Development of a Highly Integrated Communication System for use in Low Power Space Applications

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Master of Science in Aerospace Engineering

By

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AUTHORIZATION

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ABSTRACT

Development of a Highly Integrated Communication System for use in Low Power Space Applications

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Picosatellites, restricted in power, mass and volume, provide incredible educational opportunities and challenges for engineering students.

With the completion of Cal Poly's first satellite, CP1, Cal Poly's Picosatellite Project (PolySat) started its second satellite, CP2. The CP2 team wanted to develop a generic bus capable of supporting a wide variety of payloads. To this end, CP2 required significant improvement from the CP1 design.

A key area for improvement was the communication system. Designed and built by undergraduate engineering students at Cal Poly, the communication system for the Cal Poly Bus (CPB) is highly integrated and efficient. The fully redundant digital communication system and the Telemetry, Telecommand, and Control (TT&C) system have been incorporated into a single printed circuit board, increasing the flexibility of the bus.

This thesis outlines the objectives and requirements of the CPB's communication and TT&C systems and describes how those requirements are met in the design. It also discusses lessons learned and applied from CP1, the development methods employed, and modifications for in-orbit operations. Additionally, this thesis explores potential weaknesses in the design and presents test results to provide a characterization of the system.

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1 Introduction

Currently, the Aerospace industry is seeing an explosion in the demand for small satellites. However, rather than simply miniaturizing larger satellites, a number of university projects are dramatically reshaping satellite design by developing small satellites from the ground up. The main goals of theses projects are to quickly develop small and cheap satellites to be launched and operated within the academic career of a student [2]. With these goals in mind, new and interesting engineering challenges are presented to students to be solved.

1.1 CubeSat Project Overview

Started in 1999, the CubeSat Project is a collaborative effort between California Polytechnic State University, San Luis Obispo's Multidisciplinary Space Technology Laboratory, and Stanford University's Space Systems Development Laboratory. The objective of the project is to provide a learning mechanism for students to work on multidisciplinary teams and see the entire life cycle of a satellite project from requirement definition through development, testing and finally, mission operations. The CubeSat objectives are achieved through the development of a standard platform for the design of picosatellites. To make the platform viable, a common deployer needed to be developed that could interface the CubeSats with various launch vehicles, significantly reducing cost, decreasing development time and allowing frequent launches. As a result, numerous corporations, colleges, and universities from around the world are developing and launching picosatellites without having to interface directly with launch providers. [2]

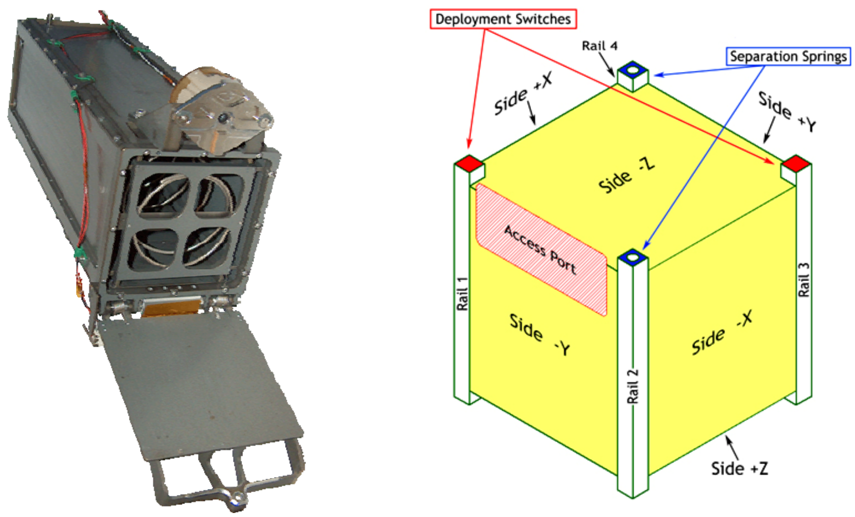

Figure 1.1.1 – P-Pod and CubeSat Specification Drawing

CubeSat developers must follow the standard, which specifies each satellite as a 10cm cube with a maximum mass of 1kg and provides additional guidelines for the location of a diagnostic port, remove-before-flight pin, and deployment switches [3]. The purpose of the specification document is to ensure that each satellite will integrate properly with the deployer and with neighboring satellites within the deployer, and that no satellite will interfere with neighboring satellites or, more importantly, the primary payloads or launch vehicle (See Figure 1.1.1).

In addition to maintaining the CubeSat standard, Cal Poly has designed, fabricated, tested, and launched deployers, called Poly Picosatellite Orbital Deployers (P-PODs), capable of deploying up to three CubeSats each (See Figure 1.1.1). Two P-PODs were used in 2003, for example, to successfully deploy six CubeSats. As the developer of the CubeSat standard and the P-POD, Cal Poly is also taking a leading role in coordinating launch opportunities for CubeSats, thus allowing developers to focus entirely on the design, construction, and testing of their satellites. Curently, Cal Poly has organized two launches. The first will launch fourteen CubeSats from mostly university developers in June of 2006. The second will launch seven CubeSats, again from mostly university developers, in August of 2006. Both of the launches coordinated by Cal Poly will be launched from Kazakhstan.

1.2 PolySat Project

Also in 1999, a multidisciplinary team of engineering students founded Cal Poly's Picosatellite Project (PolySat). This team designed, constructed, and tested CP1, Cal Poly's first satellite (See Figure 1.2.1). CP1 conforms to the CubeSat standard. Because CP1 was Cal Poly's first satellite, the team took a minimalist approach in its design, creating a very simple system that would be able to satisfy minimal mission requirements. To this end, the team developed five key design principles [6]:

- Design CP1 to meet the specific mission needs, not industry convention
- Use commercially available technologies and components whenever possible
- Replace hardware with software to minimize power consumption and design complexity
- Use simple redundant methods when possible
- Integrate systems to simplify design and reduce parts count

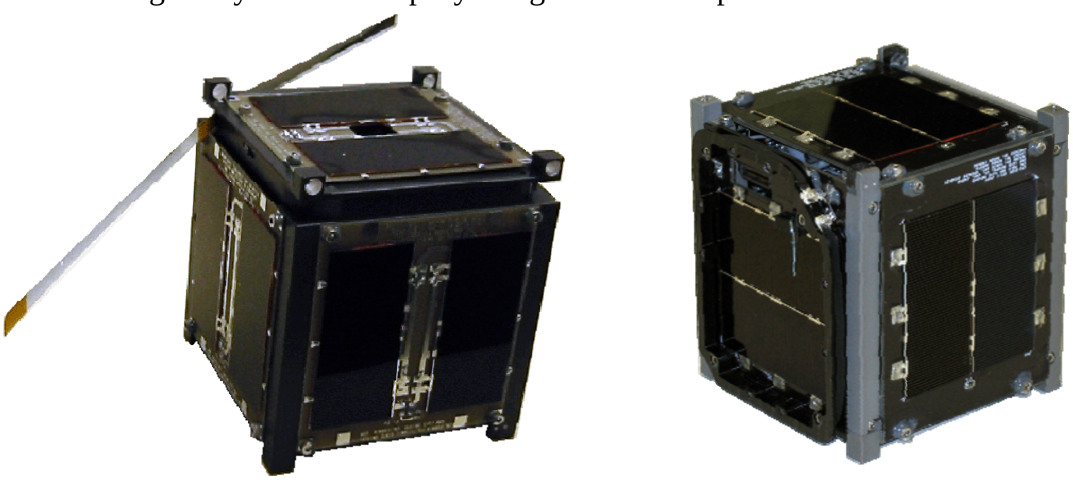

Figure 1.2.1 – CP1 (Left) CP2 (Right)

With the completion of CP1, a new team began work on Cal Poly's second satellite, CP2 (See Figure 1.2.1). Although CP1 was a reliable and efficient system, it was specifically designed around a specific payload. The fundamental aim of CP2 was to design a generic bus able to support a wide variety of payloads while keeping in mind the design principles developed for CP1. The development of a standard bus demanded significant improvement beyond the CP1 design. Some specific areas for improvement are the communication system as well as the telemetry, telecommand and control subsystem. This thesis will explore and provide recommendations for further improvement of the communication and the Telemetry, Telecommand, and Control (TT&C) subsystems developed for the Cal Poly bus (CPB) from their origins in CP1 through development and final testing.

1.2.1 Lessons Learned from CP1

In developing the communication and TT&C subsystems for the CPB, it was important to leverage the existing experience of the team by first investigating the systems designed for CP1.

1.2.1.1 Complete Off-the-Shelf Approach

Radio frequency (RF) designs are challenging, requiring significant amounts of time, resources, and knowledge to develop, so many CubeSats use complete Commercial-Off-The-Shelf (COTS) products in their communication systems. This approach was taken with CP1's communication system, which uses a modified Alinco DJ-C5T handheld FM transceiver (See Figure 1.2.2). Depending on the system requirements -- data rate for example -- the best solution for a CubeSat design may be to use a COTS radio as with CP1.

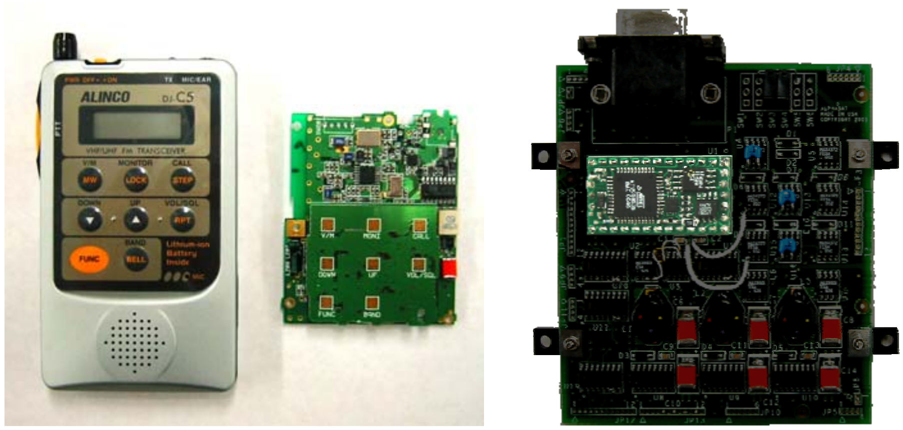

Figure 1.2.2 – Alinco Handheld Radio (Left) BasicX-24 (Right)

In addition to a COTS radio, CP1 uses a COTS microcomputer module at the core of the TT&C subsystem, the Netmedia BasicX-24 (See Figure 1.2.2). The use of this module allows most of the functionality of the TT&C subsystem to be provided in software. Consistent with the design principles of CP1, software solutions were provided to problems typically addressed with hardware wherever possible, without reducing the reliability or functionality of the system [6]. While the module adds to the complexity of the software, it adds many benefits because it weighs very little, requires very little space, and doesn't use much power.

1.2.1.2 CP1 Communication System Overview

CP1 communicates on amateur radio frequencies using a combination of Morse Code and Dual Tone Multi-Frequency (DTMF) to encode data that is then frequency modulated by the Alinco transceivers. CP1 uses two transceivers for redundancy. The command computer alternates between them on each communication cycle. The two transceivers are linked to a single dipole antenna through a custom RF printed circuit board (PCB). This PCB takes the output of both transceivers and switches the two signals as commanded by the main flight computer, which allows both transceivers to access the single antenna. Additionally, this RF PCB matches the impedance of the two transceivers to the antenna. CP1 uses the proven method of melting a nylon line with Ni-Chrome wire to deploy the antenna. The dipole antenna is constructed from steel measuring tape mounted directly to the RF PCB. [6]

The CP1 flight computer replaces the need for a hardware terminal node controller (TNC), or modem, by generating the Morse Code and DTMF tones in software. The microcontroller used has built-in functions for providing DTMF and single-tone signals from any digital output [6]. This audio signal is then sent to the microphone input of the transceiver.

Morse Code is used to identify transmissions while allowing operators to tune to the correct frequency, and DTMF data is sent at 15 characters per second. Compared to digital systems, DTMF is extremely slow, with a data rate of 60 bits per second (bps) [6]. However, CP1's mission does not require high data rates because there is not a large quantity of data to be transmitted. Despite its relative simplicity, the CP1 communication system is highly efficient.

1.2.1.3 Telemetry Telecommand and Control Subsystem Overview

The command computer for CP1 is the Netmedia BasicX-24 microcomputer module. The BasicX device has 400 bytes for RAM, 32kB of EEPROM and includes 16 input output (I/O) pins, eight of which are also analog inputs. All of the devices are contained on a single 24-pin DIP module.

At the core of the module is an Atmel 8535 RISC microcontroller running at 8MHz. The use of this microcontroller allows a programming environment that provides a comprehensive library of high-level commands. Additionally, the operating system used is capable of multitasking and can perform floating-point math, thus significantly reducing the learning curve and development time for both hardware and software. [6]

To provide diagnostic and so-called housekeeping data, several temperatures, voltages, and currents are monitored by the microcomputer. The temperature of each solar panel, the primary and secondary batteries, the transceiver, the DC-DC converter, and the command computer are all monitored. Additionally, the solar panel, primary battery, and secondary battery voltages and currents are monitored during several operating modes. To interface all of these analog lines to the command computer, four CD4051 analog multiplexers are used, allowing thirty-two channels to occupy only four analog inputs on the BX-24. [6]

Several auxiliary functions are also handled by the command system. These include the acquisition of data from the payload and the electronic controls for the antenna release.

1.2.1.4 System Limitations and Benefits

While the systems created for CP1 are innovative, they are by no means perfect. Several points should be made regarding the limitations and benefits of the design.

First, the COTS approach forces many critical parts of CP1 to be treated as a black box, since many of the inner workings of the radio and microcomputer are unknown, thereby increasing the difficulty in troubleshooting, particularly in an integrated system. Furthermore, the transceivers and microcomputer needed to be "ruggedized" to survive both the space and launch environments. Additionally, the CP1 structure needed to be designed around the form factor of the BX-24 microcomputer and Alinco transceivers.

Second, the DJ-C5T is simply an FM transceiver. Consequently, a separate TNC is required to encode data. Due to the limited space available, the encoding is implemented in software. The software TNC is limited because of the processor's constraints and the inefficiencies in the software implementation, which results in low data rates. In addition, the Alinco uses a monopole antenna with a 75 ohm impedance, while the rest of CP1 uses 50 ohm impedances. To resolve this discrepancy, the transceiver needed several modifications.

Finally, the microcomputer uses a very high level programming language, creating inefficiencies in the software implementation. This inefficiency can limit system performance.

Although CP1 has several limitations, these are outweighed by the reliability of the system and its ability to meet the mission requirements. Specifically, using a commercially available radio, providing simple redundancy to mitigate risk with two transceivers, and using a software TNC and microcomputer to replace hardware meet the design principles of CP1.

2 Cal Poly Bus Requirements

In any system development process, one of the first and most important steps is the development of system requirements. The system level requirements then drive many of the lower level requirements at the subsystem and component levels. This section outlines the defined requirements for the CPB as well as the communication and TT&C subsystems.

2.1 Objectives of the Cal Poly Bus

The aim of the CPB (See Figure 2.1.1) is to provide a platform or bus capable of supporting a wide variety of payloads. To this end, the design needs to be flexible. The most important factor in a flexible design, given the constraints of a CubeSat, is the need to maximize the power, mass, and volume available to the payload. Specifically, the team required that one third of the available power, mass, and volume be allocated to the payload. Given these requirements, the CPB's design needed to be much more flexible than CP1's, while keeping mind the design principles: replacing hardware with software, integrating subsystems as much as possible, simplifying the overall design, and using commercially available components. Additionally, the aim of university CubeSat projects is to promote education through a "learn by doing" methodology. A good method of learning about spacecraft system design is designing a new system.

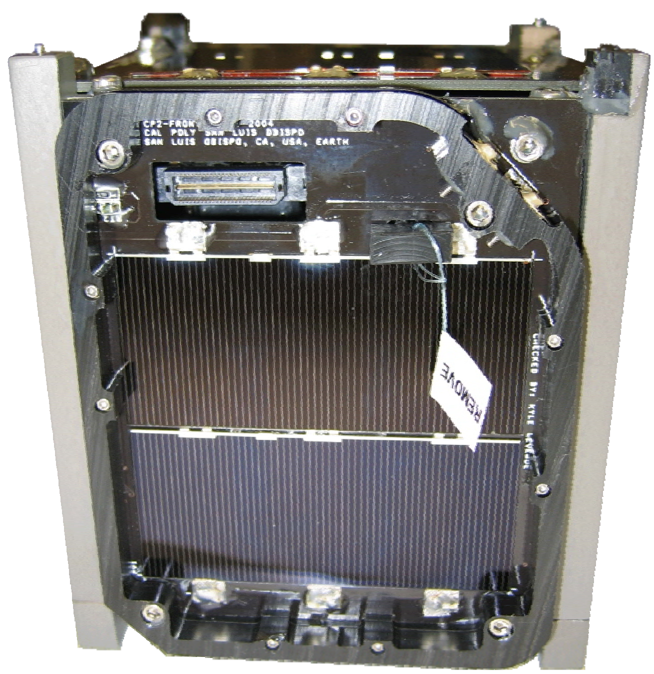

Figure 2.1.1 – CP2 Front Face with Antenna Route

2.2 Communication System Requirements

Understanding the differences between CP1 and the CPB, while keeping in mind the basic design principles, was critical to gain perspective on the requirements for the CPB's communication system. Additionally, achieving a careful balance between complexity, performance, and reliability is key to a successful system design. If the benefit of a complex system does not outweigh the required investment in time, resources, and space, it should not be implemented.

Given the CubeSat specification and the aim of the CPB, each subsystem must be designed to minimize the power, mass, and volume consumed, while maintaining an acceptable thermal range. Specifically, the power consumption of the communication system was limited to 3.5W peak.

CubeSat developers are required to coordinate with regulating bodies to be allocated a specific frequency for communication. The Federal Communications Commission (FCC) provides requirements for such frequency allocation and licensing. Receiving an allocated frequency from the FCC is time-consuming, expensive, and often beyond a university project's ability. In order to address the frequency coordination issue, the communication system uses amateur radio frequencies. Access to these frequencies is restricted to non-profit organizations that contribute to the amateur radio community.

Using amateur radio frequencies increases the teams' ability to operate the satellite. The amateur radio community has operators world-wide who can downlink data from the spacecraft, provided the satellite uses some standard method of communication. For this reason, the system was required to use the AX.25 protocol. This AX.25 protocol requires a digital system, allowing signals to be processed and modified in the digital domain through the use of software instead of hardware, which would be impossible with a purely analog system. Developed by the amateur radio community, AX.25 is a simple and reliable protocol, requiring little overhead and allowing reasonable data rates [4].

Exploring possible payloads for the CPB, the maximum expected data transmission size was found to be 40 kB [4]. Given the limited communication window of variable length for satellites in low earth orbit (LEO), and the maximum data size, the data rate required for the spacecraft can be determined. CubeSats are secondary payloads; therefore, orbit selection is limited, making design for the worst-case scenario critical. Rough calculations given the orbital parameters for a typical CubeSat launch opportunity yield a worst-case communication window with a single daily pass of 5 minutes. Specifically, the orbit analyzed is sun-synchronous with a 650-700 km altitude and a 98° inclination. This limited communication window requires a data rate of 1093 bps. Standard data rates for amateur radio frequencies are 1200 bps and 9600 bps. Therefore, the system was required to have a minimum data rate of 1200 bps.

2.3 Telemetry, Telecommand and Control System Requirements

The Telemetry, Telecommand, and Control (TT&C) system coordinates data flow, while processing commands and collecting critical diagnostic and housekeeping information for the spacecraft. TT&C must have the ability to simply communicate with the payload, the communication system, and the more than 80 sensors spread throughout the spacecraft, using minimal power. Additionally, the TT&C system needs to store the data while responding to the dynamically changing state and environment of the spacecraft while in-orbit.

TT&C is fundamentally the central nervous system for the CPB. As such, the TT&C system must be robust and failure-tolerant, allowing the spacecraft to complete its mission despite potential hardware failures. For example, a failure of a specific sensor or group of sensors should not cripple the entire system.

3 System Design and Implementation

Once requirements have been established, designers have a preliminary specification to design to. This section outlines the design created to satisfy the system requirements.

3.1 Design Approach

A common approach in CubeSat development is to use COTS elements when possible, particularly for communication systems (see Table 3.1.1).

Table 3.1.1 – Communication System Comparison [4]

Project	**Band (MHz)**	**TNC**	**Transceiver**	**Power Output (W)**
CANX-1	900	--------------	CMX469	0.5
DTUSat	440	--------------	CMX469	1.0
Voyager	440	PIC16 + MX614	VX-1R	0.5
MEROPE	144/440	PicoPacket	VX-1R	1.0
XI	144/440	PIC16	Nishi RF	0.8

The use of COTS radios is a good design choice for many CubeSats, depending on the CubeSat's requirements. There are many variables and a significant learning curve to overcome when developing a communication system. However, the largest disadvantage to a complete COTS radio approach is the inability to design a highly integrated system, as there are inherently erroneous and extra elements in a complete COTS component. Developers would have to incorporate a black box into their overall system design, creating inefficiencies in power, mass, and volume. As such, the requirements of the CPB would not allow the use of a COTS radio. Specifically, the requirement to allocate one-third of the spacecraft mass and volume to the payload precluded the use of a COTS radio, given the teams' experience with CP1.

The communication system for the CPB must be highly integrated to achieve the required one-third available power mass and volume to the payload. The only way to achieve this level of integration is to use COTS components in a custom RF design, thereby leveraging the power of developments in the wireless industry to our advantage. Cell phone companies are creating products capable of RF communication with similar power, mass, and volume constraints; clearly, this technology can be incorporated into our design.

Additionally, given the large number of housekeeping sensors throughout the CPB, it would be impossible to find a COTS TT&C system to use. Therefore, the TT&C system would also need to be a custom design. Advances in microcomputer technology will allow the use of low power and small sized microcontroller and data acquisition components.

While creating the custom designs for the TT&C and communication systems, it is critical to keep in mind the design principles from CP1. Specifically, it is important to integrate as many systems as possible and replace hardware with software.

3.2 Trade Studies

Given the design requirements and constraints, it is only through the use of COTS components that the CPB systems can be realized. CubeSats must be small; moreover, they have short mission lives and are budget-limited. COTS components, compared to space-rated or radiation-hardened components, enable higher performance at a reduced cost [7]. The tradeoff, however, is increased risk of component failure.

3.2.1 Architectural Trades

Trade studies at a high conceptual level are critical in establishing a clear understanding of how the system will work. For this reason trade studies at the system level are performed. Specifically, the question of system redundancy and the number of PCBs are traded.

3.2.1.1 Redundancy

COTS components used in CubeSats are typically not space-rated and therefore have a higher risk of failure. The risk of component failure can be mitigated in several ways, including testing and implementing redundancy into the system design. Although testing cannot show all potential failures of the system, testing can and should be done at each level of the system to expose potential failures early on. Redundancy can provide functionality even with some failures. Given the limited resources of the spacecraft, a careful balance of complexity and performance needs to be reached. Developing redundant systems can greatly increase the complexity of the entire spacecraft and may or may not provide much benefit. Therefore, redundancy should be used only to mitigate the greatest risks.

Evaluating risk is difficult for engineers with twenty years of experience, and even more challenging for graduate students. Given the critical nature of the communication link and the TT&C system, the risk of a failure for either system needs to be greatly mitigated. Both the communication and TT&C systems are complicated and therefore the use of redundancy should be carefully considered and only implemented if it results in a clear reduction in risk and an increase the overall reliability of the system.

The TT&C system spans throughout the spacecraft and has sensors in every subsystem. The communication system, however, is much more isolated and can be localized to a specific area of the spacecraft more easily. The ability to localize the system makes it less complicated to implement redundancy into the communication system than it would have been in the TT&C system. Implementing a redundant communication system helps to ensure that data can be downlinked from the spacecraft, as a communication system failure would have a more significant impact than a TT&C failure. If the TT&C system fails the mission may still be completed, depending on how the TT&C system is implemented. For example, the communication system could interface with the payload directly collecting and sending data to earth, removing the need for the TT&C microcontroller if it were to fail. In essence, the communication system's microcontrollers provide limited redundancy in the event of a TT&C failure.

Given the ability to possibly complete a mission with limited TT&C functionality, provided by the communication system, and the TT&C system's complexity, which spans the entire spacecraft, making the complete TT&C system redundant does not provide a clear benefit to the reliability of the spacecraft. However, redundancy within both the communication and TT&C systems can and should be used to increase their fault tolerance.

If the communication system were to fail, there is little chance for a successful mission. Additionally, the communication system can be designed such that it can take some responsibility from the TT&C microcontroller in the event of a TT&C failure. Also, the communication system is more modular and isolated than the TT&C system, allowing a redundant system to be implemented more easily than it could be in the TT&C. Therefore, the communication system is required to be redundant, but not the TT&C system.

3.2.1.2 Single Printed Circuit Board Design

Following the design principles from CP1, systems should be integrated as much as possible to reduce mass, and volume while improving reliability by reducing the number of interconnects between boards. Therefore, each printed circuit board (PCB) should include multiple subsystems. After careful analysis it was decided that the core of the TT&C system needed to share a PCB with the fully redundant communication system. Incorporating both subsystems onto a single PCB is only possible through the use of components optimized for micro-applications. The decision for these subsystems to share a single PCB means that the core functionally of the satellite can be contained in two PCBs, allowing roughly sixty percent of the available volume to be allocated to the payload.

3.2.2 Component Trades

In the development of the system it is important to explore a multitude of options for each needed component. This section explains the process used in the selection of the components used in the CPB.

3.2.2.1 Microcontrollers

Given the complexity of the software involved in both the TT&C and communication systems, it is important to use as much of the same hardware as possible to reduce the learning curve in becoming familiar with the microcontrollers used. [1]

The key features of the microcontroller needed in the system include the ability to operate at three volts, at least one kB of RAM and 65 kB of ROM, the ability to interface with Inter-IC Communication (I^2C) devices, and multiple general input / output (GI/O) pins. [1]

Two families of microcontrollers were considered for use in the CPB: the PIC 18 family from Microchip and the 8051 family from Silicon Laboratories. The 8051 family is designed for low power, automotive, appliance, and robotic applications. High-end models of this family meet the outlined requirements including 128kB FLASH memory, 8.4kB of RAM, and a four mA current consumption when operating at an average of 2MIPS at three volts. Additionally, the 8051 family processors include a single cycle eight by eight multiplier engine for faster data processing. [1]

The Microchip PIC18 family of microcontrollers are highly integrated, available with on-chip FLASH memory and static RAM as well as built-in serial and parallel peripheral interfaces. The PIC18LF6720 has a 256 kB of FLASH memory for program storage, 4kB static RAM for run-time variables, support for the I^2C bus and offers extremely low power requirements and power management abilities. Additionally, various PIC processors have been used in other space applications by the amateur satellite cooperation (AMSAT).

The PIC18LF6720 was selected because of its large amount of on-chip FLASH memory, low power (2.5mA at three volts while running at 4MHz), and 53 I/O pins. Also, Microchip provides a free development environment to work in, and the programmers used with the PICs are relatively low-cost.

3.2.2.2 Analog to Digital Converters

The analog to digital converter (A/D) plays a critical role in acquiring data for the TT&C system. All of the sensors in the CPB collect voltage, current, temperature, or magnetic field strength data in the form of analog voltages. The analog voltage must be converted to a digital value so that it can be sent to earth via the communication system or used to make a decision regarding the operation of the spacecraft. After exploring a multitude of A/Ds, the Maxim MAX1239 was selected. This device can read 12 analog inputs with 12 bits of resolution at up to 188k samples per second. The MAX1239 was selected because it is a low power, single chip solution that interfaces directly to the I^2C bus. Additionally, the MAX1239 contains an internal voltage reference, reducing the overall complexity of the system by removing the need for additional components to generate an accurate reference voltage.

3.2.2.3 Transceiver

The transceiver allows both transmit and receive operations to be accomplished in a single chip. Key factors in selecting a transceiver are the receiver sensitivity, transmitter power output, minimum frequency separation, completeness of the datasheet, and the maturity of the component.

Three transceivers were considered for use in the CPB: the Infineon TDA5255, ChipCon CC1000, and Melexis TH7122. Each transceiver is low power, using a three volt supply, and capable of frequency shift keying (FSK) modulation using amateur radio frequencies, 70 cm / 440 MHz.

Of the three options, the CC1000 has the most sensitive receiver, with the ability to receive signals with as little as -110 dBm (10 pW) of power. The TDA5255 has the next best receiver, with a sensitivity of -109 dBm, while the TH7122 has a sensitivity of -105 dBm. Additionally, the CC1000 has the smallest frequency separation, 1 kHz, while the other transceivers have a separation of about 10 kHz. The CC1000 datasheet gives very detailed descriptions for both the application circuit and software. The datasheets for the Infineon and Melexis transceivers were preliminary, indicating that the components are not very mature. It is difficult enough to get such complex components as the transceiver to perform as described without having to combat errors in the datasheet or component design.

The ChipCon CC1000 was selected as the transceiver for the CPB, as it exceeds the performance of the other transceivers except in transmitter output power and overall power consumption. The transmitter output power can be overcome with the RF amplifier, and the difference in overall power consumption is 41 mW, negligible when compared to the expected three watts of power consumption by the RF amplifier.

3.2.2.4 Radio Frequency Power Amplifier

To ensure a reliable downlink, the transmitter needs to output at least 200 mW. Most COTS transmitters, including the CC1000, are limited to a 10mW output power. Given the limited power available to the CPB, a single efficient chip capable of outputting a relatively high power RF signal on frequency was needed. Cell phone technology was the solution.

The only single chip solution found capable of outputting such a high power signal was the RF Micro-devices RF2117. Designed for use in cell phone transmitters, the RF2117 is capable of producing two watts of RF power output, with an efficiency of at least 50% [5]. The extra power margin will allow the design to overcome possible losses in the system. Additionally, the RF2117 is capable of 33 dB of signal gain [5]. The large amount of signal gain allows the transceiver to drive the amplifier with a low power signal, reducing overall power consumption.

3.2.2.5 Radio Frequency Switches

The communication system in the CPB is required to be fully redundant. Additionally, to reduce complexity, the spacecraft will have only one antenna. As a result, the communication system will need to share access to the antenna between both parallel subsystems. The easiest way to allow access is to use an electronically controlled switch. Furthermore, the transceiver needs to use the single antenna for both transmit and receive operations while ensuring that the amplified signal does not leak into the receiver. The two most important factors in selecting an RF switch are isolation and power loss on frequency.

Using the team's experiences from CP1 in developing redundant communication systems with a single antenna, it was decided to use the same RF switches. The M/A Comm SW-425 has 30 dB of isolation at the operating frequency and .5 dB of power loss. Additionally, the component has a very small footprint.

3.3 System Overview

All of the data collected by the CPB originates at the sensors in the TT&C system. Sensor data is collected by seven A/D's throughout the bus. The collected sensor data is requested and stored to FLASH memory by the TT&C's main microcontroller.

The TT&C's main microcontroller is responsible for overall spacecraft operation, including supervising and enabling the payload. The main microcontroller also uses the collected sensor information to control the spacecraft's tumble rate by pulsing magnetorquers included on each of the side panels to implement a B* algorithm.

The communication system for the CPB has two redundant RF systems. Each system has a microcontroller, a transceiver, an amplifier and a TX/RX switch. The two systems communicate through a single dipole antenna (See Figure 3.3.1).

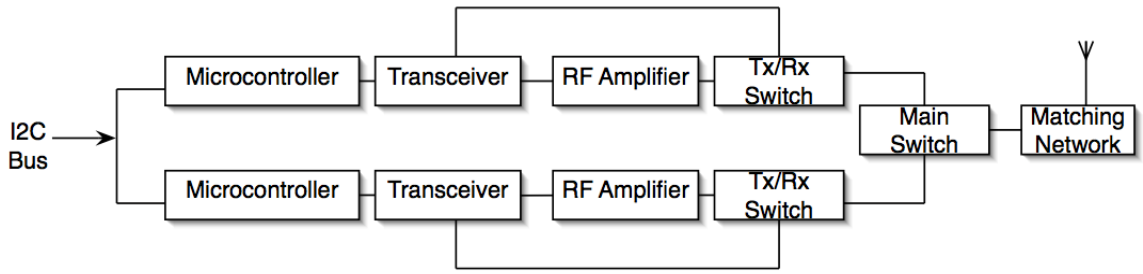

Figure 3.3.1 – Block Diagram of the CPB Communication System

Like CP1, the CPB communicates on amateur radio frequencies using a combination of Morse Code and AX.25 to encode data. This data is then modulated using frequency shift keying (FSK), which alternates the frequency of the signal to convey digital information.

As was the case with CP1, the CPB's TT&C microcontroller alternates between the two redundant RF systems during each communication cycle. For power considerations, the unselected system is set to a powered-down state. Unlike CP1, the CPB does not need a separate RF printed circuit board (PCB) for switching, as this function is accomplished on the same board that holds the transceivers. However, the CPB does use a dipole antenna, requiring impedance matching circuitry. Also, the CPB uses the same antenna design and deployment approach as CP1: a steel measuring tape antenna deployed with Ni-Chrome wire melting a nylon line.

Data sent through the antenna originates in the TT&C system, where it is then relayed to the communication system's microcontroller through the use of an I^2C bus. This microcontroller serves as the TNC or modem, encoding the data into Morse Code and AX.25 packets through the use of software rather than hardware, as was done in CP1. This same microcontroller then programs the transceiver with the necessary information defining it as a FSK transmitter, on frequency, with a specific data rate and output power. Data is then sent from the microcontroller to the transceiver through a serial interface.

The transceiver converts the digital data into an analog signal at radio frequencies. This signal is then amplified to 1.18W (30.71 dBm) before it is finally transmitted using the omni-directional dipole antenna. The receiver data path is simply reversed. The system is a textbook example of a digital communication system.

3.4 System Interfaces

The more complex the system, the more elements it contains. Each subsystem must interface with other subsystems as required for functionality. The CPB is no different; the TT&C and communication subsystems must interface directly with the electrical power subsystem and also the structure. These two interfaces are very critical to the spacecraft.

3.4.1 Power

Risk reduction is critical in spacecraft design. To this end, single points of failure in the design must be avoided, if possible. To reduce single points of failure, each of the redundant communication systems and the TT&C subsystem has its own “smart fused” power source (See Figure 3.4.1).

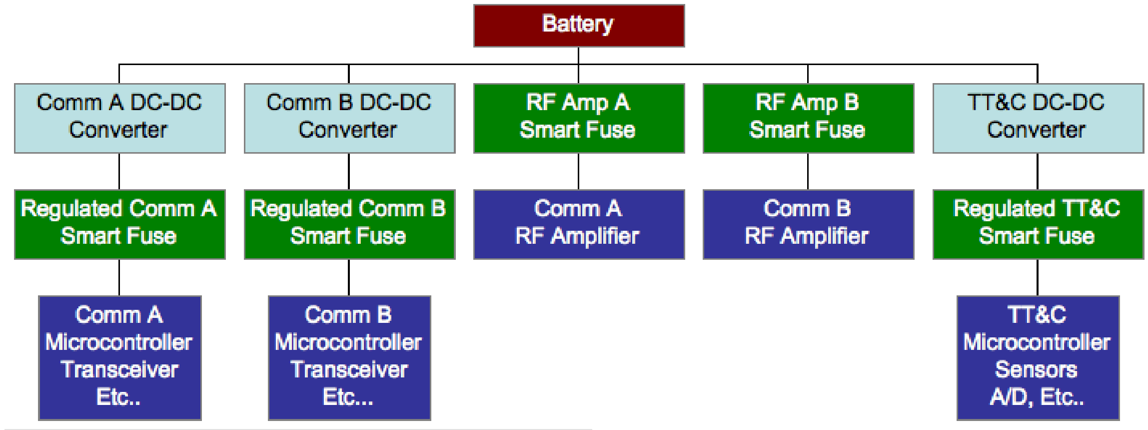

Figure 3.4.1 – Electrical Power System Overview for the TT&C and Communication Subsystems

The DC-DC converters are used to regulate the variable battery voltage to a constant three volts needed to properly run the devices in each subsystem. After each converter is a self-resetting or smart fuse. The RF amplifiers don't require a regulated supply voltage and therefore no DC-DC conversion is required, but smart fuses are included to prevent an electrical power system (EPS) failure in the event of excessive current consumption.

3.4.1.1 DC-DC Conversion

All of the devices, except the RF power amplifiers, on the CPB are designed to operate with a three volt power supply. Therefore DC-DC conversion is required to regulate the variable battery voltage to three volts (See Figure 3.4.2).

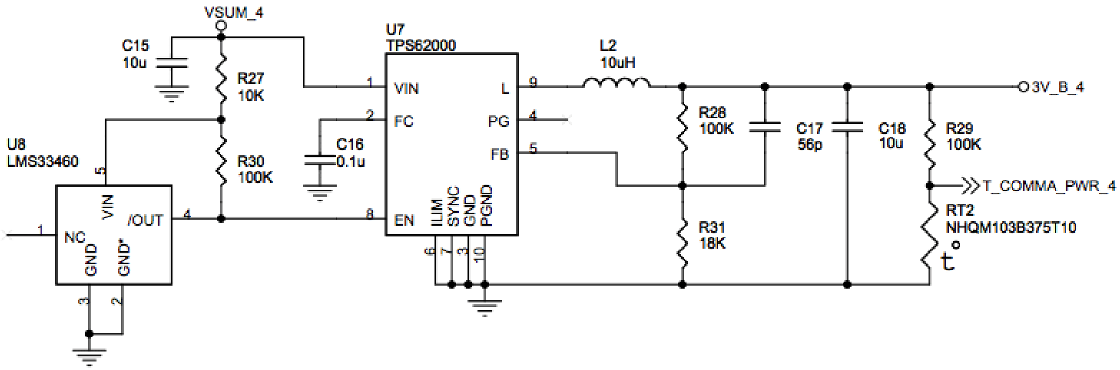

Figure 3.4.2 – DC to DC Converter Schematic

Each of the regulated branches uses this same circuit. VSUM is the raw battery voltage that feeds the Texas Instruments TPS62000 DC-DC converter. The R28 and R31 voltage divider determines the regulated output voltage, in this case three volts. U8 is a voltage detector used to shut off power to the devices on the power branch if the raw battery voltage drops below three volts. The R27 and R30 voltage divider is used to provide hysteresis so the simple unloading of the battery in a low battery voltage condition does not allow the load to be applied until the raw battery voltage reaches 3.4 volts.

3.4.1.2 Smart Fuses

Fuses are used to prevent over-current conditions from killing the satellite's EPS. If the fuse can be reset, the fault may be cleared and the spacecraft can then return to normal operation. The fuses designed for use in the CPB have a time out feature that detects whether the power branch has a fault or not (See Figure 3.4.3). If there is no fault on the branch, power is fully restored.

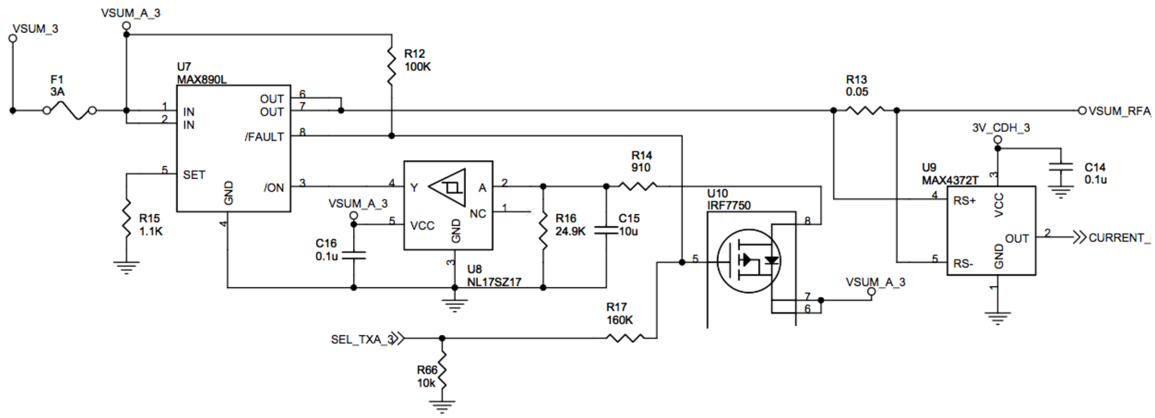

Figure 3.4.3 – Smart Fuse Schematic

The MAX890L acts as the fault detector and current limit. R15 sets the current limit for the branch. In this case the RF amplifier smart fuse current limit is set to 1.2 amps. The fault indicator, pin 8 of U7, is tied to the gate of a MOSFET. When a fault is detected or the SEL_TXA signal is low, the MOSFET turns on, bringing pin 3 of U7 high and shutting off power to the load. When there is no load, the fault is cleared, shutting off the MOSFET. With the MOSFET off, energy stored in C15 is discharged through R16. Once the voltage across C15 is less than 1V the schmitt trigger (U8) output goes low, applying power to the load. If a fault is detected, power to the load is turned off and the cycle repeats (See Figure 3.4.4). If no fault is detected, normal power is restored.

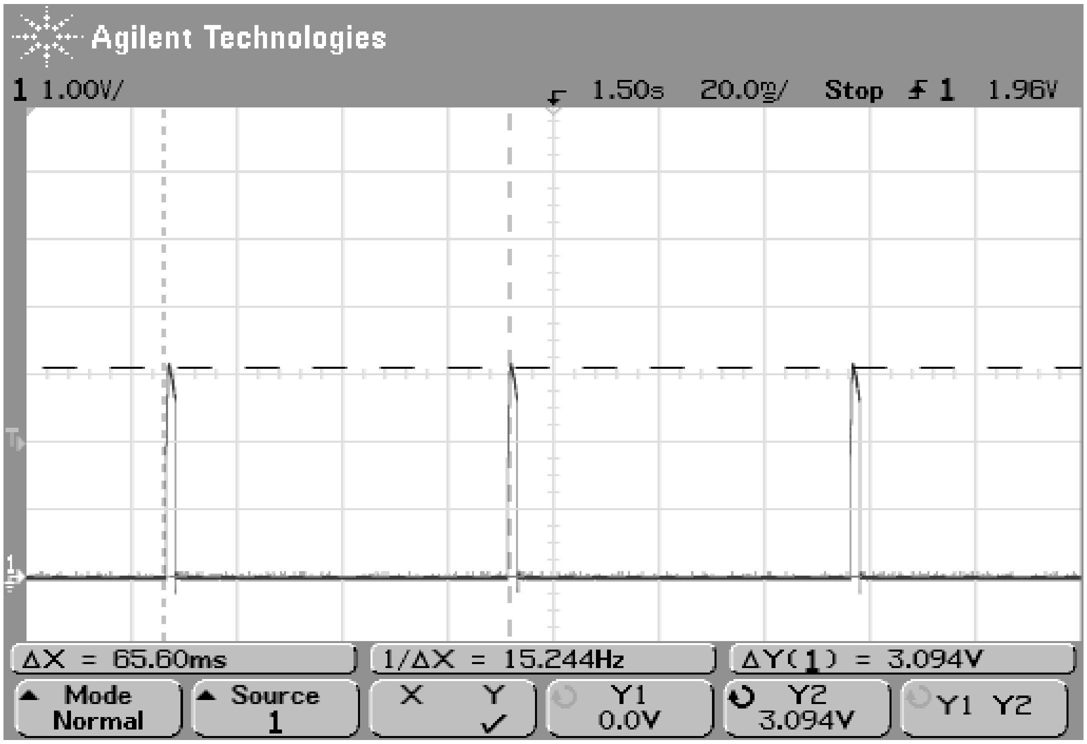

Figure 3.4.4 – Smart Fuse Timing

After the smart fuse a current sensor (U9) measures the voltage across R13 to determine the current draw of the branch. The current sensor amplifies the measured voltage that is then sent to the A/D.

3.4.2 Structural

The CPB structure provides rigid support for the sensors, electronics, and payload during transportation to the launch site and the actual launch. It is critical that each piece of the spacecraft be designed with the structure in mind. To minimize the mass, and volume of the bus, the structural interfaces of each subsystem needed to be clearly defined. Specifically, the mounting hole locations, component keep-out areas, and other constraints of the structure needed to be outlined. CAD models were used to define the structural interfaces (See Figure 3.4.5).

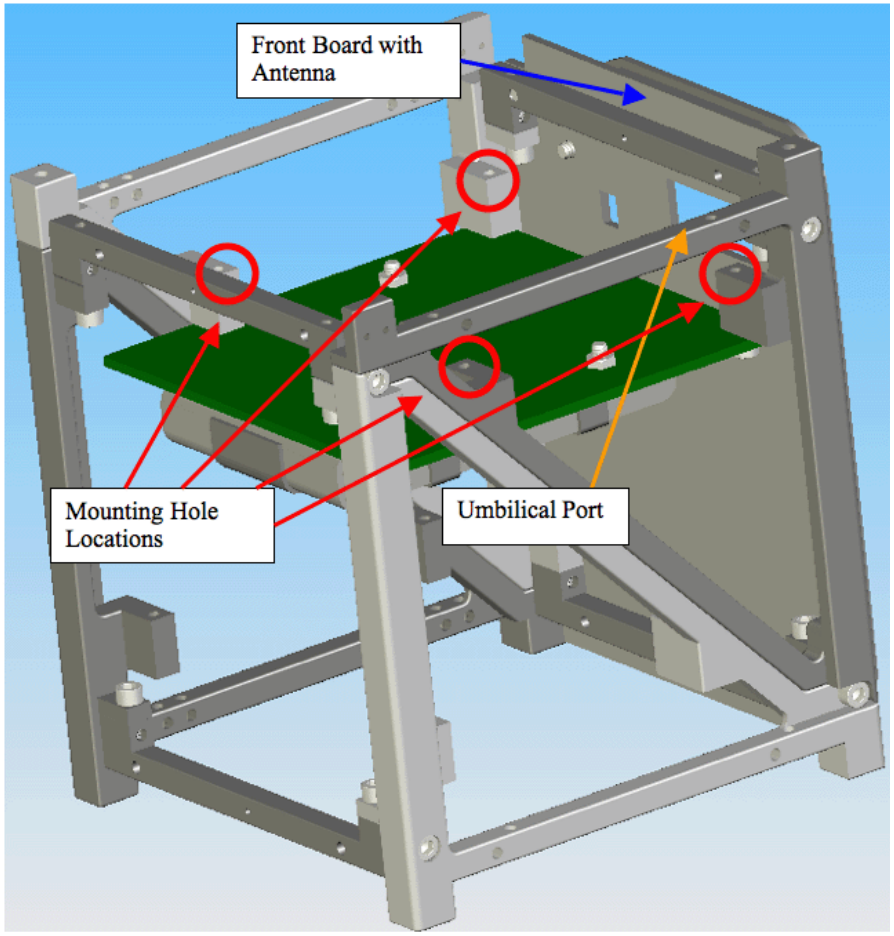

Figure 3.4.5 – CPB Structural Interfaces

The mounting holes need to be large enough to support the screw and a keep out area must be defined for the screw head and epoxy. Also, the location of the umbilical connector and the front board needed to be specified. Additionally, locations of large components on the power board, such as the remove before flight switches and inter-board connector (See Figure 3.4.6), must be identified to ensure the proper assembly of the spacecraft.

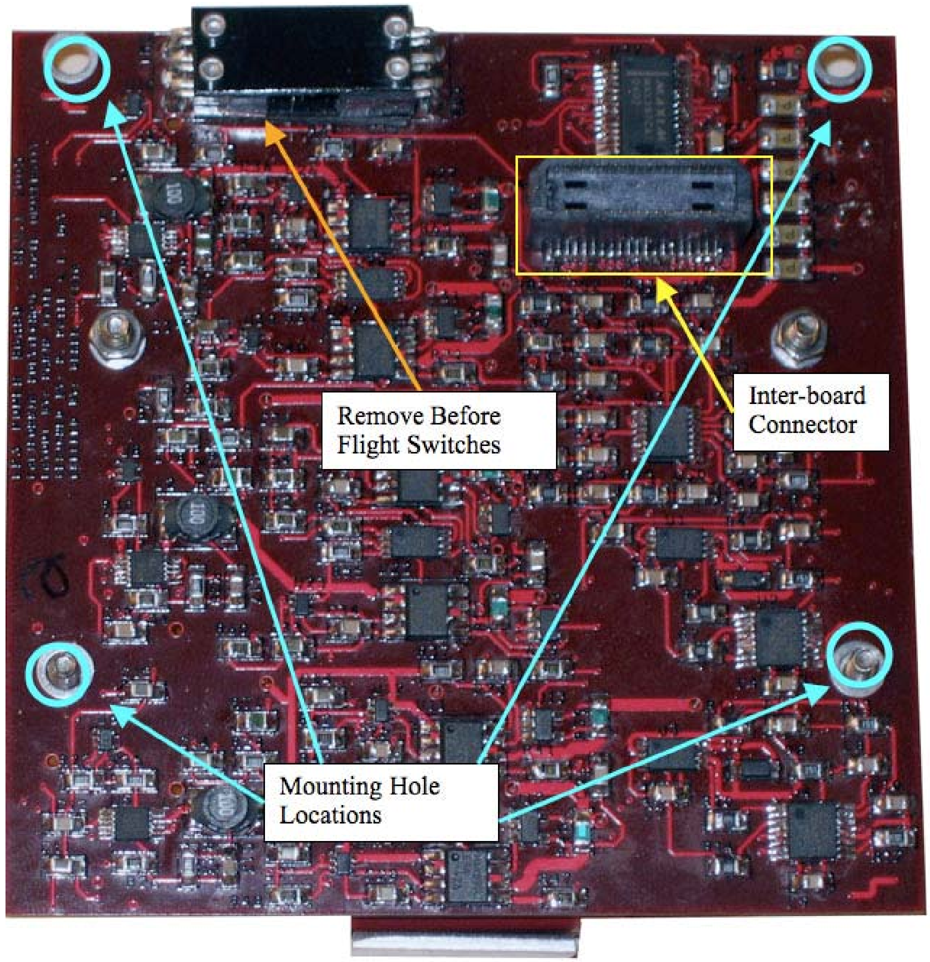

Figure 3.4.6 – CPB Power Board

3.5 System Elements

To better understand the overall system it is important to also look at each element within in the system at a low level. This section proceeds from the TT&C subsystem through to the communication subsystem one element at a time.

3.5.1 Data Acquisition

An important function of the TT&C system is to collect data regarding the operation of the spacecraft, which means that several types of sensors need to be used to collect the housekeeping data. The CPB uses four types of sensors: voltage, current, temperature, and magnetic field strength. Each sensor used conveys the collected information in the form of an analog voltage. To reduce the noise of the various sensors, a low pass filter is added. The noise-reduced analog voltage is then read by the MAX1239 A/D and converted into a digital value. Figure 3.5.1 shows the block diagram for a basic sensor.

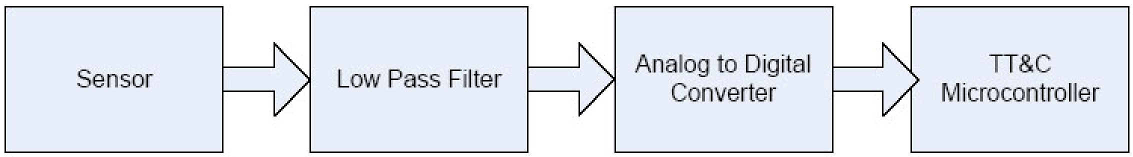

Figure 3.5.1 – Sensor System Block Diagram

During the normal operation of the satellite, the TT&C microcontroller will request the sensor data from each of the seven A/Ds throughout the bus using the I^2C interface. After data from all of the A/Ds has been collected it is stored in the on-board memory of the TT&C system. Figure 3.5.2 shows the data acquisition circuit for the communication and TT&C board.

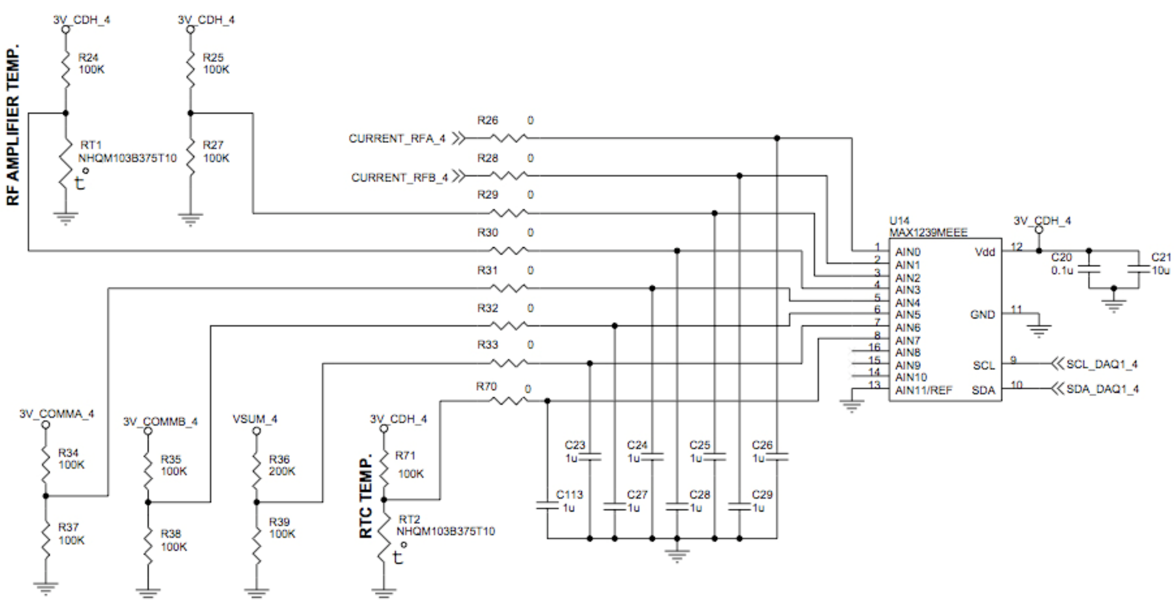

Figure 3.5.2 – A/D Schematic with Sensor Interfaces

The TT&C microcontroller can interface with the MAX1239 through the I^2C data (SDA_DAQ1) and clock (SCL_DAQ1) lines. The MAX1239 can read up to 12 analog channels at 12 bits of resolution, although on this board only eight channels are used. The channel readings include the following:

- Voltage from each supply
- Temperature near the RF amplifiers
- Temperature near the real time clock (RTC)
- Current draw by each RF amplifier

A low pass filter comprised of a resistor and capacitor is included on each of the analog channels to reduce noise on the line. The reference, and maximum allowable input, voltage for the A/D is 2.045 volts. The voltages monitored by the A/D for the temperature and voltage sensors are greater than the maximum input for the device. Thus, a voltage divider is used to proportionally decrease the sensor output voltage. The current sensors have been designed so that they do not exceed the maximum input and therefore do not require the voltage divider.

3.5.2 TT&C Microcontroller

The fundamental aim of the TT&C microcontroller is to run the satellite, coordinating data flow and processing information. The I^2C bus allows the TT&C microcontroller to communicate with multiple devices throughout the bus by using only two wires. Specifically, I^2C allows the TT&C microcontroller to receive data from the sensors and payload as requested. The payload and sensor data are stored in two additional FLASH memory modules on the PCB. The TT&C microcontroller is also required to select one of the two redundant communication systems to be used (alternating between the two) and instructs the communication system to beacon at standard intervals. Furthermore, the TT&C microcontroller must respond to commands sent from earth via the communication system, such as sending requested data or changing the mode of operation for the satellite. [1]

The application circuit for the TT&C microcontroller is as follows:

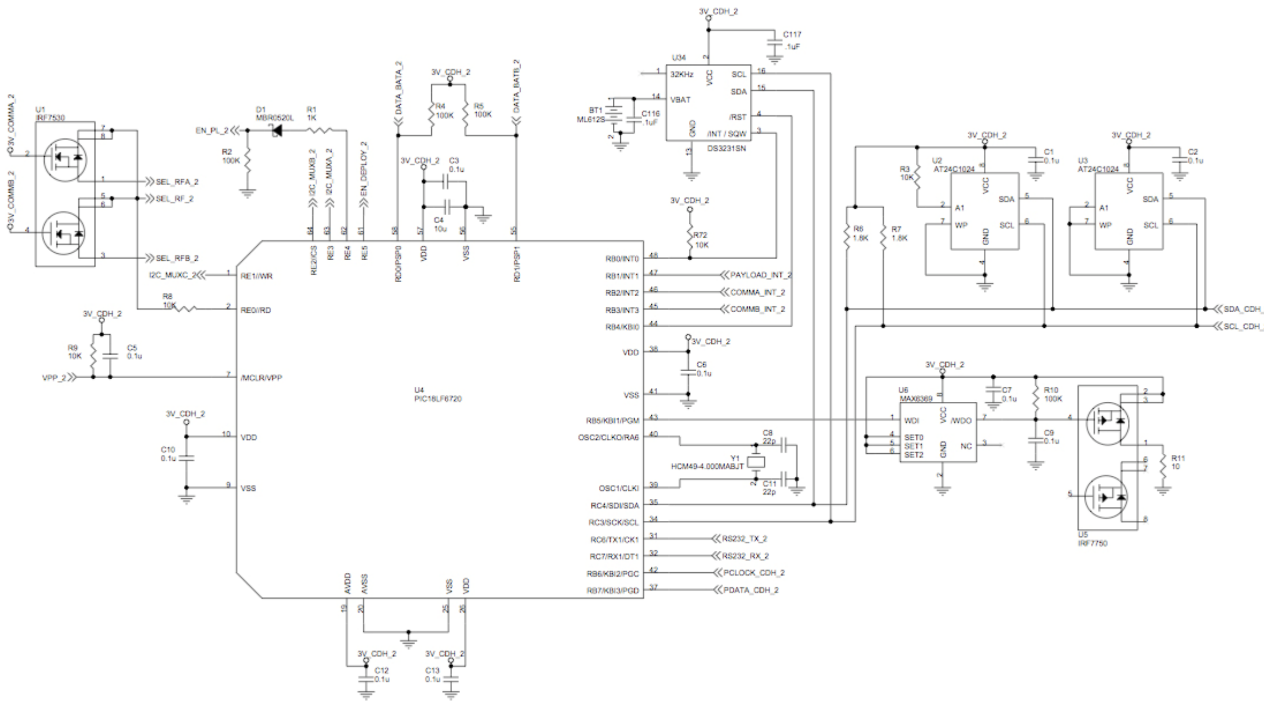

Figure 3.5.3 – TT&C Microcontroller Schematic with Support Circuitry

The main features of the circuit are these:

- Two FLASH memory modules, U2 and U3 connected to the I^2C bus
- The watchdog timer, U6
- The real time clock (RTC), U34
- The communication system select switches, U1

3.5.2.1 FLASH Memory Modules

In order to store data for an extended period of time (several orbits), on board memory must be included. FLASH memory is electronically erasable reprogrammable memory (EEPROM). The two modules are divided between bus and payload. The bus module stores housekeeping data from sensors throughout the satellite. The payload module is reserved for the payload to use as necessary depending on the requirements.

The ATMEL AT24C1024 modules selected for the CPB can store 128 kB of data each and can interface directly to the I^2C bus.

3.5.2.2 Watchdog Timer

A common approach to increase the reliability of a software-based system is to include a mechanism by which the software can be reset. One way to trigger a reset would be to use a watchdog timer. The watchdog timer must be continuously cleared by the microcontroller; if the timer is not cleared, it will output a fault signal. The CPB design uses the fault signal to turn on a MOSFET switch, which cycles power on the microcontroller by creating a low impedance path to ground through the ten ohm resistor and having the smart fuse (see Section 3.4.1.2) temporarily disable power.

3.5.2.3 Real Time Clock

Timing is critical to developing a useful system. Additionally, accurate timings encoded with various sensor readings and payload data can improve the success of a particular mission. As a result, an RTC has been added to the TT&C subsystem to provide an accurate time reference. The DS3231 RTC has an internal, temperature compensated, crystal oscillator reducing drift of the clock. The RTC circuit also includes a battery for supplementary power in the event of power loss, like a watchdog reset, ensuring no loss of time.

3.5.3 I^2C Bus

The inter-integrated-circuit (I^2C) bus, developed by Philips, allows multiple devices to communicate with one another through the use of only two wires: data and clock. I^2C is a popular method of communication in embedded applications with over 1000 devices able to use the standard. The specification allows for multiple speeds including 100 kHz, 400 kHz, and up to 3.4MHz, higher frequencies corresponds to higher possible data rates. The CPB uses the 100 kHz I^2C bus. At 100 kHz a data rate of 11 kbps can be achieved. [1]

3.5.3.1 I^2C Bus Isolation

The use of the I^2C bus is a robust and efficient method of communicating with multiple devices through a simple two-wire interface. The problem, however, is that a single failure on one of the two wires will prevent communication between all of the devices on the bus. To mitigate the risk of a failure, a switch was included on both the data and clock lines of the I^2C bus. In the event of a failure of the TT&C subsystem, specifically the loss of power, the switch, U16, will disconnect the communication system and payload from the rest of the spacecraft's I^2C bus. The isolation of the communication system (See Figure 3.5.4) and payload allows the spacecraft an opportunity to complete the mission by giving the payload the ability to communicate with earth.

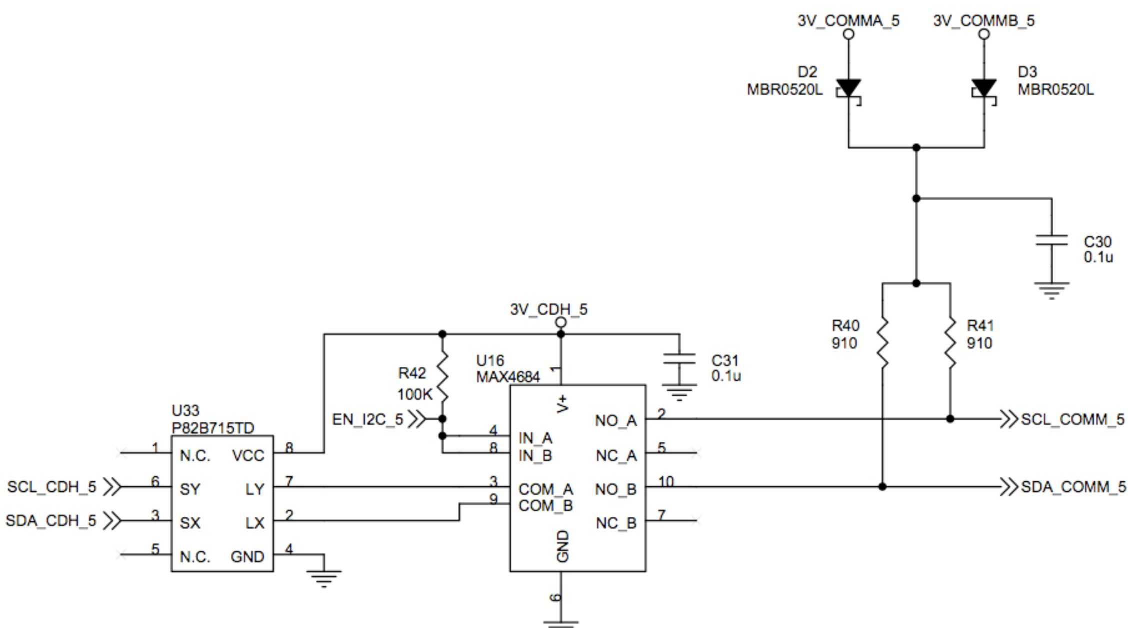

Figure 3.5.4 – I^2C Isolation Circuitry

3.5.3.2 I^{2}C Bus Capacitance

Digital signals are more tolerant to noise than their analog counterparts because digital signals rely on thresholds; as long as the low and high voltage thresholds are not improperly triggered, the signal will be correctly identified as a one or zero. The I^{2}C specification allows for four picofarad of line capacitance to ensure a high frequency of transitions from a zero to one. The I^{2}C lines on the CPB, however, have significantly more capacitance than the specification allows. As a result, the transitions from zero to one are not very quick. Figure 3.5.5 shows the I^{2}C lines of the first board revision. Clearly, the signals look more like triangle waves than the expected digital square waves. Although the data and clock lines do not look digital, all of the devices on the I^{2}C bus can correctly detect the digital ones and zeros.

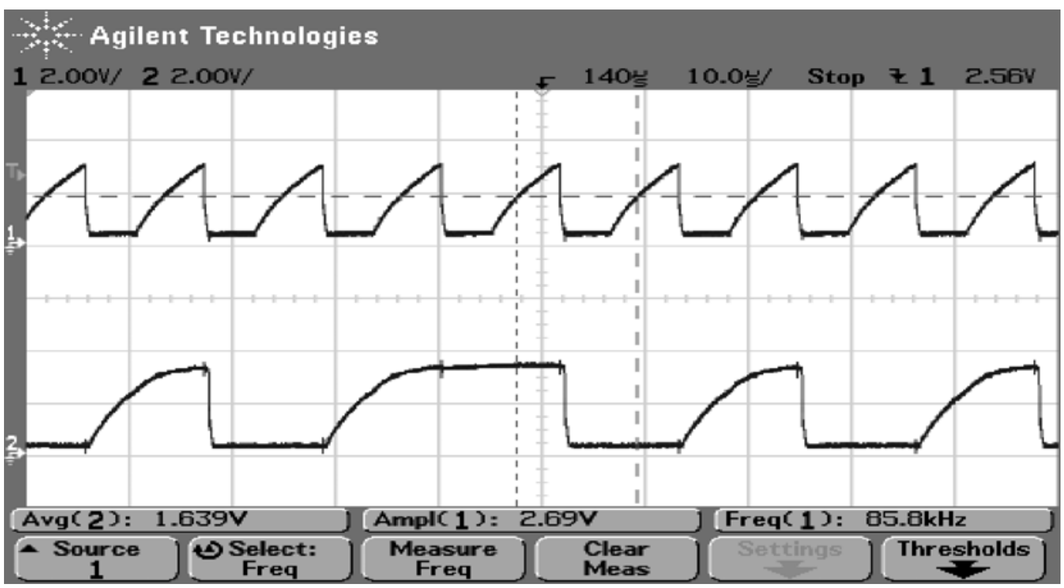

Figure 3.5.5 – I^{2}C Data and Clock Lines with High Capacitance

In an effort to improve the quality of the signals, a careful examination of the I^{2}C lines uncovered extra capacitance added by several MOSFETs used for isolation. After removing the MOSFETs, improving the layout of the PCB, and reducing the resistance of the pull-up resistors, the transition times for the signals dramatically improved (See Figure 3.5.6).

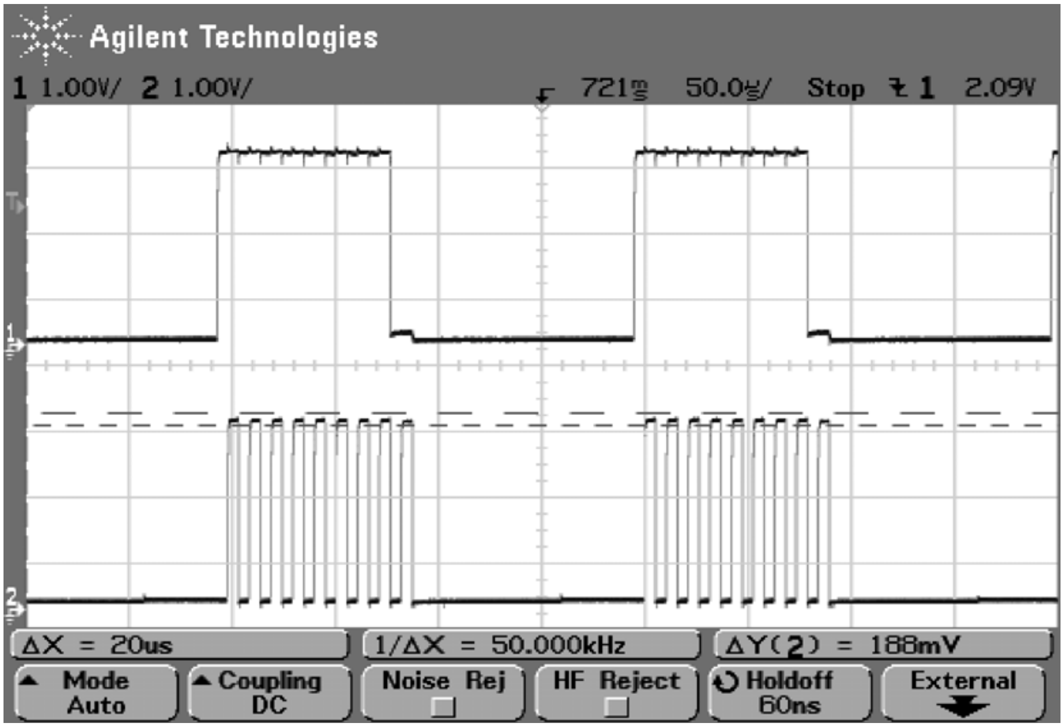

Figure 3.5.6 – I²C Data and Clock Lines with Low Capacitance

Although the transitions are much quicker and the signals look like square waves, the amount of capacitance on the I²C lines far exceeds the four picofarad maximum listed in the specification, and the use of stronger pull-up resistors is still required.

3.5.4 Communication System Microcontroller

The communication system microcontroller is responsible for receiving data from the TT&C microcontroller, encoding the data into AX.25 data packets, programming the transceiver, setting the transmit and receive switches, and turning on the RF amplifier. All of these tasks are to be accomplished through the use of software allowing the CPB to completely remove the need for a separate terminal node controller (TNC) or modem, as well as for complex circuitry needed to detect transmit or receive modes. As with the

TT&C microcontroller, the communication microcontroller is a PIC 18 and uses a watchdog timer to help increase reliability of the system; however, the communication microcontrollers do not have direct access to the FLASH memory on the bus. Figure 3.5.7 shows the communication microcontroller application circuit.

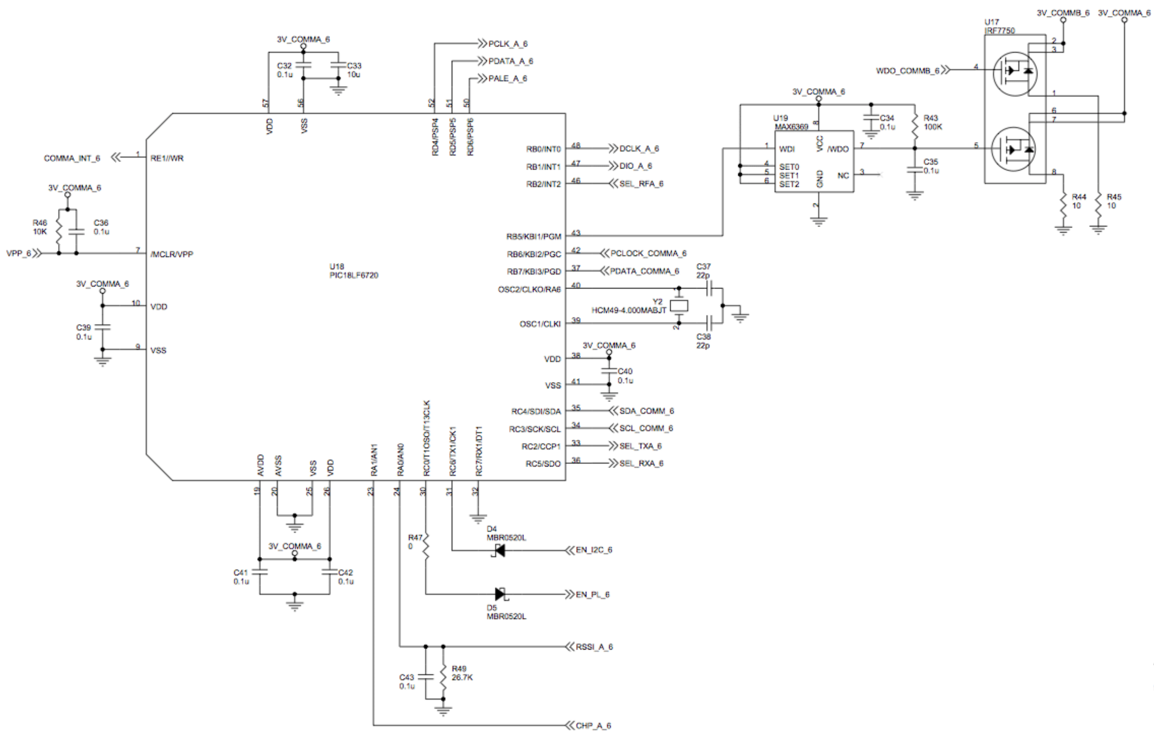

Figure 3.5.7 – Communication System Microcontroller Schematic

The microcontroller uses serial data lines to communicate with the transceiver, and it has hardware internal to the chip to implement the I^2C, decreasing the complexity of the software. The communication microcontroller has the ability to isolate the communication system and payload from the rest of the I^2C bus by toggling pin 31. Additionally, the communication microcontroller can enable power to the payload by toggling the payload enable pin (pin 30). The payload isolation and enable features of the communication microcontroller help to increase the reliability of the CPB by providing redundant, though limited, functionality in the event of the TT&C subsystem failure.

3.5.5 Transceiver

The CC1000 is a single chip that can act as both the transmitter and receiver for the communication system. Using a serial data connection, the communication microcontroller programs the CC1000, defining it as either a transmitter or receiver. The microcontroller has the ability to change a number of variables in the CC1000, such as the transmit or receive frequency, data rate, and transmitter output power, all in software. The use of software to change variables means the system can be more flexible, responding to a dynamic environment. For example, an operator could command the spacecraft to temporarily increase the power output of the transmitter to improve the communication link for a critical pass. The circuit for the transceiver is relatively simple, with a low part count (See Figure 3.5.8).

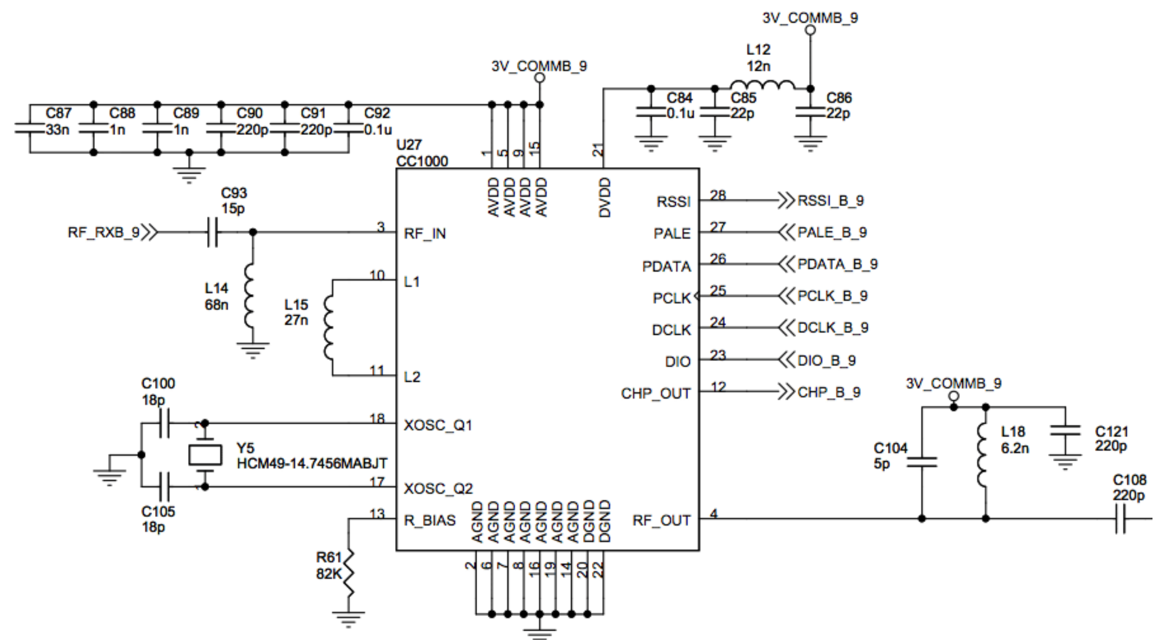

Figure 3.5.8 – Transceiver Schematic

The large number of capacitors on the AVDD pins provide filtered DC power to the analog portions of the IC, while the pi filter on the DVDD pin filters the digital power to the chip. The L network on the RF input (pin 3) provides impedance matching for the receiver input. The parallel LC network on the RF output also provides impedance matching for the transmitter, and the extra capacitor C121 acts as a RF short to clear the three-volt line of noise for the filter. L15, connected to pins 10 and 11, determines the range of allowable tunable frequencies of the phase lock loop internal to the chip. The difference of just a few nanohenries can change the tunable frequency range by 25 to 30 MHz. The 27nH value sets 430 MHz in the middle of the tuning range. Pins 23 through 27 are the serial interface to the microcontroller. Pin 28 is the receive signal strength indicator (RSSI). The RSSI is nonlinear and inversely proportional to the strength of the received signal. The stronger the signal, the lower the voltage. The RSSI is very useful in testing and debugging as it indicates whether or not a signal is being received, helping to determine whether a particular problem is more hardware- or software-based.

3.5.6 RF Power Amplifier

To ensure a reliable communication link, the RF output of the transceiver must be amplified significantly. Link analysis shows that a communication link can be established with as little as 200 mW (23 dBm) effective isotropic radiated power (EIRP) (See Appendix C). A reliable link should have a margin of at least 6 dB. The RF2117 is capable of outputting up to two watts (33 dBm) of RF output power. However, to achieve a margin in excess of 6 dB, one watt EIRP will be sufficient. Any power output above one watt from the RF amplifier can be used to overcome potential losses in the system, ensuring one watt EIRP.

3.5.6.1 Initial Circuit Design

A common approach to initial circuit design is to use the reference design provided in the datasheet, as was done with the RF2117. The reference design provided by RF MicroDevices can be seen in Figure 3.5.9.

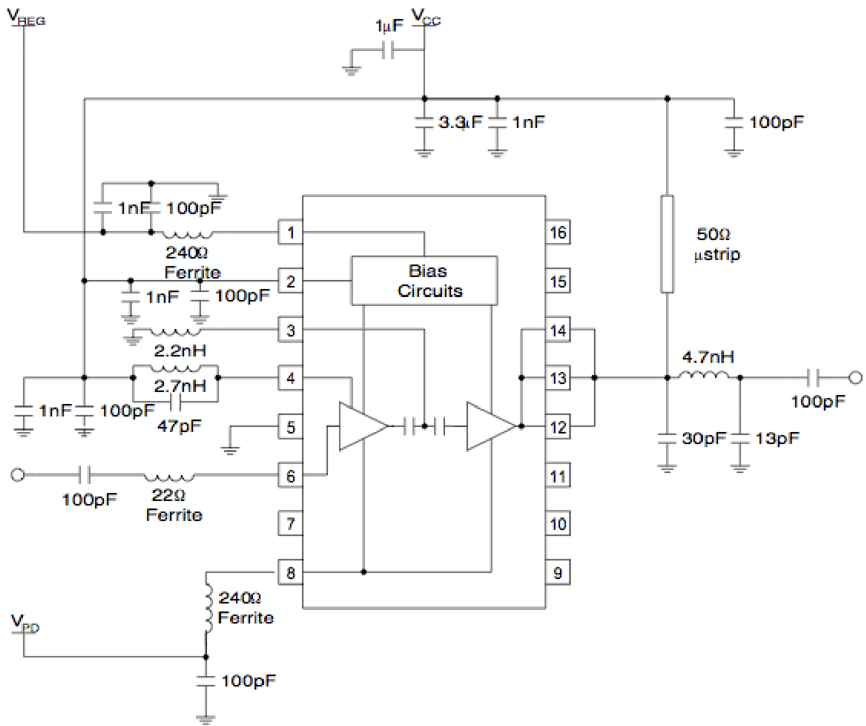

Figure 3.5.9 – RF2117 Reference Design

Some of the key features of the design are the pi network on the RF output for impedance matching, RF chokes for the DC bias circuits, and the DC blocking capacitors on the RF input and output of the chip. One interesting point regarding the design is the use of ferrite inductors with specific impedances. The use of the ferrite inductors is perhaps to provide RF shielding, noise suppression, and decoupling. However, the use of the ferrite inductor on the RF input is curious, as we found standard inductors to work better.

3.5.6.2 Power Sequencing

The process of turning on the RF amplifier is not as easy as one might think. The RF2117 includes a power down pin, V_{PD}, that can enable and disable the amplifier. This pin, however, must be toggled only after the chip is powered by V_{CC}. The initial design used the smart fuse enable line to bring V_{PD} high, enabling the amplifier, but this design did not produce the desired result. Figure 3.5.10 shows V_{PD} and V_{CC} during the RF amplifier power up sequence.

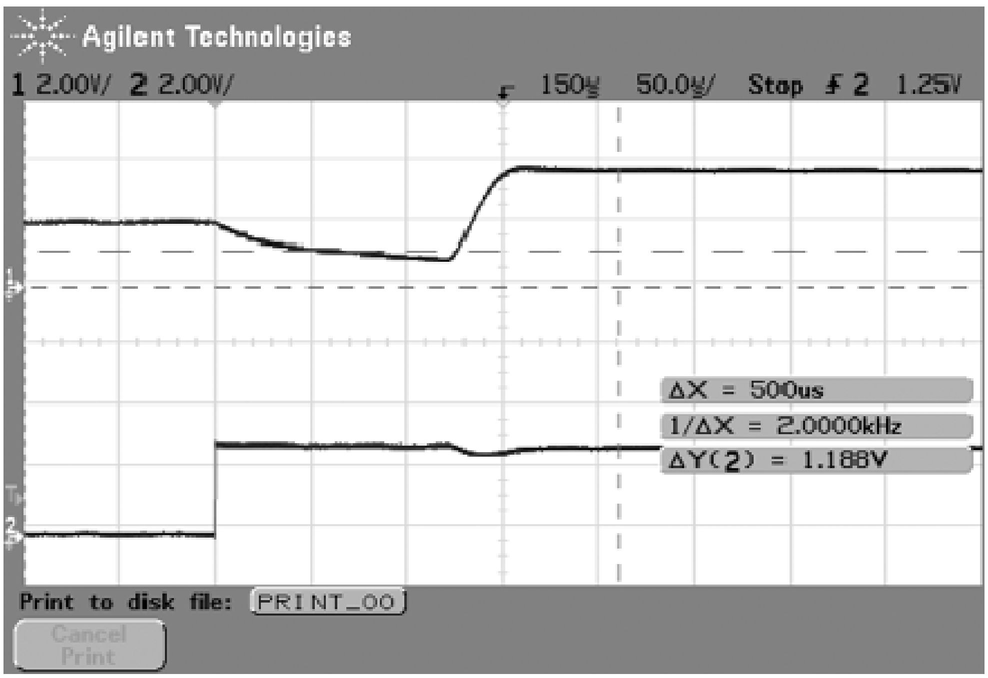

Figure 3.5.10 – Incorrect RF Amplifier Power Sequencing

In Figure 3.4.10, channel two is the line powering V_{PD}, and channel one is V_{CC}. V_{PD} is being powered 150 μS before V_{CC}. The improper power sequencing results in blowing some of the transistors in the RF output stage. The loss of the transistors degrades the performance of the amplifier, although the amplifier is still able to function.

Figure 3.5.11 shows the circuit used to correctly initialize the RF amplifier.

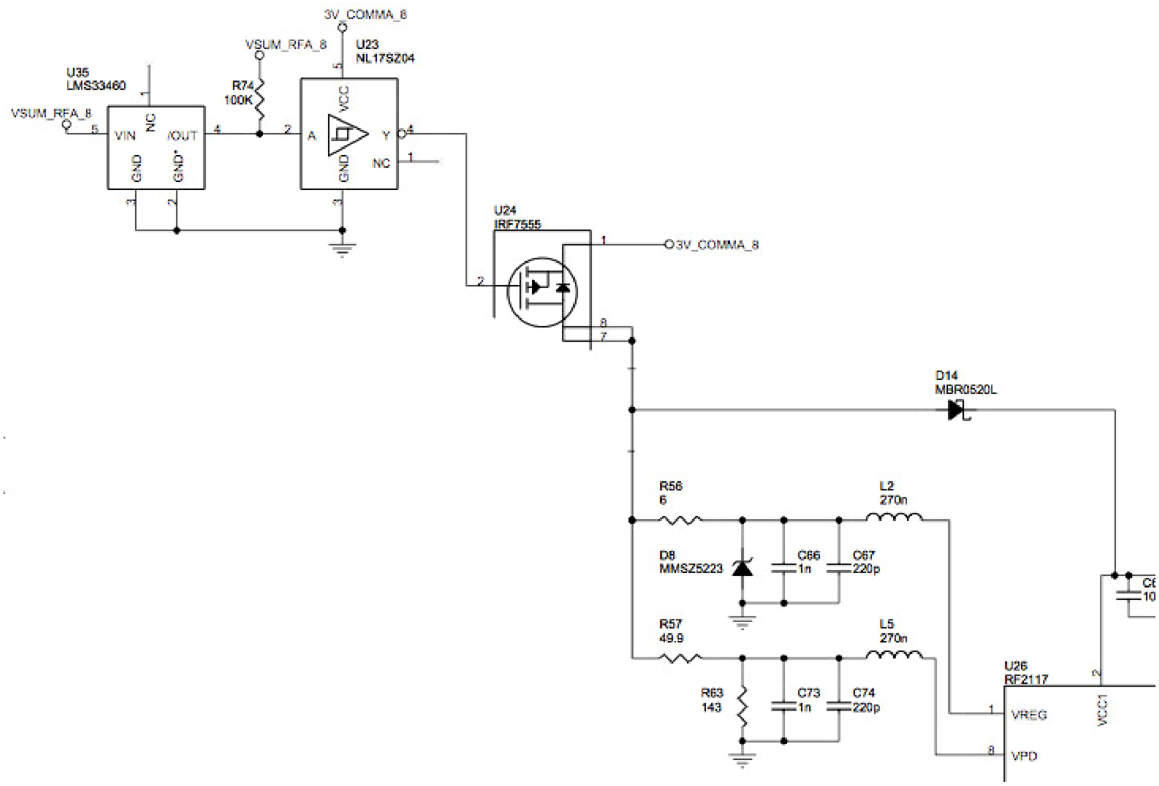

Figure 3.5.11 – Power Sequencing Circuit

U35 is a three-volt detector. When the V_{CC} voltage of the RF amplifier (pin 2 of U26) is greater than three-volts, the output of U35 goes high (4.2V); this signal is then inverted to correctly drive the gate voltage of the P-MOSFET U24. The low gate voltage on U24 turns on the MOSFET switch allowing power to be applied to V_{REG} and V_{PD} thus enabling the RF amplifier. A P-MOSFET and inverter were used rather than simply an N-MOSFET to ensure the switch was fully turned on. Testing showed that at certain battery voltages the RF amp would not completely turn on an N-MOSFET. Additionally, a schottkey diode, D14, was added to allow current to flow to V_{CC} from the three volt reference if V_{CC} is 0.3V lower than the reference. V_{CC} may have a lower voltage on power down due to the propagation delay from the detection of the three-volt level on

V_{CC} to actually turning off the MOSFET. Figure 3.5.12 shows the correct powering sequence.

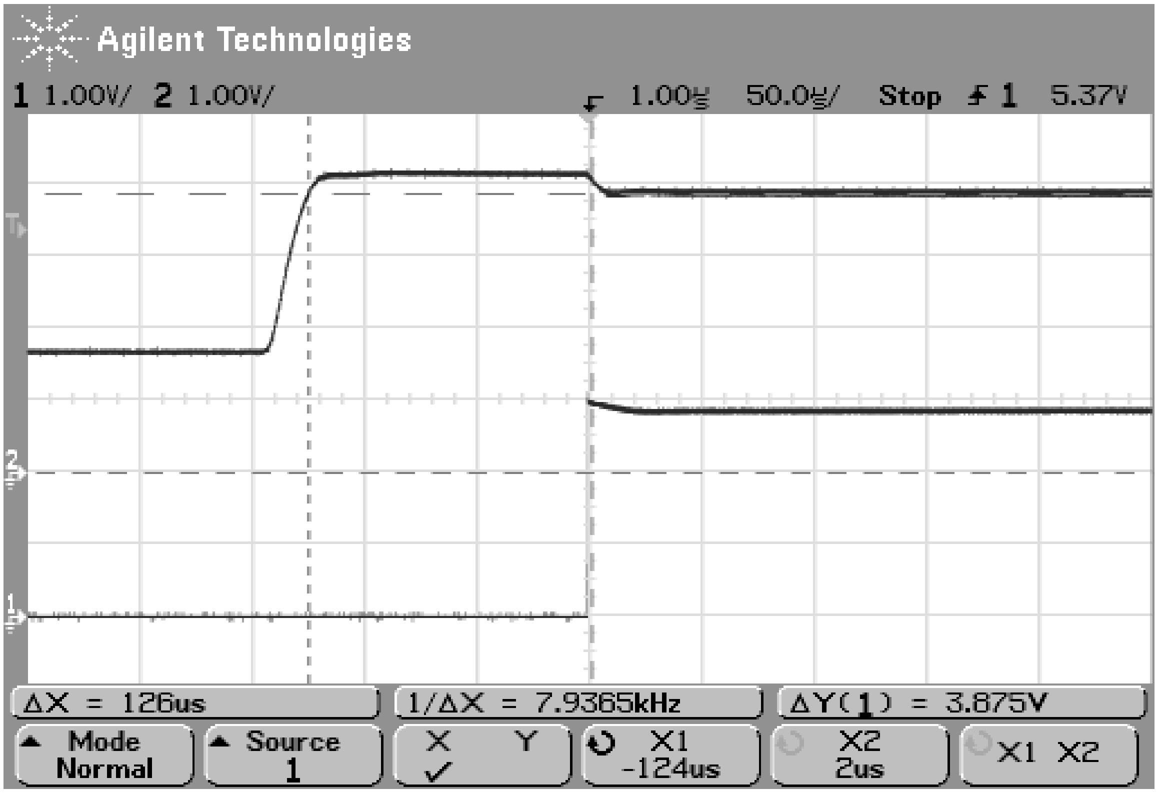

Figure 3.5.12 – Correct Power Sequencing of the RF Amplifier

Channel 2 is V_{CC} and channel 1 is the reference voltage that powers V_{REG} and V_{PD}. The V_{CC} voltage rises to 4.2V 126μs before V_{REG} and V_{PD} are powered. Additionally, the loading of the power supply can be seen as the V_{CC} voltage drops to 3.9V when the RF amp is turned on.

3.5.6.3 Impedance Matching and Output Power Optimization

Impedance matching is critical to ensure peak power and efficiency of the amplifier. In addition to impedance matching, the amplifier circuit must be tuned for use at a specific frequency. The process of impedance matching and overall circuit optimization is very iterative, requiring trial and error. However, much of the initial guesswork can be reduced if good models are used to simulate the circuit.

The use of a vector network analyzer (VNA) allows the measurement of impedance in both real and reactive components. Additionally, the VNA measures the S-Parameters of the amplifier, determining the input and output return losses and forward gain of the amplifier. The S-parameters help to quantify the quality of the impedance match between sections. Figure 3.5.13 shows the final reading of the amplifier using the VNA.

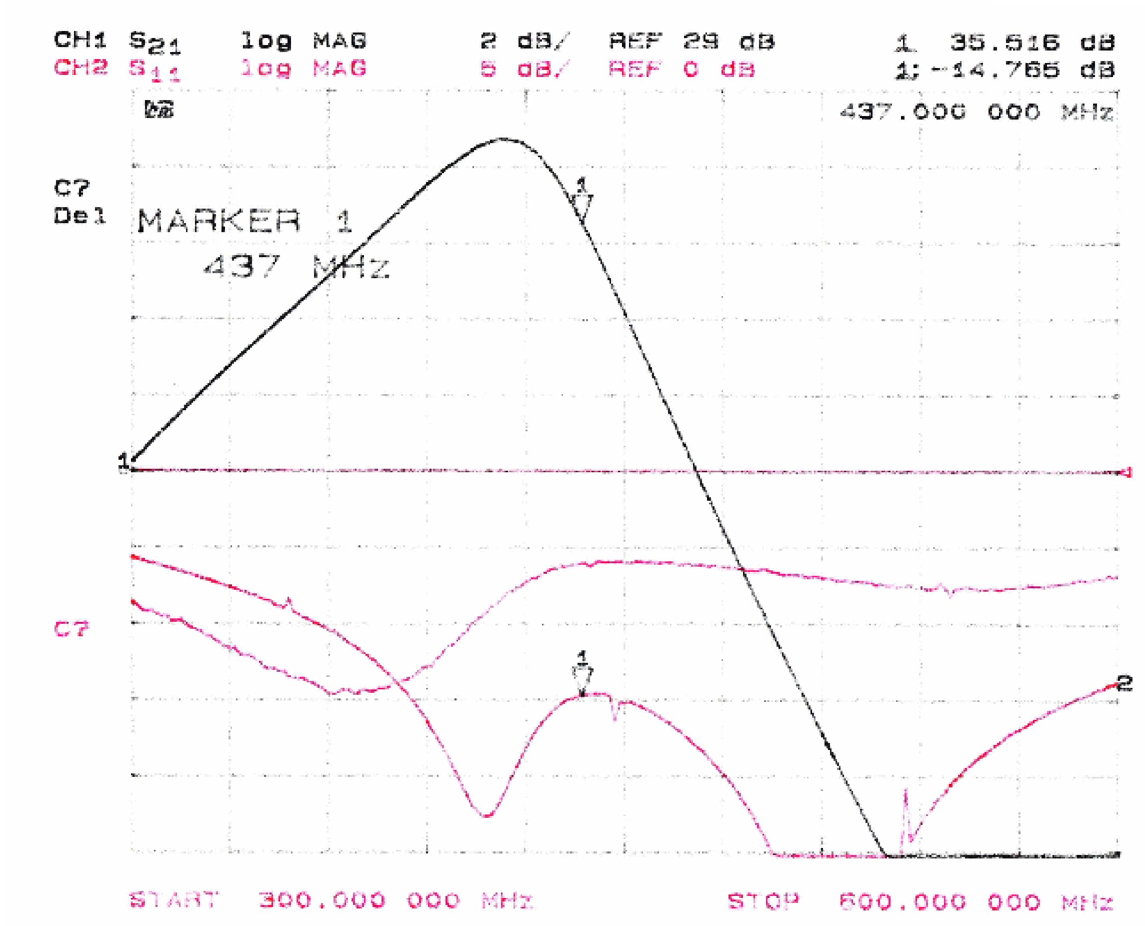

Figure 3.5.13 – Vector Network Analyzer Plot for RF2117 RF Amplifier

The channel 1 shows the forward gain of the amplifier to be 35 dB at 437 MHz and 38 dB at the peak, although the RF2117 datasheet gives 33 dB as the maximum small signal gain of the amplifier. The frequency of interest, 437 MHz, is on the right of the peak gain; this will reduce harmonics as the gain of the amplifier drops off.

Channel 2 shows the input return loss to be -14dB, which is a good impedance match. Channel 3 shows the output return loss to be -7dB, a poorer impedance match, although it was found that a poor output return loss yields peak power and gain performance.

3.5.6.4 Final Circuit Design

The final circuit design is notably different than the initial reference design. Specifically, the use of ferrite chips has been avoided and a pi network was added to the RF input of the amplifier to improve the impedance match. Additionally, a number of other component values were changed to optimize performance at 437 MHz. Figure 3.5.14 shows the final RF amplifier circuit.

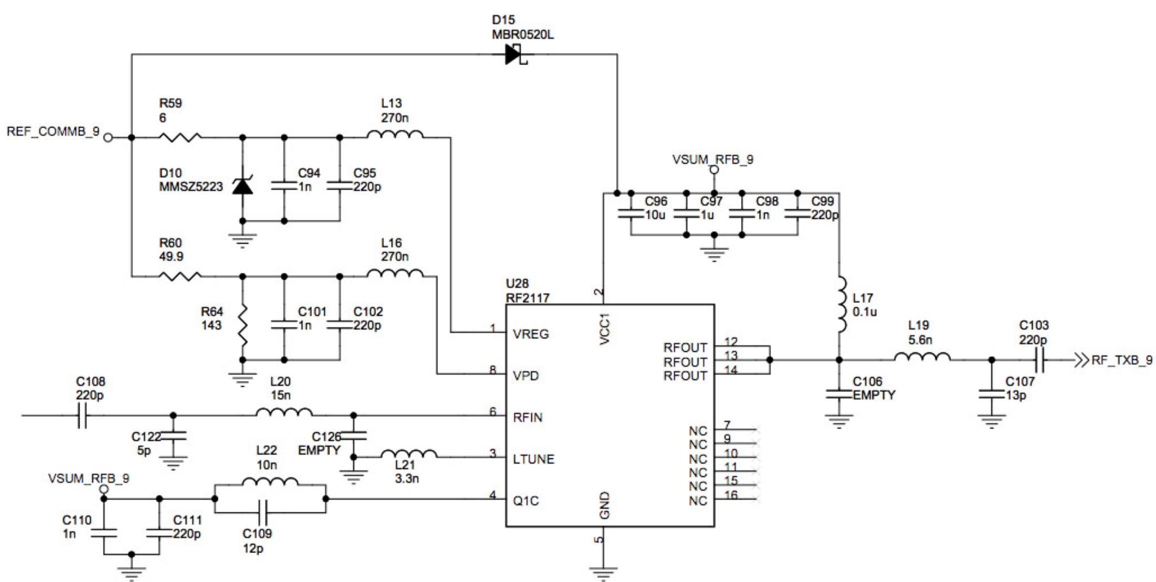

Figure 3.5.14 – RF Amplifier Final Circuit Design

V_{REG} and V_{PD} provide the DC bias for the amp, each of the lines has an RF choke of 270 nH to give high impedance at 437 MHz preventing RF leakage. Also, each of the DC bias lines includes a 220 pF decoupling capacitor after the RF choke to eliminate RF from the DC bias.

Pin 4 is the positive supply of the first stage collector. According to the datasheet, the supply should be fed through a parallel LC network, resonant at the center of the band of interest. The values selected have similar impedances at the frequency of interest. Also a decoupling capacitor, C111, is placed from the supply end of the LC network to ground. L21 is the inter-stage matching point of the amplifier. It was found 3.3 nH for L21 provides optimum performance. L17 is another RF choke providing high impedance at 437 MHz. L17 provides much of the DC power for the RF output; thus L17 must be rated for high current and have a low DC resistance. The selected inductor is rated for two amps and has a DC resistance of .05 ohms.

A pi network was included on both the input and the output of the amplifier for matching. Additionally, DC blocking caps of 220 pF are added to the input and output to ensure that no DC is fed into the RF section.

The final amplifier circuit design is capable of outputting 1.18 W (30.71 dBm) with an efficiency of 64% and a small signal gain of 35 dB.

3.5.7 RF Switches

Switches are used to select between the redundant communication systems and to allow the transmitter or the receiver of the selected communication system to have access to the single antenna. The M/A Comm SW-425 performs the switching functions for the communication system (See Figure 3.5.15).

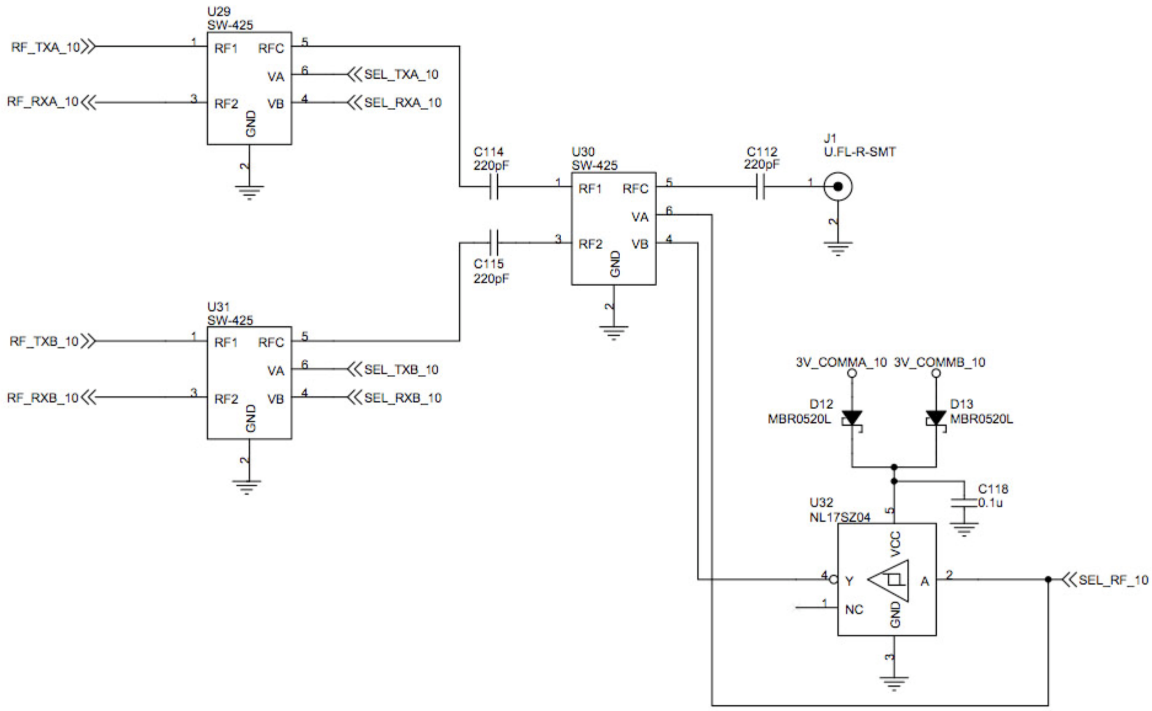

Figure 3.5.15 – RF Switching Design

U29 and U31 are the transmitter or receiver select switch for the redundant communication systems. The SEL_TX and SEL_RX signals, generated by the communication microcontroller, are used to alternate between the two states of the switch. Both signals (SEL_TX and SEL_RX) are required to correctly select a single state. U30, the communication system select switch, uses the SEL_RF signal generated by the TT&C microcontroller to determine the state of the switch. An inverter is used to ensure that if the TT&C microcontroller fails, one of the communication systems is always selected.

In addition to the state select signals, each of the switches has 220pF DC blocking capacitors on both the input and output lines. The blocking capacitors for the inputs of U29 and U30 are on the transceiver and amplifier schematic pages. Also, J1 provides the electrical connection to the antenna located on the front on the spacecraft.

3.5.8 Antenna

The CPB uses a standard dipole antenna, located on the front of the spacecraft. The signal to deploy the antenna is generated by the TT&C microcontroller, and the antenna is deployed using the proven method of melting nylon line.

3.5.8.1 Antenna RF Circuitry

For optimum power transfer the entire length of the dipole antenna should be half-wave, making each of the two elements in the dipole one-quarter-wave. The wavelength (λ) can be determined from the speed of light (c) and the frequency of interest (f) using the following relationship:

$$\lambda = \frac{c}{f} = \frac{3E8}{437E6} = 0.6864m \;\Rightarrow\; \frac{\lambda}{2} = 34.32cm \;\Rightarrow\; \frac{\lambda}{4} = 17.16cm = 6.767in$$

Unfortunately, due to the size restrictions of the CubeSat the optimum length antenna cannot be used. However, adding impedance matching circuitry to tune the RF input to the antenna can reduce losses due to the improper length of the antenna (See Figure 3.5.16).

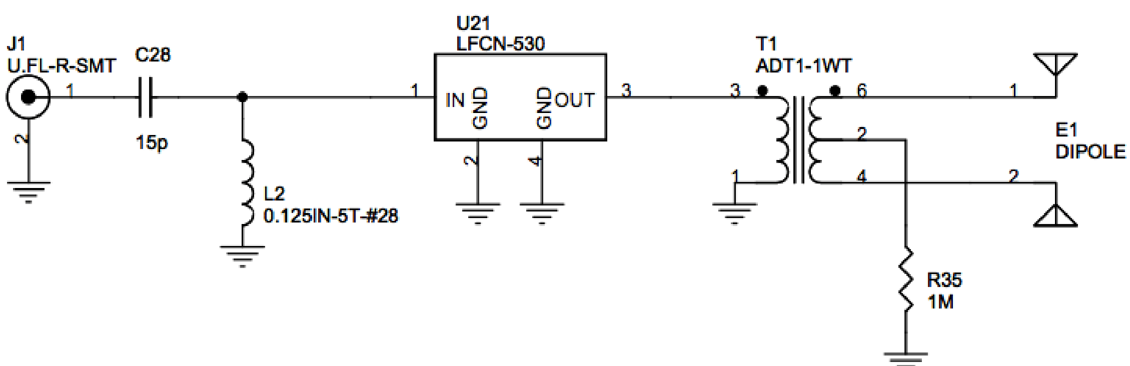

Figure 3.5.16 – Antenna with Matching Circuitry

C28 and L2 act as an L network for impedance matching. U21 is a low pass filter used to attenuate high frequency harmonics. T1 is a Balun used to optimize power transfer to and from the antenna. J1 provides the electrical connection to the TT&C PCB where the rest of the communication system is located.

3.5.8.2 Antenna Deployment Circuitry

The length of the antenna requires that it be stowed to comply with the CubeSat standard. The CPB uses a nylon line to stow the antenna (See Figure 3.5.17). The nylon line is then burned when current is allowed to run through nichrome, releasing the antenna.

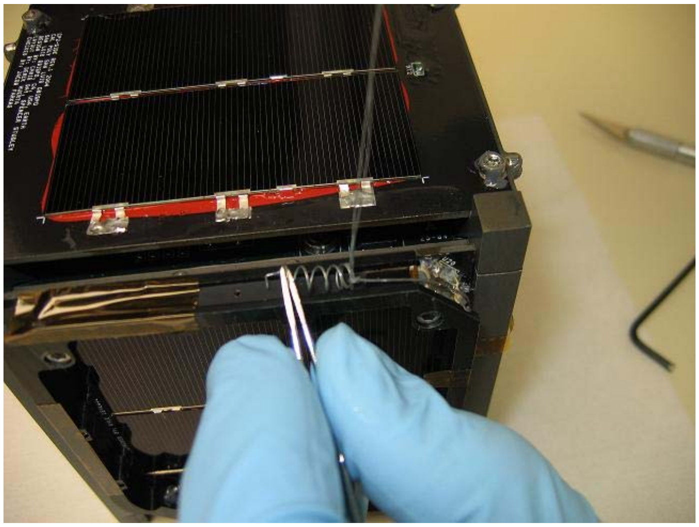

Figure 3.5.17 – CPB Antenna Deployment System

The circuit used to deploy the CPB antenna was also used in CP1 (See Figure 3.5.18).

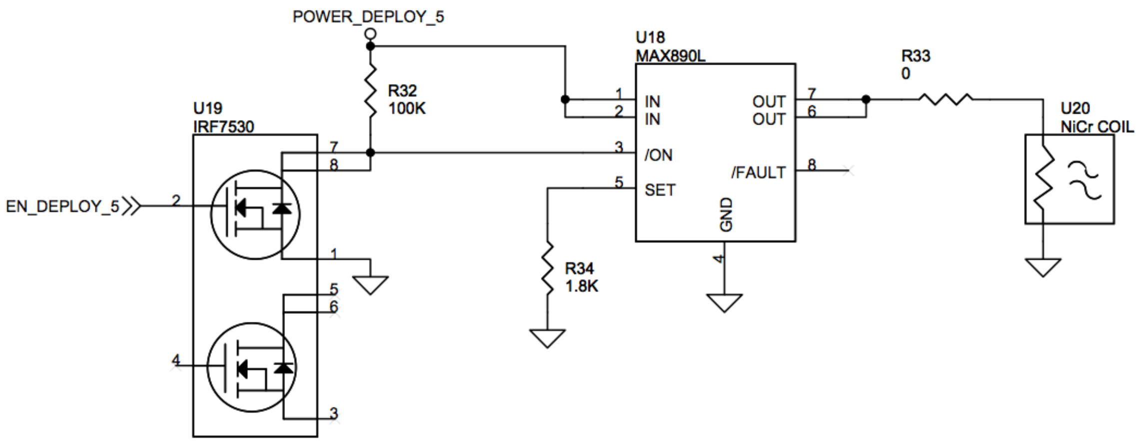

Figure 3.5.18 – Antenna Deployment Circuit

The TT&C microcontroller sends the EN_DEPLOY signal, which turns on the MOSFET pulling pin 3 on U18 low. U18, the MAX890L, sets a current limit, determined by the set resistor R34, of the load. The current limit is set to 766 mA, allowing the nichrome wire to heat up fast enough to deploy the antenna within 15 seconds.

3.5.9 Software

The highly integrated components and software used in the design of both the TT&C as well as the communication subsystems require significant amounts of software development. The CPB system software, implemented on PIC18s, has been written in C to balance code complexity with performance. C also allows programmers to complete much of the software development independent of the hardware, decreasing development time.

Moreover, increasing the use of software allows for more flexibility in the system. Specifically, the use of a software TNC completely removes a hardware element from the communication system, reducing power consumption. Also, a software TNC opens the possibility of implementing complex channel encoding algorithms, improving the link margin without changing the hardware.

In addition to the software TNC, the transceiver is software programmable, which means that many parameters can be changed in orbit by commanding the system from the earth station. For example, the transmitter output power can be adjusted, allowing for an improved communication link if necessary. Also, the transmitter and receiver frequencies can be changed independently in software. Furthermore, the transceiver is programmed with the data rate and modulation mode used. These software-controlled variables allow the CPB to support a wider variety of payloads.

3.5.10 Earth Station

The earth station (See Figures 3.5.19 and 3.5.20) is a critical yet often overlooked element of the communication system. The function of the earth station is to receive and decode data from the spacecraft, and issue commands.

Using amateur radio frequencies reduces the equipment costs of the station, because the equipment is less specialized than it would be for other frequency bands. One constraint to using this equipment is that the spacecraft must conform to amateur radio standards of communication.

Figure 3.5.19 – Cal Poly's Earth Station

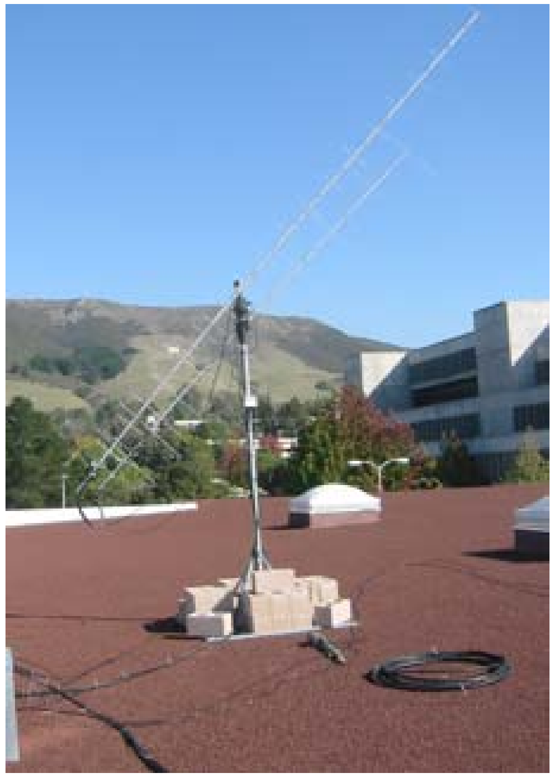

Figure 3.5.20 – Cal Poly's Earth Station Antenna

Because the system for the CPB uses FSK, it is important to note that there are two different amateur radio standards for FSK depending on the data rate used. If an amateur radio system has a data rate of 1200 bps and is said to use FSK, this system keys audio tones instead of the carrier. This method is more accurately described as "audio" frequency shift keying (AFSK). A system with a 9600 bps data rate keys the carrier frequency, which is "true" FSK. The transceiver used in the CPB modulates with true FSK. However, the 1200 bps data rate used requires AFSK to conform to the amateur radio standard. For our system to use the low cost amateur radio equipment the system must be compatible with this standard.

To resolve the FSK issue, a method of converting the keyed carrier to audio tones is needed. The solution is to use lower sideband (LSB) demodulation. A LSB demodulator reconstructs the entire message using frequency symmetry. The demodulator can generate the upper half of the spectrum given only the lower half. This process of generating the upper sideband in the demodulator results in an AFSK signal out of the radio. An AFSK signal can then be decoded using standard amateur radio equipment.

3.6 Printed Circuit Board Design

Given the requirement to integrate systems as much as possible, multiple subsystems needed to be incorporated onto a single PCB. Specifically, our so-called TT&C board needed to include the communication subsystem as well as the core of the TT&C subsystem. Incorporating both subsystems onto a single PCB is only possible through the use of components optimized for micro-applications.

The layout design reflects the data path (See Figure 3.6.1). Data is collected in the TT&C subsystem (upper right), sent to the microcontroller (bottom right), then the transceiver (bottom left), and finally the switch-selected signal is amplified and goes to the antenna (upper left).

The PCB layout is key to the overall success of any design. Due to the sensitive nature of RF designs, selecting the improper orientation of a particular component, or an incorrect trace width can often have a disastrous impact on the functionality of the system. The CPB RF system uses 50 ohm impedances, requiring 12 mil trace widths for all RF signal lines on the 6-layer board.

Furthermore, the PCB needs to be able to dissipate the heat from the RF amplifier. To improve the heat dissipation, a large copper area (middle left of 3.6.1) was added under the amplifiers.

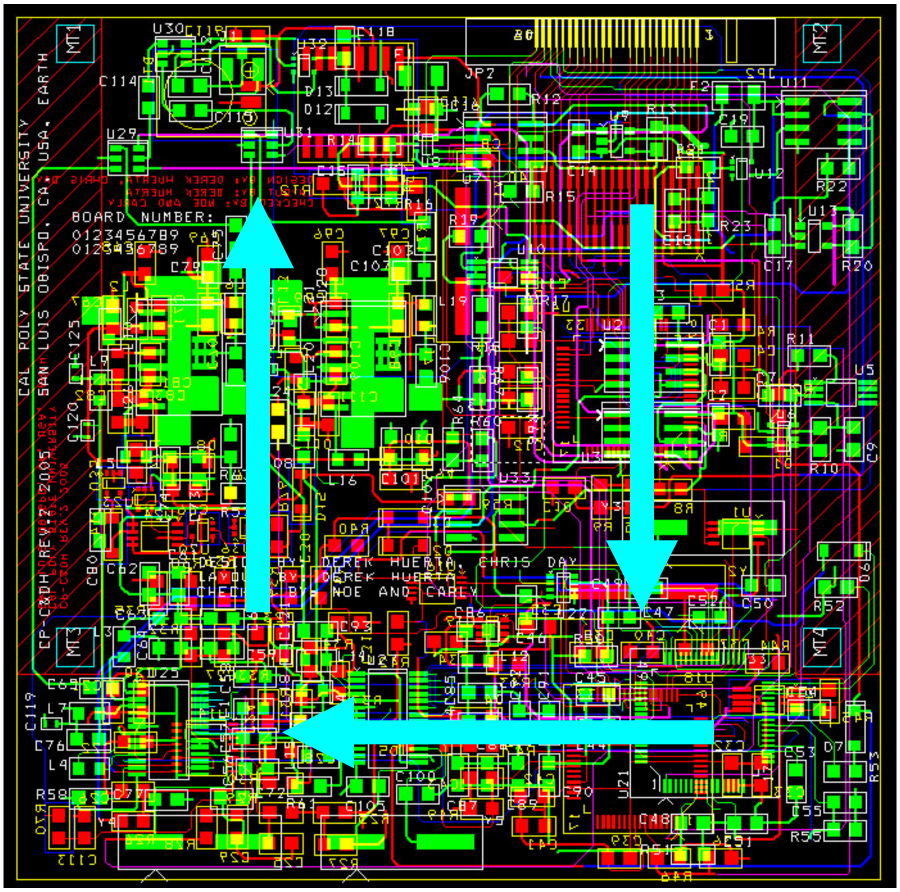

Figure 3.6.1 – PCB Layout with Data Path Shown

The PCB design is very modular with each aspect of the subsystems having their own location (See Figures 3.6.2 and 3.6.3).

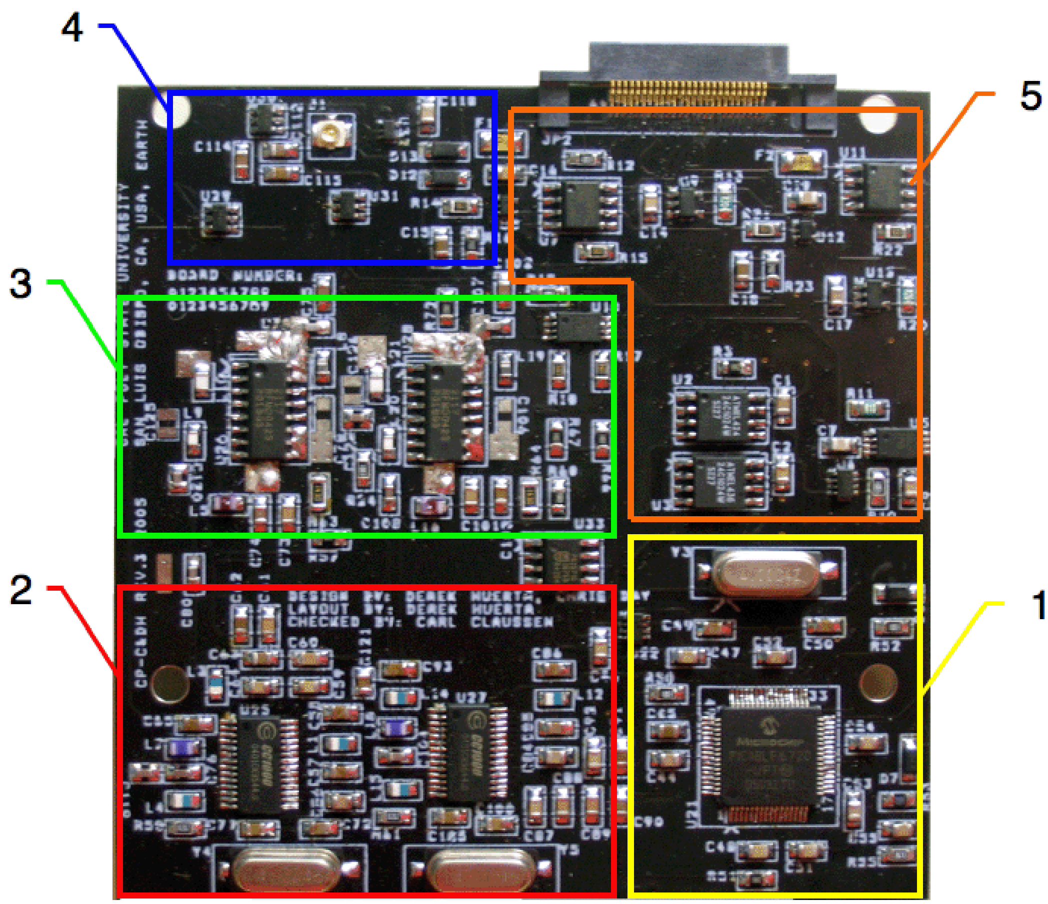

Figure 3.6.2 – Top Side of the TT&C Board

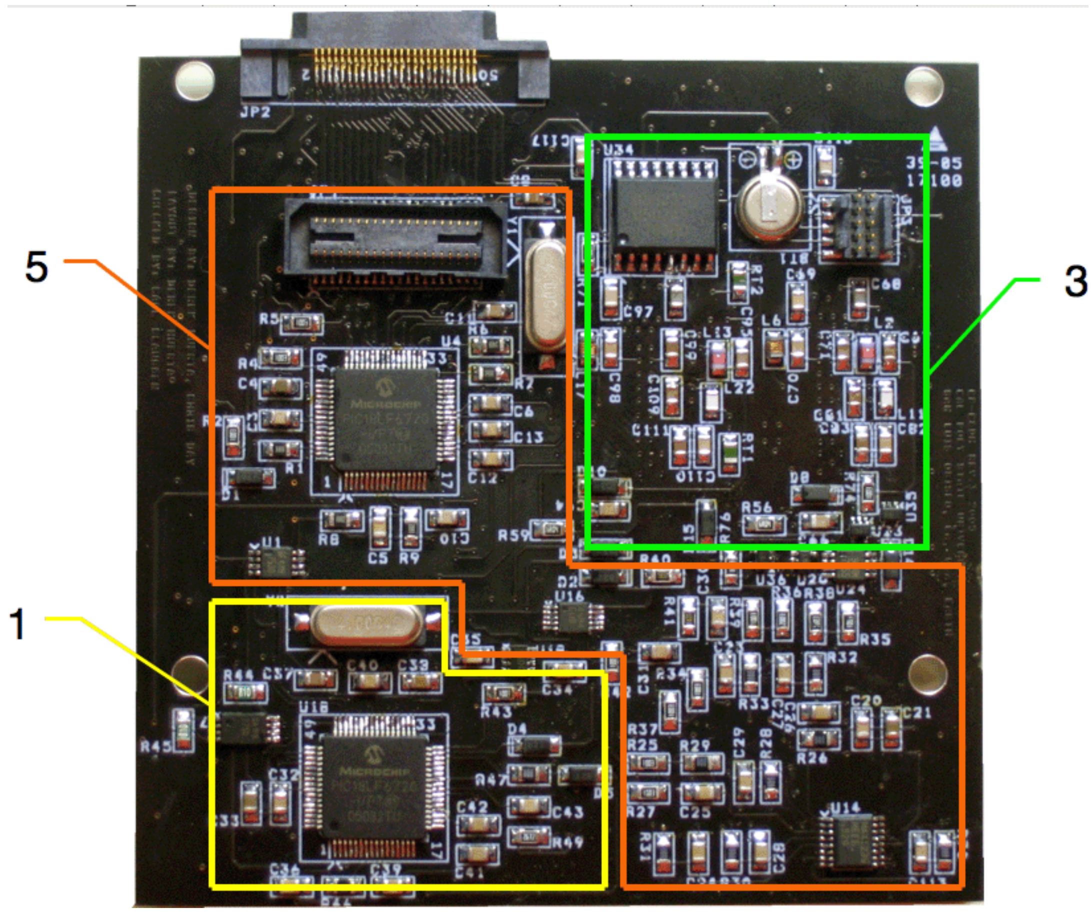

Figure 3.6.3 – Bottom Side of the TT&C Board

Table 3.6.1 – TT&C Board Elements

1	Pic 18 Communication Microcontrollers
2	CC1000 Transceivers
3	RF2117 Final Amplifiers
4	SW-425 Switches
5	TT&C Subsystem Core

4 System Level Acceptance Testing

To speed development, acceptance tests are not performed on every subassembly. Instead, the final assembly is acceptance tested. A complete satellite is built specifically for testing, and that satellite will eventually be tested to destruction. Testing techniques are borrowed from the Highly Accelerated Life Testing (HALT) and Highly Accelerated Stress Screen (HASS) methodology. The basic concept is that the test loads are increased until a failure occurs. With the failure identified and documented, corrective action is taken. The test loads are again increased and the process is repeated until the spacecraft is robust enough to reliably withstand launch and orbital environments [6].

4.1 Environmental Testing

The critical nature of the communication and TT&C subsystems requires that extensive testing be conducted to ensure system survivability during the launch and performance in orbit. Specifically, vibration, thermal vacuum, and distance tests were conducted to simulate the launch and orbital environments.

4.1.1 Vibration Testing

A key requirement in the electronic design of the CPB is its ability to endure vibration acceptance testing at 150% of worst-case launch levels. Figure 4.1.1 provides a worst-case vibration profile compiled from the published environments for several launch vehicles, including the Delta II, Pegasus, Shuttle, and Dnepr.

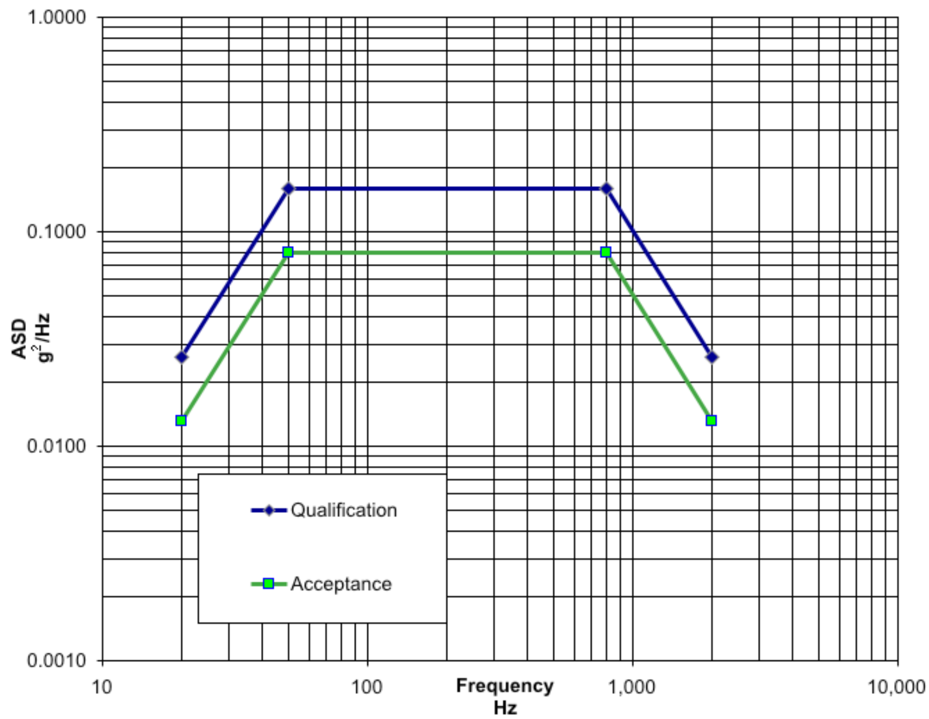

Figure 4.1.1 – Worst Case NASA GEVS Launch Profile

The CPB has been tested and survived 150% of the NASA General Environmental Verification Specification (GEVS) worst-case launch profile [6]. Currently, all satellites built with the CPB are scheduled to be launched on Russian Dnepr launch vehicles whose launch environments are much more benign than the GEVS profile. The satellites under test are in a powered down state during the vibration tests, as they would be during launch in the P-POD.

4.1.2 Thermal Vacuum Testing

The orbital environment expected for the CPB is that of any LEO satellite, a temperature range of -10 C to 60 C in a vacuum. Both of these environmental factors can be simulated using Cal Poly's Thermal Vacuum chamber. The CPB team ran a number of thermal vacuum tests to ensure normal operation of the satellite in orbit.

4.1.2.1 Component Testing

Typically, the RF power amplifier dissipates the most power in communication system designs. The RF2117 amplifier used in the CPB can consume as much as 3.5 watts at our maximum bus voltage of 4.2 volts. Even with an efficiency of 50%, the amplifier needs to dissipate 1.5 watts as heat. With the limited abilities for CubeSats in general to dissipate heat, the thermal design of the PCB needed to be verified. Our system was tested from -60 C to 70 C at 10^{-3} torr (See Figure 4.1.2). At the high temperatures, the amplifier was only 5 C above the ambient temperature. At low temperatures, the power dissipated as heat keeps the ICs much warmer than the ambient. These results indicate that the amplifier will be able to dissipate the heat generated as necessary throughout the orbit of the CPB. Additionally, the other components in the satellite were able to operate without failure for the entire thermal cycle.

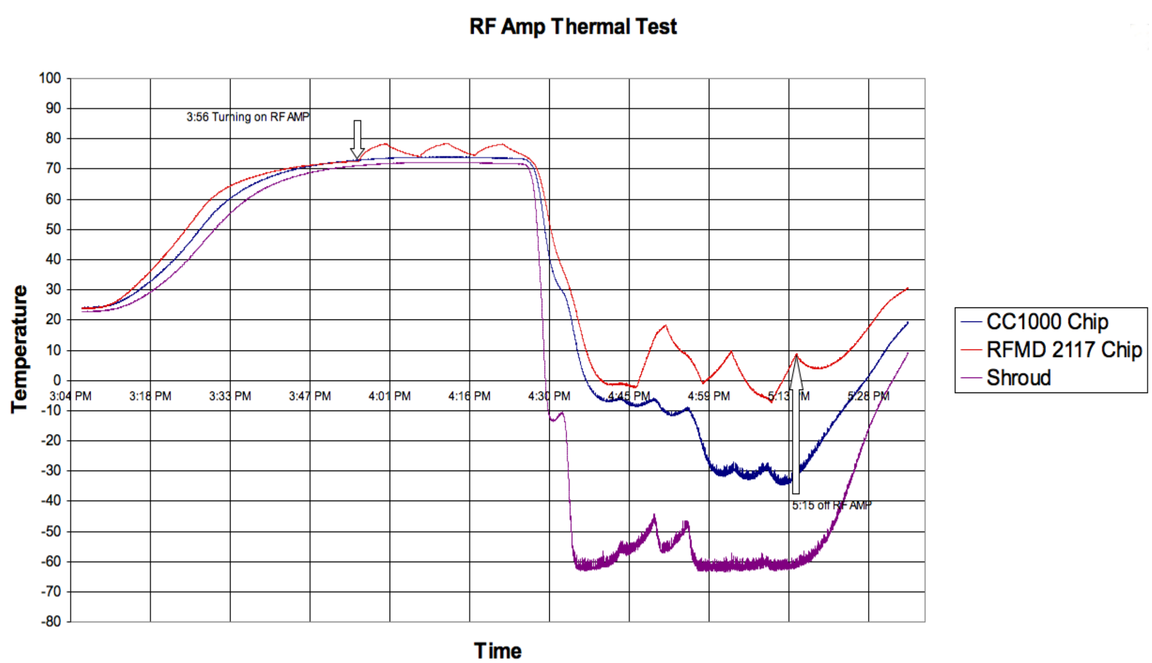

Figure 4.1.2 – Thermal Vacuum Testing Results

4.1.2.2 Antenna Deployment Testing

In addition to running the satellite at extreme cases of temperature in a vacuum, the CPB team conducted several antenna deployment tests using flight software and flight quality hardware. The antenna was correctly deployed using both a command from the earth station and the internal timer. Each deployment scenario was tested at both the high and low temperature extremes.

4.1.3 Field Testing

The easiest way to validate the assumptions made regarding system performance would be to simulate the orbital conditions and evaluate the functionality of the system. Of course, this is easier said than done. From our calculations, the path loss for the communication system was found to be 153 dB for a distance of 2,563 km, which is the distance to the spacecraft at an altitude of 700 km, 5 degrees from the horizon.

Path loss increases logarithmically as a function of distance. Therefore, simply increasing the distance between the earth station and satellite can approximate many of the orbital conditions. A distance of 6 km will have a path loss of 100 dB, compared to 153 dB for a distance of 2,563 km. Traveling 6 km and then adding 50 dB of attenuation to the signal path accurately simulates orbital conditions. The hard part then becomes finding a location 6 km away from the earth station with a direct line of sight to the satellite. The team found Perfumo Canyon to be approximately 6 km away from the earth station, with good line of sight.

With this test set-up (See Figure 4.1.3) the team verified to its satisfaction the performance of the communication system. Additionally, the EIRP of the satellite was determined to be 1W (30 dBm), which results in 9.5 dB of margin on downlink from our link calculations (See Appendix C).

Figure 4.1.3 – Field Test Set-up

4.2 Electrical Testing

Electronic functional tests are critical throughout the systems engineering process. Testing at each level of integration helps to ensure reliability of the overall system. To this end, several phases of prototypes were built at various stages of development. Bread and evaluation boards were used to verify correct functionality of the design and allowed early software development. Prototype PCBs were used to evaluate the implemented design. Finally, the highly integrated PCBs were designed and then optimized for peak performance.

4.2.1 Bread and Evaluation Boards

Once a circuit is designed, the correct functionality of the circuit must be verified. The quickest way to verify the functionality of the circuit is to build the circuit. Often simple circuits can be built using breadboards. However, complex circuits, like a transceiver, require the use of pre-built evaluation boards. A combination of bread and evaluation boards allows the functionality of the subsystem to be evaluated.

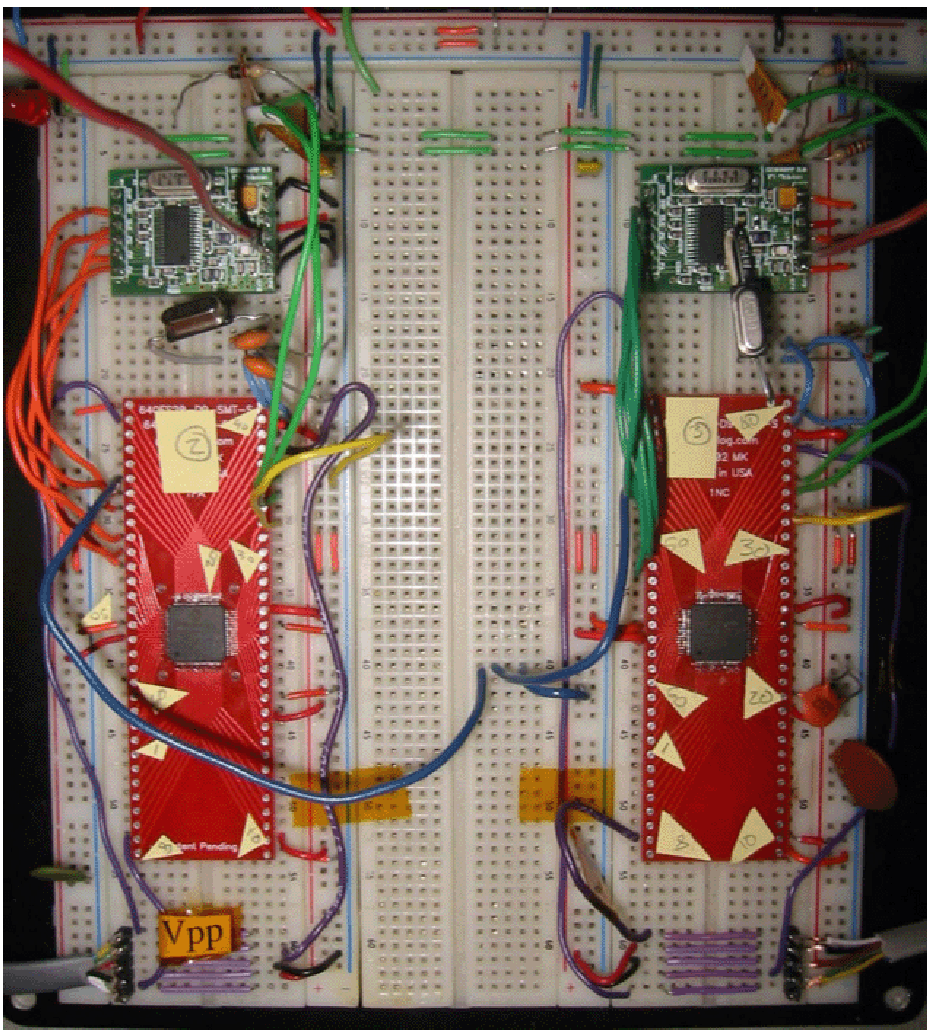

Figure 4.2.1 –Communication System Evaluation Board

Figure 4.2.1 shows the combination of evaluation and breadboards used to verify functionality of the communication system. The two large red components are the PIC microcontrollers; the green boards are transceiver evaluation boards, and the two connectors at the bottom are used to program the microcontrollers. The use of the evaluation boards allows software to be developed using the known-good hardware, reducing development time and providing a reference for the hardware to be developed from. Additionally, evaluation boards of several subsystems can be integrated to look for problems at the system level.

4.2.2 Prototype Boards

The next step in the system development is to design custom PCBs. However, due to the complexity in integrating several subsystem into a single PCB and the sensitivity of specifically the RF circuits, it is important to develop a prototype PCB that contains only parts of the subsystem. The prototype PCB helps to ensure that the electronics developed for the CPB will function correctly.

Two prototype PCBs were designed for the communication system. To simplify the design, each prototype PCB contained only a single communication system. The first prototype consisted of only the microcontroller, transceiver, and support circuitry for both. The use of this first PCB (See Figures 4.2.2 and 4.2.3) allowed the team to become more familiar with the transceiver and flush out any problems. The most significant problem uncovered with the first prototype PCB was the inability to tune to frequencies in our desired band. The problem was the size of the voltage-controlled oscillator's tank inductor of the transceiver (L4). The CC1000 datasheet suggested a value of 33 nH, but due to the CPB design, the size of the inductor needed to be reduced to 27 nH.

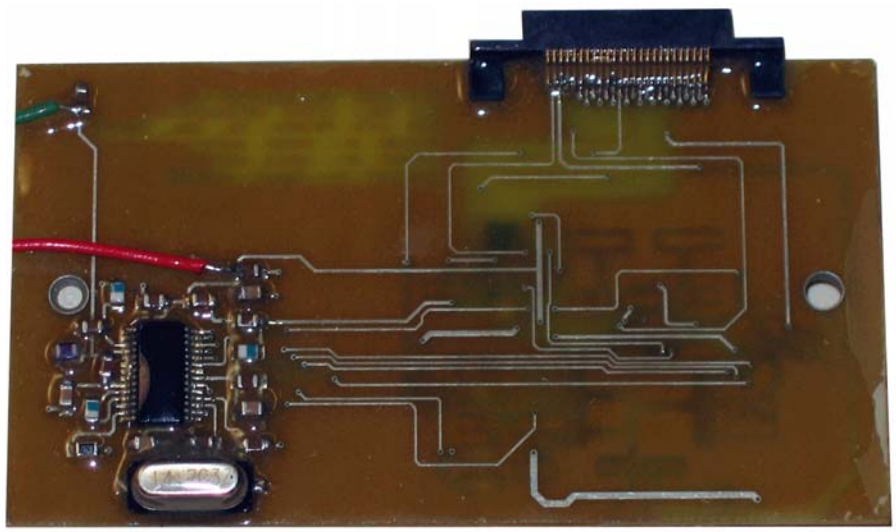

Figure 4.2.2 –Transceiver Test Board Top

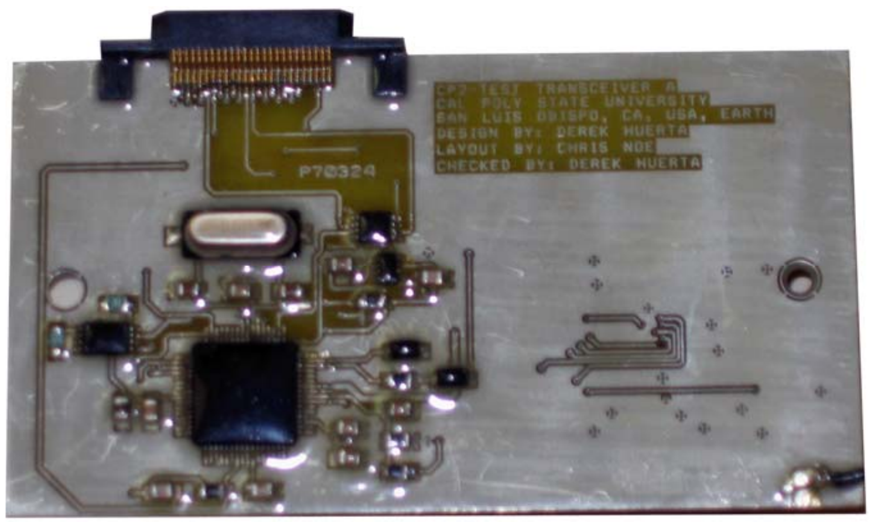

Figure 4.2.3 –Transceiver Test Board Bottom

The second prototype board (See Figure 4.2.4) used the design from the first board but added the RF amplifier. With the first PCB, the RF signal from the transceiver went directly to an antenna and the design did not need to be optimized. The addition of the amplifier required that closer attention to the RF design needed to be paid. Specifically, the impedances for the RF signal lines needed to be controlled and representative of the final PCB design. For this reason, special dielectric material (Rogers 3210) was chosen for the second PCB design. Rogers 3210 has a dielectric constant of ten, similar to the dielectric constant of a single layer in a 0.062” thick six layer FR-4 PCB that will be used in the final CPB PCB design.

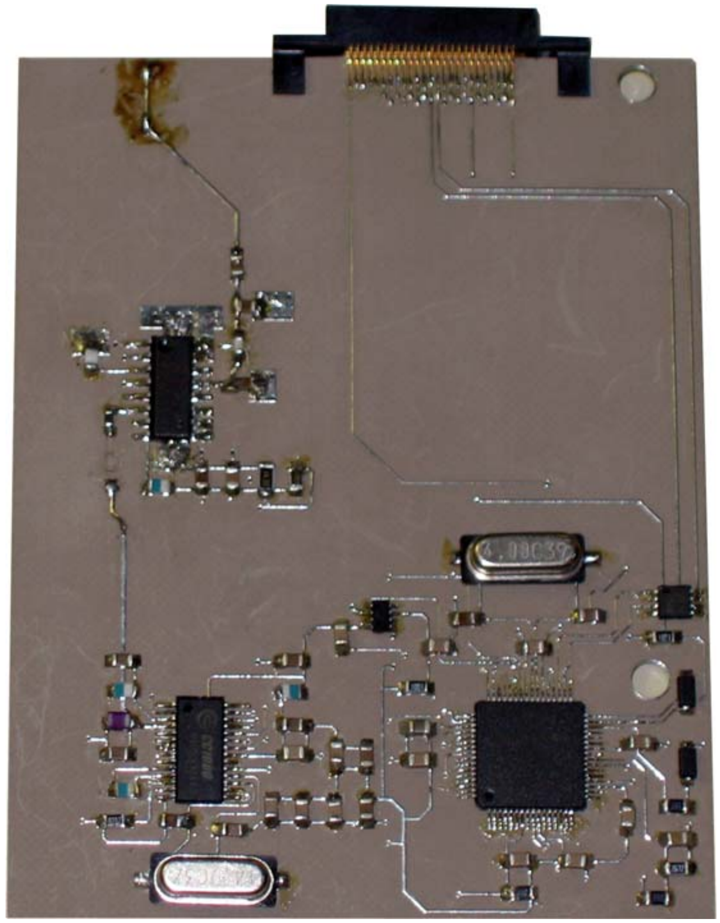

Figure 4.2.4 –Communication System Evaluation Board

The second prototype board verified the functionality of the RF amplifier. However, the performance of the amplifier on the test board was not to specification and further optimization of the layout needed to be done for the final PCB design.

4.2.3 Final Design Optimization

Once the initial circuit implementation is complete, the design must be optimized for peak performance. In particular, the communication system must be designed for maximum output power and receiver sensitivity. Additionally, the TT&C subsystem must have the sensors calibrated and filtered, if necessary.

4.2.3.1 Transmitter Output Power

Ensuring a reliable link with the earth station is often limited by the available output power of the satellite for transmit. Link calculations (see Appendix C) show that, for a data rate of 1200 bps and the parameters of our earth station, a link with 3.3 dB of margin (greater than twice the required power) can be achieved at 5 degrees off the horizon if the effective isotropic radiated power (EIRP) is as little as 190mW. These parameters are often used to assess the worst-case link.

Ensuring optimum power output requires that the RF inputs and outputs of the various sections, like the transceiver and amplifier, have the same impedance, typically 50 ohms. Additionally, the amplifier circuit must be tuned or optimized for use at a particular frequency.

Using a vector network analyzer (VNA) and an iterative approach is often the most effective way to accomplish these tasks. The VNA measures the real and reactive components of the impedance, and the gain of a section, at various frequencies.

By using calculations and simulations to select good initial values of components, and then slightly adjusting them based on the VNA results, the processes of tuning and matching the RF system becomes very methodical, though still time consuming. Lab testing showed our transmitter capable of outputting as much as 1.2 W (31 dBm). To ensure a reliable link with a minimum EIRP of 190 mW, the losses between the transmitter and the antenna are required to be less than 8 dB.

4.2.3.2 Receiver Sensitivity

The CPB receiver is capable of detecting the power of an incoming signal through the Receive Signal Strength Indicator (RSSI). The RSSI was used to determine the lowest power signal that would be correctly decoded by transmitting highly attenuated signals (See Figure 4.2.4). Through testing it was found that the receiver is able to decode signals as low as 0.31nW (-95dBm). Link calculations (see Appendix C) show that this sensitivity would yield a worst-case margin of 4 dB for uplink.

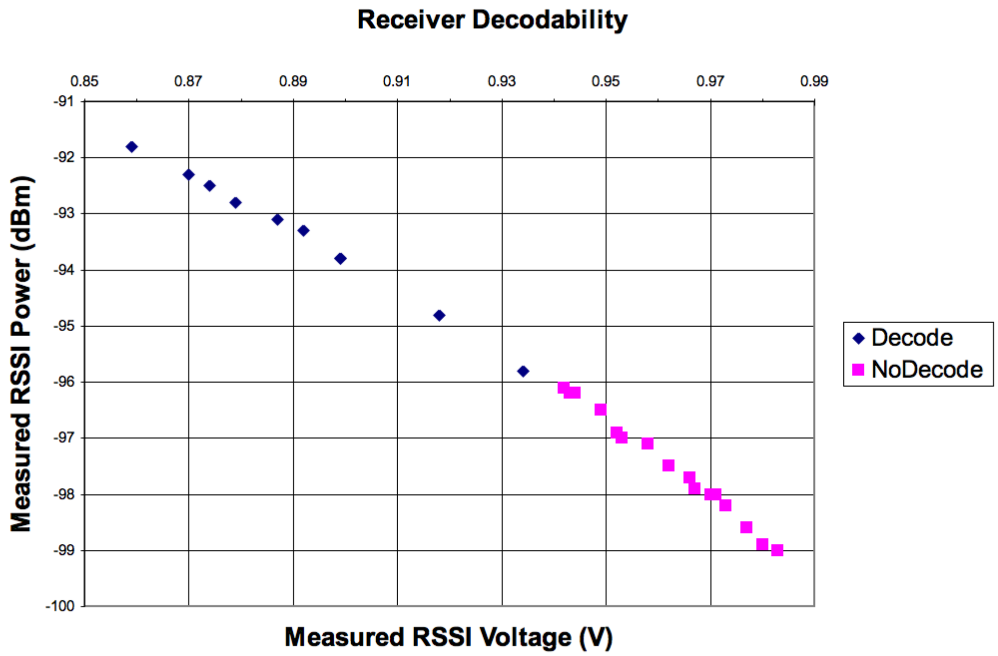

Figure 4.2.4 – Receiver Decodability Testing Results

One concern, however, is that the CPB will be a part of a cluster launch with fourteen other satellites using frequencies within the detectable range of the CPB receiver. This clustering means that the receiver may have a high noise floor, effectively resulting in a less sensitive receiver.

4.2.3.3 Sensor Calibration

In the event of system difficulty, an accurate understanding of what state the spacecraft is in is critical to resolve the issue. Consequently, each sensor must be tested and calibrated to ensure accuracy and reliability of the signal.

Measuring the specific readings using external sensing devices (i.e. a digital multimeter to read voltage) each sensor in the CPB was tested. The externally measured readings were compared to the reading collected by the TT&C system and offsets were added to software if necessary.

Additionally, the signals from the sensor to the A/D were measured using an oscilloscope. If the signals into the A/D had a lot of noise, the input filter was adjusted to reduce noise on the line. Typically, the only sensors with significant amounts of noise were the current sensors. The current sensors measure very small voltages and amplify the voltage by 50 or 100 times, resulting in large output oscillations for very small changes on the input.

5 Future Work

Given the limited resources of a university project and the expensive equipment required for RF design, more work needs to be done to gain access to the necessary equipment. Access to better RF testing equipment will allow for improvement in the impedance matches between RF components, resulting in better output power and receiver sensitivity.

Additionally, the wireless industry continues to grow at an ever-increasing rate, resulting in tremendous technological breakthroughs. It is necessary to explore the replacement of current components with newly developed technology that is better able to satisfy a CubeSat's requirements.

5.1 RF Amplifier

The RF2117 final amplifier has reached the end of its production life and will no longer be manufactured after December 2005. Therefore, the RF2117 must be replaced.

Fortunately, RF Micro Devices has released a new product capable of exceeding the performance of the RF2117. The RF5110G has a small signal gain of 32 dB and a maximum RF output power of 36 dBm (3.9 W). Additionally, the RF5110G has a smaller footprint and a more complete datasheet than the RF2117.

5.2 Transceiver

The CC1000 is not optimized for narrow bandwidth operations, like those of the CPB. As such, the transmitter consumes much more bandwidth than required and the receiver is not as sensitive to narrow band signals. The CC1020, however, is optimized for narrowband applications and has a more sensitive receiver. Additionally, because it is designed by the same company as the CC1000, the transition to the CC1020 would not be as difficult as going to a different manufacturer's component. Furthermore, the CC1020 has a smaller footprint and less support circuitry than the CC1000, making it an ideal alternative.

5.3 Improved Data Rates

As the complexity of CubeSats and their missions increase, data requirements will also increase. As such, one of the most significant bottlenecks in the data flow is in downlink. To reduce the bottleneck data rates should be increased from 1200 bps to 9600 bps. The improved data rate will increase the amount of data collected on the ground, for a nominal mission, from megabytes to tens of megabytes.

5.4 Additional Sensors for Attitude Determination

Currently, the CPB uses magnetic field sensors to determine the attitude of the spacecraft. Gyroscopes could be added to the TT&C subsystem to determine angular rates of the spacecraft in each direction, improving the accuracy of the attitude determination capability. The Epson XV-3500 is very small and could be easily incorporated into the TT&C subsystem.

6 Closing

Building on the lessons learned from CP1, the CPB team was able to design, construct, and test a system able to meet demanding requirements. Also, the design principles used become apparent in the design.

CP1 was comprised of a computer board, an RF board, and two transceiver boards. With the CPB, the team cut this board count in half, while increasing the flexibility and performance of the system. The reduction in board count comes from using COTS components and replacing hardware with software allowing the custom designed, fully redundant communication system to fit on the same board as the main computer. This smaller board count reduces constraints on the payload. Overall, the innovative design of the CPB results in an increase in system performance and flexibility.

6.1 Conclusion

The digital communication system designed for the CPB is a custom RF design comprised of COTS components as is the TT&C system. These systems are highly integrated and require minimal power, mass, and volume. Additionally, the high level of software integration maximizes the flexibility of the overall system. For example, the ability to change the transmitter output power on command is a direct result of the software control capabilities of the system. Although there is room for improvement, these systems are able to satisfy the challenging requirements.

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Appendix A: CubeSat Standard

Appendix B: System Schematics

Appendix C: Link Calculations