ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL OF SCIENCE ENGINEERING AND TECHNOLOGY

DESIGN OF REDUNDANT ON-BOARD COMPUTER AND MODEM FOR CUBESATS

M.Sc. THESIS

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Department of Aeronautical and Astronautical Engineering

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JANUARY 2012

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İSTANBUL TEKNİK ÜNİVERSİTESİ ★ FEN BİLİMLERİ ENSTİTÜSÜ

KÜP UYDULAR İÇİN YEDEKLİ UÇUŞ BİLGİSAYARI VE MODEM GELİŞTİRME

YÜKSEK LİSANS TEZİ

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OCAK 2012

Mehmet Ertan Ümit, a **M.Sc.** student of ITU **Graduate School of Science Engineering and Technology** student ID **511071143**, successfully defended the **thesis** entitled "**Design of Redundant On-Board Computer and Modem for Cubesats**", which he prepared after fulfilling the requirements specified in the associated legislations, before the jury whose signatures are below.

Thesis Advisor :	**Assoc. Prof. Dr. Gökhan İNALHAN** İstanbul Technical University	....
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	Assist. Prof. Dr. Turgut Berat KARYOT İstanbul Technical University	....

Date of Submission : 19 December 2011
Date of Defense : 27 January 2012

To my nieces,

FOREWORD

This master thesis was written during the time-period from spring 2010 until summer 2010, under the teaching supervision of Assoc. Prof. Gökhan İNALHAN
The intend of thesis is to develop a On-board Computer to increase reliability, availabe volume and power of a CubeSat.
I would like to thank my supervisor, for his great help during development of this thesis, Control and Avionics Laboratory for allowing me to work with them and their endless support, RF Laboratory of İTÜ for their knowledge, MEAM of İTÜ for their support and my collegues at Delfi-next project for being a starting point for my thesis. Last but most I would like to thank my parents, my sister, her husband, my nieces and my neighbors for their support and joy for the last year.

December 2011 Mehmet Ertan Ümit

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ABBREVIATIONS

ADC	: Analog Digital Converter
CDHS	: Command and Data Handling System
COTS	: Commercial Off The Shelf
DMR	: Dual Mode Redundant
EPS	: Electrical Power System
FSK	: Frequency Shift Keying
GS	: Ground Station
ITU	: Istanbul Technical Univeristy
ITU	: International Telecommunication Union
OBC	: On-Board Computer
PCB	: Printed Circuit Board
RTC	: Real Time Clock
SMT	: Surface Mount Devices
WDT	: Watchdog Timer

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DESIGN OF REDUNDANT ON-BOARD COMPUTER AND MODEM FOR CUBESATS

SUMMARY

CubeSats created new opportunities for academic world. Before CubeSats, only space agencies were capable of launching an experimental spacecraft. After CubeSats number of small companies and COTS products with heritage increased, therefore prices for space products dropped to a reasonable level. In addition, commercial rockets are developed with various size and payload capacities, this leads to cheaper piggyback launches. Currently even small university laboratories with limited budgets are able to develop and launch CubeSats. Today many CubeSat projects depend on COTS OBC developed almost 10 years ago.

In this thesis, a new advanced OBC is developed. Motivation of thesis is rapid developing aerospace industry of Turkey. ITUpSAT1, the fisrt satellite developed in Turkey launched in 2009 with COTS OBC and modem. It is clear that using COTS single board for each system is volume inefficient for 1U CubeSats. A new efficient design will lead advanced CubeSats.

Different hardware and software designs are implemented on OBC to ensure proper mission. A relatively new ulta-low power microcontroller is selected, older version of which has flight heritage. Software libraries are implemented for future CubeSat projects. Enhancements on COTS bus is made to increase reliability and compatibility. A simple low power modem is implemented on same board to ensure communication without increasing volume by adding another modem. Batteries are also implemented into OBC so that even failure of rest of spacecraft communication will established and at least failure reasons will be researched for future missions. All three systems are doubled to have a dual redundant system for fault tolerancy and everything is fitted on a single PCB.

The system is build and tested. Table-top and range testing are handled successfully. Table-top model tested software libraries. Range tests simulate 700 to 1400 km range between a LEO satellite and standard CubeSat GS. TVAC and radiation tests are planned and documented, but due to low budget of master thesis, this test will be handled during a real CubeSat projects testing phase.

As a conclusion a generic reliable OBC is developed. With professional fabrication and testing process could space qualify the new system and then it could be used on future projects without any problem.

KÜP UYDULAR İÇİN YEDEKLİ UÇUŞ BİLGİSAYARI VE MODEM GELİŞTİRME

ÖZET

Küp uydular geliştirilmeye başladığından beri akademik dünya için uzayın kapıları açıldı. Küp uydulardan once deneysel uydular ancak geniş bütçeli uzay ajansları tarafından atılabilmekte idi. Küp uydulardan sonra ise irili ufaklı firmalar belirli standartlara göre geliştirdikleri ürünleri piyasaya sürmeye başladılar. Bu ürünler kullanıldıkça uçuş geçmişine sahip oldular ve fiyatlar rekabet dolayısı ile azaldı. Aynı şekilde farklı ağırlık ve boyuttaki uydular için geliştirilen ticari roketler seçenekleri çoğalttıkları gibi küp uyduları da müşteri olarak kabul etmeye başladılar. Bu sayede fırlatma giderleri de önemli ölçüde azalmış oldu. Günümüzde düşük bütçeli üniversite laboratuvarları dahi rahatlıkla küp uydu geliştirerek fırlatma şansına sahiptirler. Birçok uydu projesi de yaklaşık 10 yıl önce geliştirilen hazır ürünlere dayalı olarak geliştirilmektedir.

Küp uydular genel olarak 10x10x10cm boyutunda küp olarak üretilir. Bu boyut bir birim olarak kabul edilir. İlk küp uydularda standard olarak PC104 standartlarında üretilen elektronik kartlar kullanılmıştır. Bu kartlar boyut olarak kübün içine sığabildikleri gibi üstüste konuldukları için üretilme aşamasında kolaylık getirmektedir. Aynı zamanda PC104 standardında kullanılan konnektörler karar verme ve geliştirme aşamasında çok yardımcı olmuşlardır. Buna göre geliştirilen sistemlerin hepsi uyumlu olması için bu standartlarda geliştirilmiştir.

Küp uydularda genellikle beş altsistem mevcuttur. Bunlar; Yapı, Veri ve Komut İşleme, Haberleşme, Güç ve Yönelim Belirleme ve Kontrol sistemleridir. Yapı altsistemi genel olarak uydunun dışını kaplayan iskeleti ve bunu roketten fırlatan fırlatıcı olarak tanımlanabilir. Uydu yapısı önceden belirtilen küp uydu standartlarına uygun üretilmektedir. Uydunun ağırlığını olabildiğince hafifletmek için aluminyumdan yapılır. Fırlatıcının rayı ile temas eden yüzeyleri uzayda soğuk kaynak olmasını engellemek için anodize edilir. Yapı uydu içindeki hassas elektronik ekipmanları radyasyon ve sıcaklık gibi uzayın zorlu şartlarından korur. Fırlatıcı ise uydunun rokete bağlanmasını sağlayan birimidir. Fırlatıcı küp uyduların en pahalı iki kaleminden biridir. Fırlatma sağlayıcıları küp uyduları fırlatırken esas büyük uydunun zarar görmeyeceğine emin olmak ister bu yüzden çok hassas ve dayanıklı fırlatıcılar gerekmektedir. Bu yüzden birçok küp uydu geliştiricisi fırlatıcı sistemi hazır almak istemektedir.

Güç sistemi uydunun ihtiyacı olan elektrik enerjisinden sorumludur. Güneş paneli, pil, kontrol ve regülatör gibi altsistemlerden oluşur. Uyduda kullanılacak enerji uydunun dış yüzeyini kaplayan güneş panelleri tarafından üretilir. Üretilen enerji regülatörlerde düzenlenerek elektronik sistemlere aktarılır. Fazladan üretilen enerji daha sonra kullanılmak üzere pillerde biriktirilir ve uydu gölgeye girdiğinde kullanılır. Uydu üzerindeki tüm ekipmanların harcadığı güç hassas olarak belirlenir. Aynı zamanda uydunun üreteceği güç de hassas olarak simüle edilir. Bu sayede uydu

gönderilmeden önce yörüngede uydunun nasıl çalışacağı bilinir. Tüm sistemler de buna göre tasarlanır.

Yönelim belirleme ve kontrol sistemi uydunun uzayda ne tarafa baktığını belirleyen ve buna göre baktığı yönü çeviren sistemlerdir. Bu sistem ivmeölçer, dönüölçer, manyetometre ve güneş sensörü gibi sensörleri kullanarak örneğin güneş panellerinin ne tarafa baktığı belirlenir. Daha sonra bu bilgi ve manyetik burucular gibi eyleyiciler kullanılarak güneş panelleri güneşe yönlendirilir ve bu sayede uydunun daha fazla güç üretmesi sağlanır. Genellikle daha basit uydularda yönelim için dünyanın manyetik alanı ile etkileşerek yönelimi sağlayan mıknatıs çubukları kullanılır.

Haberleşme sistemi uydunun yer ile haberleşmesini sağlar. Bazı uydular beacon gibi basit vericiler ile haberleşirken gelişmiş uydular sofistike modemler kullanarak çok daha hızlı ve verimli haberleşirler. Beacon genel olarak belirli aralıklar ile mors kodunda sinyal yayarak dünya üzerindeki dinleyicilere bilgileri yayınlar. Radyo amatörleri bu verileri düzenli olarak dinlerler bu sayede tüm dünya üzerinde uydu sinyalleri takip edilmiş olur. Diğer sistemde ise modem çok daha hızlı bir biçimde veri iletişiimi kurar. Genellikle küp uydularda bu iki sistem beraber kullanılır. Beacon tüm dünyaya uydu sıcaklığı gibi basit verileri yayınlarken, modem çekilen resimler ya da toplanan sensör verileri gibi daha büyük ve önemli verileri sadece belirli bir yer istasyonuna gönderir. Bu sayede bu iki sistemden biri çalışmasa bile haberleşme sağlanmış olur.

Veri ve komut işleme sistemi uyduyu yöneten sistemdir. Bu sistem tüm altsistemlerin çalışmasını kontrol eder ve uydunun düzgün bir biçimde çalışmasını sağlar. Bu altsistem 2 birimden oluşur, bunlar; uçuş bilgisayarı ve veriyoludur. (BUS) Uçuş bilgisayarı uyduyu yöneten birimdir. Tüm sistemlere erişimi ve kontrolü vardır. Çalışmayan sistemlere müdahele eder ve önceden belirlenmiş prosedürleri uygular. Altsistemleri açma ve kapama yetkisi vardır. Veriyolu ise tüm altsistemlere erişen ve bu sistemlere veri ve güç taşıyan sistemdir. Veriyolu sistemi güç ve veri haberleşmesinin kesintisiz ve doğru biçimde yürütülmesinden sorumludur. Veriyolu uydunun en önemli alt-sistemlerindendir.

Bu tezde yeni ve gelişmiş bir uçuş bilgisayarı geliştirilmiştir. Türkiye'nin çok hızlı gelişen uzay endüstrisi ve gelecekte yapılması planlanan küp uydu projeleri bu tez için bir motivasyon kaynağı olmuştur. Türkiye'de geliştirilen ilk uydu olan ITUpSat1 hazır sistemlerin yardımı ile geliştirilmiştir. Bu süreçte bazı sistemlerin çok fazla güç harcadığı ve yeterince sıkıştırılamadığı için boşa yer kapladığı görülmüştür. Yeni ve gelişmiş altsistemlerin daha gelişmiş küp uyduların önünü açacağı anlaşılmaktadır.

Tez için farklı yazılım ve donanımlar implement edilmiştir. Piyasadaki ürünlere gore daha yeni olan bir mikrokontrolcü uçuş bilgisayarı için seçildi. Bu mikrocontrolcüde kullanmak ve gelecekteki projelere yardımcı olmak üzere yazılım kütüphaneleri ve sürücüler geliştirildi. Halihazırda kullanılan system yollarına bazı eklemeler yapıldı. Basit ve düşük güç harcayan bir modem tasarlanarak bilgisayar ile aynı kart üzerine eklendi. Bunlara ek olarak uydunun gücünün kesilmesi durumunda dahi çalışması için aynı kart üzerine pil eklendi. Son olarak her sistemin eşi olan yedek bir sistem aynı kart üzerine eklendi. Bu sayede gelecekteki görevlerde bir sorun olması durumunda dahi en azından sorunun ne olacağı incelenebilecektir. Sonuç olarak piyasadaki ve diğer topluluklar tarafından üretilen altsistemlere göre çok daha gelişmiş bir ürün tasarlandı. Tasarlanan ürünün her türlü uzay şartına dayanması için gelişmiş yedeklilik yöntemleri kullanıldı.

Tasarlanan ürünün ilk olarak çift katlı bakır PCB olarak tasarlandı. Bu tasarımda RF sinyallerin geçtiği yollar gerektiği gibi 50 ohm olacak şekilde ayarlandı. Tasarım İTÜ MEAM laboratuarlarında bulunan PCB prototip cihazları kullanılarak üretildi. Kullanılan devre elemanları el ile üretmek için çok küçük olduğundan üretimde çok hassas cihazlar kullanıldı. PCB üzerine lehim yapmak için stencil üretildi. Stencil ile sürülen lehim üzerine devre elemanları çok hassas cihazlar yardımı ile yerleştirildi ve özel fırınlar kullanılarak lehim eritildi ve üretim işlemi tamamlanmış oldu.

Üretilen sistemi test etmek için küp uydularda kullanılan standart test metodolojisi kullanıldı. İlk olarak üretilen yazılım ve donanım masaüstünde denendi ve hataları giderildi. Daha sonra uydunun gönderileceği yükseklikte çalışacağından emin olmak için mesafe testleri yapıldı. Mesafe testlerinde ise standart bir alçak yörünge küp uydusunun 700 ila 1400 km arası değişen mesafeleri simüle edildi. Daha sonra sistemin uzay ortamında çalışıp çalışmayacağını sınamak için İTÜ bünyesinde bulunan USTTL tesislerinde termal vakum testi yapıldı. Bu testlerde sistemler çok düşük vakumde çalıştırıldı ve performansları izlendi. Aynı şekilde vakum ortamında uzay sıcaklıklarını denemek için ortam sıcaklığı değiştirildi ve çalışma performansları kaydedildi. Daha sonra tamamlanması için radyasyon testleri de planlandı ve dökümantasyonları tamamlandı. Bu sayede herhangi bir küp uydu projesi dahilinde yapılacak olan testlerin uçuş bilgisayarını uzaya kalifiye etmesi tasarlandı.

Sonuç olarak jenerik bir uçuş bilgisayarı tasarlandı, üretildi ve test edildi. İleride yapılacak olan profesyonel üretim ve testler sistemin gelecekteki görevlerde rahatlıkla kullanılmasına olanak sağlayacaktır. Gelecekte geliştirilecek olan küp uydu projelerinde rahatlıkla kullanılabilecek kalitede bir altsistem geliştirildi.

1. INTRODUCTION

Main idea of this thesis comes from CubeSat's. CubeSat is a standard for small satellites. Having a standard for a product increases COTS products, therefore decreases pricing. CubeSat standard decreases development time. Before CubeSat's, universities and small organizations were distant to space systems, due to budget and person-hour requirements of satellite projects. CubeSat's brought cost and time effective space systems especially for developing countries. Currently many universities and organizations are developing space system using CubeSat architecture.

Figure 1.1 shows Cute-1 1U CubeSat developed by Tokyo Institute of Technology launched in 2003 and it is still operational.

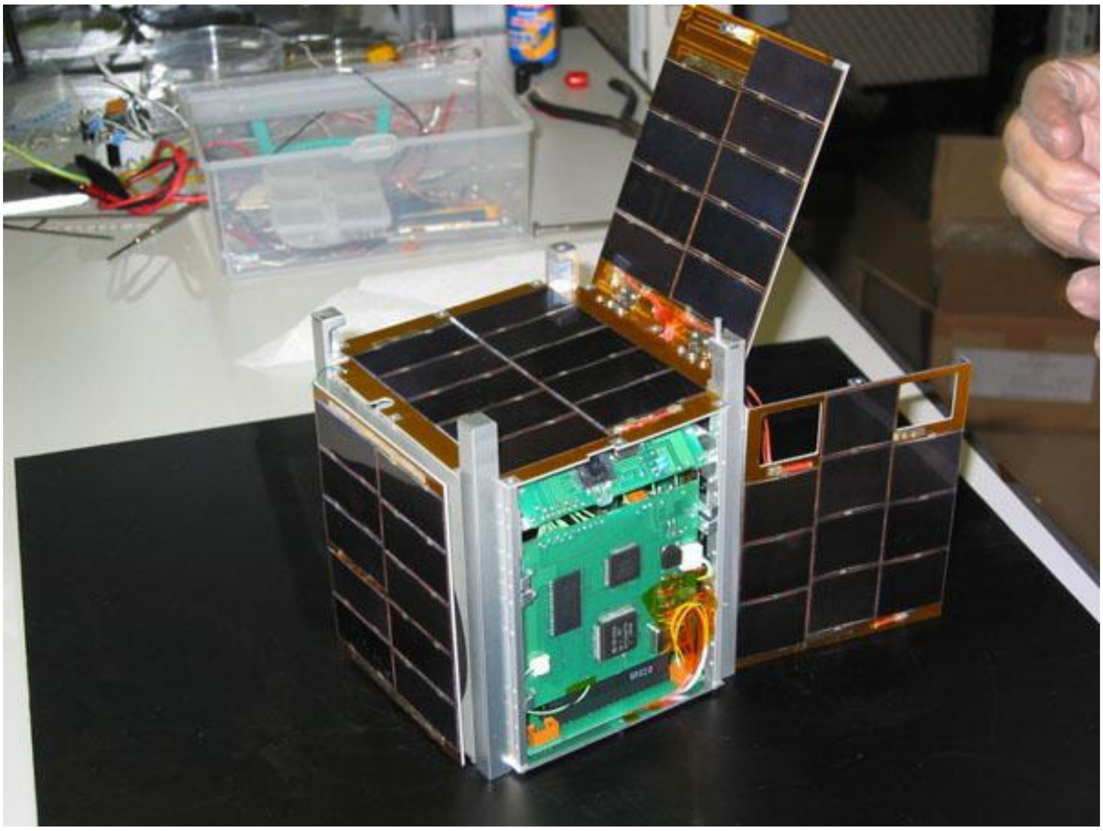

Figure 1.1 : Cute-1 CubeSat.

The idea of CubeSat comes from two astronautical engineering professor Jordi Puig-Suari and Bob Twiggs from Stanford. CubeSat project's aim is to increase accessibility to space. Presently, the CubeSat Project is over 100 international collaborators, which are universities, private companies and government organizations . Standard 1U CubeSat size is 100mm*100mm*113,5mm. Weight of the 1U CubeSat shall be less than 1,33kg. Likewise a 3U CubeSat size is 100mm*100mm*345mm. Detailed information could be found at Appendix A.1

1.1 Purpose of Thesis

The aim of this thesis is develop an advanced subsystem for CubeSats, to increase reliability, available volume and power. More than half volume of a regular 1U CubeSat is filled by vital systems such as OBC, modem and EPS, therefore a small volume is left for payload. Most of the power is consumed by modem, which left a few portion of power for actual mission payload. This thesis will present a combined ultra-low power OBC and modem system on a single CubeSat PCB. It is planned to increase available volume by 50%. Figure 1.2 shows schematic view of developed system.

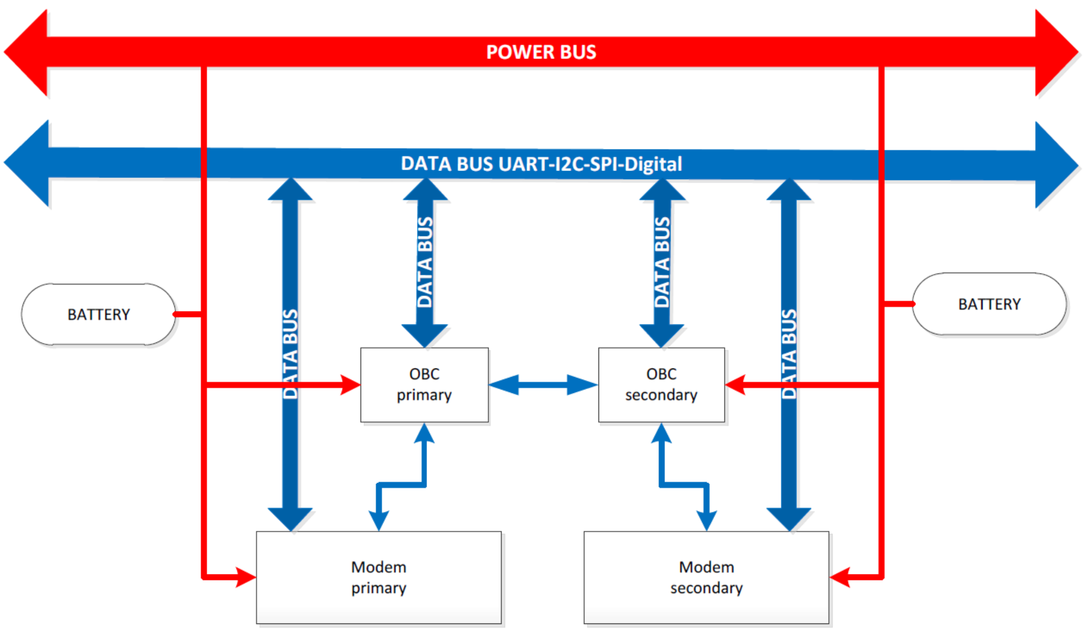

Figure 1.2 : System Schematic.

A standard CubeSat stack layout is shown on figure 1.3 and 1.4. Bottom layer is OBC from CubeSatKit. 2'nd layer is the modem from Microhard. It is planned to increase available board space from one to two PC104 boards. A combination would create space for another board. This is achieved by combining OBC and modem systems together. Dual redundant system is designed to overcome space related problems and to increase reliability with advanced capabilities

1.2 Literature Review

1U CubeSats generally consist of 5 sub-systems;

1. Electrical Power System (EPS)
    a. Batteries
    b. Solar Panels
    c. Regulators and Control
2. Command and Data Handling System (CDHS)
    a. On-Board Computer
    b. Satellite Bus
3. Power Bus
4. ii. Data Bus
5. Structure
    a. Satellite structure
    b. Deployer
    c. Thermal Control
    d. Mechanisms
6. Communication
    a. Modem
    b. Beacon
    c. Antenna
7. Attitude Determination and Control

These systems are explained in Appendix 2 in detail.

These sub-systems are available as COTS. Most of them have dependable flight heritage. The problem is most of them covers a single board. Figure 1.2 shows from bottom to top:

1. CubeSatKit FM430 OBC
2. Microhard MHX425 modem
3. Clyde Space EPS
4. Clyde Space batteries
5. Custom Attitude Control (permanent magnet)
6. Custom Payload: Camera, accelerometer, gyro, magnetometer, beacon

ITUpSAT1 was the first satellite developed in Turkey; therefore, main mission was to develop a CubeSat platform and hands on experience for future developments. ITUpSAT1 is a good example for universities that started to develop their own satellites. Stacking of ITUpSAT1 is shown on figure 1.3.

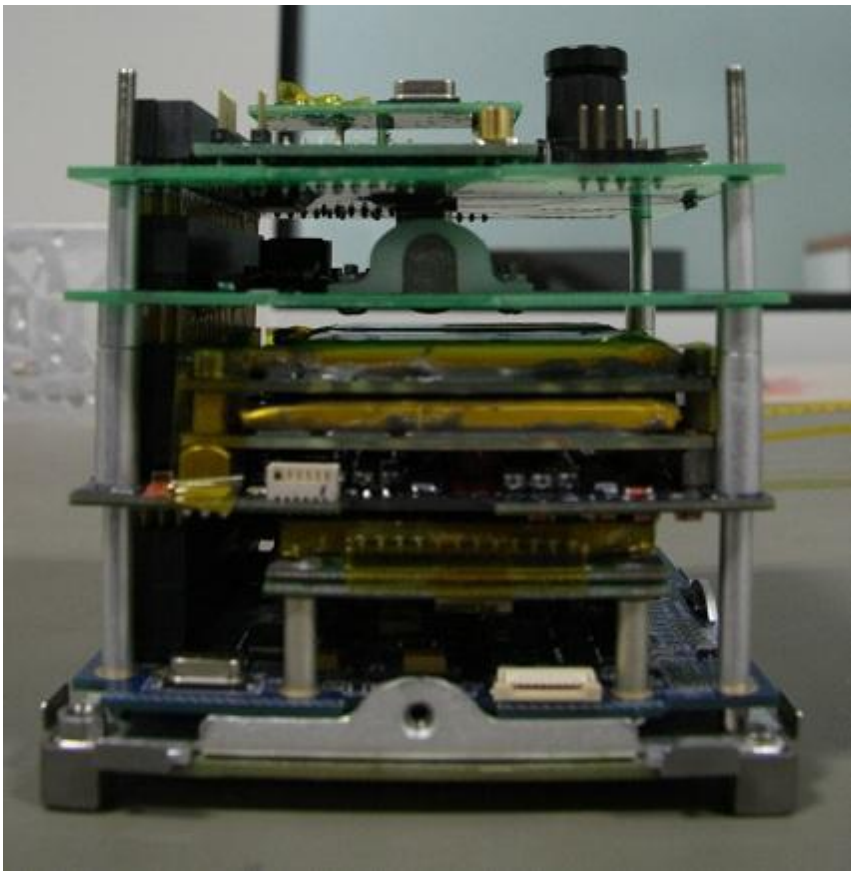

Figure 1.3 : ITUpSAT1

CubeSatKit is a common starting point for a CubeSat project. It has a rich development environment and most of current COTS subsystems are fully compatible with it. CubeSatKit stacking on figure 1.4 shows OBC modem configuration provided by CubeSatKit.

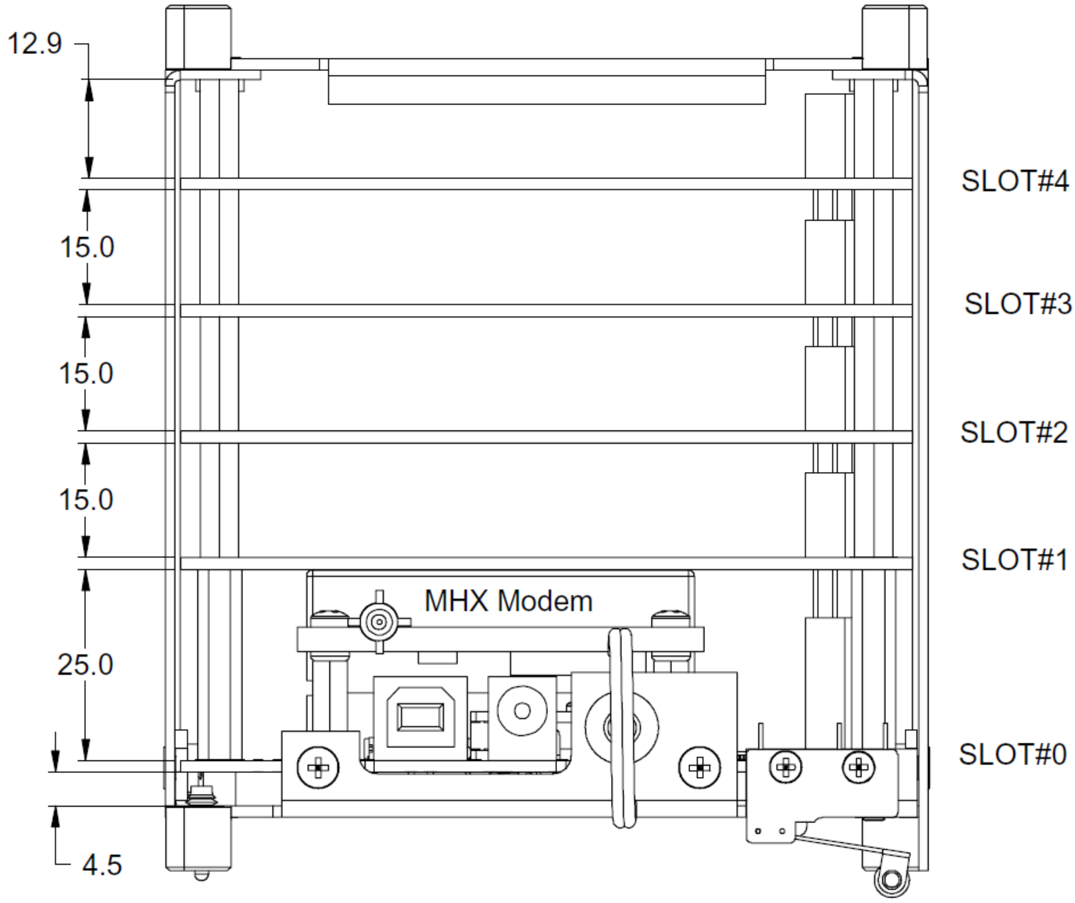

Figure 1.4 : CubeSatKit board stacking.

2. OBC

On-Board computer is the master device on the satellite. It has the ability to command other subsystems. OBC is responsible of the housekeeping. For example payload will have a data set to download or modem will have a connection with ground station. OBC has to receive the data set from payload and store it safely until next communication, when a connection is occurred data set should send to modem for downlink. Simple OBC workflow examples are shown on figure 2.1 and 2.2.

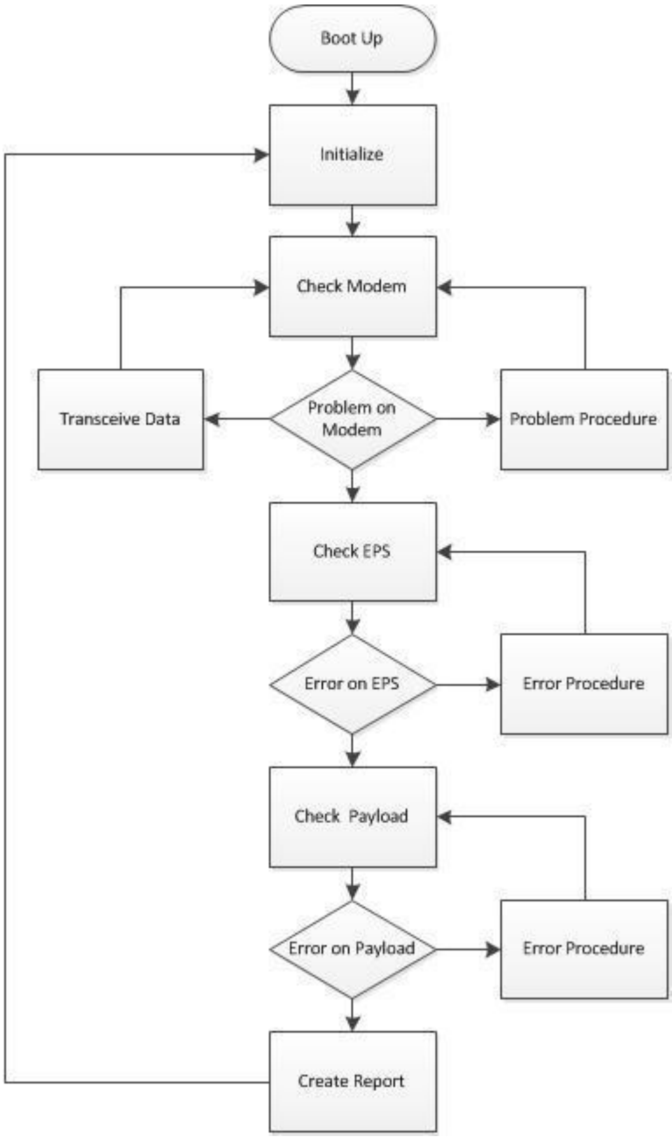

Figure 2.1 : A simple flowchart for OBC.

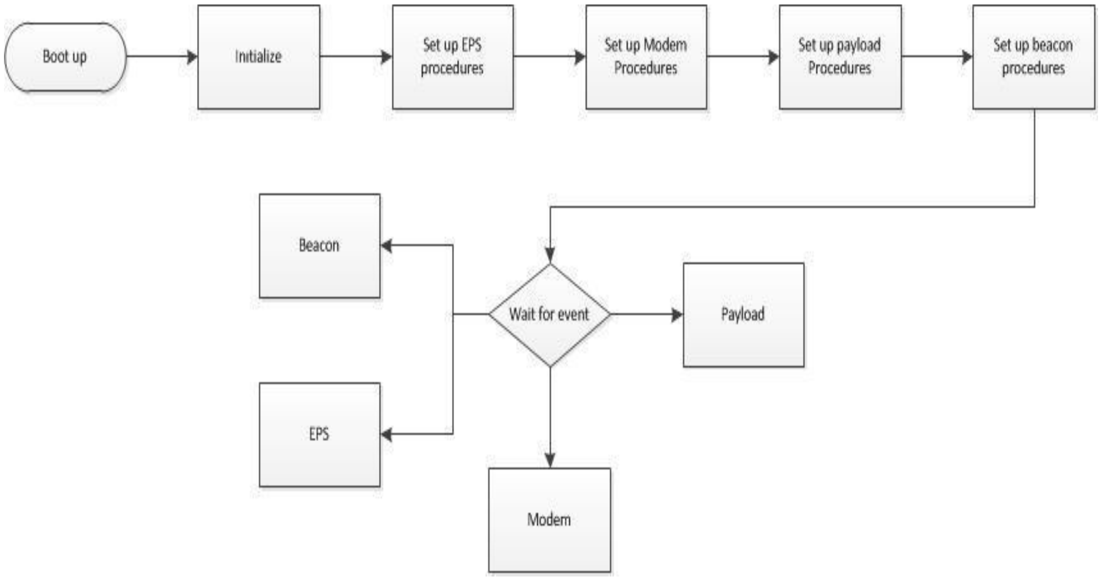

Figure 2.2 : An event – driven OBC flowchart.

CubeSat's have degraded working stages in case of an OBC failure. Systems are preprogrammed for an OCB fault state, so that CubeSat could continue working. A secondary OBC is selected before launch and programmed for a faulty OBC state. Modem is used in some cases as a secondary OBC [1]. Important information have to reach modem to be downlinked, therefore necessary information could be sorted and stored by modem. Another approach is not to use an OBC at all. Other systems could handle OBC tasks as well, but having a separate OBC increase compatibility of systems, therefore CubeSat developers usually use a separate OBC.

2.1 OBC Requirements

- OBC shall be the master on satellite data bus.
- OBC shall be able to control systems.
- OBC shall consume as less power as possible.
- OBC shall have enough processing power for housekeeping operations.
- OBC shall store and prepare data for downlink.

2.2 OBC Tasks

- Check systems monitoring

- Housekeeping systems
- Data transfer control
- From systems to OBC
- From OBC to Modem
- From Modem to OBC
- Request data and TC (Tele Commands) from systems
- Keep track of time
- Schedule the activation of systems (delay loops, RTX request, etc.)
- Validate commands
- Acknowledge commands
- Format data packages (frame, time tag, etc.) for data storage and transmission to the ground stationed.

2.3 Problems

2.3.1 Software Bugs

Software bugs could happen due to infinite loops or misused system resources (Deadlocks [2] etc.) Software bugs can occur even after detailed and long testing phases. OBC could stay on a locked state, therefore cannot accomplish its tasks.

2.3.2 Radiation Related Problems

There are five known types of radiation related problems on electrical devices. Two of them are [3] generally space related, therefore tested.

2.3.2.1 Total Ionizing Dose Effects:

The cumulative damage of the semiconductor lattice (lattice displacement damage) caused by ionizing radiation over the exposition time. It is causes slow gradual degradation of the device's performance; total dose greater than 5000 rads delivered to silicon-based devices in seconds to minutes will cause long-term degradation.

2.3.2.2 Single-event effects (SEE):

When a high-energy particle travels through a semiconductor, it leaves an ionized track behind. This ionization may cause a highly localized effect similar to the transient dose one - a benign glitch in output, a less benign bit flip in memory or a register, or, especially in high-power transistors, a destructive latch up and burnout.

2.3.2.3 Single-event upsets (SEU):

SEU are state changes of memory or register bits caused by a single ion interacting with the chip. They do not cause lasting damage to the device, but may cause lasting problems to a system that cannot recover from such an error.

2.3.2.4 Single-event latch-up (SEL):

SEL can occur in any chip with a parasitic PNPN structure. A short circuit occurs until a power cycle happens.

2.3.3 Power Consumption :

CubeSats have tight power budgets due to their small sized solar panels and batteries. A high power OBC is not desired because of available power. Using a high tech 1GHz dual core microprocessor on a 1U CubeSat won’t be a logical solution, unless specific tasks are defined.

2.4 Solutions

2.4.1 Watchdog Timer:

Watchdog timer is a hardware counter that hard resets system after pre-determined time. An efficient watchdog timer could save electronic devices from software bugs and in some cases from SEE’s. Watchdog timer could reset after every successfully completed software function in order to prevent unnecessary reset.

2.4.2 Radiation Hardening:

In many space applications sensitive electronic devices are covered with thick metal compounds to prevent radiation effects. Recent advances made lighter and thinner radiation covers.

2.4.3 Redundancy:

Redundancy is increasing the number of hardware components in order to have a fault tolerant system. A redundant system can continue working after the failure of a component. Redundant systems can overcome unexpected hardware problems such as radiation effects. Many implementation options are available such as; hot redundancy, cold redundancy, and warm redundancy. [4]

3. DESIGN FEATURES

Main perspective of OBC design for this thesis is to have a reliable system, that would work on any case. System is designed to work even other subsystem fails. Critical sub-system fails leads to mission failure. For example fail on EPS will lead to a power loss for entire spacecraft, therefore mission failure therefore a backup battery is implemented in order to have a working subsystem even after a power failure. Another important topic is communication. OBC has a UHF modem, which can be used as a primary or secondary modem or beacon. Modem and batteries combined on a single board ensures communication even after a catastrophic event. OBC is designed as dual mode redundant. If one of the subsystems would fail, backup subsystem will take over. OBC mechansim is shown at figure 3.1.

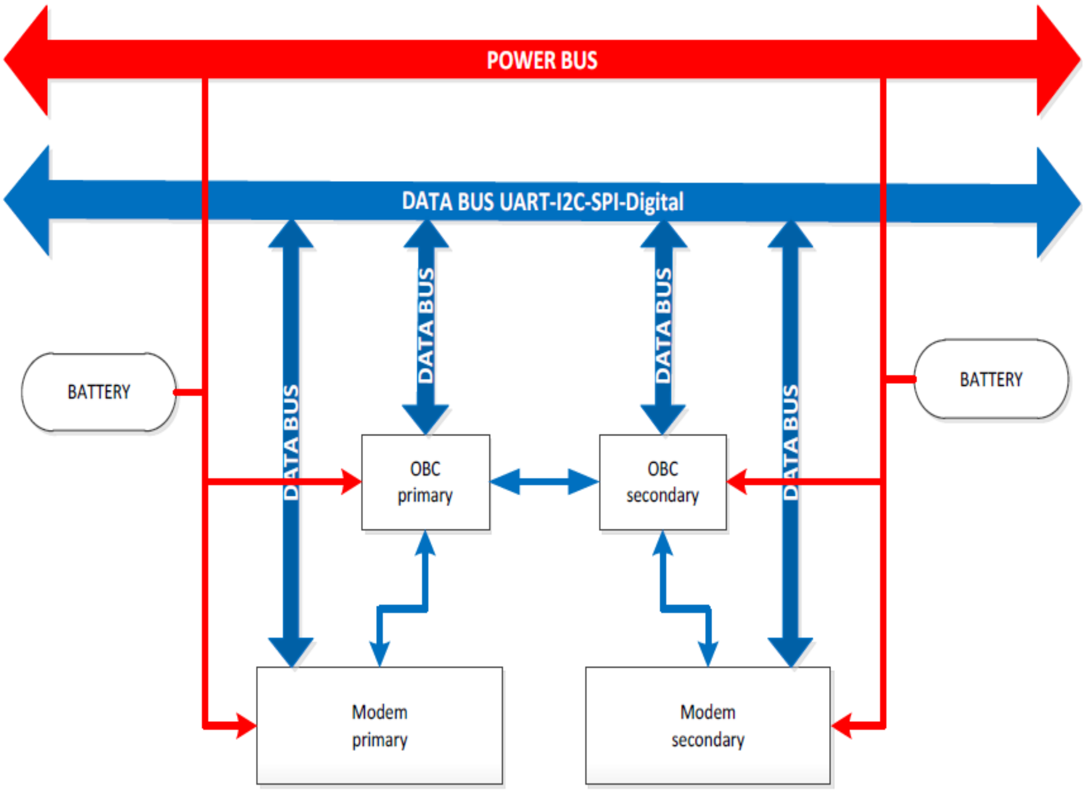

Figure 3.1 : OBC Schematics.

During normal operation subsystems are powered from EPS via power bus and batteries are blocked. OBC’s and modems are connected to data bus, but communication between OBC and modem is handled via separate bus, to ensure seamless work on bus failure. A separate bus is implemented between to OBC

3.1 Microcontroller

Microcontrollers on OBC are selected from a number of models, which have flight heritage. Dual microcontrollers set up a warm redundant system. Primary microcontroller is the master on data bus and has control on subsystems. Secondary microcontroller has the same hardware and software, but it is on watch mode on regular operation. Secondary microcontroller checks primary microcontroller and if primary fails its operations secondary takes control of spacecraft and becomes master on bus.

3.2 Modem

Modem inside OBC is not a sophisticated high power device; on the contrary, it is important to have a simple and low power design. Therefore, a 20dBm low power transceiver is selected. Receiver rate depends mostly on GS therefore uplink can be very fast, but downlink is limited due to limited power consumption.

3.3 Battery

Batteries are selected from non-rechargeable lithium based, because of their high capacity per volume ratio. Batteries are redundant as microcontroller and modem. It is planned that batteries could supply OBC for about a month with modem communication.

3.4 COTS Systems

3.4.1 FM430 from CubeSatKit [5] :

FM430 is one of the first COTS product developed especialy for CubeSats. More than 150 FM430 had been deliveren and has a flight heritage on 4 missions[6]. It is relatively old and have limited interface and processing capabilities.

3.4.2 NanoMind A712B from GOMSPACE [7] :

NanoMind has developed by the same group who developed AAUSat [8]. It has very limited flight heritage. It is a relatively new system with many interfaces and higher processing power.

3.4.3 Andrews Model 160[9] :

New model with more advanced features. It is developed for military standards, radiation tolerant and consume more power than competitors.

3.4.4 Comparison

A comparison between COTS OBC's and designed OBC is shown on table 3.1.

Table 3.1 : COTS OBC comparison table.

	FM430	NanoMind	Andrews 160	Designed OBC
Processing Power	1	3	5	2
Reliability	3	2	5	4
Flight heritage	5	1	0	0
Consumption	5	2	1	5
Interfaces	2	3	1	4
Compatibility	5	5	1	5
Price	4	2	1	5
Volume	2	3	3	5
Total	27	21	17	**30**

4. DETAILED DESIGN

4.1 OBC

Each OBC will have a single core microcontroller with required peripherals. CubeSatKit bus [5] has an isolated I2C bus available; therefore COTS CubeSat products use this configuration. Proposed OBC will have two separate buses one I2c and one SPI. Analogue signals will be measured using analogue pins, even though it is not recommended to transmit analogue signals due to signal losses and noise effects [10]. Digital I/O pins will also be available on data bus. OBC shall have a RTC in order to keep track of time. A watchdog shall be implemented on OBC in order to prevent software failures.

4.1.1 BUS

CubeSatKit Bus[5] is slightly different version of standard PC104 interface. It is widely used on custom and COTS CubeSat systems. CubeSatKit Bus was referenced on design phase of BUS system. It has a four row connector with total 104 pins available. Some pins are already used by some systems. [11] Standart CubeSatKit bus pinouts are presented on figure 4.1. Bus pinouts are merged with COTS system pinouts and presented on figure 4.2. Using 104 pin PC104 connector increases compatibility.

4.1.2 Data BUS

Data bus is chosen as I2C for compatibility. Another I2C interface is added for redundancy. Dual SPI interface is also added to communicate with SPI systems without any interface. CubeSatKit Bus already have an isolated I2C interface, therefore extra interfaces are put on other available pins.

Common pins on CubeSatKit bus are shown on figure x. Pins are selected so that no collision with other COTS systems can occur.

4.1.3 Power BUS

Power Bus is already detailed on CubeSatKit Bus. 3.3V and 5V regulated voltages are available on power bus, moreover float battery voltage could be used directly from battery [11]. No changes are necessary on power bus.

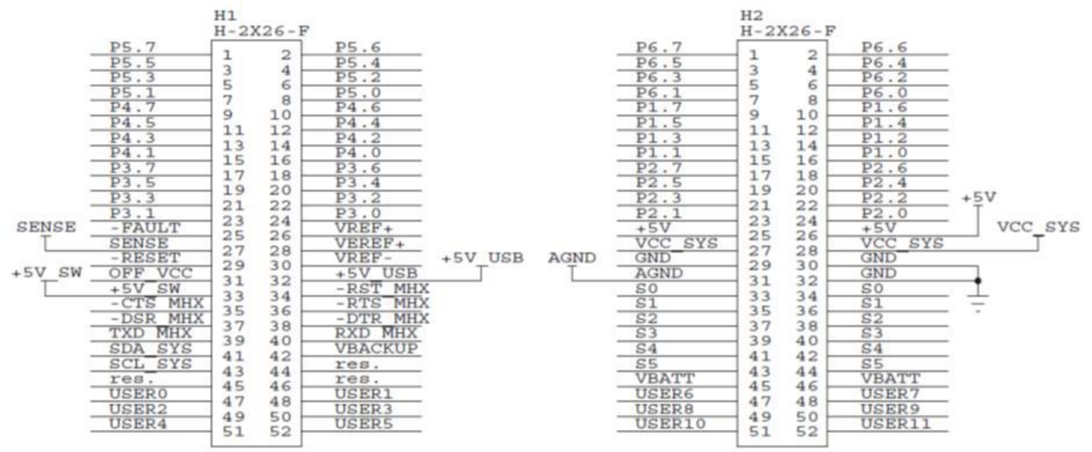

Figure 4.1 : Detailed pinout diagram of CubeSatKit Bus.

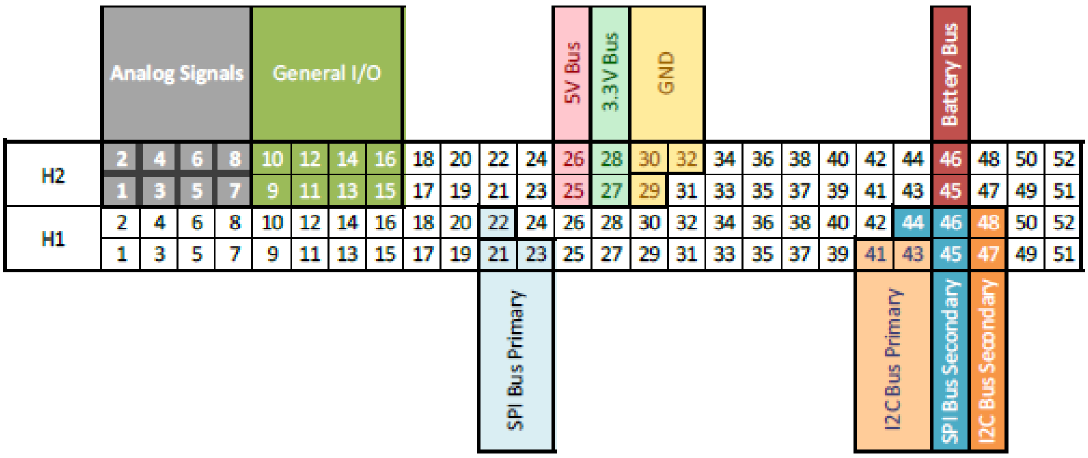

Figure 4.2 : Designed Bus pinouts.

4.1.4 Microcontroller

Microcontroller requirements are based on bus and other compatibility requirements. 3.3V working voltage and eight ADC's are required. Microcontroller shall have dual I2C's and dual SPI's. Depending on bus and OBC requirements, four different models had been chosen for a suitable OBC microcontroller comparison.

A comparison between different microcontrollers from different manufacturers is presented on table 4.1.

Table 4.1 : Microcontroller Selection.

Brand	Series	Model	Compat-ibility	Power	Processing Power	Flight Heritag	Total
Texas Instrument	MSP430	5436	1	1	1	2	5
Atmel	ARM	SAM3S	1	0	0	0	1
Microchip	PIC	18f4425	0	0	1	1	2
Atmel	ATmega	256D3	1	1	1	1	4

Depending on study on table 4.1 MSP430 microcontrollers from texas instruments was chosen. Current developments on electronic offers much more variety on microprocessors, but MSP430 has a good flight heritage and very low power consumption.

4.1.5 Libraries

A software object oriented library has developed to increase reliability and compatibility. Possible errors on errata sheet have handled carefully. Real time operating systems (RTOS) are not necessary for OBC, if developed libraries are used. RTOS add complexity to system that brings errors within. MBED [12] development platform libraries are referenced for library development. Developed driver libraries are presented on table 4.2. Different functions are available for developers to use conveniently.

Table 4.2 : Software Libraries.

Class Type	Functions	Description
ADC Analog to Digital Converter	ADC()	Constructor
	~ADC()	Deconstructor
	int ADC::read()	Read analog value
Digital I/O control	Digital()	Constructor
	~Digital()	Deconstructor
	Digital::out(int)	Set pin output
	int Digital::in()	Read pin input
I2C master	I2Cm()	Constructor
	~I2Cm()	Deconstructor
	I2Cm::setaddress(unsigned char)	Set target address
	int I2Cm::sendbyte(unsigned char)	Send single byte
	unsigned char I2Cm::getbyte()	Receive single byte
	int I2Cm::sendbytes(unsigned char*,int)	Send multiple bytes
	int I2Cm::getbytes(unsigned char*, int)	Receive multiple bytes
I2C Slave	I2Cs()	Constructor
	~I2Cs()	Deconstructor
	int I2Cm::sendbyte(unsigned char)	Send single byte
	unsigned char I2Cm::getbyte()	Receive single byte
	int I2Cm::sendbytes(unsigned char*,int)	Send multiple bytes
	int I2Cm::getbytes(unsigned char*, int)	Receive multiple bytes
Universal asynchronous receiver/transmitter (UART) Class	UART()	Constructor
	~UART()	Deconstructor
	char UART::getc()	Read single char from buffer
	UART::putc(char)	Send single char
	UART::printf(char*,int)	Send mulitple char
Flash memory control class	flash()	Constructor
	~flash()	Deconstructor
	flash::writeblock(char*, char*, int)	Blockwrite to flash
	flash::write(char*,unsigned char)	Write single byte to flash
PWM Class	PWM()	Constructor
	~PWM()	Deconstructor
	PWM::setduty(float)	Set duty cycle on PWM output pin
Real Time Clock class	RTC()	Constructor
	~RTC()	Deconstructor
	RTC::settime(char*)	Set time
	char* RTC::gettime()	Get time
Timer control class	timer()	Constructor
	~timer()	Deconstructor
Wathcdog Timer Control Class	WDT()	Constructor
	~WDT()	Deconstructor
	WDT::reset()	Reset watchdog timer
	WDT::enable()	Enable Watchdog timer
	WDT::disable()	Disable Watchdog timer

4.2 Modem

Modem is designed to establish a simple link between CubeSat and GS. Detailed modem tasks and requirements are presented on Appendix A.3. Main challenge of designing a modem is power consumption. Due to low efficiency of rf amplifiers modem is generally the most power consuming subsystem of a CubeSat [13]. To minimize power consumption a link budget optimization has been made. Link budget on table 4.3 shows required output power of modem.

Table 4.3 : Preliminary Link budget for a CubeSat.

	Worst Case		Best Case	
Frequency	UHF 437.325MHz		UHF 437.325MHz	
Distance	1400	km	700	km
Ground Station Antenna Gain	19,8	db	19,8	db
Satellite Antenna gain	0	db	3	db
Free path loss	-148,17	db	-142,15	db
Receiver sensitivity	126	dbm	126	dbm
Pointing Losses	-1	db	-1	db
Athmospheric Losses	-1,1	db	-0,6	db
Ionospheric Losses	-1,4	db	-0,4	db
Implementation Losses	-4	db	-4	db
Polarization Losses	-3	db	-3	db
Cabling and Connector Losses	-3,1	db	-3,1	db
Total	-15,97	dbm	-5,45	dbm
Output Power	16	dbm	6	dbm

Link budget on table 4.3 is based on ITUpSAT1 and its ground station downlink. Uplink is not considered, because uplink output power can be very high to compensate losses. ITU ground station has 100W (50dBm) and Delfi-C3 ground station has 1kW (60dBm) output power capability. Values are similar compared to other missions and ground stations. For a generic satellite minimum required output power is found as 6-16dBm.

4.2.1 Transceiver

For simplicity a transceiver with more than 16dBm (40mW) is selected. SI1000 from silicon labs has chosen as a transceiver. Even though si1000 does not have any flight heritage, compatibility and simplicity has great effect on selection process. Chip has an internal microcontroller, which will decrease OBC workload, such as framing or error correction. Si1000 has 20 dBm (100mW) output power. Detailed information can be found on appendix A4. FSK modulation scheme has chosen due to simplicity and availability. Hundreds of radio amateurs around the world have FSK communication capabilities. Radio amateur help is crucial on a faulty state. Different radio amateurs on different parts of the world with different ground stations can communicate with the satellite to download information or even recover satellite.

4.2.2 Communication Techiques

Different communication techniques are available for modem. Different frequencies and modulation techniques have different effects on communication [14].

4.2.2.1 Frequency

Frequency selection affects antenna size and path loss. Different frequency bands are available for communications. Table 4.4 shows RF bands and their frequencies.

Table 4.4 : Frequency Table.

Designator	**HF**	**AF**	**VHF**	**UHF**	**L**	**S**	**S2**	**C**	**X**
Band	15 m	10 m	2 m	70cm	23cm	13cm	9 cm	5 cm	3 cm
Frequency (General)	21 MHz	29 MHz	145 MHz	435 MHz	1.2 GHz	2.4 GHz	3.4 GHz	5 GHz	10 GHz

HF, UHF and S bands are reserved for amateur or non-commercial use. Other bands require complicated authorization from ITU and expensive components to use, therefore CubeSats are generally using amateur frequencies [15].

Length of the antenna is given as (4.1).

$$L = k\frac{\lambda}{4} \tag{4.1}$$

where;

λ = wavelength for given frequency

k = any constant positive number

Equation 4.1 shows that length of the antenna increases if frequency decreases frequency. Due to volume and weight considerations smaller antennas are preferred on satellites.

Free space path loss is given as (4.2):

$$Loss = \left(\frac{4\pi df}{c}\right)^2 \tag{4.2}$$

where:

f = signal frequency (in hertz),

d = the distance from the transmitter (in metres),

c = speed of light in a vacuum, 2.99792458 × 108 metres per second.

$$Loss(dB) = 20\log_{10} d + 20\log_{10} f - 147{,}55 \tag{4.3}$$

Equation 2 shows that signal loss increase with distance and frequency. Increasing frequency brings a positive effect on antenna size, but a negative effect on path loss. Spacecraft communication systems are designed to use lower frequencies as uplink and higher frequencies.

Considering antenna size, path loss and availability issues 435 MHz VHF band is chosen for uplink and downlink.

4.2.2.2 Modulation

Different modulation schemes are available [14]. FSK, ASK, PSK and OOK modulations are preferred in most simple systems due to their simplicity and availability. Different modulations and coding are used for specific space missions

[16]. FSK modulation is used in amateur radio and many CubeSat developers receive help from radio amateurs therefore they use common modulation schemes [1] [13]. COTS ground segment components are cheap, simple and compatible for radio amateurs. Therefore FSK modulation is chosen for modem modulation.

4.3 Batteries

Batteries will provide a degraded work profile, but a work profile will ensured even on a major power failure. Power system failure has the most catastrophic effect on spacecraft. No signal could be transmitted or received during a power loss. To be able to survive even on such event a simple back-up battery sub-system is set up. A detailed power budget for components is shown on table 4.5.

Table 4.5 : Power Budget.

Component	IDLE current	Active Current
MSP430(25MHz)	5	5
SI1000 (20MHz) TX	1,8	90
SI1000 (20MHz) RX	1,8	22
Total Average	6,8	58,5

A typical lithium based AA battery has the capability to supply entire system for almost 20 hours. Optimizations could be doen for increasing battery lifetime by using Duty Cylde operations. For a LEO orbit with 10 minute communication frame and 3 passes per day each battery can supply the system for a month.

4.4 Fault Tolerancy

Concepts: A DMR system is implemented with warm redundancy [17]. WDT libraries are implemented with reporting options for software fault tolerancy.

4.4.1 Redundancy

System is based on dual OBC’s to have a redundant system. A warm redundant system is implemented. Both OBC’s are running the same software. Primary OBC is the master OBC which have the master address on data bus and have access to control systems. Main task of secondary (slave) OBC is to watch master OBC for faults. On a fault state secondary OBC will take control.

Hardware implementation is handled using a simple I/O pin between two OBC’s. A clock signal with 1Hz frequency is generated by master and transmitted to slave. Slave stays on a sleep mode to save power. Slave wakes up every second and checks if the clock signal is in order. It is considered that a fault on master will disable the clock signal, therefore slave will take control. Because both OBC’s have the same software and hardware, slave could continue operation. For the worst case slave will be in charge in one second.

4.4.2 WDT

WDT is set up in order to have software fault tolerance. WDT timer is set to one second and a subroutine is programmed to reset WDT. After each subroutine in software WDT is reset by software. If a software bug or an infinite loop happens WDT reset the microcontroller in one second. Before reset date and precious information about the software such as pointer and register values are copied into flash of microcontroller for reporting. These values could be transmitted to GS for analysis. Future research such as SEE analysis could be handled using those reports.

5. MODEL

Hardware test model is developed based on development boards.

5.1 Design

Redundant OBC and Modem is designed for given requirements. Detailed design is shown on figure 5.1. For given schematic power and data pins are connected:

- A digital I/O between OBC’s.
- OBC’s are connected to bus and each other through dual I2C’s and SPI’s.
- Each OBC is connected to its modem using UART.
- A digital I/O is set up between OBC and its modem.
- Modems are connected to bus using I2C
- Analog, digital and RF grounds are connected to ground plane, bus ground and corner rod’s for maximum grounding.
- Power supply pins are connected to 3.3V pins available on bus. Those connections can be powered by batteries using bypass diodes.

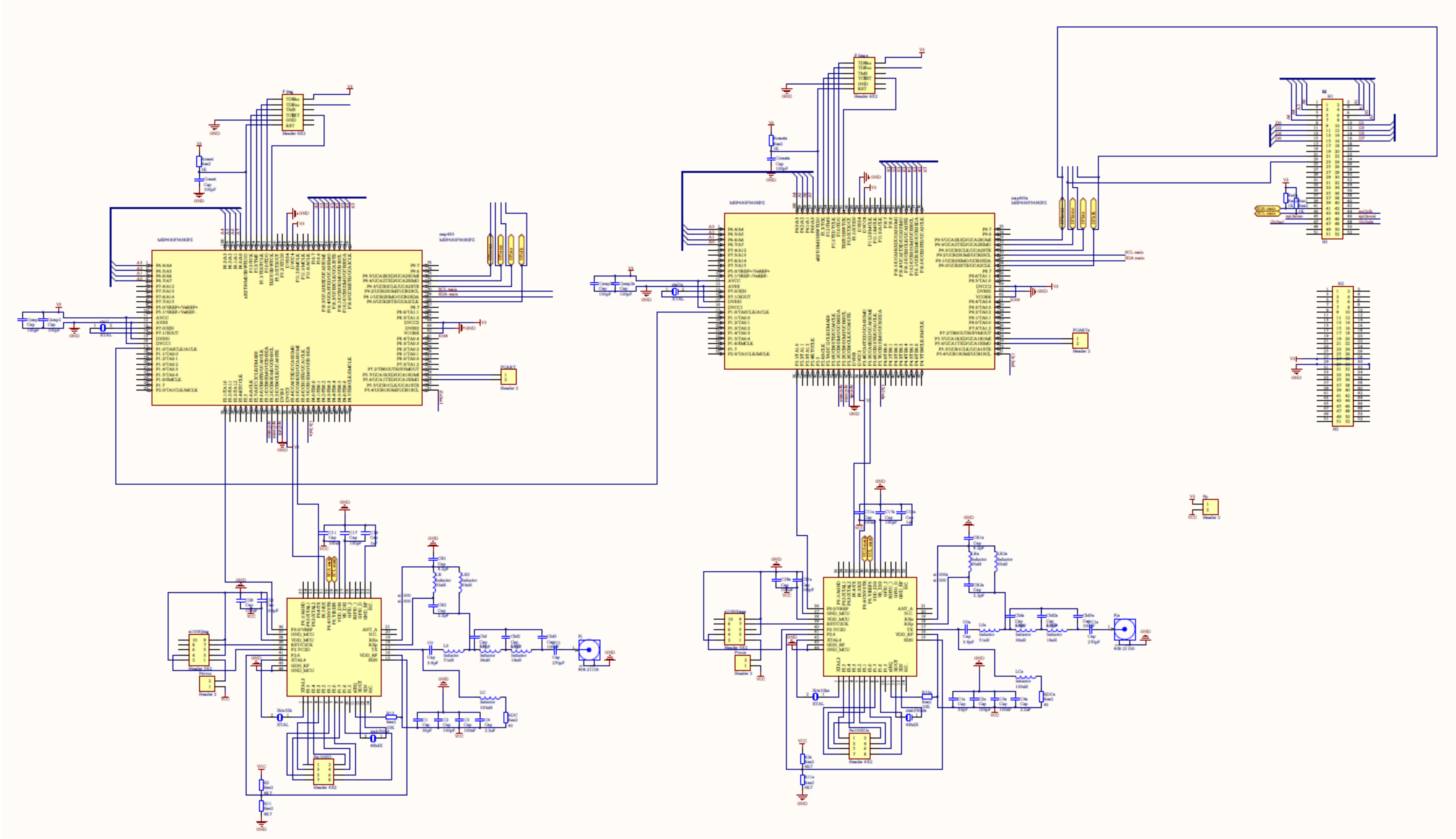

Figure 5.1 : Schematic of system.

5.2 PCB Layout Design

Four or more layered PCB's are preferred for RF designs, but due to manufacturing issues, simple 2 layer PCB is designed. Main issue of such a PCB is RF part and impedance matching [18]. Different filtering and impedence matching techniques are handled in order to have maximum RF output power [19] [20]. Designed PCB is shown on figure 5.2. Top layer is shown in red and bottom layer is shown in blue.

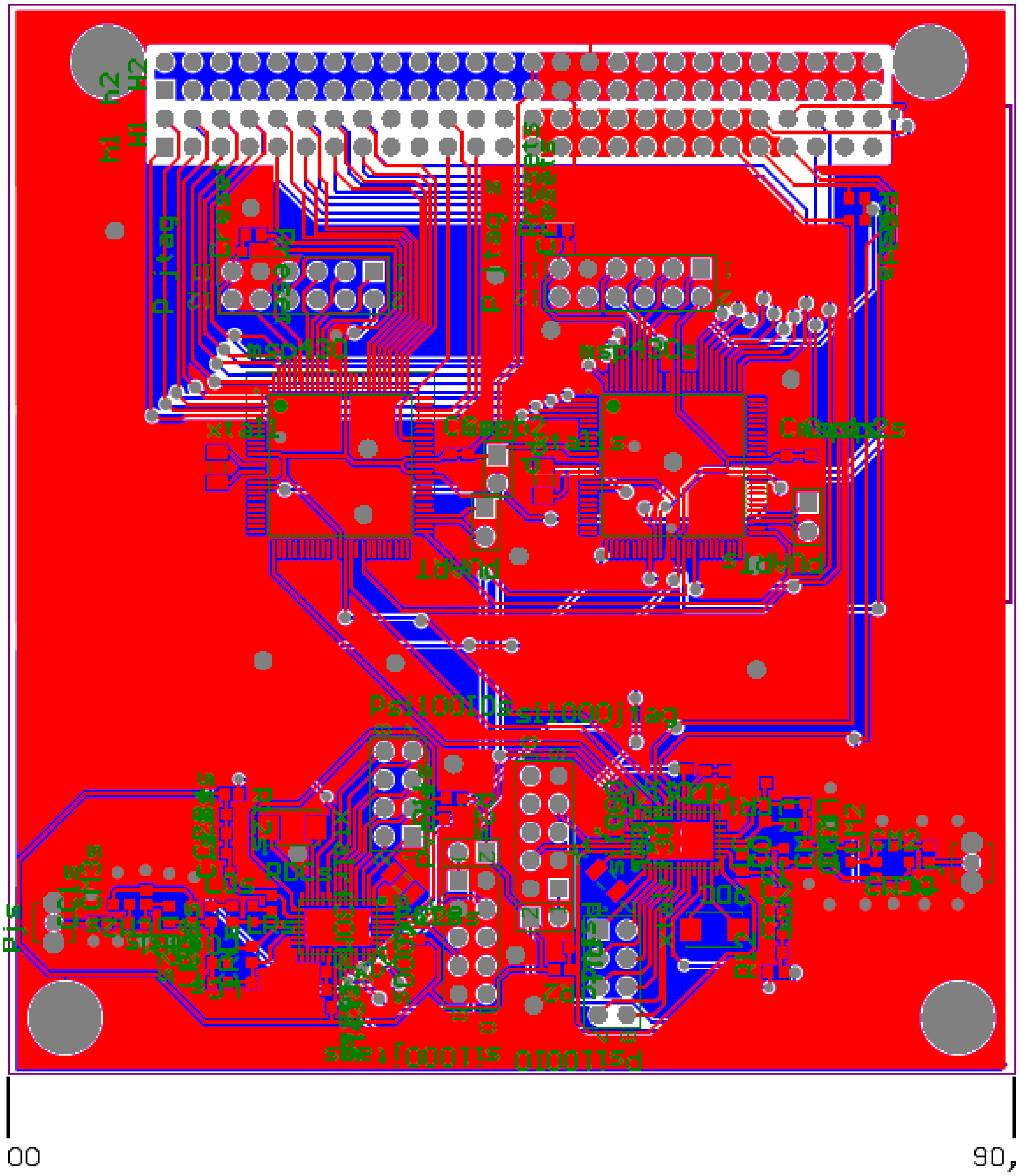

Figure 5.2 : PCB layout.

5.3 Manufacturing

5.3.1 PCB

Designed system is manufactured in ITU using MEAM laboratory's in house rapid prototyping facility. LPKF H100 model PCB prototyping machine is used for drilling holes and cutting out PCB's. LPKF laser engraver is used to mill copper plate on PCB in order to create connections. Figure 5.3 shows H100 cuts out model PCB. Figure 5.4 shows model PCB after laser engraving.

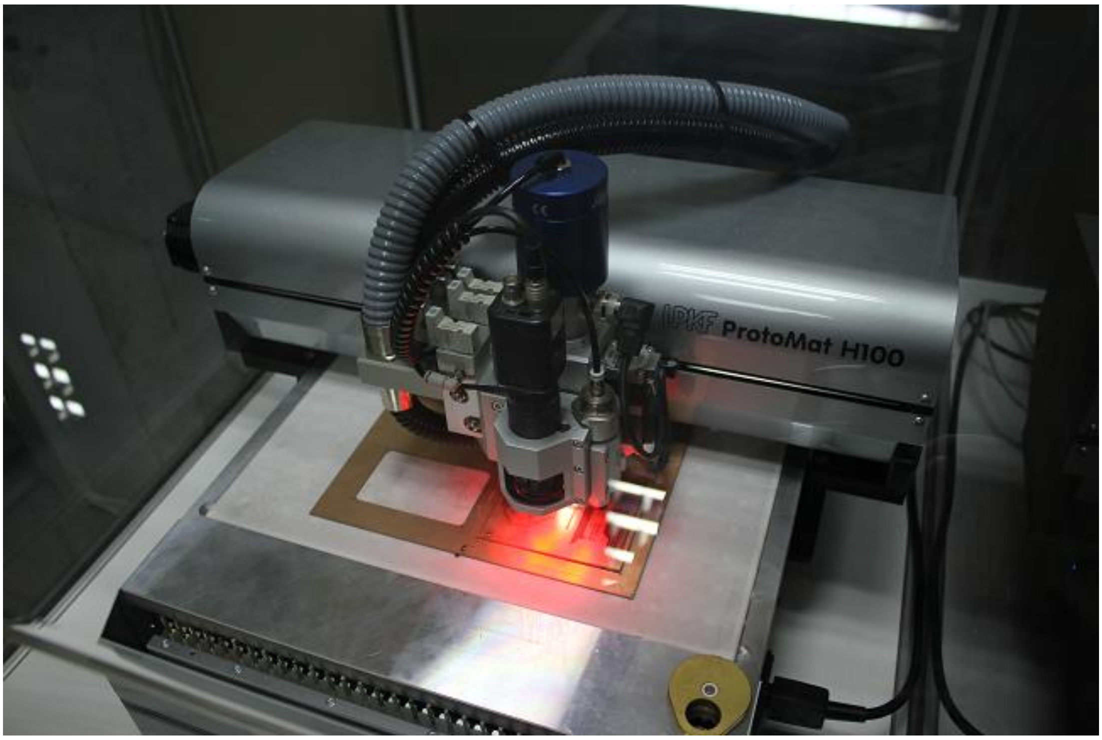

Figure 5.3 : Drilling holes using H100.

Laser engraving is used for RF PCB's due to its high quality manufacturing process, normal CNC's are much more preferred for drilling holes and cutting-out.

After machining is complete a chemical process called through-hole plating is handled to create short-circuits between top and bottom layer copper.

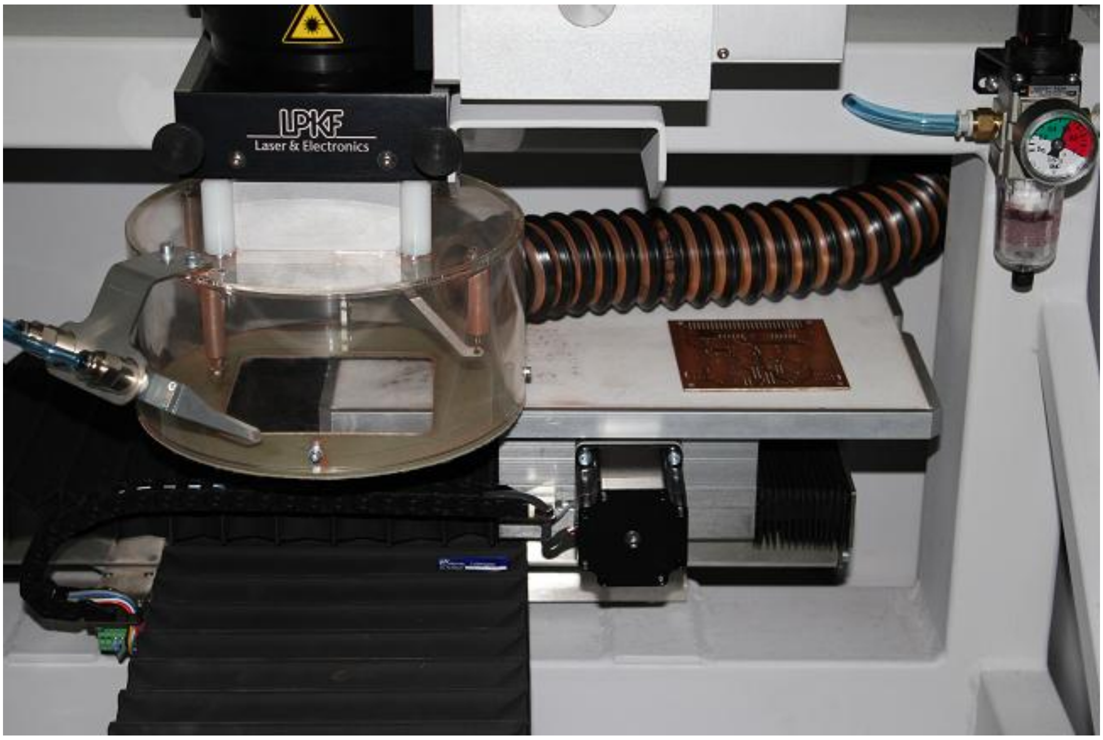

Figure 5.4 : Laser milling PCB.

5.3.2 Assembly

Very small SMD package comopnents are used on PCB in order to have a small and light system. Those components are not suitable for hand soldering, therefore a stencil and pick and place system is used for assembling board. Figure 5.5 shows standard plastic stencil for applying solder paste. Thickness of stencil is 0,125mm. This process leaves 0,125mm thick solder layer on necessary places for SMD soldering.

After solder layering components should be assembled. A special pick and place device is used for 0603 package SMD assembly. Figure 5.6 shows pick and place process. Device works with air pressure. A holder mechanism holds components with vacuum. Holder has 4 degrees of freedom and a camera for fine placement. Figure 5.7 shows holder needle, which holds and places components.

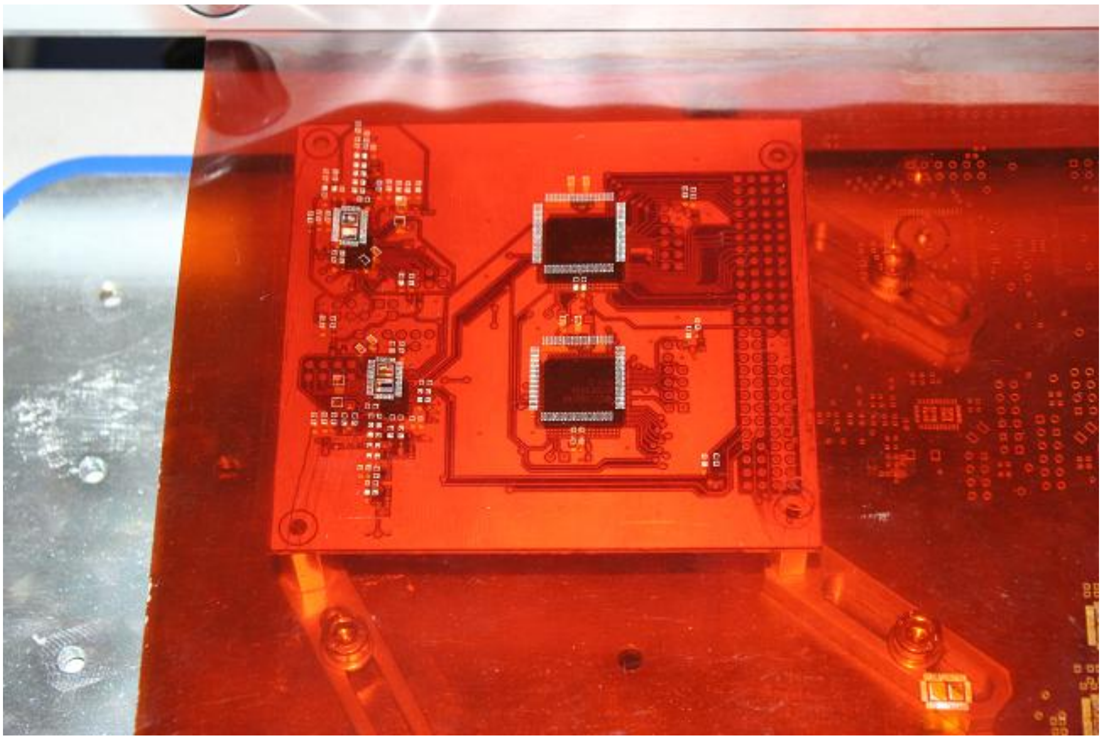

Figure 5.5 : Stencil.

Figure 5.6 : Pick and place process.

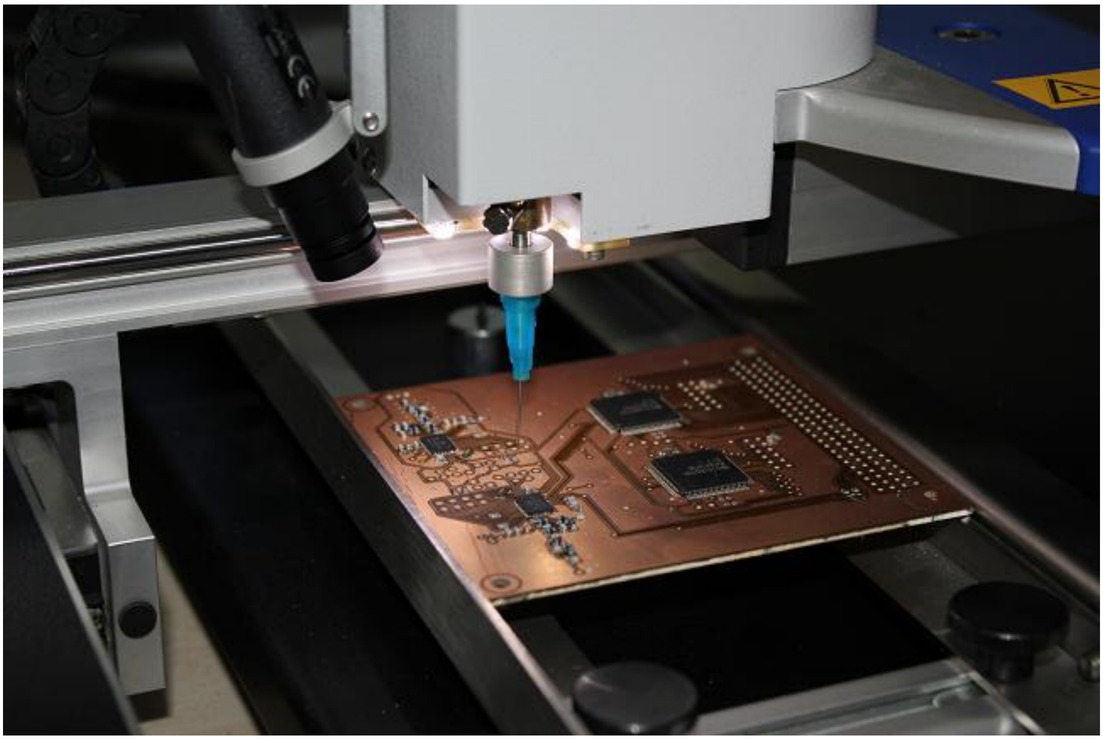

Figure 5.7 : Pick and place needle.

5.3.3 Soldering

After assembly, soldering shall be completed by melting the solder. This will be a very long and erroneous by hand soldering. A special device is used for soldering called reflow oven. This oven has high power heaters for melting solder on top layer and fans to keep the bottom layer cool enough to protect from unwanted solder melting.

Reflow oven heats up top side of PCB, because solder has lower melting point than other silicon devices soldering process completes at once. Rests of components such as connectors are hand soldered.

Final product is shown on figure 5.9. A quick inspection over the final product shows that reflow soldering was not successful. Most probably the reason was a bad quality solder.

Figure 5.8 : Reflow oven.

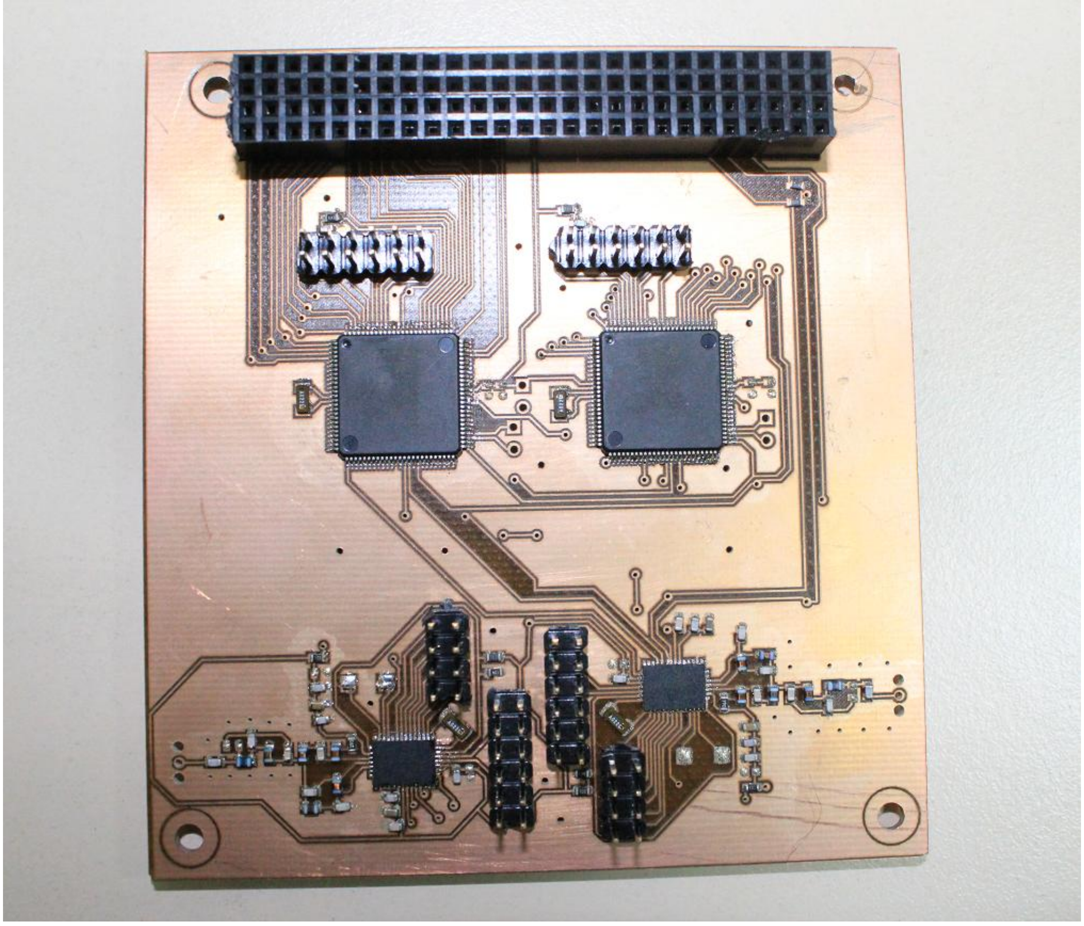

Figure 5.9 : Final circuit.

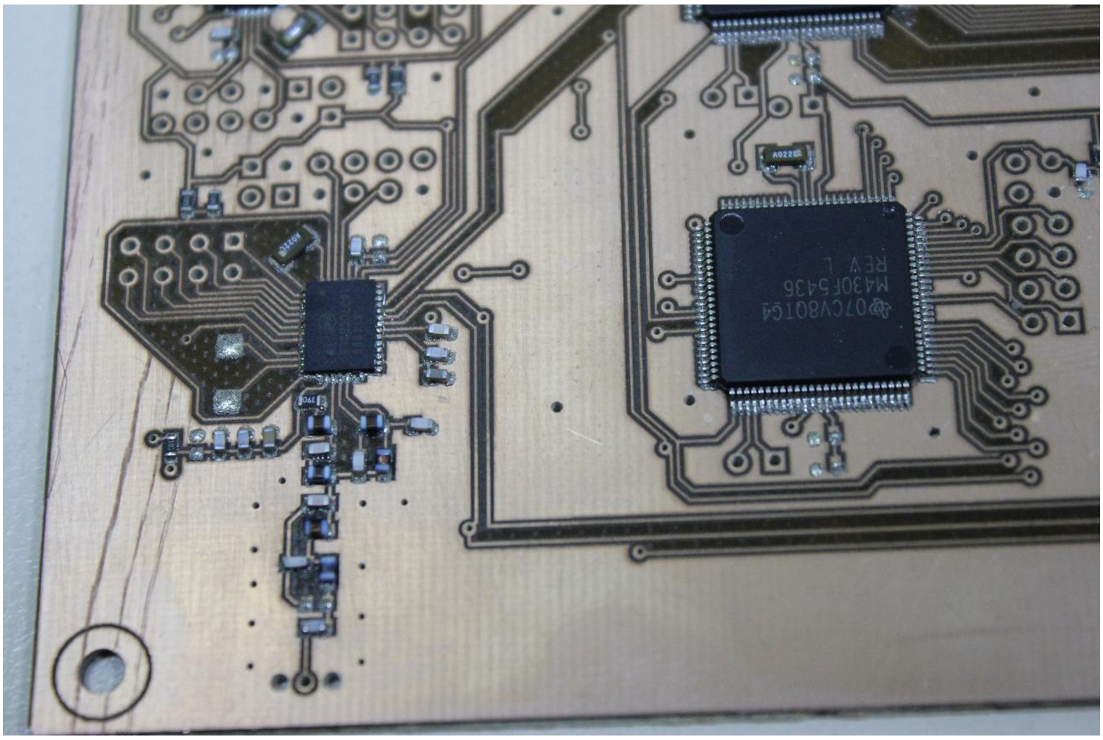

Figure 5.10 : Close-up view of the final product.

Figure 5.10 shows bad solder on both microcontroller and transceiver chips. Simple handmade repairs had been tried to fix solder issue, but due to very small component size and clearance, attempts were unsuccessful. Reader should know that soldering is a serious task and in space related companies special certified workers are employed and this was the first try of the author to solder such small, complicated and tight design. Future developments are on hold, due to budget considerations. In the future support of a real mission could provide manufacturing and implementation budget. During the timeline of this thesis manufacturing could not be finished successfully.

6. TESTING

6.1 Operational Tests

First test system is set up from development boards of microchips, due to reasons mentioned on section 5. Software drivers are tested on MSP430 development board. Various sensors are used for analog voltage reading, I2C, SPI and UART data handling without a problem.

Second test is was modem software tests. A handheld radio was used to listen modem signals. Frequency deviation and transmission speed are adjusted in order to listen signals from modem. Test system is shown on figure 6.1.

Figure 6.1 : Modem test hardware.

Third test was to combine OBC and modem. Data from computer send to microcontroller and microcontroller repeats those data to modem. In the end ASCII equivalents of characters are heard from beacon as morse signals

6.2 Range Tests

Range tests are done using ITUpSAT1 GS. Free path loss for given orbit is calculated for 700km LEO using formula 3. Best case range (700km) creates 142,2dBm loss, while worst case (1400km) creates 148,2dBm signal loss. 1km path loss is 85,3dBm for given frequency. An adjustable RF signal attenuator is used to simulate the difference. Modem is placed 1 km away from GS. A 60dB signal attenuator is placed before GS radio input. Signal strength could not be measured without a signal analyzer or a network analyzer but a weak beacon signal could listen and recorded. Figure 6.2 shows ITUpSAT1 ground station system stacked in a rack system.

Figure 6.2 : ITUpSAT1 Ground Station.

6.3 Thermal Vacuum Tests

Most important test for a spacecraft system, which uses COTS components, is considered as TVAC test. CubeSat developers generally use COTS components in their projects and those components are general developed for standard environment. Therefore, no information can be found about components vacuum characteristics.

TVAC test are done in ITU's in house facilities. The pressure inside the chamber is 10^{-5}Pa and the temperature varies from -60 to +80. Figure 6.3 shows test setup inside TVAC. PT100 thermal sensors are attached to critical components such as microcontrollers.

Figure 6.4 shows testing procedure and TVAC. After testing no physical deformation and operational anomalies were detected on systems.

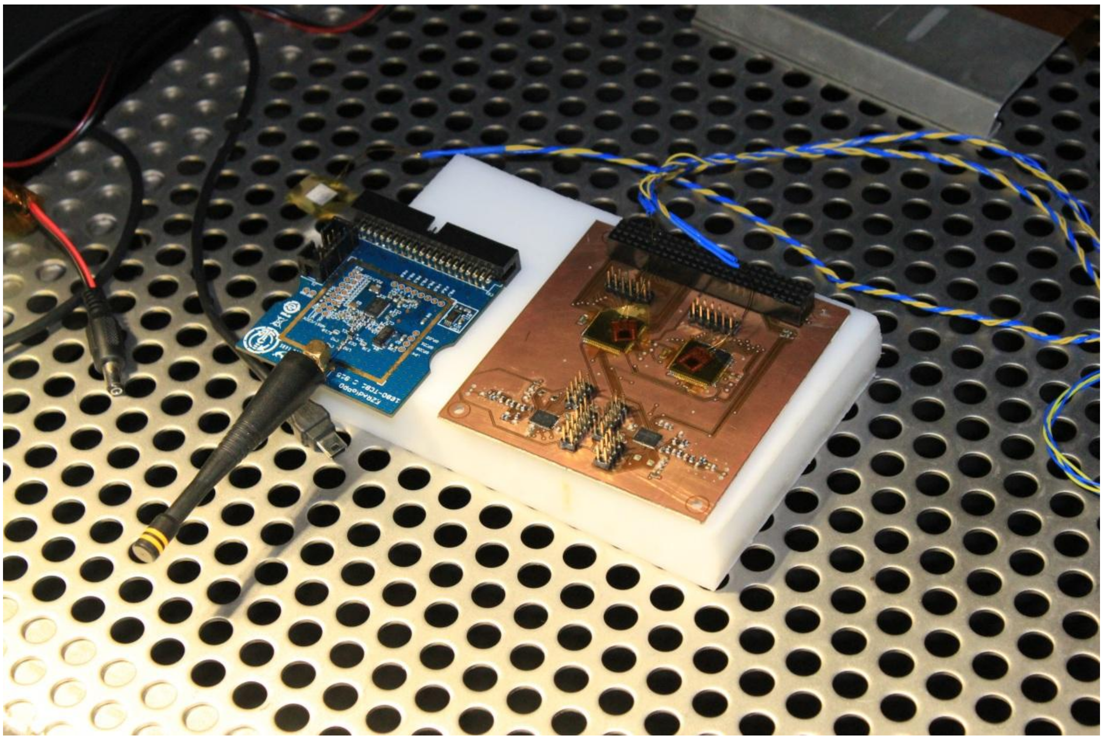

Figure 6.3 : Manufactured model and development kit inside vacuum chamber.

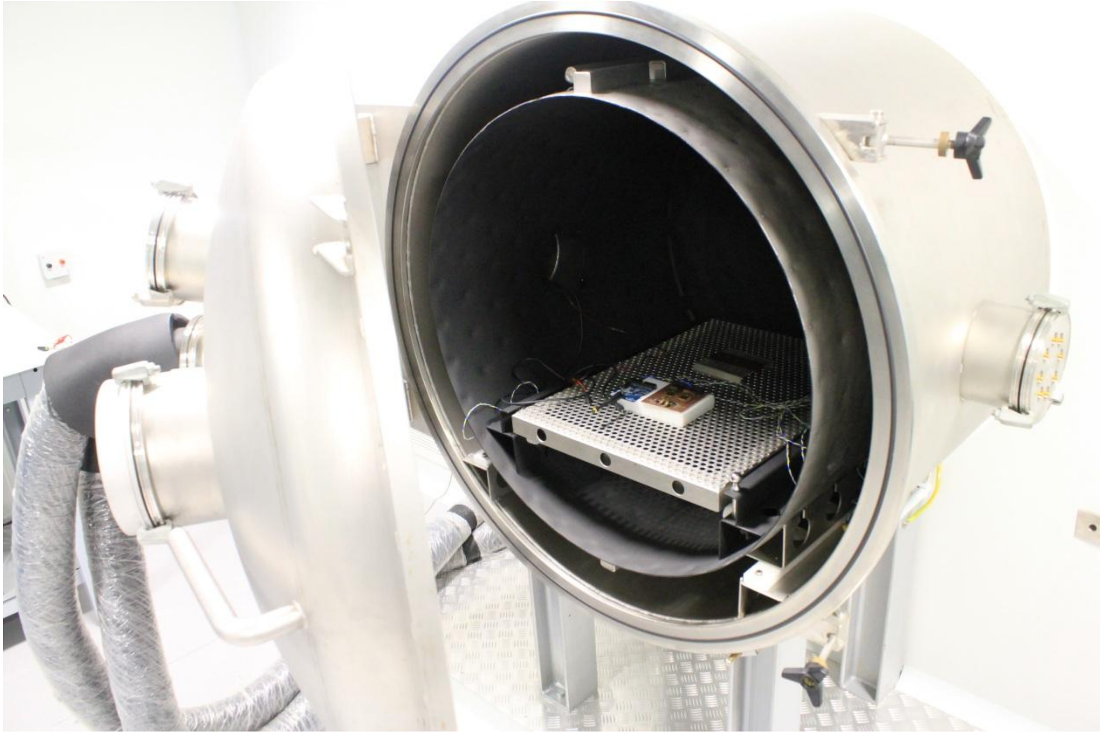

Figure 6.4 : TVAC.

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7. CONCLUSIONS AND RECOMMENDATIONS

A combined and stacked design is designed and developed. The system shows that CubeSat capabilities can be increased. More advanced missions could be accomplished with small and cheaper CubeSats. The reasons of failures could be investigated deeply and maybe even fixed.

In the future this thesis could be enchanced by completing test procedures. TVAC and radiation tests are crutial for a space mission.

A DC/DC converter could be implemented on same board to increase power efficiency. Both OBC and Modem can work down to 1.8V. A 3.3 to 1.8V DC/DC converter will increase power efficiency up to %40. That means longer battery lifetime.

Another enchancement could be adding a data storage device. Chosen microcontrollers data storage is limited to 256kbytes. This is more than enough for a simple camera mission, but for more advanced missions will require increased capacity. A simple flash memory or SD card could be imlemented on same bus.

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[20] AN436 Si4030/4031/4430/4431 PA MATCHING

APPENDICES

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APPENDIX A.1

CubeSat Standards

1. General Responsibilities

1.1 CubeSats must not present any danger to neighboring CubeSats in the P-POD, the LV, or primary payloads:

   - All parts must remain attached to the CubeSats during launch, ejection and operation. No additional space debris may be created.
   - CubeSats must be designed to minimize jamming in the P-POD.
   - Absolutely no pyrotechnics are allowed inside the CubeSat.

1.2 NASA approved materials should be used whenever possible to prevent contamination of other spacecraft during integration, testing, and launch.

1.3 The newest revision of the CubeSat Specification is always the official version

   - Developers are responsible for being aware of changes.
   - Changes will be made as infrequently as possible bearing launch provider requirements or widespread safety concerns within the community.
   - Cal Poly will send an update to the CubeSat mailing list upon any changes to the specification.
   - CubeSats using an older version of the specification may be exempt from implementing changes to the specification on a case-by-case basis.

Cal Poly holds final approval of all CubeSat designs. Any deviations from the specification must be approved by Cal Poly launch personnel. Any CubeSat deemed a safety hazard by Cal Poly launch personnel may be pulled from the launch.

2. Dimensional and Mass Requirements

CubeSats are cube shaped picosatellites with a nominal length of 100 mm per side. Dimensions and features are outlined in the CubeSat Specification Drawing (see attached). General features of all CubeSats are:

- Each single CubeSat may not exceed 1 kg mass.
- Center of mass must be within 2 cm of its geometric center.
- Double and triple configurations are possible. In this case allowable mass 2 kg or 3 kg respectively. Only the dimensions in the Z axis change (227 mm for doubles and 340.5 mm for triples). X and Y dimensions remain the same.

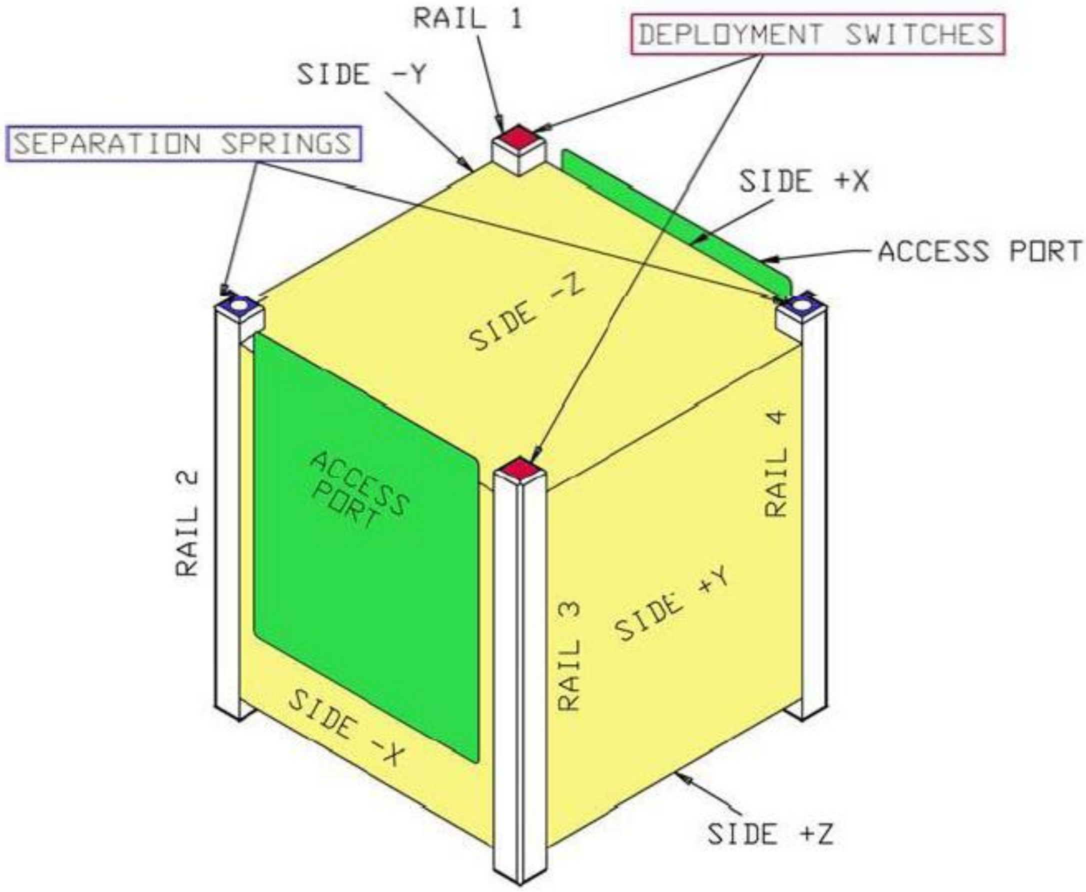

Figure A.1 : CubeSat isometric drawing.

3. Structural Requirements

The structure of the CubeSat must be strong enough to survive maximum loading defined in the testing requirements and cumulative loading of all required tests and launch. The CubeSat structure must be compatible with the P-POD.

- Rails must be smooth and edges must be rounded to a minimum radius of 1 mm.
- At least 75% (85.125 mm of a possible 113.5mm) of the rail must be in contact with the P-POD rails. 25% of the rails may be recessed and NO part of the rails may exceed the specification.
- All rails must be hard anodized to prevent cold-welding, reduce wear, and provide electrical isolation between the CubeSats and the P-POD.
- Separation springs must be included at designated contact points. Spring plungers are recommended (McMaster-Carr P/N: 84985A76 available at http://www.mcmaster.com). A custom separation system may be used, but must be approved by Cal Poly launch personnel.
- The use of Aluminum 7075 or 6061-T6 is suggested for the main structure. If other materials are used, the thermal expansion must be similar to that of Aluminum 7075-T73 (P-POD material) and approved by Cal Poly launch personnel.
- Deployables must be constrained by the CubeSat. The P-POD rails and walls are NOT to be used to constrain delpolyables.

4. Electrical Requirements

Electronic systems must be designed with the following safety features.

- No electronics may be active during launch to prevent any electrical or RF interference with the launch vehicle and primary payloads. CubeSats with rechargeable batteries must be fully deactivated during launch or launch with discharged batteries.
- One deployment switch is required (two are recommended) for each CubeSat. The deployment switch should be located at designated points (Attachment 1).

- Developers who wish to perform testing and battery charging after integration must provide ground support equipment (GSE) that connects to the CubeSat through designated data ports (Attachment 1).
- A remove before flight (RBF) pin is required to deactivate the CubeSats during integration outside the P-POD. The pin will be removed once the CubeSats are placed inside the P-POD. RBF pins must fit within the designated data ports (Attachment 1). RBF pins should not protrude more than 6.5 mm from the rails when fully inserted.

5. Operational Requirements

CubeSats must meet certain requirements pertaining to integration and operation to meet legal obligations and ensure safety of other CubeSats.

- CubeSats with rechargeable batteries must have the capability to receive a transmitter shutdown command, as per FCC regulation.
- To allow adequate separation of CubeSats, antennas may be deployed 15 minutes after ejection from the P-POD (as detected by CubeSat deployment switches). Larger deployables such as booms and solar panels may be deployed 30 minutes after ejection from the P-POD.
- CubeSats may enter low power transmit mode (LPTM) 15 minutes after ejection from the P-POD. LPTM is defined as short, periodic beacons from the CubeSat. CubeSats may activate all primary transmitters, or enter high power transmit mode (HPTM) 30 minutes after ejection from the P-POD.
- Operators must obtain and provide documentation of proper licenses for use of frequencies. For amateur frequency use, this requires proof of frequency coordination by the International Amateur Radio Union (IARU). Applications can be found at www.iaru.org.
- Developers must obtain and provide documentation of approval of an orbital debris mitigation plan from the Federal Communications Commission (FCC). Contact Robert Nelson at rnelson@fcc.org

- Cal Poly will conduct a minimum of one fit check in which developer hardware will be inspected and integrated into the P-POD. A final fit check will be conducted prior to launch. The CubeSat Acceptance Checklist (CAC) will be used to verify compliance of the specification. Additionally, periodic teleconferences, videoconferences, and progress reports may be required.

6. Testing Requirements

Testing must be performed to meet all launch provider requirements as well as any additional testing requirements deemed necessary to ensure the safety of the CubeSats and the P-POD. All flight hardware will undergo qualification and acceptance testing. The P-PODs will be tested in a similar fashion to ensure the safety and workmanship before integration with CubeSats. At the very minimum, all CubeSats will undergo the following tests.

- Vibration Test

Vibration tests serve the simulation of dynamic mechanical charges. It is tested with oscillations in the frequency response of 1 to 2000 Hz.

- Transient or virtual harmonious in the low frequency response (1 to 100 Hz)
- Chance-distributed in the high frequency response (20 to 2000 Hz) The goals of vibration tests are:
  - Proof of the durability against the appearing dynamic loads
  - Verify the faultless function of each system

For the vibration test, the satellite is housed in a test POD which is mounted to a shaker table. During the vibration test the POD, which contains the satellite, should show no natural harmonics. The dened vibration loads are measured immediately by acceleration sensors, which are mounted on dened points to the test POD. To improve the measured values, several sensors are monitoring the vibration behaviour. All these values are computed to an average value for further analyses. The vibration loads are initiated successively through three vertically main axis in the test object.

- Solar Simulation Test

The solar intensity in the low-earth-orbit is about 1371 W/m2. With the sunsimulator the effects from the high radiation to the spacecraft are tested. The sun-simulator is using a xenon lamp to simulate the radiation to the satellite. The spectrum of this lamp is except of a spectral peak, caused by the properties of xenon - very similar to the natural sun light.

- Thermal-Vacuum Test

During this test, the satellite is put into a high vacuum-chamber for several temperature cycles. Besides the number of cycles as well as the temperature thresholds for heating up and cooling down depending on the mission objectives are tested. Usually the temperature thresholds for the cooling phase are between -100°C and -180°C and for the heating phase +80°C and +130°C.

- Acoustics Test

During the launch phase of the satellite, the rocket induces sound-loads to the spacecraft structure. This sound pressure generates high loads, especially in thin parts like solar cells and PCBs. To avoid unmeant damage, the satellite has to be tested before, to confirm the sound pressure stability. To execute these tests, an acoustic noise room is necessary, which guarantees a long echo time based on its design. Standing acoustic waves can be generated. This is necessary to fulfill the requirements for the noise levels. The sound waves are generated by compressed air which is passing through special valves to excite the required frequency for the testing procedure.

First of all the satellite is tested in a level of 8 dB and 6 dB lower than the qualification level. As Second the satellite is tested in a level of 3 dB under the qualification level. Then the test with the qualification level follows and finally a low level test again. Then the measured values of both low level tests of the structures answers are compared to conclude a possible change of the structure properties. To verify the calculation of the loads the structure answers from the decline and qualification tests are compared from the classification level.

APPENDIX A.2

CubeSat Subsystems

1. EPS:

This system basically provides necessary electrical power to other systems. It has 3 sub-systems itself. These are:

1.1 Batteries:

Batteries store electrical energy for orbital eclipses when the satellite stays on the shadow of the earth, therefore no or few energy was produced. Most of the CubeSat’s have battery or other energy storage system. However there is a unique example, which doesn’t have any; Delfi-C3 [1] Delfi-C3 is a 3U CubeSat, which developed in Delft Technical University Netherlands. It doesn’t have a energy storage system. This way has its own advantages and disadvantages. The main disadvantage is power down state during eclipse. No operations could be done on this stage. But a CubeSat without a battery is simpler (their main motto)[1], lighter and more efficient. The main advantage is the CubeSat had a hard-reset every eclipse. That means even on a faulty state could be automatically overcome every orbit.

1.2 Solar Panels

Solar panels converts light energy into electrical energy, therefore generally CubeSats are covered with them. Solar Panels for terrestrial applications have between 10 to 20 percent efficiency. Due to size and weight considerations space grade solar panels have more than %30 efficiency and they are radiation resistant because solar panels are exposed to radiation more than other systems.

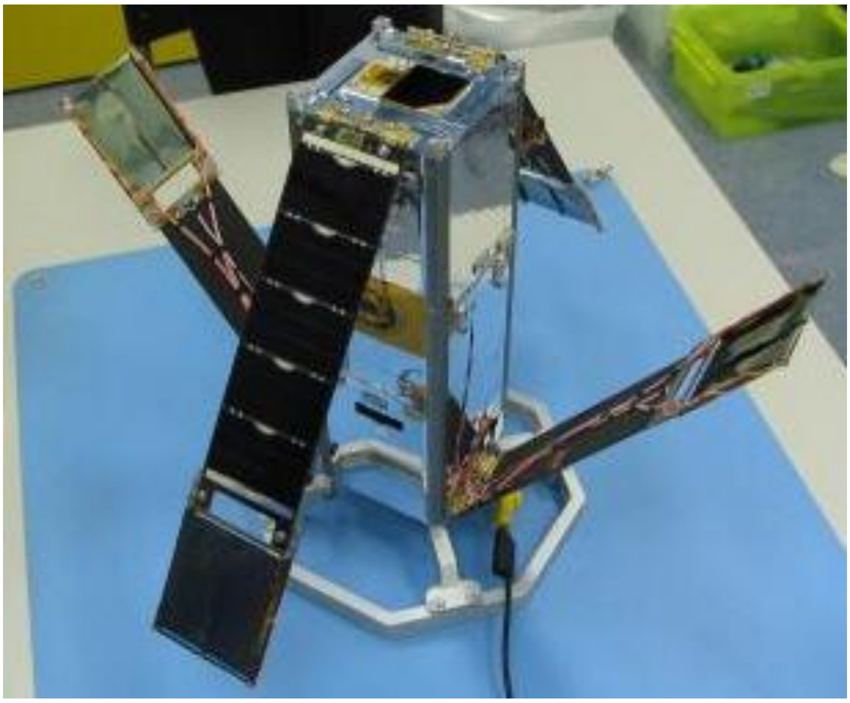

Figure A.2 : Delfi-C3 deployed solar panels.

Most of the CubeSat's use solar panels, but there is a unique example Liberdad-1 which doesn't have any. Liberdad-1 was developed by by Segio Arboleda University Colombia. It was planned to have solar cells attached to its exterior panels, but due to a problem it was launched without any. Therefore it transmit signals until it's batteries are dead. The mission was accomplished. The CubeSat was able to transmit signal for almost 3 weeks.

1.3 Regulators and Control:

Chip manufacturers use standard working voltage for their microchips. Therefore common regulated voltages are needed such as 3,3V and 5V. EPS board's mission is to maximize power production, charging batteries, regulating output voltages, executing commands and passing information about its status.

Most common example for an EPS system is Clyde-Space CubeSat EPS. It has 3 MPPT battery chargers for every axis, a detailed data interface, 3.3 and 5V regulated outputs for CubeSatKit's standard PC/104 interface.

1. CDHS:

Command and Data Handling system is responsible of controlling the satellite. It has master devices that command systems and stores important mission data. CDHS also controls data and power transmission.

1.1 OBC:

OBC is the master controller of the satellite. Depending on the mission, it can enable or disable systems to ensure robustness of the entire satellite. OBC also handles house-keeping such as making decision depending on sub-system information.

A common example to OBC systems is Pumpkin OBC. Pumpkin is one of the first companies that work on CubeSat market. Pumpkin OBC called FM430 had been used successfully on many missions as well as ITUpSAT1.

1.2 Satellite Bus:

Bus is basically a transmission line between sub-systems that handles and ensures data and power transmission. Common example to CubeSat bus systems is Pumpkin's CubeSatKit Bus. It uses PC/104 standard form factor connectors to increase compatibility.

1.2.1 Power Bus:

Electrical power generated at EPS shall be transmitted to other systems. Power bus shall be checked all time to protect systems from over-under voltage and/or short currents.

1.2.2 Data Bus:

Command and information shall be transmitted between systems. Satellites use special bus systems developed for space applications, such as SpaceWire. CubeSat's use simples systems such as I2C and SPI. I2C and SPI bus are not redundant or reliable as SpaceWire, but they are low power and a lot of COTS product support these protocols (no interface required). So that it can be used in CubeSat's. Some isolation is used between systems to have a robust data bus.

2. Structure:

CubeSat's require a solid structure to hold systems together and overcome acceleration forces during launch. Mechanic systems are considered as a part of structure.

2.1 Satellite structure:

Satellite structure is the skeleton of the satellite that holds systems together. Size of the structure is decided on. Corners of the structure shall be anodized to overcome old welding that can occur during launch and prevent successful deploy.

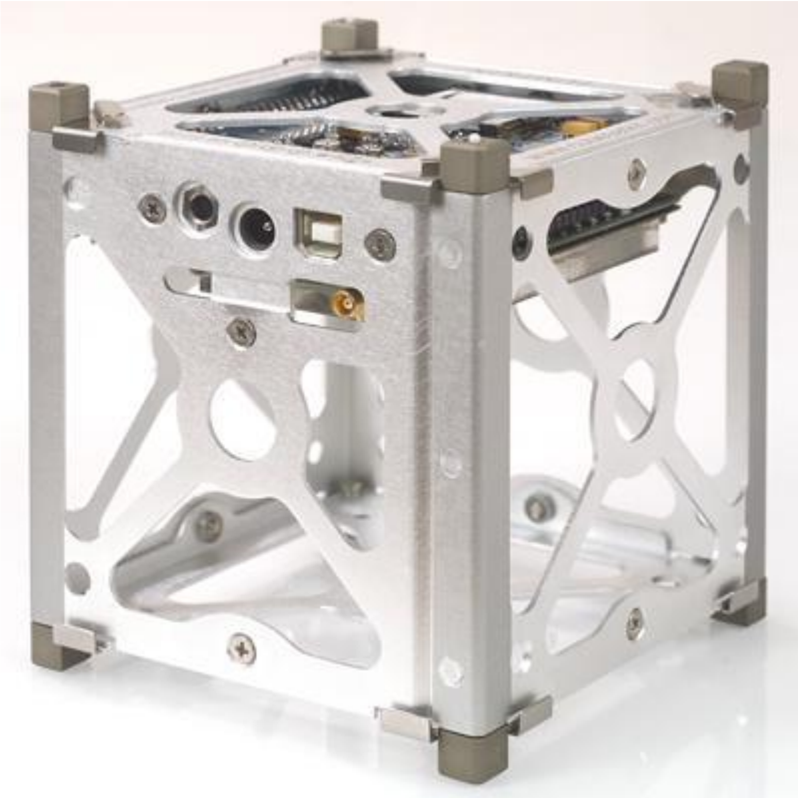

Figure A.3 : 1U CubeSat structure from CubeSatKit

2.2 Deployer:

Every satellite needs an interface for mechanic and electronic connection with the launcher rocket. A deployer ensures a secure separation from rocket and that no collision could happen after separation. CubeSat's are launched as a piggyback [piggy], therefore a problem on deployer could affect main payload and the mission.

Figure A.4 : PSLV rocket launch.

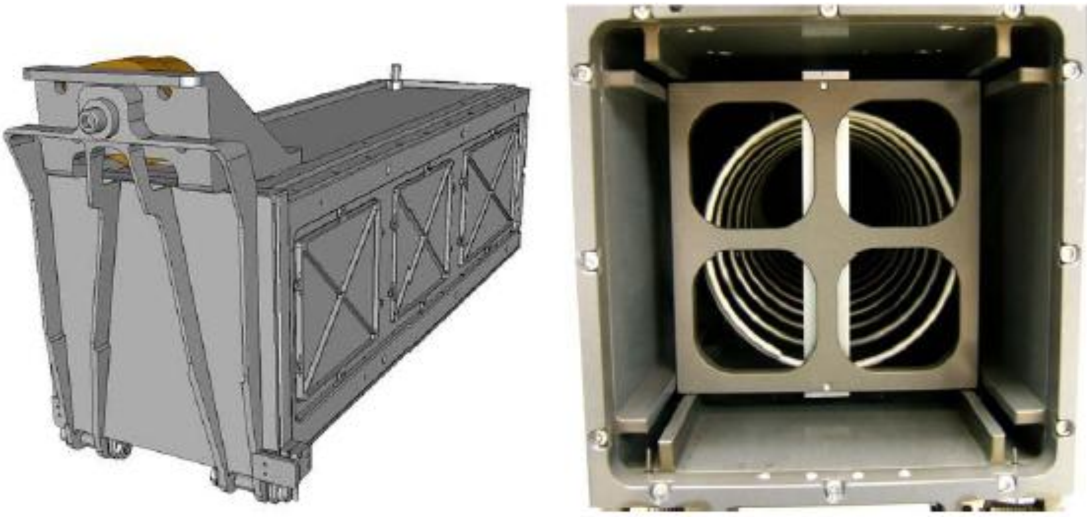

Figure A.5 : Poly Picosatellite Orbital Deployer (P-POD) and cross section.

2.3 Thermal Control:

Temperature control system keeps the satellite temperature within pre-defined limits. Waste heat, generated by systems and solar and earth infra-red radiation, needs to be radiated into space. Every system has its own temperature range, therefore conduction and radiation between systems should also be controlled. CubeSat surface is covered with solar cells to increase power generation. Remaining areas covered with different types of kapton to control heat radiation.

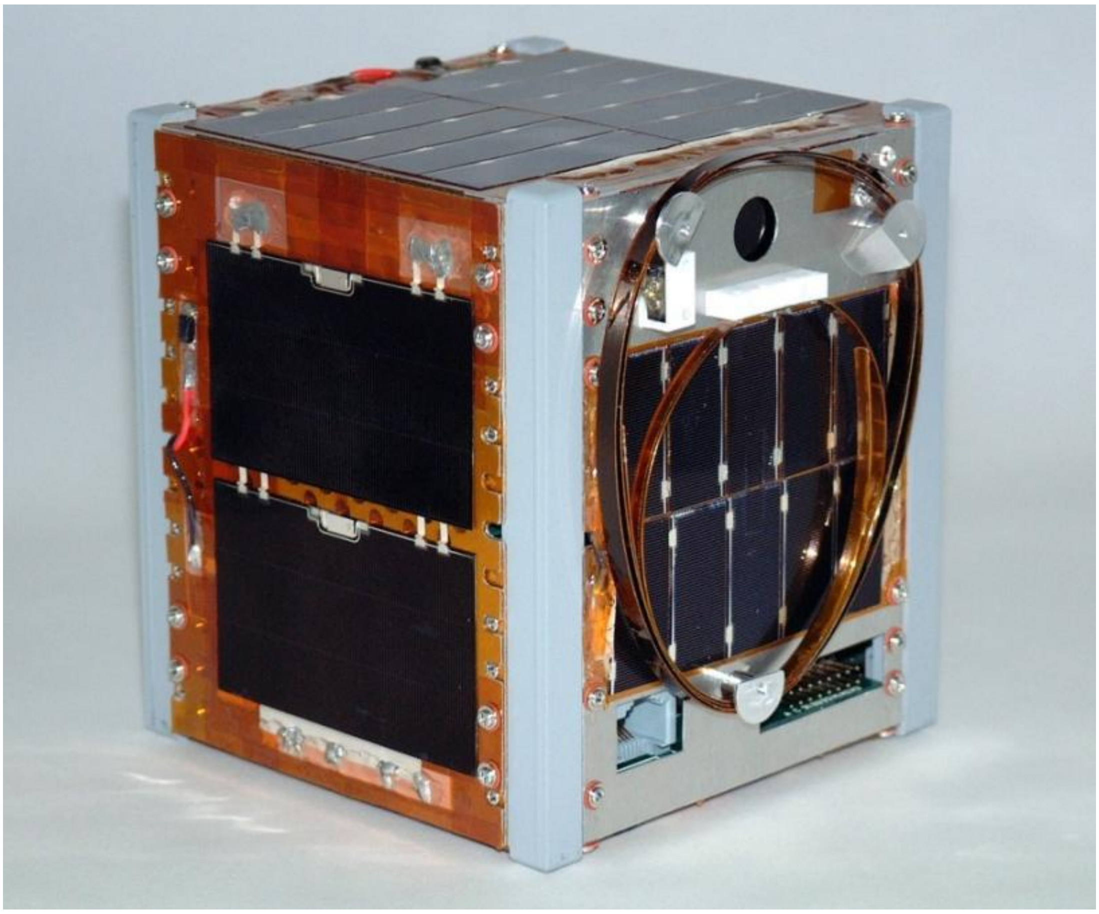

Figure A.6 : Exteriror of Tokyo University XI-V CubeSat covered by Kapton.

3.5 Mechanisms:

Due to small size of the CubeSat some systems could not fit inside deployer. An opening mechanism is required for after deployment operation. Most of the CubeSat's use UHF and VHF amateur frequency band proper antennas are supposed to be longer than satellite itself, therefore most of the satellites use custom antenna opening mechanisms to fit their antennas and deploy them after separation

3. Communication:

Satellites needs to send and receive commands and telemetry to operate

3.1 Modem:

Modem name comes from Modulator-Demodulator. It handles digital communication between satellite and ground station. Every data (command or telemetry) is transferred via modems.

3.2 Beacon:

Beacons are capable of one-way communication. CubeSat's use beacons for redundancy. Because of their simple design beacons can be used almost by every radio amateur on the world. Having a worldwide ground station network, increases satellite coverage and downloaded data.

3.3 Antenna:

Satellites use directional antennas to increase antenna efficiency; however most of the satellites don't have an attitude control system, therefore directional antennas are not common in CubeSat's

APPENDIX A.3

OBC Comparison

1. **FM430 from CubeSatKit**

- +5V single supply, 3.3V I/O
- Flight MCU is TI's single-chip 16-bit MSP430 ultralow-power RISC microcontroller with 50-60KB Flash, 2-10KB RAM, 48 I/O pins, 2 USART, 2 SPI, 1 I2C, 12-bit ADC, 12-bit DAC, 3 DMA, multiple timers, on-board temperature sensor & multiple clock sources
- Stackable 104-pin CubeSat Kit Bus connectors
- On-board low-dropout regulator and reset supervisor for maximum reliability
- SD Card socket for mass storage (32MB - 2GB)
- USB 2.0 device interface for pre-launch communications, battery charging and power
- Extensible to multiprocessor architectures, with Flight MCU NMI pin on bus
- Direct wiring for 10A Remove-Before-Flight and Launch switches
- Comprehensive overcurrent, overvoltage & undervoltage (reset) protection
- Independent latchup (device overcurrent) protection on critical subsystems
- Bus override for critical power and data/control paths
- PC/104-size footprint, with +5V and GND on
- PC/104 J1/J2 connectors
- Compatible with Pumpkin's Salvoô RTOS and HCC-Embedded's EFFS-THIN SD Card file FAT file system for ease of programming

2. **NanoMind A712B from GOMSPACE**

- Compatible with FreeRTOS and eCos realtime operating systems
- Extensive software library for FreeRTOS
- On-board temperature sensors
- Operating system + drivers preinstalled
- Compatible with ISIS, GOM, CubeSatKit and ClydeSpace products
- Attitude Stabilization System:
  - 3-Axis magnetoresistive sensor
  - 3 PWN bidirectional output 3.3-5V/±3A

- Interface to 6-analog inputs (e.g. sunsensors)
- SPI interface to e.g. gyroscopes
- High-performance 32-bit ARM7 RISC CPU
- Clock speed: 8-40 MHz
- 2MB Static RAM, 4MB Data Storage, 4MB Code Storage
- 2GB MicroSd card support
- Power monitor/power-on reset
- CAN bus, I2C interface
- Temperature tolerance -40 to 85°C
- Polyimide PCB with high thermal tolerance
- PC/104-size footprint, with +5V and GND on
- 3.3V single supply voltage

3. **Andrews Model 160**

- Dual PPC 405 (400MHz) processors or Microblaze (100MHz) processor
- 2GB of Flash, 64MB of SDRAM
- Watchdog Timer for SEU protection
- Internal Error Detection and Correction features
- Supports GPS daughter card
- Two parallel digital camera interfaces
- Reprogrammable On-Orbit
- Not fully compatible with CubeSat PC-104 standards.
- Processor Xilink Virtex 4FX with dual PPC 405 (400 MHz) / Microblaze (100 MHz)
- Radiation Capabilities: SEU/SEFI detection and reset
- Power Consumption (Nominal/Max): <5W / 9W
- Interfaces: Ethernet, RS422/485, SPI, I2C, 1553 (optional), 2 cameras ports
- Reprogrammable On-Orbit
- Input Power Options: 6.5V, 12V, 28V
- Board properties: Polyimide PCB

APPENDIX A.4

Modem Requirements and Tasks

1. Modem Requirements

- The frequencies for communicating with the satellite shall lie within the frequency bands allocated to the amateur satellite service.
- Any data transmitted to and from the satellite other than telecommands shall not be encrypted in any way
- All receivers that can receive telecommands shall be turned on by default
- All UHF and VHF antenna connections and transmission lines on the satellite will have an impedance of 50 ohm
- It shall be prevented that parties other than designated satellite operators shall be able to command the satellite
- The center frequency of the UHF signal for the Modem transceiver shall lie within the frequency band 435-438 MHz

2. Modem Tasks

- Receive telecommands transmitted by the Ground Station
- Transmit telemetry (payload and housekeeping data) from the satellite to the Ground Station
- Receive other data such as software updates transmitted by the Ground Station Network
- In the link budget a minimum link margin of 3 dB is required for all transmission links

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List of Publications and Patents:

Lessons Learned: ITUpSAT-1: 2nd Nanosatellite Symposium March 14th-16th, 2011 University of Tokyo, Japan

Design of a high-efficient, redundant, long-life Electrical Power Subsystem for Cubesats: 8th IAA Symposium on Small Satellites for Earth Observation April 04 - 08, 2011 Berlin, Germany

Development of a fly-back CANSAT in 3 weeks: 5th International Conference on Recent Advances in Space Technologies 09-11 June 2011, Istanbul, Turkey