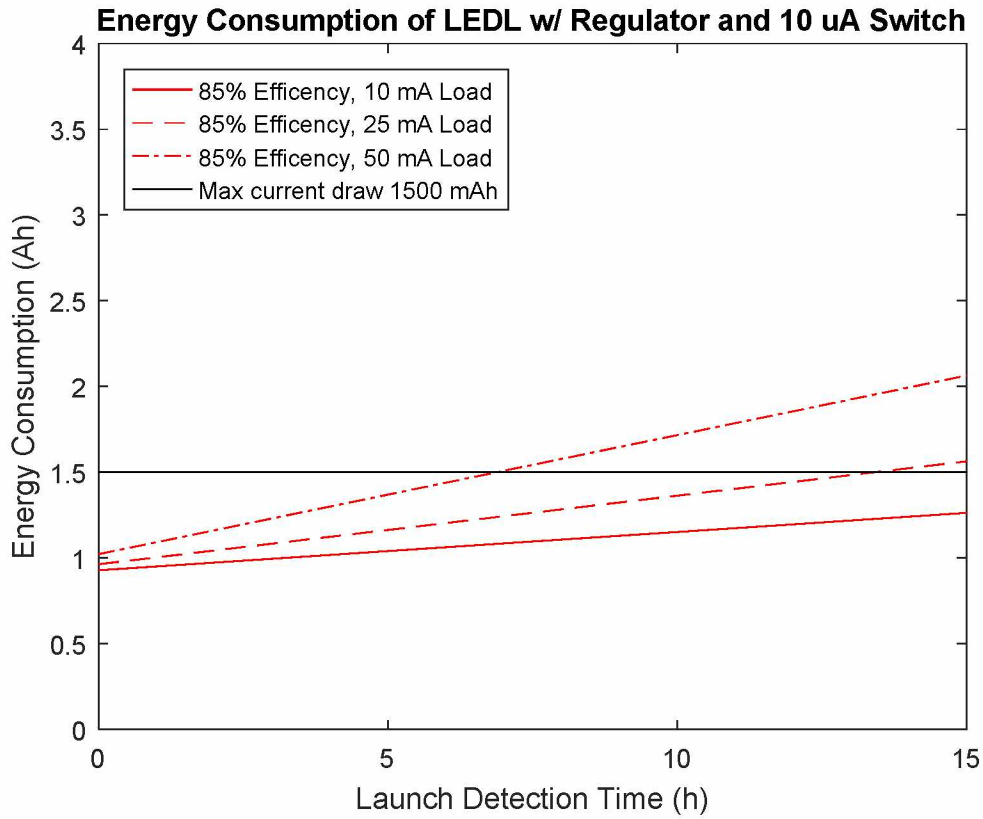


Figure 3.11: Battery life versus detection time with 10 uA switch.

As shown in Figure 3.11, if the LEDL system uses 50 mA of electronics, the system can only use 6-7 hours of detection time and still have enough energy to log data during launch. If the system utilizes 25 mA of current the system will get 14 hours of detection time, and if the system uses 10 mA of electronics the system will achieve its 15 hours of detection time.

3.3.3.4 In-House Power Switch Solution

Both switches evaluated are a problem; they both consume too much current to allow the system to be successful. A more in-depth evaluation of commercial switches showed that there are not any switches that use less than 10 uA of current. Therefore an in-house solution was designed. The system is designed using two PMOS in series. One PMOS is controlled externally by the main satellite and the other is controlled by the LEDL system. The schematic in Figure 3.12 shows several points of interest in the designed switch. First M1 and M2 are the two PMOS in series to separate the satellite electrical power system (EPS) from the LEDL system. The first PMOS M1 is controlled by a voltage source, which is a LEDL logic pin. The NMOS (U1) is controlled by a signal from CDH. When the CDH control signal goes HIGH U1 switches ON forcing the gate on M2 to go LOW which turns M2 ON allowing the satellite power bus to enter the LEDL subsystem. If the LEDL battery system should fail before the satellite EPS comes online, the satellite EPS will still power the LEDL subsystem without the PMOSs turned ON. The PMOS FETs are oriented so the internal diode is pointed towards the LEDL subsystem. If the LEDL's batteries are drained and the satellite EPS powers-on, the LEDL subsystem will receive voltage from the satellite bus less the voltage drops from the diodes, i.e. 1.9 V. This is still high enough for the system to power-on in a low power mode.

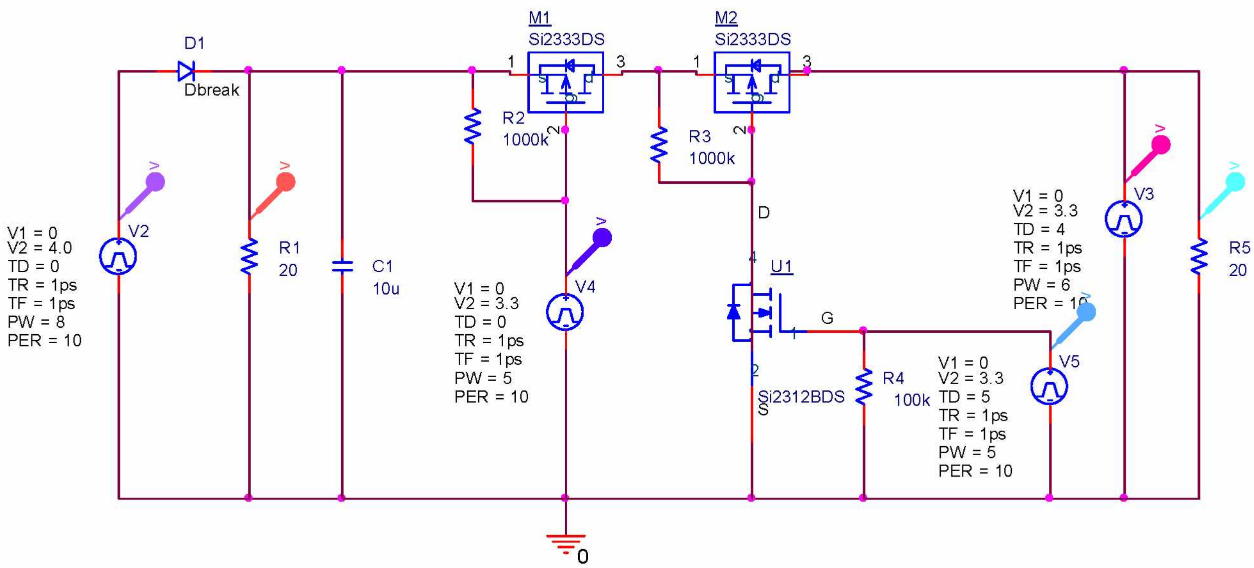


Figure 3.12: Power separation circuit with voltage probes.

Several simulations were run to show how the power switch will operate. In Figure 3.12, R1 represents the LEDL load, and R5 represents the satellite load. The first test when LEDL has power and the satellite EPS turns on shows the functionality of each PMOS turning ON. In the first simulation the voltage on LEDL and the satellite are examine under normal operating conditions of the switch as the satellite transitions from launch to orbit insertion. The second simulation is identical to the first except that the currents through the LEDL and satellite are examined. In the final simulation the voltage on LEDL is examined under the condition that the LEDL batteries are fully drained.

Figure 3.13 shows the voltage measured on R5 (satellite) and R1 (LEDL) during the transition of the satellite from launch to orbit insertion. V2 represents the voltage on LEDL's batteries and V3 represents the voltage on the satellite power bus. V4 represents a control signal from the LEDL microcontroller and V5 represents the CDH control signal. Under normal operating conditions, when the satellite is ejected from the P-POD the satellite EPS will turn ON and put voltage on the satellite bus. After some time, CDH will signal that the satellite EPS is ON by sending its control line (V5) HIGH and sending an interrupt to LEDL. LEDL responds to the interrupt by pulling its control line (V1) LOW. Additionally, LEDL will blow a fuse (D1) in series with its batteries disconnecting the battery voltage (V2). As can be seen in Figure 3.13, the voltage on R1 (LEDL) remains HIGH throughout this transition.

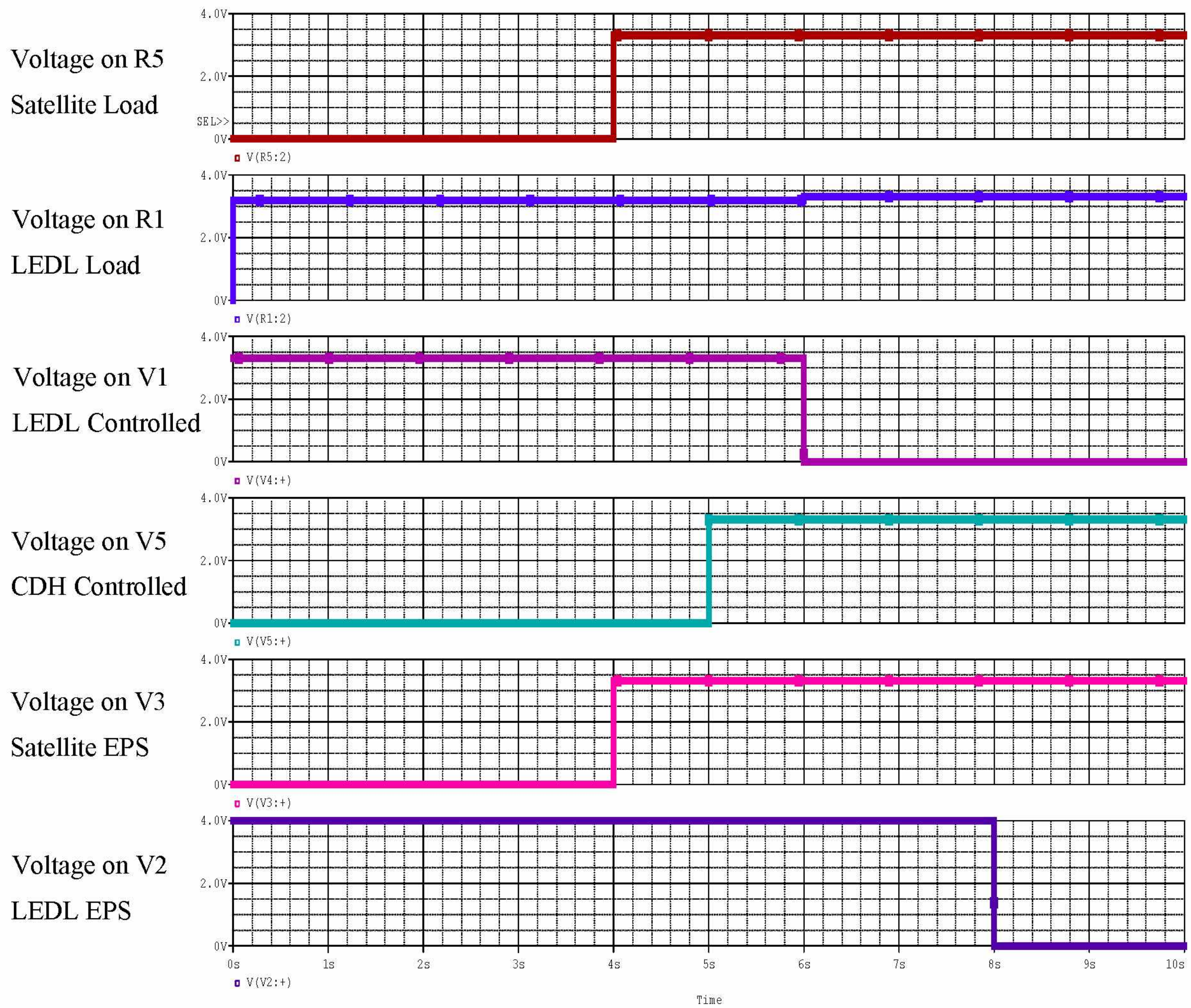


Figure 3.13: Voltage analysis of power separation circuit.

The second simulation examined the currents through the LEDL load and the satellite load, but is otherwise the same as the previous simulation. The examination of the current verifies that there is no current flowing in the satellite satisfying the CalPoly Specs [1]. Figure 3.14 shows where the currents are measured.

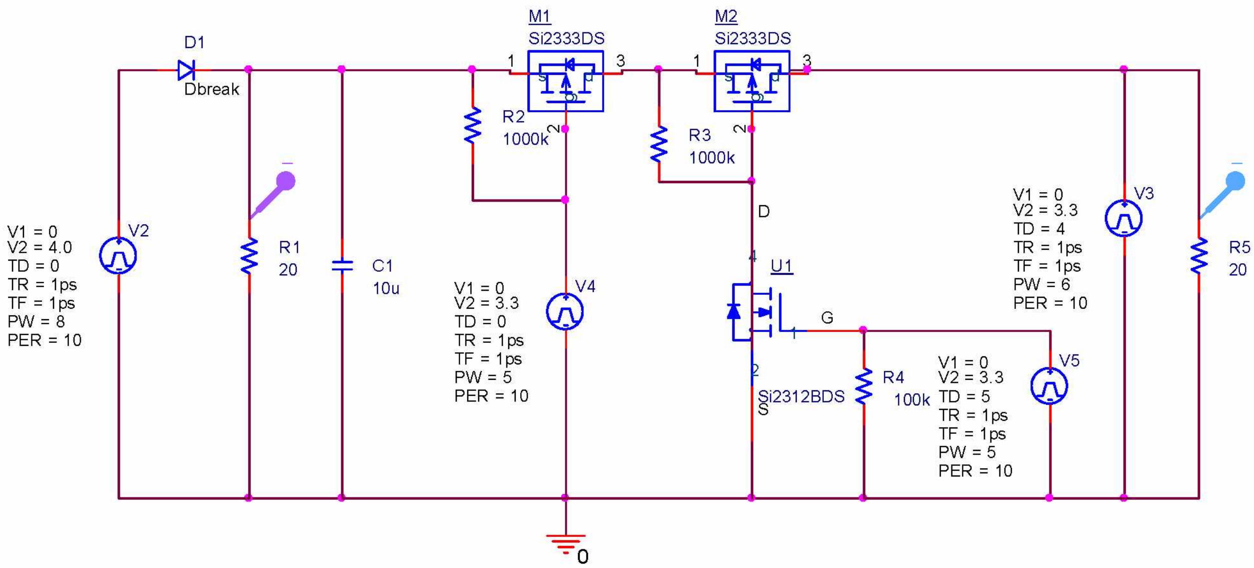


Figure 3.14: Power separation circuit with current probes.

In Figure 3.15 the analysis shows that the LEDL system is powered the whole time, again validating that the power switching circuit allows for the LEDL to swtich over to the satellite EPS. The second note is that the simulated satellite does not receive any current until the satelliite EPS turns on when it exits out of the P-POD.

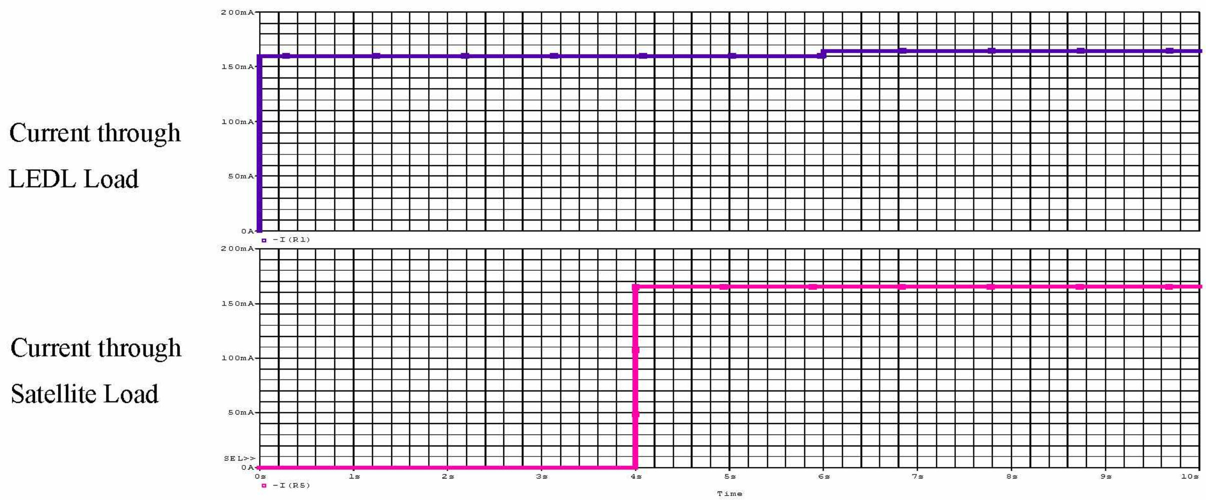


Figure 3.15: Current analysis of power separation circuit.

The last simulation examines the orbit insertion transition as before but with the LEDL batteries depleted. The simulation results are shown Figure 3.16. With the LEDL batteries depleted, the LEDL EPS (V2) is shown to be 0 V. Before the satellite EPS turns ON, the voltage across the LEDL load R1 is 0 V. When the Satellite EPS first turns ON the voltage across R1 is consistent with two diode drops from the internal diodes of the PMOSFETs. As each MOSFET gets turned ON you can see that the voltage rises on R1 by 0.7 V as each transistor turns ON. When both MOSFETs are turned ON the voltage on R1 is equal to the input voltage of V3 at 3.3 V.

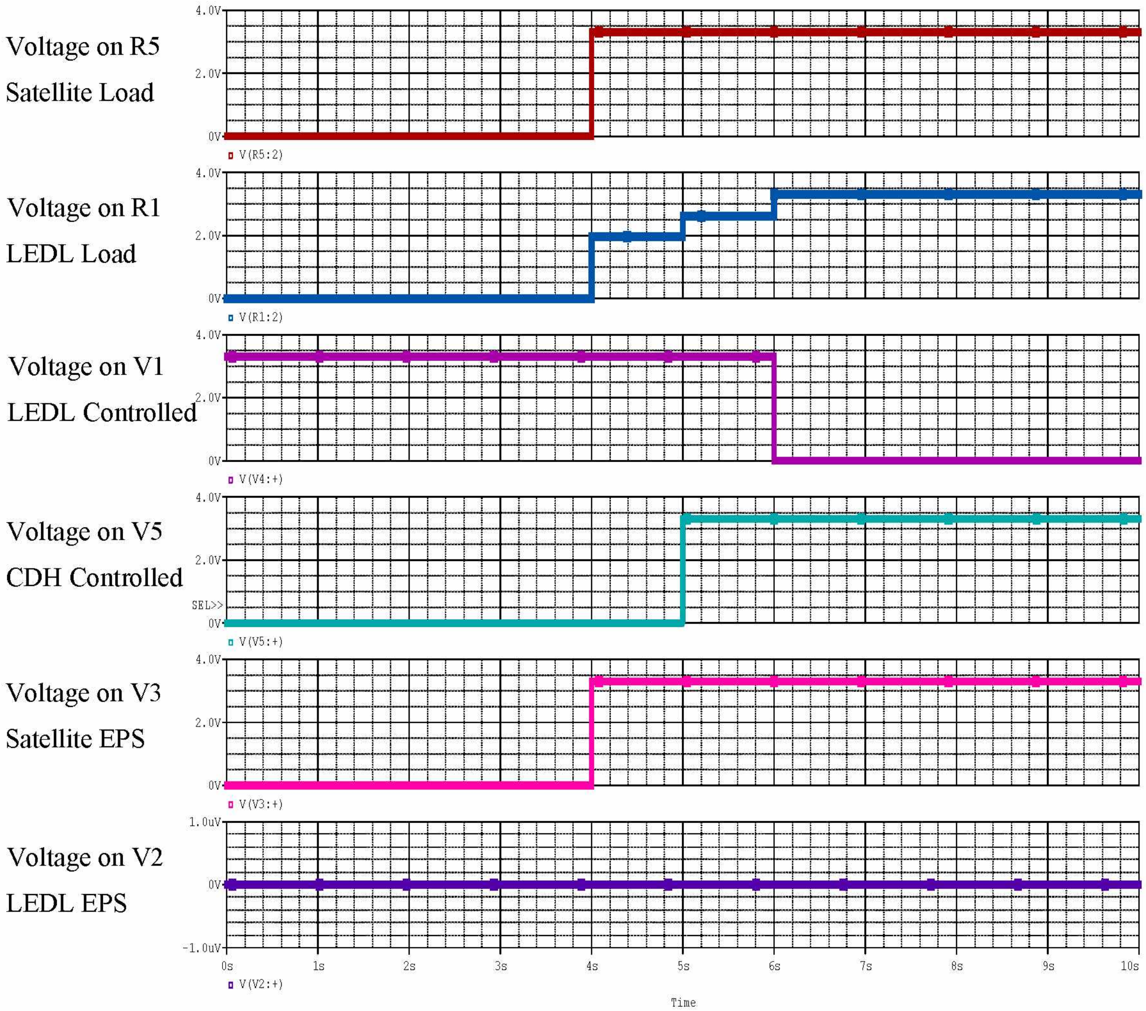


Figure 3.16: Voltage analysis of power separation circuit with drained LEDL EPS.

The previous simulations show that the power separation circuit is an adequate design that uses minimal power for the switch. This new switch design only utilizes 0.1 uA, which comes from leakage current across the pins of the PMOS. This low current is a 1/100 the expected maximum current allowed for the switch, 10 uA. Starting this system with 1500 mAh battery at 3.0 V, the voltage regulator and our in house switch, the LEDL system is able to meet LEDL requirement LEDL-001 through LEDL-004; all of these components fits together to create the power component of this satellite mission. The LEDL power system has enough energy capacity to sit on the shelf for 6 months, log data for a 2 hour launch window and be able to detect launch during the qualification testing of the satellite for 15 hours so long as the sensor current draw is less than 40 mA

Chapter 4 Critical Component – Launch Detection

This chapter discusses the second critical section, launch detect, for the Launch Environment Data Logger. Launch detection is necessary to know when the system is supposed to begin data logging. To maintain enough power to log the data, the system has to remain in low power mode until launch. Therefore the system needs to monitor its environment to determine if the launch vehicle has launched. The launch detection starts with the LEDL system in a low power mode, detects launch, evaluates launch, and confirms launch so that the system can begin to take data.

4.1 Introduction

The low power requirements from Chapter 3 emphasized the necessity that the system has to use as little power as possible to maintain enough energy to detect launch and collect sensor data. The microcontroller used for the system has multiple modes of operation. The different operations of low power modes place the microcontroller in different levels of sleep where they shut down the main 3 clocks that run the peripherals and the main CPU. By turning off the individual clocks the system can save power. The lowest power mode that the microcontroller can attain is Low Power Mode 4 (LPM4). This mode turns all the clocks off and the system requires an external signal to turn the microcontroller back on. This method allows for the system to be in sleep mode up until the launch. After launch is detected, the system logs sensor data. The remainder of this chapter discusses the launch detect requirements and examines different design choices for LEDL launch detection.

4.2 Launch Detect Requirements

The power conservation for launch detect component is very important because the system may have to wait for up to 6 months before launch and then be able to determine when launch has taken place after it has been waiting. When launch happens the system will need to be able to come out of a lower power mode and verify that launch is actually happening. If LEDL cannot detect launch, then it will not be able to meet its science mission objective, therefore detection of launch is the first requirement for this critical component (LEDL-005). In addition to the complexity, ARC1 satellite is required to go through multiple vibration tests after final integration. It is expected that the LEDL launch detect circuit will falsely trigger that launch is happening. The LEDL subsystem needs to be able to distinguish between these false triggers and actual launch. Therefore, the second requirement for this critical component is to verify that launch has happened (LEDL-006).

4.3 Detection Methods

Different methods to detect launch were examined. The microcontroller requires an external signal to indicate launch. Different types of sensors that could provide an external signal to the LEDL microcontroller were evaluated for their ability to interrupt the microcontroller. The three methods examined to achieve this were an external signal to the LEDL system, a mechanical reed switch, and a piezo electric sensor. Each of these will be discussed in detail.

4.3.1 External Signal

One way to detect launch is to use an external control signal to tell the satellite that the launch is going to occur. The external control signal would trigger an interrupt on the LEDL microcontroller bringing it out of low power mode. In order to get the external control signal to LEDL, LEDL would have to have its own radio (for wireless control) or have a physical wire (for wired control) connecting it through P-POD structure. Having a radio would violate the launch provider's regulation prohibiting RF transmission prior to orbit insertion. We investigated the possibility of the wired connection to the P-POD structure, but our request was denied by the launch provider. Although the most reliable method of detecting launch is through an external control signal, this method could not be implemented [12].

4.3.2 Reed Switch

Initially, an electrical reed switch was proposed to determine the start of launch. The reed switch is a passive component that does not consume power. The switch is an enclosed ferro magnetic material that will connect or disconnect the switch when a magnetic field is applied. Vibrations sustained during launch were expected be sufficient to open and close the switch without a magnetic field. The opening and closing of the switch would trigger an interrupt which would let the LEDL system know that launch is happening. The benefit of this idea is that the system is utilizing the physical motion of the rocket to detect launch. While this idea seems good, there are not any studies that show how reed switches operate under sustained vibrations. One study concerning the switches, Reed Relays and Electronics [13] specify that having any ferro-magnetic materials within 100 mm can interfere with the reed switch operation. The Attitude Control and Determination System contain magnetic torquers that consist of ferro-magnetic material wrapped in magnetic wire. There are 12 of these torquers within the satellite and within 40 mm of the LEDL system. Given the close proximity of the torquers, the reed switch design was not investigated further.

4.3.3 Piezo Electric Sensor

The piezo electric sensor was proposed as alternative to the reed switch. Like the reed switch, the piezo electric sensor is a passive component that does not consume power and is sensitive to vibrations. These sensors are created from tiny crystals embedded into a substrate. When the substrate is bent, the bending of the crystals cause an electric response and the crystals create a voltage. Using this component to capture the vibrations inside the launch vehicle would create a voltage on the output of the piezo electric sensor that can be used as an interrupt to the microcontroller. This allows the piezo electric sensor to be a good choice as a method to detect launch.

All piezo electric sensors are tuned to a natural frequency. The sensor chosen for the launch detect is the Volture V21B-ND [14]. It is tuned to 240 Hz (see Figure 4.1) which is within the frequency range expected by GEVS [2].

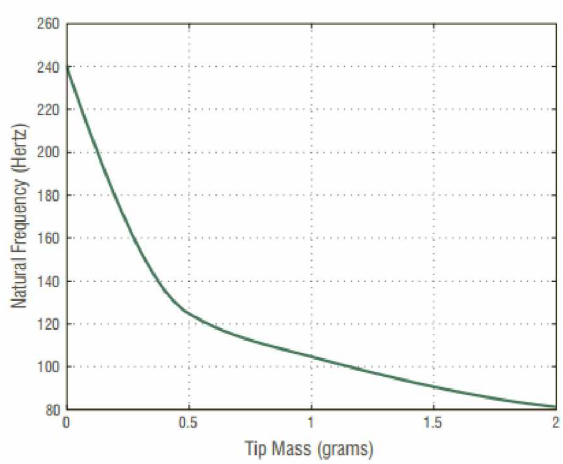


Figure 4.1: Volture 21B natural frequency to tip mass [14].

The output generated from the sensor bending is an AC signal. A full-wave bridge rectifier is used to convert the piezo electric sensor output to a DC signal. Figure 4.2 shows the full-wave rectifying circuit used to convert the AC signal from the sensor to a DC signal intended to interrupt the microcontroller. R1 is used on the output of the circuit to simulate a large load.

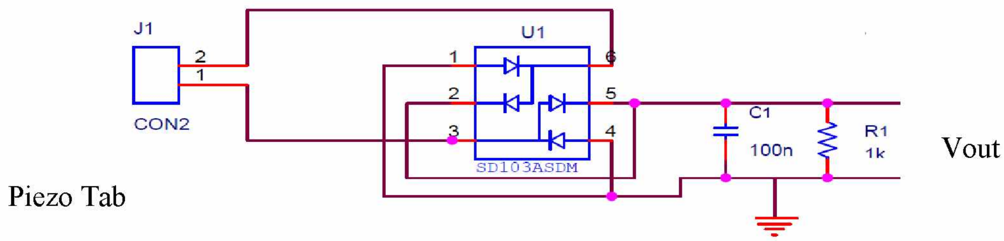


Figure 4.2: V21B-ND bridge rectifier circuit.

The piezo electric sensor was tested by applying a sinusoidal acceleration and measuring the rectified output voltage. The sinusoid was swept from 0 to 350 Hz, in increments of 10 Hz, in order to verify the sensors natural frequency. The final plot of the voltages per frequency is shown in Figure 4.3. There are several frequency bands where the sensor performs and generates adequate voltage to trigger an interrupt. Of note, neither of the two peaks shown is at the expected natural frequency of 240 Hz. This is likely to be caused by the manner in which the piezo electric sensor is mounted to the test stand.

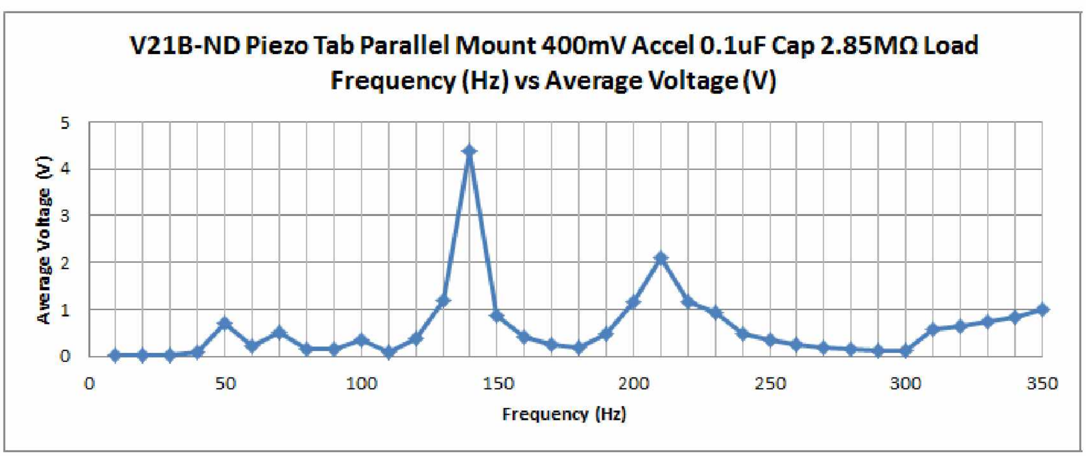


Figure 4.3: Plot of rectified voltage from vibration test.

When the satellite gets integrated into the launch vehicle the orientation of the satellite is unknown. Since the axis of any launch vibrations is also unknown, it might be desirable to measure accelerations in 3 axes. However, due to size constraints and the modular design of the satellite there is only room for two sensors on the satellite. Initially this was of some concern. However, it was felt that even if there were a primary axis of vibration that there would be enough cross-axis coupling so that measuring only two orthogonal axes would be sufficient. Therefore, to detect any launch vehicle vibrations two piezo electric sensors have been placed on the LEDL board in two orthogonal axes.

The maximum rectified voltage measured during the test was 4.5 V, which is larger than the source voltage of any electronics expected to be driven from the piezo electric sensor. To prevent the piezo electric circuit from damaging the subsequent electronics, a zener diode is used to clamp the high voltages to a safe voltage level of 2 V. The second thing noticed about the piezo vibration test is that the output voltage across most frequencies is under 1 V. The MSP triggers at 0.8 V, which leads to the possibility that the vibration output might not be sufficient to generate an interrupt at the MSP. To compensate for this, a comparator was chosen with a fixed low voltage input that will trigger when the threshold is met. This way any vibrations between 10 and 350 Hz will trigger the comparator creating an interrupt at the microcontroller. The comparators chosen are active low; this means they trigger the microcontroller by selecting the output to be low. The comparator also has a low current consumption of 15 uA, choosing this comparator increases the energy consumption and this will limit the amount of time the system can detect launch.

Figure 4.4 shows how all the pieces of the launch detect circuit are configured. The piezo electric sensors connect to the CON2 pins. The input from the CON2 feeds into the diode bride followed by the clamping zener diode and the signal is then fed into the comparator input. The comparator's output is pulled up to VCC through R57 until the comparator is triggered from the input signal. When the input is triggered, the output pin is pulled low and the microcontroller pin connected at LAUNCH DETECT is triggered.

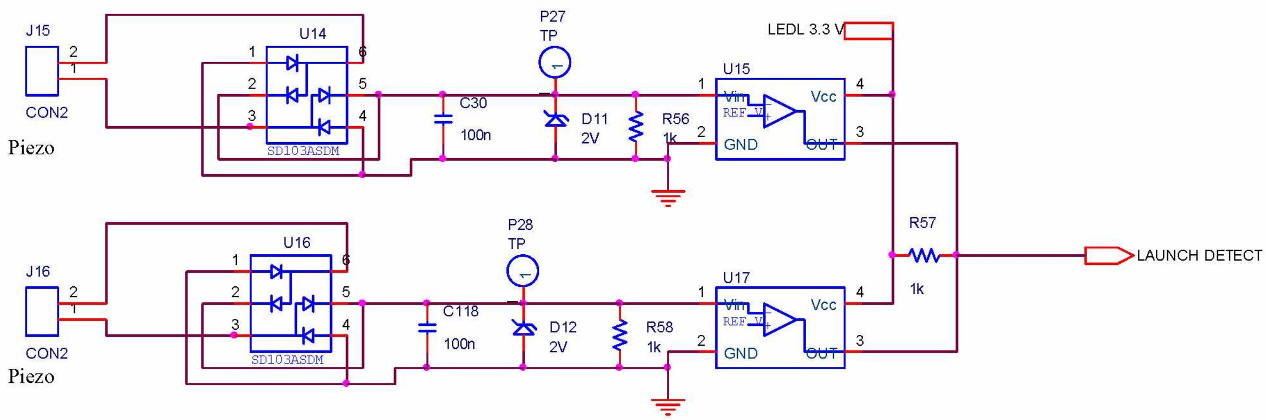


Figure 4.4: Piezo electric circuit.

ARC1 has been manifested on an Atlas V launch vehicle and when the comparators trigger the microcontroller indicating launch has occurred, the system has to verify that launch is happening. To determine if launch has occurred, the acceleration of the launch vehicle can be examined. The Atlas V User Manual shows the acceleration profile of the launch vehicle after launch. Within 5 seconds the acceleration is greater than 1 G, after 120 seconds the acceleration clears 2 G [15]. Figure 4.5 is an expanded acceleration plot of the full Atlas V profile that is shown from the Atlas V user manual. The full profile of the launch vehicle is shown in Figure 4.6. To determine if launch has occurred, the microcontroller will verify that the acceleration of the launch vehicle is 2 G after 120 seconds of sampling. The accelerometers used to verify launch will be discussed in more detail in the next chapter.

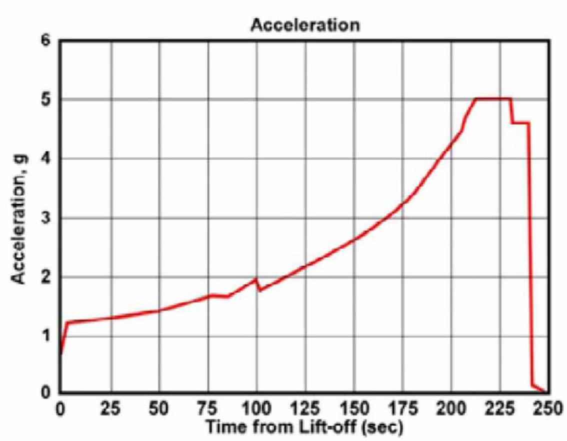


Figure 4.5: Atlas V acceleration profile for LEO of a sun-synchronous flight [15].

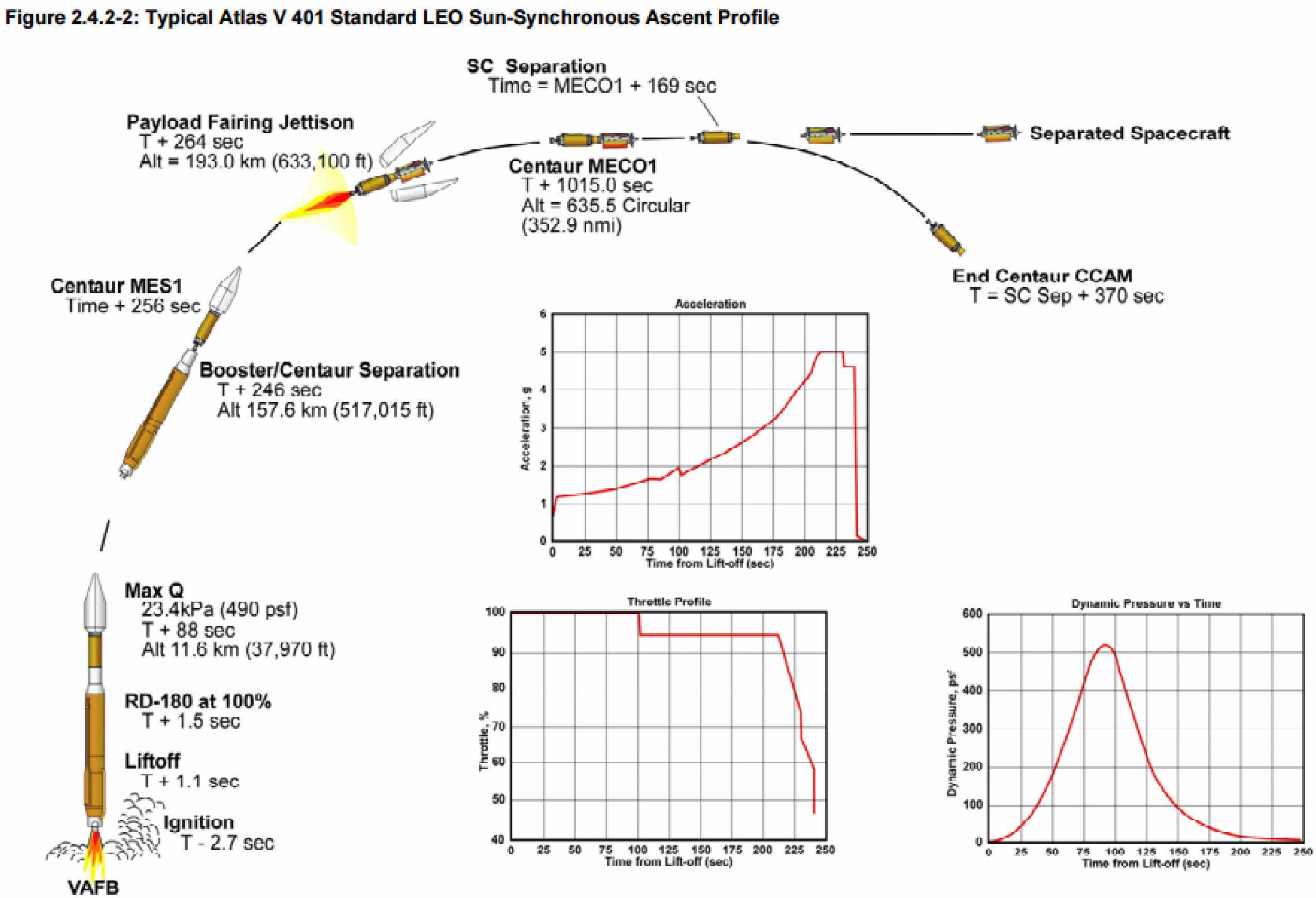


Figure 4.6: Atlas V standard LEO sun-synchronous ascent profile [15]

Chapter 5 Critical Component – Sensor Selection

This chapter addresses the sensors chosen for the Launch Environment Data Logger (LEDL) and the requirements that drove the selection of sensor chosen.

5.1 Introduction

The LEDL subsystem's purpose is to measure the environment inside the launch vehicle during ascent. The sensors used to measure the environmental data were chosen initially during the space system engineering class and little was changed. Each of the sensors were chosen based on the requirements for this system, and each will be discussed in detail followed by the sensor chosen to meet that requirement.

5.2 Requirements

The LEDL's goal is to measure vibration of the launch vehicle. The vibration spectrum of the launch vehicle can be derived through the Fourier transform of the acceleration time series data. The specific acceleration profile of the launch vehicle unknown, what is provided by GEVS [2] under section 2.4.2.3 Payload Random Vibration, page 2.4-16, is the acceptance level of testing necessary for the payload prior to launch. GEVS specifies that the payloads should be tested from "20-2000 Hz frequency range" to be adequately tested for flight conditions. Based on Nyquist sampling, the minimum acceleration sampling rate will be twice the maximum frequency at 4000 Hz. The qualification for Acceleration Spectral Density (ASD) for testing is at 14.1 G_{rms} for prototypes and an acceptance of 10.0 G_{rms} for flight model.

Frequency (Hz)	ASD Level (g^2/Hz)	
	Qualification	Acceptance
20	0.026	0.013
20-50	+6 dB/oct	+6 dB/oct
50-800	0.16	0.08
800-2000	-6 dB/oct	-6 dB/oct
2000	0.026	0.013
Overall	14.1 G_{rms}	10.0 G_{rms}

Figure 5.1: GEVS generalized random vibration test levels [2].

A secondary sensor was chosen to allow for the measurement any unforeseen vibrations outside of the expected range of acceleration provided by GEVS [2]. A larger acceleration was chosen so that the system could detect any large impulses experienced by the satellite. Since the first accelerometer required at least 10 G_{rms}, the second accelerometer to measure shock was chosen to be several times larger, a 70 G accelerometer was chosen. The two different acceleration profiles that need to be monitored lead to the sensor's requirement LEDL-007.

The secondary part to this mission is to measure the temperature inside of the launch vehicle. CubeSats are frequently mounted near the engines within the Poly-Picosat Deployer (P-POD). Since the temperature profile is unknown for the launch vehicle near the engines, other estimations of relevant temperature profiles can be used to determine what temperature range should or can be monitored. NASA metals with Teflon coating experience touch temperature of 120 C to -129 C in space. In addition the satellite is being designed with off-the-shelf components; due to this the actual temperature range measured by sensors will be more limited by the components themselves. Most common off-the-shelf electronic components tend to have upper and lower bonds of +105 C to -40 C, respectively, so a temperature sensor that can at least measure within these bounds will be used (LEDL-008).

During launch the LEDL system will log acceleration and temperature data, it will store six acceleration data at 4000 Hz and seven temperature data at 1 Hz. At a minimum, this is 24,007 samples a second. Additionally the rest of the satellite cannot be on during launch, so the data cannot be sent over live telemetry to a ground station during launch from the communication subsystem. The data taken during launch will have to be saved for later transmission once the satellite is in orbit (LEDL-009).

Once the satellite is in orbit, other systems rely on the LEDL to take data and pass the data on when needed. The LEDL system connects to sensors on the external satellite faces through connectors on the LEDL board, and therefore can easily pass the information over the common satellite bus to support other subsystems (LEDL-010).

The sensor requirements define what the LEDL system has to accomplish. The LEDL system has to take acceleration and temperature data and store the data for later use. Additionally the system will assist other systems on the satellite by providing the other system with their respective data. Each of the sensors are tested for functionally to verify that they work.

5.3 Sensors

The different sensors chosen to be used on the system are listed below.

5.3.1 Accelerometers

The accelerometer ADXL321 [16] was chosen to satisfy LEDL-007. This sensor had the closest range to the required minimum 14 G_{rms}, the ADXL321 measures to net 18 G acceleration. The accelerometer chosen to measure unforeseen accelerations above the 14 G_{rms} was the ADXL001, this accelerometer measures up to 70 G acceleration [17]. The ADXL321 is a two-axis accelerometer and the ADXL001 is a single-axis accelerometer, so there is one ADXL321 on X- and Y- Solar Panel Boards, and there are two ADXL001 on X+ and two on Y+. Only three of the sensor outputs are monitored, the Z component is duplicated so only one is sampled at the microcontroller. To generate a baseline for the accelerometers initial testing shows that changing the orientation of the accelerometer gives the voltage output equivalent to 0 G when the accelerometer is perpendicular to Earth's normal gravity vector and $\pm$1 G when the accelerometers measured axis is parallel to Earth's normal gravity vector. The accelerometers' output are 1.65 V at 0 G, for every G measured the voltage is changed by $\pm$ 0.057 V/G (18 G accelerometer) and $\pm$ 0.016 V/G (70 G accelerometer).

The accelerometers were further tested using a vibration table to monitor the acceleration profile of the sensors. The LEDL system was vibrated using a sinusoidal sweep. The frequency of the sinusoidal sweep started from 0.1 Hz, increased to 2000 Hz, and then decreased back to 0.1 Hz. The magnitude of the acceleration generated by the vibration table was set up to be on the vibration table between 0.5 and 1 G. The system was tested on each axis (X, Y, and Z), and the data was recorded to the SD card for retrieval after the test. The data shown in Table 5.1 represents each axis's output for each axis tested. This only shows the 18 G accelerometers, the 70 G accelerometers did not put out a readable profile. 1 G of acceleration is within the threshold for the 70 G accelerometer and the acceleration profile was lost in the noise, therefore the 70 G data is not shown. The table column headers are the different axis that were vibe. The first column the X axis was in normal to the vibration table and in the axis of motion. The row headings are the sensors that were measured for each test.

Table 5.1a: Vibration table data for 18 G accelerometers.

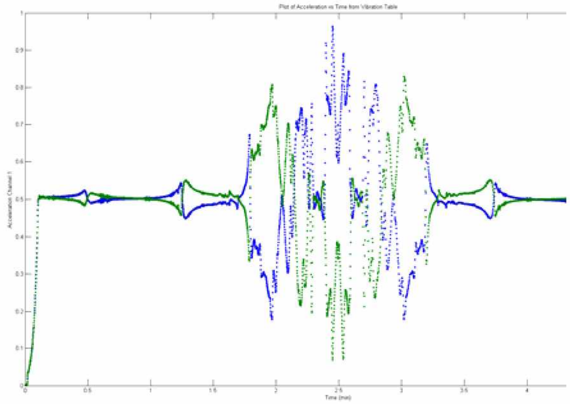
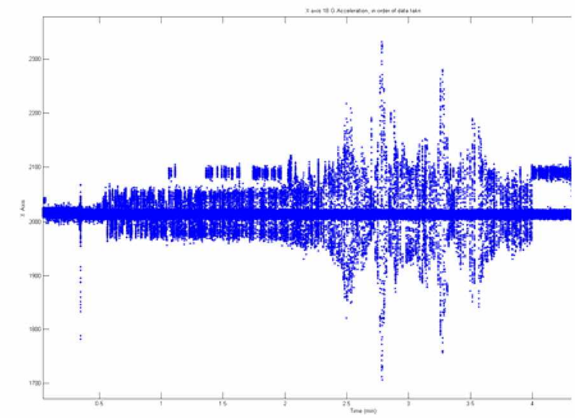
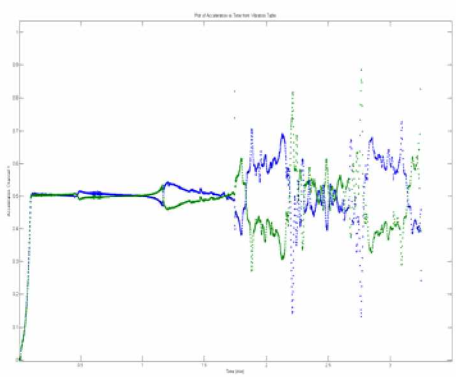
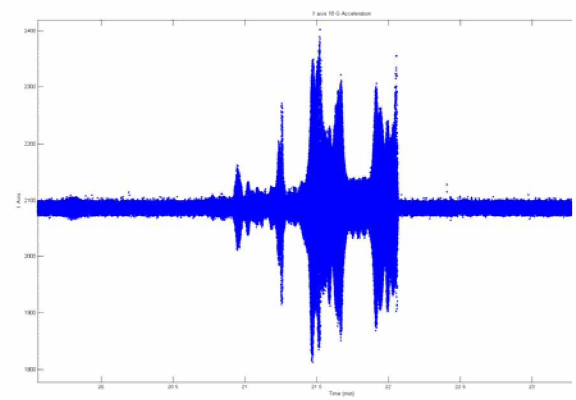
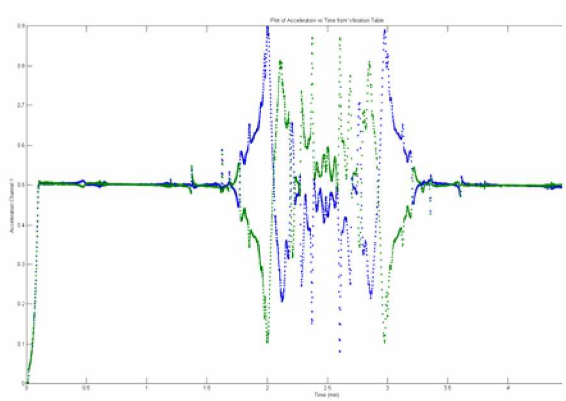
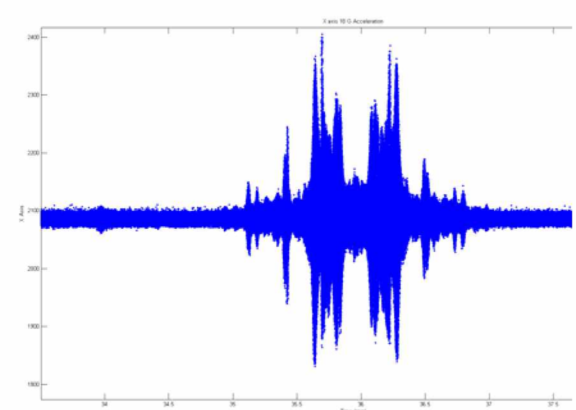
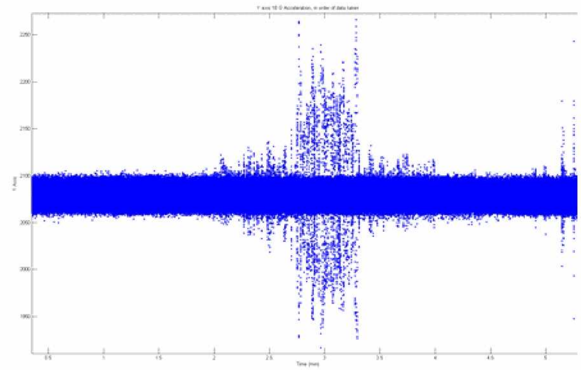
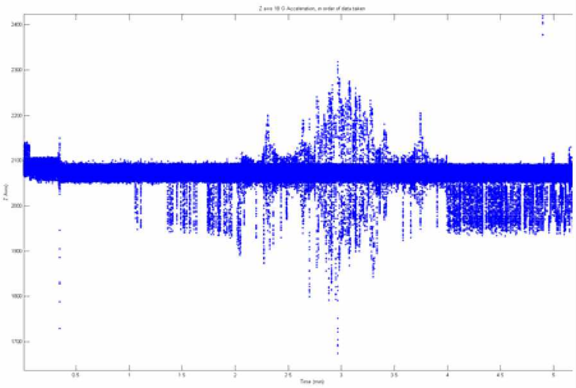
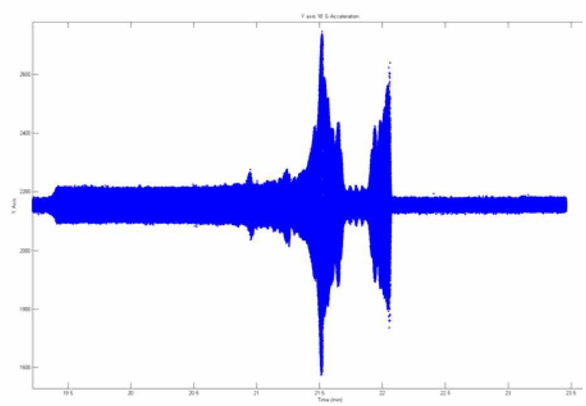
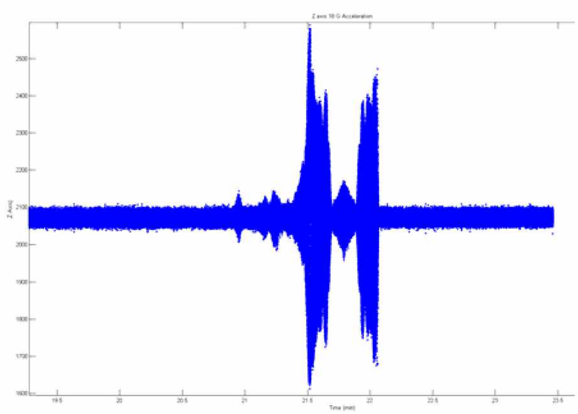
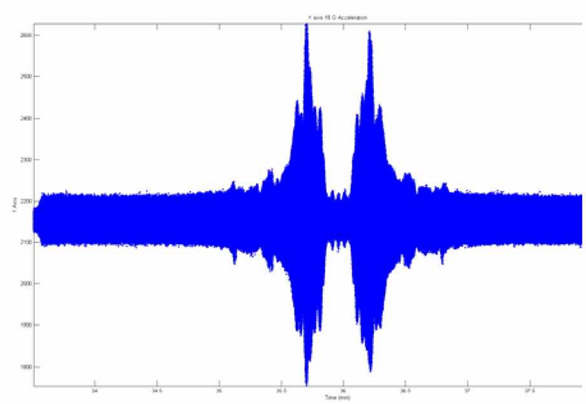
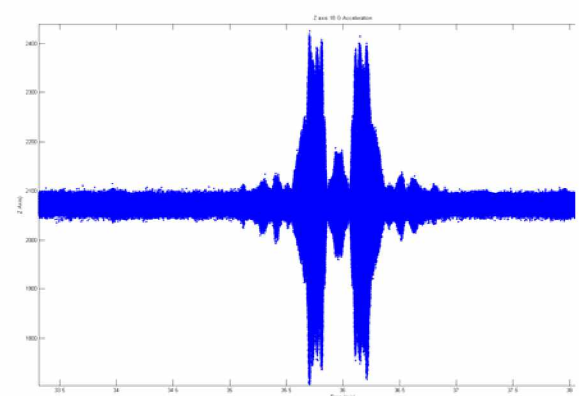
	Vibration Table Plot	LEDL X-Axis Measurements
X- Axis Vibration Orientation		
Y-Axis Vibration Orientation		
Z-Axis Vibration Orientation		

Table 5.2b: Vibration table data for 18 G accelerometers.

	Vibration Table Plot	LEDL X-Axis Measurements
X- Axis Vibration Orientation		
Y-Axis Vibration Orientation		
Z-Axis Vibration Orientation		

What is shown in these plots is that each of the accelerometers on the LEDL system is measuring acceleration across the vibrational bandwidth. The vibration table measures the acceleration on the base plate of the vibration table. The LEDL's accelerometers are higher up on the structure within the P-POD. The P-POD is then bolted to the main plate through mounting brackets. There is a lot of material between the accelerometers, so they read very different profiles. With this in mind each of the axes produced favorable results. Each of the axis measured acceleration, even though the vibration was through one axis, the structure moved enough to create accelerations in the transversal plane of the satellite and the accelerometers picked them up. In each test each accelerometer recorded vibrational data. This test proved that the accelerometers worked and are functional.

5.3.2 Temperature Sensor

The temperature sensor chosen uses the AD7410 [18], this temperature sensor has a range of +105 C to -40 C. The LEDL system has seven sensors, six on the external faces of the satellite and one on the LEDL board itself. Simple tests show that the sensors read the current room temperature and can show a temperate change by using a heat gun to change the air temperature around the sensor.

5.3.3 Support Hardware

The LEDL system provides support to other systems on the satellite. LEDL supports the Attitude Control and Determination System by sampling the gyroscopes and magnetometer data and passing the data to the ACDS system. LEDL also retrieves the telemetry from the electrical power supply. The sensors are monitored by the LEDL system, but the data is verified though other systems in the satellite and will not be discussed here. The only sensor to be discussed is the gyroscopes since they are physically located on the LEDL system. The two gyroscopes on the LEDL system are the LPY410AL [19] which measure pitch and yaw. By placing the two sensors 90 degrees from each other roll can be determined. The two sensors output all three rotations experienced by the satellite. The use of the gyroscopes is to measure the satellite tip off rate after being ejected from the P-POD. These tip off rates determine if the attitude controller can slow down the rotation of the satellite. For the satellite to be able to measure the tip off rates the satellite has to begin measuring before the satellite is ejected from the P-POD, due to the nature of the LEDL system being operation during launch, the LEDL was assigned to make these measurements for the ACDS system.

Chapter 6 Software - Control Modes of Operation

This chapter discusses the necessary code to run the Launch Environment Data Logger (LEDL). The code reflects LEDL's requirements and concept of operations for the lifetime of the subsystem, from sitting on the shelf waiting for launch, to orbit operations. Each subsection discusses the software and how the different modes of operation apply to the requirements. Included in this chapter are the data formats that are stored within the SD card. Lastly this chapter describes how LEDL will communicate with other subsystems within the satellite.

6.1 Introduction

The Launch Environment Data Logger (LEDL) has different modes of operation for each phase of the system. The basic modes of operation for the LEDL are broken up into two initiation modes, Code Initialization and Check Mode; and four operational modes, Idle Wait, Launch Detect, Log Launch Data, and Mission Support. Depending on external inputs to the microcontroller the code will change modes and begin its tasks for that mode. To help clarify nomenclature for this chapter modes and tasks will be used to help describe the software. The modes are the higher level states from Figure 6.1. The tasks are software blocks that are run concurrently using the control tasking library

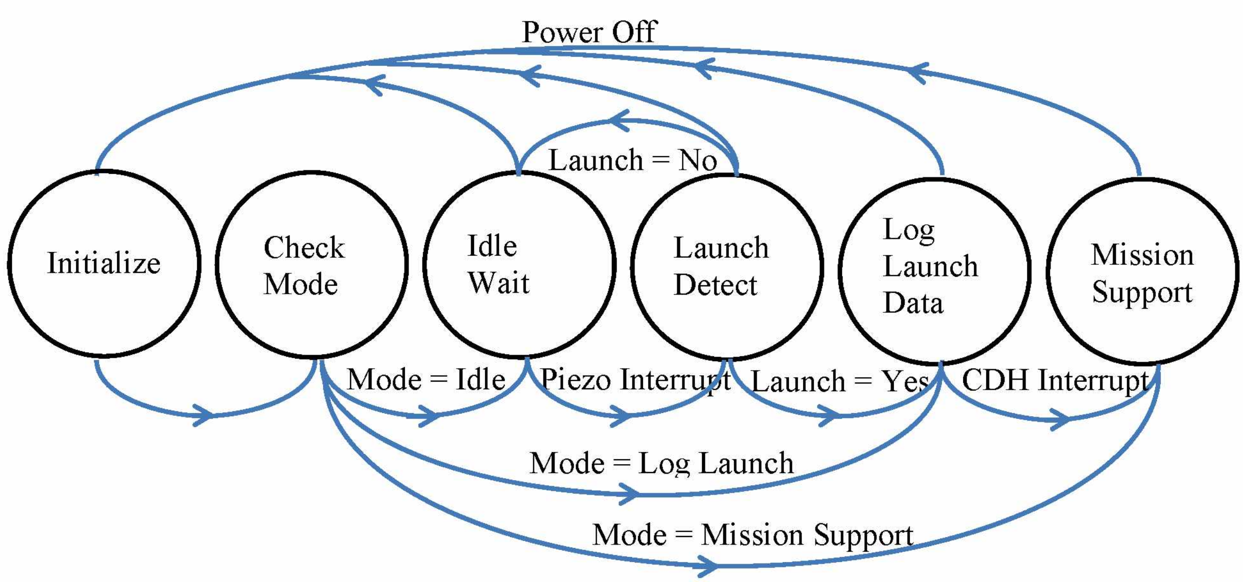


Figure 6.1: Software flow chart.

Figure 6.1 shows the basic structure of the code from initialization to final operation. On system power up the code begins to initialize all internal peripherals to the microcontroller. Some examples of the initialization are the clocks, analog-to-digital conversions and communication protocols and all external pin allocations for the MSP to all external hardware. Each hardware group will be discussed individually in the setup of the microcontroller and how it interacts with each external component. Once initialized the code moves into the second mode Check Mode. Depending on the stored mode the code enters any of the other modes Idle Wait, Launch Data Logging, or Mission Support. Idle Wait, waits for the piezo electric sensors to be triggered. Once triggered the code moves on to Launch Detect to verify that launch as occurred. If launch has occurred, the code moves to Launch Data Logging and begins to log the launch data. If launch is not confirmed, the code returns to Idle Wait. Once the satellite reaches orbit the Command and Data Handling (CDH) will send an interrupt to LEDL and the LEDL will begin its orbital operations mode Mission Support. If the subsystem is in any mode and a power failure occurs, the LEDL subsystem will turn back on, check the saved mode and will resume in the mode that the system was in prior to the power failure. The following sections provide detailed descriptions about the different code modes. This section begins with all the initialization for the microcontroller and the system's external hardware followed by a discussion of the code for each mode of operation.

6.2 Code Initialization

The Code Initialization of the Launch Environment Data Logger begins by setting up the clocks, communication protocols, and external hardware. This initiation section covers details that may pertain to single or every mode of operation. The initialization hardware is addressed individually to help clarify following sections.

6.2.1 General Code Setup

When the microcontroller turns on for the first time, it begins by initializing the clocks, and enters in a low power mode. The low power mode allows the MSP to function on a slower clock and at a lower power mode. Requirement LEDL-002 specifies that the LEDL system will need its own power supply to operate during the launch phase the system. LEDL will begin using raw battery voltage from its own power supply with the regulator shutdown. To keep the LEDL power supply from leaking into the satellite from the PMOS separation circuit discussed in Chapter 3 has the PMOSs powered up in the off position.

6.2.2 Launch Detect Setup

The launch detect setup only has to initialize the port 2 interrupt. The input to the microcontroller is set to trigger an interrupt on a high to low transition. When a trigger occurs the microcontroller services the interrupt and the microcontroller begins the launch detect algorithm.

6.2.3 Memory Card Setup

Using a SD card satisfies requirement LEDL-009 and formatting the memory space for data retrieval is important for later use. The SD card saves data in a 512 Byte block format called sectors. The memory card used on the LEDL board has 4 GB of data, the first sector is numbered 0 and the final sector is numbered 2^{31}. The SD card's memory is mapped to separate the different data types. The three types of data are the error function data, launch detect data, and the launch data. The error functions store data from sector 0 to 64. Data taken during the Launch Detect mode is stored from 65 to 1000, and data taken during the Log Launch Data mode is stored from 1000 – 2^{31}. The data format is shown in Table 6.1 and is organized into four fields. The first field is the LEDL's MODE_ID. There are three modes, Launch Detect mode, Log Launch Data mode, and Mission Support. The MODE_ID is used to identify what kind of data is in the sector. The second field is the SD address. The address that the SD card is saving to is stored in 4 bytes. This is to help the system to find the first free address in memory. The next field is any science data taken. For Launch Detect and Log Launch Data modes there is 504 bytes of science data. The last field is the check sum CRC to make sure that the data is not corrupted.

Table 6.1: SD card data format.

SD Card Data Type (size of data)			
LEDL MODE_ID (2 bytes)	SD address (4 bytes)	Science Data (504 bytes)	CRC (2 bytes)

6.2.4 Sensor Setup

The sensors are initially turned off by using the PMOS switches (see Figure A.4). The different sensors are connected to the MSP through either analog pins or I2C pins. When the sensors are initialized in the low power mode all pins are turned off to help conserve power by removing any possible leakage current.

The accelerometers and gyroscopes are connected through the microcontroller's ADC. The ADC is set up to take data continuously while Timer A is activated. Timer A provides an interrupt to the ADC every 369 ns in order to sample the accelerometers at the required rate (LEDL-007). Additionally, the ADC used in the microcontroller samples the analog data at 12 bits satisfying the minimum 8-bit resolution requirement.

The temperature sensors and magnetometers are connected to the MSP through I2C lines. The I2C allows communication of multiple sensors provided every sensor has its own address. The addresses used to identify every sensor on the bus are shown in Table 6.2.

Table 6.2: Sensor I2C address.

Sensor/Component	**Address (0x)**	**Sensor/Component**	**Address (0x)**
Temperature Sensors		Magnetometer Sensors	
T_{x+}	48	M_{x+}	14
T_{x-}	4A	M_{x-}	16
T_{y+}	49	M_{y+}	26
T_{y-}	4C	M_{y-}	34
T_{z+}	4E	M_{z+}	25
T_{z-}	4D	M_{z-}	24
T_B	4F		

6.2.5 Main Functions Called

The main() function used on the microcontroller utilize the control tasking library. The tasking library calls different tasks that allow the microcontroller to run different functions at one time. Each of the main modes of operation is set up in a software task, Launch Detect, Launch Data Logging, and Mission Support. There is an additional task that is a user interface to LEDL which allows for the user to communicate with the system over a UART serial interface using programs like Tera Term. The remaining tasks are used to support the modes, the I2C sensors task allows the LEDL to communicate with the temperature and magnetometer sensors. The ADC control triggers the timing for data collection during Launch Detect and Log Data Launch. The SD card task provides the means to save data to the SD card while the processor is doing other tasks. The last is a main function which places the microcontroller into a low power mode when there is not a runnable task.

6.2.6 Mission Support Setup

Mission Support is the final operational mode the LEDL system. The Mission Support requires that the LEDL system know that it has entered orbit. During the launch phase the LEDL subsystem is completely disconnected from the communication rails so that the LEDL subsystem will not power the other microcontrollers on the satellite by pulling the communication lines high. To communicate to the LEDL subsystem that the satellite has reached orbit the CDH is connected to LEDL through an interrupt capable pin. Pin 1 of Port 1 is set up to be interrupt capable on a low to high transition for when CDH will signal to LEDL that the satellite has entered orbit.

6.3 Check Mode

The mode of the LEDL board is checked after the microcontroller finishes initialization after power up. Each time the subsystem changes mode, the current mode is stored into the SD card sector 65. Checking the mode of the subsystem requires the subsystem to fully wake up so that it can check the memory on the SD card. To power up to active operation, the MSP turns on the voltage regulator by selecting the regulator enable high. Once the power is stable; the SD card power is turned on by turning on the sensor PMOS and initializing the SD card pins. Sector 65 in memory is read. If the CRC read matches what was printed in the sector then the sector is not corrupted and the LEDL will enter the mode saved.

The different modes stored are Idle Wait, Launch Detect, Log Data Launch, and Mission Support. If the system started up for the first time then the SD card is empty and the absence of data indicates that the system is waiting for launch in the Idle Wait mode. If the data saved is a Launch Detect, then the SD card provides data about the last launch detect and the system is still waiting for launch. When sector 65 has either Launch Logging or Mission Support saved to it, the stored mode is placed into the startup mode register and the MSP will move on to that mode. When there is no data or Launch Detect data stored into the SD card, the mode will wait in the Idle Wait for the Launch Detect signal, the SD card will be shut down, the sensor voltage will be turned off by the PMOS switch, the regulator will be placed into sleep mode and the MSP will go back into a low power mode.

6.4 Low Power Mode and Launch Detect

When the LEDL finishes Initialization and its mode is in Idle Wait, the system will stay in a low power mode until the piezo electric sensors create an interrupt to place the LEDL in the Launch Detect. Idle Wait keeps all external hardware turned off and the MSP in a low power mode to reduce current consumption. The only way to wake up the MSP out of the low power mode is utilizing an external signal to the microcontroller on Port 2 which is interrupt capable. Port 2 interrupts are set up to trigger when a voltage makes a high to low transition. The piezo electric sensors circuit pulls the interrupt pin low. The voltage change that occurs on the pin triggers the interrupt and the Launch Detect mode begins so that the MSP can determine if launch has occurred.

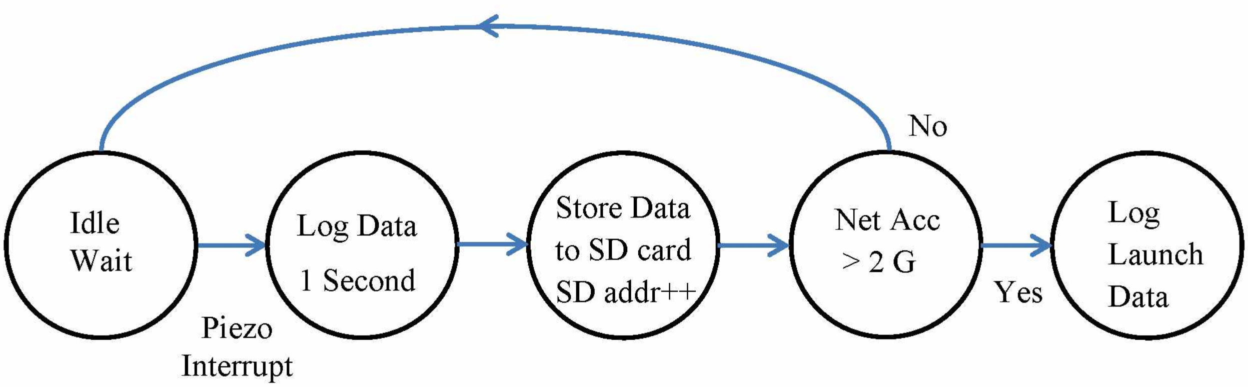


Figure 6.2: Launch detect mode flow chart.

The MSP enters the Launch Detect Mode and begins the detection algorithm to determine if launch has occurred. The detection algorithm meets requirement LEDL-006 which determines if the satellite is receiving sustained acceleration greater than 2 G. If LEDL measures greater than 2 G acceleration, it decides that launch has been detected. To measure the acceleration, the accelerometers have to be turned on and read using the ADC. The data is stored and a running average is calculated for 1 second to determine if the satellite is under a sustained net acceleration greater than 2 G. To calculate the acceleration every sample of the acceleration is added to the previous average and a new average is taken, all three axes are tracked, Xavg, Yavg and Zavg are used to find the net direction of acceleration. To determine the acceleration the 0 G offset is removed from the Xavg, Yavg and Zavg and the absolute value of the remainder is stored. Once all the samples are taken the final averages for each axis are used to find the net acceleration. The net acceleration is compared to see if the value is larger than the 2 G. If it is larger than 2 G the mode is changed to Log Launch Data, if the value is less than 2 G the mode stays the same for low power mode and will return to low power.

To keep track of the number of times the satellite wakes up from sleep and enter Launch Detect Mode; the measured and calculated accelerations are stored to the SD card for retrieval once the satellite reaches orbit. The SD card is stored with data shown in Table 6.3 and the data is stored into two places. One measurement is stored into sector 65 which is updated every time there is a Launch Detect to store the current mode. The second measurement is stored in the sequential address to log every time the LEDL enters Launch Detect. For example the first occurrence will have only one entry in sector 65, the second occurrence will store the data in sector 66 and will update the data in sector 65, the nth occurrence will be in sector 65+n and will update sector 65 with the new data. The same data format is used for both sectors, sector 65 provides the details about the mode for on startup procedures as well as provide data for Mission Support, and the remaining sectors keeps a log of how many times the system has woken up.

The data saved for Launch Detect mode is stored in the format shown in Table 6.1, mode identification, SD address, Data and CRC are stored. The science data shown in Table 6.3 is the Science Data which contains the details about the launch detect. The calculated averages, net average, and maximum and minimum accelerations are stored so the vibrations that caused launch can be analyzed. The number of wake up attempts and the vibrations associated with the wake up are logged to determine power usage based on how many times the satellite woke up. Sector 65 has the same data that is located in sector 65+n, the SD address holds the Last SD address that latest Launch Data is stored to. The SD address is used for both Log Launch Data Mode and for Mission Support. In Log Launch Data it is used to find the first free location in memory and for Mission Support it is used so the satellite can beacon how many sectors were written to. The remainder of the 504 bytes Science Data field are empty.

Table 6.3: Science data for launch detect.

Science Data (size of data)					
Xavg (2 bytes)	Yavg (2 bytes)	Zavg (2 bytes)	Net Acceleration (2 bytes)	Wake up attempt (2 bytes)	Max X (2 bytes)
Min X (2 bytes)	Max Y (2 bytes)	Min Y (2 bytes)	Max Z (2 bytes)	Min Z (2 bytes)	CRC (2 bytes)

6.5 Log Launch Data

The Log Launch Data mode is the core of the software for gathering launch data and storing it to the SD card. This mode begins either after the code checks the mode after initialization or after launch detect is confirmed. Since there are two ways to get into this mode the code starts up as if it begins from the initialization of the MSP and begins by turning on all hardware needed for logging the launch. The voltage regulator, accelerometers, temperature sensor, gyroscopes and SD card are all turned on. If they were originally turned on from launch detect mode this action has no effect on the hardware. Next the MSP has to determine if the system has entered this mode before. It does this by determining the first data free location in the SD card. The microcontroller first checks the last SD address used stored SD address of sector 65 and checks if the address is empty.

If the address was not empty the microcontroller begins looking for a free address at increments of 1000 sectors. An error could potentially occur if the microcontroller was in the middle of taking data and for some reason got reset. If the microcontroller was reset then the last address used was not saved to the SD card. This check will start from the last known location and quickly find the next address available. The code does not check every sector due to time considerations. The free sector is found by reading in the sector and looking at the first byte to determine the mode, if the mode is zero then there is not a mode written in and the MSP knows the sector is clear of data. When the first free sector is found the address is stored into the last SD card address used in 65 and the code begin data acquisition.

The system measures accelerometers, gyroscopes and temperature sensors during launch. The data is taken in a way to make sure that the minimum data rate is achieved. This was done by first separating out the data into readable tables and finding an organization of data that lead to the correct data rate required by the requirements. The data format is shown in Table 6.4.

Table 6.4 only represents the science data from the SD card format Table 6.1. Only 504 bytes are represented in this table, with each cell being 2 bytes. Each row begins with a Frame # which identifies the data block to a frame this starts at 0 and ends when the satellite reaches orbit, the second column is the sub frame ID, each row starts at 0 and ends at 8. The reason for the Frame# and SubFrameID helps identify the location of data. If any data is lost and it needs to be recovered, the exact location of the data will be known based on the Frame# and SubFrameID that are missing. The accelerometers are indicated by A, gyroscopes are indicated by G, temperature sensors are T, and Time1 and Time2 are the time measurements. In each block there are 36 individual accelerometers measurements, 3 individual gyroscope measurements, and 1 temperature measurement (1 every 113 frames). If 113 frames are created per second, this results in 4068 accelerometer samples, 339 gyroscope samples and 1 temperature sample per second generating the needed sample rates or better for the sensors.

Each of the data samples in Table 6.4 represents the science data in Table 6.1. As mentioned the data is represented with A for accelerometer data, G for gyroscope data and T for temperature data, the time stamps are shown as Time1 and Time2. Each individual sensor output is represented by A1-A6, G1-G3, T1-T7 and Time1 and Time2. The 70 G accelerometers, A1-A3, represents X axis, Y axis and Z axis. The 18 G accelerometer, A4-A6, represents X axis, Y axis, and Z axis respectively. The Gyroscopes, G1-G3, are the pitch, roll, and yaw. The temperature sensors, T1-T7, are the temperature sensors located on the external faces of the satellite and one internal on the LEDL board which matches up with the X+, X-, Y+, Y-, Z+, Z- face, and the LEDL board. The two time stamps are taken from the real time clock used in the microcontroller. Time 1 and Time 2 are upper and lower 2 bytes of the 32 bit clock tick of the microcontroller. The data is continuously taken in this data format until the satellite reaches orbit (LEDL-013).

Table 6.4: Science data for SD card for LEDL launch data.

Science Data (size of data)																													
Frame#	SFID	A1	A2	A3	A4	A5	A6	A1	A2	A3	A4	A5	A6	A1	A2	A3	A4	A5	A6	A1	A2	A3	A4	A5	A6	G0	T0
Frame#	SFID	A1	A2	A3	A4	A5	A6	A1	A2	A3	A4	A5	A6	A1	A2	A3	A4	A5	A6	A1	A2	A3	A4	A5	A6	G1	T1
Frame#	SFID	A1	A2	A3	A4	A5	A6	A1	A2	A3	A4	A5	A6	A1	A2	A3	A4	A5	A6	A1	A2	A3	A4	A5	A6	G2	T2
Frame#	SFID	A1	A2	A3	A4	A5	A6	A1	A2	A3	A4	A5	A6	A1	A2	A3	A4	A5	A6	A1	A2	A3	A4	A5	A6	G0	T3
Frame#	SFID	A1	A2	A3	A4	A5	A6	A1	A2	A3	A4	A5	A6	A1	A2	A3	A4	A5	A6	A1	A2	A3	A4	A5	A6	G1	T4
Frame#	SFID	A1	A2	A3	A4	A5	A6	A1	A2	A3	A4	A5	A6	A1	A2	A3	A4	A5	A6	A1	A2	A3	A4	A5	A6	G2	T5
Frame#	SFID	A1	A2	A3	A4	A5	A6	A1	A2	A3	A4	A5	A6	A1	A2	A3	A4	A5	A6	A1	A2	A3	A4	A5	A6	G0	T6
Frame#	SFID	A1	A2	A3	A4	A5	A6	A1	A2	A3	A4	A5	A6	A1	A2	A3	A4	A5	A6	A1	A2	A3	A4	A5	A6	G1	Time1
Frame#	SFID	A1	A2	A3	A4	A5	A6	A1	A2	A3	A4	A5	A6	A1	A2	A3	A4	A5	A6	A1	A2	A3	A4	A5	A6	G2	Time2

To start the data block, Timer A indicates to the ADC that it is time to take an ADC measurement. If this is a new data block, it starts off by storing the first Frame# and SubeframeID into a temporary storage. It then samples the ADC and stores those values.

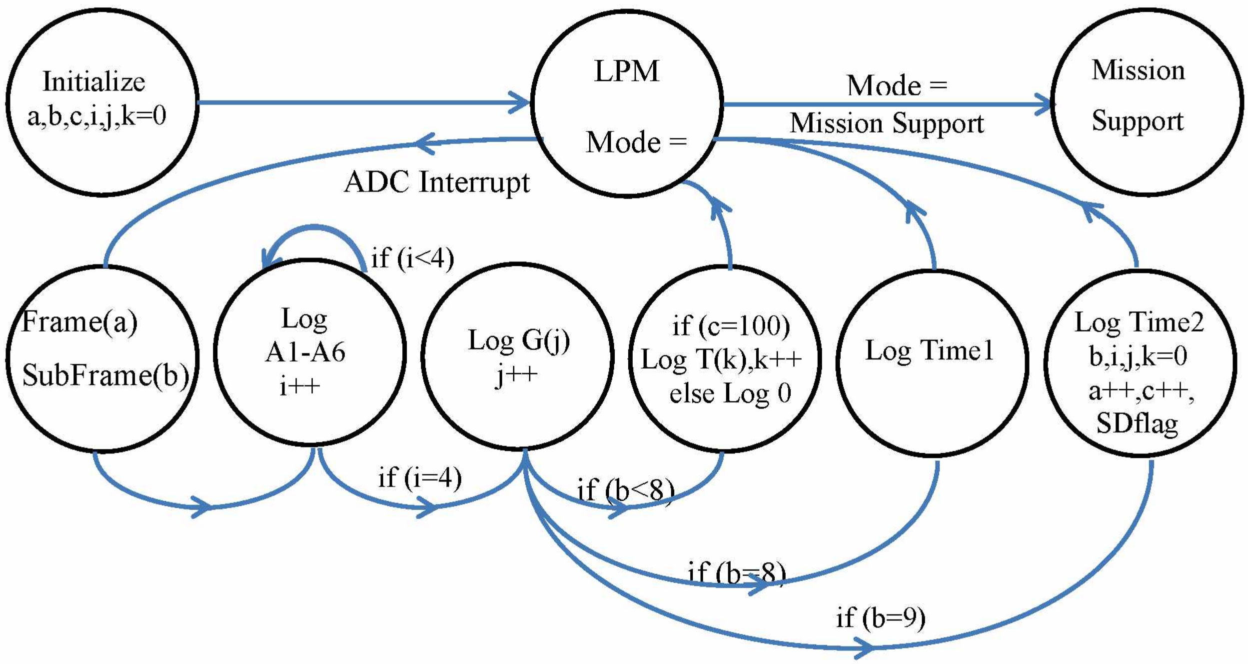


Figure 6.3: Logging launch data mode flow chart.

The code continues taking the data in the order prescribed by the data represented in Table 6.4. After the first row is complete, the code returns to a low power mode and waits for the ADC interrupt again from Timer A. It completes this 8 times finishing with the last time stamp. At the end of a block the code resets variables, increments counters, and sets the SD card write flag. The code does not write to the SD card in the same loop as shown in Figure 6.3. The code to save data is done in a separate task.

6.6 Mission Support

The LEDL orbital operation mode is the Mission Support mode. LEDL continuously takes data during the Log Launch Data and stores it to the SD card until the satellite is ejected out of the P-POD and is placed into orbit. Upon exiting the P-POD the main satellite power is turned on to the remaining satellite and the CDH system wakes up. CDH makes contact with the

LEDL subsystem by selecting Pin 1 on Port 1 HIGH, which indicates there is power on the bus and it is time for the LEDL system to enter orbital operations. The LEDL system changes to Mission Support mode and Log Launch Data exits its logging loop and shuts down the accelerometer, turns on the magnetometers for Mission Support. The system then saves the new mode to the SD card. The new data consists of the Mission Support mode and the last sector saved.

Mission Support is also task driven to drive the different functions during the lifetime of the system. The tasks are generated from the requirement to respond to different commands. A software flow chart for Mission Support is shown in Figure 6.4CDH and ACDS will periodically communicate with the LEDL using I2C commands as shown in Table 6.5 to receive sensor data so that they can conduct their own orbital operations (LEDL-010). LEDL provides data stored in the SD card over the communication bus upon request from the COMM board. When COMM requests the launch data the LEDL system will transfer one sector of data at a time to the COMM board which matches the data format from Table 6.1 (LEDL-011). LEDL is responsible for both the LEDL's health data shown in Table 6.6and EPS health data shown in Table 6.7. Upon waking up LEDL logs all EPS data and LEDL data and holds them until the CDH asks for them. Upon request LEDL will send the health data to the CDH and then retake the health data until the next request for data. Additionally the ACDS will ask for magnetometer data every second for attitude control the format the data sent over the I2C bus is shown in Table 6.8.

All I2C data packets are represented by Table 6.5. It shows the format of one data transmission across I2C. Each of the transmissions is the same for the health beacon to CDH and the data for ACDS. The only difference is the content of the Data field. The data depends on the sensor data for that individual packet.

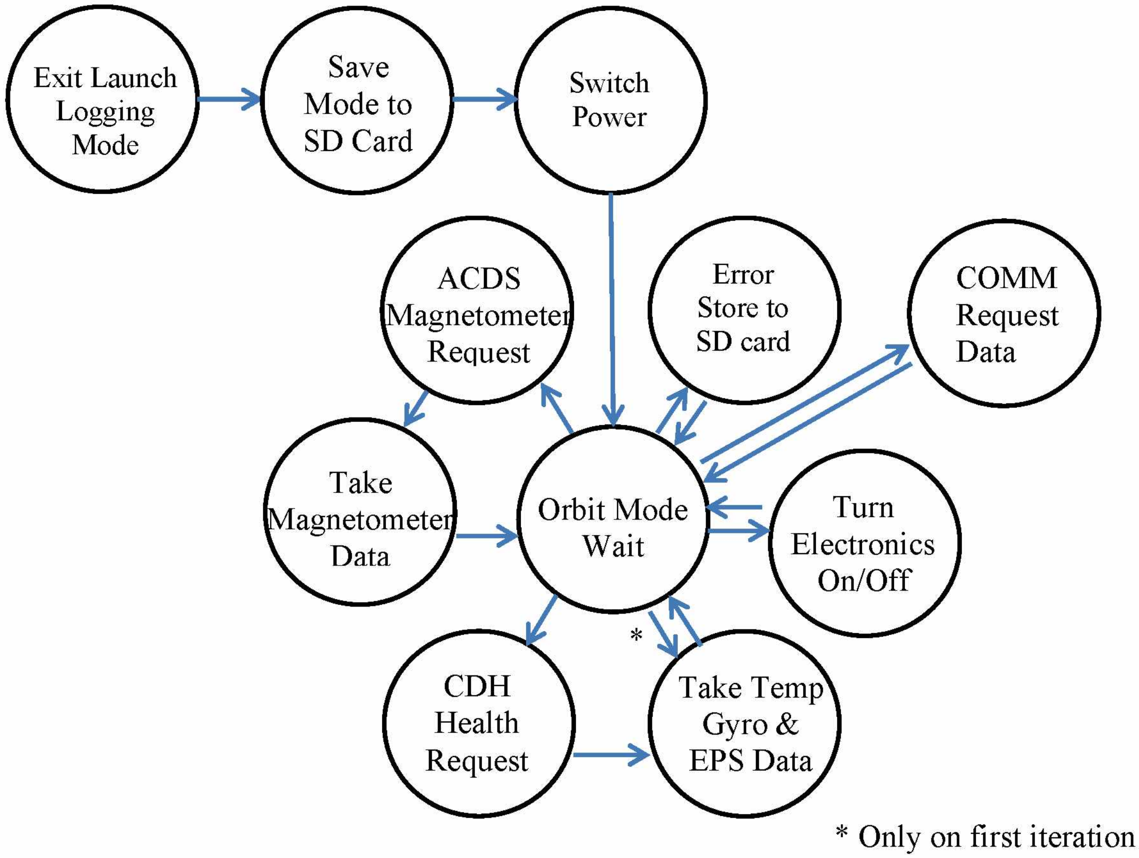


Figure 6.4: Mission support software flow chart.

The beacon for the LEDL subsystem is shown in Table 6.6and represents the LEDL's health data. The data consists of all the temperature data and the gyro data, with additional EPS data. The EPS data exceeds the maximum data bytes allowed per beacon, so the extra EPS data is appended onto the LEDL data. The beacon for the EPS system is shown in Table 6.7. The data consists of all data available on the EPS, all battery voltage, battery currents and solar cell array currents. The data samples for the ACDS are also sent through the I2C. The data is represented in Table 6.8. The data consists of all six magnetometer measurements from the solar panel boards.

Table 6.5: I2C packet.

I2C Packet				
To Address (1 Byte)	From Address (1 byte)	Size (1 byte)	Data (32 byte)	CRC (1 byte)

Table 6.6: LEDL/EPS to CDH beacon data.

LEDL/EPS Data I2C Packet								
Data Row 1	Total SD Data	X plus temp	X minus temp	Y plus temp	Y minus temp	Z plus temp	Z minus temp	LEDL Temp
Data Row 2	Gyro Pitch	Gyro Roll	Gyro Yah	EPS Stat TTC	Batt 1 Temp	Batt 0 Temp	5 V Buss Current	3.3 V Bus Current

Table 6.7: EPS to CDH beacon data.

EPS data I2C Packet							
Data Row 1	Y plus Current	Y minus Current	Y plus Voltage	Y minus Voltage	X plus Current	X minus Current	X plus Voltage
Data Row 2	X minus Voltage	Z minus current	Z minus voltage	Batt Bus current	Batt 0 current	Batt 0 Voltage	Batt 1 voltage

Table 6.8: LEDL to ACDS I2C data.

Data for I2C Packet						
Data Row 1	Mag X+	Mag X-	Mag Y+	Mag Y-	Mag Z+	Mag Z-

CalPoly Requirements require that CubeSats to respond to shut off commands from the ground station, to respond to these commands CDH will send shut off and turn on commands to each of the systems. LEDL will respond to this command and turn off and shut down all components, and will respond to the turn on command by turning on all orbital electronics and resume LEDL's tasks. To respond to each of these tasks the LEDL subsystem must communicate through SPI and I2C on the headers, this is set up through the ARC bus which initializes the SPI and I2C communication protocols. Last the LEDL subsystem logs all errors that occur during the orbital operations. When there are errors the LEDL subsystem will log them into the SD card from Sector 0 to 64. Each error logs the severity of the error, the source of the error, the error code, and any arguments about the error which are the status bits that were encountered.

Chapter 7 Conclusion and Future Work

This chapter concludes this thesis with the current mode of the LEDL system. The final work shows completed hardware with the final components. This section also include what tests can be done to support this work and modifications to the system for future improvement. Last, a final power analysis is performed to assess the effects of the selected components on the LEDL subsystem.

7.1 LEDL System Hardware and Software

The LEDL subsystem has been developed and was launched on ARC1. A final image of the LEDL board layout is shown in Figure 7.1. The final system placed the piezo electric sensor as close to the center as possible so that they would fit within the top rings of the satellite structure. Five connectors to the solar panel boards (SPB) are seen around the outside of the board. The sixth solar panel board is connected through the X+ SPB and then to the LEDL. The sensors that are located on the solar panel boards are the accelerometers, temperature sensors, and the magnetometers. The battery terminals can be noted on the top of the board. The size of the battery housing fits within the structure of the satellite with 2 mm of clearance.

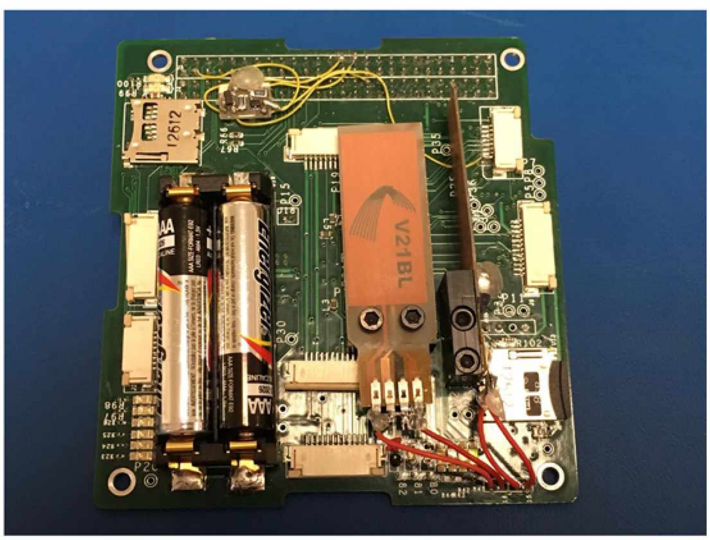


Figure 7.1: Final LEDL hardware.

On the underside of the board (see Figure 7.2) can be seen the main microcontroller, the gyroscopes circuit and the temperature sensor circuit, and last the power switching circuit. Additionally there is a second system located on LEDL but it was not discussed in this thesis.

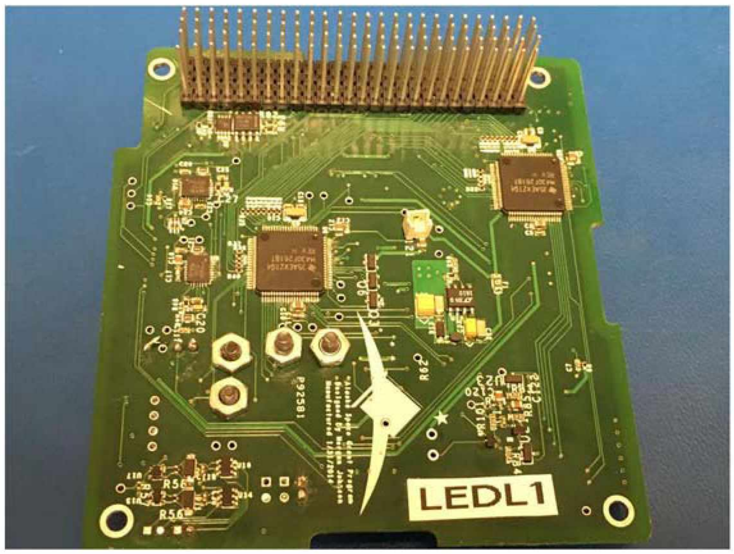


Figure 7.2: Final LEDL hardware.

Each of the sections of the LEDL system were tested for functionality and verified that each component worked the way it was intended. The power management system regulated power from the battery to 3.3 V, the regulator could be shut down to allow the microcontroller to be in a low power mode prior to launch. The system saves power by removing the low efficiency regulation while in low power mode applications. The power separation circuit was also functionally tested with hardware to verify that the simulations were correct. The piezo electric sensors were tested to verify that they could generate an output voltage that would trigger the comparator to generate an interrupt to the microcontroller to indicate launch. Last the sensors were functionally tested to make sure they worked, only the 70 G accelerometer was not able to be functionally tested on the vibration table due to the acceleration voltage output was within the noise profile generated by the accelerometer during vibration. The 70 accelerometer were benched tested, when they were connected to power, the output of the accelerometers would vary $\pm$0.025 mV per G as the axis was changed. In addition to the functional testing, the LEDL system had to undergo special EMI testing to verify that the LEDL did not emit any radiation in bands specified by the launch service provider. If the LEDL system failed the EMI testing it would have not been allowed to launch.

The system was able to meet all the requirements listed to in support of the science missions for ARC1. However, as with any system, improvements can be made. Additionally, more detailed testing of the subsystem is warranted.

Looking at a final energy analysis of the system provides an idea about how many hours the system will be able to detect launch. The only change to the energy calculation was adding the sensor currents to the launch detect E2 and launch E3 of the Equation 3.2. Figure 7.3 shows the energy analysis results.

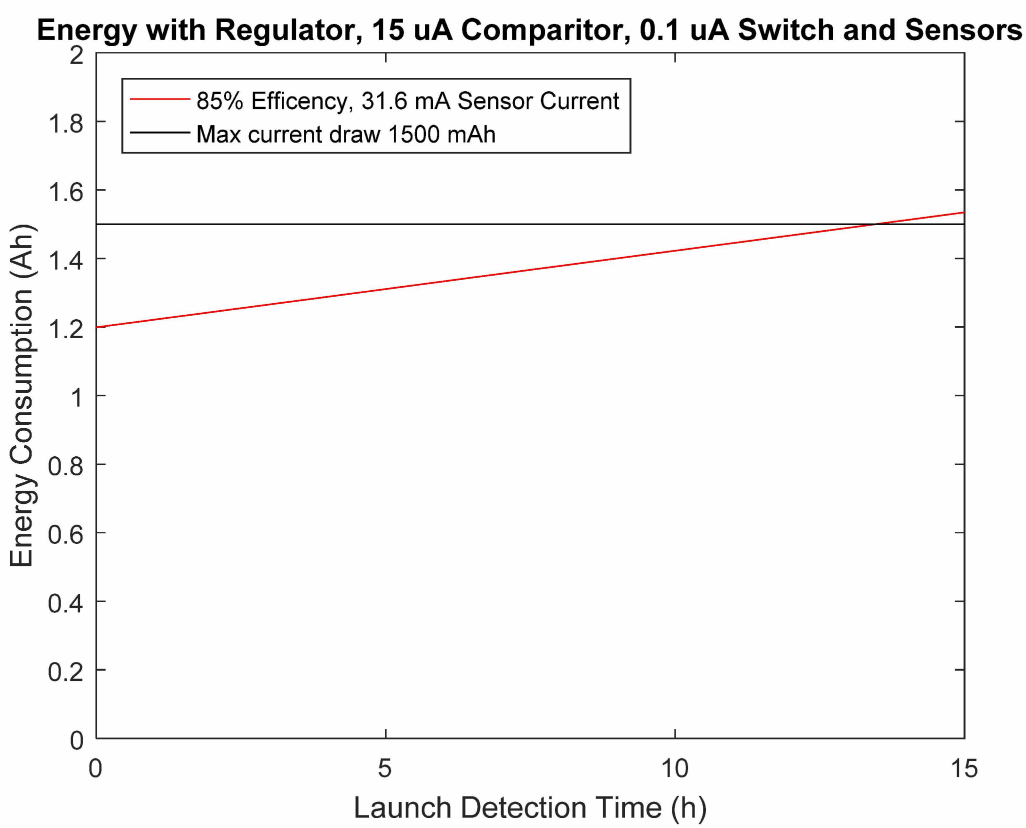


Figure 7.3: Final energy analysis for LEDL.

The analysis shows that with the sensor current of 31.6 mA and the 15 uA comparator the system can only achieve about 14 hours of launch detect before the batteries will be exhausted to the point of not having sufficient energy capacity for logging launch data. This includes the testing time of the LEDL system prior to satellite handoff and before rocket integration.

Each of the LEDL system components can be broken down to show where all the energy is being utilized for the system. Figure 7.4 shows the energy used by each component during the three modes (Idle Wait, Launch Detect, and Log Launch Data). The Idle Wait and Log Launch Data are represented by constant energy since the current energy consumption is fixed for the 6 months and 2 hours launch window. The Launch Detect mode time is still varied from 0 to 15 hours.

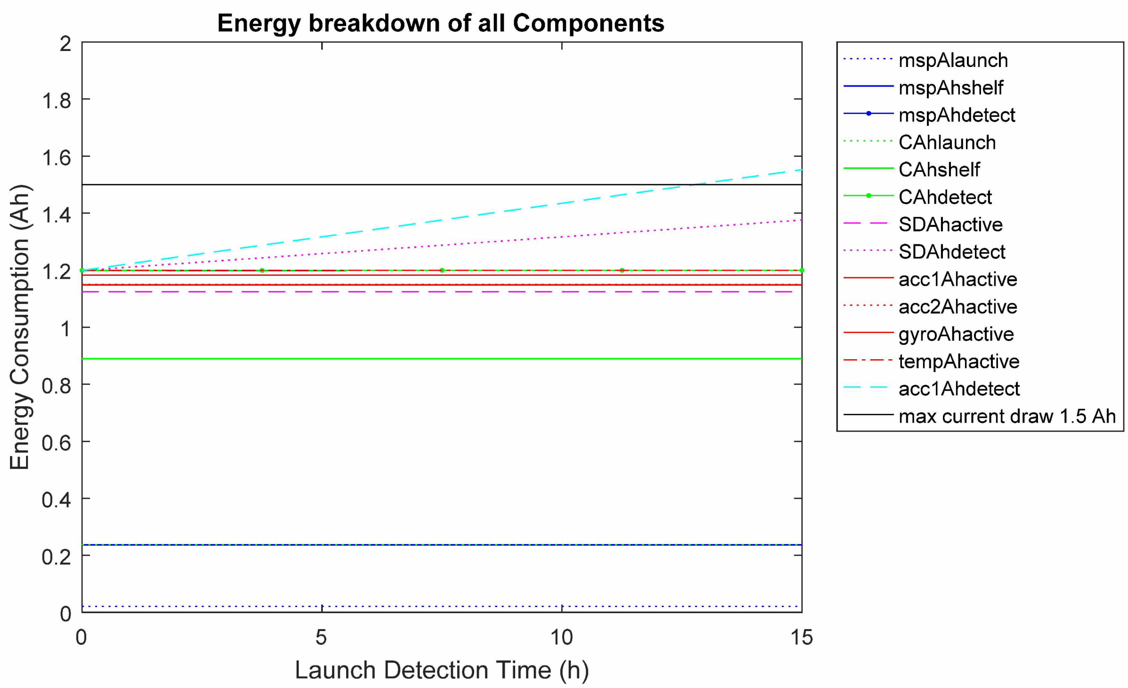


Figure 7.4: Energy breakdown of all components.

Figure 7.4 points out a lot of important details about the power consumption of the electronics. Each of the components shown represents additive currents, this allows for each part to be viewed separately. The microcontroller utilizes about 1/7 of the total power over the lifetime of the system. The comparator current takes up most of the power. It shows that it uses almost half of the total energy available for the LEDL system. If there are changes to the system the comparator should be one of the first parts addressed. Another change would be to address the current consumption of the SD card during launch detect. The LEDL system can save all launch detect data to the internal flash of the microcontroller instead of saving that data to the SD card to reduce power. Since it is only storing the environment conditions that triggered a launch and the SD card only wakes up every 9 ms for a 1 second period. Energy can be saved for increased longevity of the LEDL system by saving 0.2 Ah over the 15 hour launch detect window given to the system.

7.2 Future Hardware and Code Improvements

In the development of the next ARC satellite, there are changes that will be addressed for hardware and software improvements for the next LEDL subsystem. The main sensor to meet LEDL-007, ADXL321, is now obsolete. A new sensor has to be chosen to replace this one. Since the accelerometer has to be changed, a second consideration would be to change the accelerometer to a different type of sensor so that it would not be a MEMs device, a possible choice would be a piezo electric accelerometer. There was some concern in the ARC1 launch that the Helium used to coat the launch vehicle before launch would adversely affect how MEMs devices operate. The piezo electric accelerometers are not believed to be affected by the helium inside the launch vehicle. Changing both of the old sensors to these new sensors would remove four single axis sensors (70 G) and the two double axis sensors (18 G) and switch them to one three axis accelerometer each. The current consumption for these new sensors is also much less. For the accelerometers the current goes from 11 mA to 44 uA, a factor of 250 less current for just the accelerometers. This removes the need to have the sensor on the external solar panel boards and the sensors can be moved to the LEDL board. Another effect of switching the sensors is a reduction of traces that have to go to the external solar panel board so the connectors can be replaced with smaller connectors with fewer traces.

An additional improvement to the new ARC system is to upgrade the microcontroller. The upgrade from four to six communication ports allows the system to have an additional debugging interface and additional sensor communication options. The new microcontroller also has its own power management system that allows the microcontroller to switch between three possible power supplies. This would eliminate the need for the power switching circuit discussed in Chapter 3. In addition this system will also look into removing the comparator for future applications. The new microcontroller has an error registers that allows the use for error function protocols to keep track of the errors that accumulate in the software. This allows for better understanding of what has happened to the system when there are issues. Other updates to the code will allow for the system to become more streamlined which can make it more robust to less prone to failure points.

For ARC2, if LEDL applies all the changes discussed by removing the comparator sand the power switch, updates the sensors, and uses the new microcontroller that saves the launch data to flash memory instead of saving to the SD card has produced Figure 7.5. The big changes were the new crystal accelerometers only use 22 uA of current, and instead of there being 6 different accelerometers there are now only two. A new gyroscope was chosen that was a three axis, so it removed the need for two. The new microcontroller allowed for the switch to be removed and the comparator was also removed. Just these few changes made a huge difference on the total current consumption of the system. The system total current consumption is less than 0.5 Ah for the lifetime of the system. The LEDL system saved almost 0.5 Ah by saving to flash and changing the accelerometers, and saved another 0.5 Ah by removing the comparator. Investigating ways the system can save energy will be a focus on the next design of the system.

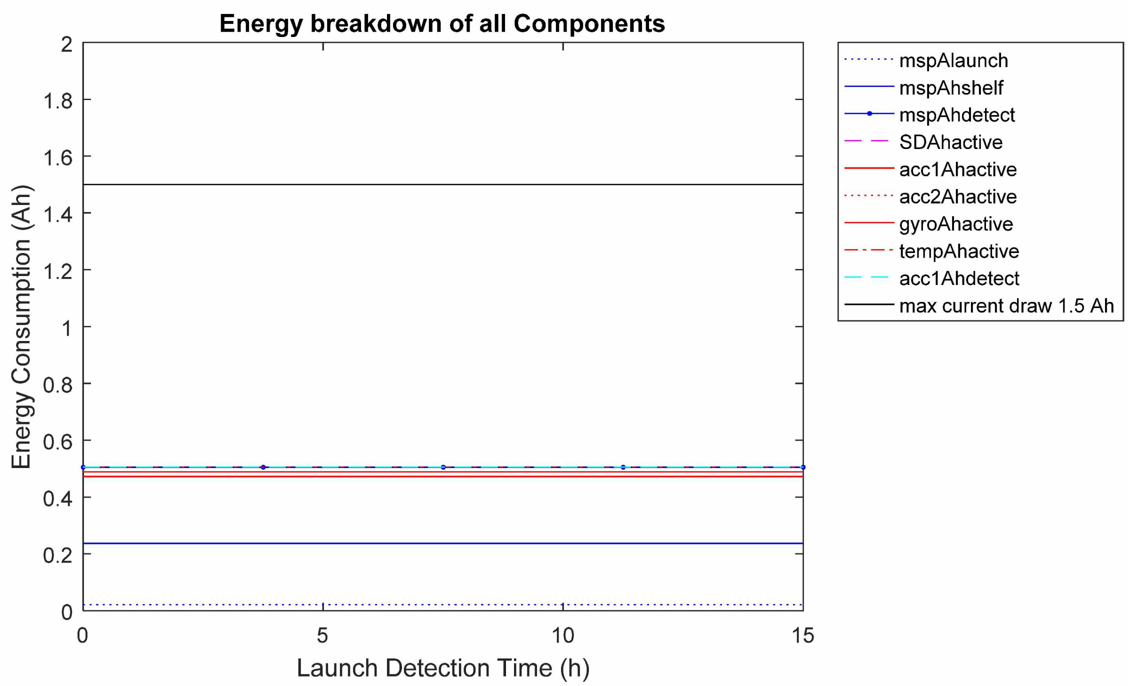


Figure 7.5: Energy breakdown of new components choices.

7.3 Future Testing

The LEDL system ran up against a tough deadline when the system was being finished. The satellite's timeline was up and the satellite needed to be delivered for launch. The LEDL system has only tested for functional verification as mentioned throughout this thesis. Additional testing which would better define the system would be useful for the long run of the mission to better understand the data that would be collected from the launch environment.

The LEDL sensors were all verified to work functionally prior to launch. The sensors compared to their datasheet and they provided measurements within the parameters listed. To have a better understanding of the data, calibration of the sensors in a controlled environment would provide detailed data of the sensors response to certain environmental conditions. These tests would provide great details about the sensors and would allow better accuracy in understanding the environment that CubeSats are placed into. These tests cannot be done at UAF due to not having the equipment needed for testing, perhaps outside resources can be acquired for these tests.

A test that would be useful to do would to see what range of frequencies the piezo tab will trigger an interrupt for the microcontroller. The first function test only swept through the first 350 Hz of the 2000 Hz frequency range expected through GEVS. A test is to determine what frequencies will turn on LEDL over the 2000 Hz would be beneficial to know without the aid of the comparator. By learning what frequencies can turn on the microcontroller from a low power mode will give a better understanding of what conditions will wake up the LEDL system prior to launch.

The last test that would be beneficial to do would be to verify the launch detect of the LEDL system. The vibration table cannot create a sustained acceleration greater than 2 G. The net acceleration of the vibration table is 1 G, equivalent to earth gravity. This test would require outside resources to generate a test that could simulate a launch condition of a launch vehicle, which is something that UAF cannot do.

Detailed tests that should be done will be to assess the actual battery lifetime of the LEDL system. The test should examine the energy capacity for the battery at different expected loads for the LEDL system. The input voltage can be adjusted to the expected battery voltages and the power can be measured at the input and output of the regulator to determine how the efficiency can change based on the voltages expected from the battery. This will provided a better understanding how the battery life is affected by the current draw of the subsystem.

7.4 Conclusion

The final LEDL prototype system was a success. The baseline system was developed and using new technology will help the next generation to be a better system that lasts longer using less energy. This system was successfully tested will be a great asset to NASA providing the environment data from inside the launch vehicle. The suggested changes will create a better design that will be validated prior to launch so that we can know that the system will be a success. By further understanding how the power system operates and how much energy the system consumes over the lifetime of the LEDL, this system can be optimized to last on the shelf longer and have extra time to detect launch. By optimizing this system and applying the proposed changes, the LEDL system will be able to meet its objective and successfully finish its mission by providing launch data from the launch vehicle.

Appendix

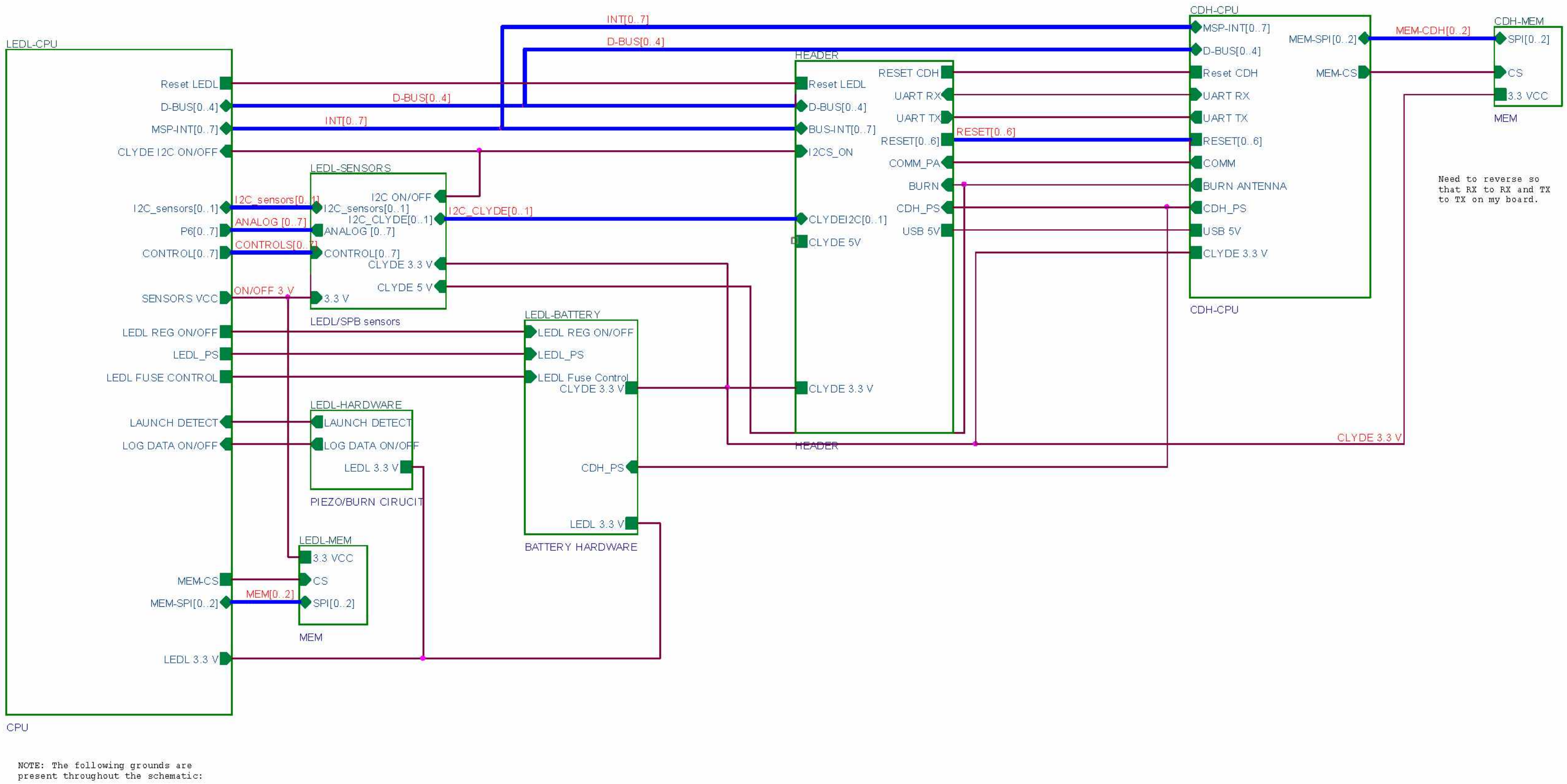


Figure A.1: Hierarchal block of upper level schematic.

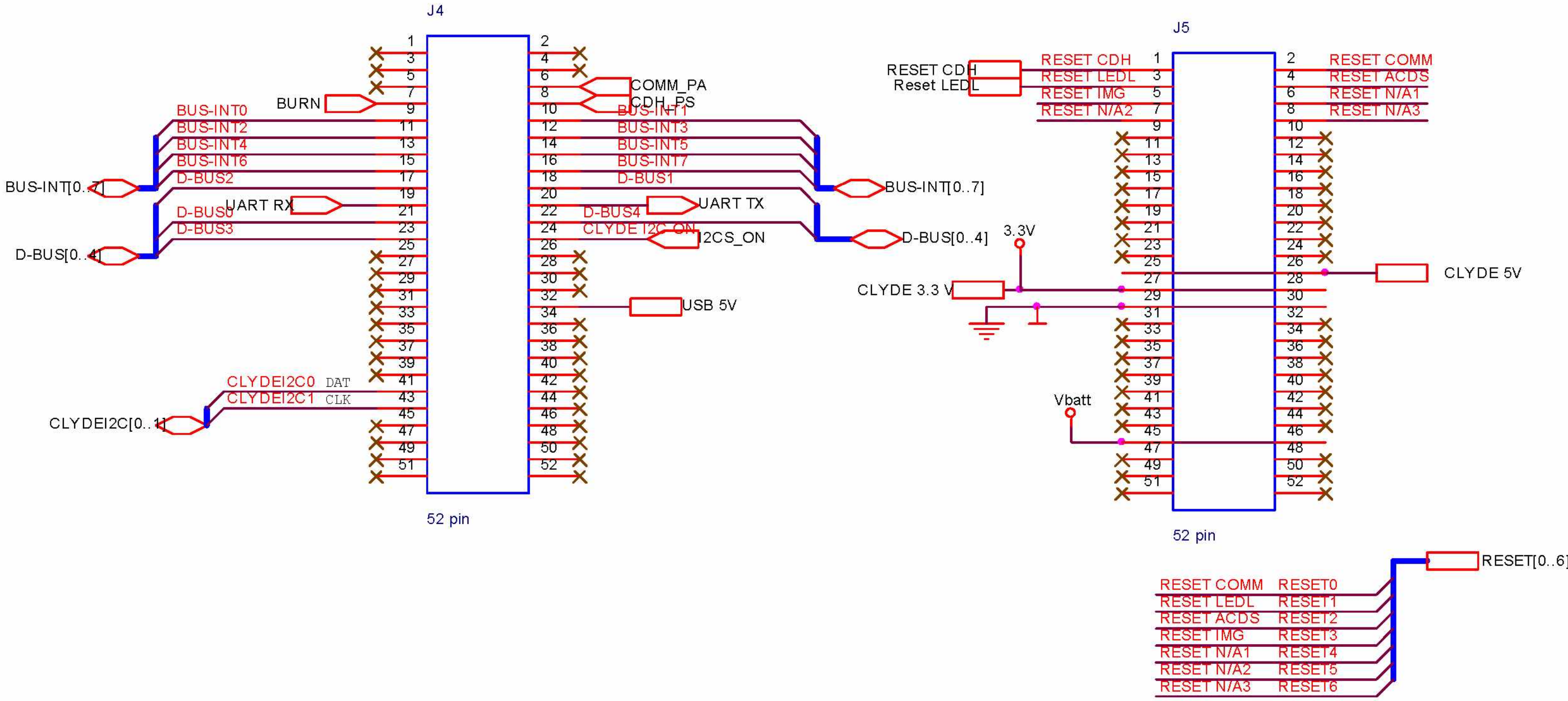


Figure A.2: Header pins of satellite back plane.

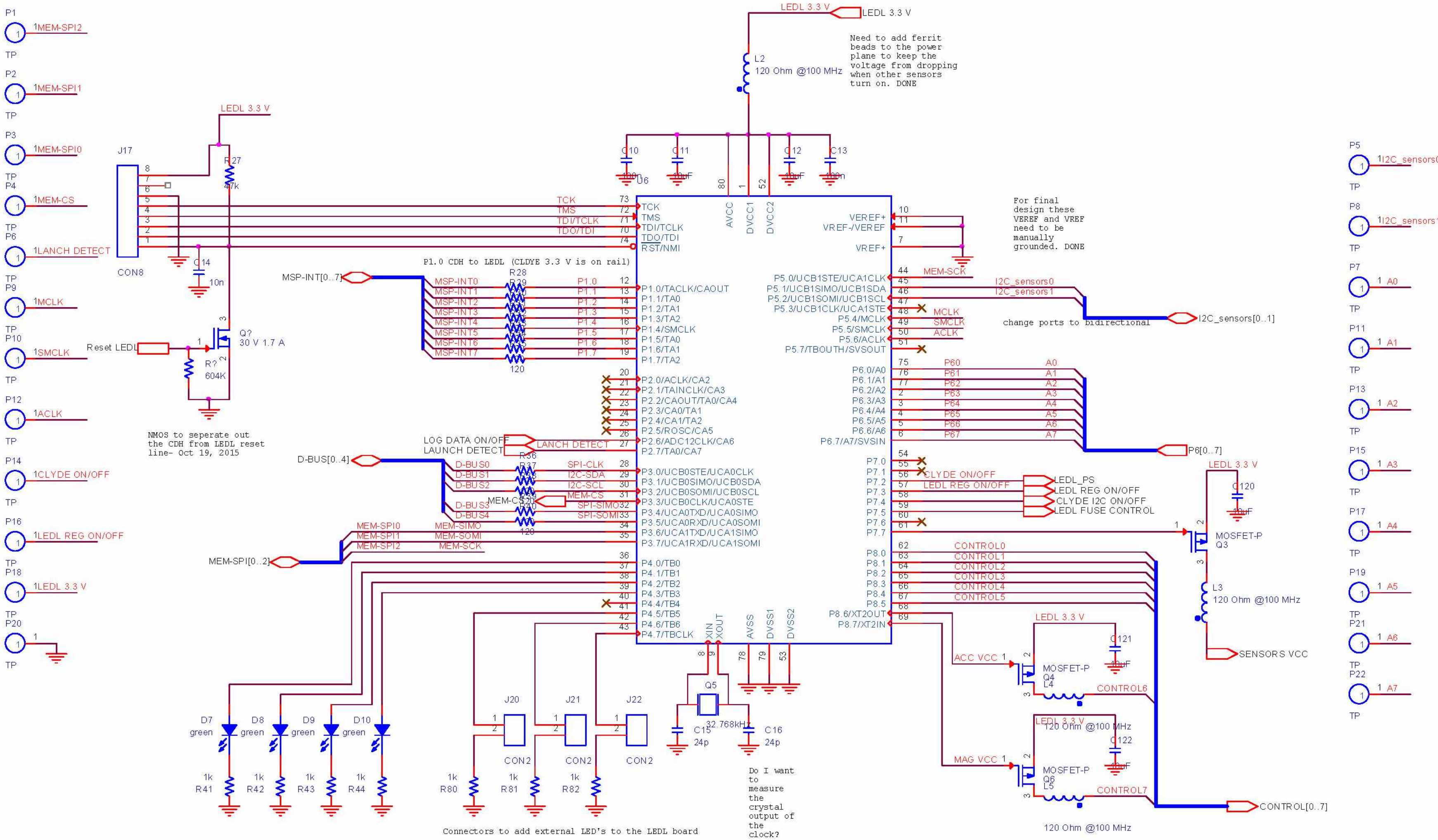


Figure A.3: LEDL microcontroller schematic.

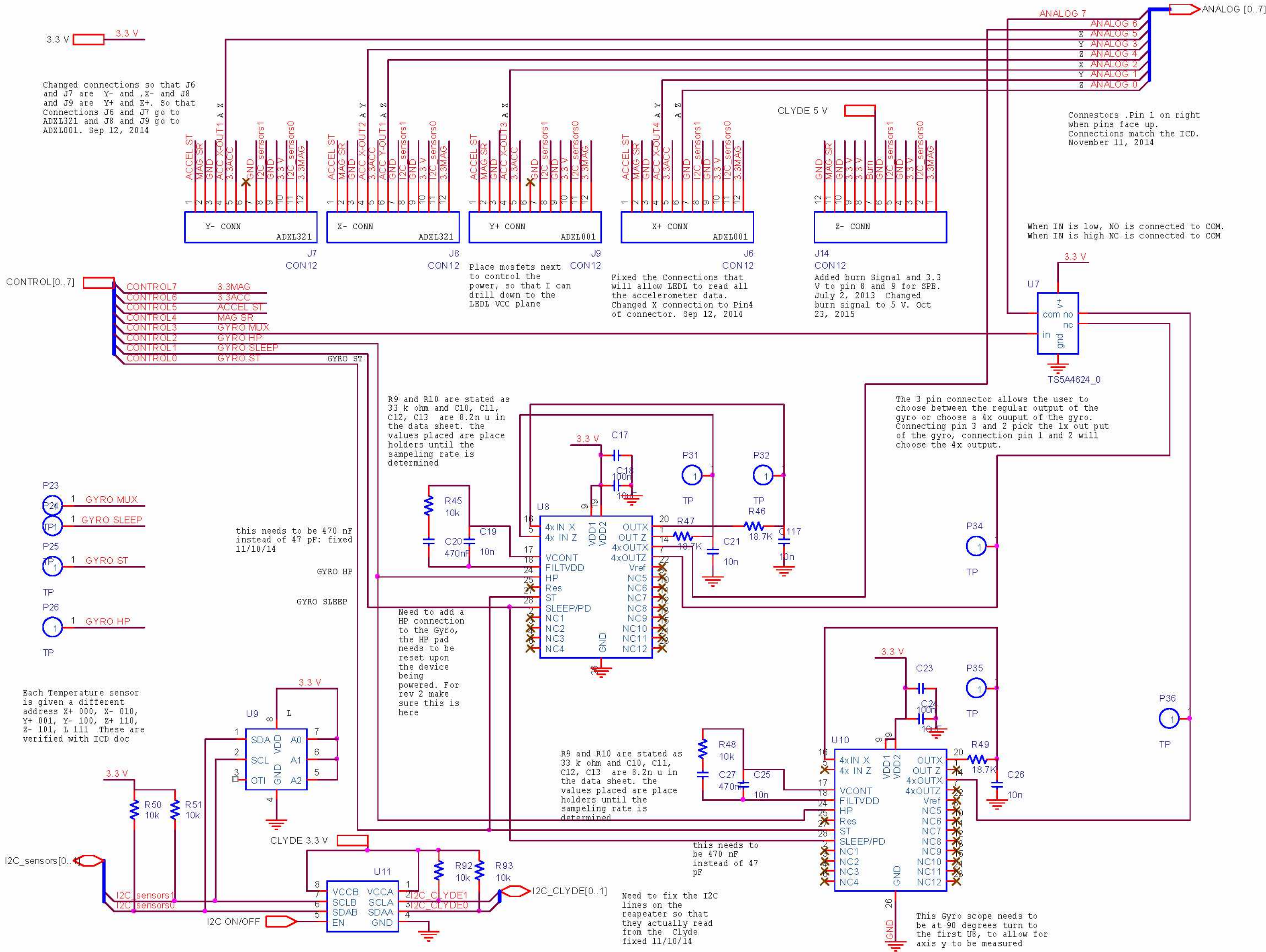


Figure A.4: LEDL sensor interface schematic.

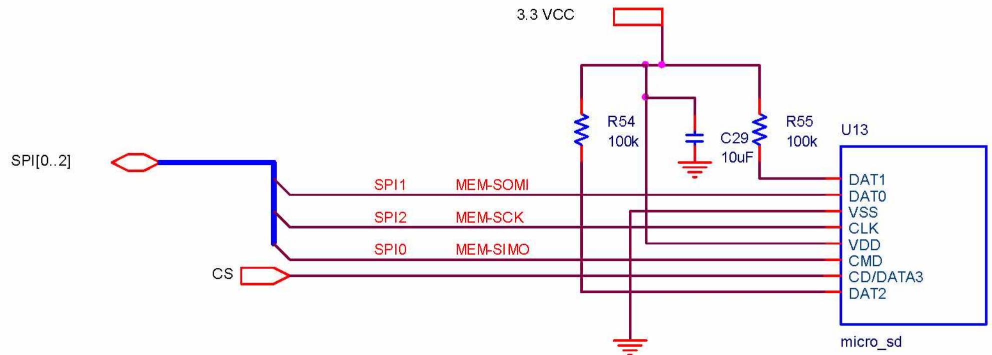


Figure A.5: Memory card schematic.

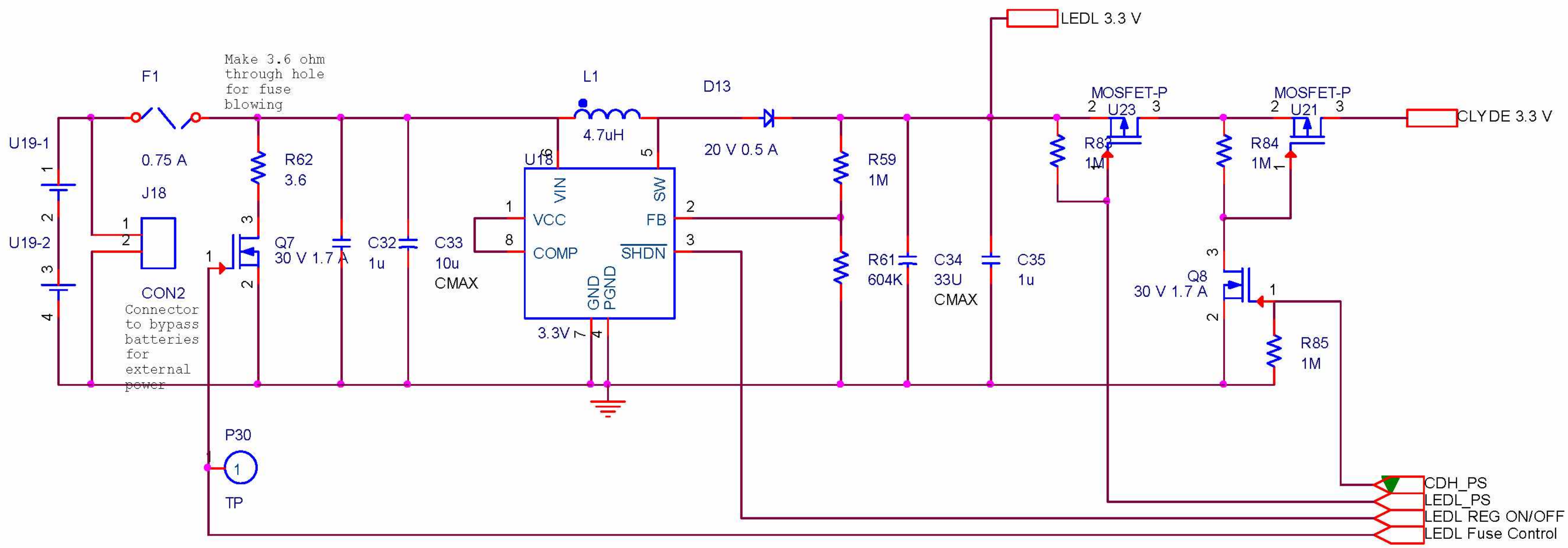


Figure A.6: LEDL EPS schematic.

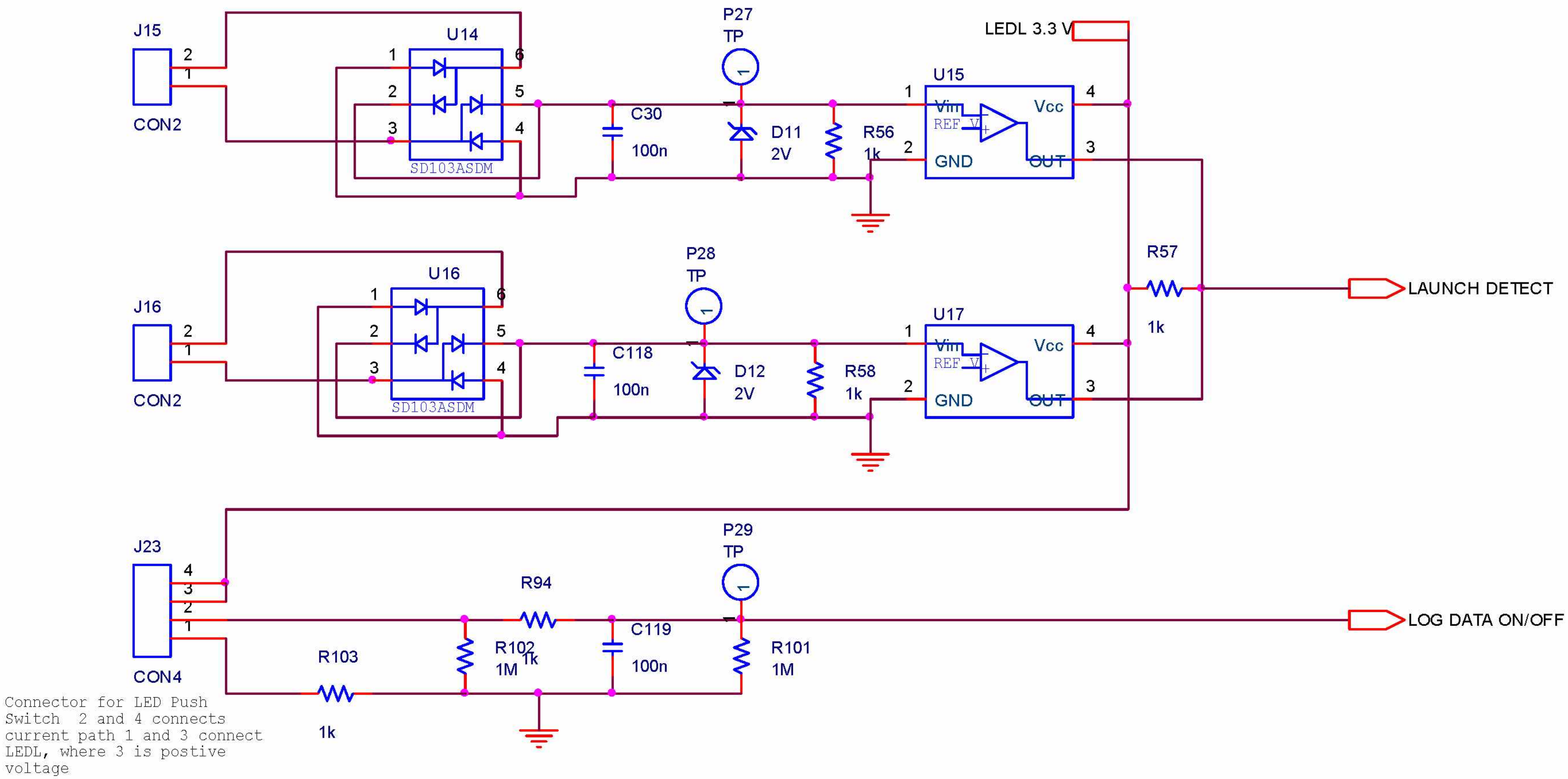


Figure A.7: LEDL piezo electric circuit.

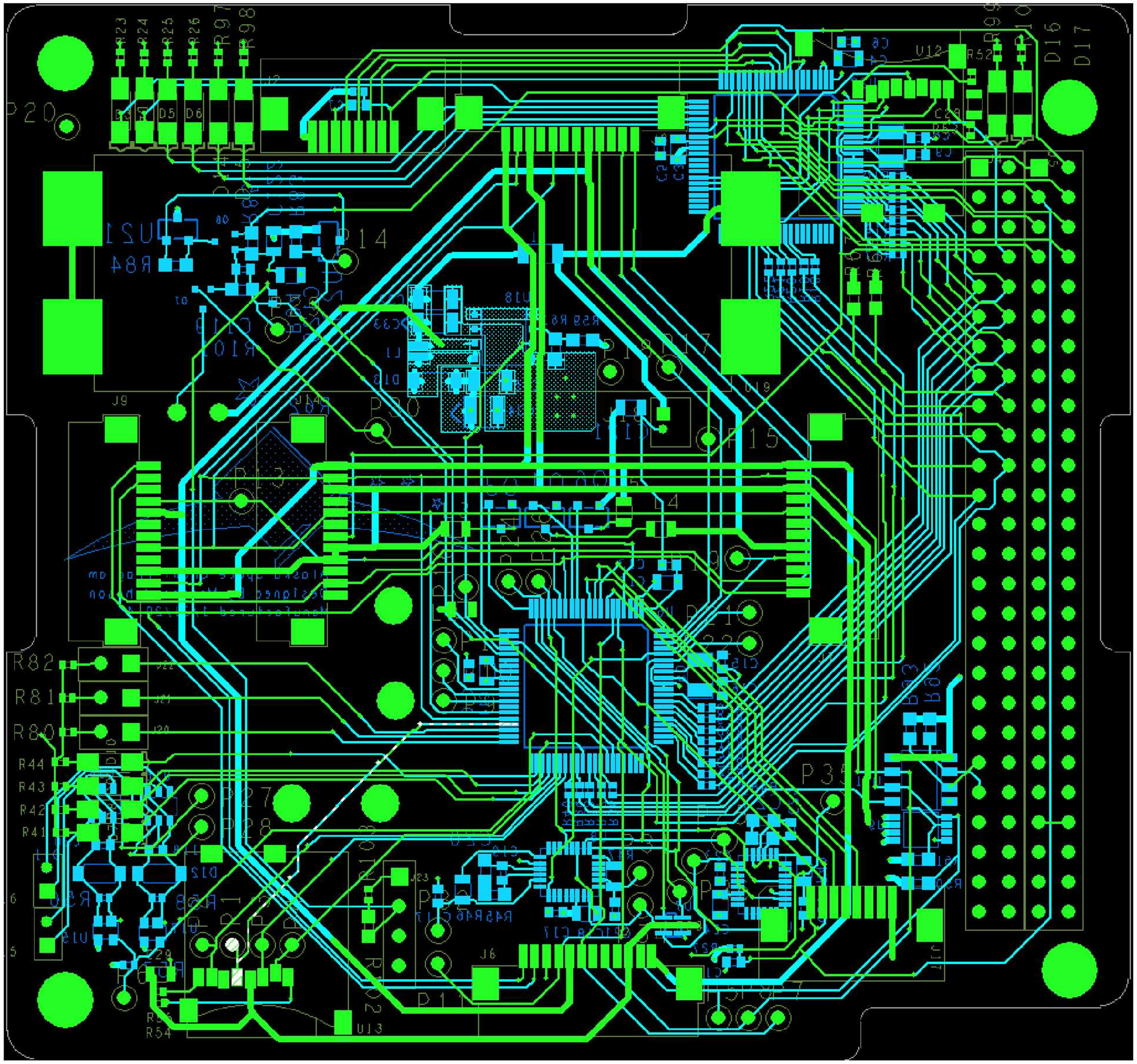


Figure A.8: LEDL board layout.

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