THE KUHABS,KUBESAT & KUTESAT-1 TECHNICAL REPORT, DESIGN OF A MODULAR PLATFORM FOR PICOSATELLITES

By

Nikhil Paruchuri

University of Kansas, 2006

B.Eng., Osmania University, India, 2003

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Dr. Glenn Prescott, Chairman

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Dr. Trevor Sorensen, Committee Member

____
Dr. Chris Allen, Committee Member

Date Submitted: _____________________

ABSTRACT

The aim of this project is to provide a description of the technical aspects of designing the avionics for the Kansas Universities High Altitude Balloon System (KUHABS), and the Kansas Universities Balloon Experiment Satellite (KUBESat); and the main Command & Control system of the first ,Kansas Universities Technology Evaluation Satellite (KUTESat) called Pathfinder-I.

The author hopes that this report will serve as a guide to future members of the Kansas Universities space program.

In the multiple mission space program at the University of Kansas, there is a need to reduce the costs and increase the performance of spacecrafts. This can be achieved by creating a standard platform that is designed based on the knowledge gained from previous satellite designs. A modular platform will form a guideline for the standardization of the design of future subsystems, which will lead to reduced design cycles; independent subsystem testing; reusability of subsystems on different missions; and lower costs.

A modular platform design is proposed and is implemented in the HABS-MK3 and the KUBESat-2 systems. The author explores the possibility of using this platform for the future HABS-MK4 which aims at commercializing the HABS system.

To Sandhya, Jagdish & Divya.

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Chapter 1 - Introduction

1-1 KU space program

Professor Robert Twiggs of Stanford University developed the concept of a "CubeSat," which is a standardized picosatellite (i.e., less than 2 kg mass), as a satellite project that can be undertaken by almost any university and completed in a relatively short period of time, so that the same students that started it can see it to fruition [1-3]. The CubeSat standard was set by Stanford University so that the satellites will all be similar enough that information and solutions can be easily shared. The result has been a free flow of information between the various CubeSat teams, thus providing many solutions that can be studied to solve various problems of satellite building and operation.

These satellites use mostly off-the-shelf parts that are inexpensive and easily obtainable. More than thirty Universities around the world have started the design of a CubeSat. The first launch of six CubeSats was in June, 2003. Even though a couple experienced problems, they successfully proved the concept. In the past four years, many papers about this system have been presented in the most prestigious conferences, demonstrating that students are learning and contributing to research. The majority of universities that have started a CubeSat program consider it primarily as a means to instruct students about spacecraft and space science. As a consequence, they start and develop projects that are very interesting from a scientific point of view, but are not part of a global plan.

The University of Kansas team has recognized the potential of picosatellites, and the slightly larger nanosatellites (up to about 30 kg), to become a primary answer to many of the challenges that the space business is facing. The Kansas Universities' Technology Evaluation Satellite (KUTESat) program goal is to develop the capabilities to design, build and test satellites that will meet those challenges, and only a systematic development of the program and of the facilities available will allow success [4,5] .

The technical objective of the KUTESat program is the development and operation of small pico- and nano-satellites that can demonstrate and test technologies and techniques necessary to accomplish various commercial and government missions. Some of the satellites will be for testing new technologies for various customers, while others will be engineering prototypes of small probes that could be carried aboard larger spacecraft. Possible missions of these latter picosatellites would be to provide an ability to inspect the main spacecraft or other nearby objects, or to measure the ambient space environment away from the influence of the main spacecraft (e.g., for a solar sail mission).

Another major objective of the KUTESat program is to flight-test, advanced nanotechnology in the form of components and subsystems (e.g., electronics, micro propulsion, inertial measurement units, and imagers) that will be useful in future government missions that are being designed to be smaller and cheaper.

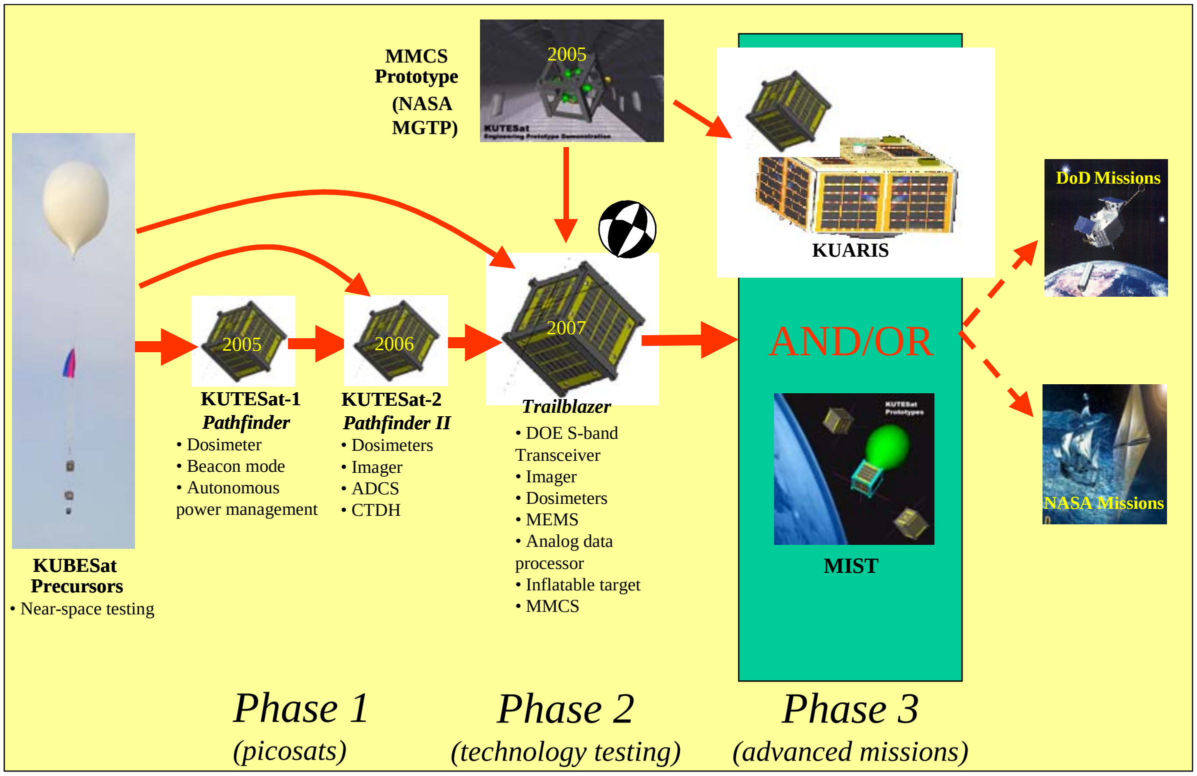


Figure 1.1: KU Space program overview

The core KUTESat program (Fig. 1.1) starts with balloonsat precursors, the Kansas Universities Balloon Experiment Satellite (KUBESat), which is flown on the KU High Altitude Balloon System (HABS). The program is then divided into three phases, each of which significantly advances the capabilities of the program. Phase 1 is to develop the capability to design, build, and operate satellites, using picosatellites that adhere to the CubeSat standard. The satellites developed and flown in this phase are KUTESat-1 (Pathfinder) and KUTESat-2 (Pathfinder II), which are scheduled for launch in 2006. These satellites will also test the core subsystems, tools, and techniques needed for Phase 2.

The objective of Phase 2 is to develop and fly a satellite that will provide a space platform to test various technologies and techniques that are of interest to the U.S. government (both civilian and defense). This satellite has recently been named

Trailblazer. An important part of Phase 2 is the development of a miniature maneuvering control subsystem (MMCS). The development will be facilitated by tests of a prototype MMCS onboard the NASA Microgravity Experiments Program aircraft during May 2006. Phase 3 currently has two possibilities - the first is an Autonomous Redockable Inspector Satellite (ARIS) experiment, and the second is a 3-satellite formation mission called MIST (Mission for the ISS, SES, and TRS) which involves three picosatellites. The Inspection Sensor Satellite (ISS) is a picosatellite similar to the one that would be carried on the ARIS mission; the Space Environment Satellite (SES) would contain miniature sensors (e.g., dosimeters) to measure the ambient space environment; and the Target & Relay Satellite (TRS) would provide an inspection target for the ISS and also act as the communication hub between the three satellite and the ground. Which of these two missions will follow *Trailblazer* depends on the funding source.

From there the program diverges into two lines leading towards possible operational applications in either DoD or NASA missions (although commercial or academic missions are also possibilities). Although this shows a progression in capabilities, the phases could eventually be concurrent, with additional Phase I (picosatellites) or Phase II (nanosatellites for technology demonstration) being built if customers are found [4].

1-2 Project overview

This project discusses the necessity of developing a modular system, and a possible design for the future space missions.

In Chapters 2&3, the projects that have been completed in the past three years are studied. This includes the High altitude Balloon (HABS), the S-band transmitter

(KUBESat-1) and Pathfinder (KUTESat-1) projects. The designs implemented in these systems and the lessons learnt from their implementation will be the basis for the design of modular electrical interface architecture.

In Chapter 4, a particular design of modular electrical interface architecture is developed. This discussion is led by the consequences of using a modular architecture in a space mission, specially the benefits of cost and time savings.

Chapters 5 and 6 discuss the current and future implementations respectively of the modular architecture.

Chapter 2 - The Balloonsat precursors

2-1 Introduction

The primary goal of the Kansas Universities High Altitude Balloon Project (KU HABS) is to build, design, test and operate a satellite like vehicle on a weather balloon, and be capable of carrying payloads –KUBESat's to an altitude exceeding 100,000 ft and successfully collect the data from the payloads using real time down linked telemetry or retrieve stored data post-flight [4]. A secondary objective of the HABS project is to operationally test the KUTESat's in a near space environment.

The budgets allotted for the KUTESat's are usually limited, and so the cost of testing equipment can become prohibitive. It is not feasible to buy pressure and temperature chambers which simulate near space conditions, nor is it cheap to purchase an anechoic chamber to test the attitude control, antenna pattern on a satellite. A cheaper and time saving alternative is to fly the KUTESat's or certain subsystems and components as a payload on a HABS flight.

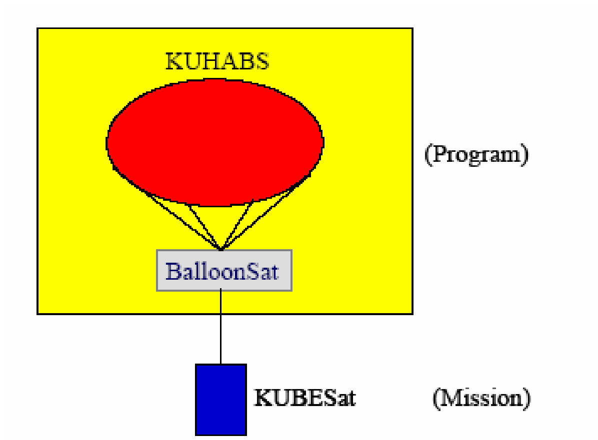
A typical HABS flight can reach a maximum altitude of ~100,000ft where the atmospheric pressure is < 1% of Mean Sea level, the temperature during the flight typically goes below -70^{o}C, the slant range can exceed 100 km from the ground station, and a typical flight lasts about 2.5 hours (comparable to the orbital period of an Earth – orbiting satellite) .The main difference between the HABS flight and LEO sat is the much lower velocity and the resulting reduced Doppler effect. The HABS flight can however be used to test the range and pattern of the communication system and antenna respectively, the battery and solar cell performance, and the performance of the subsystems at extremely low pressure and temperature.

In Spring 2003, The University of Kansas started a high altitude balloon program (HABS), initially as a collaboration between the Aerospace Engineering (AE), and the Electrical Engineering and Computer Science (EECS) senior design classes; the KU School of Education; a high school; and the Department of Energy, National Nuclear Security Administration, Honeywell Federal Manufacturing and Technologies LLC Kansas City Plant (DOE KCP).

Since the first flight in May 2003, a reliable HABS system has been built, which has been beneficial in testing components and software for the Pathfinder satellites, and is being used to help the DOE KCP characterize the flexible S-band transceiver that it is building. The first payload module, KUBESat-1 carried the DOE KCP S-band transmitter and was tested during 3 flights. The KUBESat-2 system is being developed to carry the S-band Transceiver in spring 2006.

2-2 Balloon Flight Configuration

The basic HABS/KUBESat configuration consists of a Helium-filled latex weather balloon [8, 9], a parachute recovery subsystem, a balloonsat command and control module (usually called the HABS), and the KUBESat payload module (Figure 2.1).



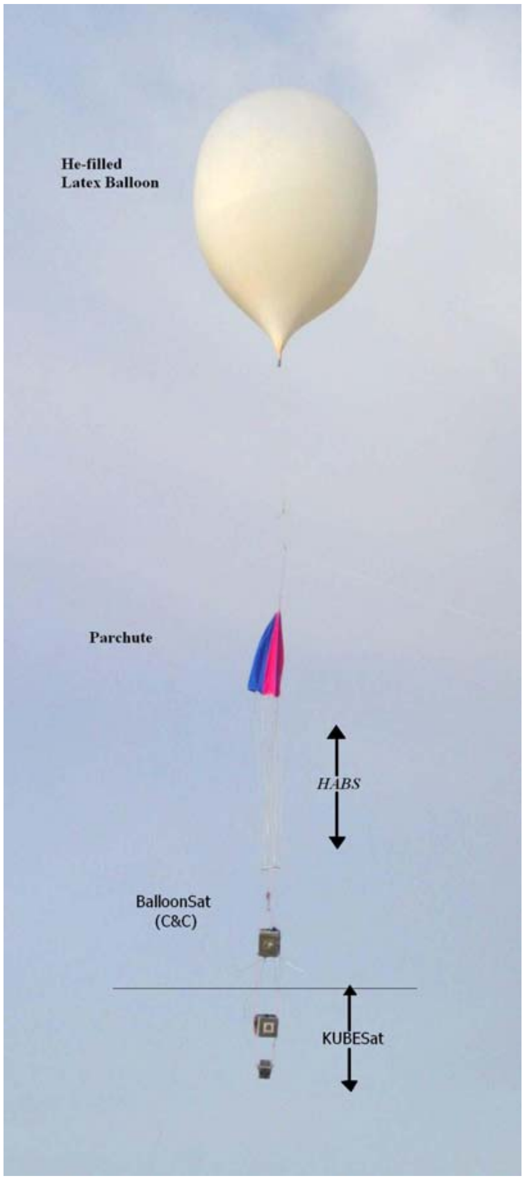


Figure 2.1: HABS-KUBESat flight configuration

In order to keep within Federal Aviation Administration regulations, each module must weigh less than six pounds and the total weight of the payload carried by the balloon cannot exceed 12 pounds. If these and other restrictions are not met, then inclusion of a radar transponder and other compliances must be made [7].

2-3 Balloon Flight profile

A normal HABS flight profile starts with ascent to a maximum altitude ,where the latex balloon bursts due the resulting expansion because of the pressure difference between the balloon(~ 1 atm) and the outside atmosphere (~ 0.01 atm)(figure 2.2) .If desired the ascent of the balloon can be terminated by severing the cord attached between the balloonsat and the balloon ,by sending a command from the ground, or by a command from the onboard controller when the designated altitude has been passed , or by an independent timer. Once the balloon is detached or has burst, the HABS descends to the ground by parachute. During the entire the flight, the HABS uses a Global Positioning System (GPS) unit to transmit its position, altitude, speed and bearing every 30 seconds to the ground .This aids in the tracking and recovery of the HABS by two mobile teams, each of which has a van equipped with HABS ground communication system, a GPS unit and ground software [10, 11] which shows the position of the recovery van and monitors the HABS (Figure 2.3). The software can predict the flight profile for various maximum altitudes, based on wind data obtained from the U.S. Weather service [12, 13, 14] , Figures 2.4,2.5. The software also provides real time prediction.

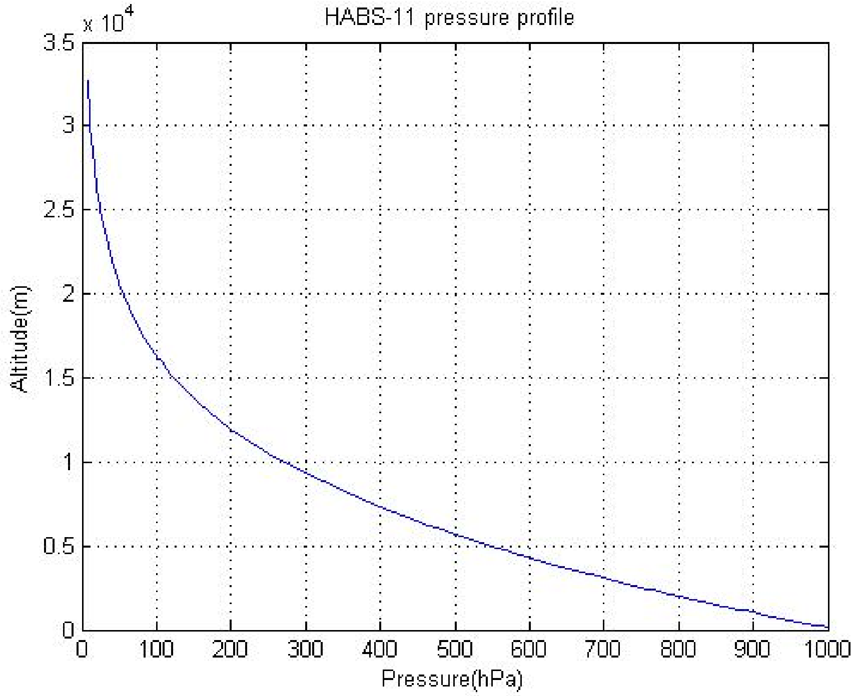


Figure 2.2: Pressure profile(Based on HABS-11 flight)

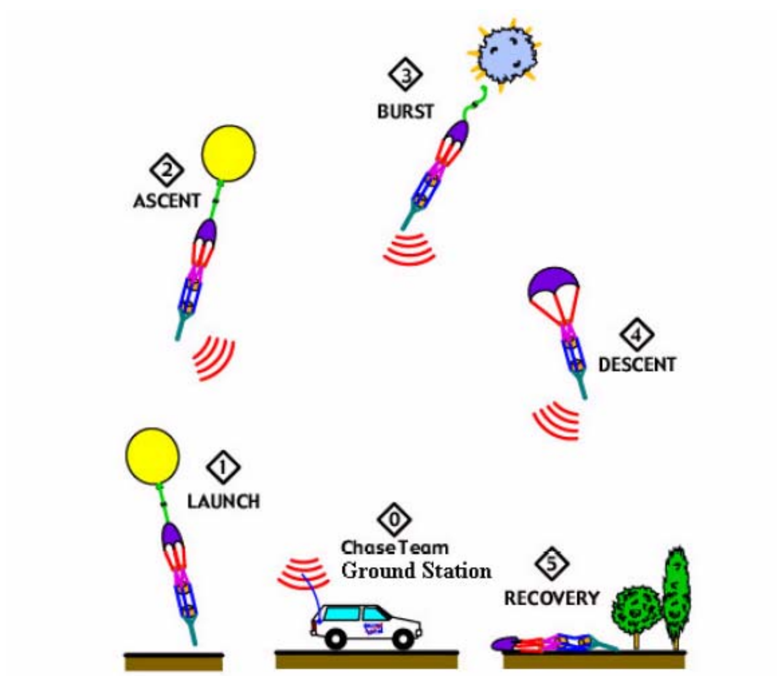


Figure 2.3: Typical flight profile of HABS [15]

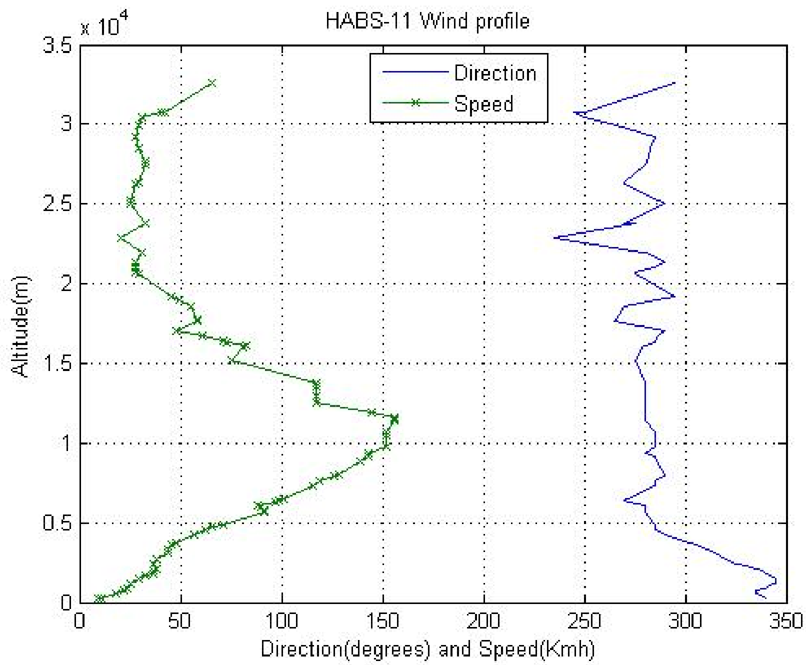


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Figure 2.4: Wind profile (for HABS-11 flight)

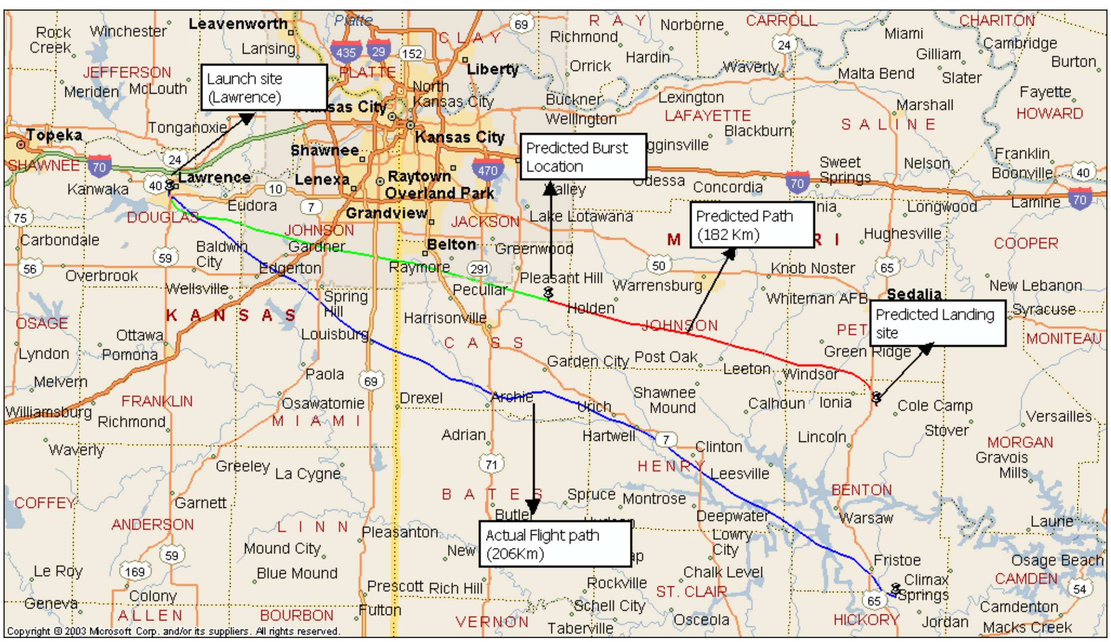


Figure 2.5: Prediction of a flight path (HABS-11 flight)

2-4 The HABS system

The HABS/KUBESat top level diagram is shown in Fig.2.6.The HABS module communicates with the ground station and the chase vehicles through a amateur radio communication system (HAM). The HABS system downlinks the GPS position data and the onboard telemetry data to the ground vehicles. This data is used to monitor the path of the flight and the status of the HABS system. The HABS system also reports its GPS data on the Automatic Packet Reporting System (APRS) frequency -144.39 MHz [16].

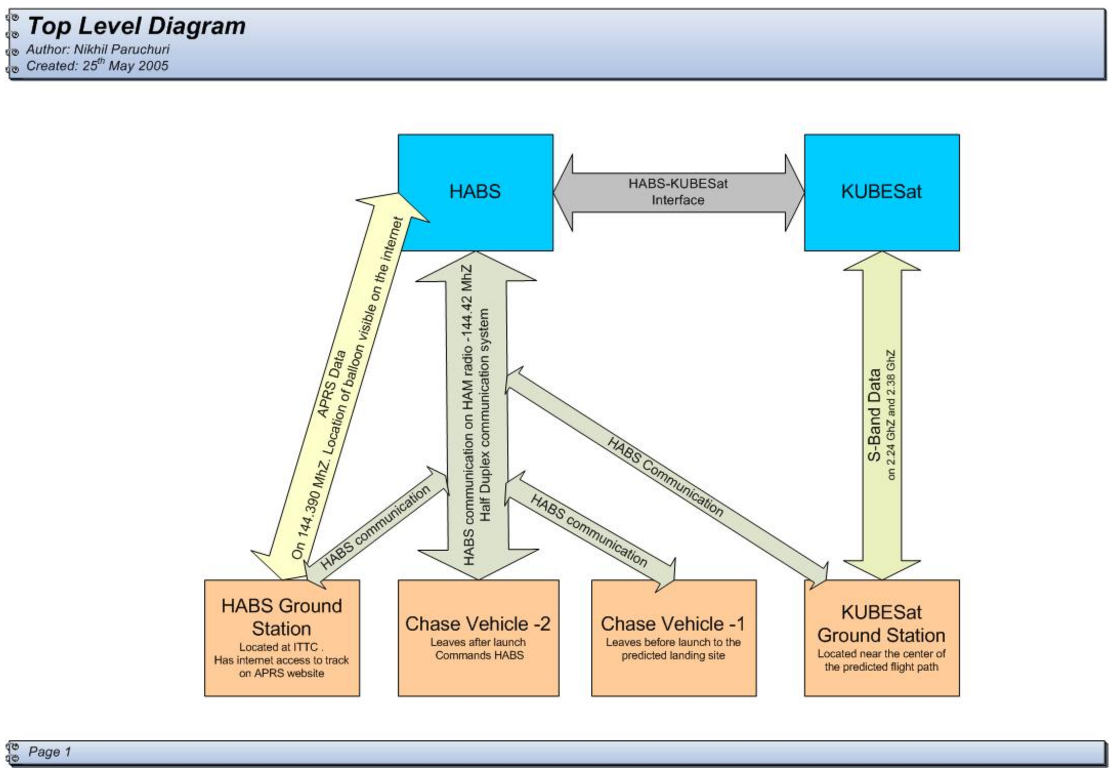


Figure 2.6: HABS/KUBESat Top level Diagram

The HABS system has an interface to the KUBESat system, which includes communication, power, control lines and analog measurement lines. The KUBESat system can have an additional ground station for communication e.g.: the KUBESat-1 and KUBESat-2 missions require an S-band communication system equipped ground station.

The HABS module has an onboard microcontroller in the Command, Telemetry and Data Handling (CTDH) subsystem; an Electrical Power System (EPS); a Communications and Tracking Subsystem; a Thermal Control subsystem; Structures and Mechanical subsystem; and a Payloads subsystem. Refer to Fig.2.7 which shows the system level design of HABS-MK3.

The CTDH system interfaces with the other subsystems and stores the voltage, temperature and system status data. It communicates with the ground station using a commercial HAM radio transceiver. Power is provided by Lithium batteries connected to a power board that distributes it to the other subsystems. The Communication and tracking system consists of a HAM radio which is the main mode of communication. It also has an APRS system which is used to report GPS data; and beacon (Audio or RF) which can be used for tracking after the system has landed in ground. The beacon is useful when the HABS systems lands in an area covered by trees or crops.

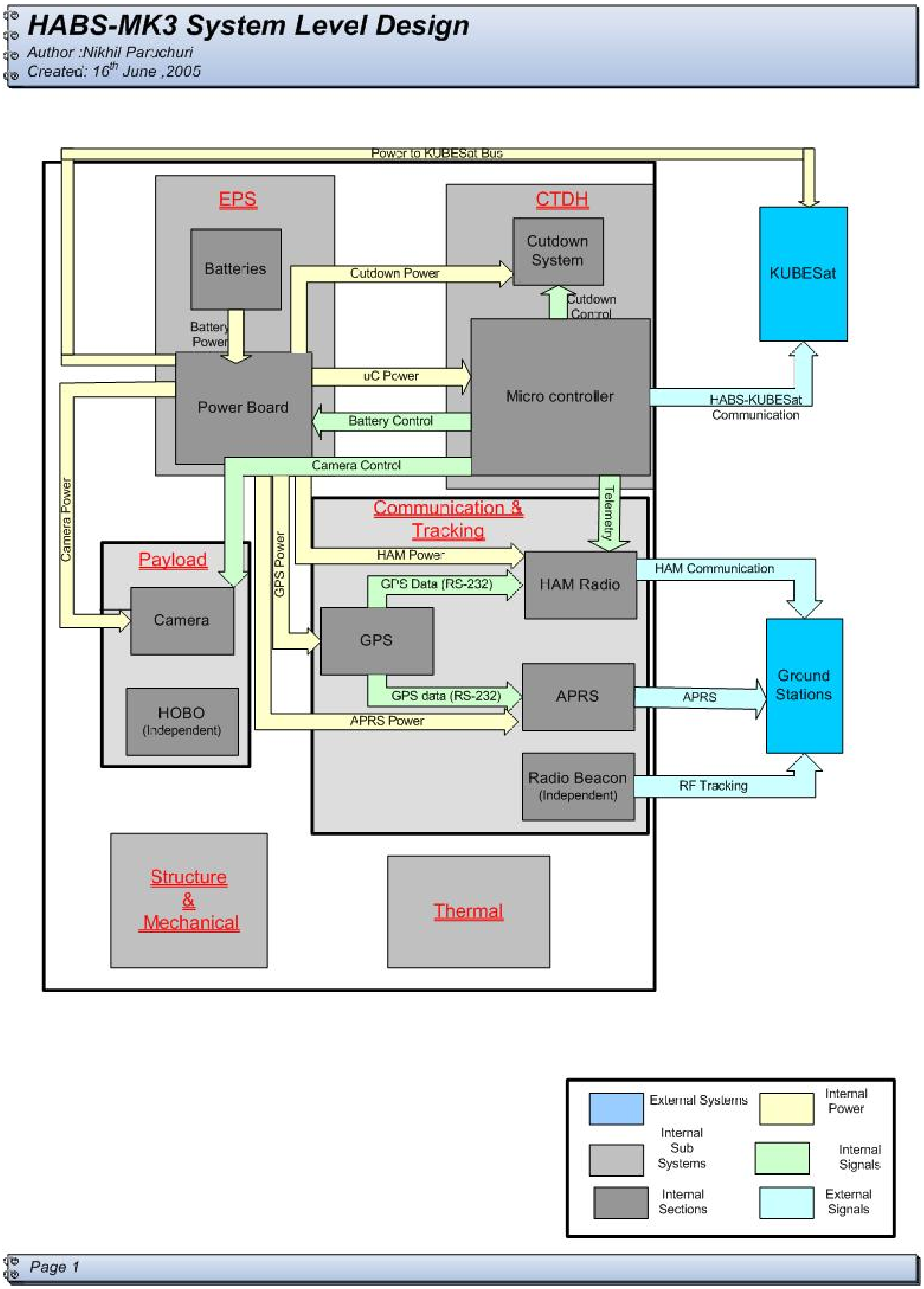


Figure 2.7: HABS Functional Diagram (from HABS-MK3 system)

The main task of the Thermal Control is to keep the interior avionics within their operational limits (-20^{o}C to + 50^{o}C), especially in the presence of external temperatures as low as -80^{o}C. This is accomplished by using a thick Styrofoam structure for the HABS box and the inclusion of hand warming bags just prior to sealing the box for the flight. While this may not be the most elegant methods for thermal control, with the weight and cost constraints it has proved to be effective. The HABS structure is made watertight and can withstand a 15 ft/sec impact onto concrete.

The Payloads subsystem includes an internal measurement system- HOBO [17], that records internal and external temperature data on a microcontroller and which is retrieved post flight. The HABS can also carry a film or a digital camera that can point at a present angle (top, down, and sideways). Figure 2.8 shows a picture taken on HABS-6 at an altitude of about 29 km, in which the curvature of the Earth, the atmospheric layer, the darkness of space, and the rays of the sun can by seen.

Figure 2.8: View of Near space taken on HABS-6 flight at 28,858 m

2-4.1 The HABS series and flights

There have been thirteen HABS flights from May 2003 until Dec 2005, of which eleven fights have been successful while two flights had major problems associated with them. The initial HABS system was built by the senior design teams for AE and EECS classes in spring 2003. This system was flown on the first HABS flight, HABS-1, and since it did not meet the requirements, it was disbanded. HABS-MK1 was built by in fall 2004 and had modest success with 2 flights of which the HABS-3 flight got lost mid flight due to power failure on the system (It was later recovered by a farmer and returned). This led to the development of HABS-MK2 in summer 2005, which had seven successful flights. This system was used to the test the KUBESat-1 system and also payload modules designed by AE 265 class.

In summer of 2005, it was decided to use the knowledge and lessons learnt in building and flying the HABS-MK2, to design HABS-MK3. The HABS-MK3 is a lighter version of HABS-MK2 and uses a few concepts of modularity. It is eventually planned to build a HABS-MK4 which will be a commercial balloon platform for testing commercial payloads. This project is slated to begin in February, 2006. Refer to Table.2.1 for a summary of the HABS flights.

Flight	**Series**	**Payloads**	**Date**	**Max. Altitude(Km)**	**Tracked w/GPS**	**Flight termination method**	**Recovery**
HABS-1	Initial	Temperature -HOBO	5/3/2003	Unknown	No	Burst	Yes[1]
HABS-2	MK1	Temperature-HOBO	12/20/2003	14	Yes	Cutdown	Yes
HABS-3	MK1	Temperature-HOBO	4/3/2004	Unknown	Partly	Burst	Yes
HABS-4	MK2	Camera , Temperature-HOBO	9/24/2004	4.5	Yes	Cutdown	Yes[2]
HABS-5	MK2	Camera , Temperature-HOBO	10/1/2004	32.8	Yes	Burst	Yes

[1] Recovered by a farmer, since the team never got the correct GPS data.
[2] Recovered by a farmer, after the team lost contact with the system due to a power failure.

Flight	Series	Payloads	Date	Max. Altitude(Km)	Tracked w/GPS	Flight termination method	Recovery
HABS-6	MK2	Camera , Temperature-HOBO	10/23/2004	29.9	Yes	Burst	Yes
HABS-7	MK2	KUBESat-1, Temperature-HOBO	2/26/2005	19.3	Yes	Cutdown	Yes
HABS-8	MK2	AE 265 student modules Temperature-HOBO	5/1/2005	10.7	Yes	Cutdown	Yes
HABS-9b[3]	MK2	KUBESat-1, Temperature-HOBO	6/25/2005	26.7	Yes	Cutdown	Yes
HABS-10	MK2	KUBESat-1, Temperature-HOBO	8/17/2005	28.7	Yes	Burst	Yes
HABS-11	MK3	Temperature-HOBO	10/22/2005	28	Yes	Burst	Yes
HABS-12	MK3a[4]	Temperature-HOBO	11/5/2005	28.1	Yes	Burst	Yes
HABS-13	MK3a	XBS module, Temperature-HOBO	11/19/2005	6.9	Yes	Cutdown	Yes

Table 2.1: HABS- flights and series

2-4.2 HABS-MK1

The HABS-MK1 was designed based on the initial design of HABS system built in spring 2003, by the senior classes of AE and EECS. Its configuration is similar to the main HABS functional diagram in Fig, 2.7 with notable exceptions being the lack of an APRS, Camera and RF beacon systems. The HABS-MK1 was flown on the HABS-2 and HABS-3 flights. During the HABS-2 flight, the uplink commands from the ground station were not received by the HABS system due to which the flight could not be terminated when desired. During HABS-3 flight, there was a failure of the main system power, due to which the system was lost. In order to design a more reliable system, the HABS-MK1 was disbanded and the HABS-MK2 was built.

[3] HABS-9 flight was cancelled when the balloon got detached from the HABS system due to strong gusts of wind at the launch site.
[4] HABS-MK3a has a lighter structure than HABS-MK3.

2-4.3 Comparison of HABS-MK1 and HABS-MK2

The HABS-MK2 was designed to be a more reliable and robust system than the HABS-MK1. It is similar to the HABS design in Fig.2.7 with the notable exception being the use of an audio beacon instead of a radio beacon. This subsection summarizes the differences between the HABS-MK1 and HABS-MK2 systems while the next subsection gives details of the HABS-MK2 in detail.

2-4.3.1 Power system

The HABS-MK1 power subsystem is shown in Fig 2.9. It consists of a 12 V, 1.86 Ah rechargeable Lithium ion battery system which is converted to +5V and +9V using NDL1205S and NDL 1209S [17] respectively to power the other subsystems. The GPS and the Cutdown subsystem have regular Alkaline 9V batteries as backup power .The 12 V main battery system consists of three 3.7 V nominal voltage,1860 mAh rechargeable Lithium Ion batteries in series. These batteries were chosen since they were being used in the Pathfinder-1 mission where they were configured in parallel.

There are two charging ports included in the system, port One is for charging two batteries that are in series, and port Two is for charging the third battery. Due to the different charging configurations, the batteries did not get charged to the same level of charge. This caused problems since one battery got discharged faster than the other two and the overall voltage dropped.

On HABS-MK2, it was decided to use batteries in parallel and to use a backup battery pack .This main power system is used power the GPS, Timer, CTDH subsystems and the KUBESat control system . The HAM radio, APRS, Cutdown and audio beacon have independent battery systems.

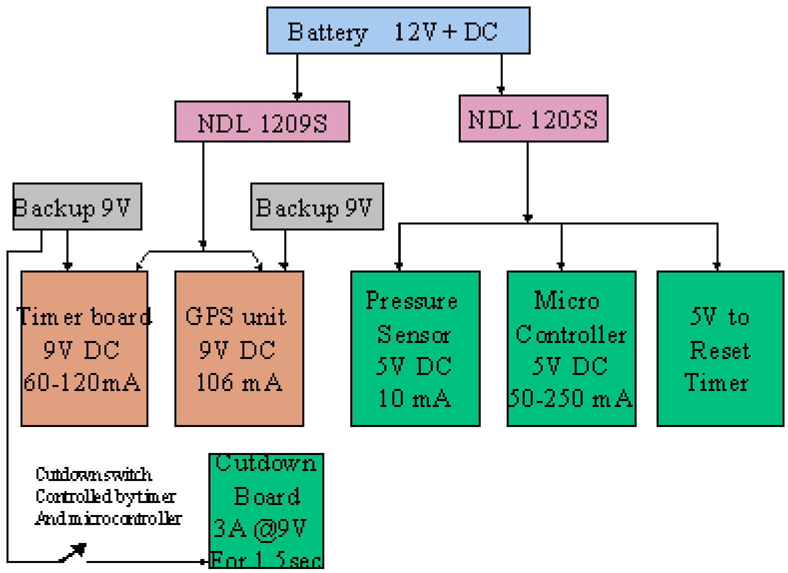


Figure 2.9: HABS-MK1 power subsystem

2-4.3.2 GPS system

The HABS-MK1 system uses a Garmin GPS-35 unit to report the GPS data to the CTDH subsystem. The Garmin GPS 35LP is a complete GPS receiver, including an embedded antenna, designed for a broad spectrum of OEM (Original Equipment Manufacturer) systems applications. The GPS 35LP can track up to 12 satellites at a time while providing fast time-to-first-fix, one second navigation updates and low power consumption [18].This unit was initially chosen since it had an in built antenna and was thus lighter in weight. It was however observed during the testing and flights that the GPS system took a long time to get a lock on the satellites when placed inside the HABS box. There were cases when after establishing a lock; the signals from the satellites were lost. This was due to the interference by the aluminum foil (Thermal blanket) which was used in the structures design. While a few changes were made on the HABS-1 system to overcome this problem, there were concerns of possible failure during a flight. The GPS 35 unit was replaced by a GPS 25 series unit from Garmin, since this had an external antenna which could be mounted on the top of the HABS-MK2 box. The GPS 25 was chosen since it was similar in design and interface to the GPS 35 with the exception of having an external antenna which provided a more reliable satellite lock and data.

2-4.3.3 APRS system

The HABS-MK2 has an additional communication system which is used to report the GPS data on the APRS network. The APRS network is amateur radio network which operates on 144.39 MHz in the United States and is used keep track of vehicles, balloons etc .A network of receivers positioned across the country record the data received on this frequency. This includes GPS data that is then used to plot the locations of the different systems on the map [19, based on their “Call signs” [20].In case of a radio communication failure between the ground station and the HABS main radio system, which can occur during and after HABS landing, when Line of Sight (LOS) communication is lost; the APRS network can be used to locate the HABS system. While this is a useful service provided for free by the amateur radio society, it is limited by the fact that an APRS ground station receiver has to be within the LOS of the HABS system in order to record its position.

2-4.3.4 Improvement in main communication's antenna system

In the HABS-MK1 system it was observed that the uplink commands from the ground station to the HABS system did not function during flights. The HABS-MK2 antenna system was improved by tuning the antenna to 144.42 MHz and by using a ground plane on the HABS system in order to improve the directivity of the antenna. These changes produced reliable uplink in the HABS-MK2 system.

2-4.3.5 35 mm film camera

A 35 film camera is used in the HABS-MK2 system, which is controlled by the CTDH subsystem. The pictures are taken either at preset times or when commanded by uplinks from the ground station. A film camera provides better picture quality at infinite focus and is easier to modify for integration with a microcontroller than a digital camera.

2-4.4 Design of HABS-MK2

The HABS- MK2 block diagram is shown in Fig.2.10. This system has the basic modules of a balloonsat, with the addition of a film camera. It has a CTDH subsystem which includes the microcontroller module which controls and communicates with the other subsystems; a Cutdown control module which is used to trigger the Cutdown system; and a camera control module used to control the film camera. The EPS system has a Power distribution section which provides a 5V bus to the microcontroller module, Cutdown system, Camera control system and the GPS module; and it also chooses between the primary and secondary power sources. The Primary battery source also provides power to the main KUBESat-1 system. There are additional batteries to provide independent power to the HAM radio, APRS radio, radio beacon, HOBO, the film camera and the Cutdown system. The choice of the power sources and the decision to use different power sources are discussed in the subsequent sections.

The communication and tracking section consists of a commercial HAM radio which provides bidirectional communication between HABS and the ground station. A GPS unit is used to provide position data through the HAM radio and the APRS radio. An audio beacon is used to help in tracking after the HABS has landed, though this has not proved to be functional as was observed during the HABS-5 flight. The audio beacon is placed on the outside of the structure and during the flight it goes through an extreme temperature range of -70°C to +30°C due to which it does not function when it lands on ground. This system was later disbanded due to its practical limitations.

The Payload consists of a film camera and a temperature data logger –HOBO [63].

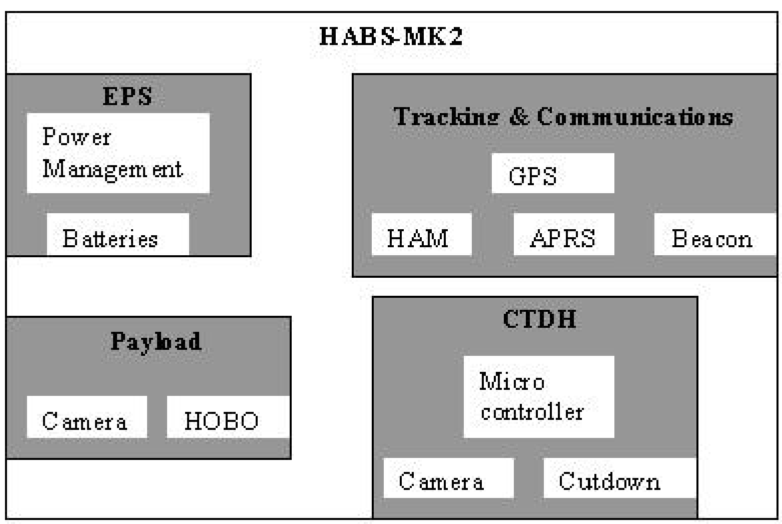


Figure 2.10:HABS-MK2 Functional Diagram

The following subsections give a detailed description of the requirements of the HABS-MK2 and the modules designed to meet those requirements.

2-4.4.1 CTDH – Microcontroller module

The heart of the Control Telemetry and Data Handling subsystem is the Microcontroller module which is built around a Freedom 16 mite v2 from STEROID micros [21].The Freedom 16 mite v2 is based on a 25.1 MHz Motorola MC68HC16Z1 microcontroller. This microcontroller is a legacy system that was chosen for the initial HABS system and has been used on the later series of HABS (MK1, 2&3). The relevant features of the microcontroller are summarized below.

- Eight A/D channels- 10 bit resolution and 10us Acquisition time.
- 128K of SRAM and 128K of EEPROM to store the program and data.
- An RS-232 port/UART port which is used to communicate with the HAM radio Terminal Node Controller (TNC).
- 15 general purpose I/O lines of which 7 can generate interrupts.
- It has a programming port and a In circuit debug/emulation port.
- “C” programmable with an extensive, well documented library of functions.
- 5V @ 120 mA.
- 2’’ *2’’ size.

While there might be many other microcontrollers available in the industry which provide similar or more features than the Freedom 16 mite v2, it was decided to use this microcontroller in HABS-MK2 due to the legacy factor and to save time and cost involved in developing a new microcontroller system.

The Microcontroller module performs the following functions in the HABS-MK2 system. Refer to the Microcontroller module schematic Fig.2.11.

- Communicates with the HAM radio’s Terminal Node Controller (TNC) using the RS-232 port CN5 of the microcontroller. The HAM radio is connected directly to the GPS unit , and the microcontroller commands the HAM radio to send GPS data every 30 seconds. The GPS data sent alternates between the GPGGA and GPRMC formats. The microcontroller also transmits telemetry data every 30 seconds.
- Measures the Primary battery and Secondary battery voltages on Ports J8 and J7 respectively.
- Measures the voltage of the first 9V battery pack, that powers the Cutdown system when triggered by the microcontroller. Port J6.
- Measures the voltage of the second 9V battery pack,, that powers the Cutdown system when triggered by the timer on the “Cutdown and Camera module”. Port J5.
- Measures the 5V bus. This is not an effective method of measuring the output of the 5V bus since the A/D reference voltage and the measured voltages are both 5V and are from the same source. This discrepancy was realized after the design was completed and this measurement was removed from HABS-MK3.Port J4.
- Senses the occurrence of a Cutdown when triggered by the timer module. Port J10.
- The main 5V bus is provided by converting the power from either the primary or secondary battery packs. During startup both battery packs provide power; the voltages of the battery packs are measured and if the Primary battery pack’s voltage is above a certain threshold it is turned on and the secondary battery pack

is turned off. More details are provided in the EPS section. Ports J14 and J15 control the Primary battery and Secondary battery switches respectively.

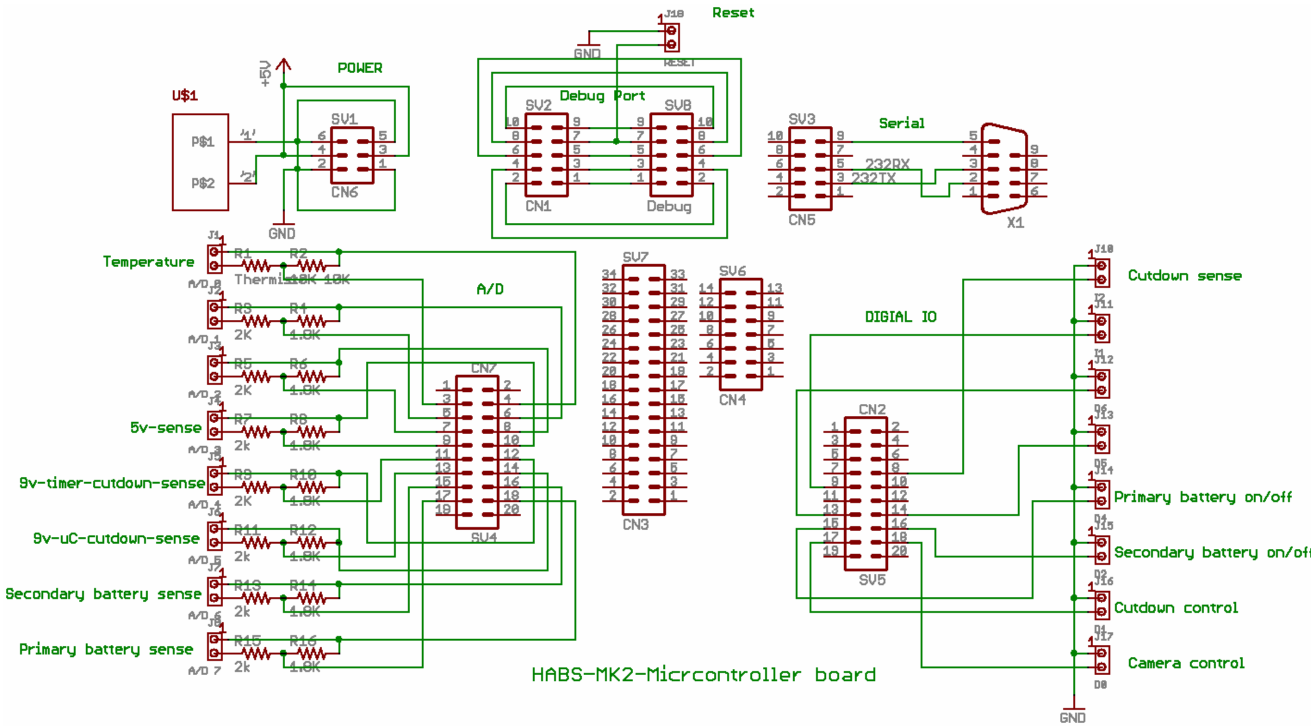


Figure 2.11: HABS-MK2-Micontroller module

- The microcontroller commands the Cutdown system when the altitude of the HABS has crossed a certain threshold altitude, determined by reading the altitude parameter in the GPS data; or when commanded by the ground station. Port J16.The threshold altitude known as "CDALT" can be pre programmed before flight or can be changed during the flight. It is usually set to 6,000 meters for a low altitude flight and 30,000 m for a high altitude flight.
- The film camera is triggered by the Cutdown & Camera control module, which is in turn triggered by the microcontroller module. Port J17. The camera is triggered after a certain number of data packets have been transmitted or can be triggered by a command from the ground station. Typically 4 data packets are transmitted

by the microcontroller every minute using the format- 1 GPGGA string,1 Telemetry string,1 GPRMC string ,1 Telemetry String. Refer to the HAM radio subsection for more details.

- The component “R1” is a Negative temperature Coefficient (NTC) thermistor of value 10 K at 25^{o}C. It is voltage divided by a 10 K resistor and is used to measure the internal temperature of the HABS system. This temperature is sent as a telemetry string.
- The Port CN1 is used to program the microcontroller which can be done even after the HABS system has been integrated.
- The port J18 can be used to reset the microcontroller without switching off the power.

2-4.4.2 HAM communication subsystem

The amateur radio service operator is commonly referred to as a ham operator. The Amateur radio service is a free service that is available for non-commercial use by the general public. Many university and amateur satellite programs use this service as the main mode of communication [1, 2, 3, 22, 23] due to the fact that it’s a free service and is available in different bands, the most common of which are the UHF and the VHF bands. The HABS-MK2 operates on the 144.42 MHz band using a commercially available Kenwood TH-D7AG [24].This is a portable radio that is equipped with a built-in AX.25 TNC required for packet operation and has a port for plugging a NMEA -0813 compatible GPS unit. There are other features of the TH-D7AG where it can be used as an APRS system, a VC-H1 visual communicator or for Sky command operations.

A comparison was made of all the portable radio sets available in the U.S. commercial market [24, 25,26] , and TH-D7AG is the only portable radio that has an integrated Terminal Node Controller (TNC). A TNC is like a modem which is used to convert the tones of the radio signals into packets, which can be sent to a computer or a microcontroller. It is possible to integrate an external TNC with a radio as is done in the pathfinder; where the primary consideration was the overall size of the communication system, and the, weight, RF power were secondary. The use of a radio with a built in TNC greatly simplifies the integration and testing with the overall system. The relevant features of the TH-D7AG are summarized in Table2.2.

Frequency	144.42 MHz
Operating Temperature range	-20oC to +60oC
Data rate	1200bps
Transmit power	0.5W
Power requirements -Standby	6V @ 70 mA
Power requirements-Transmit	6V @ 520 mA
Dimensions(W * H * D)	2.25"*4.75"*1.5"
Weight	340 g (with battery)
Antenna impedance	50 Ohm
Spurious radiation	less than -50dB
Frequency stability	+/- 15 ppm
1st IF	38.85 MHz
2nd IF	450KHz
Sensitivity	less than 0.18uV
Selectivity	-6dB at 12 KHz

Table 2.2: TH-D7AG HAM radio features

The antenna* used for this communication system is a quarter wave VHF antenna from Maxrad and is mounted on a brass mount also from Maxrad [27,28]. Since it is not

* The antenna system was designed by Yau Wang Pan , and is included in this work due to the final testing done by the author.

possible to have a large ground plane due to the weight constraints, it was decided to use three 0.5” flat aluminum rods places at 120 ^{o} as shown in figure 2.12.

Figure 2.12: HAM radio antenna (black rod) and the ground plane (three long flats rods)

The commercially bought antenna was trimmed in order to have a center frequency around the 144.42 MHz as shown in figure 2.13.

The HAM radio communication system provides GPS data and telemetry data, see Table 2.3. The GPS data alternates between the GPRMC and GPGGA formats .While both the GPS formats provide latitude and longitude, only GPGGA provides altitude while only GPRMC provides bearing and speed.

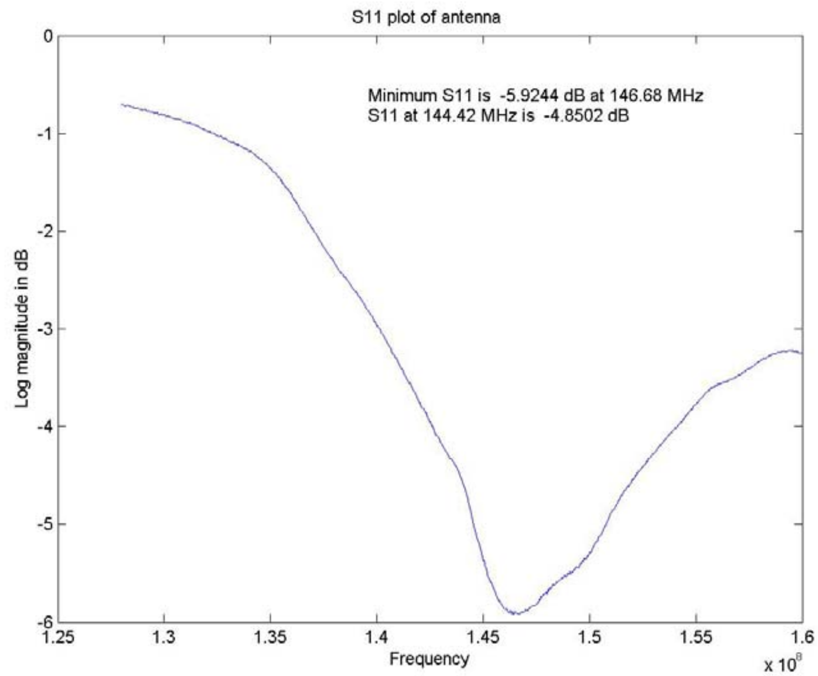


Figure 2.13: HAM radio antenna S11 parameters

GPRMC string	KC0POH-5>GPS:$GPRMC,141834,A,3900.8328,N,09426.2531,W,019.9,258.4,170905,003.4,E*6F
Telemetry string	KC0POH-5>APHABS:telem, Primary bv=3.804,uc9v=9.154, an9v=0.011, 5v=5.175,degC=3.0,cd=00
GPGGA string	KC0POH-5>GPS:$GPGGA,141904,3900.7473,N,09426.4689,W,1,10,0.8,25998.9,M,-29.8,M,,*7F

Table 2.3: Typical data transmitted by the HAM radio

Each string is preceded by “KC0POH-5” where KC0POH is the call sign assigned to the radio operator and 5 is the station ID. The value succeeding this identifies the string as a GPS string or a telemetry string from APHABS. “APHABS” is a group ID and is used by all the ground station and HABS communication systems to identify themselves as being part of a single communication group. The HABS microcontroller is programmed such that it acknowledges commands only from communication systems with “APHABS” as the group ID. The details of the GPS string are given in the GPS subsection. The format of the telemetry string is given in Table 2.4.

<1>	**Primary/Secondary**. Indicates which battery pack is powering the main 5V bus.
<2>	**bv=**. This is the voltage of the battery pack indicated in <1>.
<3>	**uC9V=.** This indicates the voltage of the 9V battery pack that is used to provide power to Cutdown when triggered by the microcontroller.
<4>	**an9V=**. This indicates the voltage of the 9V battery pack that is used to provide power to Cutdown when triggered by the timer module.
<5>	**5V=**. This indicates the value of the 5V bus. As mentioned in the CTDH subsection, this is dysfunctional.
<6>	**degC=**. Gives the internal temperature measured by the temperature sensor on the microcontroller board.
<7>	**cd=--.** This indicates the status of the Cutdown. The first bit can take the values of **‘G’**, **‘C’** and **‘A’** to indicate Cutdown triggered by altitude based microcontroller command, Ground sent microcontroller command and timer based command respectively. The second bit indicates the cumulative number of cut downs attempted.

Table 2.4: HABS-MK2 Telemetry data format

2-4.4.3 GPS unit

A Garmin GPS 25LVS unit is used in HABS-MK2 to provide positional data to the ground teams and also to the microcontroller. The GPS unit has an RS-232 port which is connected to both the HAM radio and the APRS by splitting the TX signal only. Since the RX signal on this port is connected only to HAM radio, there is no need for additional circuitry. The HAM radio receives the GPS data and transmits it every 30 seconds as commanded by the microcontroller. The microcontroller is also able to access the GPS data from the HAM radio and so does not need to interface directly to the GPS unit.

The GPS 25 LVS has an accuracy of 15 m in non-Differential GPS (DGPS) mode and 5 m in DPGS mode, though if desired the U.S. defense could chose to force the option of selective availability due to which the accuracy degrades to 100m.*This GPS unit has an external antenna which is required in order to avoid the problems faced in HABS-MK1, which used a GPS 35 that had an internal antenna and could not give reliable GPS data due to RF interference from the aluminum foil used on the HABS structure. The essential features of the GPS-25 LVS are summarized in Table.2.5. [30]

Tracking	Upto 12 satellites
Update rate	1 Second
Acquisition time	15 seconds warm up (all data known)
	5 minutes search the sky(no data known)
Position accuracy	Differential GPS(DPGS): Less than 5 meters RMS
	Non Differential GPS:15 meters RMS(100 meters with Selective availability on)
Dynamics	999 knots velocity,6g dynamics
Interface	2 RS-232 ports , NMEA 0183 Version 2.0 ASCII output
Power	5V @250 mA. The datasheet states that the current draw is 120-140 mA. It was found later that the GPS unit was damaged and when replaced by a new GPS unit, the current draw was around 100mA.
Weight	38 g
Size(W*L*H)	1.83"*2.75"*0.45"
Operating Temperature	-30C to+85C
Receiver sensitivity	-165dBW
Baud rate	4800 bps. This is the factory default baud rate and can be changed if required.

Table 2.5: GPS -25LVS relevant features

The GPS unit transmits a number of sentences in the NMEA format to the HAM radio port. Two particular sentences, GPGGA and GPRMC are of particular importance for tracking purposes and so the microcontroller commands the HAM radio to transmit only these sentences to the ground station every 30 seconds alternately. The relevant format of these sentences is given in Tables 2.6 and 2.7 respectively; the complete format can be viewed in [30]. The two sentences give the Universal Coordinated Time (UTC) and

* While this is lack of finer accuracy is not of concern during the tracking phase, it can cause problems during the actual recovery of the system, which in many cases lands among trees and fields. A beacon is useful in such scenarios.

also the latitude and longitude points, but only GPGGA gives the altitude above sea level and only GPRMC gives the speed and bearing. The GPGGA string is also used to determine the quality of the satellite lock based on <6> and <7>, and it is required that the number of satellites be more than 4 in order to get a lock on the coordinates and time.

Global Positioning Systems Fix Data (GGA)	
$GPGGA,<1>,<2>,<3>,<4>,<5>,<6>,<7>,<8>,<9>,M,<10>,M<11>,<12>,*hh	
<1>	UTC time of fix ,hhmmss format
<2>	Latitude,ddmm.mmmm format
<3>	Latitude hemisphere,N or S
<4>	Longitude,dddmm.mmmm format
<5>	Longitude hemisphere, E or W
<6>	GPS quality indication,0=fix not available,1=Non-differential GPS fix available,2=Differential GPS fix available,6=Estimated
<7>	Number of satellites in use,00 to 12
<9>	Antenna height above/below sea level,-9999.9 to 99999.9 meters

Table 2.6: GPGGA format

Recommended Minimum Specific GPS/TRANSIT Data(RMC)	
$GPRMC,<1>,<2>,<3>,<4>,<5>,<6>,<7>,<8>,<9>,<10>,<11>,<12>,*hh	
<1>	UTC time of position fix,hhmmss format
<2>	Status, A= Valid position, V=NAV receiver warning
<3>	Latitude,ddmm.mmmm format
<4>	Latitude hemisphere, N or S
<5>	Longitude, dddmm.mmmm format
<6>	Longitude hemisphere,E or W
<7>	Speed over ground ,000.0 to 999.9 knots
<8>	Course over ground, 000.0 to 359.9 degrees, true
<9>	UTC date of position fix, ddmmyy format
<10>	Magnetic variation,000.0 to 180.0 degrees
<11>	Magnetic variation direction,E or W(westerly variation add to true course)

Table 2.7: GPRMC format

The antenna used is a Garmin GA 27C [31], is a an active antenna with LNA gains of 12dB-25 dB and a noise figure of 3.5 dB max @25 C. The antenna is rated for only -30^{o} C to $+80^{o}$ C, but it has been reliable in all the flights even when the extreme temperature has been -80^{o} C.

2-4.4.4 APRS subsystem *

The Automatic Position Reporting System (APRS) is a redundant communication system used in HABS-MK2, in order to provide tracking of the system in case of a possible failure of the main HAM radio, or a software malfunction in the microcontroller. This is an independent unit that requires only the GPS unit to be connected. It also has a different power source that is independent of the main power source.

The APRS system transmits a data packet and so requires a TNC. It was initially decided to use a second TH-D7AG, but due to the weight constraint and the desire to reduce the cost an alternate was researched. The Pocket Tracker is a kit by HiValue Radio [32] , based on the TinyTrak 3 TNC and is specifically designed for use as an APRS radio system .Fig 2.14. This low cost (~$50), low weight (75g) radio system is an ideal alternative to the TH-D7AG since it is required to only transmit the GPS data on 144.39 MHz and needn't be used on any other frequency or for any other communication.

* The APRS kit was assembled by Yau Wang Pan and is included in this work due to the technical advice given by the author.

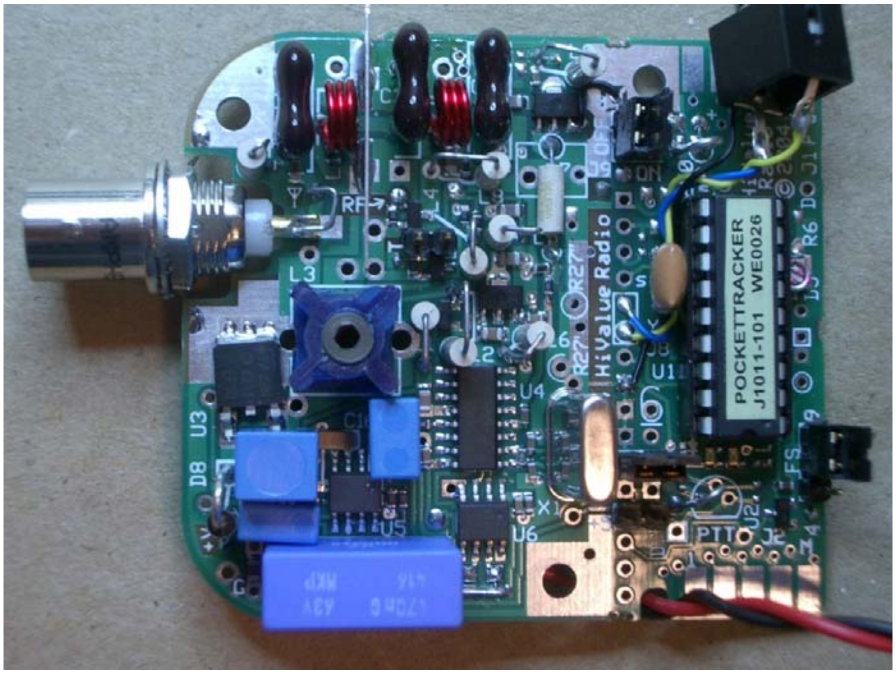


Figure 2.14: Pocket Tracker for APRS

2-4.4.5 Cutdown control subsystem

The FAA regulations 101[7] require that an unmanned balloon have two modes of flight termination. The first mode of termination is the expansion of the balloon envelope and its eventual burst due to pressure difference inside the balloon and the atmosphere at 100,000ft. The second mode of flight termination in HABS-MK2 is the use of a nichrome coil [33]. The rope connecting the HABS box and the balloon is passed through a nichrome coil of 3 Ohms resistance. When a current of around 1.5 Amps is passed through the coil, it takes 1.5 seconds to burn the rope @25^{o} C, and due to the tension in the rope, the box and the balloon separate. Tests were done at -30 ^{o} C and it was found that the time to burn the rope increased to 3.5 seconds. During a flight, each attempt at burning the rope lasts for 20 seconds. The HABS-MK2 has two independent systems to perform the flight termination or more commonly “Cutdown”. The first Cutdown system consists of a timer circuit and the second Cutdown system is part of the microcontroller module. See Fig.2.15.

Each system triggers a switch which controls the flow of current from a battery pack to the nichrome coil. The timer is preset to a fixed value before the flight by adjusting the values of two potentiometers “Pot 1” and “Pot 2” in Fig 2.16 , which shows the schematic of the Cutdown module which is designed on the same board as the Camera module.

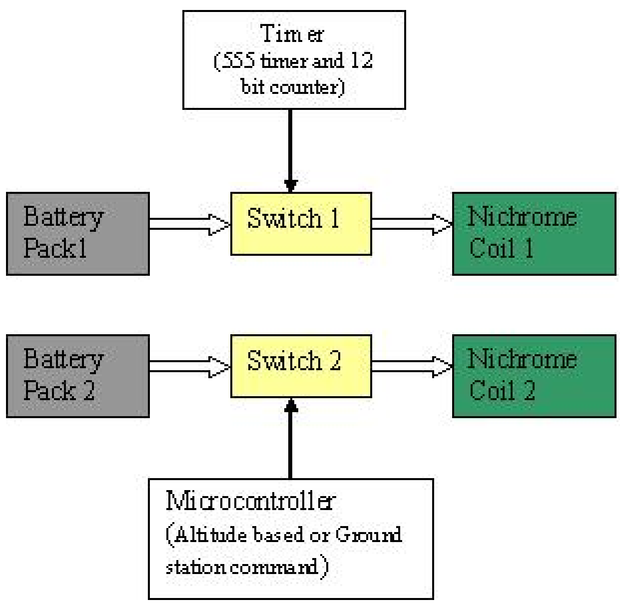


Figure 2.15: Cutdown system

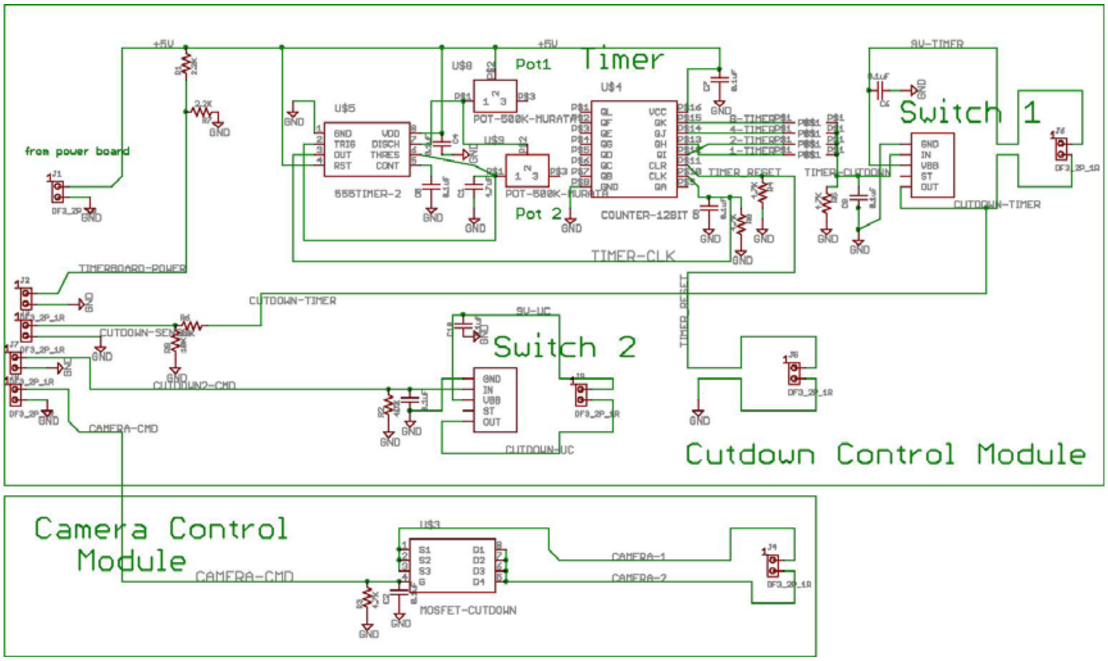


Figure 2.16: Cutdown and Camera Control Schematic

2-4.4.6 Payload- Film camera

A Canon Elph LT film camera is used on HABS-MK2. This camera is controlled by replacing the mechanical "Push button" with an electrically controlled switch, refer to Fig 2.16. The switch is triggered by the microcontroller which takes pictures after a programmable time or when commanded by the ground station. This camera was used in three flights HABS-5, 6, &7 as part of the HABS-MK2 system; and as part of the payload system in HABS-8 and HABS-13 flights. The camera malfunctioned during the HABS-7 flight and it had to be replaced by a similar camera for the next two flights. The reason for the malfunction could not be found, but it is assumed that since the camera is designed for non scientific purposes the extreme temperatures during the flight damaged components inside the camera.

2-4.4.7 Power subsystem

A typical HABS system goes through 1- 2 hours of pre launch testing, 2-3 hours of flight, and another 2-3 hours of recovery time before it is switched off. This however doesn't necessitate that all subsystems last for the entire pre testing to recovery duration of eight hours since the KUBESat system and certain subsystems such as the HOBO, Cutdown and Camera need to last only the flight time of around three hours. The power supply required by the Nicrhome wire to terminate the flight is required only for a certain number of attempts and each attempt lasts only for twenty seconds. These factors are taken into account to calculate the power and energy requirements of the subsystems in HABS-MK2, refer to Table 2.8.

Subsystem	Voltage(V)	Current(A)	Power(W)	Duty Cycle(%)	Duration(hrs)	Energy(Wh)
Microcontroller	5	0.06	0.3	100%	8	2.4
GPS 25 (Damaged unit)	5	0.25	1.25	100%	8	10
Cutdown and Camera Control	5	0.003	0.015	100%	8	0.12
KUBESat-1	-	-	0.239	100%	4	0.956
KUBESat-2	-	-	1.34	100%	4	5.36
Radio(THD7AG) Idle	6	0.07	0.42	86%	8	2.8896
Radio(THD7AG) Tx	6	0.52	3.12	10%	8	2.496
Radio(THD7AG) Rx	6	0.13	0.78	4%	8	0.2496
APRS Idle	9	0.008	0.072	96%	8	0.553
APRS Tx	9	0.11	0.99	4%	8	0.3168
Cutdown -1 Timer	4.5	1.5	6.75	0.0138889	4	0.375
Cutdown -2 uC	4.5	1.5	6.75	0.0138889	4	0.375

Table 2.8: Power requirements of HABS-MK2

The requirements of the HABS-MK2 were that the power of the system should be self contained and that it should also power the control and payload interface modules of the KUBESat's, i.e. all subsystems that were designed by the University of Kansas team for either HABS or for interfacing with payloads on the KUBESat's had to be powered from the HABS system due to the weight constraints. The KUBESat systems can have separate DC/DC converters if they have voltages that are different from HABS. In HABS-MK2 the "Primary" power source is used to provide power to the KUBESat's.

The voltage levels of both the communication systems on the HABS-MK2 are different from the main voltage bus of 5 V; and the current draw of the Cutdown systems is very high. Due to these factors it was decided to isolate the power sources, Refer Fig.2.17.

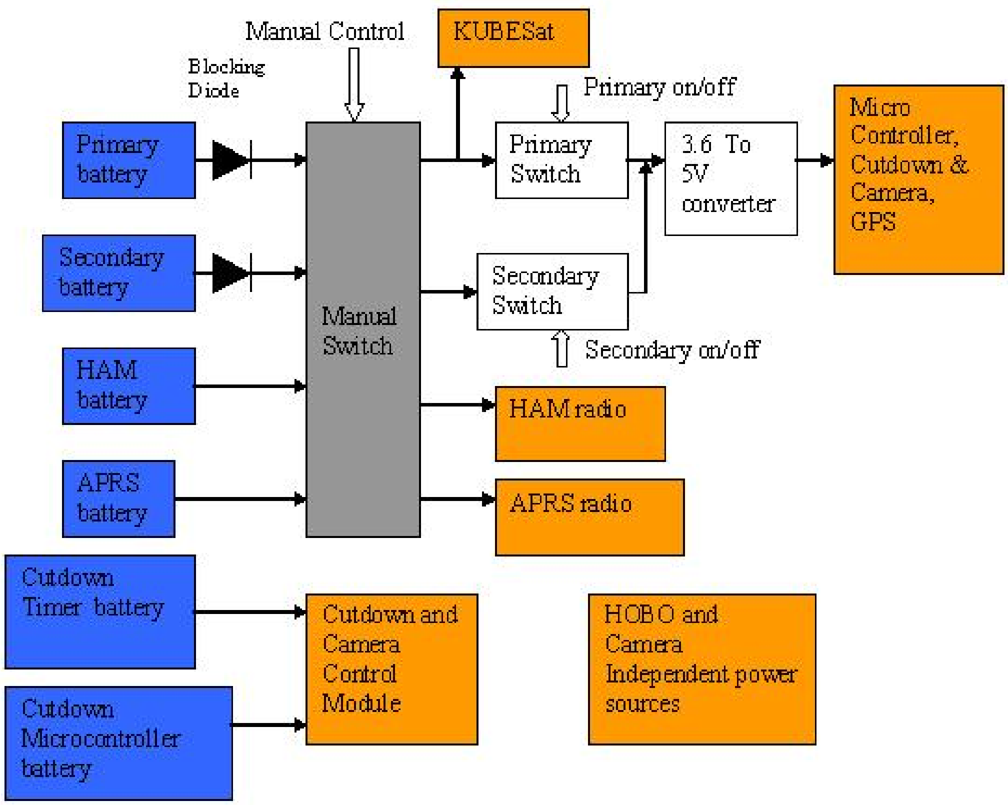


Figure 2.17: Power source distribution of HABS-MK2

The primary battery provides power to the KUBESat system and also to the 5V bus. The secondary battery is a backup power source that is used to power the 5V bus.

After the manual switch is turned on, both the Primary and Secondary battery packs provide power to the 5V bus after conversion by a DC/DC converter. The microcontroller chooses between these two sources and switches the other one off. In case of a power failure on the 5V bus, the microcontroller chooses between the two sources again. In the seven flights that HABS-MK2 has been flown, the primary battery pack was sufficient to power up the system. A blocking diode is placed after each battery since it was found during testing that there is a leakage of current from the battery that is turned on, to the battery that is turned off.

The batteries for the HABS-MK2 system were chosen based on energy requirements, weight, Energy density and the temperature ratings. Lithium chemistry batteries have been used for the main subsystems since they have a lower operating temperature point of -20^{o} C as compared to Nickel and Alkaline chemistries which can vary between 0^{o}C-10^{o}C. [37, 38].Table 2.9 lists the batteries used in the HABS-MK2 main systems, and compares the required power (after accounting for DC/DC efficiency) with the available power *.

The Primary and Secondary battery packs consist of three rechargeable Samsung ICR18650-22 Li-ion batteries [35] is parallel. These batteries were chosen after comparing them to similar Li –ion battery packs [36, 37] which met the energy requirements but had a lower energy density (Wh/g).

The current requirements of the Cutdown batteries are very high at 1.5 A and cannot be met by Lithium and Nickel batteries due to the weight constraints. Alkaline batteries available off the shelf were tested and it is found that Kroger batteries provide

* This is the available power at 25^{o} C

the best performance. These batteries have a nominal voltage rating of 9 V but at 1.5 A the voltage drops to 4.5 V.

	Required		Available								
System	**Energy (Wh)-Ren**	**Max Current (A)**	**Battery Model**	**Chemistry**	**Configuration**	**Nominal Voltage (V)**	**Capacity (Ah)**	**Max Current (A)**	**Energy (Wh) Aen**	**Energy Density (Wh/g)**	**Safety factor= (Aen/Ren)**
5V bus , KUBESat	21.4113	0.675	Samsung ICR18650-22	Li-ion	3 cells in parallel	3.7	6.6	6.6	24.42	0.17696	1.14052021
5Vbus, backup	16.0513	0.312	Samsung ICR18650-22	Li-ion	3 cells in parallel	3.7	6.6	6.6	24.42	0.17696	1.5213738
HAM radio	5.6352	0.52	Energizer e2 Lithium	Li/FeS2	4 cells in series	6	3	2	18	0.31034	3.19420784
APRS radio	0.86976	0.11	Ultralife U9VL-J	Li/MnO2	1 cell	9	1.2	0.12	10.8	0.2967	12.4172185
Cutdown	0.375	1.5	Kroeger 9V	Alkaline	2 cells in parallel	9	0.2	-	1.8	0.01974	4.8

Table 2.9: HABS-MK2 power sources

The HAM radio requires 6 V that is provided by four 1.5 V batteries in series [61] .The APRS system uses a 9 V Lithium battery from Ultralife [62], that can power the system for 10 days [*].

Figure 2.18 shows the initial schematic of the Power control board, which uses 2 amperes rated , MAX869L [39] switches to choose between the primary and secondary sources and the DC/DC converters MAX1626, MAX1709 and MAX1771 from Maxim [40-42] to convert to 3.3V, 5V and 9V respectively. This design was created when it was assumed that the HABS system would have a single power source for the 5V bus and would also be used to provide 3.3 V to KUBESat and 9V to the APRS system.

[*] The APRS system ideally requires to be powered for a maximum of 8 hours before the HABS system is recovered. There might be situations where it is not possible to immediately recover the HABS system due to the nature of the landing spot (water bodies, private inaccessible areas). In such situations, the APRS system will be able to beacon the last recorded GPS data even when the power to the GPS system drains.

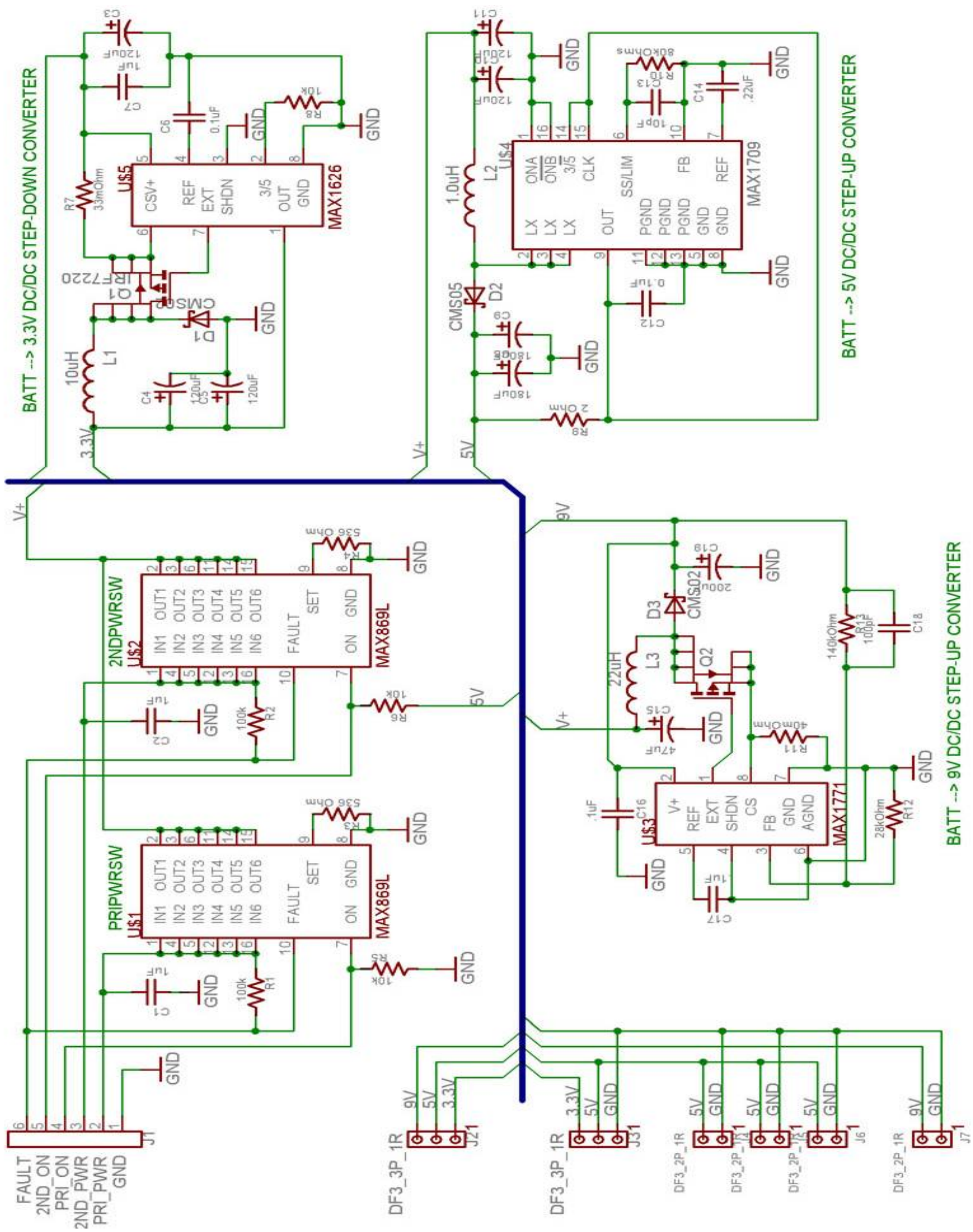


Figure 2.18: HABS_MK2_ Initial design of power distribution board [*]

[*] The Initial power board design was designed to be similar to the Pathfinder-1 design in order to test those components at high altitude.

It was later decided that the APRS system needed to have an independent power source to make it redundant, and the power to the KUBESat system would have to be flexible to account for varying voltage values of the future KUBESat systems. So the switches are used, but the DC/DC converter section was disbanded and is replaced by an MAX1771 evaluation kit. The MAX1771 DC/DC converter has a theoretical efficiency of 83% @ 300 mA load current. Fig2.19 shows the calculated efficiency for varying input voltages @25^{o} C.

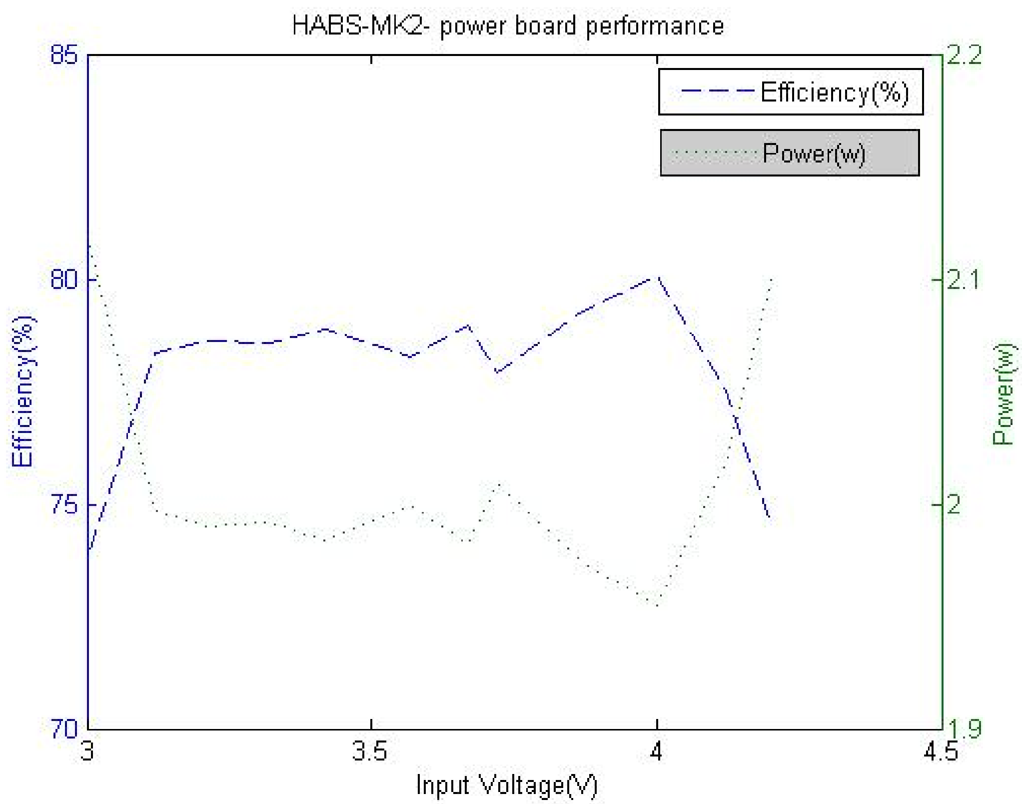


Figure 2.19: HABS-MK2 Power board performance

2-5 KUBESat-1

The KUBESat-1 system was designed to test and determine the operating characteristics and reliability of the S-band transmitter provided by NNSA Kansas City Plant. The Distributed Telemetry Transmitter (DTXR) System provided by Honeywell engineers at the Kansas City plant (KCP) is a modular data communications microwave transmitter. It consists of three separate components- a digital modulator, a power amplifier and a power converter, Ref Fig 2.20.The KUBESat-1 system provides 32 bit test data, a reference clock and controls the data rate, modulation, filtering, RF output power level and power to the S-band transmitter*.A 32 bit test string is transmitted by the S-band transmitter to the ground station , where it is compared with the expected 32 bit data and is used to calculate the bit error rate for the different transmitter configurations, at various altitudes and temperatures. A complete flight test scenario will be described in detail in later sections.

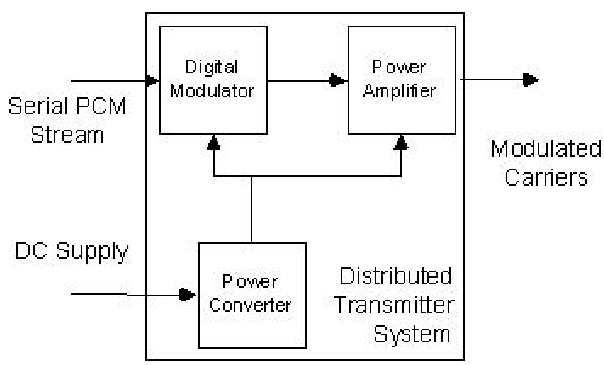


Figure 2.20: S-band transmitter block diagram

* A few details of the interface between the KUBESat-1 and the S-band transmitter cannot be provided due to the proprietary nature of the communication system developed by Honeywell. These details are available for internal review only.

2-5.1 Overview of system

The design of KUBESat-1 system is shown in Fig. 2.21., where the S-band transmitter control and data are provided by a transmitter interface board. Power in the KUBESat-1 system consists of the main bus power which is provided by HABS and is converted to provide power to the boards; and the S-band transmitter power which is provided by an external non rechargeable Lithium battery. The functions of the subsystems are described in detail in the subsequent subsections.

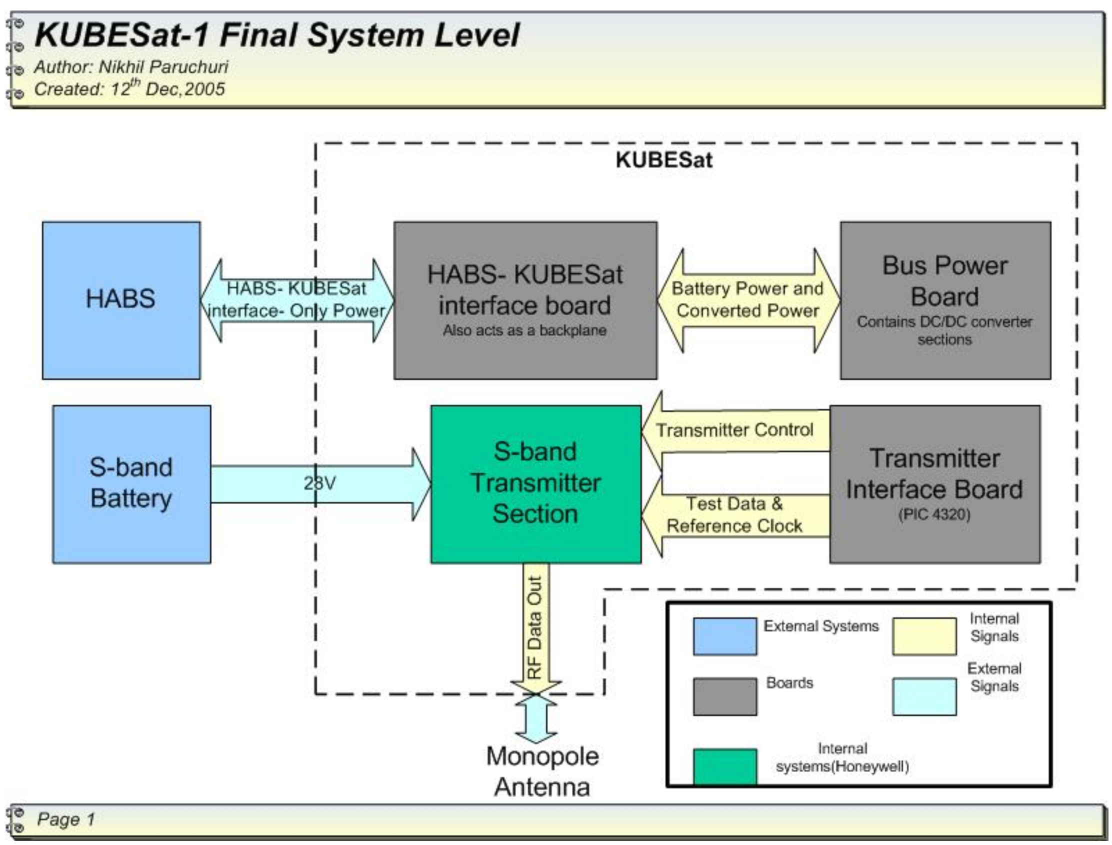


Figure 2.21: KUBESat-1sytem Design

2-5.1.1 Transmitter Interface subsystem

The S-band transmitter is characterized by transmitting a 32 bit test word for the various configurations in Table 2.10.

Data rate(Mbps)	1/5/10/20
Clock rate(MHz)	20
Filtering	Unfiltered/Filtered
Modulation	FSK/SOQPSK
RF power(Watts)	1/2/4/10

Table 2.10: S-band transmitter characteristics

The task of controlling and providing data and clock to the S-band transmitter is performed by a PIC 18LF4320 microcontroller from Microchip [43], Ref Fig.2.22. This processor was chosen because it was part of the KUTESat-1 system and it met the requirements for the transmitter interface board. The functions of this module are described below.

- The PIC controls the Modulation type, data rate and filtering type from "Modulator" port J2. These are 3.3V-high/0V –low lines, Refer Table 2.11 for the function of each control line.

Control Lines			**S-band characteristics**		
Modulation	**Data rate**	**Filtering**	**Modulation**	**Data rate**	**Filtering**
0	0	0	FSK	1Mbps	None
0	0	1	FSK	1Mbps	Gaussian-FSK
0	1	0	FSK	5 Mbps	None
0	1	1	FSK	5 Mbps	Gaussian-FSK
1	0	0	SOQPSK	10 Mbps	None
1	0	1	SOQPSK	10 Mbps	SOQPSK-A
1	1	0	SOQPSK	20 Mbps	None
1	1	1	SOQPSK	20 Mbps	SOQPSK-A

Table 2.11:S-band transmitter modulator control

- The PIC controls the RF output power by controlling the lines of the power amplifier- J4. The amplifier uses 5V/0V logic while the PIC uses 3.3V/0V and so a Maxim MAX 3378E logic level translator [44] is used. The power amplifier uses 6 control lines to vary the RF power level and a WR_NOT line that needs to be pulled low before data is written onto the 6 control lines. Refer Table 2.12.

Control lines							**RF output power(Watts)**
WR_NOT	**D5**	**D4**	**D3**	**D2**	**D1**	**D0**	
1	X	X	X	X	X	X	0
0	0	0	1	1	0	0	~1
0	0	0	1	1	1	1	~2
0	0	1	0	1	1	0	~4
0	1	1	0	0	0	0	~10

Table 2.12: S-band transmitter power amplifier control

- In the initial design, it was assumed that two antennas – a monopole and a patch would be used to transmit the S-band data and so a line to control the switch between the two antennas was required. The final design of the KUBESat-1 system that was flown used only the monopole antenna and so the antenna switch control –J6 is not required. This might however be used in future versions of the system.
- The power to the S-band transmitter is provided by an external 28V battery which is converted by the S-band power converter, to the provide power to the S-band modulator and power amplifier. The power converter is switched by the PIC – J3.A 5V- high is off and 0V-low is on.

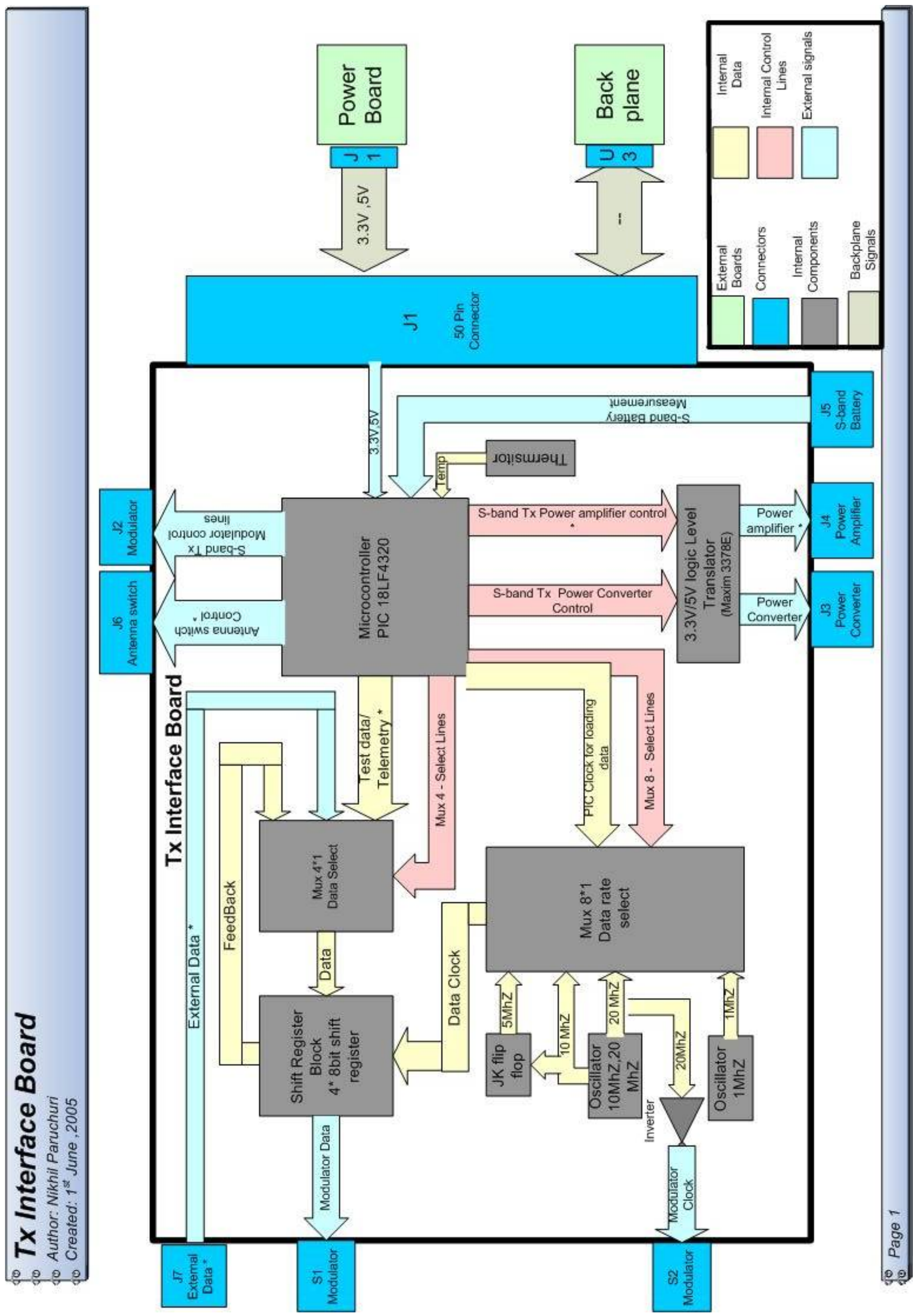


Figure 2.22: S-band transmitter interface board

*- Future versions

- The modulator requires test data to be loaded at the different data rates listed in table 2.10. This is achieved by using different clock sources and shift registers. The shift register block consists of four 8-bit shift registers. The data to this block is controlled by a 4*1 multiplexer and the data rate is controlled by varying the clock to the shift register block .The clock is fed from a 8*1 multiplexer which chooses from the four required clock rates of 1,5,10 and 20 MHz. The shift register block outputs the 32 bit test data to the modulator and also as a feedback loop. The shift register block is initially loaded by the PIC with a 32 bit test data and is clocked at a lower rate of 32.5 KHz provided by the PIC. When the system is ready to transmit the data, the Mux 8*1 block chooses the required clock speed and feeds it to the shift register.
- The Mux 4*1 block is used to select the data that is sent as input to the shift register block and can choose from the data provided by the PIC; the feedback data from the shift registers after it has been loaded by the PIC ; and external data.
- The clock sources are provided by a 1 MHz oscillator and a dual 10, 20 MHz oscillator. In order to get the 5 MHz clock, a JK flip flop is used to divide the 10 MHz by 2, since a compatible 5 MHz oscillator was not found. The 20 MHz clock is also used to provide the reference clock to the modulator. The clock to the modulator has to be buffered by using an inverter, in order to avoid the loading effects that occur when the clock is also fed to the shift registers, as was observed during the testing of the initial transmitter interface board prototype.

The PIC can also measure the board temperature and the S-band battery voltage and send it as telemetry data .This is part of a future design and is not used in the KUBESat- 1 system.

2-5.1.2 Main Bus Power subsystem *

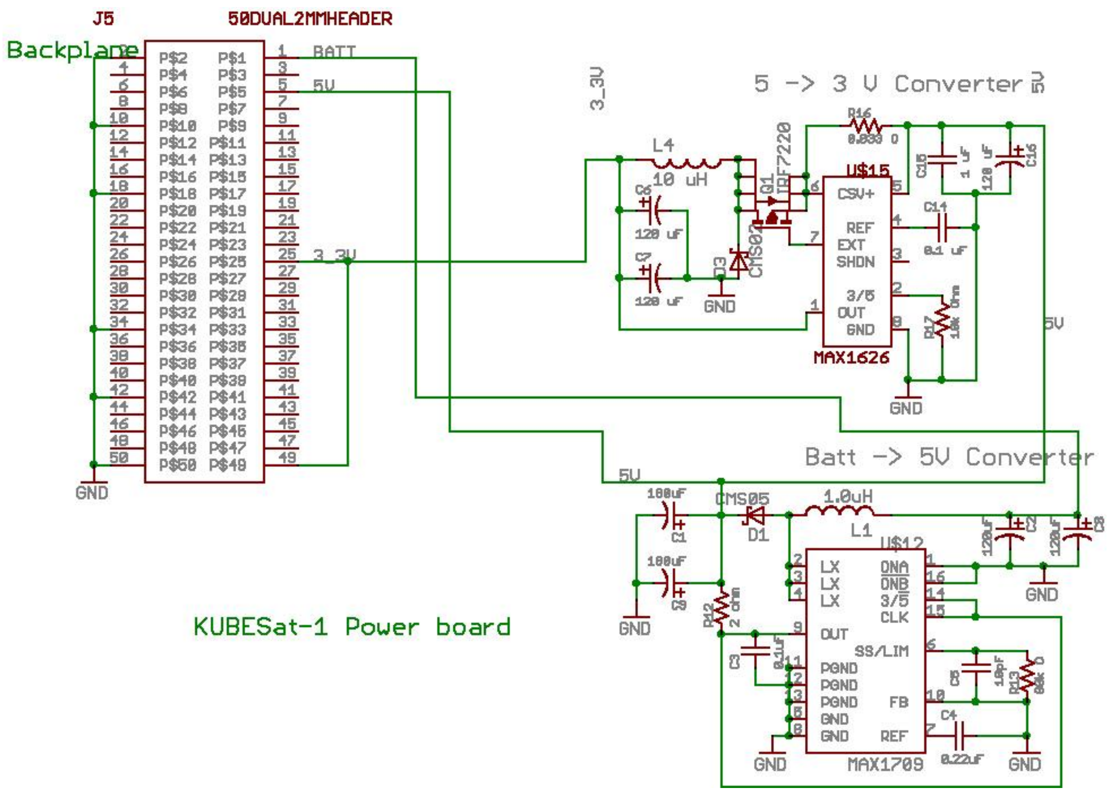


Figure 2.23: KUBESat_1 Bus power board schematic

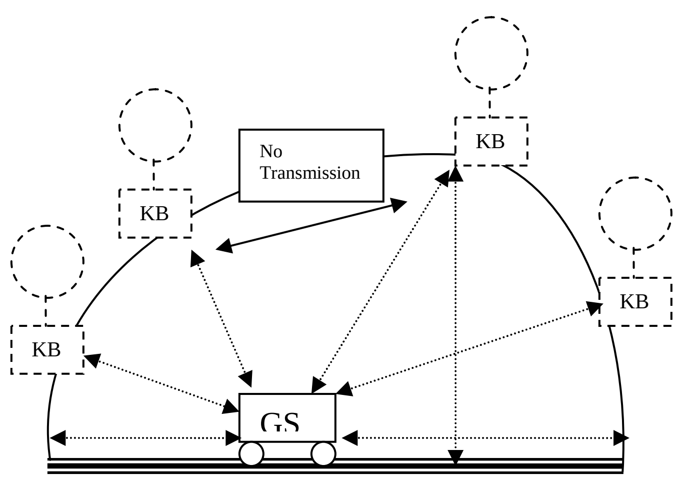
The KUBESat-1 main system power requirements are very small, since only the interface board needs to be powered. This power is provided by the HABS primary battery and is converted to the required 5V@20 mA and 3.3 V @ 10 mA by the Bus power board; Refer Fig.2.23.The DC/DC converters used are the Max1709 and Max1626 from Maxim and were chosen since they were used in the KUTESat-1 design. The

* Layout was by Daniel Duda. Initial testing was by Justin Marz. Initial design and final testing and integration performed by the author.

Lithium battery to 5V converter Max 1709 has a very low efficiency of 67% and the 5V to 3.3 V converter has a nominal efficiency of 75%, but due to the very low power requirements this system was not redesigned.

2-5.1.3 Antennas design and testing *

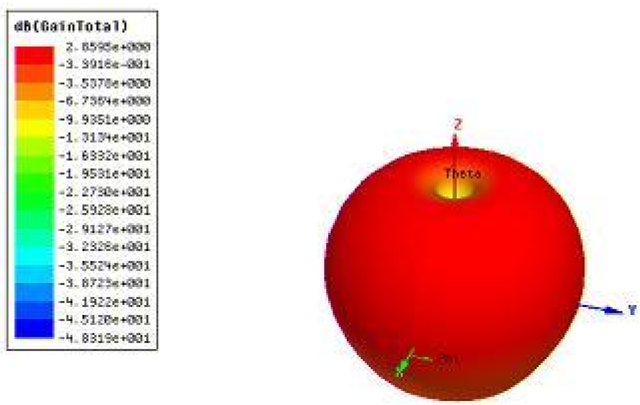
A typical KUBESat-1 flight lasts between 1 -2.5 hrs and the balloon can reach altitudes between 25 -100 K ft, depending on the duration of the flight. The ground station for the S-band receiver needs to be placed such that it is within the Line of Sight (LOS) of the transmitter and out of the null region of the transmitter antenna, refer Fig 2.24. An ideal solution would be to use a mobile ground station for the S-band transmitter as was done in the last KUBESat-1 flight, HABS-10. During the initial antenna design process it was assumed that the ground station would be fixed before the flight. Based on this assumption a monopole antenna is used on the transmitter since it provides an omni directional radiation pattern in the azimuth plane and has a null only at the center, during which no transmission occurs as shown in figure 2.24.



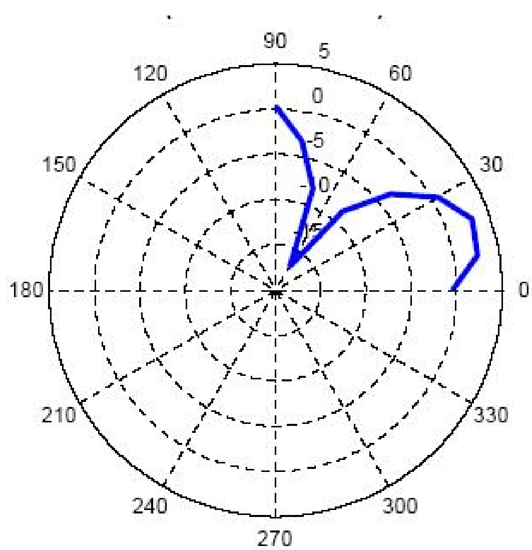
* The KUBESat-1 antenna and the ground station antenna were designed by the students of senior design classes of EECS, 2003, 2004 and 2005. The current monopole antenna on KUBESat-1 is designed by students of 2004 class and the patch antenna on the ground station is designed by students of 2005 class. The technical advice, construction and testing by the author are a part of this work.

Figure 2.24: KUBESat-1 flight profile

The ground station or the S-band receiver requires a high gain antenna in order to reduce the bit error rate and so a Patch antenna is used. The disadvantage of using a patch antenna is that it has a very narrow beam width and so has to be pointed manually towards the balloon. The two antenna designs were created using HFSS software from Agilent. The simulated radiation patterns and the radiation patterns based on tests are shown in figures 2.25 & 2.26.

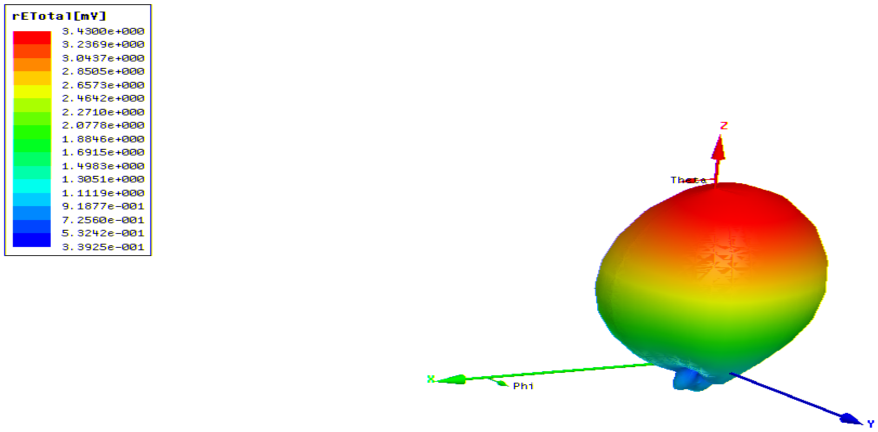


a

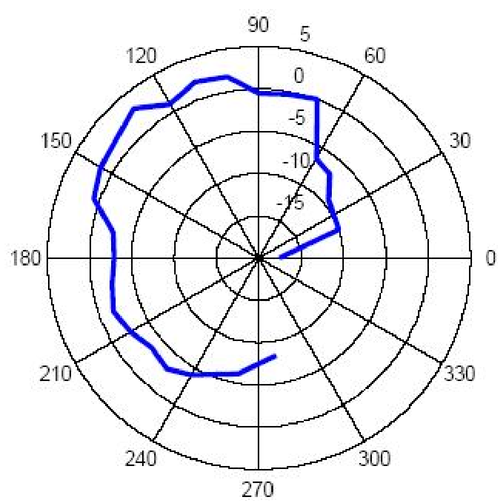


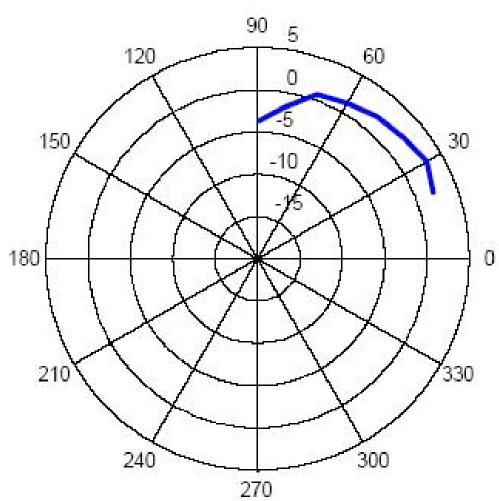
b

Figure 2.25 : Radiation pattern of Monopole antenna. a) Simulated 3-D pattern. b) Elevation Radiation pattern at Azimuth=0 and Elevation =25



a

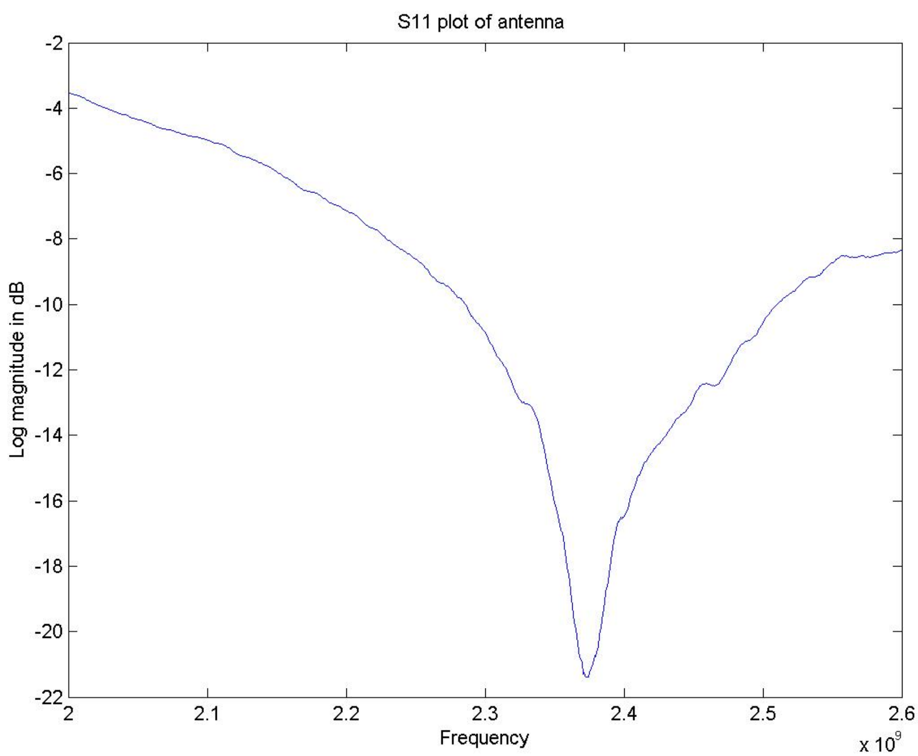




b **c**

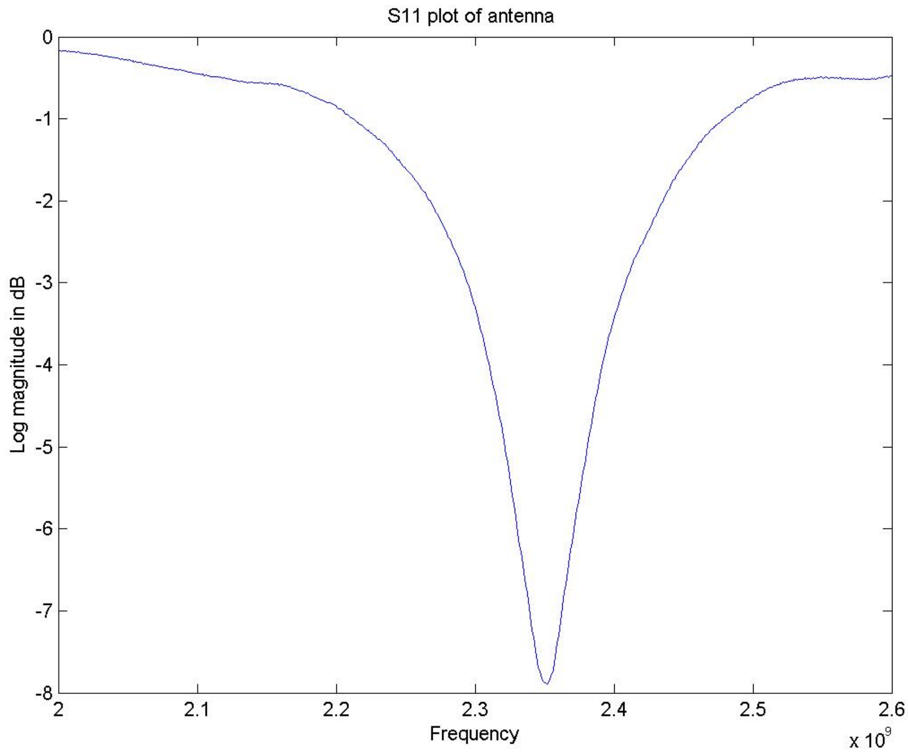
Figure 2.26: Radiation pattern of Patch antenna on receiver. a) Simulated 3-D pattern. b)Azimuth radiation pattern. c) Elevation radiation pattern; at azimuth =134 and elevation=25

The S11 parameter of the two antennas is found using a network analyzer, Refer Fig 2.27.The characteristics of the two antennas are summarized in table 2.13, and it can be observed that the antennas are not tuned to the required center frequency of 2240.5 MHz, due to which the return losses are very high. The antennas could not be redesigned since the testing was done by the author after the volunteers had completed their work on the antennas and had graduated. In spite of the antennas having deviant center frequencies, they have been used in the KUBESat-1 flights and have produced satisfactory results*. It is however recommended that the antennas for the future KUBESat systems be redesigned.



a

* During the HABS-10 flight, the KUBESat-1 system was tested with these antennas and produced a 0 BER on most test cases and a very low BER on the other cases.



b

Figure 2.27:S11 parameter of a) monopole antenna b) Patch antenna

Antenna parameter	**Monopole(Tx)**	**Patch(Rx)**
Center frequency(MHz)	2375	2350
3 dB bandwidth(MHz)	2360-2390	2320-2380
Return loss(dB) at center frequency	21.5	8
Return loss(dB) at 2240.5 MHz	8.5	1.5
VSWR at center frequency	1:1.183	1: 2.322
VSWR at 2240.5MHz	1: 2.204	1: 11.6
Simulated gain(dB)	2.85	5.42
Gain(dB) from testing	3	3
Beam width(azimuth)	360	130
Beam width(elevation)	120	50

Table 2.13: Summary of KUBESat-1 transmitter and receiver antenna characteristics

2-5.2 Testing of KUBESat-1 and S-band transmitter

During a flight, the KUBESat-1 system changes the characteristics of the S-band transmitter for different test scenarios and the ground station records and analyzes this data with the expected data. The ground station receiver needs to be in the same configuration mode as the S-band transmitter in order to receive the correct data, i.e. the modulation scheme, data rate and the filtering scheme have to be similar in order to record and compare the data.

Since there is no mode of communication between the KUBESat-1 system and the ground station, the configuration settings of the transmitter are pre preprogrammed such that the initiation and the duration of each test scenario are performed at pre determined times. A flight plan is created before each flight, which gives the time of initiation and duration of each test range, Refer Fig. 2.28 & Table 2.14. Each test range consists of a number of test cases, which are different transmitter configurations.

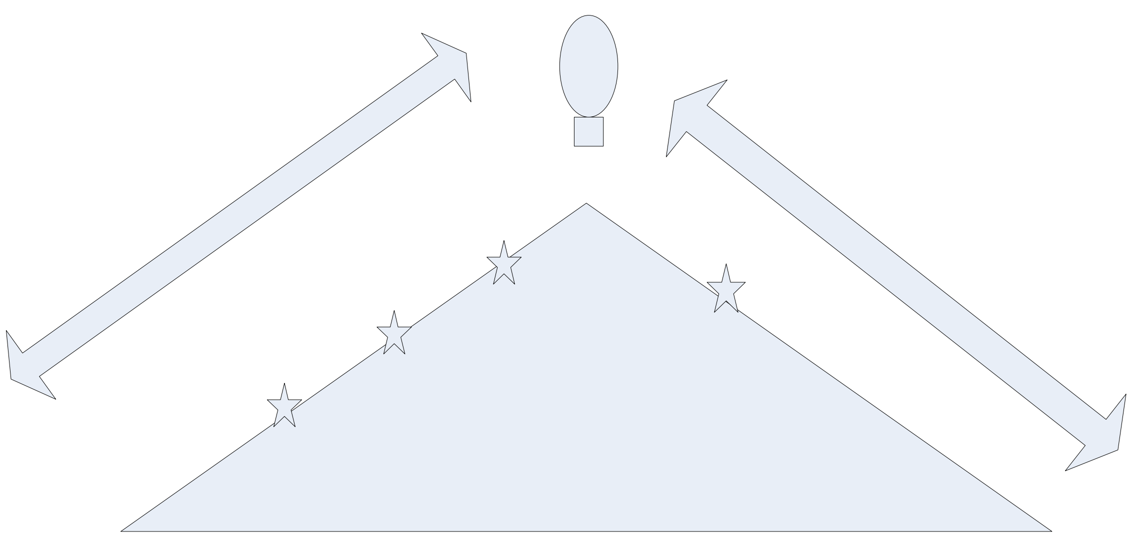


Figure 2.28:KUBESat-1 flight, test ranges

Phase	Total Time (seconds)	Total Time min, seconds
KUBESat Power On	0	0
KUBESat Launch	1200	20 min
R1 Start	1800	30 min
R1 End	3400	56 min, 40 sec
R2 Start	3580	59 min, 40 sec
R2 End	5180	86 min, 20 sec
R3 Start	5360	89 min, 20 sec
R3 End	6960	116 min
R4 Start	7260	121 min
R4 End	8860	147 min, 40 sec

Table 2.14: KUBESat-1 flight plan used for HABS-9b flight

The initial design of the S-band transmitter needed to be characterized for 32 different test scenarios, Refer table 2.10. It was however observed during the tests in the lab that the S-band transmitter’s power amplifier was malfunctioning and so was replaced by another power amplifier which had a fixed output power of 10 Watts, which reduced the number of test scenarios to 8. Table 2.15 lists the different test cases; and the test ranges that consist of these cases. The duration of each test case is varied according to the requirements of Kansas City plant, and in between each test case a delay is included where no transmission occurs, so as to differentiate between the test cases.

Test Case	Flight Location	Modulation Type	Data Rate (Mbps)	Filtering	Output Power (Watts)
1	R1,R2,R3,R4	FSK	1	Unfiltered	10
2	R1,R2,R3,R4	FSK	1	Unfiltered	10
3	R1,R2,R3,R4	FSK	5	Unfiltered	10
4	R1,R2,R3,R4	FSK	5	Unfiltered	10
5	R1,R2,R3,R4	FSK	1	GFSK	10
6	R1,R2,R3,R4	FSK	1	GFSK	10
7	R1,R2,R3,R4	FSK	5	GFSK	10
8	R1,R2,R3,R4	FSK	5	GFSK	10
9	R1,R2,R3,R4	OQPSK	10	Unfiltered	10
10	R1,R2,R3,R4	OQPSK	10	Unfiltered	10

Test Case	Flight Location	Modulation Type	Data Rate (Mbps)	Filtering	Output Power (Watts)
11	R1,R2,R3,R4	OQPSK	20	Unfiltered	10
12	R1,R2,R3,R4	OQPSK	20	Unfiltered	10
13	R1,R2,R3,R4	OQPSK	10	SOQPSK-A	10
14	R1,R2,R3,R4	OQPSK	10	SOQPSK-A	10
15	R1,R2,R3,R4	OQPSK	20	SOQPSK-A	10
16	R1,R2,R3,R4	OQPSK	20	SOQPSK-A	10

Table 2.15: Test cases for KUBESat-1 flight

Chapter 3 - KUTESat-1, Pathfinder design

3-1 Introduction

(Based on the original KUTESat program description by Dr.Soresen in June, 2002)

The objective of the first satellite mission is to develop and operate a simple cube satellite of about 1 kg in mass, called KUTESat-1, that will be flown in low Earth Orbit (LEO). This will be a satellite similar to cube sats being developed by several universities, and take advantage of their combined launch opportunities (where several cube sats are launched on the same vehicle thus reducing the per satellite cost).The purpose of this mission is to develop the capability and experience at the University of Kansas (& other Kansas Universities) to design, develop and operate a satellite. The KUTESat-1 will consist primarily of a transmitter and receiver to prove that it is in communication with the ground. It will probably have small solar cells as well as battery for power. It will not have any attitude control and will be allowed to tumble in orbit. If there is enough margin, then a simple payload such a dosimeter or imager may be included. Experience, skills, and tools obtained during this phase will help KU develop the more ambitious satellites of the subsequent missions.

The above were the objectives of a group of graduate and undergraduate students that embarked on building the first satellite from Kansas in fall 2002. The author was not part of the initial group of students that designed the engineering prototype of the satellite, but was later recruited as the System's engineer for the avionics subsystems due to his experience with the HABS and KUBESat projects. The author would like to acknowledge here that the core of the initial avionics system was designed by Leon Searl; from whom the he took over as the lead systems engineer for the testing and integration phase of the KUTESat-1 program in summer 2004. The main contribution to the KUTESat-1 program involved complete testing of the CTDH subsystem; overlook and train personnel for testing of the EPS ,ADCS,COMM subsystems ; technical input in the redesign of the payload subsystem; Final integration and testing of the satellite. Since the main contribution by the author was in the CTDH subsystem and the final integration and testing, only those sections will be discussed in detail in this work; other subsystems, operations and management are discussed in the thesis reports of fellow project members [45-47,64].

3-2 The CubeSat standard

(Derived from the document provided by the California Polytechnic State University [48])

This is a summary of the specifications provided by the Launch coordinator Cal Poly, to CubeSat developers like KU. While Cal Poly provides guidelines regarding the CubeSat, it is the responsibility of the developer to ensure the safety and success of the CubeSat missions by implementing good engineering practice, testing and verification of their systems.

A CubeSat is a 10 cm cube with a mass of up to 1kg that is launched with other CubeSats on a launch vehicle (LV) as a secondary payload to reduce the overall cost of the launch per satellite. The Poly Picosatellite Orbital Deployer (P-POD) is Cal Poly's standardized CubeSat deployment system that is capable of carrying three standard CubeSat's and serves as the interface between the CubeSats and LV, Refer Fig. 3.1. The CubeSats slide along the rail into orbit when the P-POD is deployed.

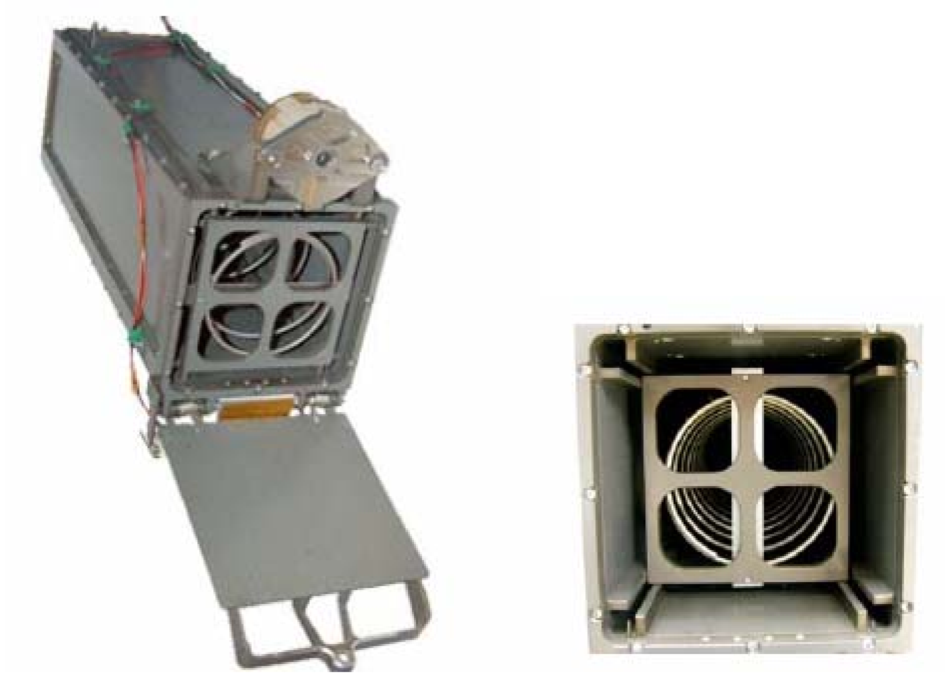


Figure 3.1:Poly Picosatellite Orbital Deployer (P-POD)

Dimensional and Mass requirements

The CubeSats are cube shaped picosatellites that have a nominal length of 100 mm per side, a mass that cannot exceed 1 kg and the center of mass must be within 2 cm of its geometric center. Double or triple configurations are allowed, where the weight can be 2 or 3 kg and the satellites can be expanded along the Z axis.

Structural requirements

The structure of the CubeSats must be strong enough to survive the maximum loading defined in the testing requirements and the cumulative loading of all required tests and launches. The rails must be hard anodized to prevent cold welding during ejection and must provide electrical isolation between the CubeSats and the P-Pod. The material for the structure should be Aluminum 7076 or 6061-T6 or similar .The structure should have spring plungers (see Fig. 3.2.) in order to help in separating the CubeSats from the P-POD. Any deployable such an antenna should be constrained by the CubeSat and should not use the P-POD rails or walls, so as to not jeopardize the mission.

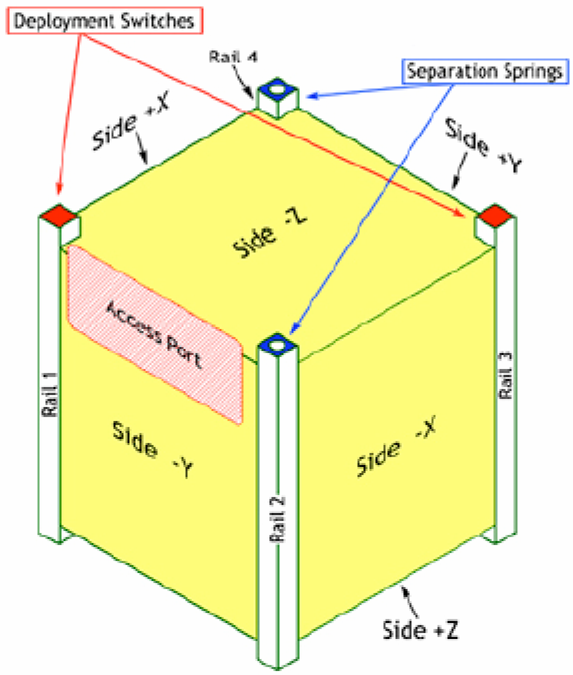


Figure 3.2: CubeSat structure drawing

Electrical requirements

The electronics inside the CubeSat should not be active during launch in order to prevent electrical or RF interference. This is achieved by using a deployment switch that is activated once the CubeSat is released in to orbit. There should be a Remove Before Flight (RBF) pin that is required to deactivate the CubeSat during integration with the P-POD and should be accessible from the outside. It is also recommended to have a port on the outside which can be used for system diagnostics and battery recharging after the

CubeSat is integrated with the P-POD. The location of this port and the RBF should be located in the area marked “Access port” in Fig. 3.2.

Operational requirements

It is required that the transmitter on the CubeSat must have the capability of being shutdown when using rechargeable batteries, as per FCC regulation. The antenna deployment from the CubeSats may occur 15 minutes after ejection from the P-POD in order to allow adequate separation of the CubeSats. The initial lower power beacon transmission may occur 15 minutes after ejection and complete transmission may occur 30 minutes later. Since most CubeSats use the amateur frequency band, allocation of frequency should be coordinated with International Amateur Radio Union (IARU).The developers should also be in regular communication with the launch coordinator in order to comply with testing, fit check etc.

Testing requirements and qualification

The CubeSats will undergo Random vibration testing; thermal bake out to ensure proper out gassing of components; and will be qualified through visual inspection and a P-POD fit test in order to determine if the CubeSat meets the requirements set by Cal Poly.

3-3 Overview of original system

The KUTESat-1, Pathfinder was originally designed to be a baseline for the future satellites by KU. With this view in mind, the subsystems were designed to be decentralized with a microcontroller PIC controlling each subsystem and a main computer residing on the Control, Telemetry and Data handling subsystem which would be the master microcontroller. This is a deviation from the usual designs in the early CubeSats that have a single microcontroller doing all the tasks [4, 49-51], due to the time line and the constraints posed by the small weight and volume of the CubeSats. The original design is shown in figure 3.3.

This system includes a HAM transmitter and receiver to provide communications with the ground. The payload consists of four dosimeters and a digital imager. It has solar cells on all six sides of the satellite for primary power and Lithium Ion batteries for secondary power. A magnetometer and sun sensors provide the attitude determination, and torque coils for attitude control. The CTDH system connects to all the other subsystems through a backplane and is developed around a uCDimm Dragonball processor module. Thermal control for the batteries and the main processor is provided by heaters.

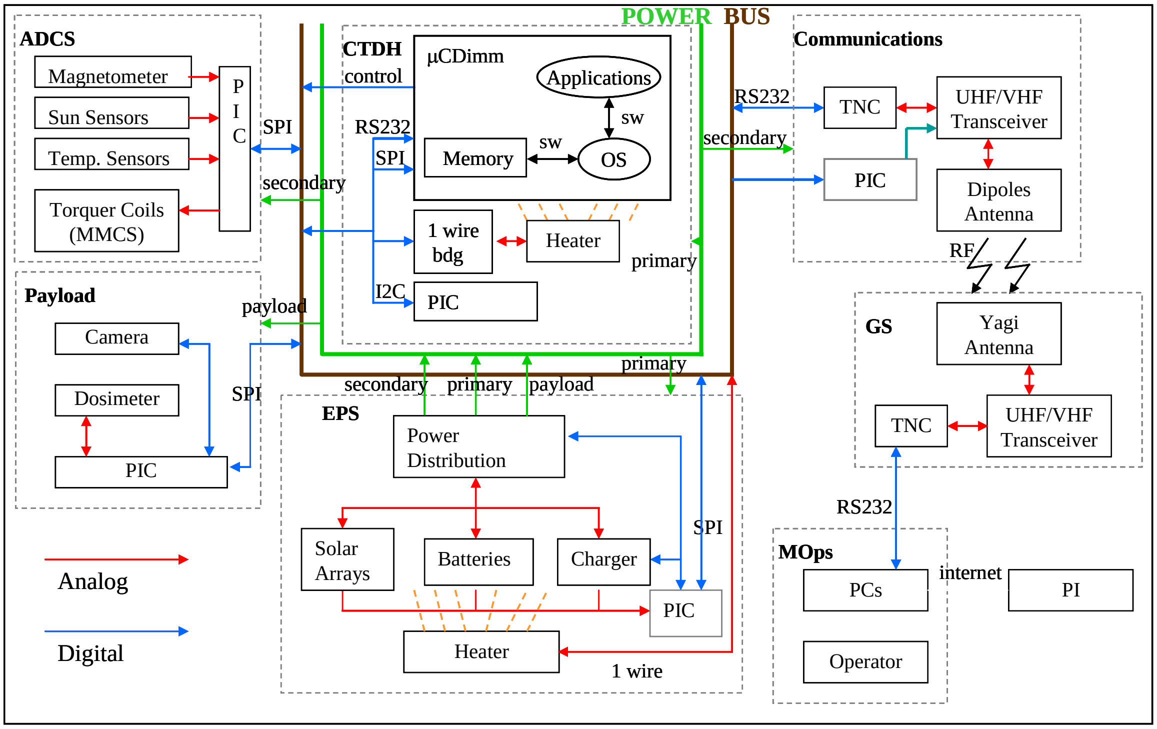


Figure 3.3: KUTESat-1 original system design

3-4 Control, Telemetry and Data handling subsystem (CTDH)

The Command, Telemetry and Data Handling subsystem is responsible for the following tasks on the KUTESat-1 system:

- Command and communicate with the individual subsystem PICs
- Capture health and status information; and instrument data
- Receive commands from the Ground station
- Control transmission of telemetry and instrument data to the ground station
- Control the modes of operation of the satellite based on ground station commands.

All tasks for the CTDH are performed in concert with the other subsystems of the satellite, as shown in Fig. 3.4.

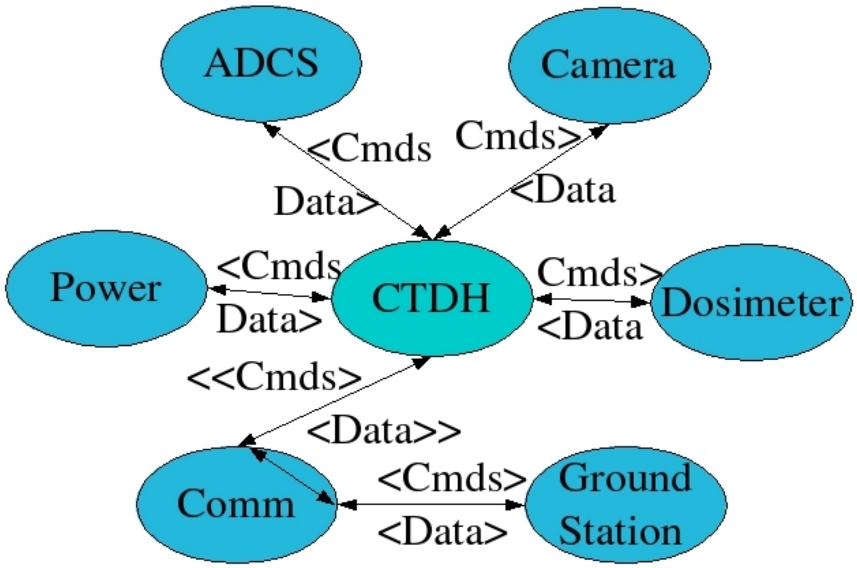


Figure 3.4: System Data and flow control

The CTDH is composed of a Mother Board[*] which consists of a uCDimm module and a PIC processor; and a Backplane that each subsystem is soldered into. All electrical connections between the Mother board and the other subsystems are over the copper traces on the backplane.

The CTDH communicates with all subsystems over one or more of the 3 serial communications buses provided by it: Serial Peripheral Interfaces (up to 5 interfaces), Inter-IC and 1- Wire. A fourth serial communication bus RS232C is provided to communicate with the Terminal Node Controller (TNC) on the COMM subsystem.

3-4.1 Backplane

The backplane is composed of the physical board and the electrical lines on the board. The purpose of the board is to carry the power lines from the Power subsystem to the other subsystems; and the signal lines from the CTDH subsystem to the other

[*] Since the Mother board is the core of the CTDH system and the backplane is only a physical interface, the two terms Mother Board and CTDH board will be used interchangeably.

subsystems. The design of the subsystem is driven by the satellite requirements plus the following goals:

- Carry all of the required power between the subsystems. There should be no need for other cables between the power subsystem and the other subsystems.
- Carry the entire signal lines needed between the CTDH and the other subsystems.
- Provide a structure for the mechanical attachment of the subsystem boards
- Provide as much flexibility for current and future use of the backplane as possible .i.e. in case of change of power requirements by the subsystems, the backplane should not have to be redesigned since this would require a change of interface of all the other subsystems.

The Functional diagram of the backplane is shown in Figure 3.5, where individual subsystem boards are attached to the backplane to share the electrical signals and are provided with mechanical support. Figure 3.6 shows the layout of the backplane. The subsystems are connected through their headers to the 50 pin sockets on the backplane during testing; and are directly soldered into the holes for the flight model. The width of the traces and the thickness of the copper on the board are important considerations to take, that depend on the current requirements, temperature cycling, bond strength and signal integrity. A good reference for these considerations is "High –speed Digital Design: A handbook of Black Magic" [52] . The traces on the KUTESat-1 backplane are 32 mils wide and 7 mils apart; and when passing near the connector holes the trace width is reduced to 12 mils and they are 7 mils away from the holes copper trace. The backplane is built on a FR4 with 1/2 Oz copper cladding which is the usual material available with board manufacturers.

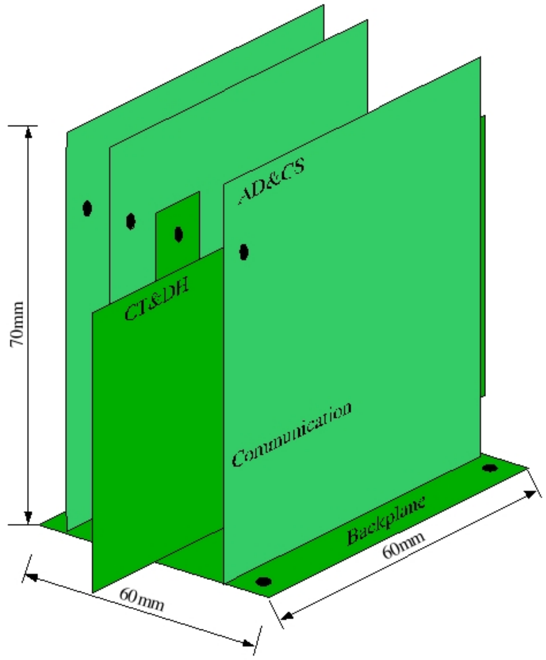


Figure 3.5: Functional diagram of the backplane

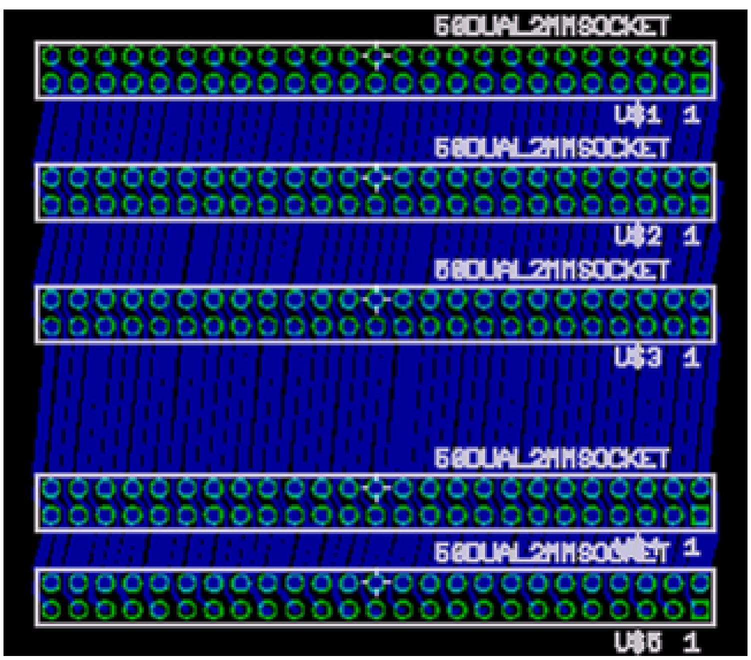


Figure 3.6: One of the versions of the backplane

3-4.2 Power and signal Bus

The Power and Signal Bus are the traces on the back/bottom side of the backplane that carry power to the subsystems from the Power subsystem and signals between the subsystems and the CT&DH subsystem.

Line Group	**Number of Lines**
Power	19
Signal	31
Total	50

Table 3.1:Number of Signal and Power Lines on Backplane

3-4.2.1 Power Lines

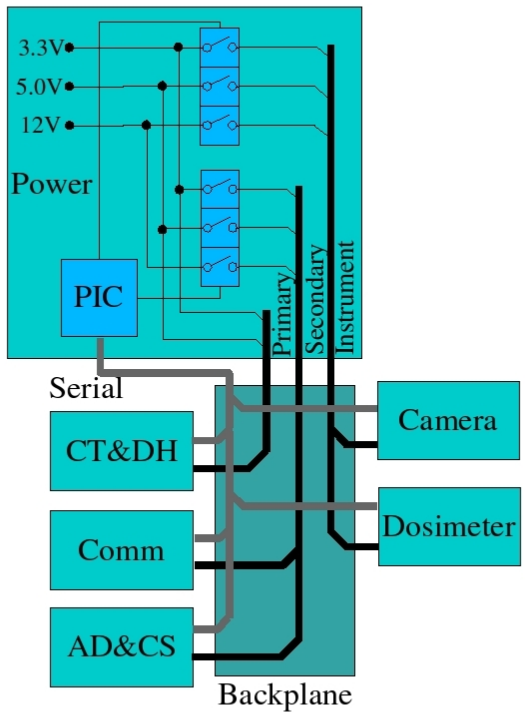
The power lines deliver power to the subsystems from the Power subsystem. The power lines are divided into 3 groups .Refer to Figure 3.7.

- Primary
- Secondary
- Payload

The Primary lines deliver power only to the CTDH over the backplane and are turned on by the Power subsystem PIC when there is sufficient power from the solar cells and/or the batteries do so.

The Secondary lines deliver power to the Communication ; and Attitude determination and Control subsystems. These power lines are run though a switch on the Power subsystem before reaching the backplane. This switch is controlled by the CT&DH subsystem by sending ON/OFF commands to the Power subsystem.

The Payload lines deliver power to the Payload subsystems. These power lines are run though a switch on the Power subsystem before reaching the backplane. This switch is controlled by the CT&DH subsystem by sending ON/OFF commands to the Power subsystem.



<u>Figure 3.7: Distribution of power on the backplane</u>

The connector pins on the headers of the subsystems can carry a current of 1.5 Amps. This is closely matched by the current carrying capacity of 1.4 Amps for traces of width 32 mils , thickness of ½ Oz copper and a 10^{o} C increase in temperature of trace*.

The number of pins required to carry a specified current to a group of subsystems shall be based on the 1.4 amp current capacity of the trace and connector pins with a 30 % safety margin. So the design current capacity for each power line is 1.4 amps * 0.7 = ~1.0 Amps.

* Refer to the backplane testing subsection for a description of a major mistake made in this calculation

Subsystem Group	Voltage	Max Current	# Lines
Primary	3.3	240 mA	2
“	5	10 mA	1
Secondary	3.3	520 mA	3
“	5	150 mA	2
“	12	0mA	2
Payload	3.3	35mA	1
“	5	0mA	1
“	12	30 uA	1
GND	Gnd	955 mA	6
Total Pins			19

Table 3.2: Backplane power line final current limits

There is a second pin for the Primary 3.3V line to provide redundancy to the CT&DH.

The Secondary subsystem 3.3V, 5V and 12V lines have an additional line each for potential expanded power usage.

Some power lines currently have no expected usage and are reserved for future use.

There are extra GND pins for future expanded power usage of the subsystems.

3-4.2.2 Signal Lines

The signal lines are all CMOS level 3.3V, excepting the RS-232 signals. All signals originate or terminate at the CTDH subsystem. Table 3.3 gives a list of all the groups of signals on the bus, and Table 3.4 gives a complete list and description of Power and Signal Lines on the bus.

Signal Type	Number of Signals (Pins)
Reset	5
Interrupt	5
SPI	8
I2C	2
1-Wire	1
RS232	2
PWM	1
PGM	7
Total	**31**

Table 3.3 The number of backplane lines for each group of signals

Reset Signals

The CTDH uses these lines to reset the subsystem PICs when programming the PICs; and when it is unable to communicate with them and senses that the PICs software is malfunctioning due to an SEL or SEU event. There is an RST0 on the CTDH board that is used to reset the PIC on that board.

Interrupt Signals

Subsystem PICs use the interrupt signals to tell the CTDH that they have some information to send. Each subsystem is assigned an individual interrupt line and is assigned an interrupt level based on the priority. ADCS, COMM and EPS have a level 4 interrupt; the payload has a level 1 interrupt line and INT5 is a level 2. The INT0 line on the CTDH is used by the PIC to interrupt the uCDimm and is a level 4.

Serial Peripheral Interface (SPI)

The Serial Peripheral Interface is the fastest serial interface on the backplane (1 MHz, full duplex). The CTDH is the master on the SPI bus and all the other subsystems are slaves. All the subsystems connect to the Data In, Data out and Clock signals. Each subsystem uses one of the SPI enable lines, which are controlled by the CTDH to decide which subsystem it wants to communicate with.

The SPI bus has the advantage of not needing to have address overhead like the I2C and 1-Wire serial interfaces but the disadvantage of needing a separate enable line for each component on the bus.

Signal Group	Pin no.	Signal Name	Description	Signal Group	Pin no.	Signal Name	Description
Primary Power	5	PRI 5v	5 V to CTDH	**SPI**	20	SPIOD	SPI output data from CTDH to PIC's
	25,49	PRI 3.3v	3.3 V to CTDH		22	SPIID	SPI input data from PIC's to CTDH
Secondary Power	1,9	SND 5v	5 V to COMM & ADCS		24	SPICLK	SPI Clock
	21,33, 45	SND 3.3v	3.3 V to COMM & ADCS		27	SPIEN1	Enable SPI communication with EPS PIC
	13,41	SND 12v	12 V to COMM & ADCS		28	SPIEN2	Enable SPI communication with COMM PIC
Payload power	17	INST 5v	5 V to Payload - Dosimeter & Camera		31	SPIEN3	Enable SPI communication with ADCS PIC
	29	INST 3.3v	3.3 V to Payload - Dosimeter & Camera		30	SPIEN4	Enable SPI communication with Payload PIC
	37	INST 12v	12 V to Payload - Dosimeter & Camera		48	SPIEN5	Future use
Reset	19	RST1	Reset EPS PIC	**1Wire**	4	ONEW	1- wire line
	26	RST2	Reset COMM PIC	**RS232**	14	TX	Transmit data from CTDH to TNC on COMM
	23	RST3	Reset ADCS PIC		16	RX	Received data from TNC on COMM to CTDH
	46	RST4	Reset Payload PIC	**PWM**	12	PWM	Pulse Width Modulation for regulating Heater
	38	RST5	Future use	**PGM**	3	PGMD	PIC Program Data Line
Interrupt	35	INT1	CTDH interrupt from EPS PIC		7	PGMC	PIC Program Clock Line
	32	INT2	CTDH interrupt from COMM PIC		44	PGMEN1	Program Enable line for EPS PIC
	39	INT3	CTDH interrupt from ADCS PIC		11	PGMEN2	Program Enable line for COMM PIC
	36	INT4	CTDH interrupt from Payload PIC		15	PGMEN3	Program Enable line for ADCS PIC
	43	INT5	Future use		47	PGMEN4	Program Enable line for Payload PIC
I2C	6	I2CC	Inter IC Clock		40	PGMEN5	Future use
	8	I2CD	Inter IC Data	**Ground**	2,10, 18,34, 42,50	GND	Ground

Table 3.4: Classification and description of Power and Signal Bus on backplane.

Inter-IC (I2C)

The I2C bus is a serial two wire bus for communications between the CTDH and the subsystems. Up to 1024 devices can be on the bus and has a speed of 400 kbps, half duplex.

The advantages of the I2C bus is that it only requires 2 signal lines and many devices can be on the bus. The disadvantages include having to add logic of pull-up and pull-down resistors to devices to set their addresses plus the bus is only 400kbps at half duplex.

1-Wire

This serial interface protocol developed by Maxim, Dallas Semiconductor has a single wire that carries both signal and power to the device.

RS232 Serial

This is the RS-232, 2 wire serial communication interface that is used to transmit to and receive data from over the RF link through the Terminal Node Controller (TNC) on the COMM subsystem.

Pulse Width Modulation (PWM)

This interface is primarily intended to be used to modulate the power delivered to the heater, but can be used by any other subsystem.

In-circuit Programming lines

The PICs that are used on the CTDH and the other subsystems are from the PIC18LF2220/2320/4220/4320 family [43] that are capable of low voltage programming while they are in the circuit. The CTDH can reprogram the PICs during development or in orbit. The subsystem to be programmed is enabled by the specific Program Enable line PGMENx, and the Data and Clock lines are used to program the PICs.

3-4.2.3 Flexibility of the Bus design

The design of the backplane was created before the components of each subsystem were completely identified. In order to create a flexible system that could be used for any changes that were made in the future , during the satellite design and test phase, a number of redundant power and signal lines were included. All the major IC communication standards SPI- Motorola; I2C-Phillips ;1-Wire- Maxim, Dallas Semiconductor; and RS-232 are provided on the backplane bus since there isn't a single standard protocol that is used by all the digital systems . A common set of CMOS voltages 3.3V and 5 V; and a standard payload voltage of 12 volts is provided to the subsystems ; since the design of the subsystem could change at a later stage in the satellite construction cycle. The main flexibility provided in the system is the inclusion of PICs on each subsystem in order to reduce the tasks of the CTDH.

This flexible design allowed for a change in the design of the camera system on the payload at a later stage by using the INT5, RST5, PGMEN5 and SPIEN5 signal lines for controlling and interfacing with the new camera design . The flexible design also allowed for an easier transition to the final satellite design, which will be described in later sections.

3-4.3 CTDH board

The CPU uCDimm module on the CTDH is responsible for controlling all command, telemetry and data handling. The module contains a Motorola (now Freescale) DragonBall VZ running at 33MHz with 4 MB of Flash memory and 8 MB of RAM memory. The Flash contains a ROM file system of the uCLinux UNIX embedded operating system. The DragonBall processor provides the on chip peripherals so that no external devices are needed for the following hardware interfaces:

- SPI Bus
- Interrupts
- RS232
- I/O pins and software implement the following
    - Reset signals
    - In-Circuit Programming for the Subsystem PICs
    - SPI Bus enable signals

Custom software for each subsystem runs on the uCDimm module. The subsystem software uses the uCDimm software to communicate with each other and the PICs on their subsystem boards.

An application on the uCDimm is able to reprogram the Flash of the subsystem PICs using the GPIO lines of the uCDimm that have been designated for PIC reprogramming. This allows for reconfiguring the functions of the subsystem PIC's during a flight or for software updates.

A PIC is on the CTDH board to:

- Monitor the health of the uCDimm

- Provide the I2C bus
- Provide the 1-wire bus
- Perform A/D measurement to record the uCDimm and board temperatures
- Switch on the Heater when the temperature falls below normal operating point.

The PIC can reset or toggle the input power switch of the uCDimm to handle Single Event Upset (SEU) and Single event Latch up (SEL) events when it detects problems on the uCDimm health output line. The uCDimm can do the same thing for the PIC.

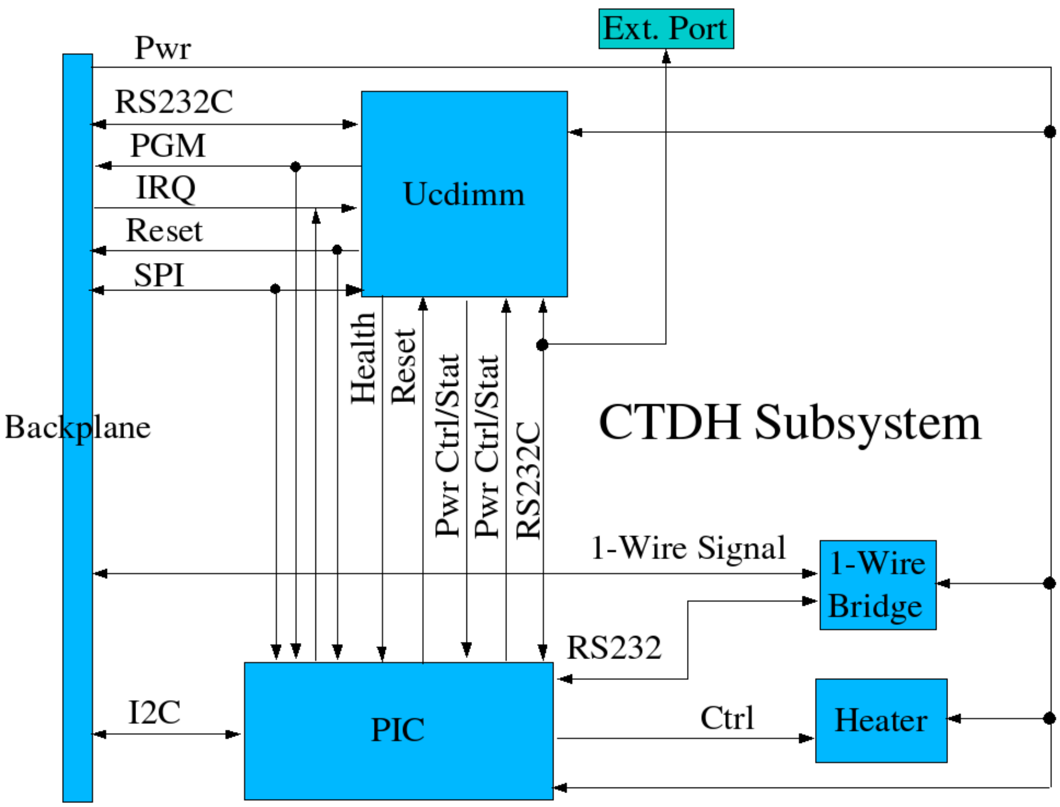


Figure 3.8:CTDH board Functional Diagram

3-4.3.1 uCDimm unit

The uCDimm unit consists of a uCDimm module and its power switch. The uCDimm unit interfaces with the backplane, the PIC unit and the external RS232 connector. The signals and power lines to the backplane have been discussed earlier in the subchapter “Backplane”. The other lines on this unit will be described in the following sections.

uCDimm Module

The uCDimm module [65] is a DragonBall processor, 4MB of ROM, 8 MB of RAM on a 144 pin SDRAM format board. It is installed in connector J4 on the CTDH board, Refer Figure 3.9 which shows the uCDimm section of the Mother board schematic.

The uCDimm can be programmed using the external port J2 while in circuit using the RS232 lines TSTTX and TSTRX .The PIC unit also connects to the same RS232 signals that are connected to the external jack. The PIC can use this connection to reprogram the uCDimm boot loader if needed. See the Boot Strap mode of the DragonBall processor [54] .The uCDimm communicates with the Terminal Node Controller on the COMM subsystem through its other RS232 signals RX and TX. The uCDimm requests the PIC on the COMM subsystem to switch on the radio and the TNC when it needs to communicate with the ground station.

Like the control lines available on the backplane to control the PIC’s , the uCDimm has the PGMEN0,SPIEN0,RST0 and INT0 to program, communicate, reset and get interrupted respectively by the PIC on the Mother Board.

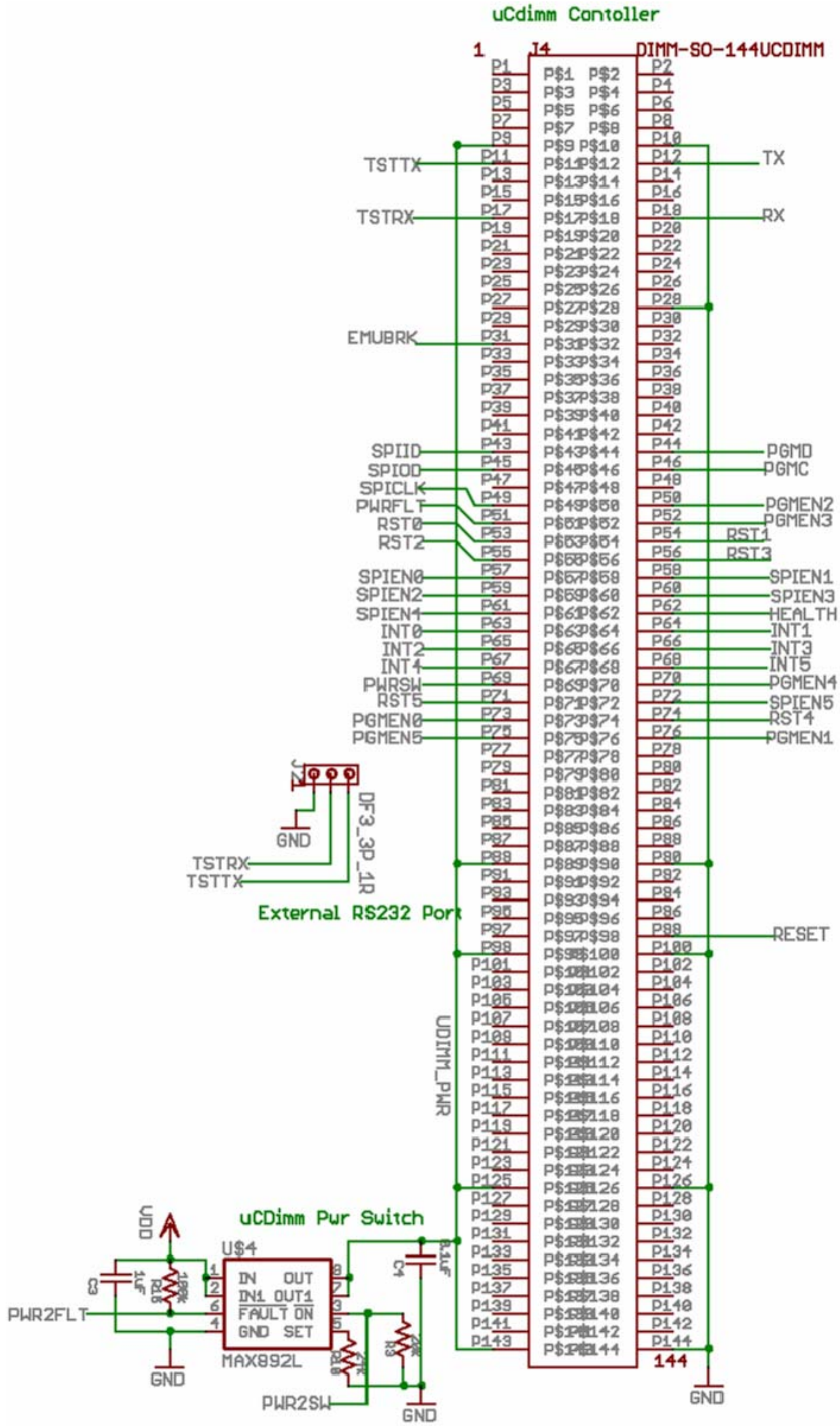


Figure 3.9: KUTESat-1 Mother board schematic –showing uCDimm unit

uCDimm Power Switch

The uCDimm power switch Max892L [55] from Maxim delivers current limited power to the uCDimm. The On/Off line PWR2SW is pulled low by a resistor to be default ON and is controlled by the PIC. This switch can have its current limit set up to a limit of 250mA. Since the uCDimm does not draw more than 40mA the current limit is set to 50mA [*]. The reason to set the current limit as low as possible and still be able to power the uCDimm is to be able to catch a Single Event Latch-up (SEL) as soon as possible and prevent a burnout of a pin on the uCDimm. When a SEL occurs a temporary short circuit occurs in a chip causing a high current drain that can permanently damage the afflicted chip. SELs can be removed by cycling the power of the chip. If the SEL causes a current drain greater than the switch's set current limit, the FAULT signal of the switch PWR2FLT is asserted by the switch. The PIC detects the FAULT signal on one of its interrupt pins and software in the PIC cycles the state of the ON input of the switch. This causes the power to the uCDimm to be cut and then restored, removing the SEL.

3-4.3.2 PIC Unit

The PIC unit is composed of a micro-controller 18LF2320 from Microchip [43], temperature sensors, a current limited power switch, and a 3.3V to RS232C logic level translator, Refer Fig. 3.10. The current limited power switch delivers power from the backplane to the micro-controller and is controlled by the uCDimm. The micro-controller is a watch dog for the uCDimm, an I2C master for the backplane, PWM source

[*] This value is based on the initial assumption of the uCDimm modules current requirements. The actual requirements are higher as described in the test results of the CTDH

for the backplane and the 1-Wire controller. It also can use the RS232C logic level translator to reprogram the uCDimm boot loader through its UART serial interface.

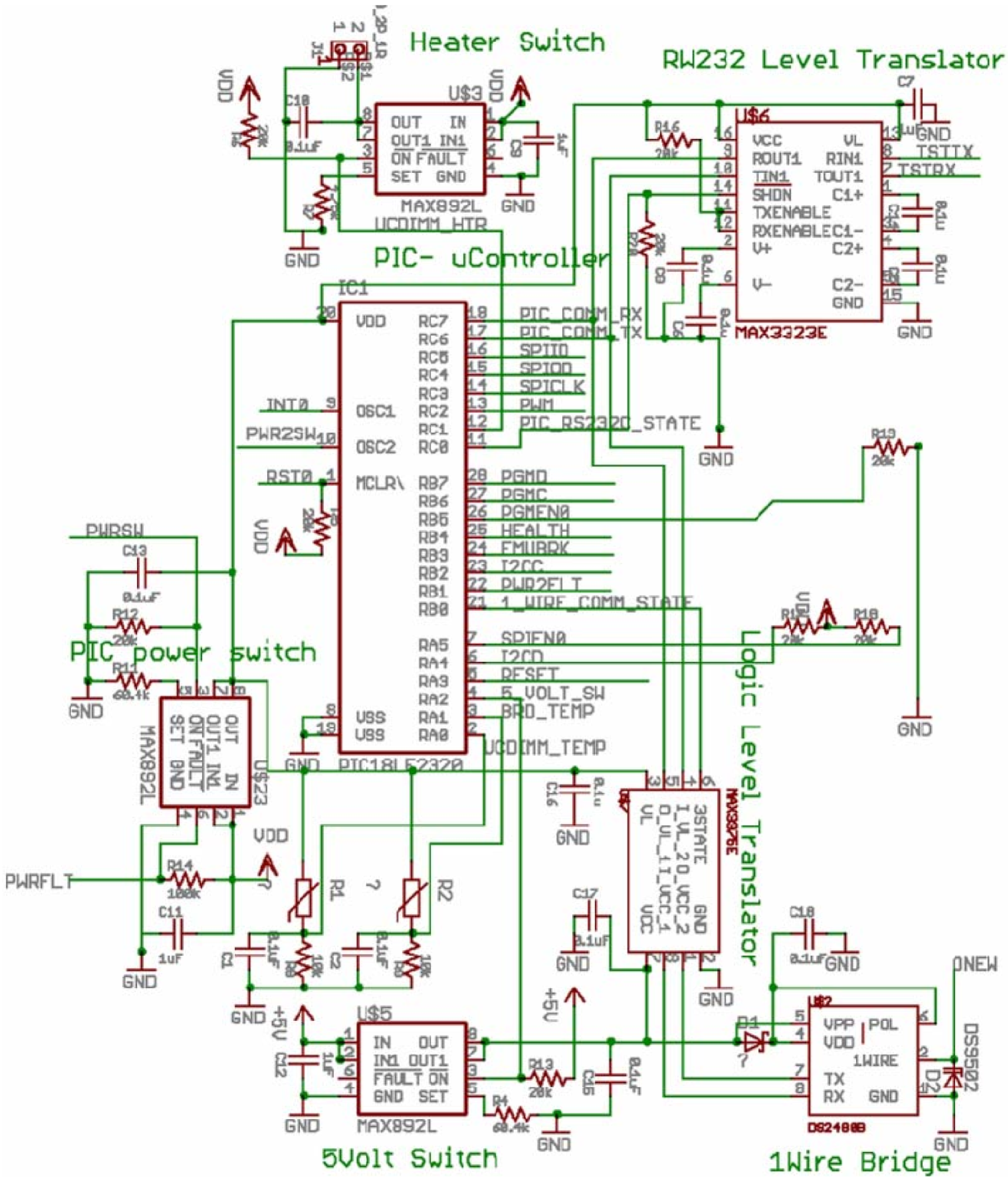


Figure 3.10: KUTESat-1 Mother board schematic- PIC, 1-Wire, and Heater Units

PIC microcontroller

The PIC microcontroller is responsible for monitoring and maintaining the health of the uCDimm unit. In case of a Single Event Latchup (SEL) on the uCDimm module, which it detects by monitoring the HEALTH and PWR2FLT lines, it can enable the RESET line or toggle the power PWR2SW line. To reprogram the boot loader of the uCDimm, the PIC must disable the 3.3V-5V translator (1_WIRE_COMM_STATE) and then enable the ports on the 3.3V-RS232C translator (PIC_RS232C_STATE). The uCDimm must then reset the uCDimm (RESET, EMUBRK) in the proper sequence to put the uCDimm into Boot Strap mode.

Since the PIC will not reprogram the uCDimm and communicate over the 1-Wire bus at the same time, it shares its UART lines between the two modules.

Temperature Sensors

The PIC monitors the temperature of the uCDimm and the board using two temperature sensors. The sensors are configured as voltage dividers utilizing a thermistor (Betatherm 10k3A1A) and a resistor (10K ohm). Each thermistor is connected to positive 3.3V and the resistor is connected to GND. The voltage at the point between the two components is measured by an A/D on the PIC. The following equation determines the resistance of the thermistor:

R = R0 * exp (Beta / T – Beta / T0)

Where:

R0 = Resistance at temp T0 (ohm) = 10000

Beta = Beta of the resistor = 3892

T0 = 25C = 298K

T = temperature in K

PIC Power Switch

The PIC Power Switch is identical to the uCDimm Power Switch except that it is controlled by the uCDimm and the current limit is 20mA. The PIC power switch also delivers power to the two temperature sensors and the RS232C logic level translator.

RS232C Logic Level Translator

The RS232C Logic level translator MAX 3323E from Maxim allows the PIC's 3.3V CMOS level UART signals to be translated to the RS232C level signals used by the uCDimm. This device is in shutdown mode by default and is only needed when the PIC has decided that the uCDimm has a problem with its boot-loader in flash memory due to bit changes caused by ionizing radiation..

3-4.3.3 1-Wire Unit

The 1-Wire unit is responsible for sending data originated by the PIC to the 1-Wire devices on the backplane and returning data from the 1-Wire devices on the backplane back to the PIC. Since the 1-Wire protocol and voltage levels are not directly supported by the PIC , the 1-Wire unit has been added to the CTDH. The unit is composed of a Current Limited Power Switch- Max892L; a 3.3V-5V Logic Level Translator- Max3375E; and a 1-Wire Bridge- DS2480B, all of from Maxim, Refer Figure 3.10.The 1-Wire bridge converts from 5V logic level UART signals to the 1-Wire protocol. The 5V logic signals come from the 3.3V-5V logic level translator and the 5 Volt power for the devices comes from the 5V current limited power switch. The purpose of the diode D1 in the 1-wire bridge is only as a voltage drop so that VDD is at a lower voltage than VPP as required in the device's data-sheet.

3-4.3.4 Heater Unit

The Heater Unit is a current limited power switch Max892L that runs off of the 3.3V primary power from the backplane. It is controlled by the PIC -UCDIM_HTR line and switched on when the temperature of the uCDimm fall to below 0^{o} C. The current limit is set to maximum 250 mA and can be modified depending on the heater element used.

3-4.3.5 Physical Specifications

Dimensions

CTDH Mother board – 69.35mm (wide) x 71.22mm (high) x 1.58mm (thick).

Backplane – 100.55mm (wide) x 96.730mm (long) x 1.58mm (thick).

Mass

CTDH Mother board- ~30 Grams

Backplane board- ~10 Grams

3-4.3.6 Radiation Effects

Ions from the sun and deep space can cause Single Event Upsets (SEU) and latch-ups (SEL). A SEU causes the binary value of a digital gate to flip from 0 to 1 or 1 to 0. A SEL is a short circuit of a gate that causes high current that can damage the gate.The Navy has a web site that has an on-line calculator for determining the probability of SEU and SELs [53] . In order to do the calculations , the two variables of the Bendel-2 function referred to as A and B are required.

Although the Bendel-2 parameters for the DragonBall VZ could not be found, the parameters for the Motorola 68332 processor were found [56]. This processor has the same core as the DragonBall VZ. The parameters are A=17 and B(calculated)=23.6. Note that these parameters are per device, not per bit.

The Space Environments and Effects (SEE) study uses an orbit of 650km and an inclination of 96 degrees. Shielding is assumed to be 1/64" aluminum. Both minimum and maximum solar environments are examined. Magnetic weather is both calm and stormy. The following is the result of the study.

Orbit	Shield 1/1000 inch	Sol Env	Magnetic Weather	Trap Model/val	SEU/dev/day
650x96	065	Min	Calm	Min/avg	2.24943e-4
650x96	065	Max	Calm	Max/avg	1.47620e-4
650x96	065	Min	Storm	Min/avg	2.25387e-4
650	065	Flare/wk	Calm	-	2.35562e-3

Table 3.5 Radiation Effects on M68332 Processor

With a minimum solar environment and calm magnetic weather we can expect an SEU every 4446 days. In stormy magnetic weather an SEU occurs on average every 4436 days.

3-5 Testing and Lessons

As the systems engineer the author had to test the hardware of the CTDH system; and assist the software engineers with the CTDH testing and with the inter subsystem testing.

3-5.1 Hardware tests

3-5.1.1 Manufacturing of board

The initial engineering model boards for all the subsystems were manufactured in house, in order to reduce the costs.A milling machine was borrowed from another research group –RSL at the university. The boards were double sided boards that had vias to connect the two sides. Since the vias were not through hole plated, all traces for the through hole components had to be made from the pin lead side only, which caused inefficiencies in the board layout. Figure 3.11 illustrates this problem for the 50 pin header used on the CTDH Mother board, where all traces from the pins were laid from the bottom side of the board only.

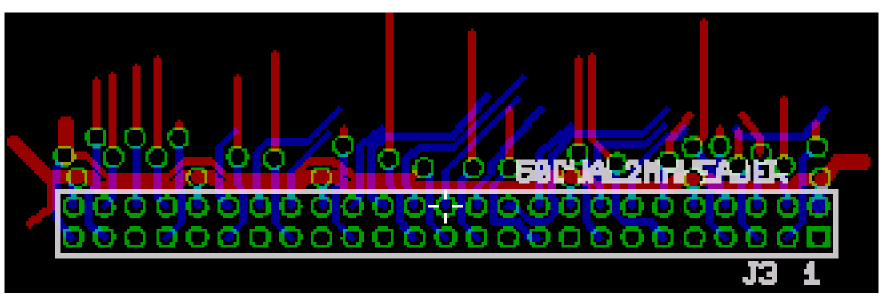


Figure 3.11:Layout of 50 pin Header

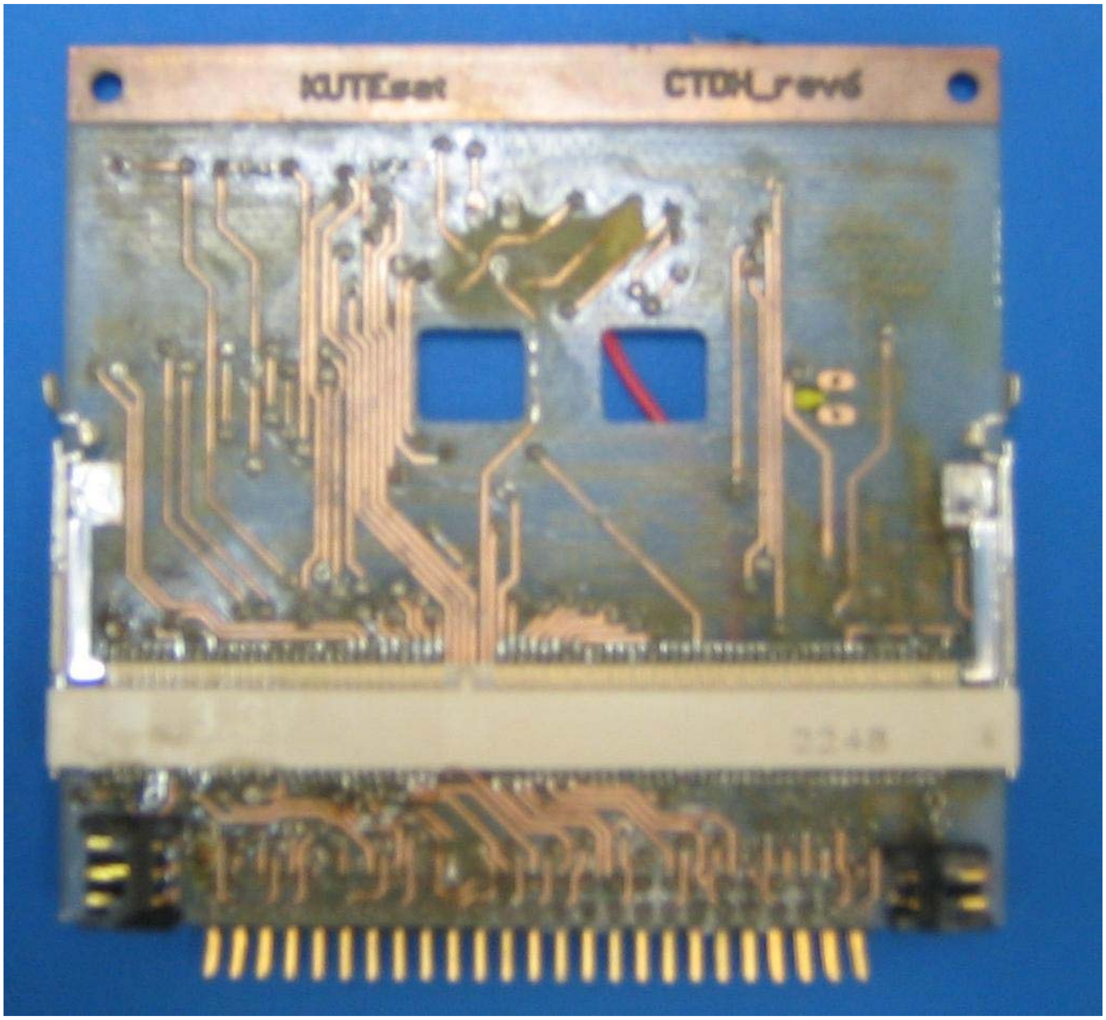


Figure 3.12: Picture of Original CTDH board –Manufactured in house

Once the boards were manufactured, the vias had to be filled using copper wire which was a tedious process; and then tested for any defects that occurred during manufacturing like a disconnected trace or non alignment of the vias on the bottom and top sides of the board. Figure 3.12 shows the bottom side of the original CTDH mother board that was manufactured in house. Since the pads were not tin plated, soldering of Surface Mount Devices(SMD) was a very messy process which led to short circuiting between adjacent pads; and weak solder joints between the device leads and the pads. The main problem that occurred was during the soldering of the 144 DIMM connector for the uCDimm module, where a microscope had to be used to troubleshoot and clean up the shorts between a few pads.

3-5.1.2 Backplane board hardware testing

The backplane is a passive board that contains only traces connecting the subsystems. The testing involved checking for connectivity between the boards, and for short circuits between adjacent traces and pads.

The width of the traces are 32 mils, designed according to calculations for a 1.4 A capacity , 10 ^{o}C rise ,0.5 oz copper thickness. The calculations did not however consider the effect of vacuum, due to which the effective rise in the copper traces temperature will be higher due to a lack of medium (air) to conduct the heat. Assuming that the width of the trace required for an internal trace; and that of an external trace in vacuum are similar, a 32 mil trace has a 0.5 A current carrying capacity, with all other considerations being the same. Assuming a 30 % safety margin, each trace can carry only 350 mA, which will still meet the requirements of the system, Refer to Table 3.2 in the backplane design subsection.

3-5.1.3 CTDH mother board hardware testing

Three problems were encountered during the testing of the mother board.

SPI lines

It was discovered that the SPI output and input communication lines from the uCDimm module to the CTDH PIC and to the backplane were interchanged. This was rectified for the final design.

Sensors

The thermal sensors on board are for measuring the temperature of the board and the uCDimm , and were placed near the core of the uCDimm. It was later realized that in space, there is no atmosphere to conduct the heat from the microcontroller to the sensors. This was a fundamental mistake that was overlooked earlier and was rectified by placing a thermally conductive tape between the sensors and the microcontroller.

Power switches

The initial estimates of the power requirements of the uCDimm were wrong. The uCDimm requires 110mA for normal operation, 140mA for external programming and 200mA for a FLASH erase. This required a change of the current limiting switch on board.

3-5.1.4 Lessons learnt

The author's and his team mates experience over the last 3 years shows that the time and effort spent in manufacturing and trouble shooting an in house manufactured board may not be worth the perceived saving of costs. There are manufactures available in the market [57] which provide basic board manufacturing for a very nominal rate and have a turn over time of only 24 hours. During the initial phases of design and testing, it is recommended that only a few subcomponents of a complex board be tested on in house manufactured boards and for an engineering model the board be manufactured outside.

Figure 3.13 shows a version of the CTDH board that is used in KUBESat-2. This board has through hole plated vias and tin plating on the pads which allows for faster testing.

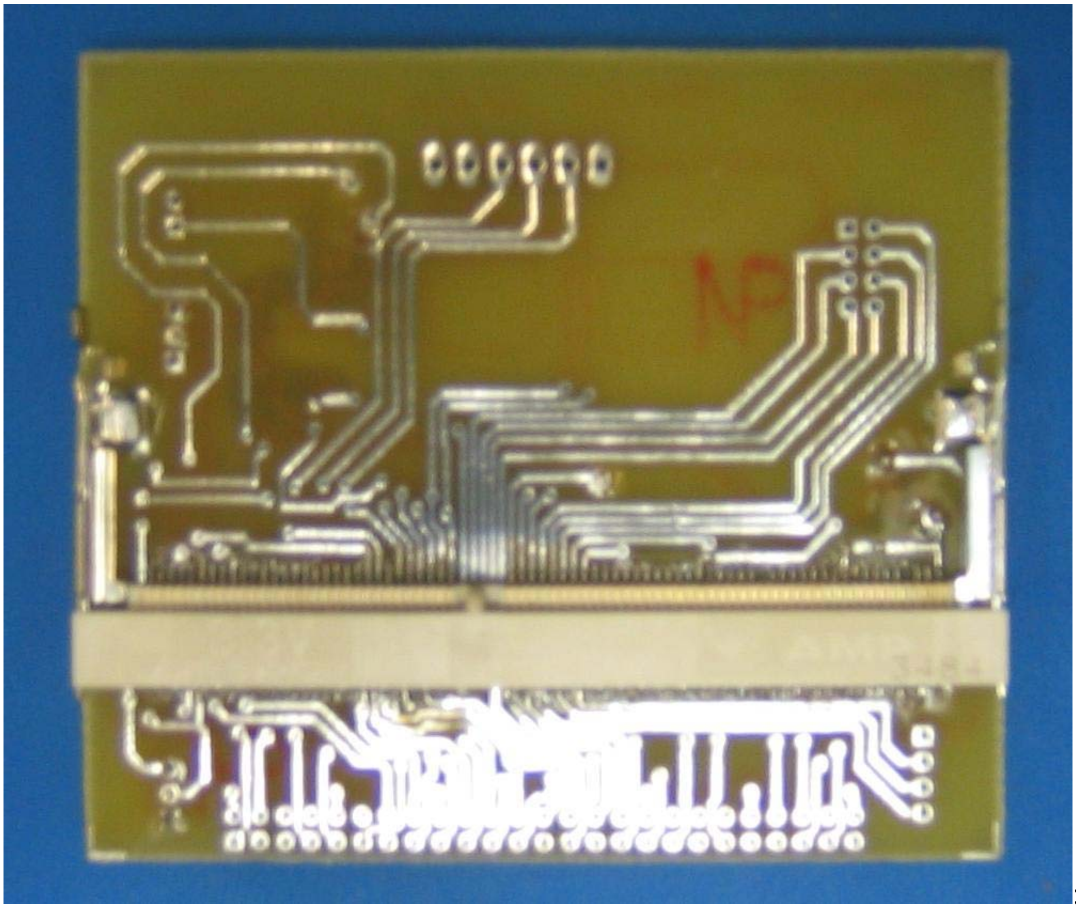


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Figure 3.13CTDH board with basic tinning and through hole plating

3-5.2 Software testing

The software testing* included in this work is a basic proof of concept testing which involves

- Programming the uCDimm from the external port

* The software testing for the CTDH mother board was performed by a software engineer Karthik Varadarajan and the author.

- Control the uCDimm lines
- Program the PIC from the uCDimm
- Control the PIC lines
- Control the Power switches
- Perform A/D measurements from the PIC
- SPI communication between uCDimm and PIC
- Monitoring of uCDimm Health. Reseting and reprogramming the uCDimm

While it is not possible to give detailed results of each of the above tests, a summary of the results is described below.

The uCDimm can be programmed and debugged while in circuit, from a Linux machine over an RS232 port. There are issues with programming of the PIC by the uCDimm and so an external programmer had to be purchased. This programmer [59] is unreliable and does not provide in circuit debugging; but due to the short time available before delivery and the lack of a perceived alternative at that time, testing was continued with this programmer. The PIC can be programmed but there are problems accessing the EEPROM of the PIC and so data cannot be stored by the PIC. This requires that the A/D measurements made by the PIC are to be sent as output on a different output port in real time and cannot be stored for retrieval at a later stage. There also are problems associated with the use of multiple A/D ports which is surprising since the PIC on the COMM subsystem does not have a similar problem.

The main issues with the Mother board however occurred in the SPI communication between the uCDimm and the PIC. Initial efforts to have these microcontrollers communicate failed. A PIC development board, Figure 3.14 was built.

The purpose of this board was to provide a platform for programming and testing the PIC; and to test the SPI communication between two PICs. After complete testing of the PIC and the success with SPI communication between two PICs, we tested the SPI communication between the uCDimm and the PIC, which produced mixed results. The uCDimm can send commands to the PIC and receive acknowledgements , but the PIC cannot perform A/D measurements when the SPI communication is enabled. This defeated one of the main purposes of the uCDimm's function which is to gather telemetry data from individual PICs and transmit it to the ground station.

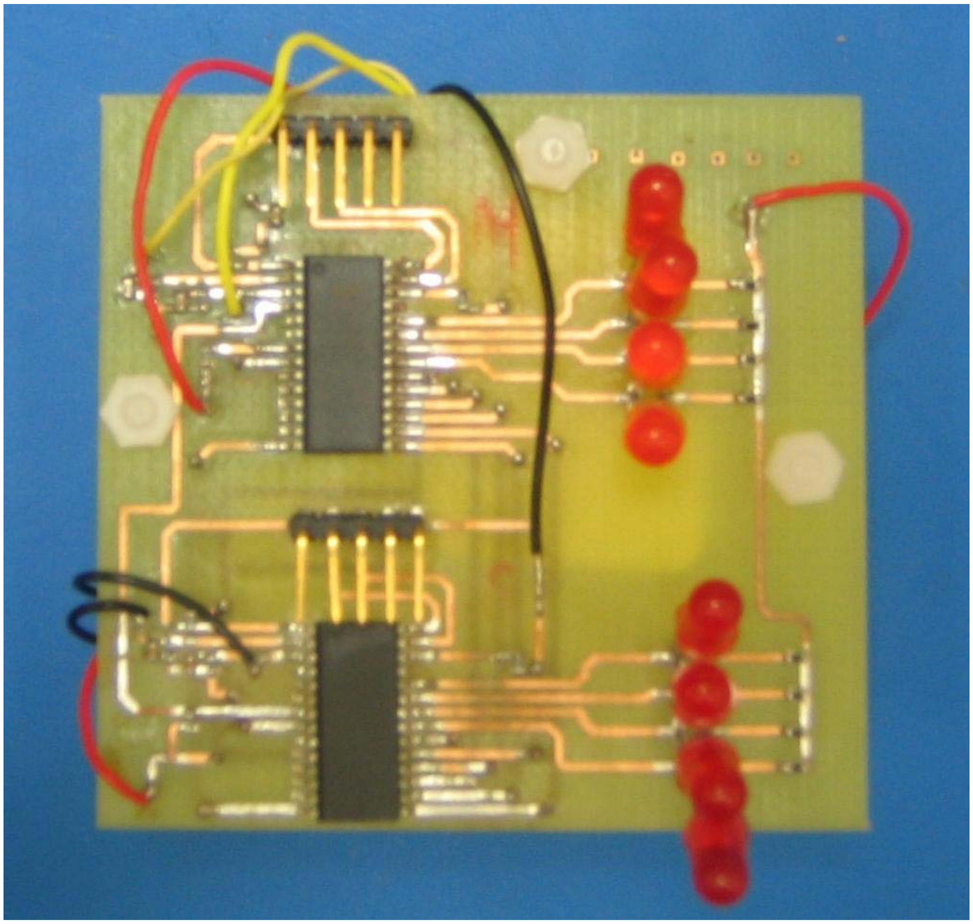

Figure 3.14: PIC development board

Due to problems with SPI communication and other issues, the scope of the KUTESat-1 project had to be changed. This will be discussed in a later subchapter.

3-5.3 Lessons learnt

The author hopes that these inputs will help future system engineers overcome the problems that were faced in the first satellite.

- When designing a new subsystem, test the unknown parts before building an engineering prototype. This will help overcome surprises at a later stage when it might be too late to redesign the subsystem.
- Invest time and money in buying or designing development boards for the microcontrollers. The team initially wanted to program the PICs using the uCDimm and so did not invest in a development kit for the PIC. This meant the functionality of the PICs could not be tested until the uCDimm software was at a mature stage.
- Due to the small factor of Surface mount components, it can be tough to access signal lines during testing. It is advisable to include test points on the boards which can be accessed for delivering power, controlling signal lines or for getting status of signals lines

3-5.4 Flight Model of CTDH mother board

Figure 3.15 shows the flight model of the CTDH mother board, which was also manufactured at an outside facility [58] and includes solder masking.

Figure 3.15: Flight model of CTDH

3-6 Final design for KUTESat-1

The KUTESat-1 was finally delivered in April, 2005 to California Polytechnic State University. The satellite delivered was a downsized version of the original version. Due to problems with the SPI communication, and with a few other subsystems, the final version included only the COMM, EPS subsystems and a Dosimeter, Refer to Figure 3.16. The power is delivered by the EPS system ,whose PIC is programmed to initiate antenna deployment after start up and then to provide power to the COMM subsystem which goes into Beaconing mode. The Dosimeter is the only payload that is included in the system. The COMM performs A/D measurements of temperatures on the COMM subsystem and battery; the voltage of the battery; and the output voltage of the dosimeter. These are reported to the ground by the COMM PIC as Morse code.

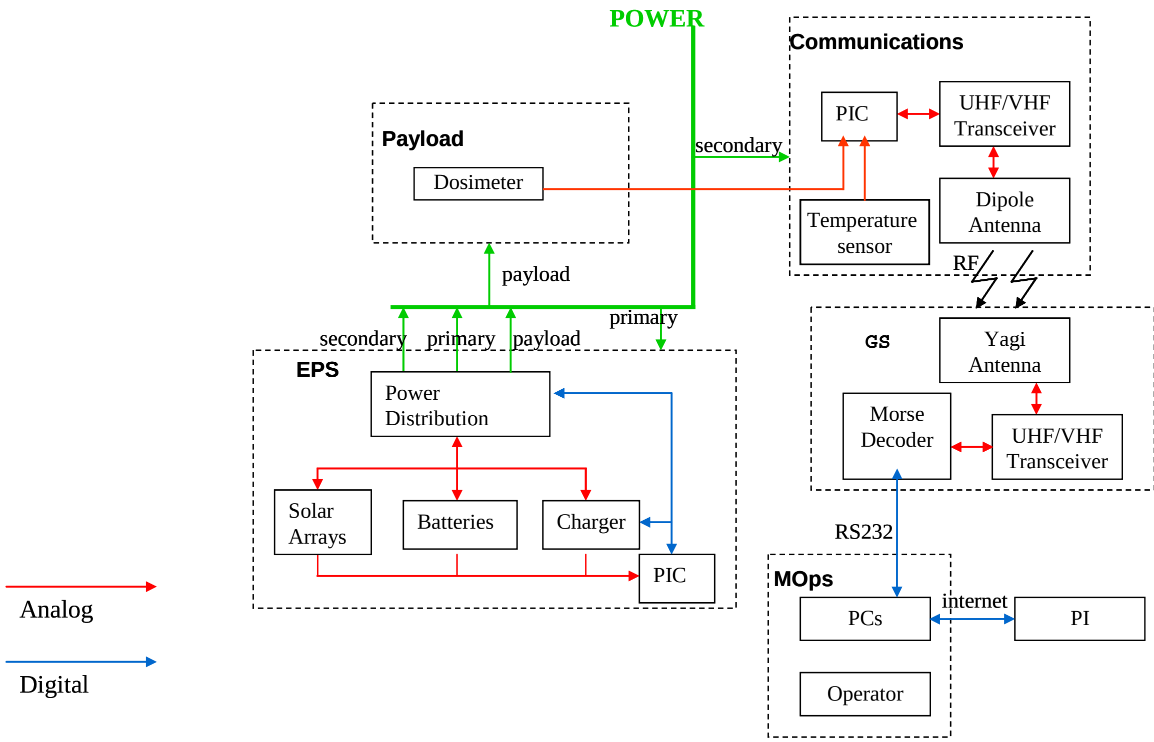

Figure 3.16: Final design of Pathfinder

Chapter 4 - Design of a Modular platform

4-1 Literature review

4-1.1 Creating Standards

There have been many efforts in the past to create standards for space applications in order to reduce the cycle times and program costs associated with the development of space systems. These standards include the NASA Standard Spacecraft Computer, NSSC-1 in the 1960's, the MIL-STD-1553B bus adopted from military aircraft in the 1980's; and Futurebus+ backplane standard (IEEE 896 family) that got withdrawn in 2003[1] .

These standards have been designed for the larger satellites and are not suitable for the pico/nano satellites due to the constraints of mass and power. The recently held Small Satellite Conference, 2005 addresses to an extent, this void in standards for launch vehicles, spacecrafts, subsystems and components.

The U.S. aerospace industry has traditionally be a performance driven industry that is characterized by high value, low volume products with multi –year development. The difficulty of placing a spacecraft in orbit makes it very important to accomplish a mission at minimum risk of failure, than to lower costs that may introduce risk to the mission. Over the past few years however, there has been an emphasis on faster

[1] Doug Caldwell." The Standardization Process: What works; What doesn't". 19th Annual AIAA/USU Conference on Small Satellites, Logan, Utah.

development time, low cost missions for testing new payloads[1] ; which has led to the development of the picosatellite community.

Standards are required to put together the lessons learnt from previous trials and errors. Standards help in the rapid development of new designs; create a platform for future more complex systems; provide the flexibility of replacing one payload with another payload to meet the same standards. Traditionally standards have evolved from small user groups that are later adopted by the larger community. The CubeSat standard [2] was used by five universities in 2000, and is now adopted by over 40 universities around the world. While no current standards exist for the pico/nano satellite bus, they can be adopted from other markets (e.g.: RS-422 driven by the electronics markets), or developed over time by common engineering considerations (28 V bus)[3].

The Office of Force Transformation (OFT) has developed TacSat-1 as part of the Operationally Responsive (ORS) Experiment[4] . The ORS experiment is designed to provide a rapid, tailored and operationally relevant experimental space capability to tactical forces [5] ORS is concerned with the dramatic reduction in timescale for designing, building, integrating and launching, and bringing online a give space system.

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[1] Siegfried W.Janson."Micro/Nanotechnology for Micro/Nano/Picosatellites". AIAA Space 2003 Conference and Exposition, Long Beach, California, Sep. 23-25, 2003

[2] Heidt, H., Puig-Suari, J., Moore, A., Nakasuka, S. and Twiggs, R. (2000). CubeSat: A New Generation of Picosatellite for Education and Industry Low-Cost Space Experimentation. Paper SSC00-V-5, 14th Annual/USU Conference on Small Satellites, Logan, Utah.

[3] Stacy Garfield, Stanley O.Kennedy,Jr. and Quinn Young . "Finding the Balance in Standard Bus Design". 19th Annual AIAA/USU Conference on Small Satellites, Logan, Utah.

[4] Operationally Responsive Space (ORS) Experiment. "TacSat-1". http://www.oft.osd.mil/initiatives/ors/

[5] Brown, Kendall K. "A Concept of Operations and Technology Implications for Operationally Responsive Space". http://www.airpower.maxwell.af.mil/airchronicles/cc/brown2.html

The DARPA Falcon program [1] has created a low cost launch capability; but there is still the difficulty of creating a spacecraft and its payload rapidly. The Air Force Research Laboratory (AFRL) is addressing this issue of rapid avionics systems by spearheading a standard for the avionics and software in a space craft, based on the terrestrial Plug and Play (PnP) technology developed for USB devices.

The Space plug-and-play Avionics (SPA) program [2] adopts the terrestrial PnP USB standard and includes a 28 V line at 3 amperes; and includes two synchronizing pulse lines to synchronize the subsystems in the satellite. The program based on the work done for a previous Adaptive Avionics Experiment (AAE)[3], identifies four distinct elements leading to a modular, PnP avionics capability: appliqué sensor network, adaptive wiring manifold, high performance computing on –orbit, and software definable radio. The USB based SPA-U will be initially tested using Commercial Off The Shelf (COTS) components and later Spacewire [4] based SPA-S and Ethernet based SPA-E will be developed and tested.

4-1.2 Designing a Modular Platform architecture

Traditionally, spacecrafts have been designed with a high degree of mission specificity and are made to be used only once. With increasing interest in low –cost small satellites and reuse of designs, there is however a necessity to create a product platform to

[1] Walker,Steven. " Falcon". http://www.darpa.mil/tto/programs/falcon.htm

[2] Jim Lyke, Don Fronterhouse , Scott Cannon, Denise Lanza, Wheaton(Tony) Byers. " SPACE PLUG-AND-PLAY AVIONICS". AIAA 3rd Responsive Space Conference 2005.

[3] Denise Lanza, Jim Lyke,Paul Zetocha,Don Fronterhouse and Dave Melanson. " Responsive Space through Adaptive Avionics". Space 2004 Conference, San Diego, California.

[4] Spacewire: http://www.estec.esa.nl/tech/spacewire/overview/

meet these objectives. A product platform allows common elements to be used in the production of a whole family of product variants, giving time and cost improvements whilst still allowing customization.

A Modular system is one, which is composed of a number of self contained units, which can be easily removed and replaced without requiring significant architectural changes to the rest of the system. The replacing module may have a different performance, but it will still interface with the existing system. The recent Small Satellite Conference, in 2005 address the applicability and issues of designing a Modular Platform for small satellites[1,2] .

Modular platforms for spacecraft

- Improve the system performance by offering the flexibility of replacing modules when required. They create standard interfaces which allows for the subsystems to be developed independently. A power module which uses NiCad batteries is easily replaceable by one using Li Ion batteries since they provide standard voltages and currents.
- Decreases time spent for integration and testing, since the interfaces are well defined standards which allows for testing the subsystems independently. The modules help in pinpointing the root cause of a system testing failure; and if required a troublesome module can be replaced by another in a short duration.

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[1] Quinn Young. “Modular Platform Architecture for Small Satellites: Evaluating Applicability and Strategic Issues”. 19th Annual AIAA/USU Conference on Small Satellites, Logan, Utah.

[2] Jenny Kingston.” Modular architecture and product platform concepts applied to multipurpose Small spacecraft”. 19th Annual AIAA/USU Conference on Small Satellites, Logan, Utah

- Reduce non recurring engineering costs by reusing modules.
- Multiple missions can be designed by using the core modules and adding new mission specific payload modules when necessary. The core modules would include C&DH, Power, Attitude determination and control, Communications. This would allow the developer to focus on the design of the payload mission.
- Allows the possibility of mass production.

A modular system however comes at the expense of

- Increased costs due to the initial costs in a developing a platform. The mass and power requirements of a modular system will be higher than a system that has been optimized for a particular mission.
- It is hard to foresee the objectives of future missions and design an interface standard which can accommodate all these requirements.
- Not being compatible with highly specialized missions.

4-1.3 Modular designs for satellites

There have been efforts in the past few years to design modular space crafts for various small satellite missions. A summary of a few of these efforts is included below.

The Self –assembling Wireless Autonomous and Reconfigurable Modules (SWARM) at the Massachusetts Institute of Technology (MIT)[1,2] demonstrates the use of modular spacecraft, which are capable of self-assembly and reconfiguration while

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[1] Lennon Rodgers, Nicholas Hoff, Elizabeth Jordan, Michael Hieman, David W.Miller."A Universal Interface for Modular Spacecraft". 19th Annual AIAA/USU Conference on Small Satellites, Logan, Utah.

[2] SWARM : http://spacestation.mit.edu/spheres/swarm/index.htmlerence for Small Satellites.

utilizing wireless communication. They have created an interface which allows for autonomous Docking and Undocking; Transfer of mechanical, thermal and electrical loads; and provide a connection for Data and Communication through Bluetooth technology. These modules weigh about 50 kg and the power requirements of the whole space craft is around 650 watts.

AeroAstro Inc. has been actively developing modular spacecrafts. Space Frame[1] is a reconfigurable spacecraft architecture that uses standard structural modules and interfaces that are created by grouping together related subsystems .The Small Spacecraft for Observation and Utility Tasks (SCOUT) [2] contracted by the DARPA aims to create spacecrafts that can be used for multiple missions; be assembled rapidly before launch and tested. The small space craft (50-100 kg) can be built using modules that can be plugged and played. The software on the Command and Data Handling unit provides built in tests to help in reducing the time for testing and integration. The SMARTBus™ defines systemic, mechanical, electrical and logical interfaces that allow spacecraft modules to interact with each other based on their functions rather that their implementation[3]. This is based on the SPA standard being developed by AFRL, but the onus in this project is not just to develop Plug-and-Play modules, but to also design modules which provide information about their function; and key parameters such as power requirements, volume, mass, location in the space craft. This software is divided

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[1] Jon Miller, Jim Guerrero, David Goldstein, Tony Robinson . " SpaceFrame: Modular Spacecraft Building Block for Plug and Play Spacecraft". 16th Annual/USU Conference for Small Satellites.

[2] Aaron Rogers, Glen Cameron, Luis Jordan. " SCOUT: A Modular, Multi-Mission Spacecraft Architecture for High Capability Rapid Access to Space". 17th Annual AIAA/USU Conference for Small Satellites.

[3] Lusi G.Jordan,Scott A.McDermott. " Plug-and-Sense: An enabling onbard networking technology for modular spacecraft". 19th Annual AIAA/USU Conference on Small Satellites, Logan, Utah.

into seven layers such that each layer is dependent only on the adjacent layer and is not concerned with or even aware of the non- adjacent layers.

The Thunderstorm Effects in Space: Technology (TEST) [1] nanosatellite (30 kg) developed by Taylor University and University of Illinois is designed with all subsystems filling 10 cm dimension cube modules or multiples of this base size. The size increment is based on the CubeSat program. Each module includes a common interface board that acts a bridge between the instruments, the attitude control, the power control and the communications. The interface board has a PIC18F8520 microcontroller that is responsible for controlling the instruments; collecting instruments data; and monitoring the various health and diagnostic information.

4-2 Proposed platform

The previous subchapter gives an insight into the necessity of designing a modular product platform for multi missions. A few examples of such platform have been explored; but they have been implemented for larger satellites (30-100 kg). A picosatellite design by the StenSat Group [66], is a CubeSat that offers the flexibility of flying different payloads using the same core satellite; but this is a very limited system since no changes can be made to communications, power, and microcontroller subsystems without an overhaul of the whole system.

A modular platform is necessary for the space program at the University of Kansas, due to the multiple missions that are planned for the future. It is desired to build a platform which will be used by both the Balloon projects and its payloads; and by the

[1] David L. Voss, A. Kirchoff, D. P. Hagerman, J.J. Zapf, J. Hibbs, J. Dailey, A. White, H. D. Voss, M. Maple and Farzad Kamalabadi. “TEST: A modular scientific Nanosatellite”. Space 2004 Conference, San Diego, California

satellite projects. While the design implemented in this report is based on the constraints of a picosatellite (<2 kg), a similar approach can be used for designing a platform for heavier and larger satellites if required in the future. The core of this design is based on the initial design by Leon Searl for the KUTESat-1 project [67].

The design process will be divided into the backplane design and the electrical interfaces; software and logical interface. The mechanical and thermal interfaces are beyond the scope of this report.

4-2.1 Software and logical interface

The software design should be such that a change in the payload, or equipment at a later stage, should not require major changes to the software design. This is achieved by breaking down the software into modules or layers so that a particular layer depends only on the adjacent layer and is not concerned with non adjacent layers. This idea is similar to the software design by Aero Astro [68].

A PIC is provided on each subsystem to perform low level tasks such as A/D measurements, control the I/O ports, record status of Input ports. A change in the subsystem will require a change of code on the PIC that is required to control and interface with the subsystem. The application software for each subsystem will however run on the CTDH processor and it will be unaware or unconcerned with the changes made to the subsystem since the interface between the application software and the PIC is standardized. Refer to Figure 4.1.

The communication between the CTDH and the PICs is controlled by a Serial library on the CTDH. The Serial library decides upon the type of communication bus to use, which can be I^2C, RS-232 etc. The Serial bus receives commands from the Data Handler which is a gateway and traffic controller for the commands from the subsystem software to their hardware and the measurement results from the subsystem hardware to the subsystem software. The Data handler is also responsible for collecting measurement and command data for telemetry archiving and download, Refer to Figure 4.2.

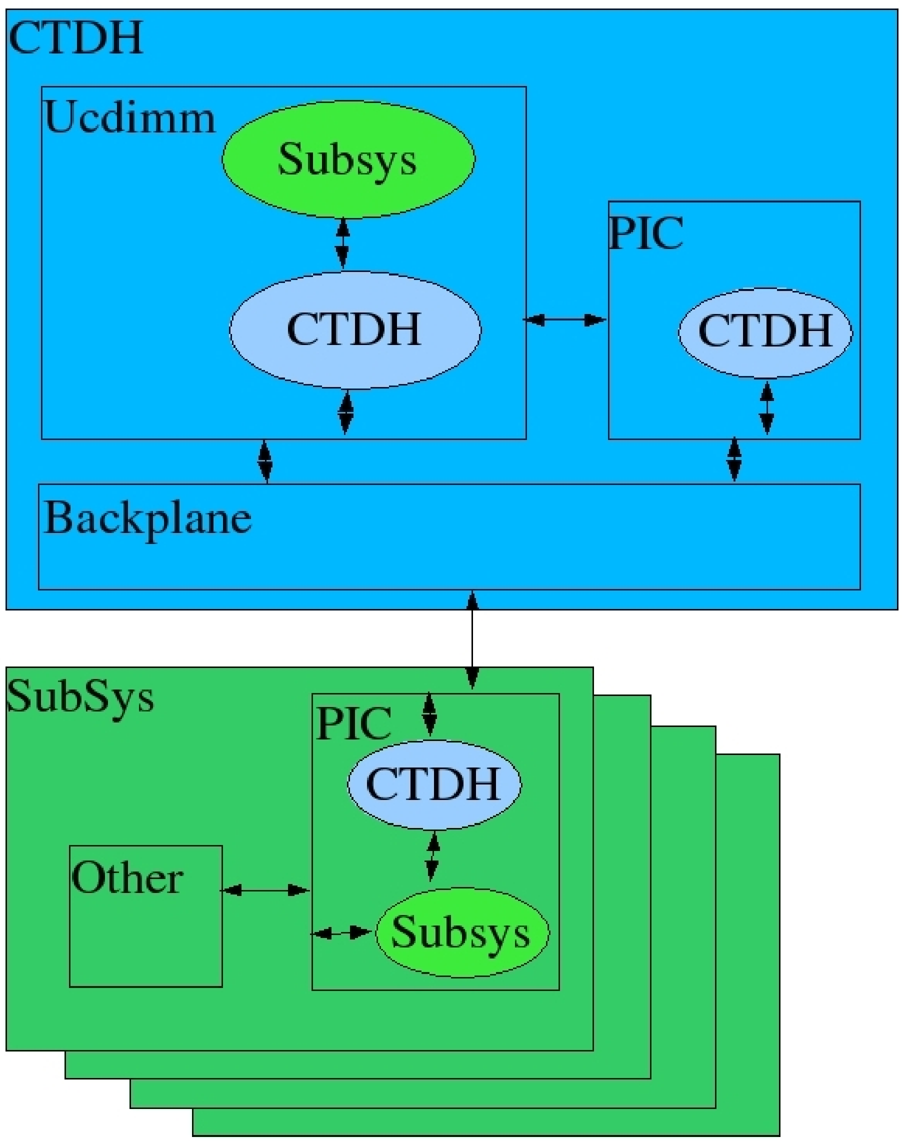


Figure 4.1 : Logical interface of Application software with PICs

The Data Handler also interfaces with the Power application to determine if the subsystem PICs are in “NORMAL” mode of operation since it will communicate with the PICs only in that mode.

The orbit library is required by the Power and ADCS applications for current and future orbital positions of the satellite. The File system is used to store the archived data; and the camera data, and can be downloaded at a later stage. The Telemetry Multi-cast is used to broadcast specific telemetry data to any one on the ground. The command execution is provided by the operating system shell.

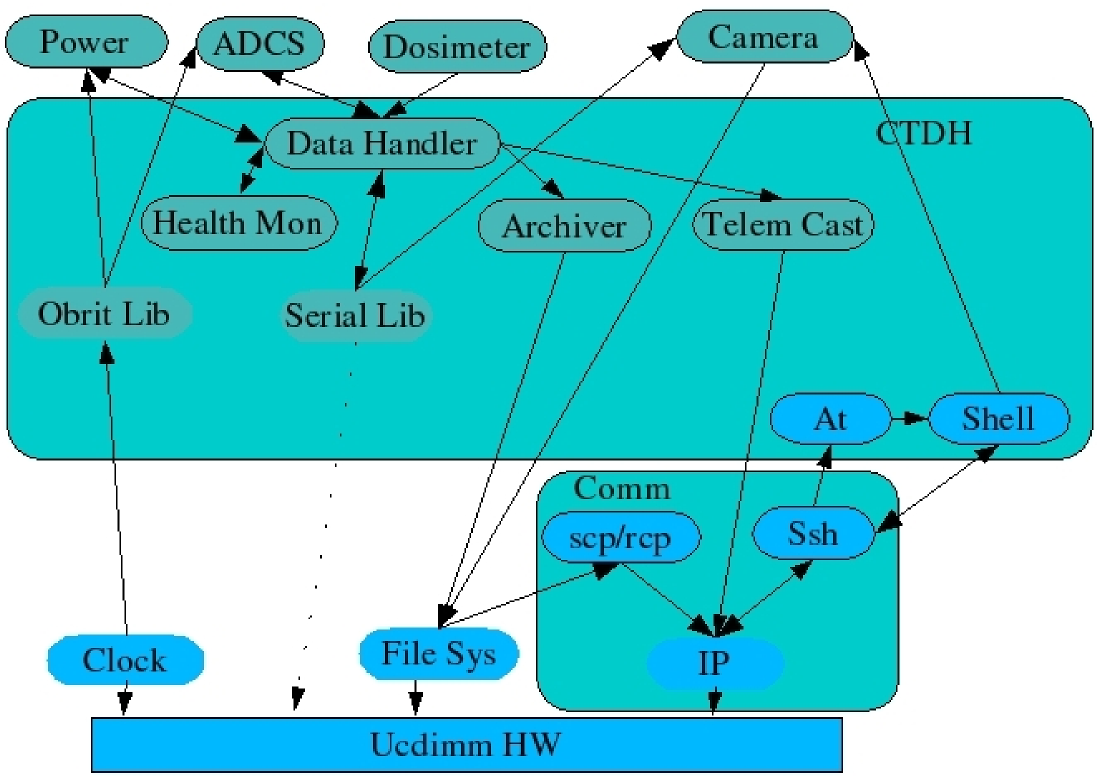


Figure 4.2: uCDimm top level software

The software structure described so far is based on the design of the software for the original KUTESat-1 design. This is not a mature design and changes and revisions have to be made in the future. A few recommended additions required to realize a modular system are:

- The communication between the applications should be arbitrated by the Data handler. Each application should be capable of providing certain resources .An application that requires a certain resource will send a request to the Data handler, which will broadcast this request to the other applications. Applications will respond to the request and let the Data handler know if they can support the request and with what limitations. An example of such a process would be the Camera application requesting that the spacecraft be oriented in a certain direction. The Data Handler broadcasts this request and the ADCS responds to this request. The ADCS will determine the feasibility of the request, the time required to process the request. A possible contention might occur when the Power application and the Camera application desire to orient the satellite in different directions at the same instant. The Data Handler needs to prioritize these requests.
- Re configurability of the PICs and the uCDimm through programming. This can be done when the application software checks the code on the PICs and determines that there are errors. New updated code can be ported onto the PICs and uCDimm after a launch if it is desired.

4-2.2 Backplane and Electrical Interface

There are many backplane standards that are available in the commercial market such as the VMEbus standard; and in the military such as the MIL-STD-1553B. These standards have been developed over the years based on the requirements of their respective markets. They are however not applicable to the small satellite systems especially to the picosatellites due to the small size and weight constraints. A new standard that offers flexibility and provides for future needs of picosatellites in the KU space program is required. This design could be adopted by the larger picosatellite community if it's proven to be reliable, modular design.

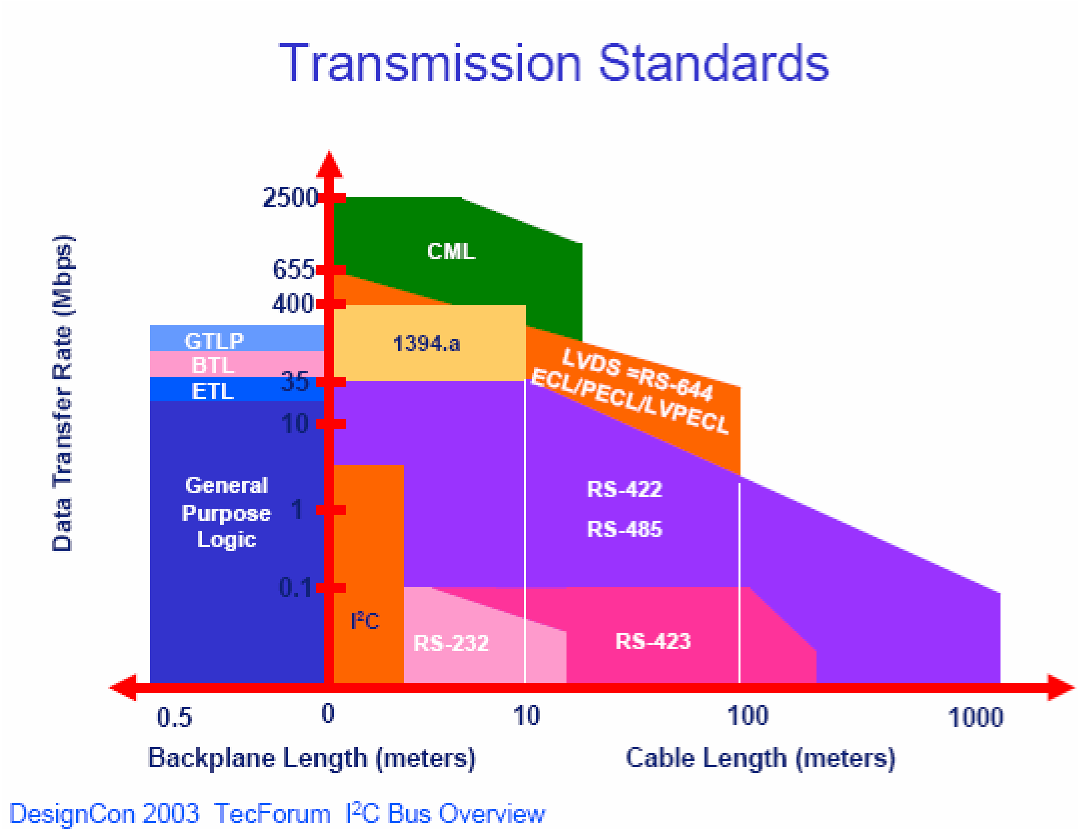
The design of the backplane can be divided into communications, power and control. The standards for each of these subsections will be designed based on their current implementation and a research at the future needs.

4-2.2.1 Communications bus

The communication bus standards are dictated by the choice of microcontrollers and microprocessors. An investigation of the commonly available microprocessors from Motorola, Atmel, and Microchip emphasize the SPI, I2C and UART/RS-232 standards. These communication buses can however be modified to provide other standard buses such as Ethernet, RS-485, IEEE 1394 etc with the addition of hardware which is not desirable since it leads to increase in the volume and power requirements. Figure 4.3 from [69], compares the different transmission standards available.

I²C bus

The Inter-integrated-Circuit or I_2C bus specification was originally developed by Philips Inc. for the transfer of data between ICs at the PCB level [70,71]. The physical interface for the bus consists of two open-collector lines; one for the clock (SCL) and one for data (SDA), Refer to Figure 4.4. The SDA and SCL lines are pulled high by resistors connected to the V_{DD} rail. The bus may have a one Master/many Slave configuration or may have multiple master devices. The master device is responsible for generating the clock source for the linked Slave devices.



<u>Figure 4.3: Comparison of Transmission standards</u>

The I_2C protocol supports either a 7-bit addressing mode, or a 10-bit addressing mode, permitting 128 or 1024 physical devices to be on the bus, respectively. In practice, the bus specification reserves certain addresses so slightly fewer usable addresses are available. For example, the 7-bit addressing mode allows 112 usable addresses. All data transfers on the bus are initiated by the master device and are done eight bits at a time, MSb first. There is no limit to the amount of data that can be sent in one transfer. After each 8-bit transfer, a 9th clock pulse is sent by the master. At this time, the transmitting device on the bus releases the SDA line and the receiving device on the bus acknowledges the data sent by the transmitting device. An ACK (SDA held low) is sent if the data was received successfully, or a NACK (SDA left high) is sent if it was not received successfully. A NACK is also used to terminate a data transfer after the last byte is received.

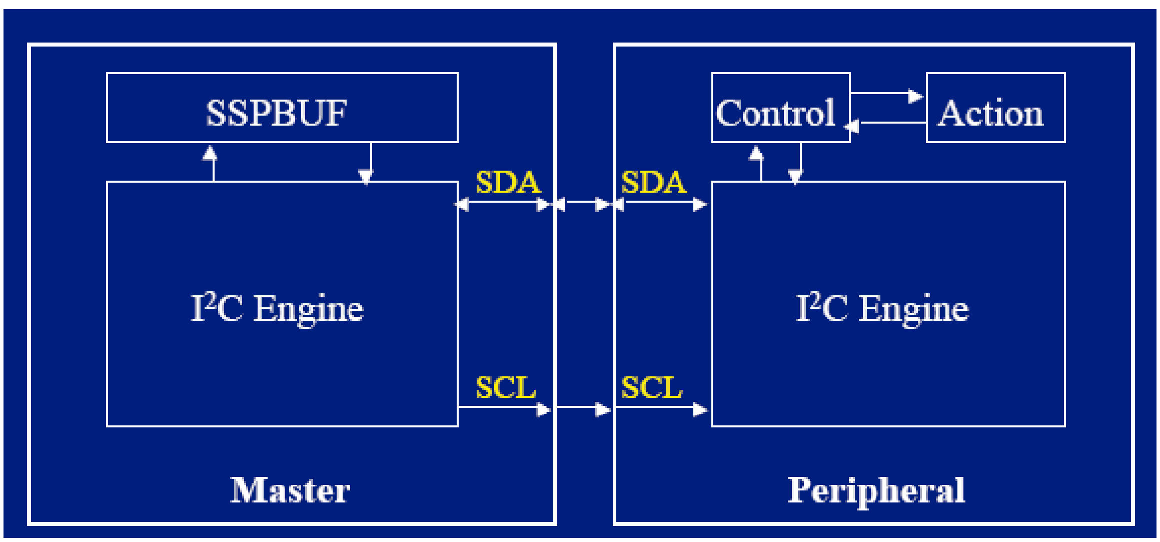


Figure 4.4: I2C Master and slave configuration

SPI

Serial Peripheral Interface (SPI) is a serial bus standard established by Motorola and supported in silicon products from various manufacturers [72,73]. It is a synchronous serial data link that operates in full duplex mode and reach speeds of 10 Mbps. The bus may have one master/one slave or one master/multiple slave's configuration.

SPI specifies four signals: clock (SCLK); master data output, slave data input (MOSI); master data input, slave data output (MISO); and slave select (SS). SCLK is generated by the master and input to all slaves. MOSI carries data from master to slave. MISO carries data from slave back to master. A slave device is selected when the master asserts its SS signal. If multiple slave devices exist, the master generates a separate slave select signal for each slave, Refer to Figure 4.5.

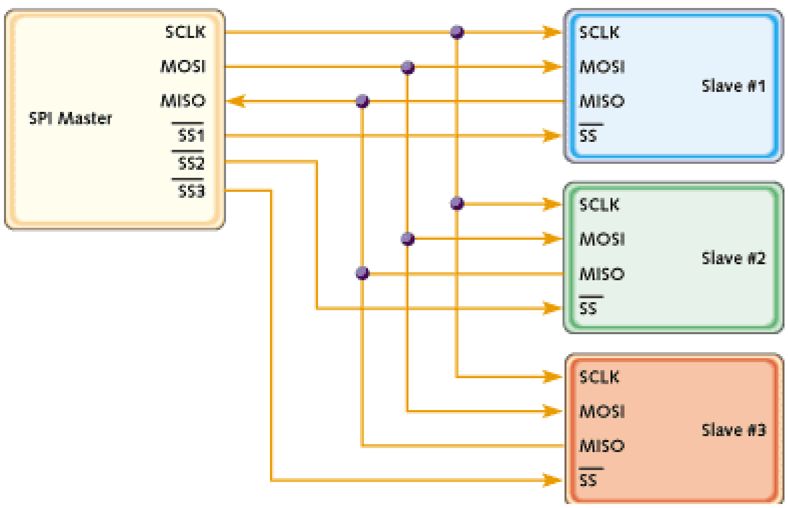


Figure 4.5: SPI single master, multiple slaves' configuration

RS-232

TIA/EIA-232-F (RS-232) is a common interface that can be found on almost every personal computer. RS-232 is a complete standard, not only including electrical characteristics, but physical and mechanical characteristics as well, such as connection hardware, pin-outs, and signal names. A point-to-point interface, RS-232 is capable of moderate distances at speeds up to 20 kbps. While not specifically called out in the specification, speeds of greater than 115.2 kbps [74] are possible over short distances with low capacitance connections. An RS-232 bus is an unbalanced bus capable of full-duplex communication between two receiver/transmitter pairs.

Comparison of communication standards

Table 4.1 gives a comparison of the three communication standards that have been described in the earlier subsections.

Name	**Sync/Async**	**Type**	**Duplex**	**Max Devices**	**Max speed(kbps)**	**Pin count**
I^2C	Sync	Multi-master	Half	2	(3)	2
SPI	Sync	Multi-master (1)	Duplex	(2)	>1,000(4)	3+N(6)
RS-232	Async	Peer	Duplex	(2)	19.2(5)	2

Table 4.1: Comparison of communication standards

1. The SPI standard does not support Multi-Master configuration. There are however fault detection implementations based on the Slave Select Line that can used.
2. The number of devices depends on the bus speed and the capacitance of the trace/cable.
3. The initial I^2C standard specified a low speed (100 kbps), later a medium speed (400 kbps) and then a high speed (3.4 Mbps) standard.
4. The SPI bus has been known to operate at 10 Mbps.
5. Though not specified by the standard, higher speeds of 115.2 kbps are achievable.
6. A slave select is required for each additional slave.

While I^2C is an ideal choice for applications which have multiple slaves, since it requires only two lines, it has issues with the addressing scheme. The SPI bus and the UART are simpler to implement as they have less overhead.

Final communication bus choice

The RS-232 standard is a simple plug and play protocol that can be used by the master to control the subsystems. It can also be used for testing from the PC since a HyperTerminal on the PC can act as the master. In order to communicate with multiple slaves, a MAX3323E RS-232 transceiver switch needs to be implemented on each subsystem boards. This chip converts the CMOS voltage levels of the UART on the microcontroller to RS-232 standard. It has a shutdown pin which is controlled by the master to enable communication with that particular slave, Refer to Figure 5.2 in the next chapter where it is implemented in the HABS-MK3 system.

The RS-232 standard cannot be used for high speed data transfer and a choice has to be made between SPI and I^2C. It is decided to implement both the buses in the design. The CTDH based on a Motorola chip (from legacy) can use the SPI to interface with the subsystems. The I^2C can be used by a second master microcontroller for controlling the flow of images and video data.

4-2.2.2 Power bus design

The microprocessors and other CMOS devices that are used in the design of low to medium speed systems run on 3.3 V and 5 V. The PCI standard bus [75] provides 3.3 V, 5 V, 12 V and -12 V lines. Many avionics and aerospace systems use 28 V to power their systems, and so it has become a common engineering practice.

Taking these factors into considerations, the power bus should be distributed as dictated by table 4.2.

Type	Subsystems to include	Voltage levels	Current rating
Primary	C&DH, main communications system	3.3 V,5 V,12 V	Low(<1 amperes)
Secondary	Attitude control and determination, Imagers, secondary communications system	3.3 V,5 V,12 V ,28 V	Medium(1-2.5 amperes)
Payload	Payloads	3.3 V,5 V,12 V ,28 V	High(>2.5 amperes)

Table 4.2: Power distribution on the backplane

The Electrical and Power system should consist of two core battery sections: the main battery module will be used for powering the Primary and Secondary systems; the Payload battery module will be used for powering the payloads. Depending on the payloads being flown the mission, the battery module can be replaced if necessary. The objective of including two battery modules is due the fact that payloads typically have high current requirements, and it is advisable to isolate the core satellite system from any failures caused by a customer's payload.

It is also required to have separate analog and digital grounds in all subsystems. This helps isolate the noise created by the high speed digital circuits from the sensitive analog measurements. The analog and digital grounds will be connected only at a single point on the Power subsystem.

4-2.2.3 Control bus design

Interrupt lines

Each of the subsystems should be able to interrupt the CTDH processor in case of an emergency, or as acknowledgement, or when it requires to communicate with the CTDH.

Reset Lines

The reset lines from the CTDH to the subsystem microcontrollers can be used to reset the program running on the subsystem microcontrollers or they could be used in the reprogramming of these microcontrollers.

Programming lines

The initial design in the KUTESat-1 system provides for programming of PICs on the subsystems. A programming Data (PGMD) and a programming clock line (PGMC) are required to program the PICs. Each PIC needs to be enabled by a separate PGMENx line.

In order to account for future substitution of the PICs with other controllers, possibly an FPGA or a CPLD device, provision needs to be made for in circuit programming of these devices. JTAG is a boundary –scan technology that is used to test the FPGA/CPLD devices and can also be used to program them. Four lines: Test Data In (TDI), Test Clock (TCK), Test Mode select (TMS) and Test Data out (TDO) are required to test, program these systems. In order to program multiple devices, each devices programming lines should be connected to a switch, which is enabled by the CTDH system.

The CTDH system can program both PIC devices and FPGA devices since both have separate enable lines and they can share the programming lines. A switch on the CTDH system can choose between JTAG programming and PIC programming.

4-2.3 Final Backplane interface design

The table 4.3 summarizes the discussion of the backplane design by listing the number of lines required for interfacing a CTDH system with five subsystems. It is assumed that a pin on the connector can carry about 0.5Amperes.The power requirements of the Primary, Secondary and Payload subsystems are assumed to be 1 A, 2.5 A and 5 A respectively. Additional power lines are included for redundancy and for future expansion. An additional subsystem requires 5 additional control lines to be added.

Signal group	**Type**	**Number of lines**	**Signal group**	**Type**	**Number of lines**
Communications	RS-232 Tx	1	**Power**	Secondary 28 V	2
	RS-232 Rx	1		Payload 3.3 V	2
	RS-232 enable	5		Payload 5 V	2
	I2c Data	1		Payload 12 V	3
	I2c Clock	1		Payload 28 V	10
	SPI Data out	1		Analog ground	20
	SPI Data In	1	**Control**	Interrupt	5
	SPI clock	1		Reset	5
	SPI enable	5		Programming Data/TDI	1
Power	Primary 3.3 V	2		Programming Clock/TCK	1
	Primary 5 V	2		TMS	1
	Primary 12 V	2		TDO	1
	Secondary 3.3 V	2		Programming enable	5
	Secondary 5 V	3		Digital ground	5
	Secondary 12 V	3	**Total**		**94**

Table 4.3: Final backplane design of modular platform

Chapter 5 - Implementation of the Modular platform – HABS-MK3, KUBESat-2

The modular platform bus designed in chapter 4 is used in the construction of HABS-MK3; and the KUBESat-2 system which is designed for interfacing the S-band transceiver system.

5-1 Necessity of HABS-MK3

The HABS-MK2 has had 7 successful flights, three of which were to test the S-band transmitter from Kansas City Plant (KCP) in the KUBESat-1 module. The KUBESat-2 system however consists of a transceiver which is heavier that the transmitter section and in order to stay within the weight limit dictated by the FAA 101 regulations, a lighter version of HABS module was required to be designed. It was also required to make the HABS module more robust and reduce the time spent for initial testing, pre flight assembly and the maintenance of the system. Figure 5.1 shows a picture of the old HABS-MK2 system where the subsystem boards are mounted on four standoffs. Each subsystem board is connected to the other boards through wires. It was determined that the standoffs needed to be replaced in order to reduce weight ; and the wires had to be replaced or reduced since in the past there have been instances of broken wires and connections. The amount of time required for pre flight assembly and testing in the HABS-MK2 system was close to 2 whole days and it was necessary to reduce this time.

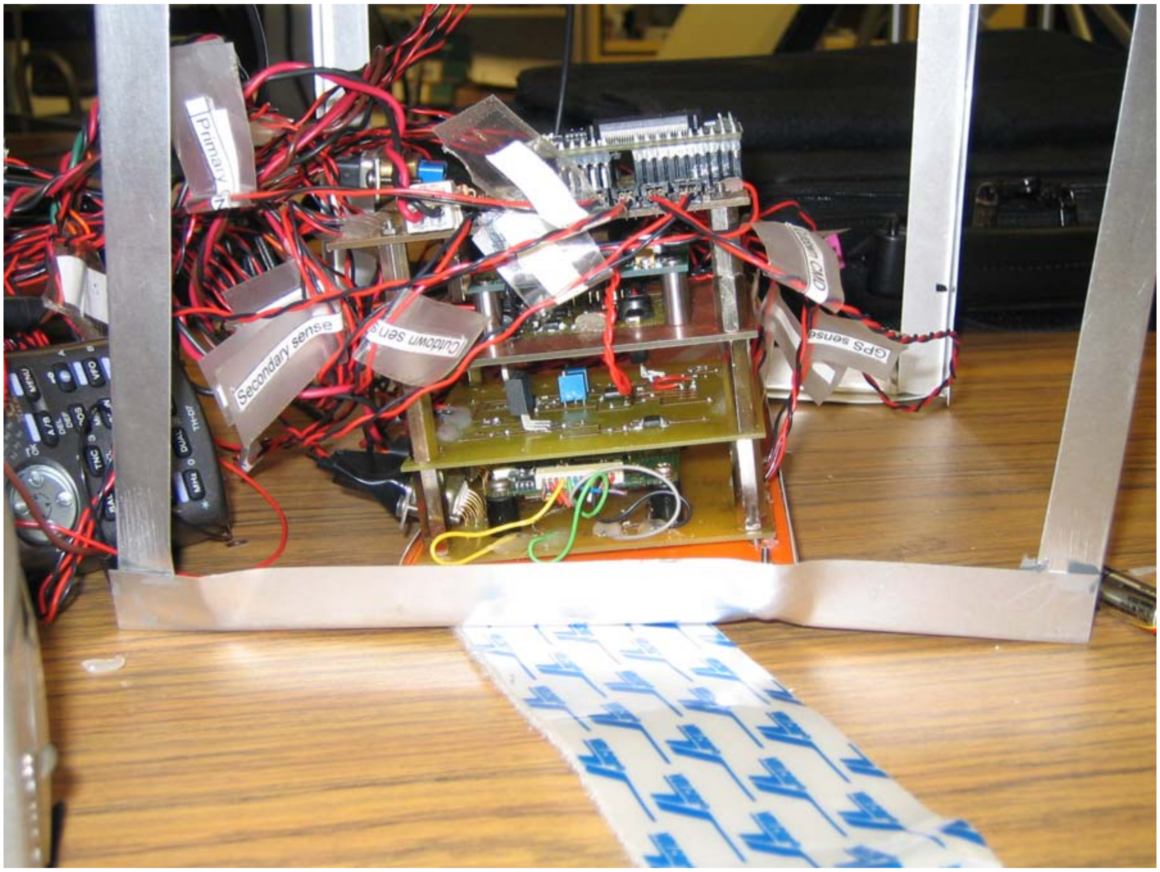


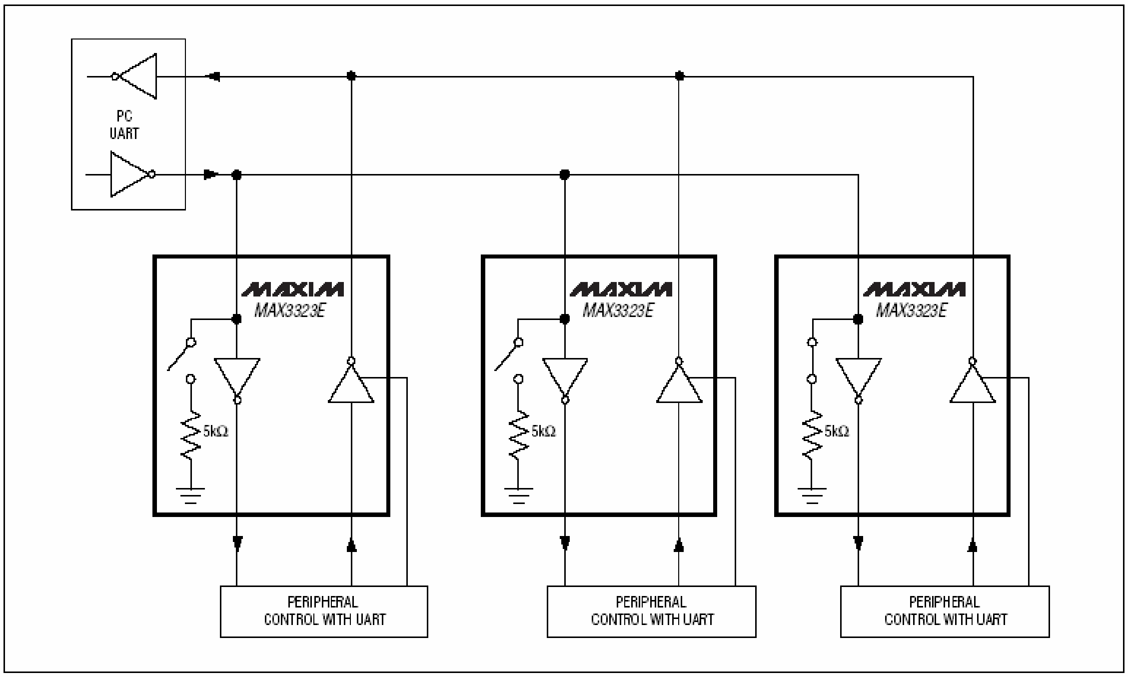
Figure 5.1: HABS-MK2 mounting of subsystem boards

5-1.1 Implementation of standard bus- with modifications*

Functionally the HABS-MK3 module is similar to the HABS-MK2 module, and in addition has a communication interface to the KUBESat-2 system. This is required to relay commands received from the ground station to the S-band transceiver, and is required for synchronization; more details are included in the KUBESat-2 subchapter. The HABS-MK3 system includes a single microprocessor (Freedom 16, similar to the HABS-MK2 system) in the Control, Telemetry and Data Handling subsystem, and all

* The author's role in the HABS-MK3 project was that of technical mentoring and management of the new team. All changes and redesigns made from HABS-MK2 to HABS-MK3 had to be pre approved by the author.

A/D measurements and control are performed by this processor. The RS-232 bus on the processor is shared between communication with the HAM radio; and communication with the microprocessor on the KUBESat-2 system. Max3323E RS-232 transceivers are used to switch the communication between the two buses, Refer to Figure 5.2.



<u>Figure 5.2: Multidrop application of the UART port</u>

The subsystem boards have a common interface as defined by the backplane signal and power lines, Refer Figure 5.3. The headers on each subsystem board are connected to the receptacles on the backplane and are hot glued for flight configuration to maintain mechanical stability. The connectors for the RS-232 communication on the CTDH board are included on board and so the backplane does not contain these signals. At present 21 Signal and Power lines of a possible 32 (determined by header size) are used, Refer to Table 5.1.

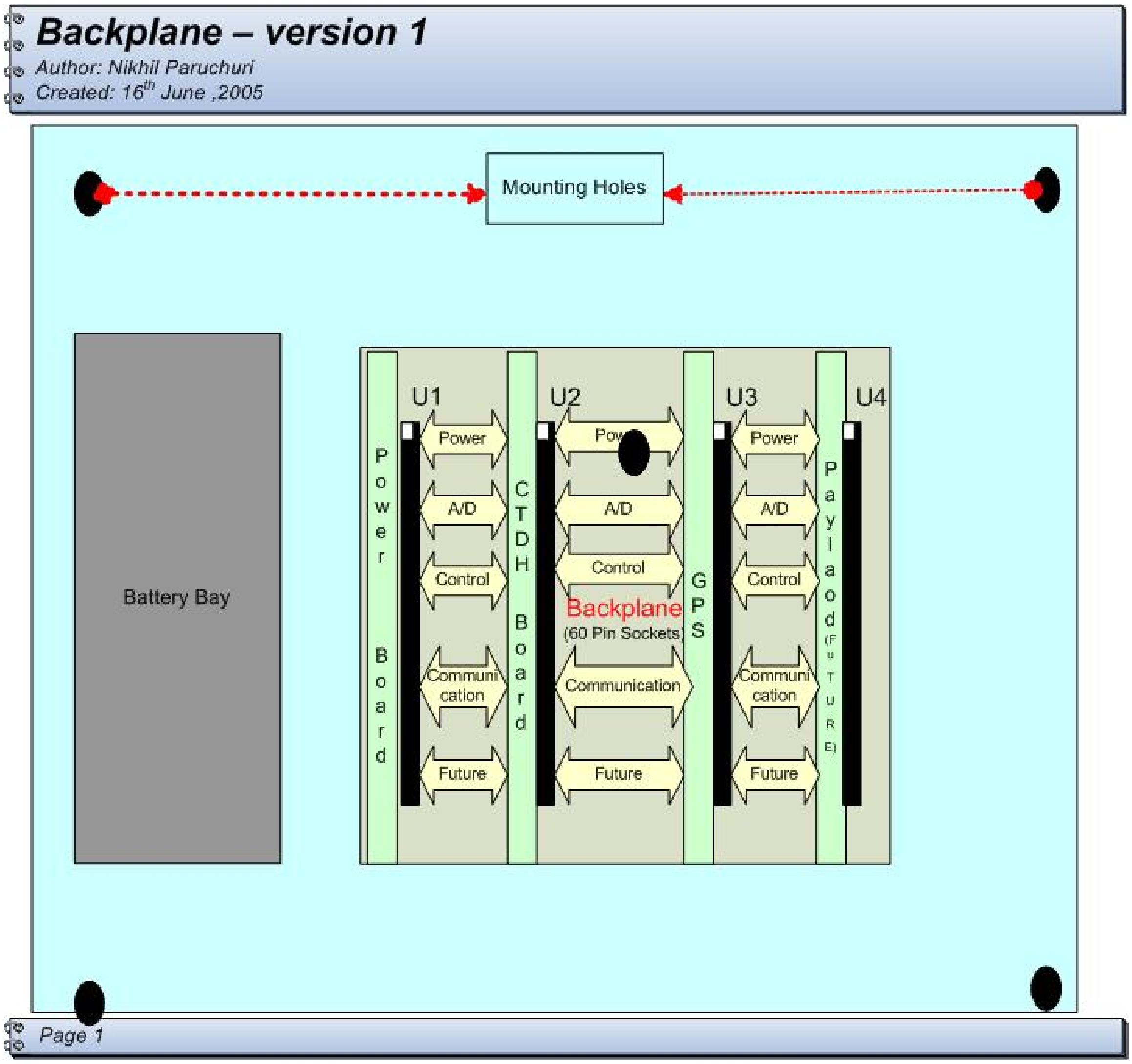


Figure 5.3: Backplane design for HABS-MK3

Sl No	Description	From	To	Pin No
1	Digital Ground	Power	All	1
2	Analog Ground	Power	All	2
3	5V bus	Power	All	3
4	CTDH Power	Power	CTDH	4
5	CTDH Gnd	Power	CTDH	5
6	Bat sense 1	Power	CTDH	6
7	Bat sense 2	Power	CTDH	7
8	Bat choose 1	Power	CTDH	8
9	Bat choose 2	Power	CTDH	9
10	Kubesat Pwr choose	Power	CTDH	10
11	Kubesat Pwr	Power	CTDH	11
12	Kubesat Gnd	Power	CTDH	12
13	GPS Power	Power	GPS	13

14	GPS Gnd	Power	GPS	14
15	Camera Control	Camera	CTDH	15
16	Camera Gnd	Camera	CTDH	16
17	Cutdown Control	Camera	CTDH	17
18	Cutdown Gnd	Cut-down	CTDH	18
19	Cutdown battery sense	Cut-down	CTDH	19
20	Ham bat sense	Power	CTDH	20
21	APRS Bat sense	Power	CTDH	21

Table 5.1: HABS-MK3 backplane signal and power lines

5-1.2 Results

The redesign in the structure and the avionics of the HABS module has resulted in a decrease in the overall weight by 1 pound .The number of wires have been decreased and now, only include wires from the batteries to flight switch; the CTDH to the HAM radio; and the GPS to the HAM and APRS radios. These are essential wires that cannot be eliminated. Each subsystem was tested independently and the overall integration time took a few hours instead of a week as had been the case in HABS-MK3. The HABS-MK2 system has been flown on three missions and will be used in the future for the KUBESat-2 missions.

5-2 Design of KUBESat-2

The KUBESat-2 system is designed to test the S-band transceiver system from KCP. It consists of three modules; a transmitter similar to the one used on the KUBESat-1 system; a receiver; and a diplexer to isolate the transmitter and receiver signals from the antenna. The power converter on the transmitter subsection will be used to power the receiver too; the diplexer is a passive device.

The Top level diagram of the KUBESat-2 system is shown in Figure 5.4.The CTDH subsystem is developed around a uCDimm processor; similar to the KUTESat-1 original design; and is used to communicate with the Freedom 16 microcontroller on the HABS-MK3 system .The CTDH also interfaces with the S-band transmitter and receiver subsystems through the Tx and Rx interface boards . Each of these subsystems is controlled by an individual board which is developed around a PIC 18LF4320 micro processor. The PICs can communicate with the uCDimm processor either over Serial Peripheral Interface (SPI) or the RS-232 bus.

The power to the KUBESat-2 system is provided by two power sources. The S-band transmitter and receiver require 5 V and 28 V lines which are provided by the S-band power converter after converting a 28 V line from an external battery. The CTDH, Rx interface board and Tx interface board require 3.3 V and 5 V lines which are provided by the Bus power board. The HABS system feed a 5v line to the main Bus power board.

The S-band system can be operated based on preprogrammed commands like the KUBESat-1 system, where the PICs configure the S-band system into different test profiles after power up. This mode of operation is however very rigid since no changes to the S-band characteristics can be made in real time and this causes problems with synchronization between the ground station and the KUBESat-2 system. To avoid these problems, it is required that the ground station be able to communicate with the KUBESat-2 system.

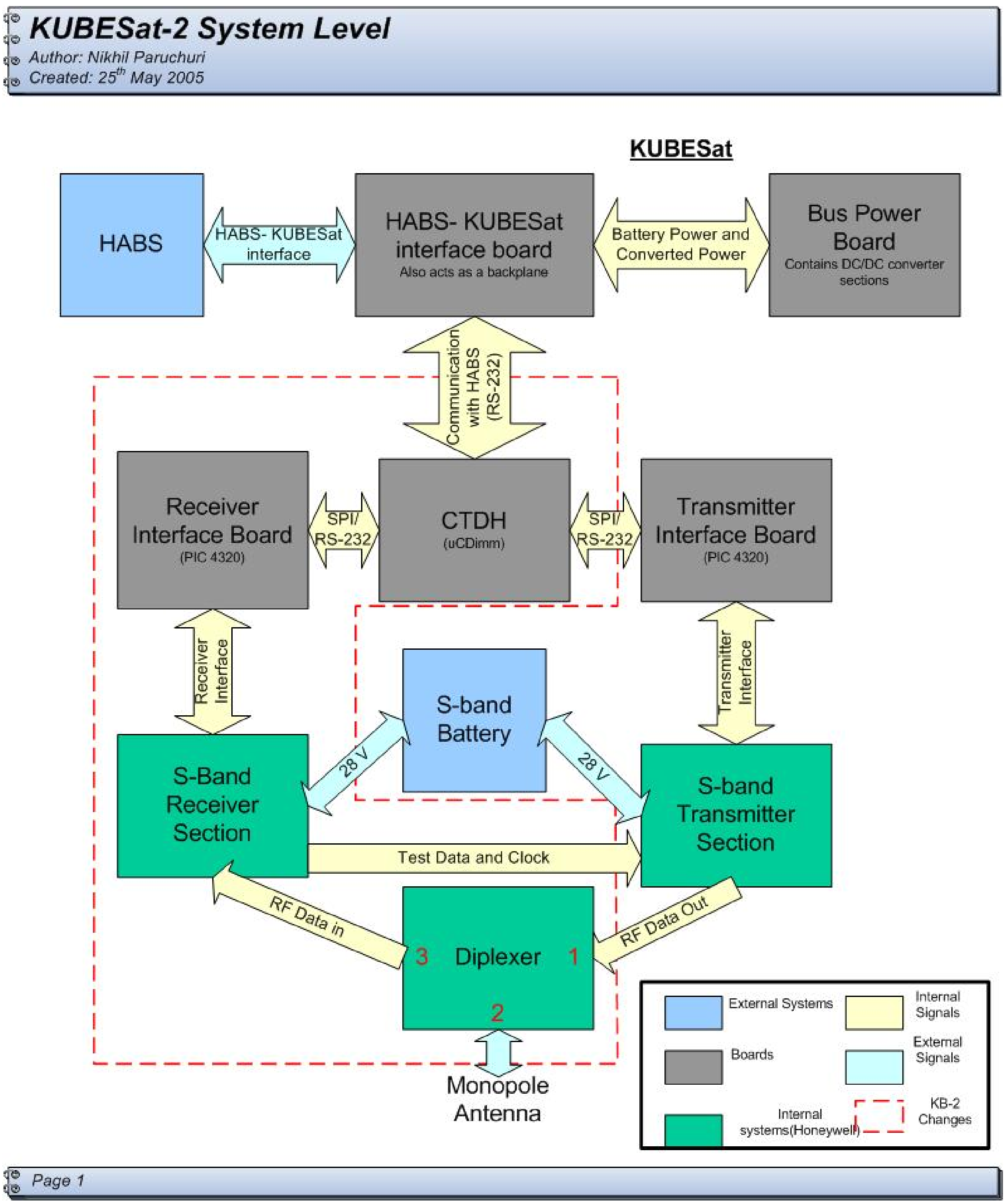


Figure 5.4: KUBESat-2 system level diagram

The HABS system routes all KUBESat-2 communication received from the Ground station over the HAM radio link, to the uCDimm processor in KUBESat-2 over an RS-232 bus.

The commands from the ground station to KUBESat-2 have the format <Test Range>, <Test Cases>, <Duration>. Two possible scenarios are possible during the flight

- The Ground station can configure the S-band transceiver to perform a group of test cases which are classified as Test Ranges. When commanded to go into a particular test range, the S-band transceiver is configured into different test cases for certain duration. The number of test cases and the type of test cases in each test Ranger are pre programmed. The command for this situation is < Test Range Number>,<x>,<Duration of each test case (in seconds).
- If it is required to test only a few test cases , or in case of errors to retest a particular test case, then the command is <x>,<test case numbers>,<duration>. The S-band transceiver is configured to test all the test cases included in the <Test case numbers> parameter.

The Ground station initiates the S-band testing after it receives an acknowledgment for the command sent to the KUBESat-2 system. The ground station sends a string of 32 bit test word’s which are received by the KUBESat-2 S-band receiver. The receiver demodulates the data and routes this data to the transmitter. The data is then modulated by the transmitter and is transmitted over the S-band link. The ground station demodulates this received data and calculates the bit error rate by comparing the transmitted string with the received string.

5-2.1 Backplane Design

The design of the backplane Signal and Power lines for the KUBESat-2 system is derived from the general bus configuration proposed in the previous chapter, Refer Table 5.2.

Pin no	Signal name	Description	Pin no	Signal name	Description
1	Battery	External battery connection. For testing only	2	GND	ground
3	PGMD	PIC programming -Data Line	4	UART-En3	Enable RS-232 PIC-3
5	+5V -Secondary	5V to Secondary systems	6	NC	Not connected
7	PGMC	PIC programming -Clock Line	8	NC	Not connected
9	5V_ON_Pull_Up	Used to pull up external devices while system is switched off	10	GND	ground
11	PGMEN 2	Program Enable PIC(Rx)-2	12	NC	Not connected
13	NC	Not Connected	14	2TX	Tx from uCDimm to HABS RX
15	PGMEN3	Program enable PIC-3	16	2RX	Rx from uCDimm to HABS TX
17	5V-Primary	5V to Primary systems	18	GND	ground
19	RST1	reset PIC (Tx)-1	20	SPIOD	serial output to PIC from uC Dimm
21	+3.3V-Primary	3.3V to Primary systems	22	SPIID	Serial input to uC Dimm from PIC
23	RST3	Reset PIC-3	24	SPICLK	SPI clock
25	+3.3V – Secondary	3.3V to Secondary systems	26	RST2	Reset PIC(Rx)-2
27	SPIEN1	SPI enable PIC(Tx)-1	28	SPIEN2	SPI enable PIC(Rx)-2
29	NC	Not Connected	30	UART-En1	Enable RS-232 PIC(Tx)-1
31	SPIEN3	SPI enable PIC-3	32	INT 2	Interrupt uCDimm from PIC(Rx)-2
33	+3.3V-Primary	3.3V to Primary systems	34	GND	ground
35	INT 1	Interrupt uCDimm from PIC(Tx)-1	36	S-band_battery_ voltage_HABS	A/D measurement of S-band battery voltage, by HABS
37	NC	Not Connected	38	NC	Not connected
39	INT 3	Interrupt uCDimm from PIC -3	40	External_ Temperature_HABS	A/D measurement of External Temperature , by HABS
41	NC	Not Connected	42	GND	ground
43	External control	External control from HABS(future use)	44	PGMEN1	Program enable PIC(Tx)-1
45	UART-Tx	Tx from uCDimm to PIC	46	UART-En2	Enable RS-232 PIC(Rx)-3
47	UART-Rx	Rx from uCDimm to PIC	48	NC	Not connected
49	+3.3V – Secondary	3.3V to Secondary systems	50	GND	ground

NC	POWER	Programming	SPI	RS-232	GND	Others

Table 5.2 : KUBESat-2 backplane signal and power lines

The I2C bus, 28 V and 12 V power lines are not included, and provision is made for communicating with only three PICs. The Power bus consists of 5 V and 3.3 V for the Primary subsystem – the CTDH; and Secondary subsystems- the Transmitter and Receiver interface boards. The power to the KUBESat-2 Main bus is provided by the HABS system and during a flight it is controlled by commands from the ground station. The S-band power is controlled by controlling a pin on the S-band power converter: ON- 0 V and OFF- 5 V. A 5V_ON_Pull_Up line is provided by the HABS system to pull up the S-band Power converter pin and switch it OFF until the main KUBESat-2 bus is powered ON and takes control of the power to the S-band system.

Figure 5.5, shows the design of the backplane. There are five sockets provided, of which four are used in the current design and one is designated for future systems. The 2TX and 2RX lines are RS-232 communication lines between the HABS microcontroller and the uCDimm on KUBESat-2.

The UART-Tx and UART-Rx lines are RS-232 communication lines between the uCDimm and the PICs. The uCDimm can enable the PIC it wishes to communicate with by controlling the UART-Enx line, where x is the PIC number. For high speed communication (1 Mbps), the uCDimm communicates with the PICs over the SPI lines, and it chooses the PIC using the SPIENx line. The PICs use the INTx lines to interrupt the uCDimm and these can be used for acknowledgements during communication or for initiating communication.

The S-band-battery-voltage-HABS and the External-Temperature-HABS lines are connected to the A/D port on the HABS microcontroller to sense the S-band battery voltage and the KUBESat-2 temperature respectively. These telemetry data points are indicators of the health of the S-band transceiver system.

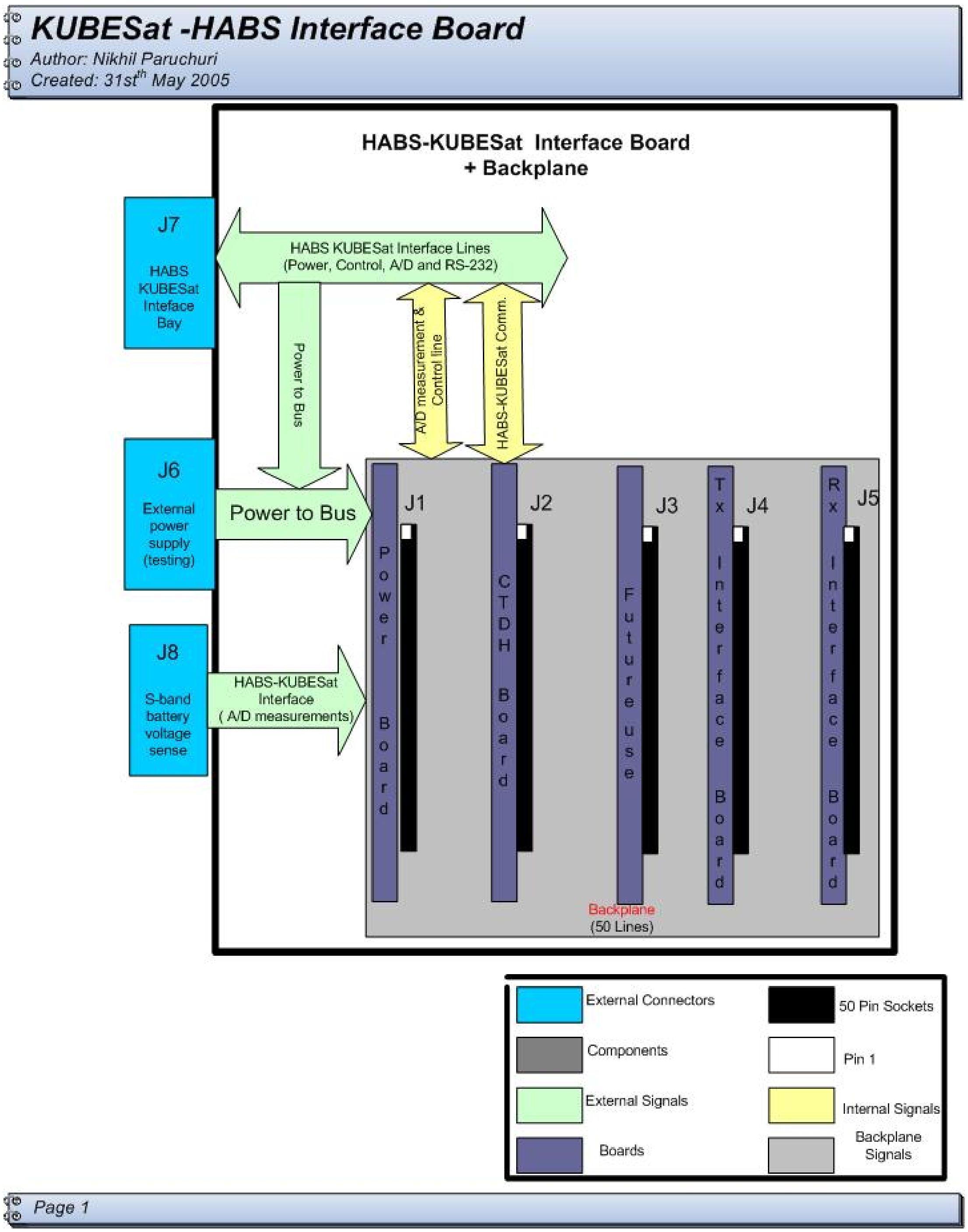


Figure 5.5 : KUBESat-2 backplane design

5-2.2 Tx-interface design

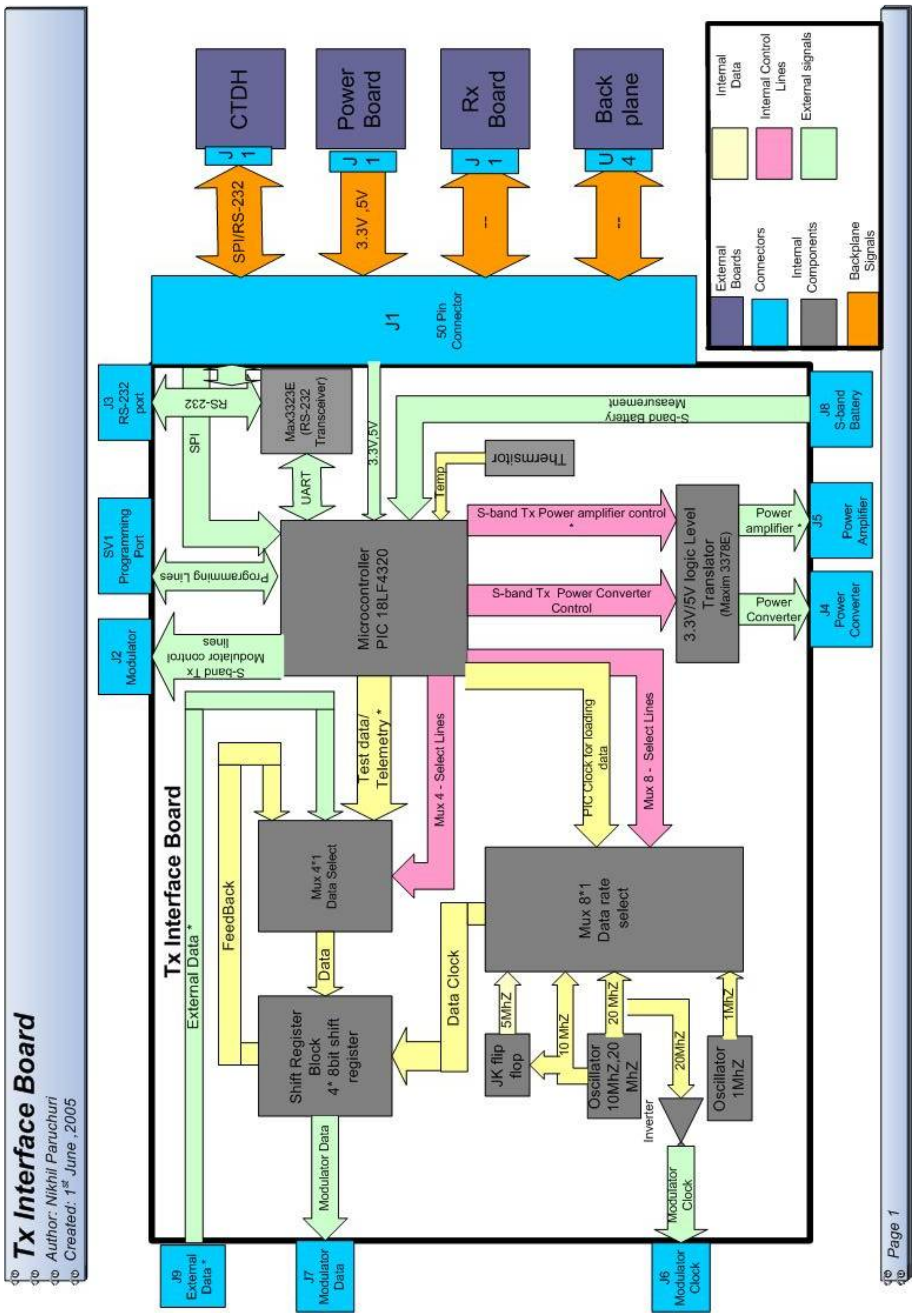


Figure 5.6: KUBESat-2 Tx-Interface board design

The Tx- interface board design is similar to the design used in KUBESat-1 system, Figure 5.6. The few changes made include

- Inclusion of an RS-232 transceiver – MAX 3323E to enable RS-232 communication between the uCDimm and the PIC.
- A few test points and a programming port are included in the design to help in trouble shooting during the initial testing phase.

In the KUBESat-2 system the Tx-interface board is used to only configure the S-band transmitter since the data and clock are provided by the S-band receiver. The Tx interface board however incorporates the functionality of providing the data and clock so that it may be used when testing the S-band transmitter separately.

5-2.3 Rx- interface design

During the initial design process of the KUBESat-2 system, the customer KCP required that the S-band data received from the ground station, be buffered and then routed to the Transmitter. After further analysis, it was decided to abandon this requirement due to the technical difficulties and arising time constraints of configuring a storage device which could be used for data received at 1-20 Mbps for duration of 60 seconds.

The current design of the Rx- interface board, Refer Figure 5.7, is used for controlling the characteristics of the S-band Receiver based on the commands received from the uCDimm processor. It is built around a PIC18LF4320 processor from Microchip. This board too includes an RS-232 transceiver- Max3323E for RS-232 communication with the uCDimm.

The PICs used in KUBESat-1 and KUTESat-1 systems were programmed using a kit developed by DIY Electronics Ltd [59] . This programmer however was unreliable and did not provide in circuit debugging. For the KUBESat-2 system it was decided to use a new programmer available from the PIC manufacturer [60] . This programmer requires an external oscillator to provide the clock to the PIC in order to perform in circuit debugging.

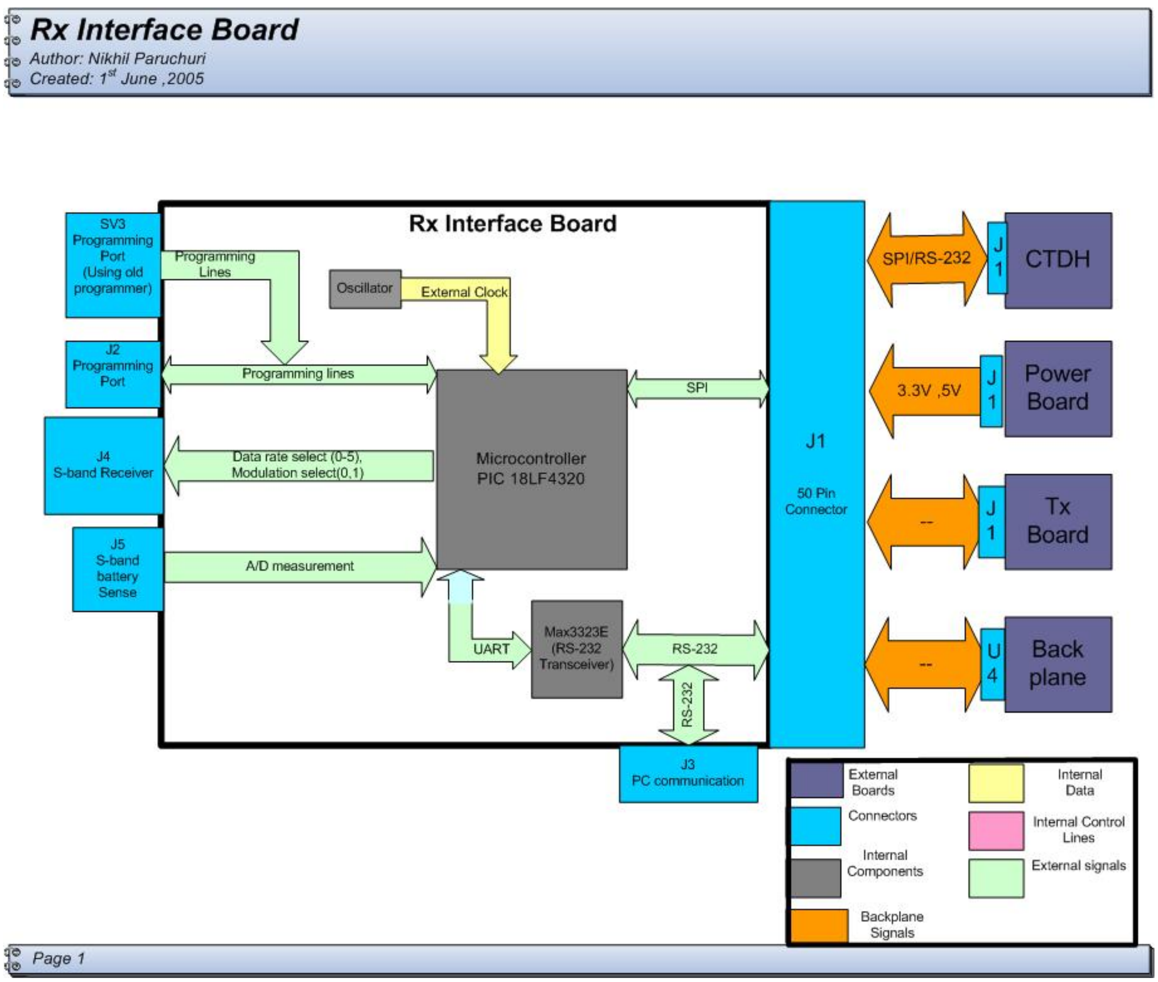


Figure 5.7 : KUBESat-2 Rx interface board design

5-2.4 CTDH design

The tasks of the CTDH system are

- Control the functions of the subsystem microcontrollers
- Collect A/D data from the subsystems
- Communicate with ground station through HABS system.

While the above tasks can be performed by any microprocessor, it was decided to use the uCDimm processor since it is a part of the core picosatellite project. This allows for testing of a few functionalities of the uCDimm processor at the extreme conditions during a flight. At the time of writing of this document, the software for this system is not mature and hence the software functional description is not included.

The board has two RS-232 ports for communicating with the HABS microcontroller and the PICs, Refer Figure 5.8. It has an SPI test port that can be used to test SPI communication with external PICs. The CTDH provides two serial communication buses to communicate with the PICs. The RS-232 bus is to be used for controlling the PICs and can be used for low rate data transfer such as the A/D measurements of the S-band battery voltage and the external temperature. The SPI bus is reserved for future use where higher rates of 1 Mbps will be required, such as for transferring the S-band data.

Three external ports have been included in this design to control a few characteristics of the S-band transceiver. These include control of the power converter (1 line), Modulator (3 lines) and Demodulator (7 lines). These lines have been included for redundant control of the S-band transceiver when communication with the PICs fails or can be used for control of other subsystems that will be included in the future designs.

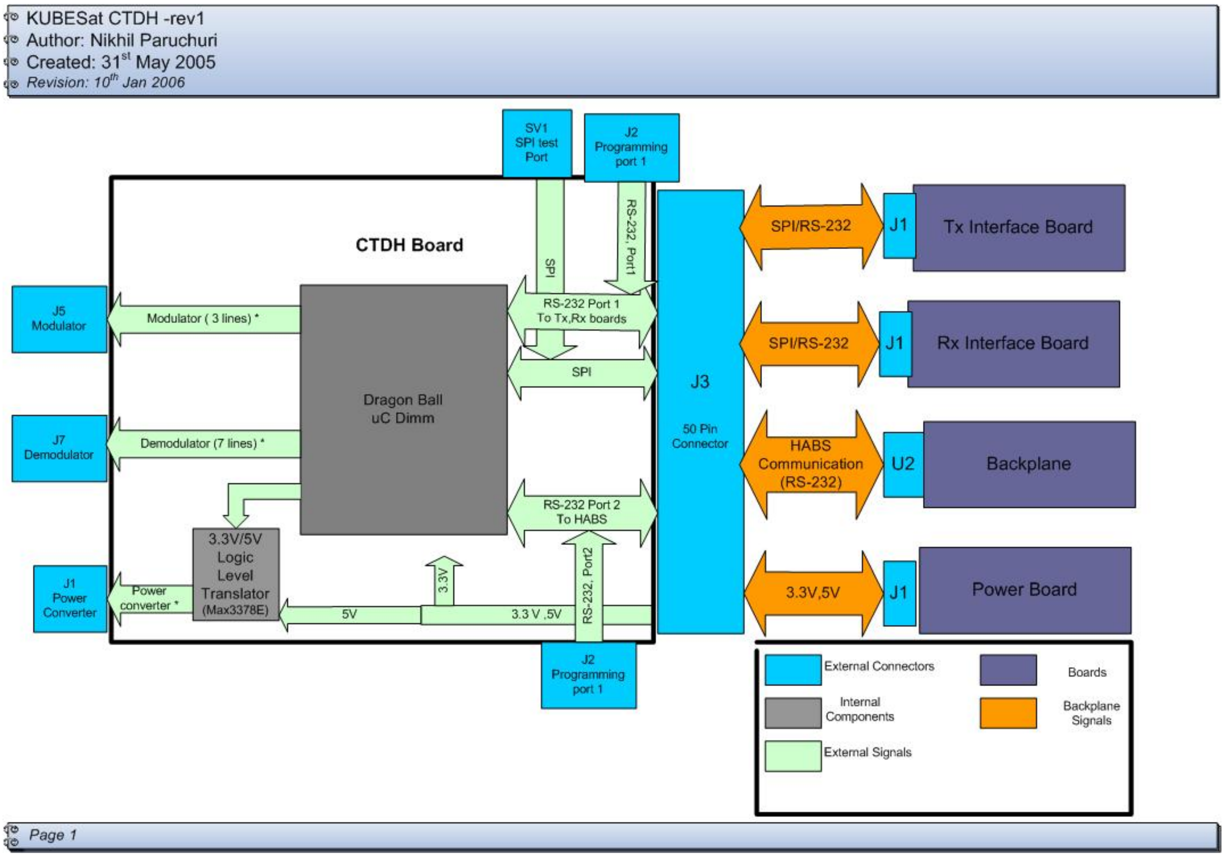


Figure 5.8: KUBESat-2 Control Telemetry and Data Handling Design

5-2.5 Other subsystems and Results

The Power board design is similar to the design used in the KUBESat-1 system and includes only a 5 V to 3.3 V converter since the 5 V is provided by the HABS system. The antenna, diplexer, S-band transmitter and receiver, and the S-band external battery will be provided by KCP.

The Rx and Tx interface boards have been tested to verify that the PICs can be programmed while in circuit. The new programmer was tested on the Rx interface board and has been useful in debugging. The software for the CTDH system is not yet mature and in the future will test communication between the uCDimm and HABS; and communication between uCDimm and the PICs. The complete system tests including the S-band system will be performed at a later stage after KCP delivers the S-band system.

Chapter 6 - Future work

6-1 Commercial HABS – HABS-MK4

The main objective of the HABS missions has been to test payloads at near space conditions. The KUBESat-1 and KUBESat-2 payloads from Kansas City Plant (KCP); and student payloads on the HABS-8, HABS-13 flights have been the initial proof of concept payloads. In order to extend the HABS program to other potential payload customers, it was decided by the KU Project Investigator and the Primary buyer KCP to develop a HABS system which would have certain improvements over the existing HABS-MK3 system. These were:

- Ability to hover at, within a given altitude band for a specified period of time. The depends on the maximum capabilities of the HABS power and thermal systems.
- Ability to provide a controlled landing to a designated or safe area.
- Provide a standard power, data and command interface to user payloads (internal to HABS or externally attached modules), to minimize the time and effort to integrate a payload into the HABS and increase the ease of testing and overall system reliability.
- To integrate KCP's S-band transmitter into the data downlink subsystem, thus providing greater bandwidth and flexibility for customer needs than can be provided through the basic HABS telemetry and communication subsystem.
- Other improvements in the HABS command and control vehicle, such as multi channel real-time video output; multiple digital cameras capable of shooting images at various angles, such as above, below, and to the side; and more

compact and accessible avionics and batteries. Also the ability to carry greater weight to higher altitude is of interest.

- Investigate the possibility of producing the HABS as a whole or in parts that could be sold to various customers that want to control their own high altitude balloon system.

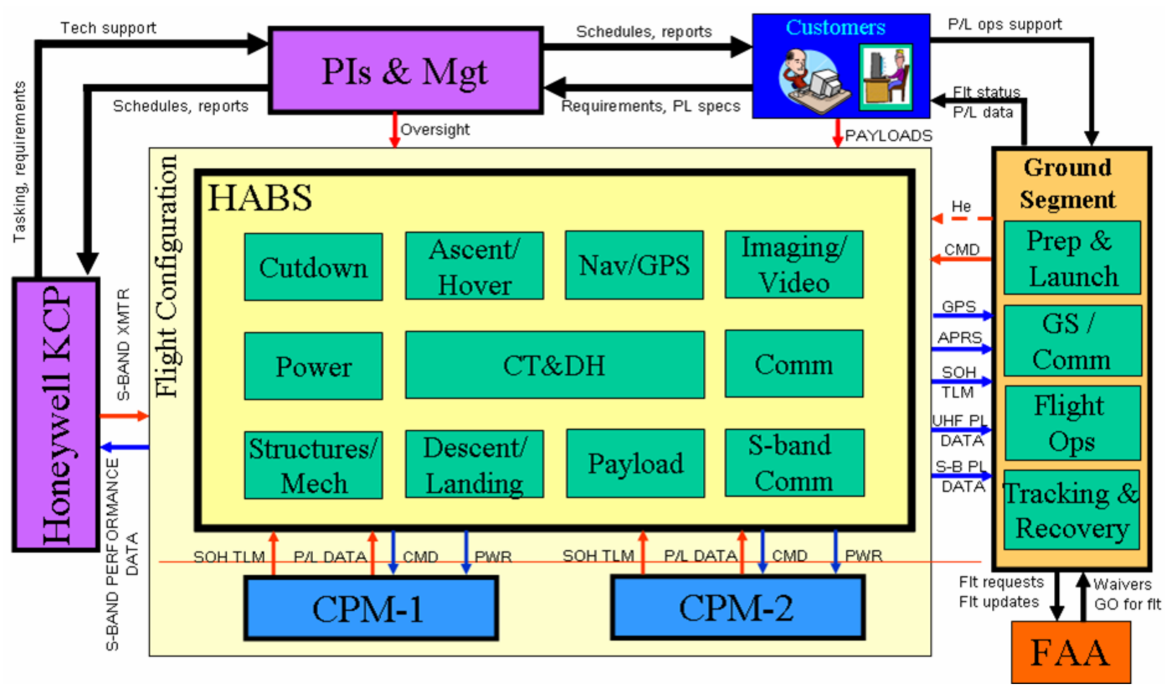


Figure 6.1: HABS MK4 operational Functional Architecture

The purpose of this proposed research effort is to develop the HABS system, called the HABS Mark 4, to accomplish these above areas, Refer to Figure 6.1. The eventual goal is to develop such a system and license it to a commercial company for making a profitable commercial venture of it.

The author's role in this project is to provide a guideline for designing the subsystems; and a design for interfacing these subsystems along with the payloads based on the lessons learnt from the earlier designs. It is also of interest to make this a modular design since a similar system will be flown on future KUTESat missions.

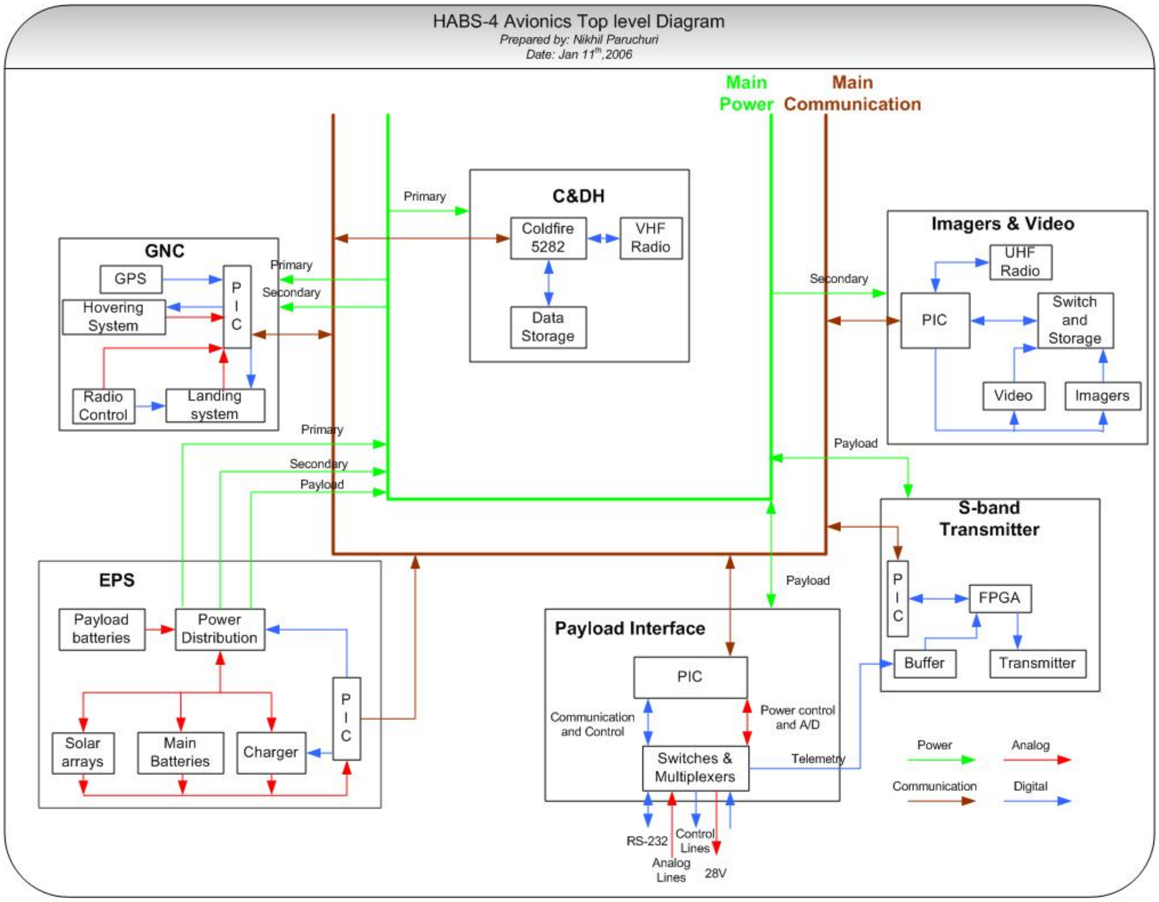


Figure 6.2: HABS-MK4 subsystem level diagram

The proposed design for the avionics of the HABS-MK4 is shown in Figure 6.2.The Control and Data Handling (C&DH) is designed around a uCDimm core from Arcturusnetworks, which includes a Cold fire 5282 processor from Motorola. This is uCLinux based system and is an advanced model of the Dragonball processor also from Motorola. The C&DH uses a VHF radio, possibly a TH-D7AG from Kenwood, to transmit the system health and telemetry data; and receive commands from the ground station. It is also responsible for monitoring the status of all the other subsystems.

The Guidance and Navigation Control (GNC) subsystem consists of a GPS unit that is used to record and report the GPS coordinates of the system to the ground station through the C&DH. The GPS data is also used by the PIC processor in the GNC system to control the Hovering system and the Landing system. The Hovering system is used to maintain the altitude of the HABS system and could consist of a gas valve to control the flow of Helium from the balloon into the atmosphere in order to control the descent; and a ballast control system to control the ascent. The Landing system is responsible for controlling the path of the HABS system after it has been detached from the balloon. This could be done autonomously based on the GPS data by controlling a parachute. A Radio Control unit similar to the one used by hobbyists to fly Radio Controlled Airplanes could also be used to provide manual control of the Landing system. The Radio Control unit interfaces with the PIC and this interface could be used to request a particular video feed from the Imagers and Video subsystem.

The Imagers and Video subsystem includes CMOS imagers located at different locations in the HABS system to give a three axis view. A single or multiple channel video system could be also be provided, which would be useful in providing a safe landing spot for the HABS system. The imagers and Video units are controlled by a PIC, which chooses amongst the imager and Video data to transmit based on the commands received from the C&DH subsystem. Since the data rate will be high, simple VHF radio will not suffice; and a UHF radio system will have to be used. It might be possible to use the S-band transmitter instead of the UHF radio depending on the power, weight and volume constraints.

The Electrical Power System (EPS) will be similar to the KUTESat-1 power design. A PIC interfaces with the C&DH subsystem to decide on the Primary, Secondary and Payload power distribution. The bus voltages should be 3.3 V, 5 V, 12 V and 28 V. The Main batteries will be used to provide the 3.3 V, 5 V and 12 V lines and they can be recharged by solar cells. The 28 V power line required by the external payloads and the S-band transmitter should however be provided by a Non rechargeable 28v battery due to the high power requirements (~28 V @160 Ah for a 15 hour flight).

The S-band transmitter subsystem consists of a PIC which interfaces with the C&DH subsystem to control the S-band transmitter characteristics; and the Payload Interface subsystem to transmit the payload data. The data to the S-band transmitter is first stored in a buffer and then processed by a Field Programmable Gate Array (FPGA), which provides the necessary encoding; error correction; and formats the data into packets. The FPGA then transmits the data through the S-band transmitter.

The main objective of the HABS-MK4 system is to provide a modular interface for carrying payloads which usually have an RS-232 interface and a 28 V power requirement.[*] The Payload interface board consists of a PIC which controls the Payloads based on commands received from the ground station through the C&DH. The PIC also collects important analog data from the payload subsystems and reports it to the ground station on the VHF link. The PIC communicates with the individual payloads on an RS-

[*] This observation is made by the author based on research of payloads on other similar balloon projects and a review of some of the products available from aviation vendors. A different interface to the payload can easily be designed by replacing the Payload interface section without the need for an overall redesign of the main HABS system.

232 bus, which can be used to command the payloads or collect low rate telemetry. The high data rate telemetry is routed by the PIC to the buffer in the S-band transmitter subsystem. Individual 28v power lines that can be controlled by the PIC are provided to the payloads. Multiple payloads can be attached to this subsystem by multiplexing and switching the A/D ports, Digital I/O lines and the RS-232 port.

The communication between the subsystems is through an RS-232, SPI or I2C bus. The C&DH is the master of the RS-232 bus and is used to control the subsystem PICs and collect important subsystem telemetry. The SPI bus can be used by the C&DH to collect high rate data such as the GPS data or the Images data. The I2C bus can be used by the Payload Interface subsystem to control and communicate with the S-band transmitter subsystem, to facilitate the flow of data from the payloads to the S-band system.

6-2 Conclusion

A few proposals have been made for the future satellite projects by KU. These satellites will be used for testing payloads like the Space Plug-and-Play Avionics (SPA) being developed by the Air Force Research Laboratory (AFRL); S-band transceiver by Kansas City Plant (KCP; an imager by Fundamental Technologies LLC; A MEMS based Gyroscope by Jet Propulsion Laboratory (JPL); a Micro Maneuvering Control System (MMCS) developed by KU etc.

In order to gain success with these missions it is very important that a mature modular system be developed based on the previous designs and the lessons learnt from the design and implementation of the HABS-MK4 system. The author has provided the basic ground work for designing such a system. The author hopes that the future teams will implement these design guidelines and make necessary changes for improving the system design based on their experiences.

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