İSTANBUL TECHNICAL UNIVERSITY ★ INSTITUTE OF SCIENCE AND TECHNOLOGY

DESIGN STUDY OF A COMMUNICATION SUBSYSTEM AND GROUND STATION FOR ITU-pSAT II

M.Sc. Thesis by
Melih FİDANOĞLU

Department : Institue of Science and Technology

Programme : Defence Technologies

JANUARY 2011

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JANUARY 2011

İSTANBUL TEKNİK ÜNİVERSİTESİ ★ FEN BİLİMLERİ ENSTİTÜSÜ

ITU-pSAT II İÇİN İLETİŞİM ALTSİSTEMİ VE YER İSTASYONU TASARIM ÇALIŞMASI

YÜKSEK LİSANS TEZİ

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OCAK 2011

FOREWORD

First of all, I would like to thank my advisor, Gökhan İnalhan for the opportunity to work in the fantastic setup of Control and Avionics Laboratory and to work with the research team here.

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January 2011

Melih Fidanoğlu
Mechatronics Engineer

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ABBREVIATIONS

ADCS : Attitude Determination and Control System
AFSK : Audio Frequency Shift Keying
AIS : Automatic Identification System
AM : Amplitude Modulation
AMSAT : The Radio Amateur Satellite Corporation
ARQ : Automatic Repeat reQuest
ARR : Andøya Rocket Range
ASK : Amplitude Shift Keying
BPSK : Binary Phase Shift Keying
CCSDS : The Consultative Committee for Space Data Systems
CRC : Cyclic Redundancy Check
D-STAR : Digital Smart Technologies for Amateur Radio
DTMF : Dual Tone Multi Frequency
DTU : Denmark Technical University
EELV : Evolved Expendable Launch Vehicle
EIRP : Effective Isotropic Radiated Power
ELF : Extremely Low Frequency
ESA : European Space Agency
ESPA : EELV Secondary Payload Adapter
FEC : Forward Error Correction
FM : Frequency Modulation
FSK : Frequency Shift Keying
GFSK : Gaussian Frequency Shift Keying
GMSK : Gaussian Minimum Shift Keying
GS : Ground Station
HF : High Frequency
HISS : Hawk Institue fir Space Sciences
HRD : Ham Radio Deluxe
ISM : Indsutrial, Scientific and Medical
ISO : International Standards Organization
LEO : Low Earth Orbit
MSK : Minimum Shift Keying
NASA : National Aeronautics and Space Administration
NSC : Norwegian Space Center
NSP : Nanosatellite Communication Protocol
NUC : Narvik University College
OOK : On-Off Keying
OSCAR : Orbiting Satellite Carrying Amateur Radio
OSI : Open Systems Interconnection
P-POD : Poly-Picosatellite Orbital Deployer
PM : Phase Modulation
PSK : Phase Shift Keying
PSLV : Polar Satellite Launch Vehicle
QPSK : Quadrature Phase Shift Keying

RF : Radio Frequency
RLP : Radio Link Protocol
SCORE : Signal Communications Orbit Relay Equipment
SFL : Space Flight Laboratory
SPL : Single Picosatellite Deployer
SRLL : Simple Radio Link Layer
SSB : Single-Sideband Modulation
SSDL : Space Systems Development Laboratory
SUPSI : University of Applied Sciences of Southern Switzerland
T-POD : Tokyo Picosatellite Orbital Deployer
TNC : Terminal Node Controller
UHF : Ultra High Frequency
UTIAS : University of Toronto Institue of Aerospace Studies
UTMB : University of Texas Medical Branch
VHF : Very High Frequency
X-POD : eXperimental Push Out Deployer

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DESIGN STUDY OF A COMMUNICATION SUBSYSTEM AND GROUND STATION FOR ITU-pSAT II

SUMMARY

This thesis is about the communication part of the ITUpSAT II satellite project of Control and Avionics Laboratory of Istanbul Technical University Aeronautics & Astronautics Faculty and supported by TUBITAK.

This thesis will start by giving a brief history of artificial satellites in general, and then describes the concept of the cubesat. As one of the aims of the cubesats are low cost design and launch, a special attention is given to cubesat launch deployers.

Second chapter gives information about several subsystems of the first cubesat project in Turkey, ITUpSAT I. This chapter is closed by giving the flight results of ITUpSAT I, which is an analysis of the strength of beacon signals.

Third chapter is about ITUpSAT II. In this chapter, a brief information is given for each subsystem. As the satellite is still in design phase, the descriptions about subsystems are subject to change.

Fourth chapter describes the communication subsystems and ground stations of some of the cubesats. As there are more than a hundred launched cubesats, in this chapter, the cubesats are chosen in terms of the peculiarity of the work, and the extend of spearheading in the cubesat community.

Chapter five, six and seven will give theoretical background for communication systems. Specifically, chapter five will give information about modulation techniques. As the communication between satellites and ground station is digital communication, analog modulation techniques are described briefly, and special attention is given to digital modulation techniques. In chapter six, protocols are described. Here, especially AX.25 protocol is given a special attention, because in most of amateur satellites and cubesats, this is the protocol that is used. In chapter seven, link budget calculation is described following a brief power budget calculation.

Eighth chapter is about hardware options for communication subsystem used on cubesats. In this chapter, only commercially available communication subsystems are considered. Also, only the transceivers for 70cm and 13cm bands are considered, because it is planned to use these bands for ITUpSAT II.

Ninth chapter is about the hardware and software options for ground station. In this chapter, the hardware part mainly evolves around the transceiver. In software part, transceiver controllers, rotator controllers, satellite trackers and digital mode softwares are described.

ITU-pSAT II İÇİN İLETİŞİM ALTSİSTEMİ VE YER İSTASYONU TASARIM ÇALIŞMASI

ÖZET

Bu tezin konusu İstanbul Teknik Üniversitesi Kontrol ve Aviyonik Laboratuarı tarafından yürütülen ve TÜBİTAK tarafından desteklenen ITUpSAT II projesinin iletişim kısmıyla alakalıdır.

Bu tezde ilk olarak yapay uyduların tarihi hakkında kısa bir bilgi verilecek, ardından da küpsat konsepti anlatılacaktır. Küpsatların amaçları arasında düşük dizayn ve fırlatma maliyeti yer aldığından dolayı, küpsat fırlatma dağıtıcılarına özellikle değinilmiştir.

İkinci bölümde Türkiye'nin ilk küpsat projesi olan ITUpSAT I uydusunun çeşitli altsistemleri hakkında bilgiler verilmiştir. Bölümün sonunda ise ITUpSAT I'in uçuş sonuçları verilmiştir, ve bu sonuçlarda beacon sinyalinin gücü analiz edilmiştir.

Üçüncü bölüm ITUpSAT II uydusu hakkındadır. Bu bölümde her altsistem hakkında kısa bilgiler verilmektedir. Uydu halen tasarım halinde olduğu için, altsistemler hakkında verilen bilgiler değişime tabidir.

Dördüncü bölümde ise bazı küpsatların iletişim sistemleri ve yer istasyonları anlatılmıştır. Şu an itibariyle yüzden fazla küpsat fırlatıldığı için, bu bölümde belli başlı uydulara yer verilmiştir. Seçimde ana kriterler olarak yapılan çalışmanın özgünlüğü ve de küpsat camiasında yarattığı etki dikkate alınmıştır.

Beşinci, altıncı ve yedinci bölümler iletişim sistemleri hakkında teorik artalan bilgisi vermeyi amaçlamaktadır. Beşinci bölümde modülasyon teknikleri hakkında bilgi verilecektir. Uydular ve yer istasyonları arasındaki iletişim sayısal haberleşme olduğundan dolayı analog haberleşmeye kısaca, ve dijital modülasyon tekniklerine daha ayrıntılı bir şekilde değinilecektir. Altıncı bölümde protokoller tanıtılacaktır. Burada tanıtılan protokoller arasında özellikle AX.25 protokolü üzerinde durulacaktır, çünkü amatör uyduların ve küpsatların haberleşmesinde genellikle AX.25 protokolü kullanılmaktadır. Yedinci bölümde ise kısa bir güç bütçesini takiben link bütçesinin hesaplanması üzerinde durulacaktır.

Sekizinci bölümde küpsatlardaki iletişim altsisteminde kullanılan donanım seçenekleri üzerinde durulacaktır. Burada sadece ticari olarak ulaşılabilecek iletişim sistemleri ele alınacaktır. Ayrıca, ITUpSAT II uydusunda 70cm ve 13cm bandlarının kullanılması düşünüldüğünden sadece bu bandlarda çalışan alıcı-vericiler ele alınacaktır.

Dokuzuncu bölümde ise yer istasyonu için donanım ve yazılım opsiyonları ele alınacaktır. Bu bölüm genellikle alıcı-verici üzerine olacaktır. Yazılım kısmında ise alıcı-verici kontrolcüleri, rotator kontrolcüleri, uydu takip yazılımları ve dijital mod yazılımları anlatılacaktır.

1. INTRODUCTION

This diploma thesis describes the construction of communication subsystem of the planned cubesat ITU-pSAT II, and construction of the design of ground station which is to be built at Istanbul Technical University.

In the introduction, a brief history of the artificial satellites, cubesat concept, a review of other cubesat's communication systems and other cubesat makers' ground station will be given, followed by an introduction of ITU-pSAT II satellite.

1.1 A Brief History of the Artificial Satellites

Although mathematicians such as Isaac Newton, Leonhard Euler and Joseph Louis Lagrange made some theoretical contributions to astronautics, the question of space flight started literally with novelists Jules Verne [1] and Edward Everett Hale. Edward Everett Hale brought the idea of artificial satellites through his short story, The Brick Moon. Later, Jules Verne followed the trend in his novels such as The Begum's Millions, and From the Earth to the Moon, and gave ideas about artificial satellites, rockets and other launch types.

First academic treatise on rocketry for launching spacecraft came from Konstantin Tsiolkovsky through "The Exploration of Cosmic Space by Means of Reaction Devices" in 1903. In his publication, Tsiolkovsky calculates that the required speed for a minimal orbit around the Earth is 8 km/s, and he uses a multi-stage rocket with liquid propellants to launch the space vehicle to the orbit [2].

Development of liquid-fuelled rockets by Robert Goddard at the early 1920s made the spaceflight possible. In particular, his two patents, which are multi-stage rocket design and liquid-fuelled rocket design, both of which were patented at 1915, can be regarded as important milestones in space travel. Goddard also created and built the world's first liquid-fueled rocket, and launched on March 16, 1926 [3].

In 1928, Herman Potočnik published his book "The Problem of Space Travel – The

Rocket Motor". In his book, he describes a space station and calculates its geostationary orbit. In addition to this, he writes about communication between these satellites and the ground station using the radio.

In 1945, Arthur C. Clarke conceived the idea uf using the communications satellites for mass communications in a Wireless World magazine article. In his article on extraterrestrial relays, for worldwide coverage, he describes a three-satellite worldwide network. It is possible to have a coverage of entire planet except polar regions [2].

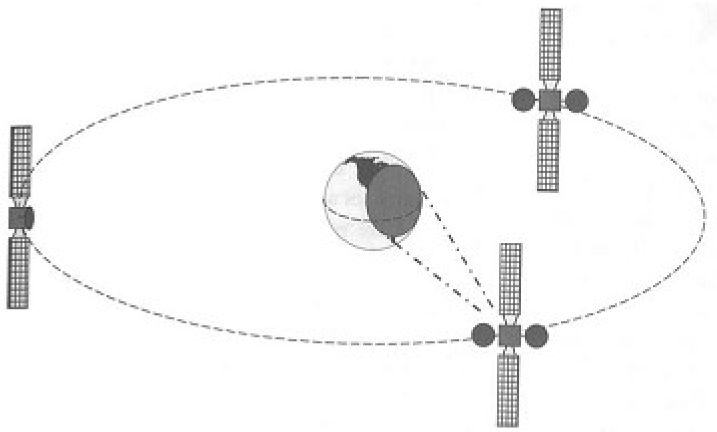

Figure 1.1 : Three geostationary communication satellites can provide nearly worldwide coverage.

There are a few hundred satellites that are currently operational, and thousands of unused satellites and satellite fragments on several orbits, as well as the satellites that reentered the Earth. Here, some of the satellites that have historical importance will be discussed.

1.1.1 Early history of artificial satellites

Sputnik-1 was the first Earth-orbiting artificial satellite. It was launched on October 4, 1957 into an elliptical LEO by the Soviet Union. It transmitted radio signals at 20.005 and 40.002 Mhz for 22 days, and remained on orbit for three months before reentering the Earth's atmosphere [4]. This satellite can be seen as the start of Space Race between United States and Soviet Union.

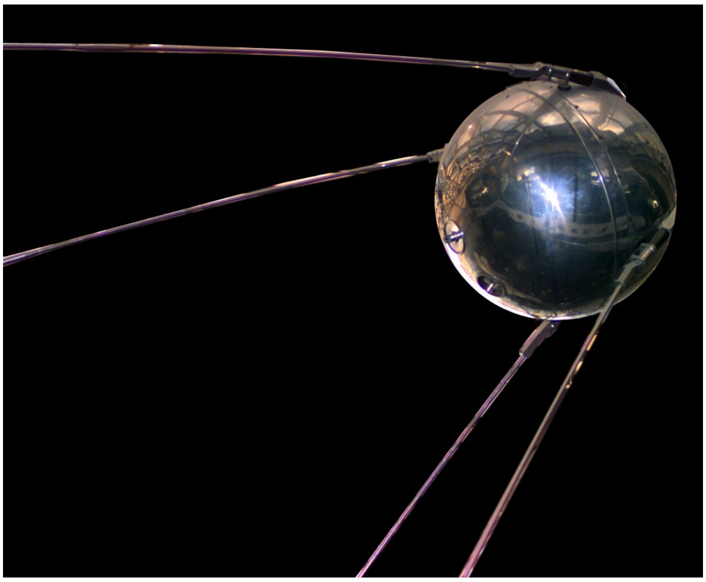

Figure 1.2 : Sputnik-1 is the first artificial satellite.

Sputnik-2 was launched on November 3, 1957. It was the first spacecraft to carry a living animal (besides microorganisms), a dog named Laika, into Earth orbit. The dog died after a few hours, due to overheating and stress [5]. Korabl-Sputnik-2, commonly known as Sputnik-5, housed two dogs named Belka and Strelka, and other several animals, and was launched on August 19, 1960. It returned to Earth the next day with all of its passengers alive [6].

Explorer 1 was the first Earth satellite of the United States. It was launched on January 31, 1958 into a highly elliptical orbit with a perigee of 358 km and an apogee of 2550 km. The satellite housed an Iowa Cosmic Ray Instrument, and it was the first spacecraft to detect the Van Allen radiation belt. It returned data for four months until its batteries finished, and remained in orbit until 1970 [7].

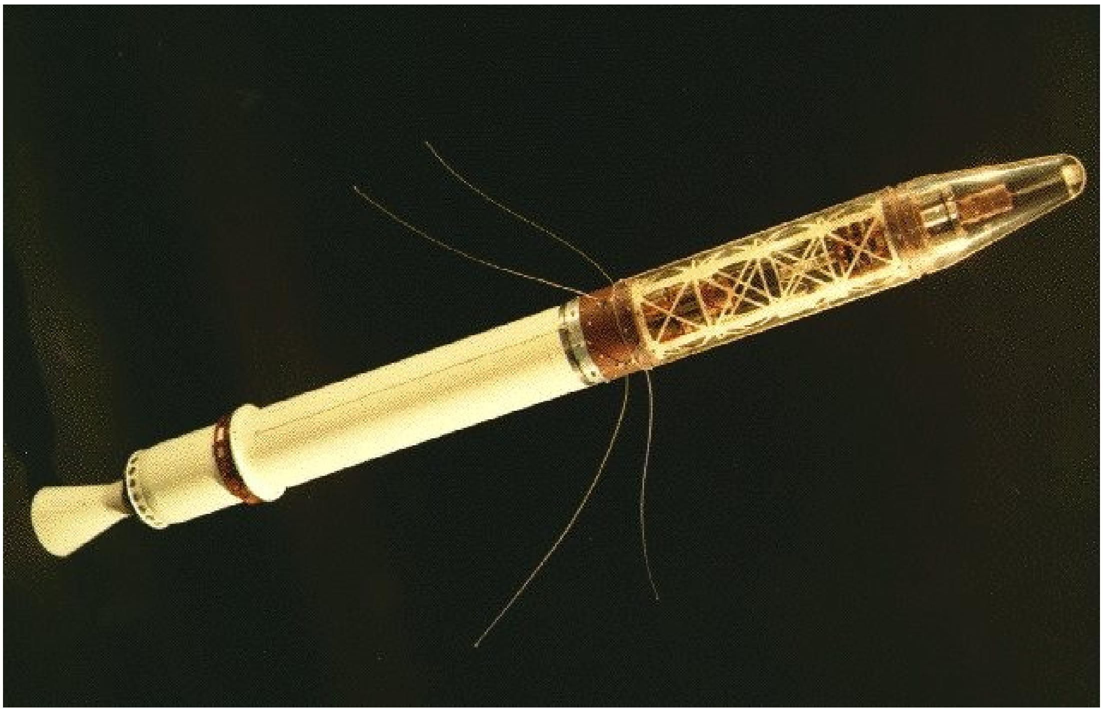

Figure 1.3 : Explorer 1 is the first US satellite.

Vostok 3KA spacecraft was another milestone in artificial satellite history. The spacecraft, which was launched on April 12, 1961, carried a human into outer space for the first time. The passenger of this flight, which is also the first manned orbital flight, was cosmonaut Yuri Gagarin [8].

Figure 1.4 : Vostok-1 carried the cosmonaut Yuri Gagarin to orbit.

In the following years, several countries sent their satellites to orbits, however only a handful of them have launch capability. The countries that have launch capabilities are Russia and Ukraine (both former Soviet Union countries), United States, Japan, China, India, Israel, and Iran. Also there is ESA (European Space Agency) that has launch capability. United Kingdom and France launched with their own rockets, but now they both launch satellites under ESA [2].

First communications satellite was Project SCORE (Signal Communications Orbit Relay Equipment). It was launched on December 18, 1958 with an Atlas-B rocket. It broadcasted a Christmas message via short wave frequency from US President Dwight D. Eisenhower [9].

As geostationary orbit was deemed to be too speculative after the launch of Sputnik and SCORE, efforts were concentrated for LEO satellites with passive reflector and active repeater technology. Until the launch of first geostationary satellites, projects like Echo, Advent, Telstar, Courier, and Relay were pursued by organizations like NASA and AT&T [10].

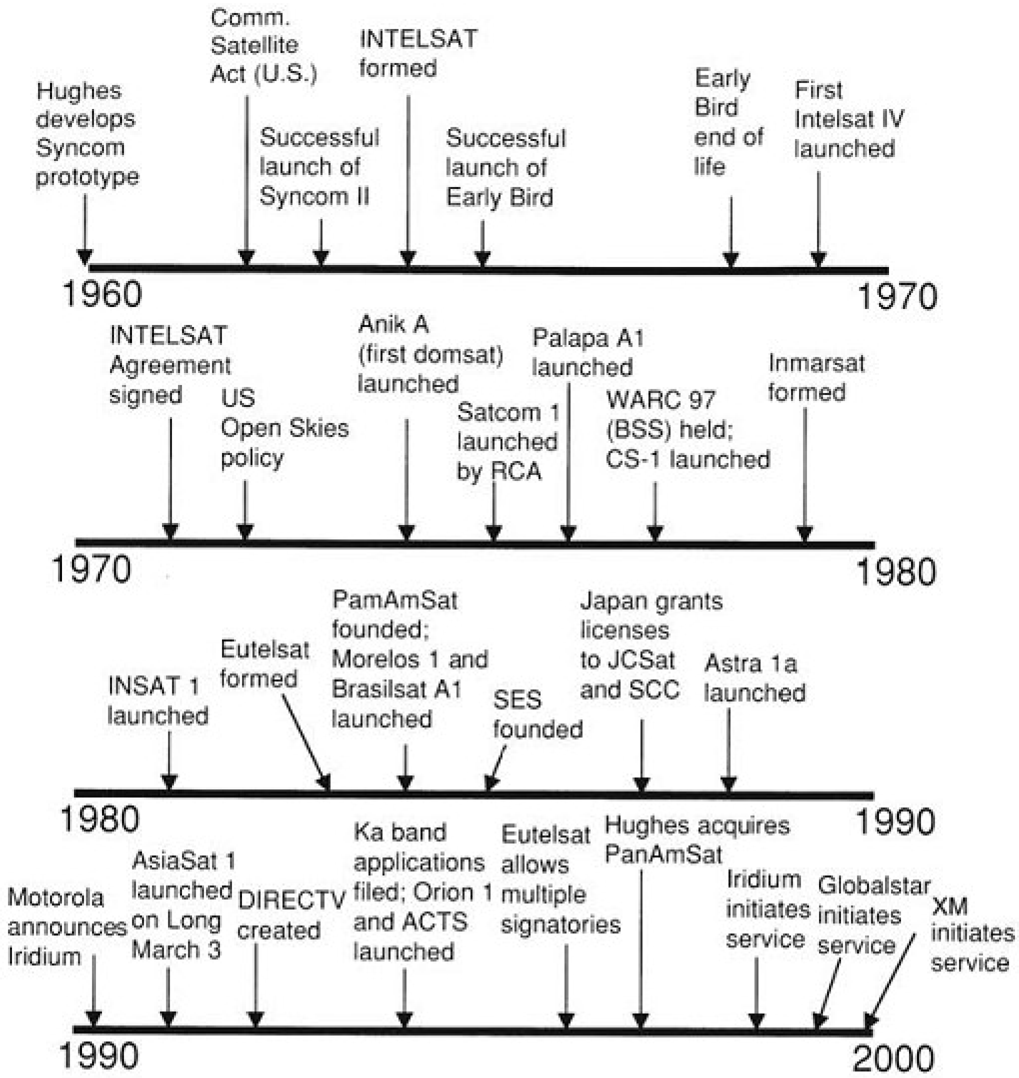

Figure 1.5 : Timeline of critical events in the satellite communications industry.

Project Echo was first passive communications satellite. It was launched on August 12, 1960. The satellite was a metalized balloon shaped satellite, and microwaves were reflected or bounced off its surface, which makes it not a transmitter but a reflector [11].

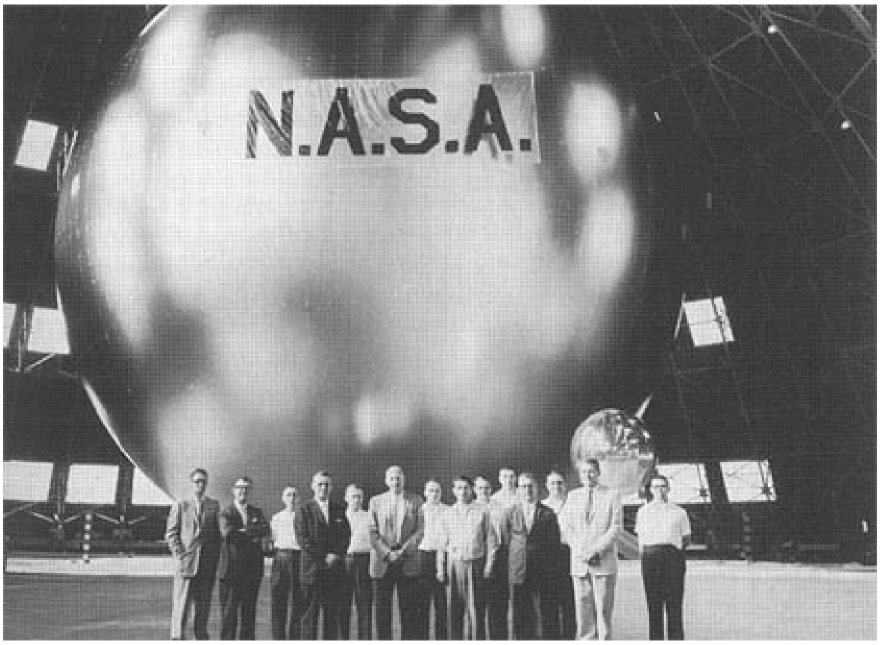

Figure 1.6 : Echo-1 was a balloon shaped satellite.

World's first active repeater satellite was Courier 1B. It was launched on October 4, 1960. The satellite used approximately 19000 solar cells and Nickel Cadmium storage batteries. It had a message transmission capacity of 55000 bit/s. The satellite worked successfully for seventeen days [12].

Figure 1.7 : Courier 1B with its many solar cells.

Early years of the satellite launches saw many firsts. Telstar 1 was the first ever satellite to relay television signals. The satellite, which was launched on June 10, 1962, and it relayed the first television pictures, telephone calls, fax images and provided the first live transatlantic television feed. It also relayed the first publicly available live transatlantic television signal, thus taking a step in taking the communication to the masses [13].

Syncom program, where Syncom stands for synchronous communication satellite, started at 1961. The three satellites of Syncom program used spin stabilization for orientation control and microwaves for communication. Syncom II was launched at July 1963, and became the first operational geostationary satellite providing intercontinental telecommunications, although first geostationary satellite was Syncom I, which went silent due to electronics failure. These two Syncom satellites, along with their sister satellite Syncom III, are still in orbit [14].

Figure 1.8 : Syncom II is the first geostationary communication satellite.

1.1.2 Amateur radio satellites

After listening the signals from the first satellite, Sputnik-1, willing amateur radio operators all around the world accepted to tune in Explorer's radio signals. Around the same time, a West Coast group of Hams toyed with the idea of launching an amateur satellite into orbit. After all, Hams thought that they all knew about satellite communications. This chapter will investigate the important events in the amateur satellite history, whether this satellites are amateur radio satellites, or the satellites open to amateur use.

This group from California later organized a group called Project OSCAR (OSCAR stands for Orbiting Satellite Carrying Amateur Radio). After a series of high level exchanges between Project OSCAR members, the American Radio Relay League and the United States Air Force, first satellite called OSCAR-1 was launched as a secondary payload to the satellite Discoverer XXXVI. It was launched on December 12, 1961.

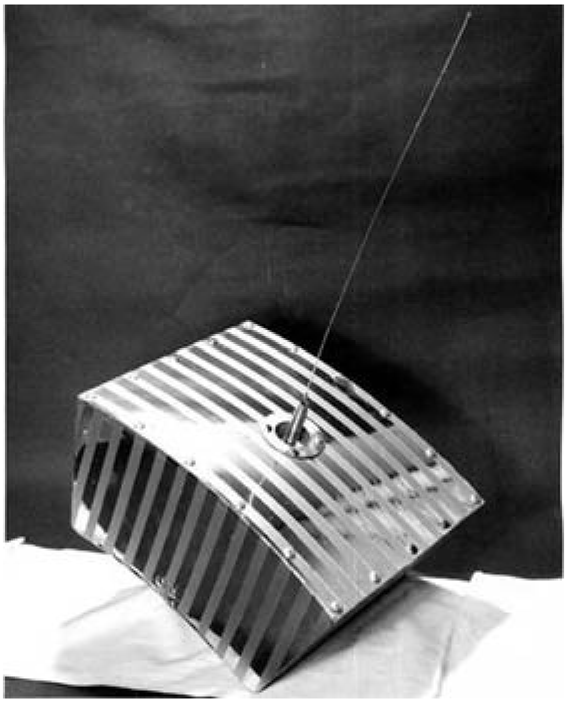

Figure 1.9 : OSCAR-I is the first amateur satellite.

OSCAR-I satellite was the first satellite to be launched as a secondary payload. It carried a small beacon transmitter, allowing the ground stations to measure the radio propagation through the atmosphere, and also an internal temperature of the satellite. More than 570 radio amateurs dorwarded their data to Project OSCAR data reduction center, which may be seen as an overwhelming success.

Oscar-III was the first amateur satellite to carry a transponder. It could receiver signals in the vicinity of 146 Mhz, and retransmit them near 144 Mhz with a power of about 1W.

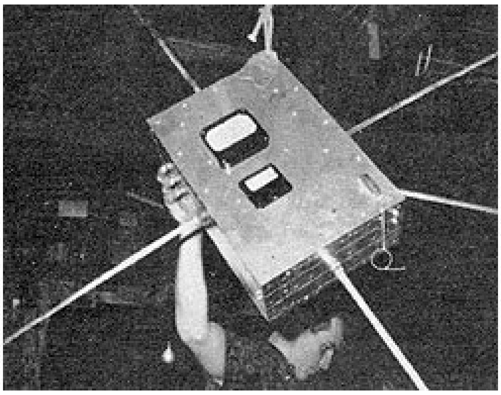

Figure 1.10 : OSCAR-III is the first amateur satellite with a transponder.

1.2 Cubesat Concept

Cubesat is the name given to cube shaped picosatellites with the length of 10 cm for each side (1U, 10cm x 10cm x 10cm), and with a maximum mass of 1 kg. The cubesat concept and program started in 1999 at Space Systems Development Laboratory of Stanford University under the leadership of Robert J. Twiggs. The concept was proposed initially at the USSS (University Space Systems Symposium) by Robert J. Twiggs between November 6-8, 1999 at Hawaii [15].

1.2.1 Cubesat standard

The Cubesat standard became a success with over 100 groups developing satellites, and as of 2009 27 Cubesats in orbit, another 24 awaiting launch, and at least an additional 30 looking for launch opportunities. The National Science Foundation alone has announced funding for two to three triple sized satellite projects each year, each requiring a full PPOD launch. Similar projects are supported in Europe by national Space Agencies, for instance DLR [16].

1.2.2 Cubesat launch deployers

Launch deployers are one of the biggest factors at providing reliable and cost-effective transport of small satellites into orbit.

Developers generally look for the opportunities to launch their cubesats as a supplementary payload, and with one or more small satellites are transported into space as piggybacks together with a large satellite, which is generally main payload. In the figure, cubesats are attached to CAS's EELV Secondary Payload Adaptor (ESPA) as secondary payloads [17]. These picosatellite or nanosatellite launchers encapsulate the cubesats completely during the launch process. By doing so, damages to the main payload that is the result of the significant overloads, which occurs during the picosatellite disconnection, are prevented. After reaching the desired orbit, separation process is initiated by ground station. Following this process, picosatellite can start its mission functions.

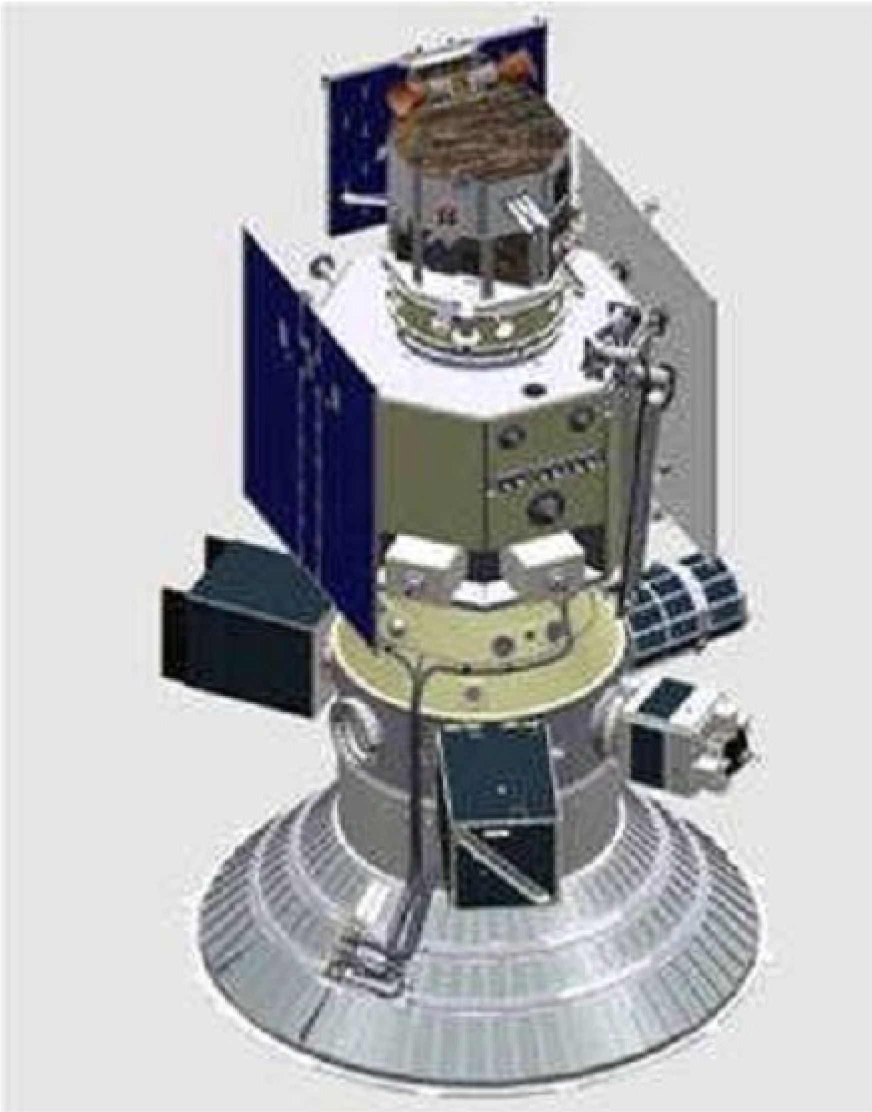

Figure 1.11 : CSA's EELV Secondary Payload Adapter (ESPA) ring

There are a handful of launch deployer producers world wide. Some of them are capable of holding multiple cubesats in its structure, and some are designed for single cubesat. There are also non-standard deployers because of non-standard sizes or different deploying mechanisms.

1.2.2.1 P-POD from CalPoly

P-POD, which stands for Poly-Picosatellite Orbital Deployer, is developed by

California Polytechnic State University. Most of the cubesats were launched using P-POD launchers. It has three versions with backward compatibility. Versions with launches are given below:

- MK-I was used for Eurokot launch in 2003. Two MK-I P-PODs carried four of the six satellites.
- MK-II was used at three launches. In Dnepr 1 launch at July 2006, five P-PODs carried fourteen cubesats. In Minotaur launch at December 2006, it carried GeneSat. In Dnepr 2 launch at April 2007, seven cubesats were carried with three launchers from Cal Poly.
- MK-III was used at five launches [18].

Figure 1.12 : P-POD MK-III.

Main properties of P-POD are:

- Aluminum 7075
- Spring loaded pusher plate

- Guiderails support satellites
- 3 access holes, 1 per cubesat
- Mountable in one orientation
- 1.6 m/s ejection speed [19]

From MK-I to MK-III, several modifications were done to improve release mechanisms, to provide easier satellite integration and to increase reliability [20].

1.2.2.2 X-POD by UTIAS/SFL

The XPOD stands for eXperimental Push Out Deployer, was developed by Space Flight Laboratory of University of Toronto Institue of Aerospace Studies. Being the second most populer picosatellite deployer to date, its size can be adjusted to standard sizes of cubesats, i.e. 1U/2U/3U, or, depending on the mission, customer specific size.

Its design includes:

- Titanium or magnesium alloy
- Spring loaded pusher plate
- Guiderails support satellite
- Single access hole
- Mountable in two orientations
- 1.0 m/s ejection speed

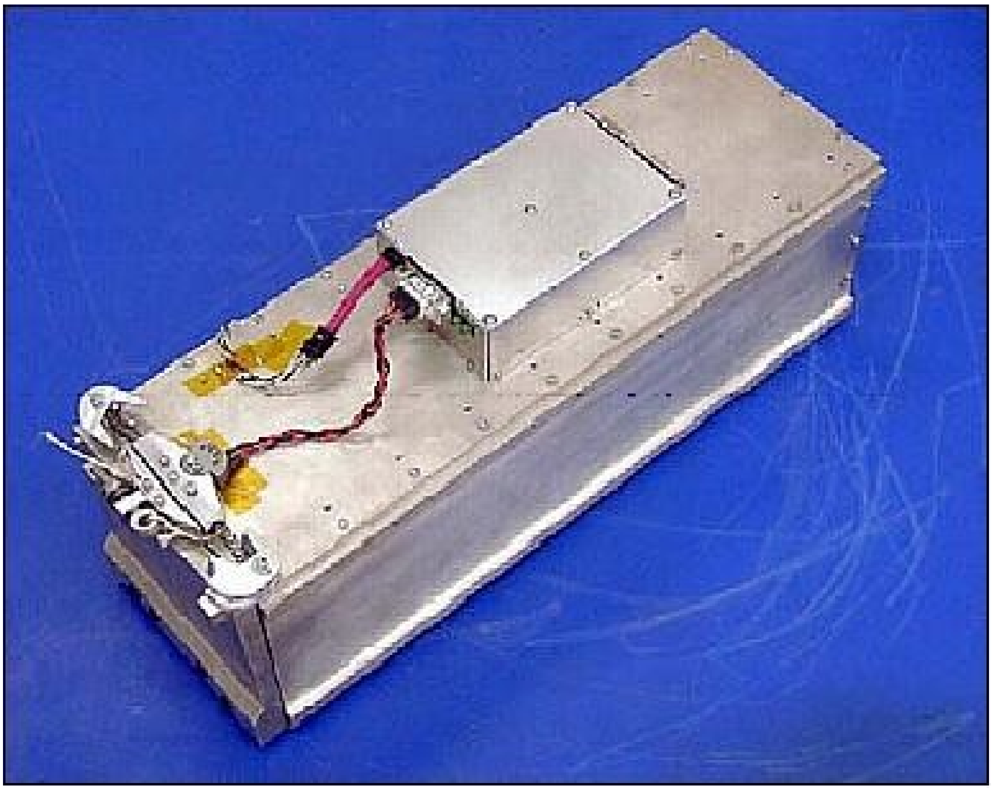

Figure 1.13 : XPOD (eXperimental Picosatellite Orbital Deployer).

Its release mechanism include:

- Bold with vectran cord
- Redundant melting wires
- Deployment electronics with battery
- Sensor to detect lid opening
- Sensor to detect satellite deployment [21]

1.2.2.3 ISIPOD by ISIS – Innovative Solutions In Space

ISIPOD is developed by ISIS – Innovative Solutions In Space from The Netherlands. It has 1U/2U/3U versions, as well as custom versions for custom satellites. 2U/3U versions and possible custom versions can launch 2U/3U satellites as well as a combination of 1U/1.5U/2U satellites [22].

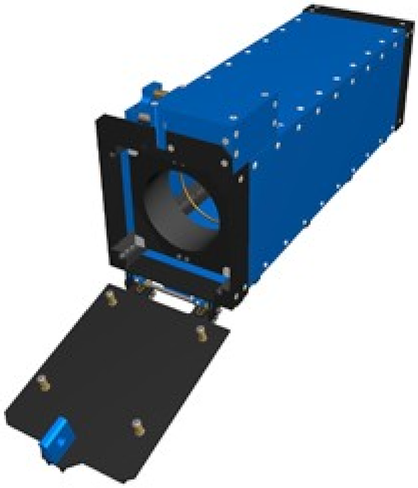

Figure 1.14 : 3U ISIPOD.

Its design includes:

- Nanosatellite is fixed in ISIPOD by fitting spring
- Lid opening and satellite ejection is not separated
- Lid blocks at aperture angle 105º
- Acceleration plate supported by guiderails
- Lid opening is indicated by sensors
- 1.6 to 2.0 m/s ejection speed

1.2.2.4 SPL by Astro- und Feinwerktechnik Adlershof GmbH

SPL stands for the Single Picosatellite Launcher, and was developed by Astro- und Feinwerktechnik Adlershof GmbH. This deployer provides individual deployment for picosatellites.

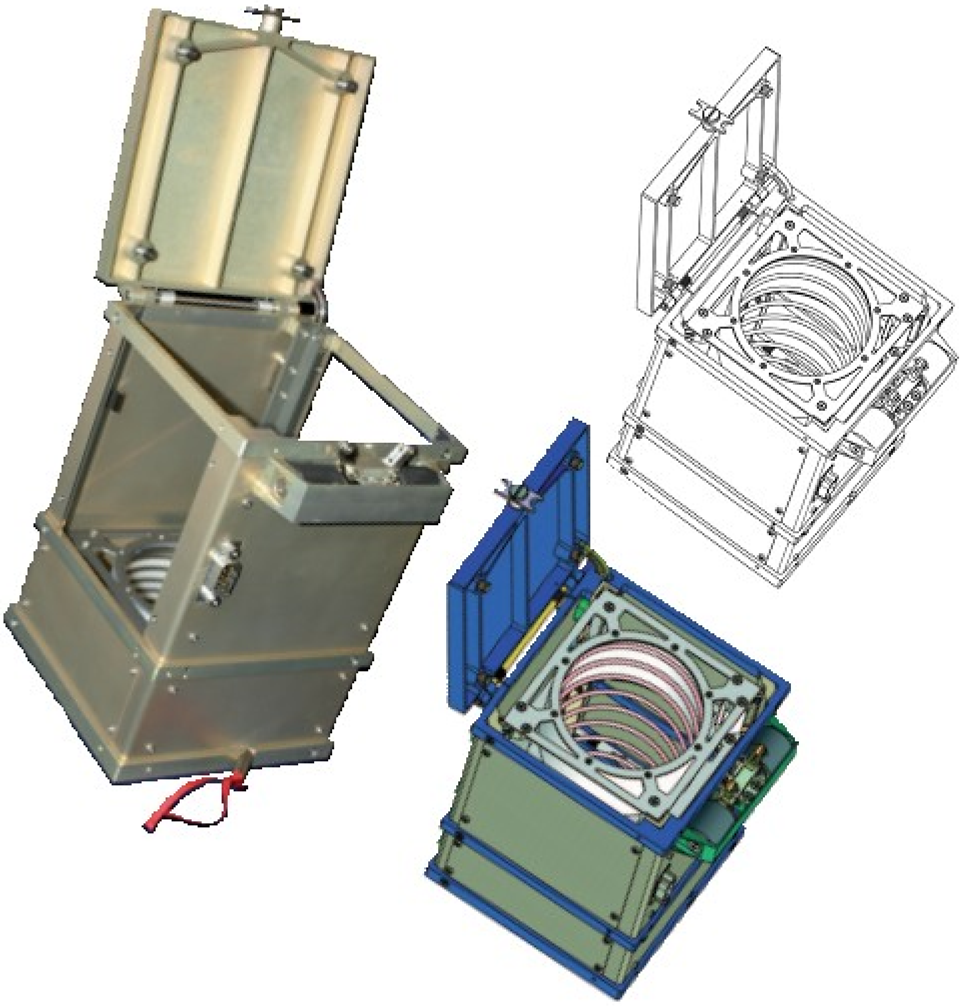

Figure 1.15 : Single Picosatellite Deployer (SPL).

The separation process is divided into two phases: Unlocking phase and deployment phase. By separating these processes, a constant deployment velocity (1.4 m/s), low angular momentum and low rotation rates are achieved.

Further features of SPL include:

- mechanical and electrical redundant actuators
- defined adjustment of the satellite by springs
- controlled deployment by guide rails in frame
- affirmation signal for successful deployment
- closed envelope for high safety standard

It is also confirms to standards defined by Cal Poly [23].

1.2.2.5 T-POD by Tokyo University

T-POD, which stands for Tokyo Picosatellite Orbital Deployer, was developed by Tokyo University. The pod was used to deploy XI-IV into the orbit. In SSETI Express mission, it was used to launch the cubesats UWE-1 from Germany, XI-V from Univesity of Tokyo, and NCube-2 from Norway, however, this time the pods was provided by UTIAS/SFL with design based on T-POD.

Figure 1.16 : T-POD is produced by University of Tokyo.

PSD, which stands for PRISM Hosyutsu Souchi (Housyutu means ejection, and Souchi means satellite in Japanese), was used for launching PRISM nanosatellite. It is an improved model of T-POD [24].

1.2.2.6 FlyMate by INSA de Lyon

FlyMate was developed by Novanano [25] and INSA de Lyon.

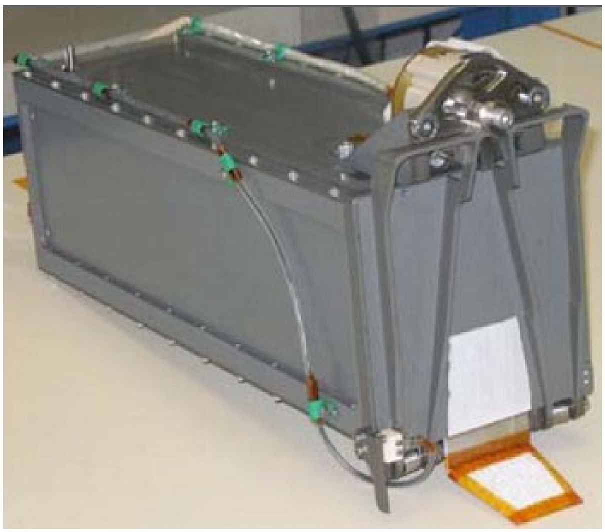

Figure 1.17 : FlyMate produced by Novanano and INSA de Lyon.

One of the main advantages of this deployer is accommodation of satellites with protruding elements, resulting more space for "passengers". Other design elements include:

- Controlled ejection mechanism without springs and door-locking, with guidance and locking provided by the same mechanism
- Satellites are ejected one at a time.
- Up to 60 mm distance between satellites.
- Ejection system based on motorized mechanism, electronic control module, and composite ropes.
- Adjustable ejection speed up to 2.0 m/s [26].

1.2.3 Launches

First cubesat launch took place at November 30, 2003. Several launches took place after that, with varying success rates. The list of cubesats can be seen in appendix A.1 [27]:

2. ITU-pSAT I OVERVIEW AND FLIGHT RESULTS

ITU-pSAT I is the first student designed pico-satellite of Turkey, developed by the Aeronautics and Astronautics Faculty of İTÜ. Aimed at giving the students an opportunity to develop hands-on experience across all the development and operation stages of a satellite, it carries two experimental payloads: a low-resolution camera with on-board image processing, and passive magnetic stabilization with a magnetic rod accompanied by a board to examine its performance.

This section will describe the subsystems of ITU-pSAT I, and will give flight results of the satellite briefly.

2.1 ITU-pSAT I Subsystems

The design philosophy of the satellite revolves around a simple but expandable bus.

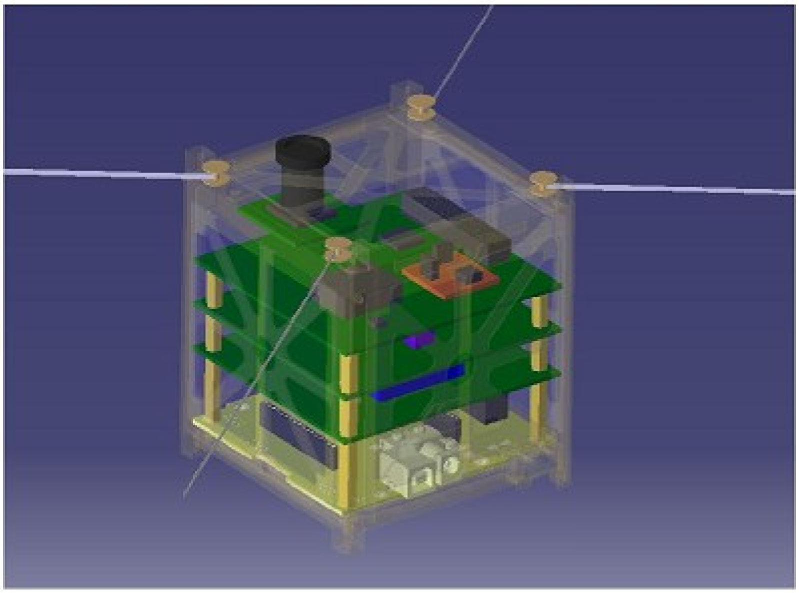

Figure 2.1 : ITU-pSAT I CAD model.

2.1.1 Structure

The structure of the satellite was provided as a part of the CubeSat Kit by Pumpkin Inc. For the main structure, Aluminum 5052-H32 was used. Other features include stainless steel for fasteners and the Remove-Before-Flight pin.

2.1.2 Electrical power subsystem

Power system of ITU-pSAT I consists of solar cells, and a regulator board and associated batteries. It features a PC/104 form factor and integrates seamlessly with the rest of the satellite.

2.1.3 Communication subsystem

The communication system of the satellite has two components, and these two components work in 70 cm band. These are beacon and MHX modem respectively.

Both beacon signal and telemetry broadcasting via MHX-425 modem works under the same frequency 437.325 Mhz, and they work alternately. Beacon uses CW modulation, and broadcasts satellite identification name, satellite name, and battery condition in Morse code. Modem, on the other hand, is used for downlinking telemetry data and a photograph taken by the low-resolution camera.

2.1.4 Command & data handling subsystem

For on-board computer of the satellite, FM430 flight module of Pumpkin Inc is used. It has an SD card interface, a USB port, an external power supply connector, and an interface to MHX modems. FM430 is based on MSP430F1611 microcontroller and runs a real-time operating system called Salvo, which is also a product of Pumpkin Inc. On-board software controls all of the subsystems via I2C bus.

2.1.5 Attitude determination and control subsystem

Attitude determination system includes three gyros, and a three-axis accelerometer from Analog Devices, and a three-axis magnetometer from Honeywell. Attitude control system consists of a passive AlNiCo magnet.

2.1.6 Low-resolution camera

A low-resolution CMOS camera is the second payload of ITU-pSAT I. With its 640x480 pixels resolution, with 700 km orbital height, each image will cover an area of approximately 757x567 km^2. Taken images will be compressed in JPEG format before downlinking to the ground station [28].

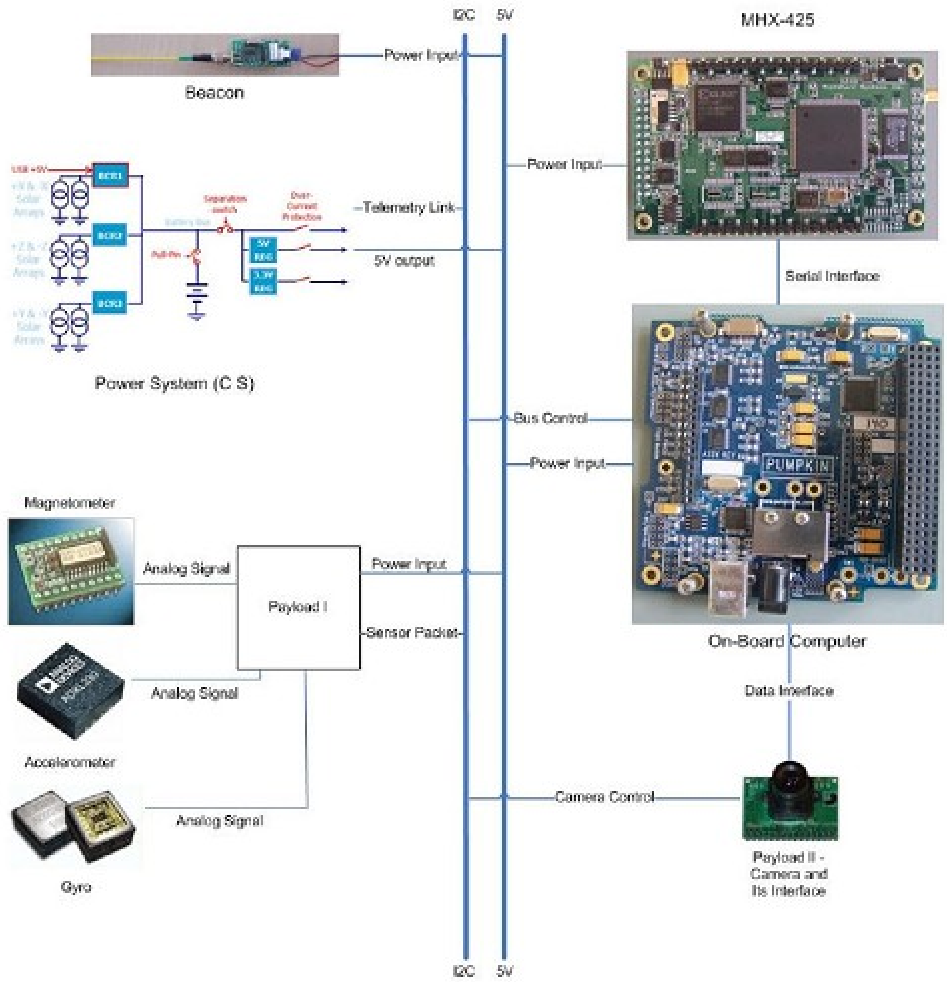

Figure 2.2 : ITU-pSAT I System Architecture

2.2 Flight Results

ITU-pSAT I was launched on September 23rd, 2009 using PSLV-C14 from Satish Dawan Space Center [29], Sriharikota, India. Main payload of PSLV-C14 was Oceansat-2, with a weight of 958 kg, along with six nanosatellites [30].

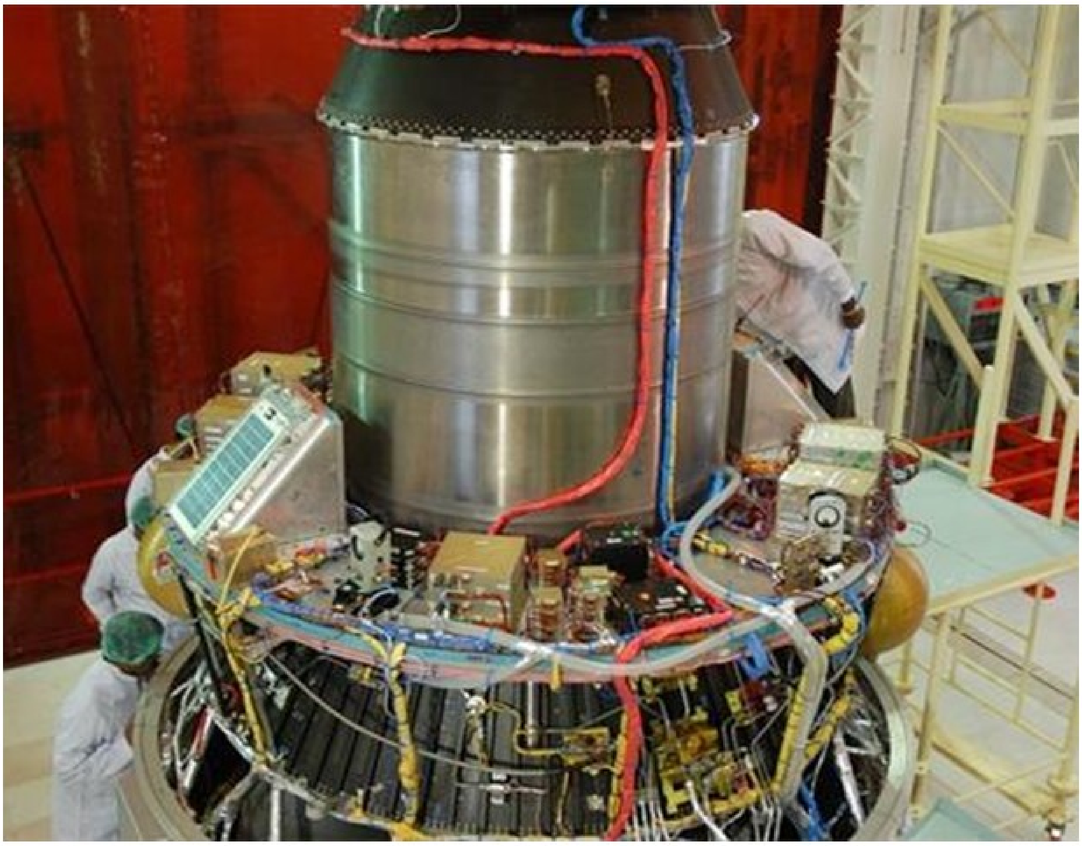

Figure 2.3 : ITU-pSAT I on the launch platform in compartment of payload.

On the night of September, 23rd 2009, first and only telemetry of the ITU-pSAT I was taken, and only the header of picture could be taken. However, despite several attempts to communicate with MHX modem of the satellite, communication could not be established with the modem again.

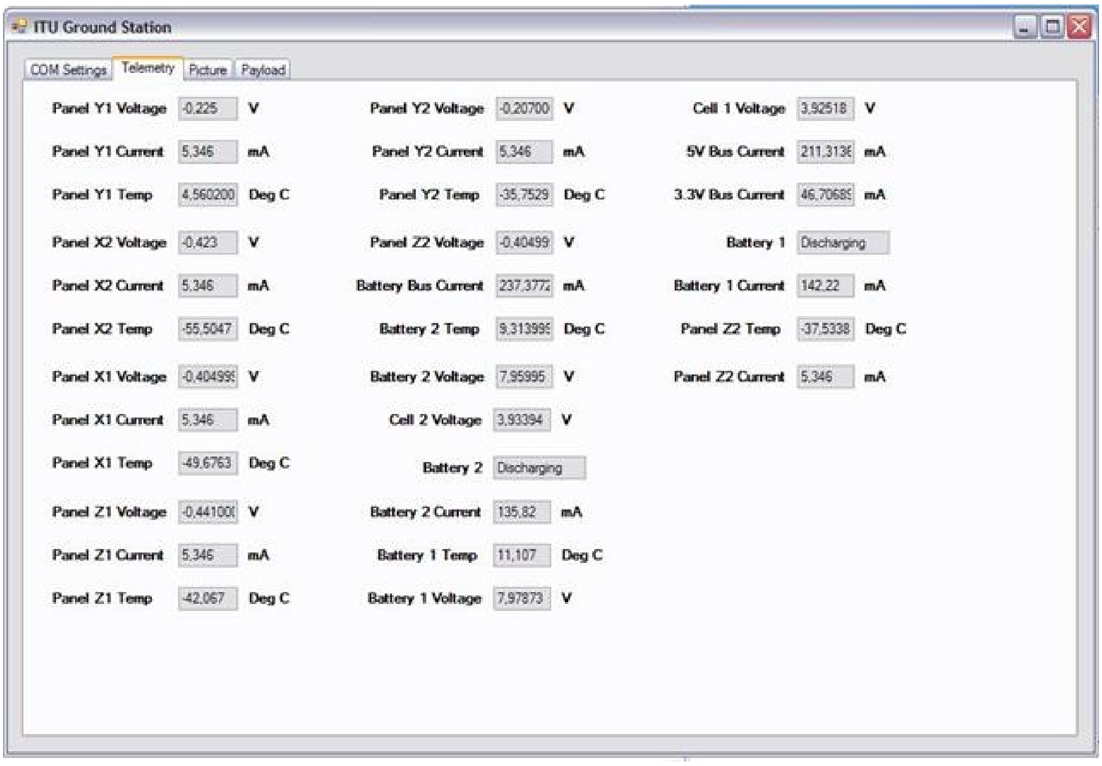

Figure 2.4 : Telemetry taken from ITU-pSAT I.

With nearly sixteen months passed since the launch of ITU-pSAT I, it continues to transmit beacon signals. By examining beacon signal power received at the ground station, some information about the status of the satellite can be obtained.

For analysis of the beacon signals, a program called Xbat [31] is chosen. This program was developed at the Bioacoustics Research Program of the Cornell Laboratory of Ornithology, and generally used for analysing sounds from marine and terrestrial environments. By visualising the sound files, the results that are given in the graphics below were obtained.

Figure 2.5 : ITU-pSAT I pass on June 14, 2010 at 13:06.

In the figure above, the faint points on the signal indicates that the monopole antenna on the ITU-pSAT I is perpendicular to the ITU ground station. The time interval between two weak signal strength is 4.3 seconds, indicating that the satellite revolves around itself at 8.6 seconds, or $8.7/2\pi \approx 1.368$ rad/sec.

Figure 2.6 : ITU-pSAT I pass on June 20, 2010 at 12:58.

In the figure above, the time interval between two weak signal strength is 4.35 seconds, indicating that the satellite revolves around itself at 8.7 seconds, or $8.7/2\pi \approx 1.384$ rad/sec.

Other analyses show similar results about rotating speed of the satellite, which is around 1.38 rad/sec [32].

3. ITU-pSAT II OVERVIEW

ITU-pSAT II is the second student satellite project of ITU Control and Avionics Laboratory. Its main mission is to demostrate on-orbit an advanced ADCS for nano-satellites (1-10 kg) with high precision three axis control needs. Other payloads include a high resolution camera to take high resolution images (100-200 meters per pixel), expandable solar panels and composite side panels, a star tracker, and 13 cm band communication system. ITU-pSAT II will have dimensions of 10 x 10 x 30 cm and a weight of approximately 4 kg.

In addition to the development of ITU-pSAT II satellite, the scope of the project includes a Hardware-in-the-Loop Test system for testing operational properties of ADCS, an air bearing table, and a Helmholtz coil.

Table 3.1 : Total Weight, Power and Volume Budget of ITU-pSAT II

Subsystem	Dimensions (mm)	Mass (gr)	Power (W)
OBC	80x80x40	250	0.5
EPS	90x90x70	500	2
Beacon	80x80x20	100	0.3
PLIU	25x60x80	200	0.3
ADCS	100x100x80	907	2
Communication	100x100x40	250	2
Structure	100x100x300	600	0
Panels	N/A	350	0
GPS	90x60x30	100	1
Nano Moment Control Gyro	30x30x50	150	0.3
Camera+Hardware	N/A	400	1
Star Tracker Hardware	90x90x20	150	0.4
Total	100x100x300	3957	6.2

3.1 Structure

A modular cell system makes the core principle of the structural design of ITU-pSAT II, and AL 7075 is chosen as material. The satellite cell structure is designed as a rack system, and the boards are pushed into these rack system. This approach enables rapid assembly/disassembly of other subsystems, thus enabling faster integration and testing processes. In addition to the rapid integration capacity, the rack system allows horizontal or vertical assembly of the boards into the structure.

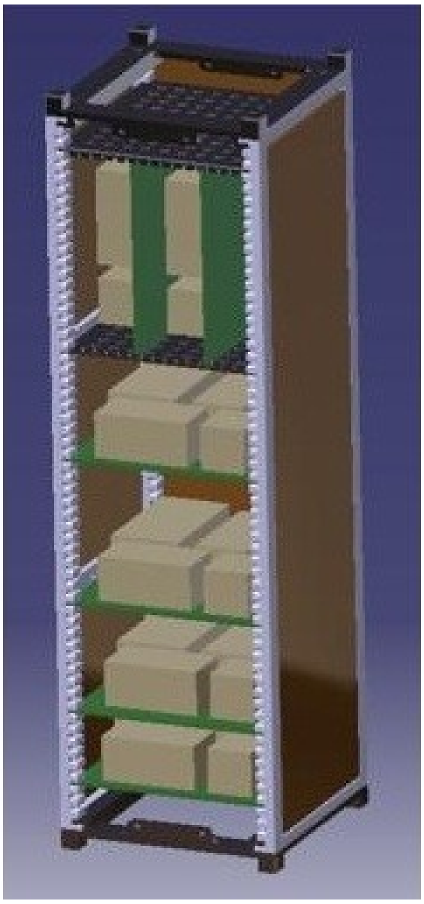

Figure 3.1 : ITU-pSAT II structure

3.2 Attitude Determination and Control Systems

General outline of ADCS and its components are displayed in the figure below.

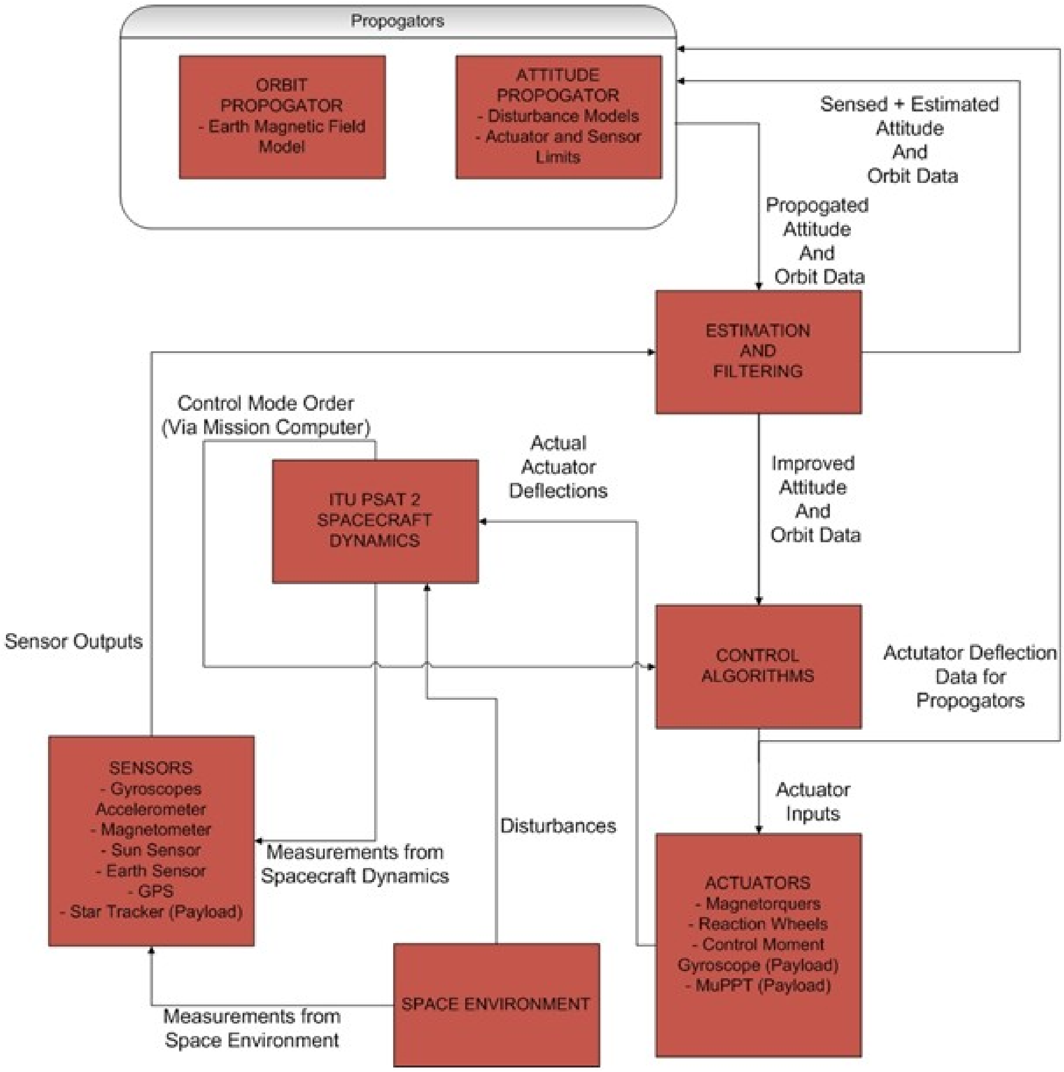

Figure 3.2 : ADCS Diagram of ITU-pSAT II

ADCS of ITU-pSAT II consists of three distinct hardware layers integrating sensors, actuators, and ADCS computer over the CAN bus. The sensor layer embeds a set of low-cost inertial and magnetic sensors, sun/earth sensors, a GPS receiver and an in-house developed star-tracker. The actuator layer includes a redundant assembly of reaction wheels, magnetic torquer coils and an experimental set of uPPTs (micro pulse-plasma thrusters) with one-axis micro CMG (control moment gyro). Embedded within the ADCS Computer is a filter which allows the asynchronous fusion of filtered sensor data with outputs from the orbit and attitude propagation algorithms. Propagation algorithms simulate the spacecrafts dynamical response (including effects of disturbances, and uncertainties in sensor and actuator models) and compare it with actual sensor data to improve accuracy of determination of spacecrafts attitude and orbit position. These filtered and fused state data is fed to a fault-tolerant and reconfigurable control layer. The control layer is divided into different operation modes and associated control strategies depending not only on the actual spacecraft operation mode (such as de-tumbling or high-precision attitude control for image capturing) but also depending on the health-status of the individual sensors and the actuators.

3.3 Attitude Control Systems

In ITUpSAT1, there was a passive magnet for attitude control. With the passive magnet, the aim was stabilizing the satellite by allowing it to rotate around itself once per period on the orbit. However, rotation speeds of ITU-pSAT I showed that, a passive magnet is not enough for stabilizing the satellite.

There will be two types of controllers in ITUpSAT2, which are reaction wheels and magnetotorquers respectively. A brief explanation of these components of attitude control subsystem is given below.

3.3.1 Magnetotorquers

Magnetotorquers are used for detumbling mode, which is reducing the angular velocity to zero, thus making the satellite stable. It is especially important after the satellite leaves the rocket, because the satellite may have high angular velocities. The control algorithm uses the principle of reducing magnetic field vector's variation to zero.

After reducing the angular velocity to zero, barring unforeseen events such that failure of reaction wheel, the current control algorithm does not use magnetotorques for further control [33].

Magnetic torque generator uses the principle of producing a magnetic dipole moment with the use of a circularly wrapped, in which electrical current passes. This magnetic dipole moment interacts with the Earth's magnetic field and creates a torque. With use of three magnetic torque generators, it is possible to create magnetic torque in three dimensions.

3.3.2 Reaction wheels

Reaction wheels are used for controlling the satellite when the satellite is in flight mode. In flight mode, with the use of attitude determination system, the orientation of the satellite is changed.

Flight mode, thus reaction wheel is used after the satellite is stabilized, so the system will be in use all of the time when the satellite is in the orbit [33].

Reaction wheel operates through the principle of conservation of angular momentum. Accelerating a reaction wheel brings a proportional response by the rest of a spacecraft. By this principle, and depending on the precision level of the reaction wheels, the satellite can be controlled accordingly [34].

3.4 Attitude Determination Systems

Attitude determination hardware and algorithms helps at determining position and orientation of the satellite with respect to earth. There are two main attitude determination systems. These are attitude determination using magnetometer outputs, and star tracker systems. In the time of writing, these two separate attitude determination algorithms did not fuse together yet. Also, in the future, there may be other types of sensors for better attitude determination by using the methods of sensor fusion and by providing redundancy.

3.4.1 Magnetometer

For attitude determination via magnetometer, an Extended Kalman Filter is used. Attitude determination system compares the outputs of the magnetometer with magnetic field vector of the earth. For this to be done, both direction and magnitude of the magnetic field at the location of the satellite must be known. The magnetic field is calculated in two steps. First step is calculating the position of the satellite using two line element sets. An orbit propagator calculates the orbit of the satellite, thus provides the position of the satellite with respect to time. Second step is calculating the magnetic field of the earth at the position of the satellite which was determined by the orbit propagator. With the use of International Geomagnetic Reference Field, the magnetic field can be calculated. With the help of magnetic field vector, satellite dynamics and control inputs, an Extended Kalman Filter can determine the orientation of the satellite [35].

3.4.2 Star tracker

Considering the travel speeds relative to the Earth, and distance from the Earth, stars can be considered as fixed light sources, and their direction does not seem to change with respect to the observer, which, in this case, is star tracker. Thus, star trackers are used for calculating the orientation of the satellite.

In the software part of the star tracker, there are two modes. First mode is 'Lost in Space' mod, and it is used for general searching. The other mode is called 'Continuous Watching' mode, and in this mode, previous states of the stars are known.

In addition to the movement of the satellite, there will be radiation and rapid temperature variations on the sensors, which all contribute to blur the image of the star map. For this reason, the image must be filtered, even though the magnitude of the blurring is not known precisely. In star matching layer, Voting Algorithm of Kolomenkin is used.

Star tracker's another requirement is that, it must give attitude information to the onboard computer in the rate of 5Hz. For this, in addition to the software part, there are hardware requirements too. As a processor, AD BF537 DSP, and as a vision sensor, OV9655 CMOS is chosen [36].

Figure 3.3 : SVR-1 kit, with AD Balckfin DSP and OV9655 CMOS sensor module.

3.5 High Resolution Camera

High resolution camera is the payload of the satellite. The aim with this camera is to take photos that have a resolution of one to two kilometers per pixel [37].

3.6 Electrical Power Subsystem

ITUpSAT II will be a 3U cubesat, and that means satellite will have approximately

0.14 m2 surface area. With solar panels on each side, excluding the areas that are occupied with communication and attitude determination systems, and with the use of 28% efficient solar cells [38], the mean power produced by the satellites will be about 11 Watts.

The prototype circuit consists of CAN BUS interface, microcontroller, bus current measurement module, OBC regulator module and battery charge module.

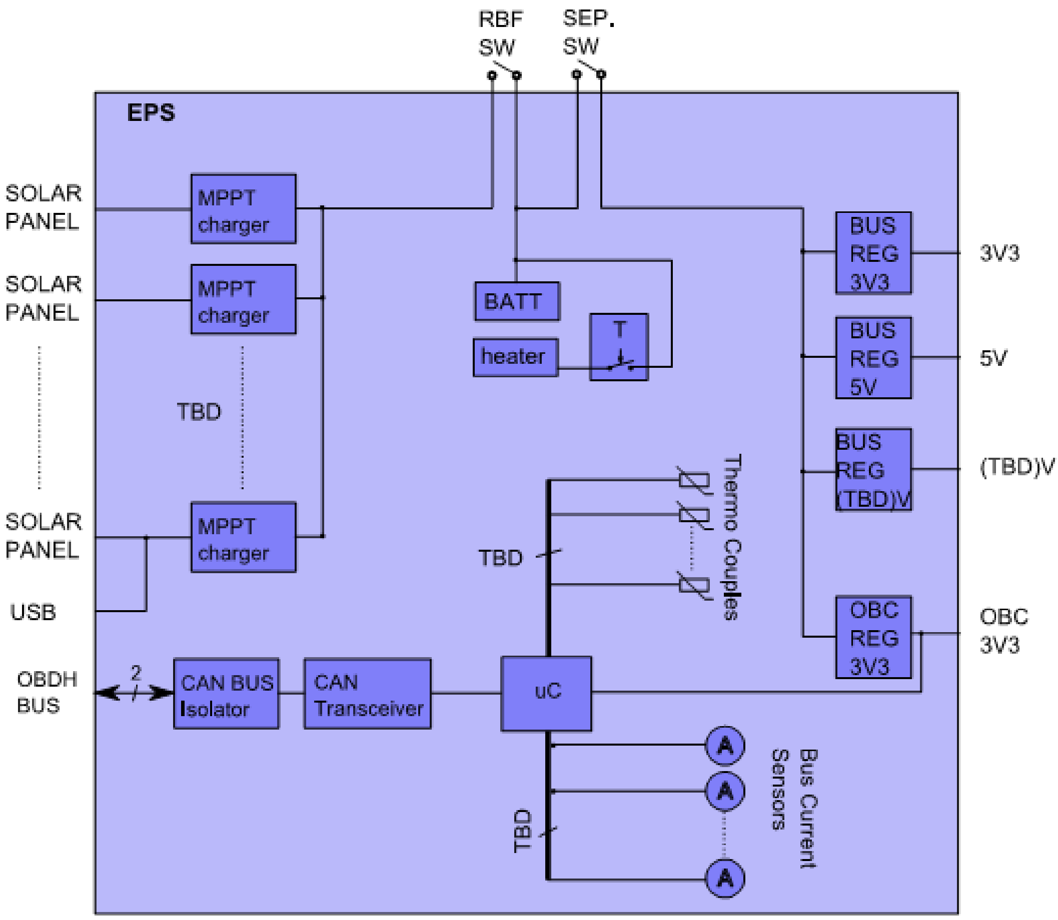

Figure 3.4 : Prototype Electrical Power Subsystem.

3.7 Communication Subsystem

There will be two types of communication systems on the satellite. First one will be beacon signal, and it will give some of the critical telemetry data in addition to satellite definition signal. It will work on 70 cm band, but there is a possibility that it can work in 2 m band.

Other type of communication system will be at S-band, or 13 cm band. This mode will be used for transferring image data from the satellite, and may be used for uploading new software.

4. COMMUNICATION SYSTEMS AND GROUND STATIONS OF OTHER CUBESATS

In this section, a survey of the communications systems of other cubesats and ground stations will be investigated. Since some of the cubesats done by the same organization shares similarities in terms of communications systems, and since generally each of these organizations use the same ground station or stations for communication, this section will review the cubesats in organizational order.

4.1 Communication Systems of Other Cubesats

In this chapter, communications systems of cubesats and their respective ground stations are covered. The decisions about which organizations are chosen depend on the available information, peculiarity of the work such as a unique band, and the extend of spearheading in the cubesat community.

4.1.1 UTIAS/SFL

University of Toronto Institue for Aerospace Studies Space Flight Laboratory made several nanosatellites as well as a bunch of microsatellites. The Canadian advanced nanospace eXperiment program consists of several nanosatellites. CanX-1 and CanX-2 were launched at June 2003 and April 2008 respectively.

4.1.1.1 CanX-1

CanX-1 is a 1U cubesat with a mass of less than 1 kg. The mission of the cubesat is testing several components for use in future cubesats, and creating know-how for future missions. Some of the technologies used in this cubesat include a low-cost CMOS horizon sensor and star-tracker, active three-axis magnetic stabilization, GPS-based position determination and an ARM7 central computer [39].

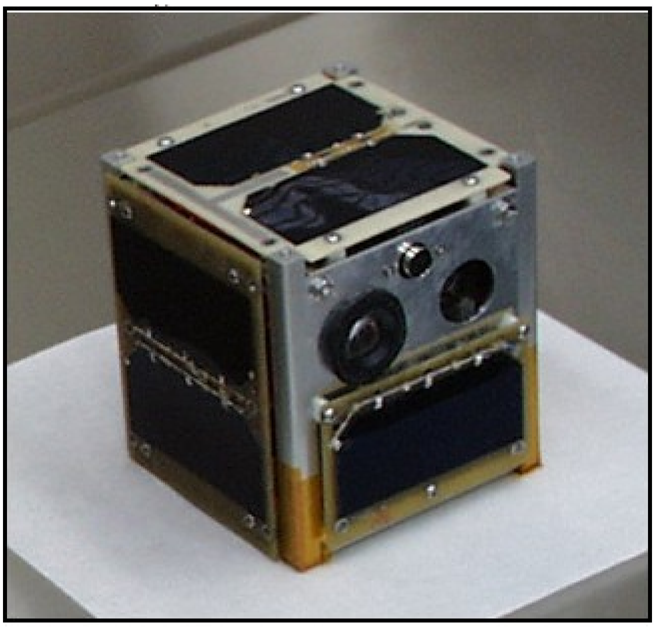

Figure 4.1 : CanX-1 satellite.

In communication subsystem of the satellite, there is a radio receiver, a radio transmitter, antennas, antenna switching hardware and a terminal node controller (TNC). Transceiver of the satellite works in 70 cm band for both uplink and downlink, and has a half-duplex design. Doppler correction is performed at the ground station [40]. A Melexis chip constitutes the heart of the radio, and with its power amplifier it gives 27 dBm or 500 mW output power. It uses a custom made protocol with MSK modulation with 1200 baud rate [41].

It was not heard after the launch, one possible explanation for this is power failure.

4.1.1.2 CanX-2

CanX-2 is the second satellite sent by the UTIAS/SFL. It is a triple cubesat with dimensions measuring 10 x 10 x 34 cm and a mass of 3.5 kg. With its size, it hosts several experiments and evaluates technologies that will be used in future missions. Specifically, these technologies will be used in formation flying of CanX-4 / CanX-5 dual satellites, and includes propulsion system, custom radios, and commercial GPS receiver. The experiments include GPS radio occultation experiment to characterize the upper athmosphere, an atmospheric spectrometer to measure green gases, a network communications experiment and a space materials experiment.

One of the methods used in this satellite is a new type of protocol. This protocol is called nanosatellite communication protocol (NSP). The aim of NSP is to dynamically transfer the data. Network protocol is activated in response to incoming data, then it is relayed to other satellites or ground stations. Also there are new implementations for dealing with data transport errors [42].

It uses a full-duplex communication scheme. Uplink is done at UHF frequencies with 4 kbps and downlink is done at S-band with 32 to 256 kbps. Although it is possible to downlink with UHF transmitter with half-duplex communication, the amount of data necessiates the use of S-band transmitter, which also enables full-duplex communication. The modulation for UHF modem is Gaussian Frequency Shift Keying (GFSK) modulation scheme with 4000 bit/s information rate and has an output power of 30 dBm. S-band transmitter has an output power of 27 dBm and uses BPSK or QPSK modulation scheme [41]. CanX-2 uses VHF bands for beacon signal, and in addition to identification, it gives some telemetry data. Especially the failure of the first satellite plays a role for the use of beacon [43].

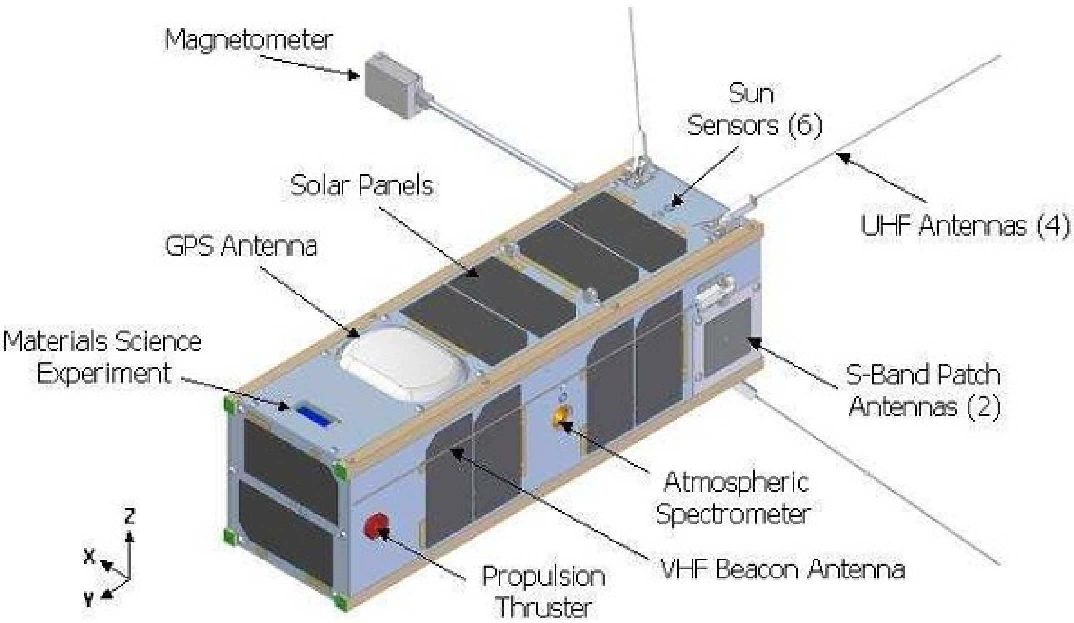

Figure 4.2 : CanX-2 nanosatellite.

The satellite uses a quad-canned turnstile antenna arrangement for UHF, which provides near omni-directional coverage during commissioning. For S-band, it uses two right hand circular polarized patch antennas mounted on each side of the satellite.

However, according to an amateur radio operator, the beacon signal was descoped from the final design, and 70 cm band is not active. All uplink and downlink is done from S-band [44].

4.1.1.3 UTIAS/SFL ground station

As the satellites uses multiple frequencies, a ground station that is capable of accommodating all of these satellites. There are three antenna structures corresponding to three different bands. For receiving S-band signals, 2.08m parabolic dish antenna is used. This right-hand circular polarized antenna has a gain of 32.2 dBic along its boresight. For UHF signals, two 435MHz 42 element Yagi-Uda antennas are used. They provide 21 dBic gain. For VHF signals, single Yagi-Uda antenna is used.

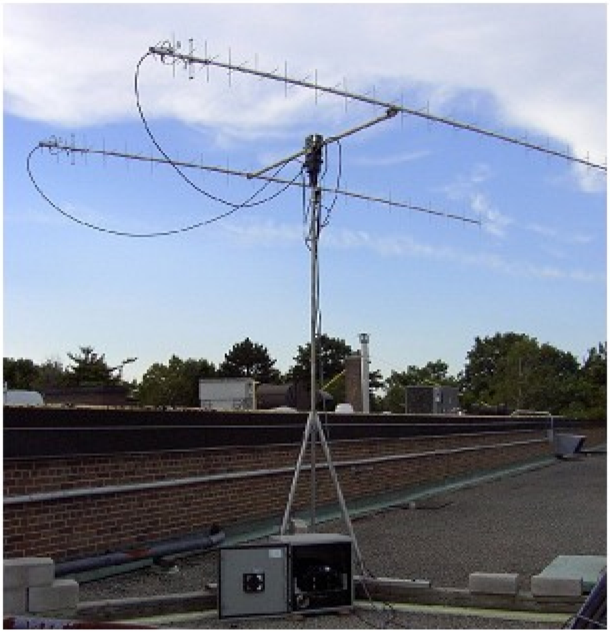

Figure 4.3 : UTIAS/SFL UHF antenna.

For each communication channel, different radios are used. For S-band, PSM-4900 made by Datum Systems is used. For UHF link, half-duplex Yaesu FT-897 is used, and Yaesu FT-847 is used for VHF link to receive analog Morse code signals.

Figure 4.4 : S-band antenna stacked with VHF antenna.

As antenna rotators, AlfaSpid Radio's product, which has full azimuth/elevation design, is used. Limit switch at azimuth axis is added to the system later. Rotator control is accomplished by designing a custom microcontroller board with Atmega32 8-bit controller.

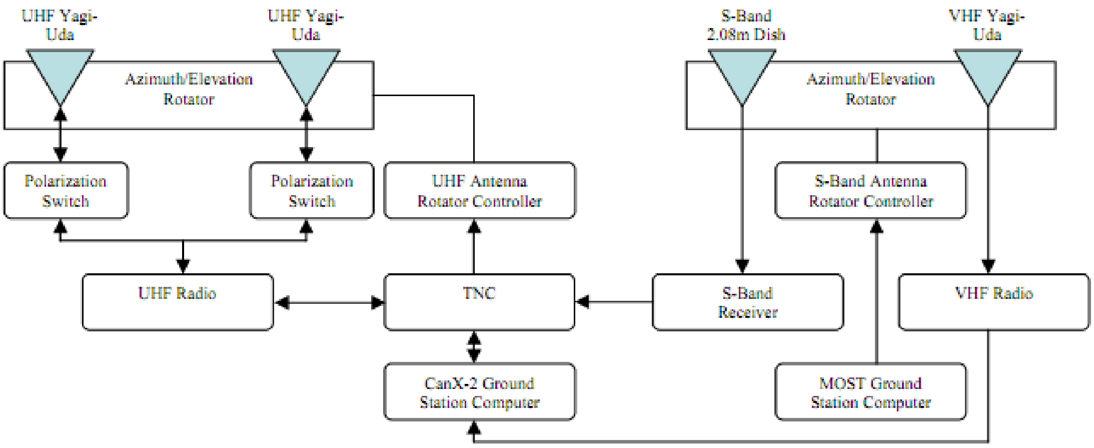

Figure 4.5 : UTIAS/SFL Ground Station architecture.

For Terminal Node Controller (TNC), 200MHz ARM based Single Board Controller, which runs an embedded linux operating system, is integrated to a custom made control board [45].

4.1.2 Denmark Technical University

Denmark Technical University launched its only satellite at June 2003. This satellite is called DTUsat-1.

4.1.2.1 DTUsat-1

DTUsat-1 is done by Denmark Technical University and launched at June 2003. Aside from generating know-how, the main payload is an electrodynamic tether for dumping the satellite. As a secondary payload, a calibrated test transmitter is used. The radio transmitter is half duplex, with 2400 bps data rate and AFSK modulation in the 70 cm band. The modems of the satellite are constructed using CMX469 integrated circuit.

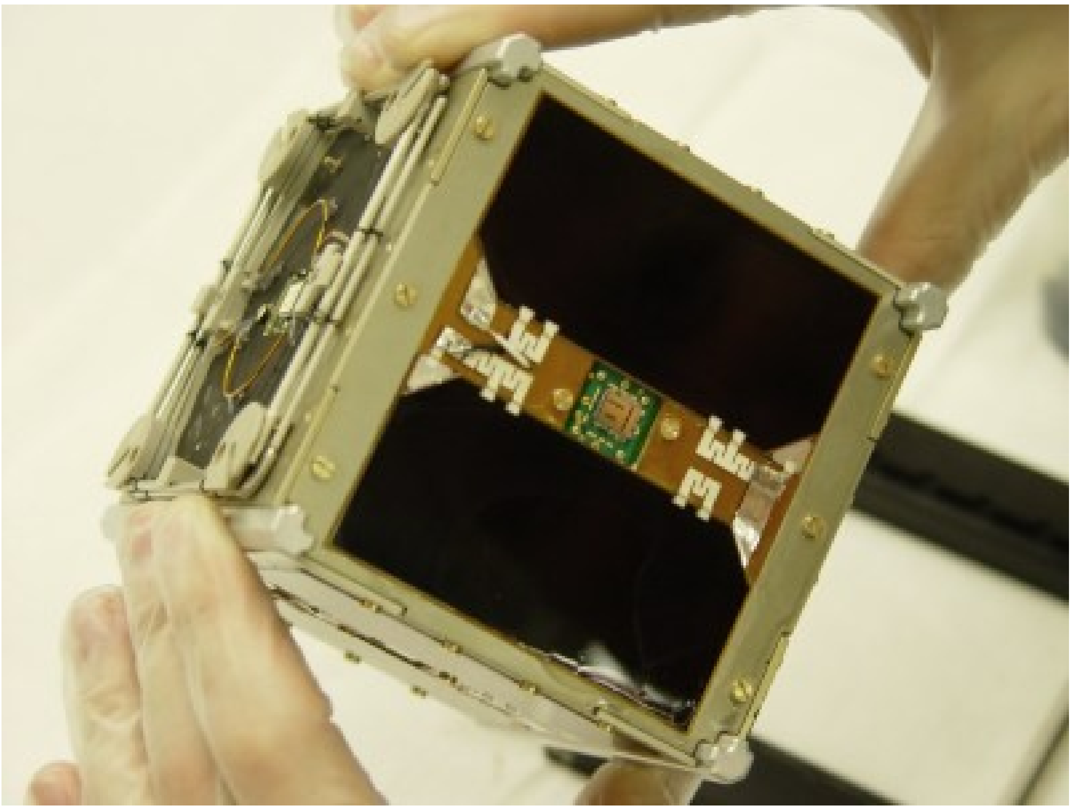

Figure 4.6 : DTUsat-1.

It was never heard in orbit despite trying to contact for months [46].

4.1.2.2 DTU ground station

At ground station, two Yagi-Uda antennas are used. Antennas are model 20438 made by the company F9FT. Rotators are Yaesu G5500, which is a popular choice among cubesat users. Transceiver is Yaesu FT-847. Between this transceiver and PC, Paccomm TNC-NB96 is used, which is capable of 1200/9600 bps data rates [47]. The software on the ground station is made by DTUsat team, and has a custom interface.

Figure 4.7 : Construction of DTU Ground Station.

4.1.3 Aalborg University

Aalborg University launched two satellites to date. First cubesat, named AAU Cubesat was launched at June 2003, and second cubesat named AAUSAT-II launched five years later at April 2008.

4.1.3.1 AAU CubeSat

AAU CubeSat is a 1U cubesat. Its mission is to take pictures of the surface of the Earth with its CCD camera.

The used radio is model SX450 from Wood and Douglas, and has a transmitting power of 500 mW [48]. It uses a half duplex communication system at 437.9 Mhz. The radio is connected to MX909A modem by MX-COM Inc, which uses GMSK modulation [49]. Although both the radio and modem are capable of 19200 bps baud rate, it is set to 9600 bps due to hardware supplied by OSSS are set to 9600 bps. As antennas, two perpendicular dipole antennas are used.

Figure 4.8 : An artist's conception of AAU-Cubesat in orbit.

In the communication scheme, the application data is passed to the AX.25 protocol. This protocol outputs frames of up to 240 bytes of data to the modem. Then, the modem breaks up the frames, and adds overhead bytes for FEC scheme, checksumming and sender/receiver synchronization. This created data is then modulated using GMSK modulation scheme and sent to the radio [50].

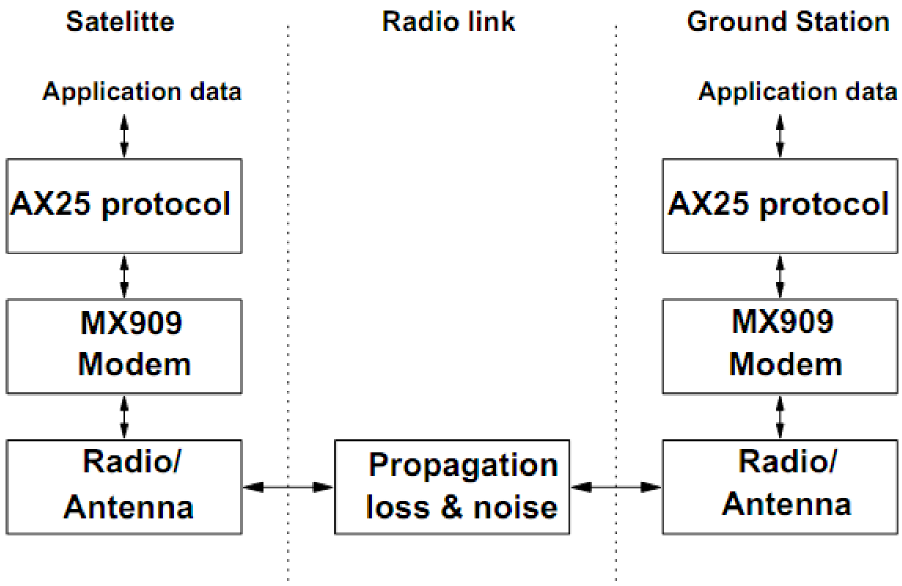

Figure 4.9 : AAU Cubesat communication system diagram.

After two and a half months after launch, batteries lost too much capacity to continue operations.

4.1.3.2 AAUSAT-II

AAUSAT-II has dimensions of 10 cm at each side and weights less than 1 kg. Its primary goals are two science experiments, namely an ADCS system and a gamma ray detector.

For communication subsystem, and for all other subsystems except OBC, PIC18LF6680 is used. The radio is made by a German radio amateur, and has a transmitting power of 650 mW with a frequency of 437.425 MHz. The selected modem is CMX469A chip by CML Microcircuits and uses FFSK/MSK modulation. Baud rate is selectable between 1200 and 4800 baud rates, and can be changed from ground station. Antenna is a crossed dipole with an impedance of 50Ω. The modulation used is AX.25 [51].

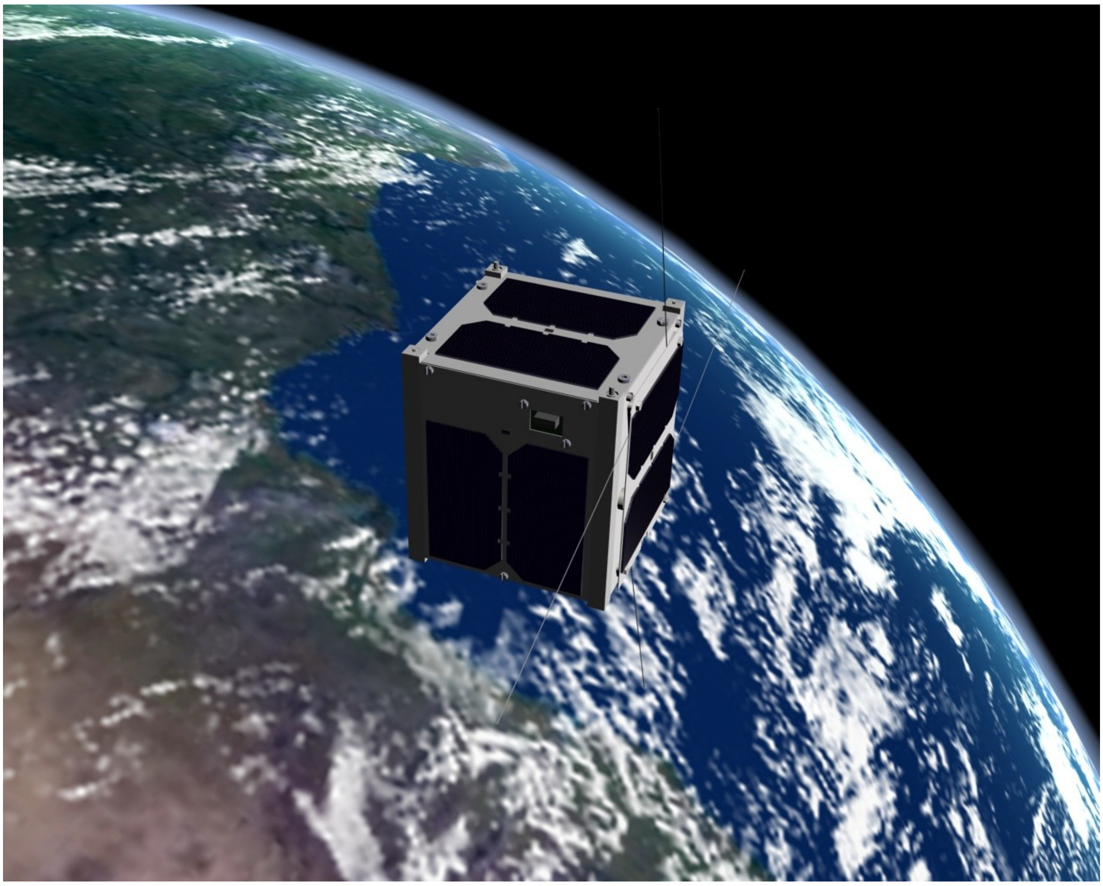

Figure 4.10 : AAUSAT-II with crossed dipole antennas.

4.1.3.3 Aalborg University ground station

Ground station at Aalborg university is used for tracking both Aalborg university satellites and SSETI-Express satellite done by ESA's education department.

The antenna consists of two parallel crossed Yagi antennas, each with a gain of 14 dBd and a combined gain of 17 dBd. Antennas are WX-7036 or CP-30 crossed Yagi-Uda antennas. The antenna is connected to Beko HLV-1100 amplifier. As rotator and rotator controller, Yaesu G-5500 antenna rotator and rotator controller is used [52]. For rotator control, an I/O board, Data Translation DT2811 is used [53]. The transceiver for the ground station did not change from AAUSAT-I to AAUSAT-II, and it is ICOM IC-910H, which is one of the few alternatives for VHF/UHF bands. The reasons for this selection are gives as frequency scanning, automatic frequency control, and adjustable squelch level [54].

In the software part, for orbital prediction program, Predict Client is used. It works under Linux operating system, and released under the GNU.

4.1.4 Stanford University

Space Systems Development Laboratory (SSDL) of Stanford University made several cubesats under the name CP, and also one other called Quakesat. Quakesat was launched at June 2003.

4.1.4.1 QuakeSat

QuakeSat's main scientific mission is gathering Extremely Low Frequency (ELF) magnetic signal data, which will be studied in relation to earthquake activities. Quakesat has a dimension of 10 x 10 x 30 cm and a weight of 3 kg. With these dimensions, it is possible to fit nearly 30 cm magnetometer inside the structure. Also, four solar arrays and the magnetometer are deployable.

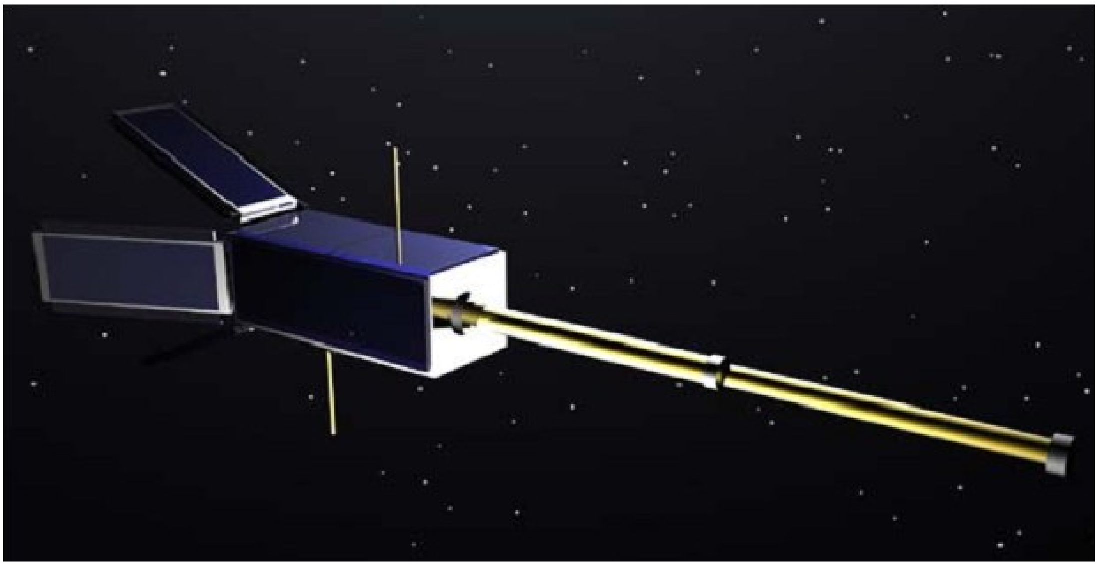

Figure 4.11 : QuakeSat with its solar panels opened.

For Command & Data Handling system, Prometheus processor from Diamond system is chosen, and linux operating system is used for controlling it because of ease of communication libraries. For radio and modem on the satellite, Tekk T-Net Mini 9600 Baud, which is a half duplex crystal controlled radio, and Tigertronics Bay Pac 9600 modem is used respectively. The radio is capable of giving 2 Watts of output power. With the frequency in the UHF band (436.675 MHz), it has margins of 37.1 dB on uplink and 34.9 dB on downlink. As protocol, AX.25 is used, although it is noted that it is inefficient, because a single bit error means loss of a full packet. Also, software modem should produce lower bit error rate than hardware TNC. For antenna, four antennas that are quarter wavelength long are used [55][56].

Figure 4.12 : Bay Pac modem and Tekk Radio.

4.1.4.2 Stanford University ground station

Aside from tracking the satellites via the ground station, some implementations are done for increasing operation quality. These include a web site for controlling the ground station remotely, and a camera that focuses on the radio and modem for visual feedback. The QuakeSat ground station software controls the mentioned website for a remote user to schedule and manage satellite contacts, as well as controls the radio and the modem.

There are two ground stations for SSDL. First one is called Mercury. This ground station were constructed for following the microsatellites done by SSDL, Sapphire and OPAL. Afterwards it was also used for tracking QuakeSat. The ground station is capable of using 2m and 70cm bands. The ground station is equipped with a full duplex transceiver that is capable of operating on 2 m and 70 cm bands, two Yagi antennas for 2 m and 70 cm bands, a TNC as a modem, using AX.25 and capable of 9600 baud rate, and a WEFAX weather station [57].

Figure 4.13 : Initial transceiver and TNC for ground station Mercury.

Another ground station was formed at 30 miles (48 km) east of Fairbanks, Alaska. The reason for selecting that location is that, QuakeSat (and future possible satellites) are following polar orbit. Thus, a LEO satellite can be tracked at every revolution instead of per seven revolution in average. In addition to regular construction of antennas, because of the cold weater with temperatures below -10ºF (-23ºC), 100W patch heaters are added to the antenna azimuth-drive and elevation-drive gears.

Figure 4.14 : Fairbanks Ground Station Equipment Rack.

Also, automation process plays an important role in the ground station. The aim of the automation of the contact software is to reduce errors, maximize contact time, and minimize wear and tear on the support staff. Two primary tasks are automated with this software, namely, file download and flash memory management [56].

From the picture, it can be seen that the transceiver is ICOM IC-910H, and the rotor is Yaesu G5500.

4.1.5 Tokyo Institue of Technology

Tokyo Institue of Technology launched two satellites to date. These are CUTE-1, CUTE 1.7 + APD, and CUTE-1.7+APD II. They were launched at June 2003, February 2006, and April 2008 respectively.

4.1.5.1 CUTE-1

CUTE stands for CUbical Titech Engineering Satellite. Its dimensions are 10 x 10 x 10 cm and weights less than 1 kg. There are two missions for this satellite. These are to receive satellite telemetry and understand satellite conditions, or shortly gaining experience for future missions, and compare AX.25 with SRLL (Simple Radio Layer Link) protocol.

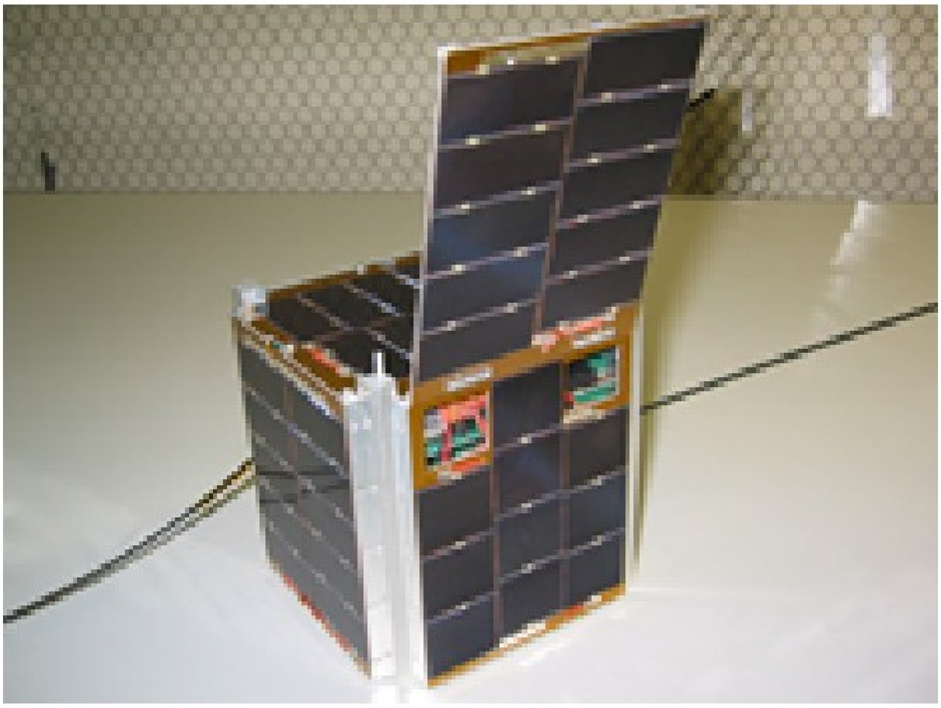

Figure 4.15 : CUTE-1 flight model.

Uplink is used for changing communication protocol. Transceiver for uplink is in 144 MHz band, and Alinco DJ-C1 is used for this. The uplink commands are sent in DTMF (Dual Tone Multi Frequency) to the satellite. For downlink, two different transceivers are used. For CW, a transceiver from Maki Denki is used, and for FM transmission, Alinco DJ-C4 is used. CW is used for telemetry downlink. As it is not used for testing new technology or approaches, high success rate from CW transmission is expected with its 100 mW output power. For CW transmission, PIC16LC73A-04I is chosen. FM transmission is used for testing and comparing SRLL protocol with AX.25 protocol. It has an output power of 350 mW. Modulations for TNC's are FSK modulation, and TNC works at 1200 baud rate. As for modem, MX614 is used [58][59]. The communication subsystem diagram can be seen in the picture below:

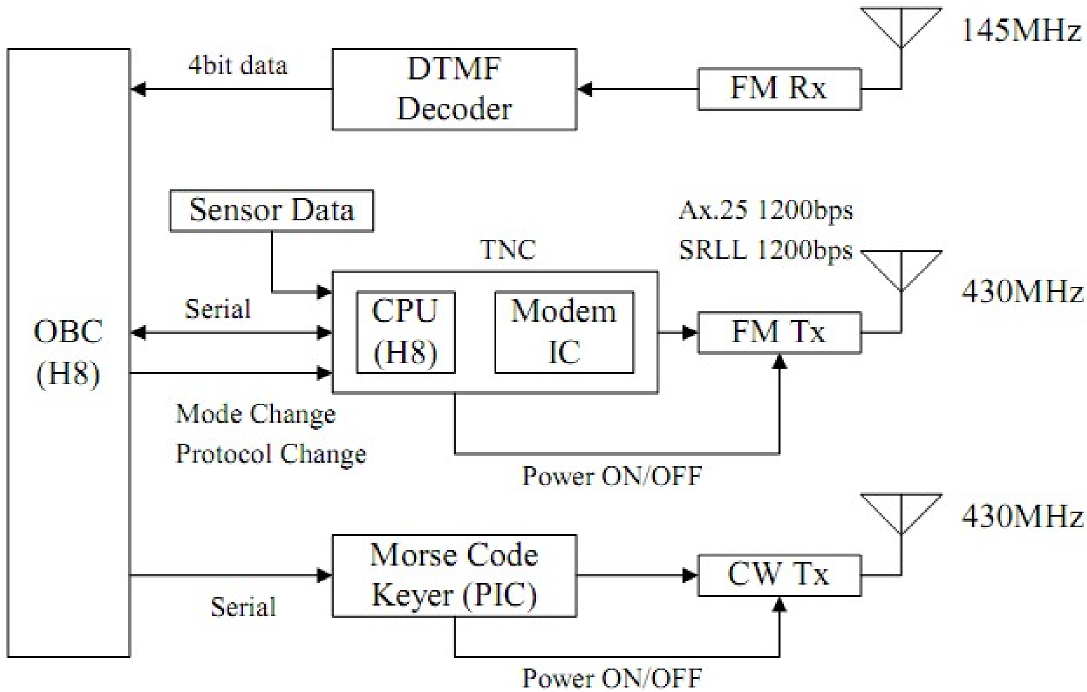

Figure 4.16 : CUTE-1 Communication System block diagram.

CUTE uses a handheld radio's, which is Alinco DJ series, as its communication subsystem. It can be seen in the picture below:

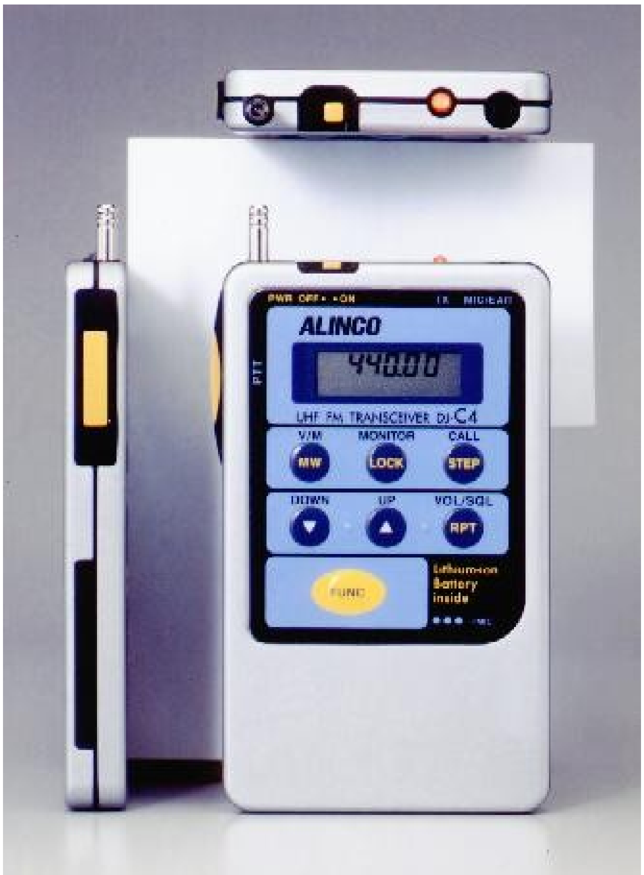

Figure 4.17 : A COTS handheld radio.

As the time of this thesis, the satellite is still operational.

4.1.5.2 CUTE 1.7 + APD

CUTE 1.7 + APD is the second satellite launched byTiTech. It has dimensions of 20 x 10 x 10 cm, making it 2U cubesat, and weights about 2 kg. There are several missions for this satellite. These are:

- A new design methodology, taking the use of COTS parts further. More specifically, two PDAs, where one of them is for redundancy, are used as onboard computer. The PDA is 100 x 70 mm, and uses Windows CE.NET 4.1 operating system.
- Attitude determination and control experiments. For attitude control, three magnetic torquers is used for three-axis stabilization, with an implemented control algorithm. For attitude determination, three ADXRS gyroscopes from Analog Devices, a HMR2300 magnetometer from Honeywell, and a bunch of S6560 photodiode from Hamamatsu Photonics for sun sensors are used.

- Digital Repeater, or shortly digipeater. As it is a part of the communication system, it will be described in more detail.
- Tether deployment experiment. As IADC (Inter Agency Space Debris Coordination Committee) guidelines say that, satellites in LEO must be de-orbited within 25 years. The electromagnetic tether will be tested for de-orbiting the satellite.
- Avalanched Photo Diode, or APD. It will be used for observing low energy charged particle density on LEO [60].

Figure 4.18 : Hitachi PDA NPD-20JWL.

In the communication subsystem, four different transceivers are used. For command uplink and telemetry downlink, Alinco DJ-C5 is used. This selection enables one less transceiver than CUTE-1, which used two different Alinco models for different bands. Uplink is at 144 MHz band, and uses AFSK modulation at 1200 bps or GMSK modulation at 9600 bps with AX.25 and SRLL protocols options. Telemetry can be received by amateur radio operators in addition to TiTech ground station. It works at 437.505MHz, and uses AFSK modulation at 1200 bps or GMSK modulation at 9600 bps, with AX.25 and SRLL protocol options. The digipeater, which is one of the missions of the satellite, uses 1268.5MHz for uplink, and uses GMSK modulation at 9600 bps with AX.25 or SRLL modulation. Te transceiver for this is Kenwood TH-59. Finally, for beacon, an Invax transceiver is used with CW modulation at 437.385MHz frequency [61].

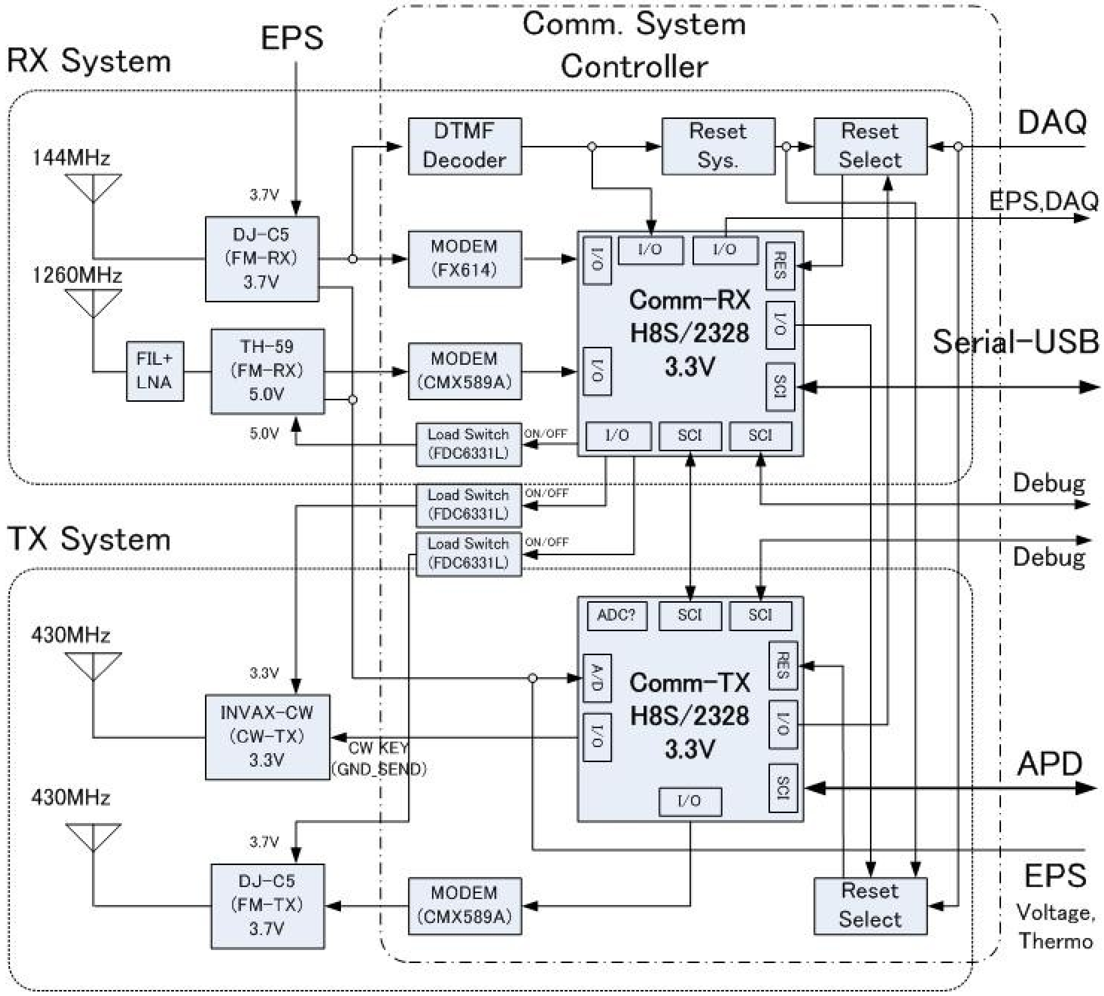

Figure 4.19 : CUTE-1.7 + APD Communication Subsystem block diagram.

Also, for resetting purposes, a DTMF decoder is added to the system. For uplinks, FX614 and CMX589A modems from CML Microcircuits are used, while for downlink, a CMX589A modem is used. The placement of the modems can be seen in the diagram above.

Figure 4.20 : From left to right, Alinco DJ-C5, CW-TX, and Kenwood TH-59.

From May 2006, it transmits an unmodulated carrier on the UHF frequency.

4.1.5.3 CUTE 1.7 + APD II

CUTE 1.7 + APD II is the third satellite launched by Titech. It has similar missions and communication subsystem to CUTE 1.7 + APD. In fact, it is an evolution of the second satellite. It has dimensions of 22 x 18 x 11.5 cm, which is about 2 times larger than CUTE 1.7 + APD, and has a mass of 3 kg.

There are several missions of this satellite. These can be given as:

- Extended use of COTS parts, including two PDAs (Hitachi NPD-20JWL) for redundancy and amateur radio transceivers for communication.
- An attitude determination and control experiment. For attitude control, three magnetic torquers are used. For determination part, two Hamamatsu S6560 diodes on each side of the satellite excluding the top side, Analog Devices ADXRS150 gyroscope (possible three of them for each axis), and Honeywell HMR2300 magnetometer are used. Several estimation algorithms are tested with these hardware.

- APD sensor. It is used for observing low energy charged particle density in LEO.
- Digital repeater. It has similar architecture to the second satellite of Titech. It will be described in more detail.

Electrodynamic tether mission from the second satellite is discarded, because the orbit of this satellite is too high for such a mission to succeed.

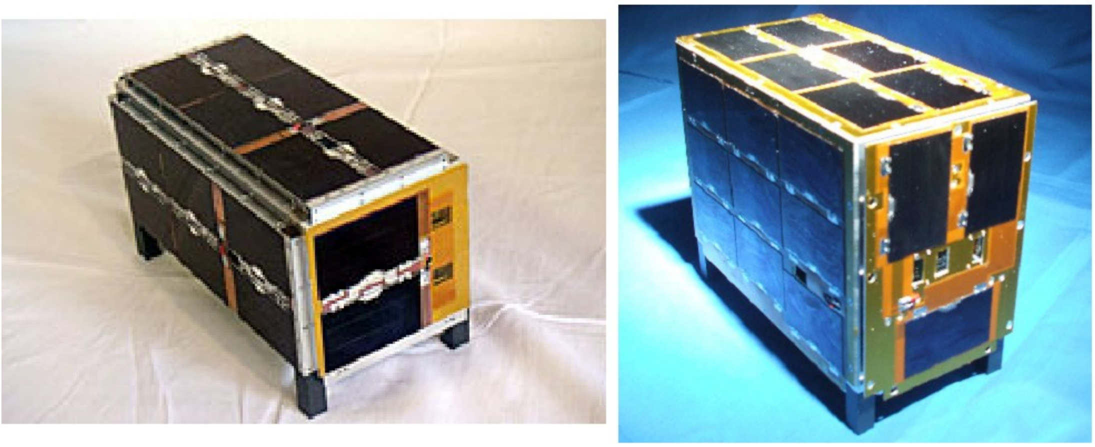

Figure 4.21 : CUTE-1.7 + APD (left) and CUTE 1.7 + APD II (right) shares a similar design.

Aside from possible implementation differences to communication subsystem, the general design remain same with CUTE-1.7 + APD. For 144 MHz AFSK (Audio Frequency Shift Keying) with 1200 bps baud rate uplink, and 437.475 MHz AFSK and GMSK modulated packet downlink with 1200 bps and 9600 bps baud rates respectively, Alinco DJ-C5 transceiver is used. While command uplink is reserved by Titech ground station, all downlinks are open to the amateur radio operators. For digipeater, Kenwood TH-59 is used. It uses GMSK (Gaussian filtered Minimum Shift Keying) modulation with 9600 bps baud rates at 1267.6 MHz. For beacon signal, an Invax transceiver is used with CW modulation at 437.275 MHz. Except beacon signal, all of these communications can be done by AX.25 or SRLL protocols [62].

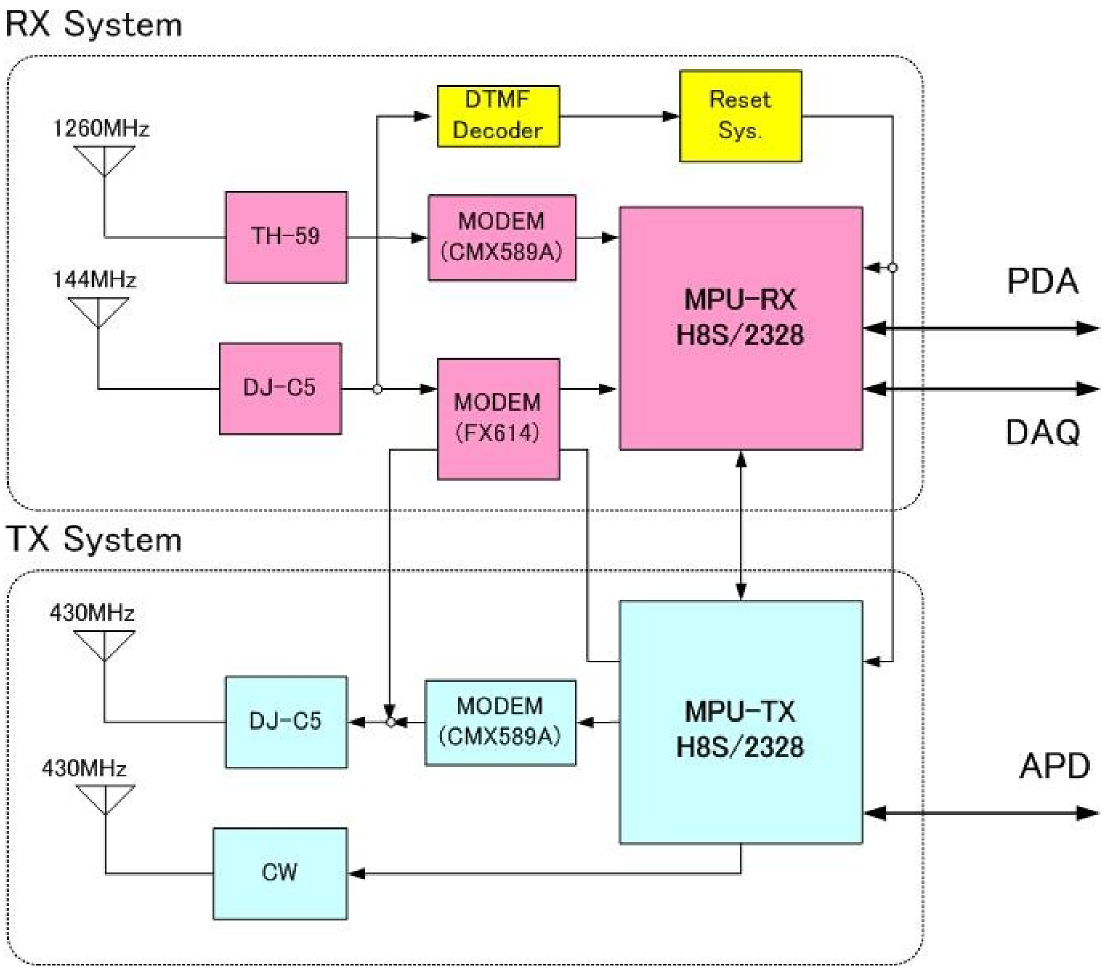

Figure 4.22 : CUTE 1.7 + APD II Communication subsystem block diagram.

In the diagram above, it can be seen that, CMX589A modem from CML Microcircuits is used for uplink on 1200 MHz band and for downlink on 430 MHz band, while FX614 modem from CML Microcircuits is used for uplink on 144 MHz band. Also, there is an DTMF Decoder for system resetting purposes [63].

4.1.5.4 Tokyo Institue of Technology ground station

Despite the small size of the satellites, tracking them by using all of the bands require a complex ground station.

As can be seen from the figure above, four transceivers are used for communicating with the satellites. The transceivers are one Yaesu FT-736 for 144 MHz band, two Yaesu FT-847 for 440 MHz band, and one ICOM IC-910H with UX-910 module for 1200 MHz band. The TNCs are Tasco TNC-555, possibly for only AX.25, and a custom made SRLL TNC. For tracking the satellites, a RAC805 satellite tracker is used, which is capable of tracking up to 80 satellites with Doppler shift compensation [64]. The schematic of the ground station can be seen below.

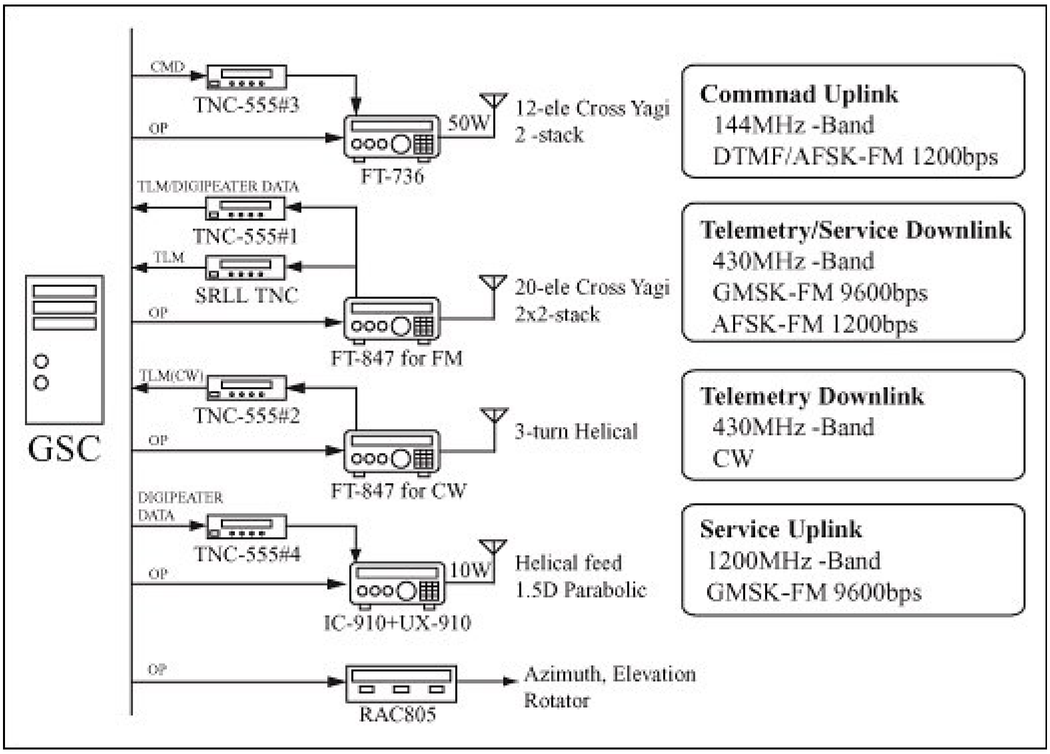

Figure 4.23 : Titech Ground Station block diagram.

The actual ground station indoors hardware can be seen in the picture below.

Figure 4.24 : TiTech Ground Station.

In the figure below, there are two 144MHz, four 440MHz Yagi antennas stacked with a 1200MHz dish antenna. Using more than one antenna for VHF and UHF bands may give more gain. However, looking at the length of the Yagi antennas shows that an antenna array is used instead of one antenna with high gain. There may be two reasons for that. One of them is that, with shorter antenna, a better pointing accuracy can be obtained. The other reason is that, with right hand and left hand polarized antennas stacked together, a better communication link can be obtained, because the orientation of the satellite cannot be guaranteed.

Figure 4.25 : TiTech Ground Station antennas.

4.1.6 University of Tokyo

University of Tokyo launched XI-IV and XI-V at June 2003 and October 2005 respectively.

4.1.6.1 XI-IV & XI-V

XI (sai) stands for X-factor Investigator. XI-I through XI-III were built as bench models. Initially, XI-V was engineering model of XI-IV. However, XI-V was launched two years later than XI-IV, and differs from XI-IV by its different solar cells and a higher resolution camera, as well as different software implementation.

Not surprisingly, they share the same missions. These are, command uplink and data downlink, and taking photos.

In the communication subsystem, 2m and 70 cm bands are used. Downlink is done at 437.490 MHz at 1200 bps baud rate, with 600 mW output power. For TNC, PIC16C622 is used for encoding the telemetry data in AX.25 protocol format. FSK modulation is done by MX614. For uplink, 145.835 MHz is used with 1200 bps baud rate, with same modulation and protocol as 70 cm band. The demodulator and TNC are MX614 and PIC16C711 respectively. CW modulation is used for beacon signal, which has an output power of 100 mW and operates at 436.8475 MHz, and data is created by PIC16C716. For transmitters, half wave dipole antennas are used, and for the receiver, half wave monoopole antenna is used [65].

4.1.6.2 University of Tokyo ground station

The ground station of Intelligent Space Systems Laboratory mainly consists of commercial products. For transceiver, an ICOM IC-910D is chosen. This is Asian version of IC-910H. It is used for downlinking CW signal, and connected to a TNC Tasco-555. An ICOM IC-970J is used for command uplink and downlink of telemetry data, and connected to Tasco TNC-505 for uplink and downlink.

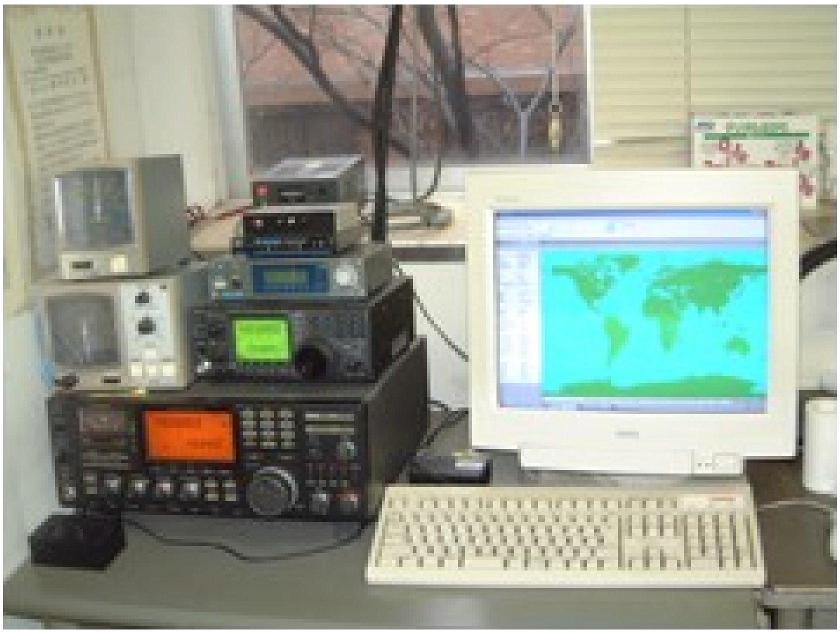

Figure 4.26 : GS room in the University of Tokyo.

For antennas, VHF and UHF antennas from Creative Design are used. For VHF, x213 model is chosen, and for UHF x727 model is chosen. They are controlled by azimuth and elevation rotators, again produced by Creative Design. Models for azimuth and elevation are RC5A-3 and ERC5A respectively. Two power supplies, namely GSS1200 and GSV3000 concludes the ground station design.

Figure 4.27 : VHF and UHF antennas on the University of Tokyo Ground Station.

4.1.7 ARR/NSC

NCUBE-2 and NCUBE-1 were launched at October 2005 and July 2006 respectively. The project was initiated by Norwegian Space Centre and Andøya Rocket Range, and students from the Norwegian University of Science and Technology, the University of Oslo, the University College of Narvik, and the Agricultural University of Norway worked on the project.

4.1.7.1 NCUBE

NCUBE-1 and NCUBE-2 satellites are identical satellites [66]. Their main mission is to demonstrate ship traffic surveillance from a LEO satellite using the maritime Automatic Identification System (AIS). In the content of this mission, AIS-messages will be received, stored and retransmitted. Another mission is to demonstrate an attitude control hardware that is a combination of passive gravity gradient stabilization and active magnetic torquers [67].

These two satellites have fairly unique and complicated communication systems. For uplink of AIS signals, it uses two different frequencies, namely 161.975 and 162.025 Mhz, although for NCUBE-2, only one of them was used for simplifying the design. It is connected to a MX589TN GMSK modem [41]. Another TNC takes data from various subsystems via a data selector, and passes appropriate datas to appropriate transmitters, and also used for taking uplink commands from VHF band receiver, which has a frequency of 145.980 MHz. S-band transmitter, which has a frequency of 2407.25 Mhz in ISM band, is used for transmitting AIS data, and UHF band transmitter with the frequency of 437.305 Mhz [68] is used for the chosen one of the other telemetry datas.

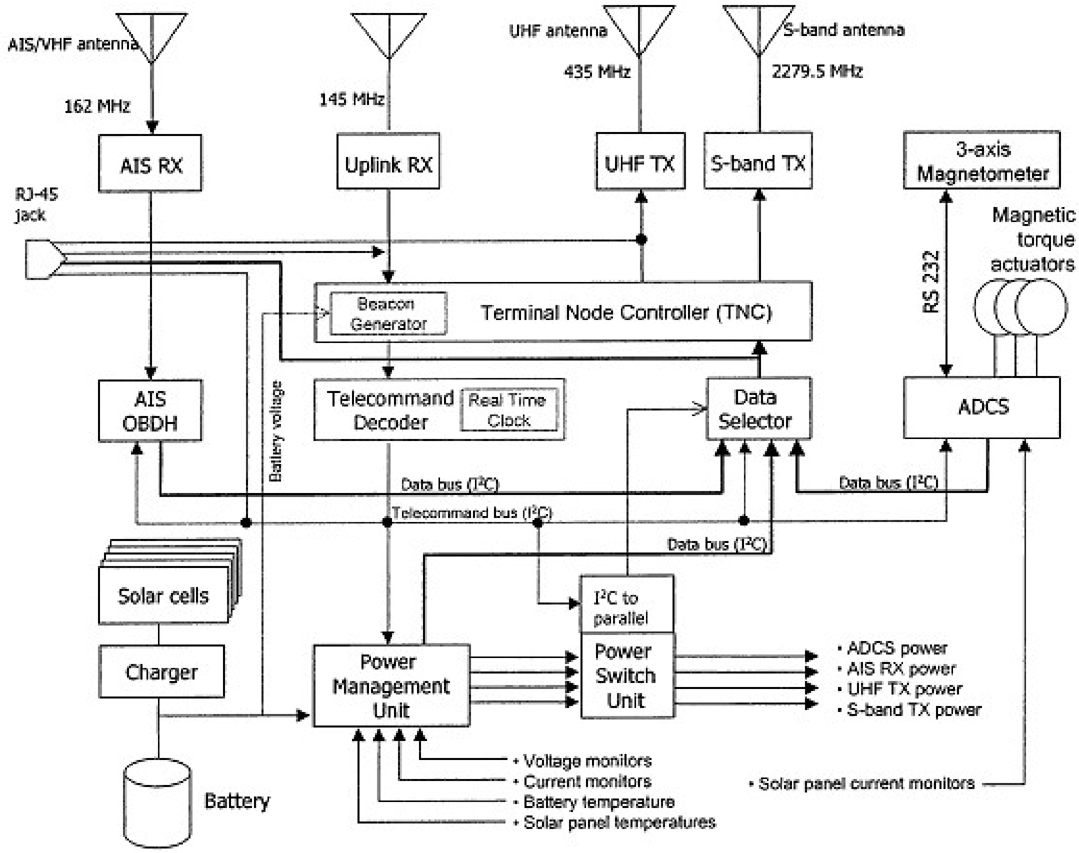

Figure 4.28 : NCUBE Satellite System architecture.

The protocol used in NCUBE is AX.25 protocol, and it has either 1200 or 9600 bps data rate. UHF transmitter has an output of 0.5 W, and S-band transmitter has an output of 0.8 W. For VHF and UHF bands, monopole antenna is used, and for S-band, a patch antenna is used. All of these antennas are placed in the nadir surface of the satellites.

NCUBE-1 was a victim of DNEPR-1 launch, and no contact can be established with NCUBE-2 satellite.

4.1.7.2 Narvik University College ground station

One of the main reasons for selecting this university for constructing a ground station was that, it was the northernmost location among the participating universities. Although this ground station is in the process of an overhaul for future use, including the future projects of Narvik University College's (NUC) HiNCube and University of Oslo's CubeSTAR, in this thesis, the version that was constructed for tracking NCUBE satellites will be considered [67].

The ground station at Svalbard was not only a ground station, but it was planned to be a Mission Control Centre. The ground station at NUC is the primary location for processing the data except AIS packets, and it allows remote connection to GS.

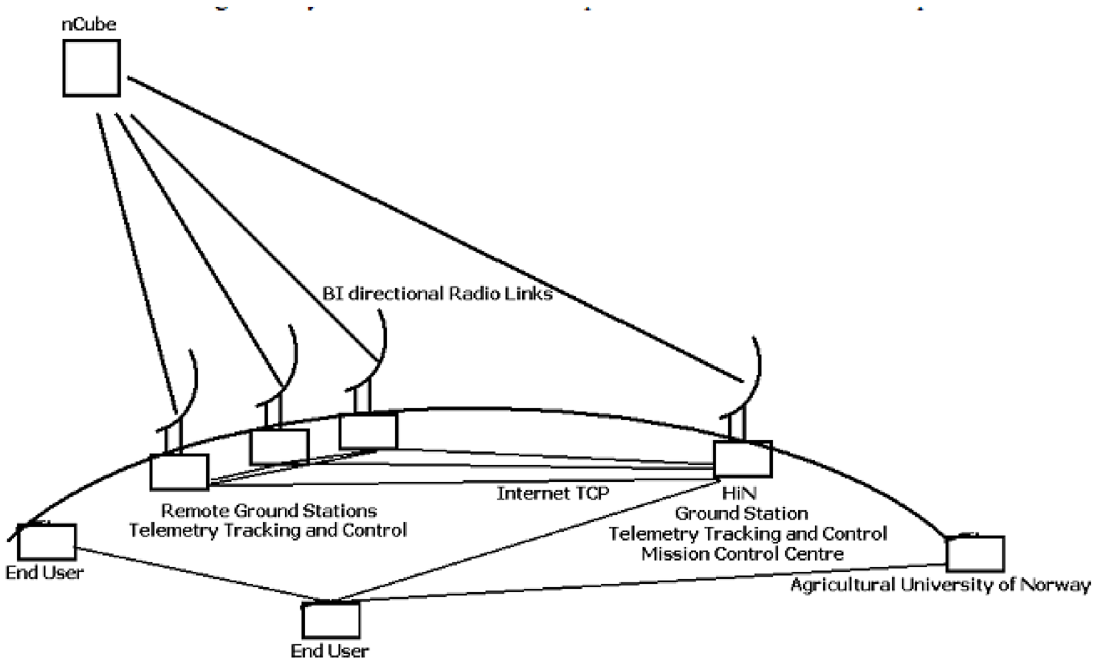

Figure 4.29 : Communications architecture for NCUBE project.

In hardware part of the ground station, Yagi-Uda antennas were used for VHF and UHF bands. The models that were chosen are 9-el and 19-el antennas from Antennes Tonna (AFT F9FT). They are rotated by positioners from M2 Inc. For azimuth, the model OR2800P-DC is used, and for elevation model MT-3000 is used. These can be controlled via RS-232 or directly with the buttons in front of it. More detailed information about rotators can be seen in M2 Inc's website.

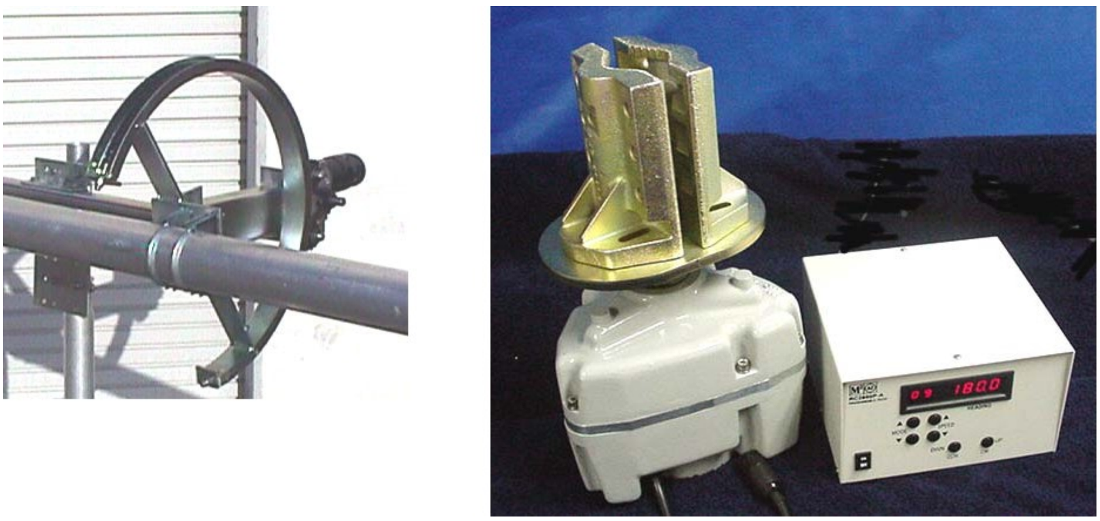

Figure 4.30 : Elevator and azimuth rotators MT-3000 and OR2800P-DC.

As a way to prevent damage to the transceiver from lightning, two lightening arrestors were installed, and they can handle up to 2000 W before grounding the signal.

Due to the location of the GS, very low temperatures occur. The minimum temperatures at Narvik fluctuates around -20ºC. First components that will be affected by low temperatures are RG family cables, however, they did not implement additional protection it seems.

The aims of the software are:

- Present system/user data from nCube satellite and relay them to a remote user
- store commands and data from communications for later retrieval
- transmit a desired signal, possible from a remote user, which can be detected and interpreted onboard the satellite

For implementing these goals, all the equipments are interfaced with transmission control protocol and internet protocol (TCP/IP).

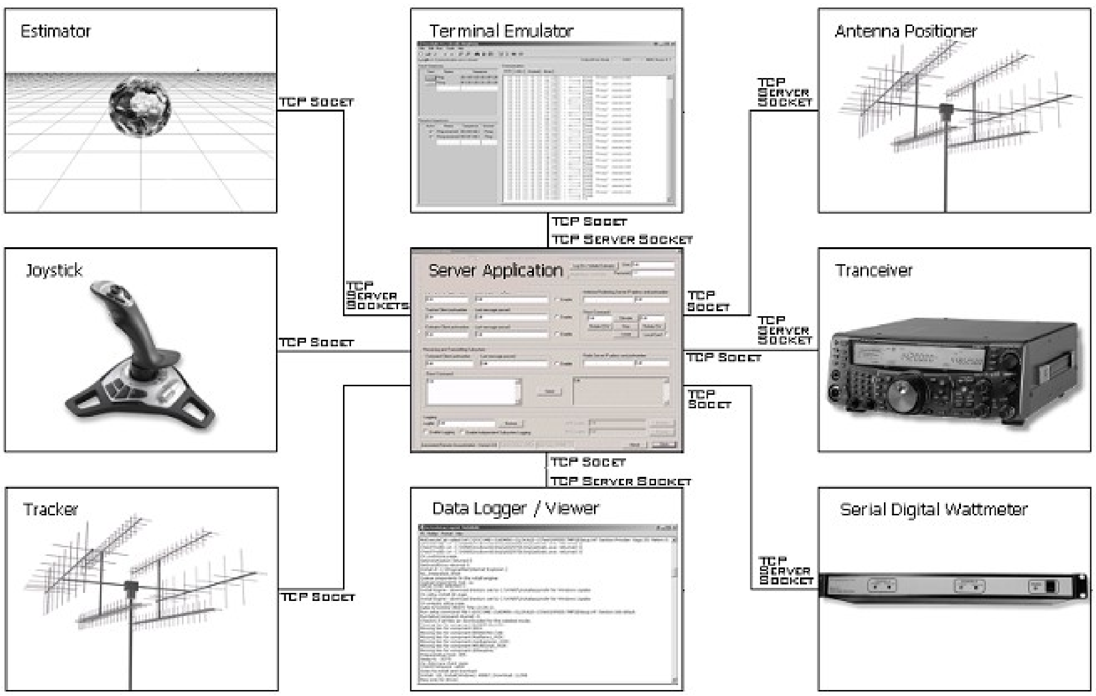

Figure 4.31 : Wiring diagram of the internet connected modules.

More detailed information about these remote control software, master thesis of Åge-Raymond Riise can be seen.

In addition to remote control program, NOVA is used for tracking with WiSP as its backup, hyperterminal for accessing TNC. As transceiver, Kenwood TS-2000 is used [69].

4.1.8 University of Würzburg

University of Würzburg launched two cubesats to date. These are UWE-1, which is launched at October 2005, and UWE-2, which is launched at October 2009. Another cubesat is in the works with a name UWE-3.

4.1.8.1 UWE

UWE stands for University Würzburg's Experimental satellite. It has dimensions of 10 cm at each side, and has a mass less than 1 kg. The objective behind the UWE program is to develop the technologies needed for formation flying with extremely small satellites [70]. These are adaptation of parameters for the telecommunication link using internet protocols to deloays and disturbances, use of micro-Linux as on-board operating system, and testing of triple-junction GaAs solar cells [71].

UWE-1 and UWE-2 (and possibly UWE-3) use the same satellite platform with differences in attitude determination system for UWE-2, and an additional attitude control system for UWE-3 [70].

The communication with the ground station is done with UHF band. With an end-fed half-wave antenna, the radio transmits about 1 W power. AX.25 protocol is used, and its parameters can be changed from the ground station. Also, transmission rate and modulation can be changed between 9600 baud FSK and 1200 baud AFSK.

4.1.8.2 University of Würzburg ground station

The ground station consists of COTS components. The rotator is Yaesu, and the transceiver is ICOM IC-910H. Antennas are 2m and 70cm Yagi-Uda [70].

Figure 4.32 : GS antennas at the University of Würzburg

For ground station control, Mercury GS system, which was developed by Stanford University using GSML standard, are used[72].

4.1.9 Hankuk Aviation University

Hankuk Aviation University launched HAUSAT-1 with the failed DNEPR-1 launch at July 2006. Another satellite, named HAUSAT-2, is being developed by Hankuk Aviation University.

4.1.9.1 HAUSAT-1

HAUSAT-1 is developed by Space System Research Laboratory (SRLL) of Hankuk Aviation University. It has dimensions of 10 cm at each side, with a mass less than 1 kg. Main mission objectives are collecting the satellite position data with a spaceborne GPS receiver, experiment on deployment mechanism of solar cell panel and homemade sun sensor, and get telemetry data from various sensors.

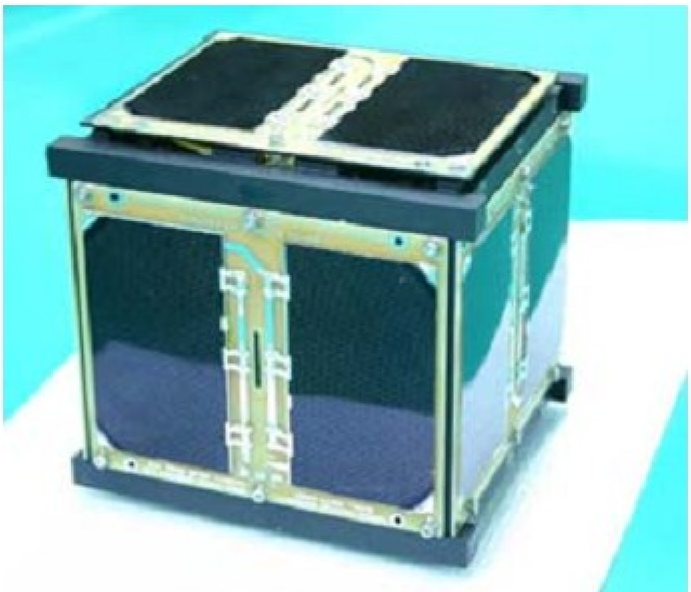

Figure 4.33 : HAUSAT-1 flight model.

Communication subsystem on Hausat-1 consists of a transmitter, receiver, and a TNC with modem and antenna [73]. For uplink, it uses 2m band with the frequency being 145.840 Mhz, and for downlink, it uses 70cm band with the frequency being 437.465 Mhz. FSK modulation is used with AX.25 protocol [74].

4.1.9.2 Hankuk Aviation University ground station

HAU ground station consists of ICOM IC-910H transceiver that is connected to a TNC Kantronics KPC-9612+. HL-350VDX power amplifier and GSV-3000 power supply is used. Antenna is controlled by Kansas City Tracker Interface card, and is able to correct Doppler Effect [73].

4.1.10 California Polytechnic University

Being one of the universities that developed the cubesat standard (the other being Stanford University) [75], and P-POD, it is no surprise that this university is among the frontrunners in terms of number of satellites launched.

The launches in chronological order are: CP-1 and CP2 at July 2006 with DNEPR-1 launch, CP-3 and CP-4 at April 2007 with following DNEPR launch, and CP-6 at May 2009 with Minotaur 1 launch. All of the satellites are 1U, and have a mass less than 1 kg.

4.1.10.1 CP-1

CP-1 is the first cubesat of Cal Poly. Its main payloads are a sun sensor from Optical Energy, and experimented with a cheap transceiver and DTMF modulation scheme to transfer basic telemetry and sun sensor data do the ground. Also, a single magnetic torquer embedded within a side panel is used.

Figure 4.34 : CP-1 flight model.

The communication subsystem comprised of two modified Alinco DJ-C4 transceivers [76]. The communication subsystem, with its DTMF modulation, has an output power of 300 mW, and uses the frequency of 436.845 Mhz [77]. The Morse Code and DTMF tones are generated in software, thus replacing the need for hardware TNC. Also, the flight computer alternates between two transceivers on each communication cycle. Finally, a dipole antenna is linked to two transceivers via a custom RF printed circuit [78].

It couldn't be deployed to orbit, due to launch rocket failure.

4.1.10.2 CP-2 & CP-4

CP-4 is the same model with CP-2. Due to the launch failure of Dnepr rocket, another CP-2 satellite was launched into the orbit with the following Dnepr launch, instead of CP-4 satellite, which contained a CPX bus and deorbit experiment. As the Russian government didn't let Cal Poly to change the name of the satellite, second CP-2's name was changed to CP-4, and original CP-4 is not deployed [76].

Its main missions are to create a "CP" bus that contains all the subsystems except the payload, thus an attempt to standardizing a CubeSat bus. Second mission is an energy dissipation experiment [79].

Figure 4.35 : CP-2 and CP-4 flight model.

Instead of software TNC on CP-1, these two satellites use a microchip as a hardware TNC, however this microchip was not produced as a TNC-only microchip. It is PIC18LF6720, and supports I2C communication bus. The reasons for selecting this microchip are amount of on-chip Flash memory, low power consumption, and number of I/O pins. For transceiver, Chipcon CC1000 is selected after making comparisons between Infineon TDA5255, Chipcon CC1000, and Melexis TH7122. Chipcon is selected because its sensitivity is higher, it has the smallest frequency separation, and maybe most importantly its datasheet is more detailed. The maximum output power of this transceiver is 10 mW. As radio amplifier, RF Micro-devices RF2117 is chosen, and it has 33 dB of signal gain.

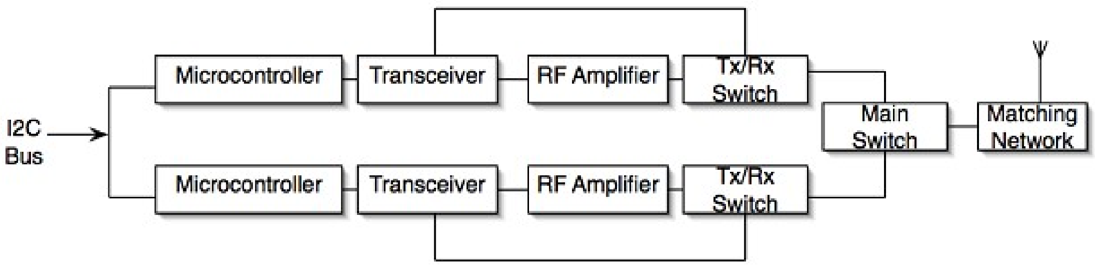

Figure 4.36 : Block diagram of the CPB communication system.

CP-2 and CP-4 have the similar redundancy scheme with CP-1, the two same systems work alternatively. With only one dipole antenna on the satellite, a switch is implemented on the same circuit of communications subsystem, with switch being M/A Comm SW-425.

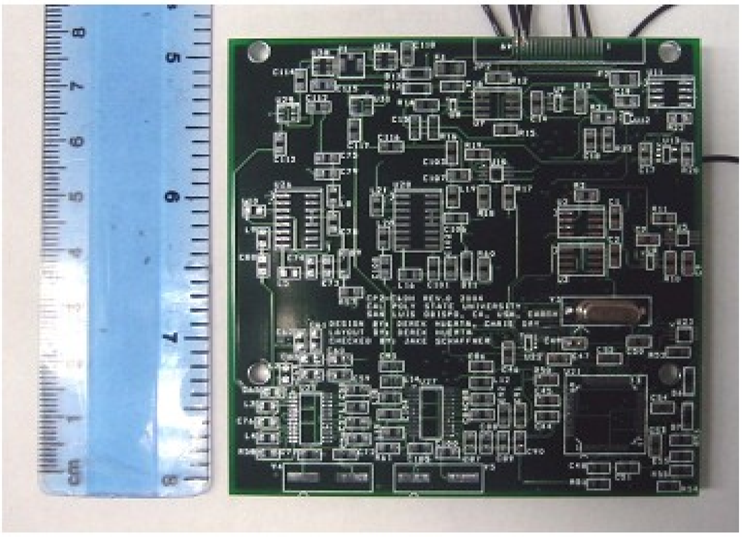

Figure 4.37 : Communications subsystem board of CP-2 & CP-4 cubesats.

The communication system uses FSK, with AX.25 and Morse Code [78].

CP-2 flew on failed Dnepr launch, and CP-4 (second CP-2) failed after three months in orbit, possibly due to a failure on I2C bus on the satellite [76]. The frequency is 437.325 Mhz [80].

4.1.10.3 CP-3

CP-3 is similar to the satellites CP-2, with some incremental updates. The only major difference between CP-2 and CP-3 is the payload that each flew [81]. It introduces several bus improvements and a more robust software [76].

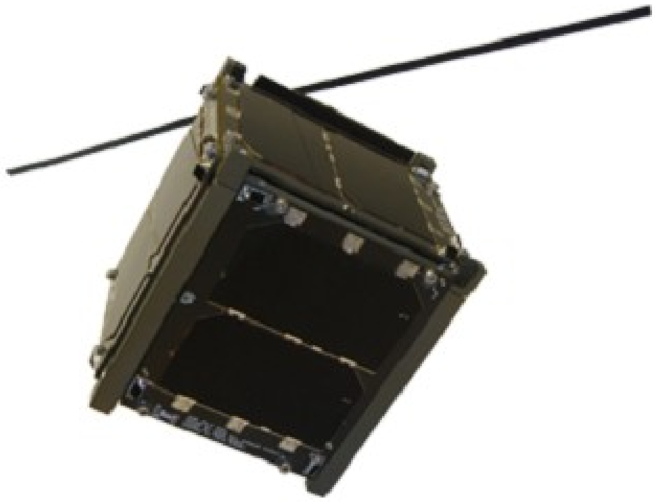

Figure 4.38 : CP-3 is Cal Poly's third satellite.

The satellite goes silent away for many weeks at a time. Possible explanation for this is an undesired permanent magnet on the satellite, and B-dot algorithm is not able to correct this because of one mislabeled variable in the algorithm [41].

The frequency used is 436.845 Mhz, with FSK modulation [82].

4.1.10.4 CP-6

CP-6 cubesat is an improvement of CP-3 satellite. There are two hardware modifications, namely adding a low noise amplifier to the receiver, and adding tri-state buffers between the cameras and the payload processor. Also there are major software modifications [76]. Its missions are attitude determination and control using 2-axis magnetometers and magnetotorquers, and en electron collection experiment.

It uses FSK modulation on SSB (single side-band), and it is tuned to LSB with the frequency of 437.365 Mhz [83].

4.1.10.5 California Polytechnic University ground station

There are two ground stations that belong to PolySat project at Cal Poly. These are called Hertz ground station and Marconi ground station. Hertz is constructed first.

Hertz ground station was built mostly to talk with CP1. It consists of a Yaesu 847 radio that is connected to 2m and 70cm antennas, and a HF antenna.

Figure 4.39 : Antennas of the Hertz GS at Cal Poly.

Yaesu 847 transceiver, which is connected the antennas with SSB Electronics amplifier and LMR-400 coax cable, supports HF, VHF and UHF bands, and has two VFO's (or supports Cross-band Full Duplex operation [84]) which allows transmit and receive simultaneously by using two different bands for each. The amplifier is connected to the antenna end of the cable. 70Cm antenna is 436CP42 from M2 Inc, and 2m antenna is (possibly) 2MCP22 from M2 Inc. The antenna is controlled by Yaesu G5500 azimuth/elevation rotator. A custom breakout box is made to key the transmitter and take audio from transceiver. For tuning the radio, a CAT interface is used with a null-modem adapter.

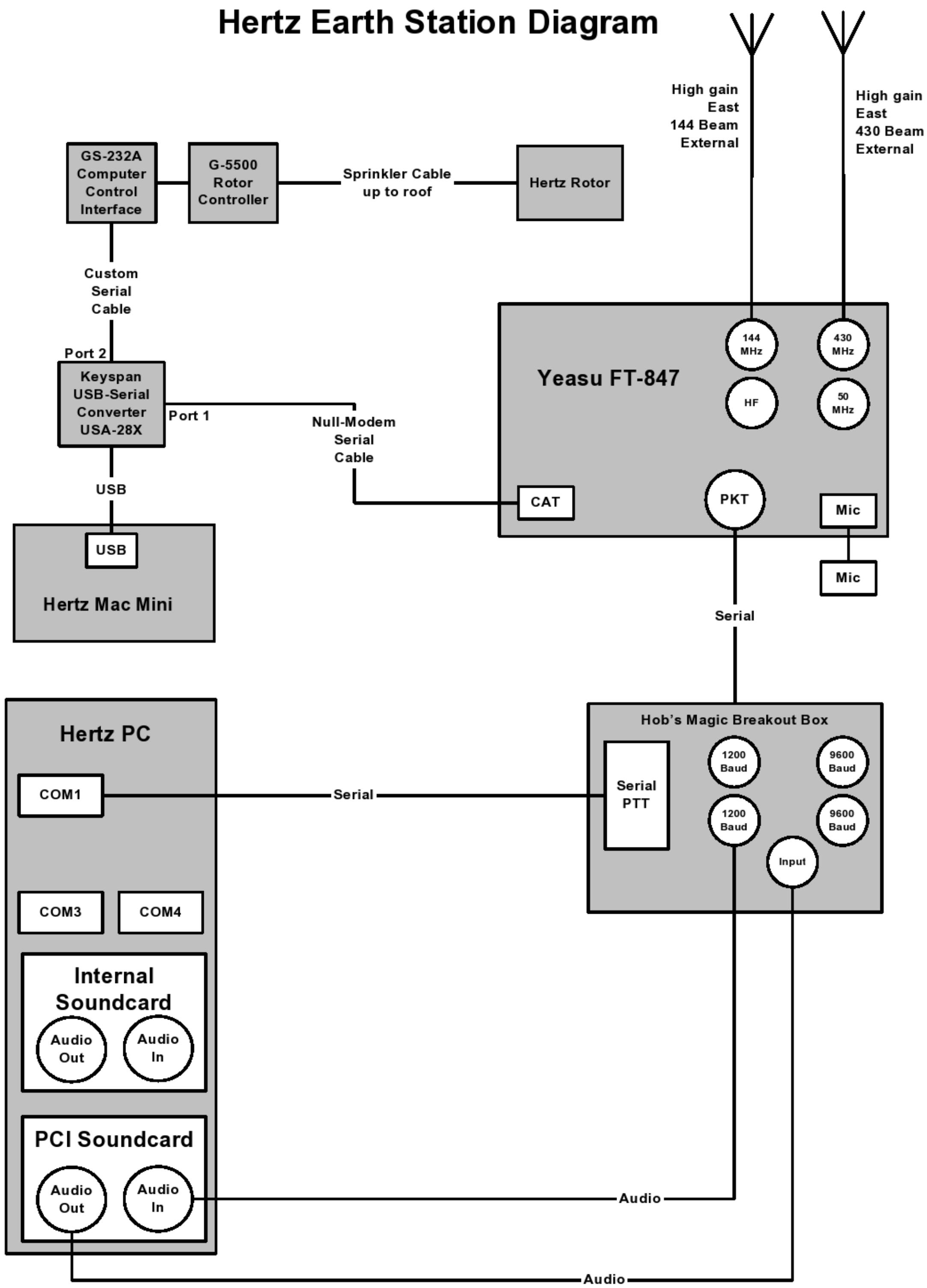

Figure 4.40 : Hertz Earth Station diagram.

Marconi ground station is the newer one, and built primarily to handle communications with CP2. The radio is ICOM-910H, which became almost a standard in cubesat community (currently it is out of production [85], with newer model IC-9100 not approved yet). It is connected to M2 Inc 436CP30 antenna, which is for 70 cm band. SSB amplifier is mounted between the antenna and transceiver, and connection between antenna and transceiver is done with LMR-600 coax cable. For testing purposes (that is, for using an internal antenna), a switch is implemented just before the radio. Switch is Delta 2N antenna switch.

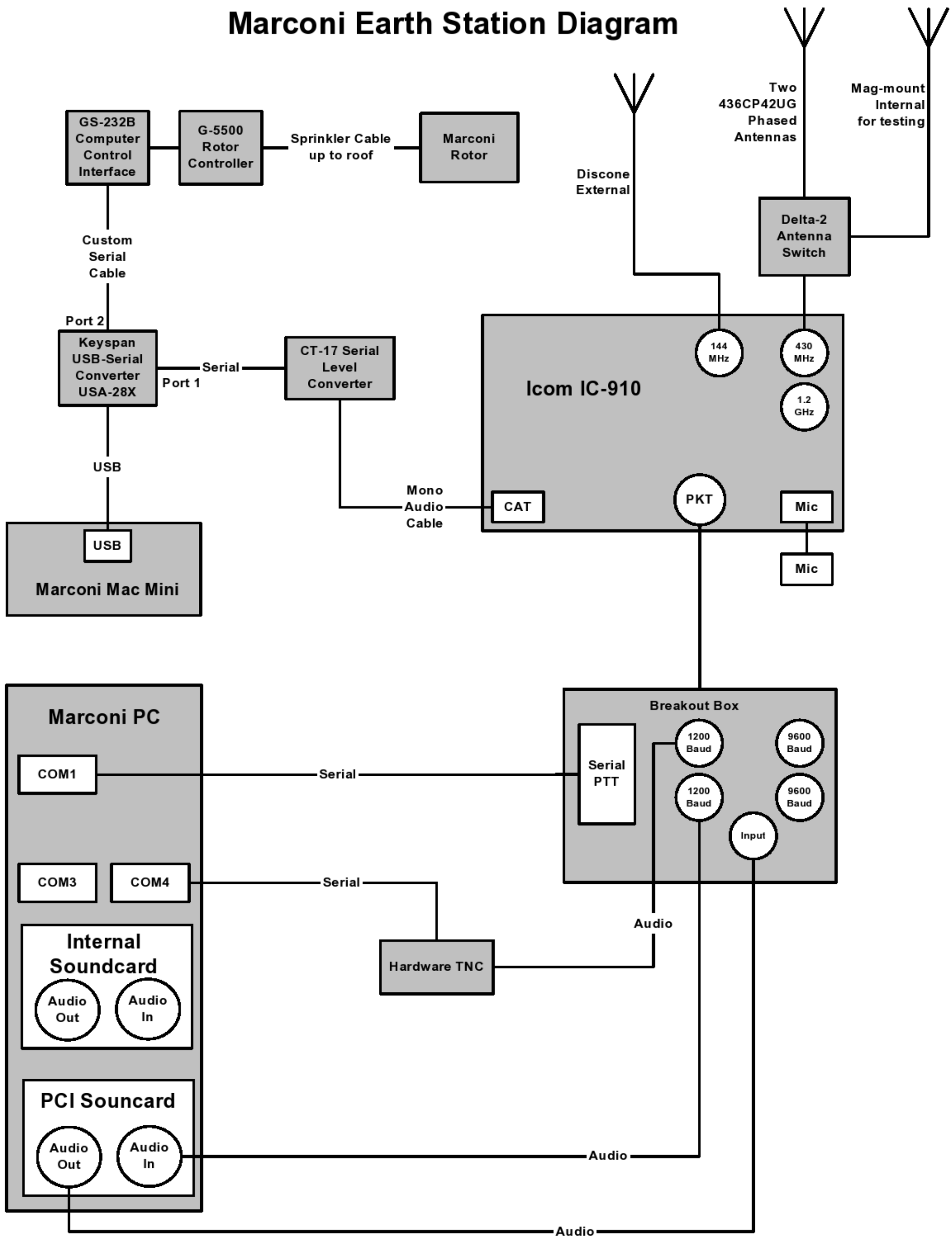

Figure 4.41 : Marconi Earth Station diagram.

All of these antennas are connected to the roof with JRM23810 tower [86].

In the software part, for software TNC, MixW program is used. It is used as a primary way to decode data, although there is a hardware TNC for backup. For satellite tracking, mainly MacDopplerPRO is used, thus requiring MAC computers. This program has interfaces for both radio and rotors. Also, SatPC32 is used on Windows XP computers.

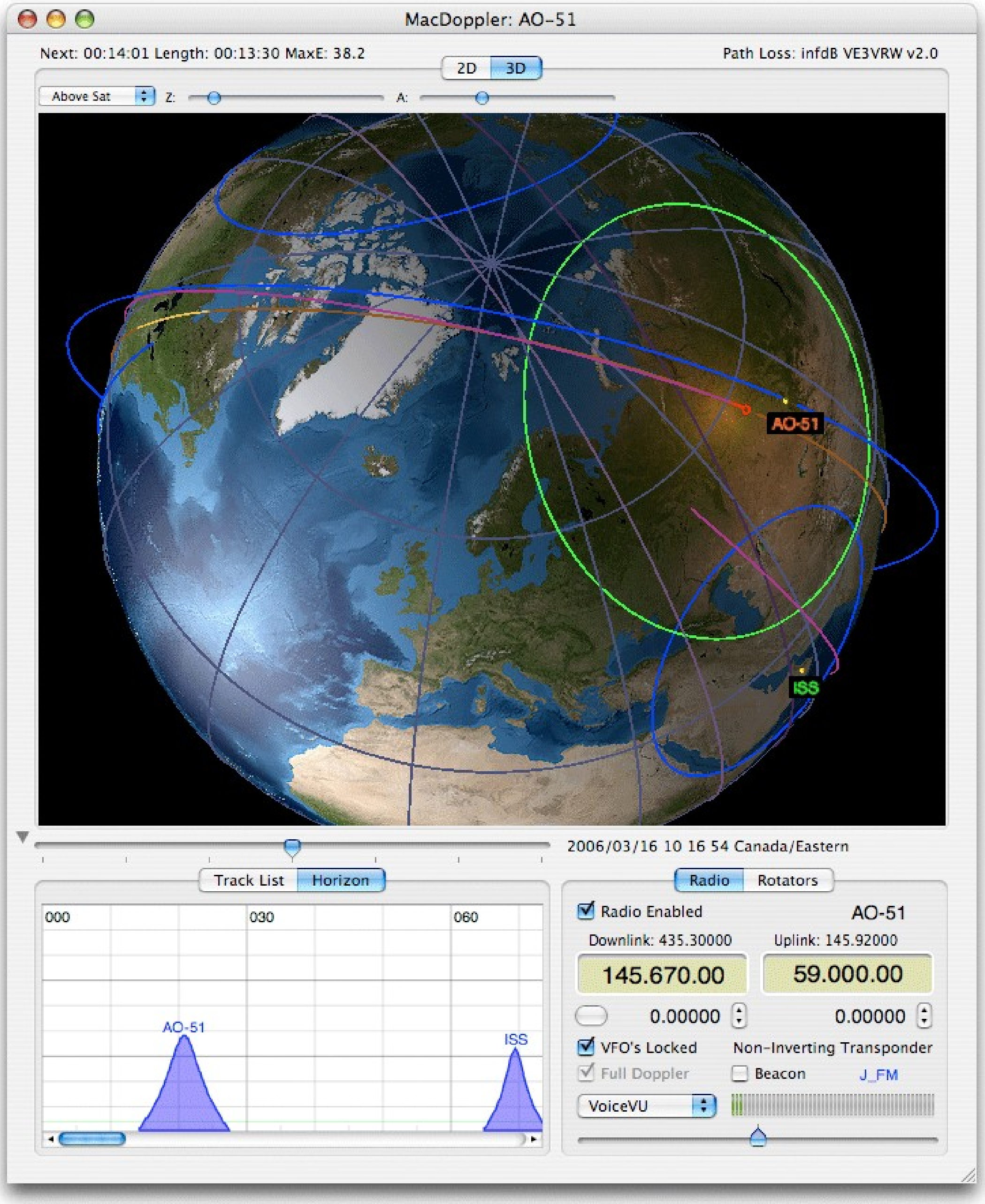

Figure 4.42 : MacDoppler interface.

5. MODULATIONS

In telecommunications, modulation is the process of conveying a message signal inside another signal that can be transmitted. This message signal can be an analog signal or a digital signal. Depending on the signal type, transmitter channel medium, required bit error rate etc., modulation selection may change.

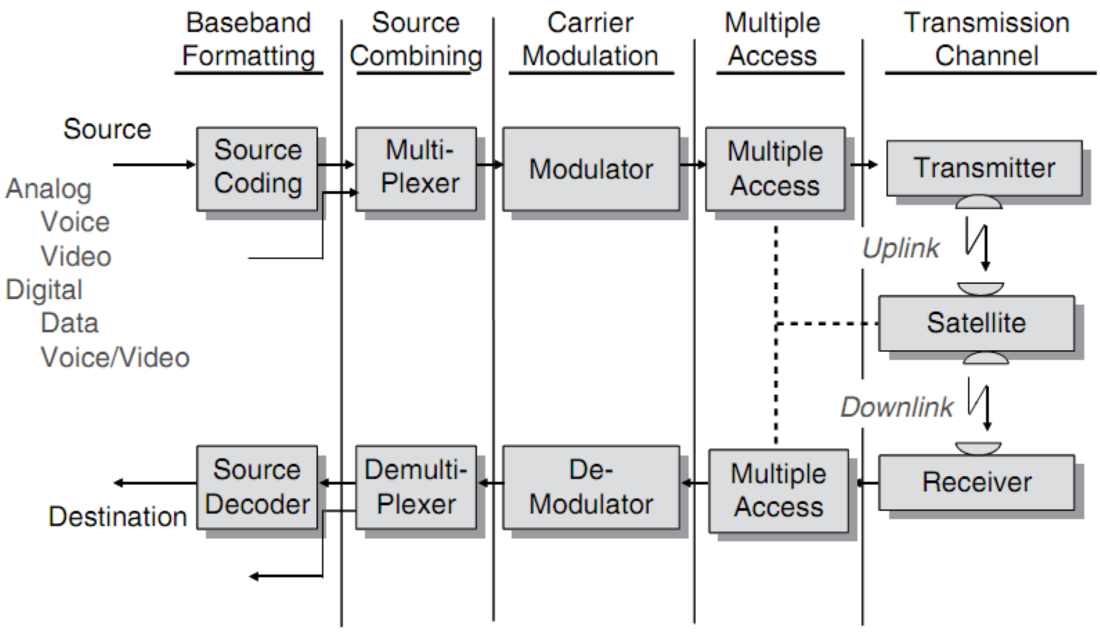

Figure 5.1 : Signal processing in satellite communication [87].

There are two basic criteria for comparing the performance of modulation schemes that are given in the following subchapters. These are power efficiency and bandwidth efficiency.

Power efficiency is defined as the required bit energy to noise Power Spectral Density (PSD) ratio for a certain Bit Error Probability (BEP) over a Gaussian channel.

Bandwidth efficiency is defined as the number of bits per second that can be transmitted within one Hertz of the system bandwidth [88].

5.1 Analog Modulation Techniques

Most of the satellite communications involve data in digital format. However, there are analog telephony and video signals supplied by earlier generation satellites. Also, most, if not all, of the cubesats launched use digital modulation techniques because of the usage of digital data.

The basic analog modulation schemes are amplitude modulation (AM), single-sideband modulation (SSB), frequency modulation (FM), and phase modulation (PM). As these modulation techniques are not used in cubesats, only brief definitions will be given.

5.1.1 Amplitude modulation

Amplitude modulation works by varying the strength of carrier signal according to the information signal that is being sent. It is often used to refer AM radio [89].

5.1.2 SSB modulation

Single-sideband modulation is a special case of amplitude modulation. As amplitude modulation produces an output that uses twice the bandwidth of the baseband signal, it is not efficient. Single-sideband modulation prevents bandwidth doubling, and also power wasted on carrier, but at the cost of increased device complexity [90].

5.1.3 Frequency modulation

Frequency modulation (FM) varies instantaneous frequency of the carrier signal in relation to information signal. It is often used to refer FM radio, which is used at VHF radio frequencies [91].

5.1.4 Phase modulation

Phase modulation (PM) varies phase of the carrier signal instantaneously in relation to information signal.

5.2 Digital Modulation Techniques

Most, if not all, of the cubesats use digital modulation techniques in uplink and downlink of the signals. It is a foregone conclusion that ITU-pSAT II will use digital modulation in conveying signals, whatever modulation it is.

In modulation, the digital symbols are carried with a carrier signal. This signal is a sinusoidal signal.

$$s(t) = a(t)\sin[2\pi f(t)t + \phi(t)] \quad \textbf{(5.1)}$$

In this sinusoidal signal, a(t) is amplitude, f(t) is frequency, and ø(t) is phase of the carrier signal. Basic modulation schemes are done by changing one of these parameters, and keeping other two parameters unchanged. According to which parameter is changed, a signal modulation occurs [88].

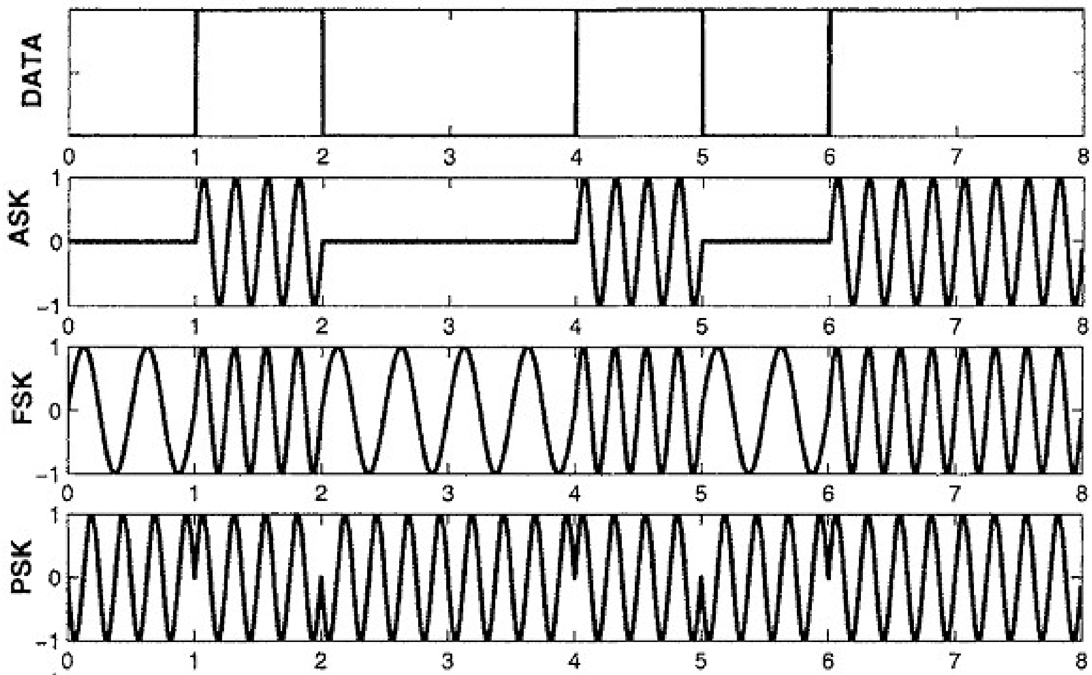

Figure 5.2 : A data signal is modulated on ASK, FSK, and PSK respectively [88].

5.2.1 Amplitude shift keying

In this modulation type, digital symbol is encoded in the amplitude of the signal. Its simple version is called on-off keying (OOK), which can be seen in the figure above. In OOK, digital signals 1 and 0 are represented by an amplitude A and amplitude zero respectively. This type of modulation is used for transmitting Morse code, and also called continuous wave.

ASK can be used for transmitting signals that has more than two levels, which corresponds to more than one digit in binary system.

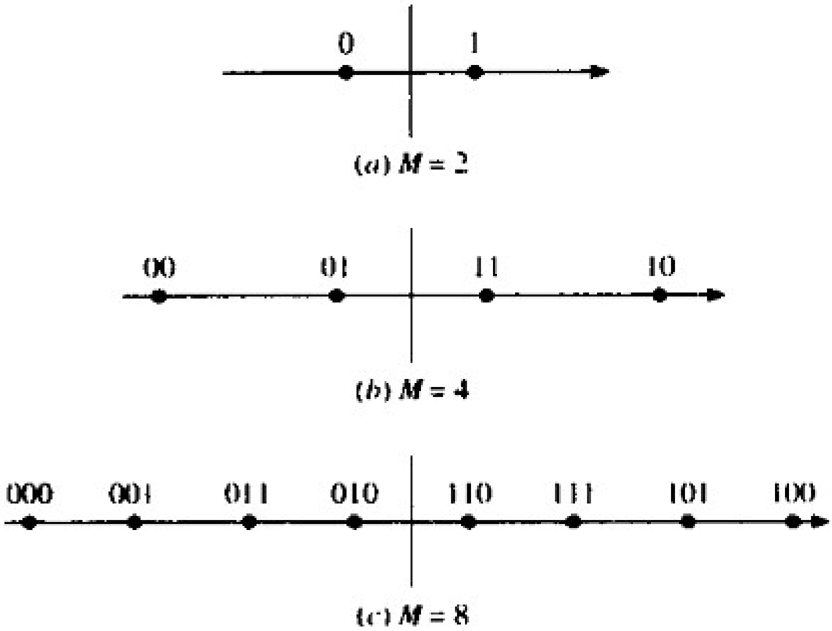

Figure 5.3 : Signal space diagram for ASK modulation with different possible amplitude levels.

As can be seen from the graph above [92], as amplitude levels increase, Hamming distance between modulated signals decrease proportionally. Although modulation and demodulation of ASK is simple, the efficiency of this modulation decreases more than other types of modulation techniques as levels increase [93].

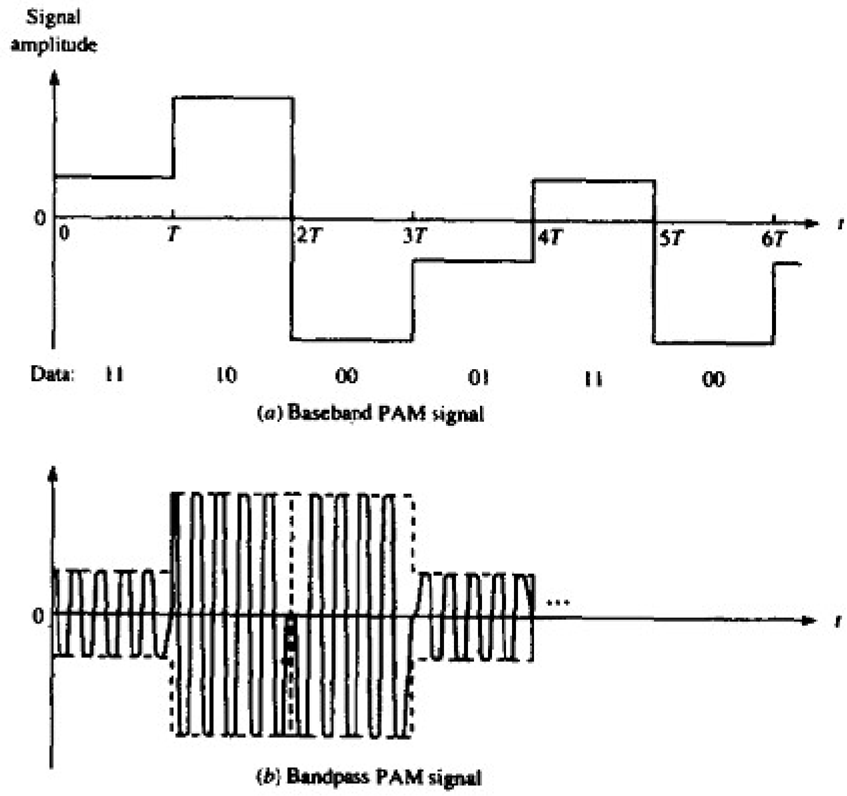

Figure 5.4 : An example to a baseband signal with 4 levels of amplitude, and ASK modulated signal.

A special case of ASK modulation is quadrature amplitude modulation, or QAM. In this modulation type, two baseband signals (or one baseband signal, with its odd and even numbered symbols respectively) are modulated on two quadrature carriers, that is two ASK modulated carriers with a phase difference of 90º.

5.2.2 Frequency shift keying

In this modulation, different digital symbols are represented by different frequencies. There are two special cases of FSK. These are MSK (Minimum frequency-shift keying, or minimum shift-keying), and AFSK (Audio frequency-shift keying).

In MSK, the difference between higher and lower frequency is identical to half bit rate. Waveforms used to represent 0 and 1 bit differ exactly half a carrier period.

In AFSK, digital data is represented by changes in the frequency of an audio tone, which makes it possible to transmit over radio or telephone. It is generally used in radio applications, and used for modulating an RF carrier. As it is not efficient in power and bandwidth as other modulation techinques, it is not used (or seldomly used) in high-speed data communications [94].

5.2.3 Phase shift keying

In this modulation, different phases of the carrier corresponds to different symbols. PSK is well suited to satellite links, because it has got the constant envelope, and it has better spectral efficiency than FSK modulation.

There are different forms of phase shift keying depending on the number of bits per symbol.

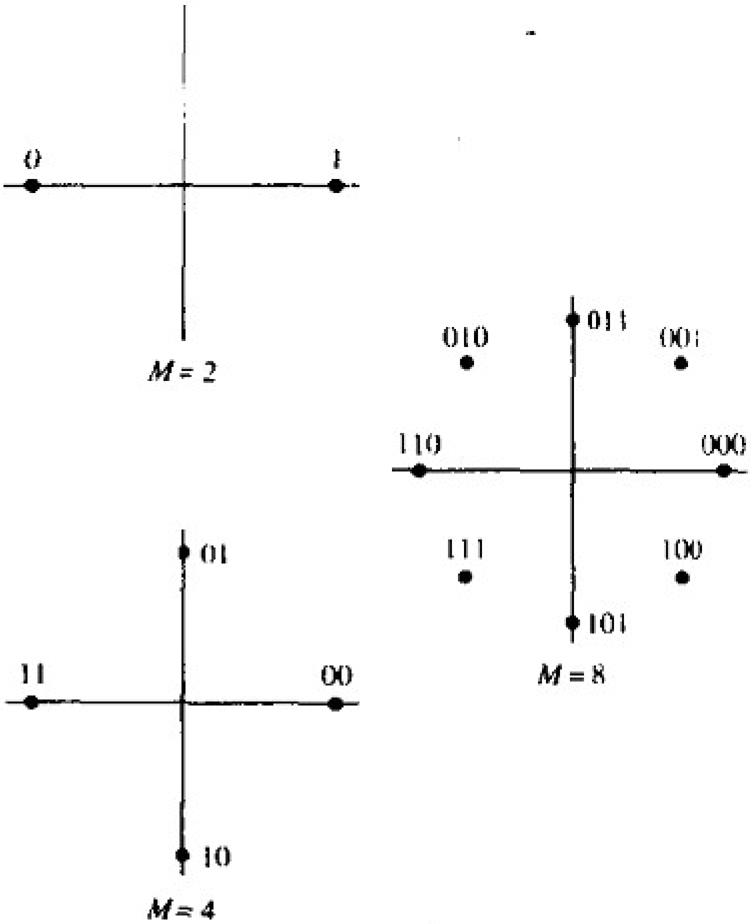

Figure 5.5 : Signal space diagrams for BPSK, QPSK, and 8-PSK

In the figure above, it can be seen that as the number of bits per symbol increases, the phase angle between different symbols decreases proportionally [92].

In PSK, generally gray mapping is used. In gray mapping, adjacent symbols differ by only one bit [88].

BPSK : Binary PSK, is the simplest form of PSK modulation. It is essentially the same with binary ASK modulation. As there is only one bit per symbol, gray coding is trivial.

QPSK : Quadrature PSK, or sometimes Quadrature Amplitude Modulation (4-QAM) is a PSK modulation technique with two bits per symbol. The difference between APSK and QAM comes from the root concepts of these techniques [95].

M-ary PSK : For more than two bits per symbol, M-ary PSK is used. It can take names according to number of bits per symbol, for example 8-PSK for 3 bit, 16-PSK for 4 bits and so on. For getting same bit error rate (BER) requires higher energy than lower order PSK [96].

It is also possible to combine two or three of these modulation techniques, which may be represented by two or three dimensional signals. Generally, for two dimensional symbols, ASK and PSK modulations are combined, and for three dimensional symbols, both ASK, FSK, and PSK are combined.

5.3 QAM

Quadrature amplitude modulation is a modulation scheme that combines phase and amplitude modulation. The information is conveyed both as amplitude and phase. While it has high bandwidth efficiency, the non-constant envelope degrades its performance due to amplifier nonlinearities.

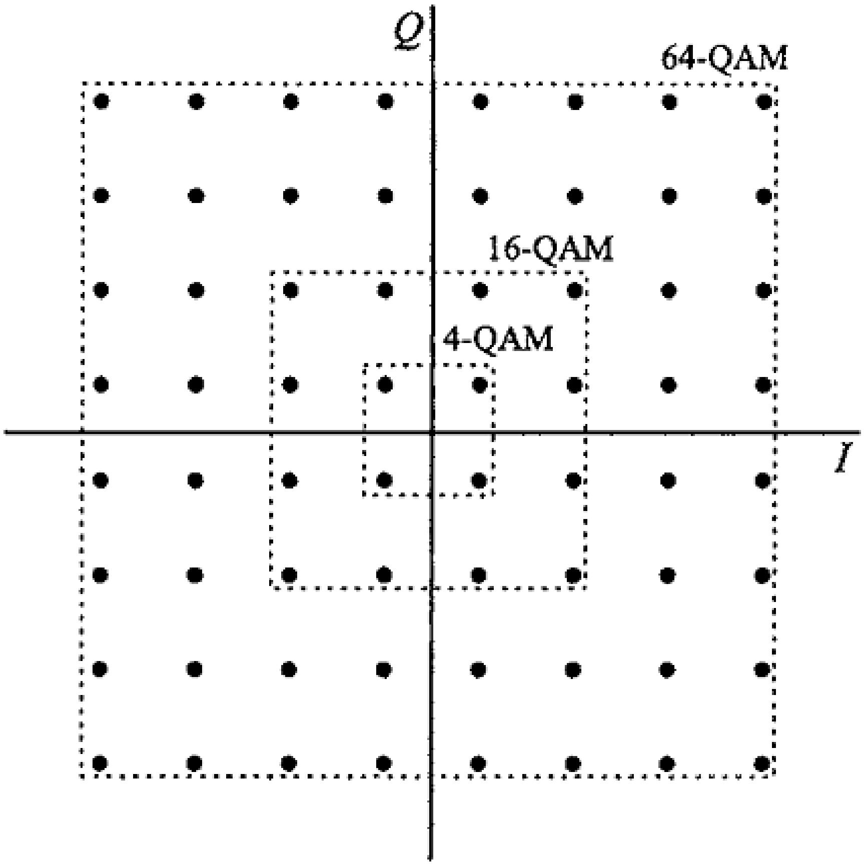

Figure 5.6 : Square QAM constellation diagrams for M=4, 16, and 64.

In the figure above [88], it can be seen that 4-QAM is the same modulation with QPSK.

5.4 Amplitude Phase Shift Keying

Amplitude and phase shift keying, or asymmetric phase shift keying is another combination of ASK and PSK modulations. In APSK, constellations are made up of concentric PSK rings, with several possible points per ring. It has the advantage of being more resilient to non-linear distortions than QAM constellations.

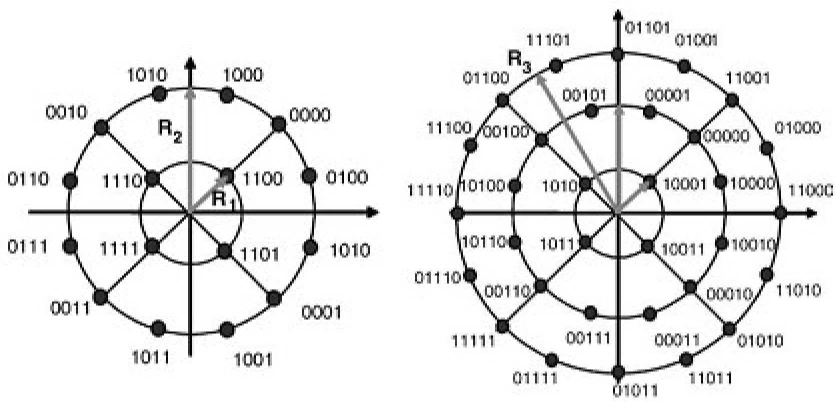

Figure 5.7 : 16-APSK and 32-APSK modulations.

As can be seen in the figures above [96] and below [88], phases of different levels do not need to be same.

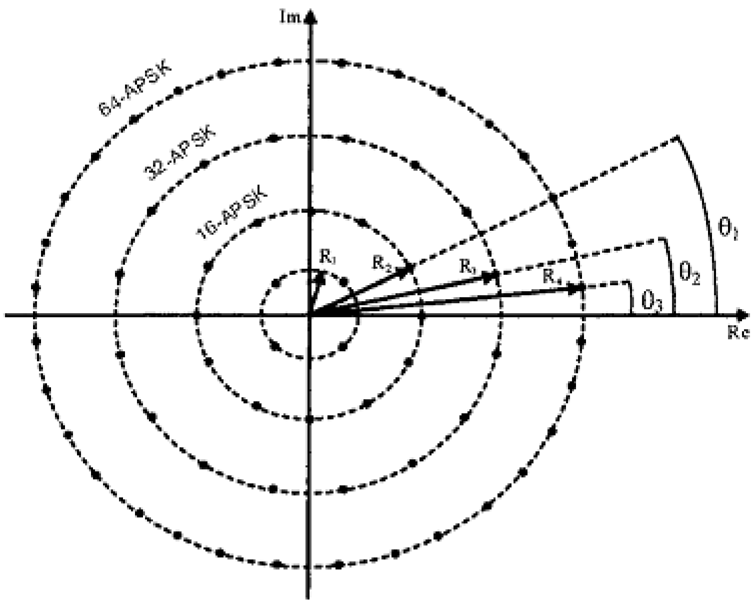

Figure 5.8 : Higher order APSK modulations with different phases per level.

6. PROTOCOLS

A protocol is a set of guidelines or rules. In human communication, it refers to the rules of appearence, speaking, listening and understanding. These protocols of conversation help people to communicate with each other successfully. In computing and telecommunications, there are strict rules for successfull host-to-host communication. These rules apply to different levels of communications ranging from the physical connections to how host listen, interrupt, terminate connection and so on. Some of the best known protocols in communication systems include IPX/SPX, X.25, AX.25, AppleTalk and TCP/IP [97].

For establishing a successful communication between the receiver and the sender, a protocol must should adhere the following issues:

- In a transmission path, the bitstrings are exchanged, be it one way or two way exchange. These bitstrings are divided in fields and each field carries information relevant to the protocol. In general there are two fields, which are called header area and data area. Data area consists of things related to the actual message, whereas header area consists of things related to the protocol, thus it is irrelevant or partially relevant to the message. Notable thing that is relevant to the actual message is CRC fields containing checksums. Bitstrings longer than maximum number of units are divided into appropriate size, and sent in several packets.

- No network is error-free. So for a high success rate, detection of transmission error is necessary. For this, a CRC field is added at the end of the packet, which makes it possible to correct the errors. The success of error correction depends on error bit rate, length of packet and CRC field and some other things like modulation technique used.

- Acknowledgements of correct reception of packets. For determining if the packet is received correctly, an acknowledgement mechanism is required. Receiver sends the sender an acknowledgement packet if the message is received correctly, or depending on the protocol, receiver may send a packet that tells that it received the packet wrong. It is not necessary to send an acknowledgement packet, moreover, in protocols like IP or some point-to-multipoint protocols, no acknowledgement packet is sent back.

- Direction of transmission flow needs to be addressed. In half-duplex link, a sender must wait until transmission line becomes idle. Then, it sends a request message, which indicates that it want to send a message. When the receiver responds with an acknowledgement signal, the transmission begins. With this type of arrangements, transmission flow is controlled.
- Due to the size of the data, not all of the data can be sent in one packet. Sometimes, some packets are lost, some are duplicated, some arrive out of sequence. For receiving the data in a sequenced order, the sender sequences the data. So that, which packets are lost, or are not received properly can be retransmitted, and data can be sequenced at the receiver end.
- A means of flow control. If the sender transmits faster than the processing speed of receiver, somehow a way of slowing down the sender must be arranged.

There are some protocols suitable for cubesat to ground station, and vice versa communication. Some of them are already in use in some cubesats, some of them are possible to use.

6.1 OSI Reference Model

All of the protocols used in several communication architectures are defined with respect to a reference model, which is the OSI layer model. Although not all of the protocols use all of the layers of OSI layer model, understanding this reference model is still useful.

In 1977, the International Standards Organization (ISO) started to work on Open System Interconnection (OSI) for utilizing the full potential of computer networks.

ISO 7498, which is the document that describes the basic OSI reference model, is divided into two major sections. The first section describes the elements of the architecture, which are the building blocks to construct the famous seven-layer model. The second section describes the services and the functions of the layers.

The idea behind layering is to divide the total problem into smaller pieces. In this concept, each layer provides services to the layer above itself (highest layer is an exception to this), and by using this services it creates its own services for passing to the higher level layer. Another principle of layering is to create independence between each layer. Thus, higher layers know the services, but do not need to know how this services were created.

Each N^{th} layer uses the services of the lower $(N-1)^{th}$ layer, and by adding its peculiar functionality, provides services for the higher ($(N+1)^{th}$) layer. These seven layers are chosen for breaking up the problem into smaller size, and they can be processed relatively independently. The brief descriptions of these layers are given below:

- Application Layer: This layer is the highest layer, thus it does not provide service to any other layer. Application layer is concerned with the semantics of the application. While all application processes reside in application layer, not all of the application layer is part of the OSI system. Only the common application service is the way for users of OSI to access OSI services.
- Presentation Layer: The primary purpose of this layer is to provide independence to application processes from differences in data representation. The presentation layer protocol allows user to select a presentation context, which may be specific to an application, or to a type of hardware.
- Session Layer: This layer's primary purpose is to provide the mechanisms for organizing and structuring the interactions between application processes. These mechanisms are two-way simultaneous and alternate operations, the establishment of synchronization points, and the definition of special tokens for structuring exchanges. Shortly, session layer provides the structure for controlling the communication.
- Transport Layer: This layer provides transparent transfer of data between end systems.
- Network Layer: The task of this layer is to provide independence from the data transfer technology and independence from relaying and routing

considerations. Its functions are:

  - the concenation and routing functions, related to routing and relaying among concatenated networks;
  - the subnetwork convergence functions, related to the functions necessary to enhance a particular network to allow data transfer accross it to meet the requested quality of service parameters;
  - and the subnetwork access functions, which concerns with using the available data-link service to provide an abstract subnetwork.

- Data Link Layer: This layer provides the functional and procedural means to transfer data between network entities. It also detects and corrects errors, which may occur in the physical layer, if possible.This layer is very sensitive to physical transfer technology, and there may be several protocols in this layer.
- Physical Layer: This layer provides the mechanical, electrocal, functional and procedural standards to access the physical medium [98].

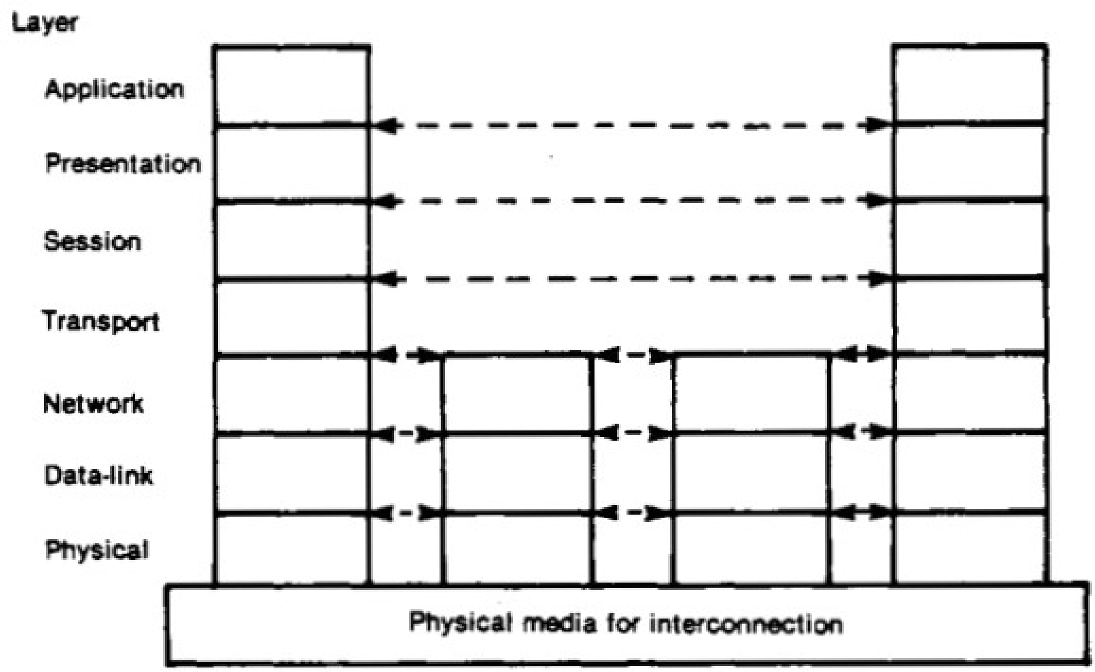

Figure 6.1 : Seven layers of the OSI architecture.

6.2 AX.25 Protocol

AX.25 is the protocol used in Packet Radio Communication. Since several cubesats uses this protocol, and it is related to Amateur Radio and Packet Radio, it is good to give a brief information about these as well.

6.2.1 Amateur radio

Amateur radio, or ham radio, is both a hobby and a service in which participants, called hams, use various types of radio communications equipment to communicate with other radio amateurs for public services, recreation and self-training. Here, amateur does not mean a lack of skill or quality, but means it operates outside the control of official, government or commercial organizations, and also means a radio amateur must not be paid for providing communications to others. There are an estimated 600 thousands amateur radio operators in USA, and two million worldwide[99][100].

One of the aims of the cubesats is or should be the collaboration with amateur radio users. With their collaboration, the coverage of the satellite around the earth may increase greatly. So, although it is not a must for communication system to be compatible with several amateur radio operators' ground station systems, it will greatly increase the communication capabilities of the satellite, both as a redundant system and increased coverage.

The amateur radio community is known as The Radio Amateur Satellite Corporation, shortly AMSAT. It was first formed in the District of Columbia in 1969 as an educational program. The inspiration for this organization was Project OSCAR, which built and launched the first Amateur Radio Satellite on December 12, 1961, called OSCAR-1. AMSAT was founded to continue the efforts of this Project Oscar group [101].

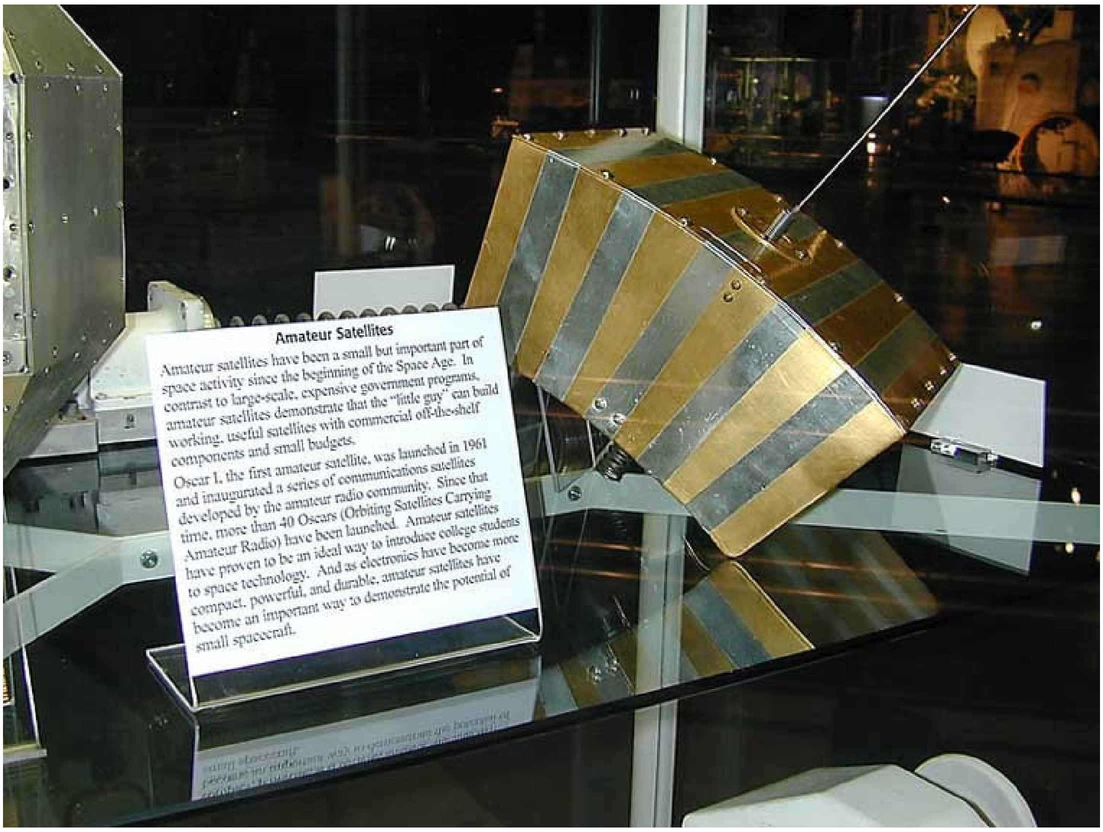

Figure 6.2 : A full scale model of the original OSCAR satellite.

6.2.2 Packet radio

Packet radio is a particular digital mode of amateur radio communications which corresponds to computer telecommunications. In this communications, there is a terminal node controller corresponding to the telephone modem, amateur radio transceiver corresponding to the telephone, and radio waves in air corresponding to telephone lines. Packet radio takes a stream from a computer and sends that via radio to another similarly equipped amateur radio station.

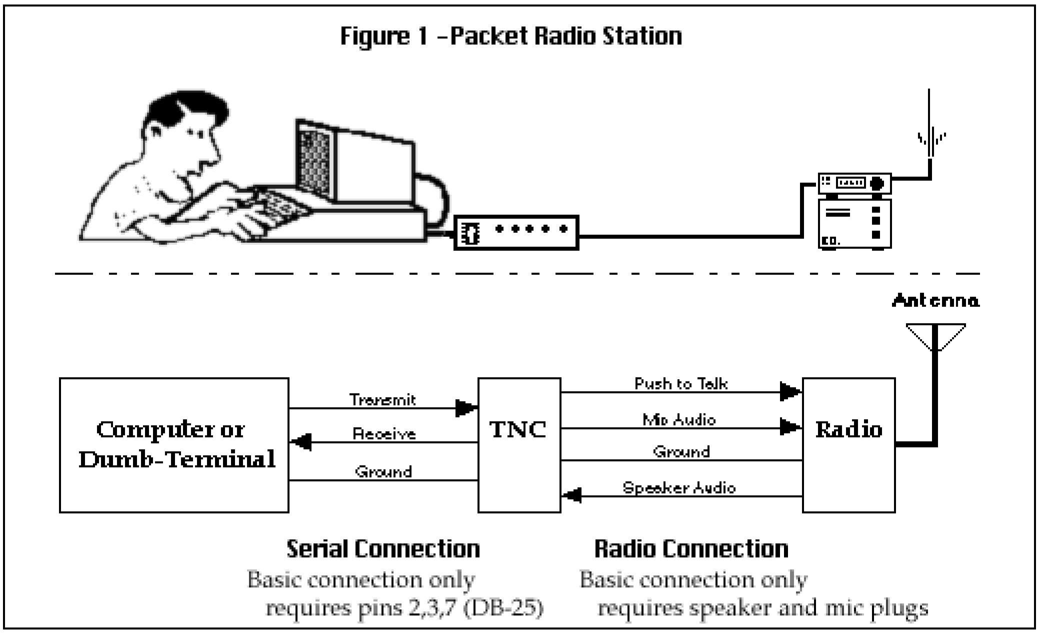

Figure 6.3 : Packet radio station.

There are three key components of the packet radio station. These are terminal node controller, computer (or terminal), and radio.

Terminal Node Controller (TNC): A terminal node controller contains a modem, a computer processor, and a circuit for converting the communications between the computer via RS232 (or more recently, USB) and packet radio protocol in use. A TNC assembles a packet from data received from the computer, computes an error-check (CRC) for the packet, modulates it into audio frequencies, and puts out appropriate signals to transmit the packet over connected radio. It also reverses the process, translating the audio that the connected radio receives into a byte stream that is then sent to the computer.

Computer, or terminal: Computer hosts the user interface programs. There exist terminal or terminal emulator programs, packet-specific programs, or just dumb terminals.

Radio: Radio is needed for sending and receiving data packets with UHF/VHF or other frequencies [102].

Since the article was written some 15 years ago, there are a lot of development in the hardware and software parts of the packet communication. This thesis will not address all of the developments about packet radio over these years.

6.2.3 AX.25 protocol

AX.25, or amateur X.25 is the communications protocol used for packet radio. It was developed in 1970s and based on wired network protocol X.25. AX.25 occupies first, second and third layers of the OSI networking model, and is responsible for transferring data packets between nodes and detecting errors introduced by the communications channel. AX.25 supports a limited form of source routing, because it does not support switching [103].

In TAPR TNC-2 equipment, which I think is a reference model in the point of view of AX.25 protocol, uses layer 1, 2 and 7. These are considered the minimum configuration for reliable communications. And although a network layer protocol is defined, it is rarely used, and some sources about AX.25 protocol doesn't even mention this layer. So, basically, AX.25 protocol corresponds to data layer in OSI model.

Packet radio networks use three layers in the OSI reference model. These layers are physical, data, and network layers. Physical layers corresponds to the modems and radio channels, and AFSK modulation and 9600 bit/s rate is common nowadays. Data link layer corresponds to AX.25 protocol that will be described below. And network layer, which is used for providing automated routing of data between stations, can use any network layer protocol [104].

There are three types of frames, which are supervisory frame, unnumbered frame and information frame [105]. Supervisory frames, or S-frames are used for flow and error control whenever piggybacking is impossible or inappropriate, such as when a station does not have a data to send. Unnumbered frames, or U-frames are used for link management, they exchange session management and control information between connected devices. Information frames, or I-frames transport user data from the network layer, and also they include flow and error control information piggybacked on data [106]. S-frame and U-frame may or may not be used in communication, but I-frames are used. The frames can be seen in the pictures below. Note that first bit to be transmitted is on the left side.

Table 6.1 : Unnumbered and Supervisory frame construction.

Flag	Address	Control	Info	FCS	Flag
01111110	112/224 bits	8/16 bits	N*8 bits	16 bits	01111110

Table 6.2 : Information frame construction.

Flag	Address	Control	PID	Info	FCS	Flag
01111110	112/224 bits	8/16 bits	8 bits	N*8 bits	16 bits	01111110

In all of the bits except FCS, least significant bit is sent first. In FCS, most significant bit is sent first. Also, for not confusing other fields with flag field, after five 1's one 0 is added.

Flag Field: It is one octet long. The flag is used for delimiting frames, so occurs both at the start and at the end of each frame. A flag consists of a zero, followed by six ones followed by another zero, which is 01111110. This sequence is not allowed to occur anywhere else, which is caused by bit stuffing.

Bit stuffing: For preventing another sequence to be mixed with flag field, the sending station monitors the bit sequence for a group of five or more contiguous “1” bits. When five contiguous “1” bits are sent, the sending station inserts a “0” after the fifth “1” bit. In reception, any time five contiguous “1” bits are received followed by a “0” bit, that “0” bit which follows five contiguous “1” bits is discarded.

Address field: The address field identifies both the source and the destination of the frame. On addition, the address field contains the command/response information and facilities for layer 2 repeater operation.

Control field: The control field identifies the type of frame being passed and controls several attributes of the layer 2 connection. It is one or two octets in length.

PID field: The protocol identifier (PID) field appears in information frames only. It identifies which kind of layer protocol, if any, is in use. The encoding of PID field is given below:

Table 6.3 : PID Definitions.

HEX	Binary	Translation
**	yy01yyyy	AX.25 layer 3 implemented.
**	yy10yyyy	AX.25 layer 3 implemented.
0x01	00000001	ISO 8208/CCITT X.25 PLP
0x06	00000110	Compressed TCP/IP packet.
0x07	00000111	Uncompressed TCP/IP packet.
0x08	00001000	Segmentation fragment
0xC3	11000011	TEXNET datagram protocol
0xC4	11000100	Link quality protocol
0xCA	11001010	Appletalk
0xCB	11001011	Appletalk ARP
0xCC	11001100	ARPA Internet Protocol
0xCD	11001101	ARPA address resolution
0xCE	11001110	FlexNet
0xCF	11001111	NET/ROM
0xF0	11110000	No layer 3 protocol is implemented
0xFF	11111111	Escape character. Next octet contains more level 3 protocol information
Escape character. Next octet contains more level 3 protocol information	00001000	

Information field: The information field conveys user data from one end of the link to the other. There are five types of frames that information field is allowed. These are I (information) frame, UI (unnumbered information) frame, XID frame, TEST frame and FRMR (frame reject) frame [107].

There are some limitations associated with AX.25 protocol. One of the limits is the speed used for transmitting packet radio data. The typical values are 1200 bit/s, and rarely (almost non-existant) it passes 9600 bit/s [103]. Considering that the satellite has an average passing time in line of sight of the ground station, which is about 10 minutes, 9600 bit/s corresponds to 5.76 mb at each pass. Moreover, when things like handshaking, full-duplex communication, unhealthy links due to the weather, satellites orientation, atmospheric events and so on are considered, data potential may decrease further.

When transmitting data which is too big to transmit in one pass, the remaining data must be buffered for transferring it at a later time. However, AX.25 protocol discards the buffered data when a connection is lost. For solving this problem, the satellite needs to keep track of which data is sent and may be deleted from the memory, and which data is not sent and must be kept in memory. This must be done in a higher layer.

Another property of AX.25 is that, it lacks ability to handle priorities. All data is transmitted in the order it is sent to the TNC. Prioritation between different data sources in the satellite must also be implemented in the OBC. Although it is possible to send UI frames for avoiding normal flow control, it is a very unreliable procedure.

AX.25 protocol supports connection oriented frames with I-frames, and connectionless frames with UI-frames. The connectionless frame can be used for the satellite beacon since this form of communication is only one way and need no acknowledge responses. The connection oriented mode will be used when a ground station asks for connection [105].

6.3 AMSAT-DL Protocol

Amsat-DL is the protocol used in Amsat Phase 3 satellites. It is not common in the amateur radio society and requires more dedicated software to receive and process [108].

6.4 RLP Protocol

Radio link protocol is an automatic repeat request (ARQ) fragmentation protocol used over a wireless air interface. It is generally used in GSM networks [109].

6.5 IEEE802.2-LLC Protocol

IEEE 802.2 LLC protocol is a protocol on data layer in OSI reference model [110]. It is used in applications such as Wi-Fi, GPRS and WLAN.

6.6 NSP Protocol

The NSP, or Nanosatellite protocol was developed at University of Toronto. NSPv2 is used at CanX-2 nanosatellite. It is a combination of the industrty standart High Level Data Link Control (HDLC) protocol and SFL controlled open standart simple serial protocol (SSL). NSPv2 combines the functionality of the layer 2 and the layer three of the Open Standart Interface (OSI) model. The ground station (relieves the satellite) is responsible for detecting erroneous or dropped packets and is responsible for reinitiating retransmission. If satellite receives packet with errors, then it drops the packet and sends no response to the ground station. If the packet is received without error but with incorrect parameters, then the satellite sends NACK packet depending on the command definition. If ground station receives incorrect packages, again it drops the package without processing. Then GS may send an identical request or request a retransmission. In short, satellite never asks for retransmission of erroneous packages, but GS does.

NSP frame format can be seen in the following table.

Table 6.4 : NSPv2 frame construction.

Flag	Destination Address	Source Address	Command	Data	CRC	Flag
8 bits	8 [16] bits	8 [16] bits	8 bits	Variable	16 bits	8 bits

Flag field: Flag field is used for delimiting the beginning and end of a NSP frame. It is defined as 01111110, or 0x7E. All frames have this beginning and end fields, thus frames do not share flag fields. Although it lengthens some or all of the frames, not sharing this flag makes it easier the frame to be detected correctly.

CRC field: This field is 16 bits wide and used for error checking. CRC is calculated using entire frame excluding end flags, bit stuffing and escape characters. Most significant Byte is written to the left of the field. A 16-bit CRC can detect all single-bit errors, all two-bit errors, all odd bit errors and errors spanning up to 16 bits, which makes 99.995% error detection rate, or 10^{-5} bit error rate.

Destination address field: This field identifies the receiver of the packet. If the nanosatellite does not have the same address, then it will drop the packet. This address can be extended to 16 bits. When extended to 16 bits, additional 31 addresses and 1 address for broadcasting can be defined.

Source address field. This field identifies the address of the sender. It can also be extended to 16 bits for accommodating more ground stations.

Command field: This field is divided into four sub-fields. These are command, acknowledge, packet identifier and poll/finish. Command field is 5 bits long, and allows 32 unique commands per station. Acknowledge field is one bit long. A value of 1 signifies acknowledgement and 0 signifies no acknowledgement. Packet identifier bit is a single bit and alternates between the value of 1 and 0 for every packet send from the ground station. Response carries the same value in packet identifier bit. P/F bit is used in two ways. From ground station to satellite, 1 means satellite is allowed to send a response to ground station. From satellite to ground station, 1 means the satellite is finished with transmission.

Data field: This field's length is variable. It can have a maximum size of 256 bits, and minimum size of 0 bits.

Packet collision is not explicitly handled, but avoided using timeouts and by permitting only the ground station to initiate retransmissions [111].

6.7 XSTP Protocol

This is a custom protocol derived from AX.25 standart protocol. It was developed by the University of Toronto for their CanX satellite series mission.

6.8 SRLL Protocol

This frame is based on AX.25 frame, and developed by Tokyo Institue of Technology. It has the ability to cancel the error, and correct it to the original data [108]. Error correction code is created by an implementation that is based on Hamming code [112]. The frame structure of SRLL protocol is given below:

Table 6.5 : SRLL frame construction.

Frame detection code	Data	Error Correction Code
32 bits	128 bits	64 bits

6.9 D-Star Protocol

D-Star, which stands for Digital Smart Technologies for Amateur Radio is a digital voice and data protocol specification. It was developed by the Japan Amateur Radio League as part of the investigation into digital technology for amateur radio [113]. It is claimed that D-Star have clearer signals and uses less bandwith than modulations such as amplitude modulation, frequency modulation and so on.

A problem about D-Star is that, it uses a closed source proprietary voice codec (and since I could not find about D-Star frame anywhere, it also uses proprietary encoding for data too), so an end user is unable to create or modify frames.

Since it is a new protocol, only ICOM offers D-Star compatible radios.

D-Star transfers both voice and data via digital encoding in VHF, UHF and 1.2 GHz amateur radio bands [114]. Although it is not clear that, there is a dedicated data protocol for VHF and UHF bands, in 1.2 GHz band, the data rate is 128 kbit/s, which corresponds to about 75 mb in a ten minute pass[115].

6.10 CCSDS Standard

In the early years of space projects, there were no established standards available. With the advent of microprocessor-based systems, telemetry systems allowed more flexible approaches, and the base for a standardized communications protocol emerged.

The Consultative Committee for Space Data Systems (CCSDS) released several technical recommendations on data formats and transmission methods for telemetry and telecommand. The examples are the Packet Telemetry Recommendation, and the Telecommand Recommendation. The Packet Telemetry Recommendation defines standard units for transferring telemetry from spacecraft to ground. The Telecommand Recommendation defines standard data units for sending commands from the ground station to the spacecraft.

CCSDS stands for The Consultative Committee for Space Data Systems. It is founded in 1982 by the major space agencies of the world, the CCSDS is a multinational forum for the development of communications and data systems standards for spaceflight.

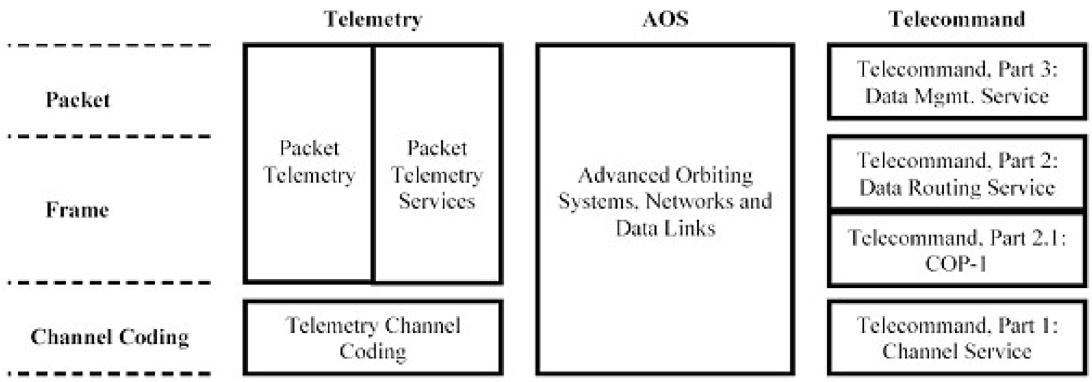

Figure 6.4 : Structure of the CCSDS Standard.

In the original CCSDS recommandations, protocols of two layers are defined in single recommendation, and some packet structures are defined in distinct recommendations. These problems in original recommendations made it hard to understand and hard to implement.

Due to these problems, the recommendations have been restructured. In this new structure, each recommendation defines only a single layer (or sub layer) of the OSI reference model, and allows implementing other protocols in place of CCSDS defined protocols [116].

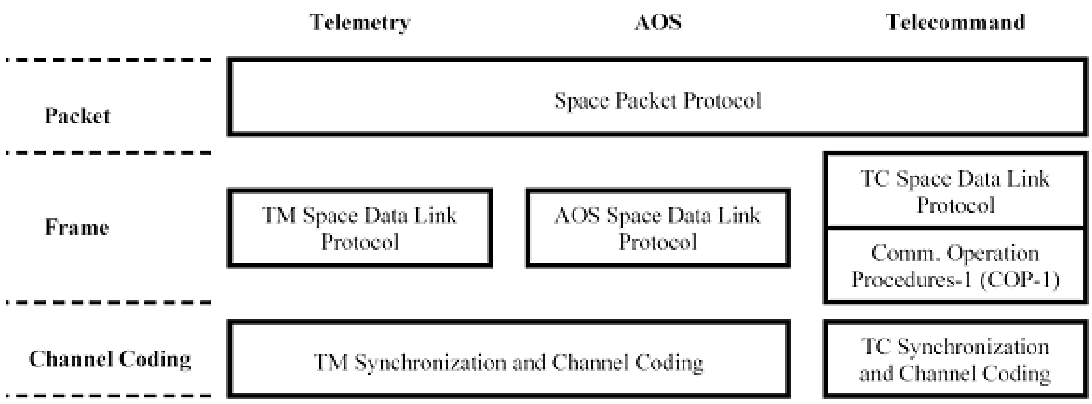

Figure 6.5 : Restructured CCSDS Standard.

7. CALCULATIONS FOR COMMUNICATION SUBSYSTEM

In this chapter, calculations of the power budget, link budget, and other things such as protocols will be discussed. The results will determine the hardware and software requirements for the satellite and ground station.

The hardware and software selections require an iterative process. Selection requirements are determined by mission requirements, such as the transceiver capacity for downloading high resolution images, and mission requirements are determined by selection requirements, such as the maximum resolution of images for a chosen transceiver.

7.1 Power Budget

Nearly all of the subsystems will consume power, and with limited power production and power storage capacity, some limitations about power can be expected. The communication subsystem may work all of the time, or some of the time depending on the power budget. The same may be true for some or all of the other subsystems.

7.1.1 Solar panels

Final design of the satellite is not finished at the time of this thesis. In the first iteration, all sides of the satellite will have solar panels. Second or further design of the satellite may have unfolded solar panels, but they will not be considered here. For being on the safe side, considering the worst case scenario is a better approach.

Whether the solar panels are made by ITUpSAT group by using solar cells, or bought readily from a company, the power production capacity will be similar.

The basic specs of the GomSpace solar cells are given below [38]:

Table 7.1 : Specifications of GomSpace Solar Panels.

Size	Voltage	Current	Power
82.5x98x2.1 mm	4.64-4.84 V	490-508 mA	2270-2400 mW

The given specs are for 10x10 cm^2 surface. Due to the satellite being a 3U satellite, there will be four 30x10 cm^2 surfaces, and two 10x10 cm^2 surfaces. So, the power produced at each surface will be proportional to the surface area. However, the sun light cannot be perpendicular to the surfaces at all times. The power produced by the solar panels are proportional to the projectile area with respect to sun [117]. For a random scenario, the angle distribution can be thought as continuous uniform distribution. Also, if a solar panel does not see sun, the opposing solar panel sees, which means we can take solar panels as pairs. So, the mean power coefficient for each pair of solar panels is:

$$Mean\, area\ coefficient = \int_0^{\pi} \frac{\sin\alpha}{\pi} d\alpha = \frac{2}{\pi} \quad \textbf{(7.1)}$$

There are seven pairs, so the mean power produced will be:

$$(2270 \sim 2400) \times 7 \times \frac{2}{\pi} = 10115 \sim 10695\, mW = 10.115 \sim 10.695\, W \quad \textbf{(7.2)}$$

For the worst case scenario, the percentage of the orbit in eclipse should be calculated. If the satellite's height from ground is taken as 720 km, and the radius of the earth is 6378 km, then, the percentage of the eclipse is:

$$2 \times \arcsin\left(\frac{6378}{7098}\right) = 2 \times 1.1135 = 2.233\ radians \quad \textbf{(7.3)}$$

Then the percentage is:

$$\frac{2.233}{2\pi} = 0.3554 \quad \textbf{(7.4)}$$

Then, the satellite is in dark at 35.54 % of the orbit, or sees the sun at 64.46 % of the orbit. As a result, the energy produced per day is about $10.129 \times 24 \times 0.6446 \simeq 156.7\, Whr$.

Although there aren't exact power consumption values for each subsystem of the satellite, a preliminary approach can be given [38].

Table 7.2 : Power Budget.

Component	Power
OBC	0.5W
EPS	2W
Beacon	0.3W
PLIU	0.3W
ADCS	2W
Communication	2W
Structure	0W
Panels	0W
GPS	1W
nMKJ	0.3W
Camera	1W
Star Tracker	0.4W
Total	9.8W

7.2 Link Budget

Radio waves are a type of electromagnetic radiation with wavelengths in the electromagnetic spectrum longer than infrared light. Electric and magnetic fields are two components of EMI, and these two components oscillate perpendicular to each other and to the direction of the energy propagation [118].

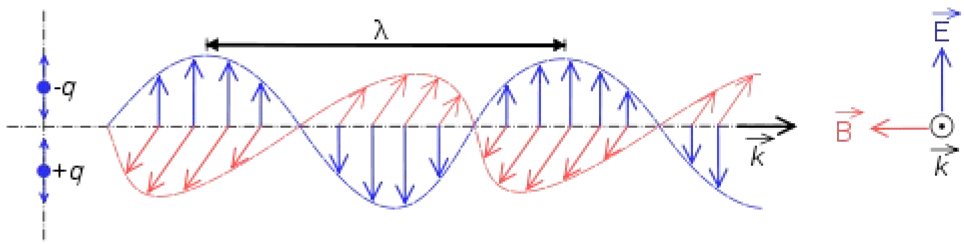

Figure 7.1 : Direction of the electromagnetic propagation (K), electric field (E) and magnetic field (B), with wavelength λ.

7.2.1 Link budget derivation

The relationship between frequency and wavelength is:

$$\lambda = \frac{c}{f} \tag{7.5}$$

A point power source radiates its power in all directions equally. Thus, at equal distances from the point source, which corresponds to the surface of a sphere, transmitted power is distributed equally. Then the power density at the surface, that is, power flux density, becomes:

$$pfd = \frac{p_t}{4\pi r^2} \, watts/m^2 \tag{7.6}$$

Effective isotropic radiated power, or *eirp* is an important parameter in the evaluation of the RF link. It can be given as:

$$eirp \equiv p_t g_t \tag{7.7}$$

or in decibels:

$$EIRP \equiv P_t + G_t \tag{7.8}$$

Then $(pfd)_r$ becomes:

$$(pfd)_r = \frac{p_t g_t}{4\pi r^2} = \frac{eirp}{4\pi r^2} \tag{7.9}$$

or in decibels:

$$\begin{aligned} (PFD)_r &= 10\log\left(\frac{p_t g_t}{4\pi r^2}\right) \\ &= 10\log(p_t) + 10\log(g_t) - 20\log(r) - 10\log(4\pi) \\ &= P_t + G_t - 20\log(r) - 10.99 \\ &= EIRP - 20\log(r) - 10.99 \end{aligned} \tag{7.10}$$

In some datasheets, the power produced by transceiver in logarithmic scale is given as dBm instead of dB. The reason is that, in practical radio world, the power levels are in the order of millliwatts instead of watts [119]. A simple conversion between these two power levels are:

$$10^3 \, mW = 1\mathrm{W} \tag{7.11}$$

Then, the conversion in decibels is:

$$dBm - 30 = dB \tag{7.12}$$

Another factor at radiated power is antenna gain. The gain of a perfect antenna with an aperture area A is given as:

$$g_{ideal} = \frac{4\pi A}{\lambda^2} \tag{7.13}$$

Physical antennas are not ideal, because there are reflections and losses. Considering these factors, an effective aperture area can be defined, A_e, which is related to ideal aperture area A by a coefficient called aperture efficiency η_A as:

$$A_e = \eta_A A \tag{7.14}$$

Then, the real gain becomes:

$$g_{real} = \frac{4\pi A_e}{\lambda^2} = \eta_A \frac{4\pi A}{\lambda^2} \tag{7.15}$$

In technical specifications of several antennas, the antenna gain is expressed as dBi. dBi is the amount of focus applied by the antenna with respect to an isotropic radiator. Another measurement unit is dBd, which is given with respect to a reference dipole antenna [120]. The relationship between them is given as:

$$dBi = dBd + 2.15 \tag{7.16}$$

Then, the gain becomes:

$$G = 10\log\left[\eta_A \frac{4\pi A}{\lambda^2}\right] \; dBi \tag{7.17}$$

Effective aperture can be explained as:

$$A_e = \frac{g\lambda^2}{4\pi} \tag{7.18}$$

A typical directional antenna has some directivity, meaning emitted power will be concentrated on a certain direction, and the same thing holds for receiving power. In an antenna pattern, there are two important parameters, which are boresight and ½ power beamwidth (or shortly beamwidth). The boresight direction is the direction of maximum gain. The value g refers to this gain in above equations. Beamwidth is the angle between half power (-3 dB) points of the main lobe.

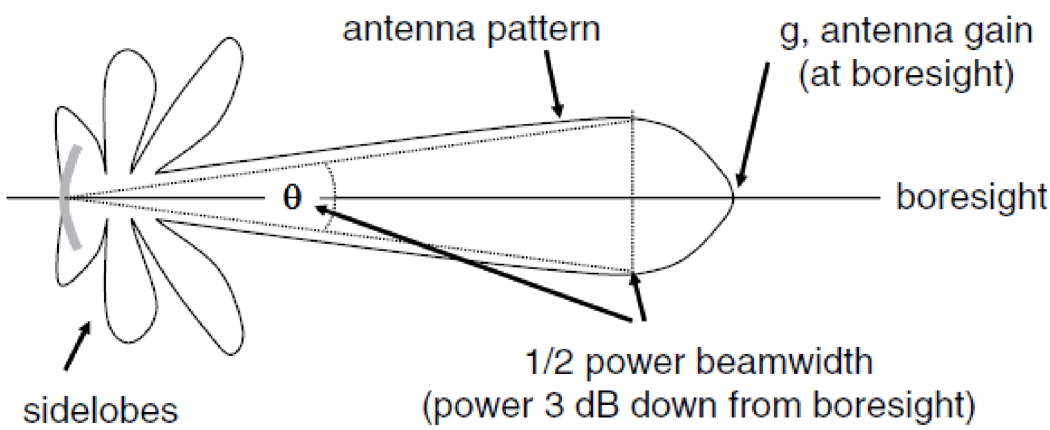

Figure 7.2 : Antenna pattern.

Sidelobes are the regions where the gain increases and that has different direction than boresight. It is a possible concern for noise and interference, because there may be other sources of power in the same frequency in those directions.

The power received with an antenna that has a gain g_r and effective area A_e is:

$$p_r = (pfd)_r A_e = \frac{p_t g_t}{4\pi r^2} A_e \qquad \textbf{(7.19)}$$

Replacing A_e with $\frac{g\lambda^2}{4\pi}$ gives:

$$p_r = \underbrace{\left[\frac{p_t g_t}{4\pi r^2}\right]}_{\boldsymbol{pfd}} g_r \underbrace{\left[\frac{\lambda^2}{4\pi}\right]}_{\boldsymbol{s}} \qquad \textbf{(7.20)}$$

where pfd is power flux density, and s is spreading loss.

$$s = \frac{\lambda^2}{4\pi} = \frac{7.152\times 10^{15}}{f^2} \qquad \textbf{(7.21)}$$

or if we specify the frequency as Mhz:

$$s = \frac{7152}{f^2} \qquad \textbf{(7.22)}$$

or in decibels:

$$S = -20\log(f) + 38.55 \qquad \textbf{(7.23)}$$

Rearranging the received power equation in a different form:

$$p_r = p_t g_t g_r \left[\left(\frac{\lambda}{4\pi r}\right)^2\right] \qquad \textbf{(7.24)}$$

The term in brackets is called free space path loss, and denoted by l_{FS}.

$$l_{FS} = \left(\frac{\lambda}{4\pi r}\right)^2 \qquad \textbf{(7.25)}$$

then, in decibels:

$$L_{FS} = 20\log(r) + 20\log(f) - 147.56 \;\; dB \qquad \textbf{(7.26)}$$

We are dealing with distances in te range of hundreds of kilometers, and frequencies about 430MHz and 2400Mhz. Then, it is better to specify frequencies in MHz, and distances in km, then:

$$L_{FS} = 20\log(r) + 20\log(f) + 32.44 \ \ dB \tag{7.27}$$

Then, basic link equation becomes:

$$p_r = p_t g_t \left(\frac{1}{l_{FS}}\right) g_r = \frac{eirp}{l_{FS}} g_r \tag{7.28}$$

or, in decibels:

$$P_r = EIRP + G_r - L_{FS} \tag{7.29}$$

There are five variables in this formula, which are power transmitted, emitter gain, receiver gain, frequency and distance.

7.2.2 Distance derivation

At 90° passes, which means that when the satellite passes above the ground station, the distance to the ground station is at a minimum. At the line of sight, it is at a maximum. The satellite travels 720 km above the surface of the earth, thus the minimum distance is 720 km.

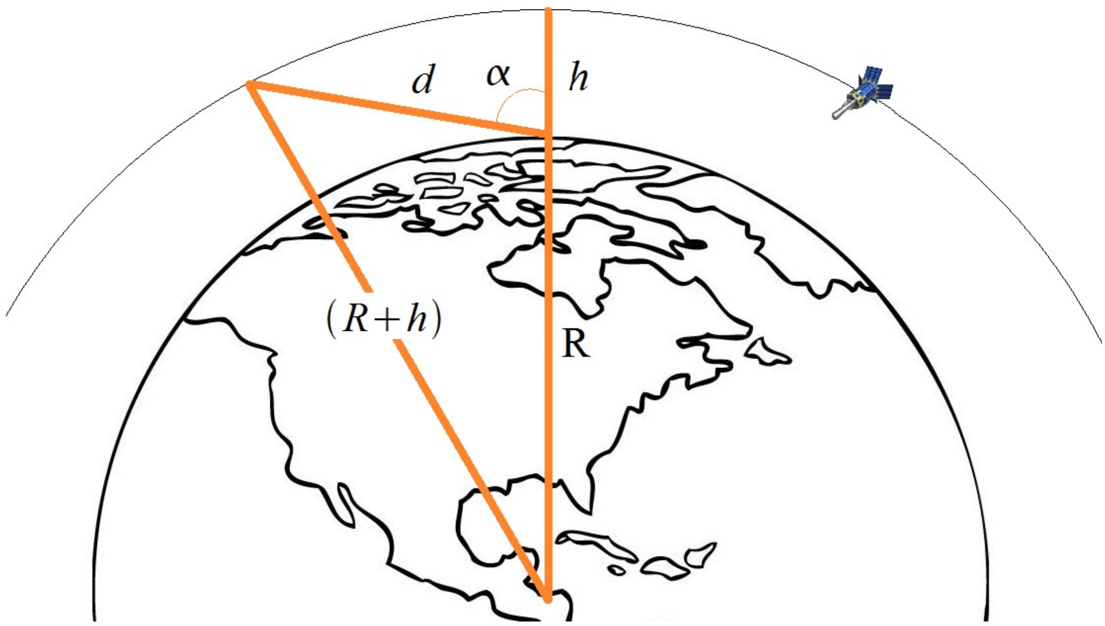

Figure 7.3 : Satellite distance at an elevation angle α.

The maximum distance can be calculated simply by law of cosines.

$$(R+h)^2 = R^2 + d^2 - 2\mathrm{dR}\cos(\alpha + \pi/2) \tag{7.30}$$

Rearranging terms:

$$d^2 + d\,(2\mathrm{R}\sin\alpha) - h(2\mathrm{R} + h) = 0 \tag{7.31}$$

Then, the roots can be found by the quadratic formula:

$$d_{1,2}=\frac{-2\mathrm{R}\sin\alpha\pm\sqrt{(-2\mathrm{R}\sin\alpha)^2+4\mathrm{h}(2\mathrm{R}+h)}}{2} \quad \textbf{(7.32)}$$

The maximum distance occurs when the angle α is taken 0. The height h is 720 kilometers, and radius of earth R is 6378.1 kilometers (when the earth is thought as perfect sphere). Then, the positive root of this equation is 3114.9 kilometers.

The minimum and maximum distances found by formula above are given in the table below.

Table 7.3 : Free Space Path Loss, for minimum and maximum distance, and for 70cm and 13cm bands.

Frequency\Distance	720 km	3114.9 km
430 MHz	142.25 dB	154.97 dB
2300 MHz	156.82 dB	169.54 dB

7.2.3 Noise components

The noise is introduced to the system from the transmitter through final part of the signal detection and demodulation. There are two types of noises, which are thermal noise and quantum noise respectively. Thermal noise is the electronic noise in the components of the receiver created by the thermal agitation of the charge carriers, usually electrons [121]. Quantum noise, or shot noise is the error of description of any physical system within classical theories [122]. In very high frequencies, the quantum noise dominate over thermal and other types of noises, which is not the case for the frequency bands used. The treshold between thermal and quantum noise can be found by the formula below:

$$f\approx 21\,t_e \quad \textbf{(7.33)}$$

where frequency is given in GHz, and temperature is given in Kelvin.

In transmission path, receiver antenna catches radio noise from the sky, which is called radio noise. In addition to this radio noise, every active and passive electronic device in transmission path produces thermal noise. This thermal noise effects the accuracy and precision, thus reliability of the devices and communication path.

Radio noise or sky noise can be introduced into the transmission path from both human and natural induced sources. It is added to the system through an increase in the antenna temperature. The natural induced sources are:

Cosmic and galactic radio noises: are random noises that originate outside the Earth's atmosphere. It is about 2.4°K for frequencies above 1 GHz, so they ignorable.

Athmospheric noises: are caused by things like oxygen, water vapor, clouds and rain. It is most severe for frequencies above 10 GHz.

Noise power is defined by the Nyquist formula, which is given below:

$$n_N = k\, t_e\, b_N \quad Watts \tag{7.34}$$

Hereh, k is Boltzmann's constant with $k = 1.39 \times 10^{-23} \frac{J}{K}$, t_e is the equivalent noise temperature of the noise source in K, and b_N is the noise bandwidth in 1/s or Hertz.

Noise power density or noise power spectral density can be defined as:

$$n_0 = \frac{n_N}{b_N} = \frac{k\, t_e\, b_N}{b_N} = k\, t_e \quad Watts/Hz \tag{7.35}$$

Noise figure, or shortly nf, is used for quantifying the noise produced by any electronic component in the communication path. This quantifying is done by comparing input signal power to noise power ratio to output signal power to noise power ratio. Namely:

$$nf = \frac{\frac{p_{in}}{n_{in}}}{\frac{p_{out}}{n_{out}}} \tag{7.36}$$

If the equation is written in terms of device parameters, then it becomes:

$$nf = \frac{\frac{p_{in}}{k\, t_0 b}}{\frac{g\, p_{in}}{k\,(t_0 + t_e)\, b}} \tag{7.37}$$

where t_0 is the reference temperature, being the temperature of the device itself. It is generally taken 290 K, although if the mean working temperature changes, it must be changed also. If the telemetry taken from the ITU-pSAT I is considered, the mean temperature of the satellite is close to 290 K, which means, for future calculations, this value can be used. g is the gain of the device. It can be taken 1 if it doesn't amplify or minify the signal. Simplifying the equation gives:

$$nf = 1 + \frac{t_e}{t_0} \quad \textbf{(7.38)}$$

or in logarithmic scale:

$$NF = 10\log(1 + \frac{t_e}{t_0}) \quad \textbf{(7.39)}$$

The noise power of the device in terms of noise figure is:

$$\begin{aligned} n_{out} &= g\,k(t_0 + t_e)b = g\,k\,t_0(1 + \frac{t_e}{t_0})\,b \\ &= nf\;g\,k\,t_0\,b \\ &= nf\;g\,n_{in} \end{aligned} \quad \textbf{(7.40)}$$

Also, the output noise power can be written as sum of two components as:

$$\begin{aligned} n_{out} &= g\,k\,t_0\,b + g\,k\,t_e\,b \\ &= g\,k\,t_0\,b + g\,k\left(\frac{t_e}{t_0}\right)t_0\,b \\ &= \underbrace{g\,k\,t_0\,b}_{\textit{Input noise contribution}} + \underbrace{(nf-1)\,g\,k\,t_0\,b}_{\textit{Device Noise Contribution}} \end{aligned} \quad \textbf{(7.41)}$$

Effective noise temperature can be expressed in terms of noise figure by:

$$t_e = t_0(nf - 1) \quad \textbf{(7.42)}$$

or in decibels:

$$t_e = t_0(10^{\frac{NF}{10}} - 1) \quad \textbf{(7.43)}$$

Figure of merit is used for specifying the quality or efficiency of the receiver portions of a satellite's communication links. It is defined as the ratio of receiver antenna gain to the receiver system noise temperature.

$$M = \left(\frac{G}{T}\right) = G_r - T_s = G_r - 10\log(t_s) \quad \textbf{(7.44)}$$

where G_r is the gain of antenna in dBi, and t_s is the receiver system noise temperature in K.

Carrier-to-noise ratio is defined as the ratio of average carrier power c, to the noise power n. Carrier to noise ratio, or shortly CNR, is the signal to noise ratio, or SNR, of a modulated signal. The term is used to distinguish the CNR of the radio frequency passband signal from the SNR of an analogue base band signal after demodulation. The $(\frac{c}{n})$ is the primary parameter of interest for defining the overall system performance in a communications system.

Carrier to noise ratio can be defined as power received to noise power ratio, all of which were defined before. If they are rewritten:

$$p_r = p_t g_t g_r (\frac{1}{l_{FS} l_0}) \quad \textbf{(7.45)}$$

With p_r being receiver power, g_t being transmit gain, g_r being receive gain, l_{FS} being free space path loss, and l_0 being other losses.

The noise power is:

$$n_r = k\, t_s b_N \quad \textbf{(7.46)}$$

Then,

$$\left(\frac{c}{n}\right) = \frac{p_r}{n_r} = \frac{p_t g_t g_r \left(\frac{1}{l_{FS} l_0}\right)}{k\, t_s b_N} \quad \textbf{(7.47)}$$

If expressed in dB scale, then:

$$\left(\frac{C}{N}\right) = EIRP + \left(\frac{G}{T}\right) - (L_{FS} + \sum Other\ Losses) - 226.8 - B_N \quad \textbf{(7.48)}$$

For digital communications systems, for describing the link performance, the bit energy e_b is more useful than carrier power. The relationship between carrier power and bit energy is as follows:

$$e_b = c\, T_b \quad \textbf{(7.49)}$$

where c is the carrier power, and T_b is the bit duration in seconds.

The energy per bit to noise density ratio, $\left(\frac{e_b}{n_0}\right)$ is the most frequently used parameter to describe digital communications link performance. It is defined as:

$$\left(\frac{e_b}{n_0}\right) = T_b \left(\frac{c}{n_0}\right) = \frac{1}{R_b}\left(\frac{c}{n_0}\right) \quad \textbf{(7.50)}$$

where R_b is the bit rate, in bits per second [87].

8. HARDWARE OPTIONS FOR COMMUNICATION SUBSYSTEM

ITU-pSAT II will communicate with ground station by using two bands. These bands are 70 cm band (430-450 Mhz), and 13 cm band (2.3-2.31 Ghz).

8.1 70 Cm Band

This band is used for transmitting housekeeping data primarily, although it may also be used for transferring pictures in case of anything happens to 13 cm band transmitter. In addition to housekeeping data, a separate or embedded beacon will be used for sending identification code, as well as some critical telemetry data using Morse alphabet. The alternatives that are sold as packages are given below.

NanoCom U480: It is 435-438 MHz half duplex transceiver with -120 dBm (-150 dB) sensitivity. It has FM and FSK modulation and demodulation with 1200, 2400 and 4800 baud rates. The interface it uses is I2C interface. It also has CCSDS frame support with FEC and Viterbi decoding. CCSDS frame is given in the appendix with FEC and Viterbi decodings. In addition to this frame support, it also supports custom framse like AX.25, thus allowing to implement frequently used or original protocols. Is is priced at 7200€.

NanoCom TNC1: It is a terminal node controller for NanoCom U480. It has an USB interface, and it is KISS-TNC compatible. The data socket is 6-pin data socket, and it is compatible with for example ICOM IC910H transceiver. Although the transceiver supports up to 9600 baud rate, this TNC also supports it, it is not recommended for U480, thus limiting the use of higher baud rates. It is priced at 750€ [123].

The communication subsystems that are sold at ISIS, or cubesatshop do not have uhf uplink/downlink specifications, but only have vhf uplink/uhf downlink or uhf uplink/vhf downlink options. Considering the satellite will have uhf uplink and/or downlink, s band uplink and/or downlink and gps, there will already be too much antennas on the satellite and the ground station. Thus, vhf link should be avoided if it is not absolutely necessary [124].

8.2 13 Cm Band

13 cm band will have one modem, and it will be used for downloading high resolution images. There aren't many available commercial transceivers for this band. There are limited options due to size and power constraints of the cubesats. The options are MHX 2400 and MHX 2420 desktop and n2420 OEM modems from MicroHard Systems Inc. [125], TX-2400 and TX-2400M-10 transmitters from Spacequest [126], and an TXS from NanoCom [127].

8.2.1 MHX transceivers

Microhard Systems Inc. is a company that specializes in the design and manufacture of long range robust wireless data equipment. The company produces modems, gateways, ethernet bridges, and antennas in several bands and with several types. 70 cm band modems were used in several cubesats including ITU-pSAT I, and modems on other bands were used in some cubesats, such as 13 cm band modem on GeneSat-1.

There are two alternatives in the 13 cm band modems. These are MHX 2400&2420, and Nano n2420.

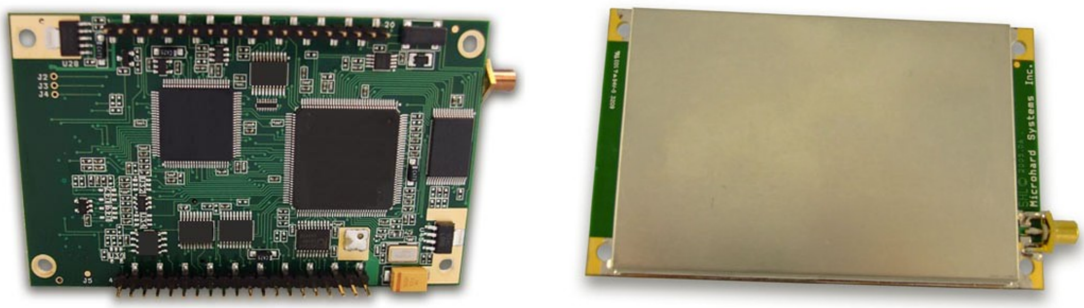

Figure 8.1 : Microhard MHX2420 bottom and top view

MHX2400 [128] and its successor MHX2420 [129] are two modems that are in production by Microhard. As they are done for long range communication, they are strong candidates for cubesat usage. Some of the important technical properties of these modems are:

- 2.4000 to 2.4835 Ghz frequency range
- 32 bits of CRC, with optional FEC in MHX2400, and ARQ in MHX2420
- -108 dBm sensitivity at 115.2 kbps

- 100 mW to 1W adjustable output power (MHX2420), 1 W user configurable (MHX2400)
- Operating modes: Point-to-point, point-to-multipoint, repeater (with store&forward feature in MHX2420), TDMA, multimaster, and additional peer-to-peer in MHX2420
- 2400 bps to 115.2 kbps data rate in MHX2400, 19.2 to 230.4 kbps data rate in MHX2420
- 75 gr weight in MHX2400, 55 gr weight in MHX2420
- 89mm x 53.4mm x 17.8 mm dimension

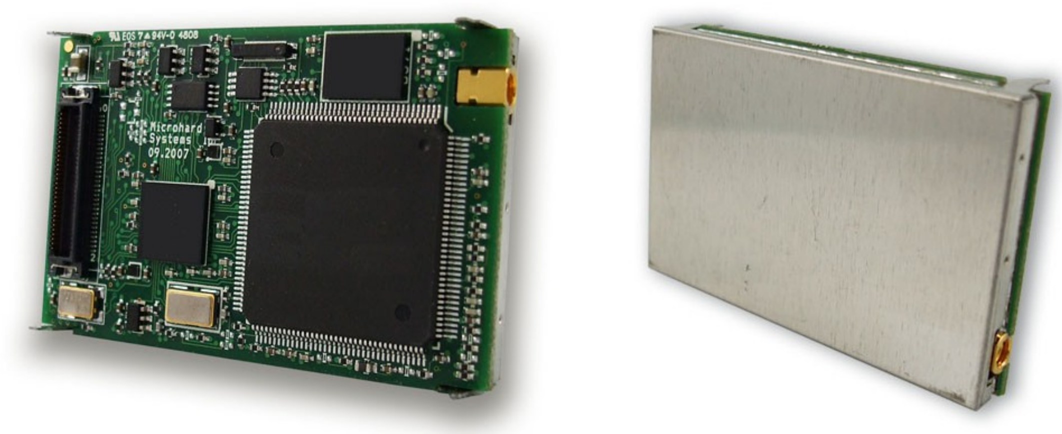

Figure 8.2 : Microhard n2420 bottom and top view

n2420 [130] is also capable of transmission at 13 cm band. It has two versions. n2420F version has a link rate of 115-230 kbps, and n2420T has a link rate of 1.2 Mbps. Some of its technical properties are:

- 2.4000 to 2.4835 Ghz frequency range
- Forward Error Detection codes: Hamming, BCH, Golay, Reed-Solomon algorithms
- 32 bits of CRC, ARQ
- -99 dBm @ 10^{-4} bit error rate for n2420T, -107 dBm @ 10^{-6} bit error rate for n2420F
- 100 mW to 1 W adjustable output power
- Operating modes: Point-to-point, point-to-multipoint, store&forward repeater,

peer-to-peer

- 19 gr weight
- 32mm x 51mm x 6.35mm dimension
- Power consumption: 0.297 to 0.462 W at Rx, 3.3 to 4.29 W at Tx

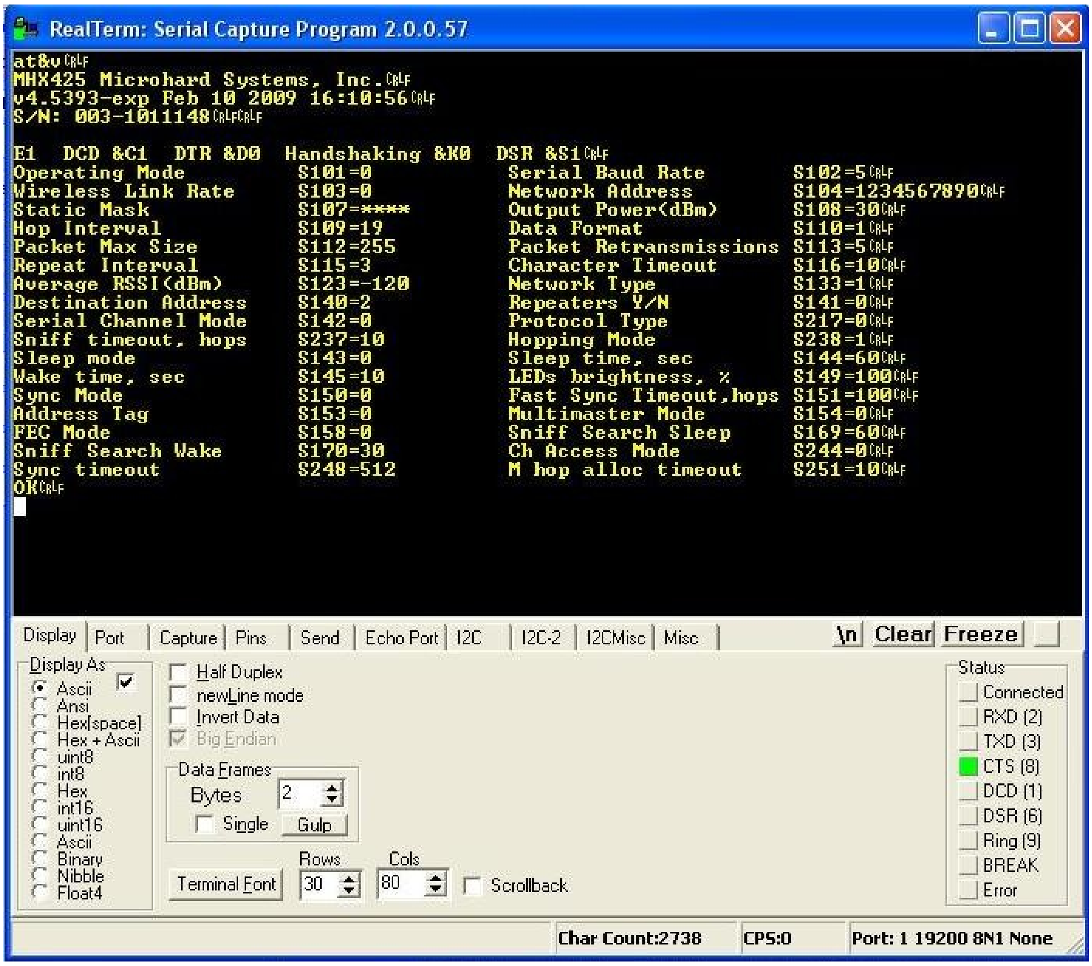

Figure 8.3 : Settings of MHX425, viewed from a hyperterminal program Realterm.

There are strong and weak points of these modems which must be taken into consideration. The strong points are:

- Extensive backward and forward error correction schemes
- Weight and dimension, especially n2420
- Several link rate options, which may allow to change the link rate according to success rate of S-band communication in flight with the help of lower frequency transceiver and with the appropriate algorithm in OBC
- Highly customizable (similar customization options to MHX425 of ITU-

pSAT I may be expected, which can be seen above)

The weak points are:

- They are not space qualified, however there are successful transmissions in flight with MHX modems
- They behave like black boxes, for example the modulations that are used are not known
- The ground station requires same (or similar) modem, which makes it hard to use other ground stations, or amateur radio operators for that matter.

The prices of these modems are not written in the website. Considering MHX425 modem was bought for about $2000, and comparing UHF band transceivers and S-band transceivers of other companies, the price of S-band modems will be expected to have a price of about $4000 each.

8.2.2 SpaceQuest transceivers

SpaceQuest is a company that specializes in producing flight-qualified systems and providing expertise in space systems. The company's productions include several products in antennas, radio and modems, power products, command&data handling products, attitude determination and control products, and satellite ground station equipments.

There is one S-band transmitter that is suitable for use in ITU-pSAT II. It is called TX-2400.

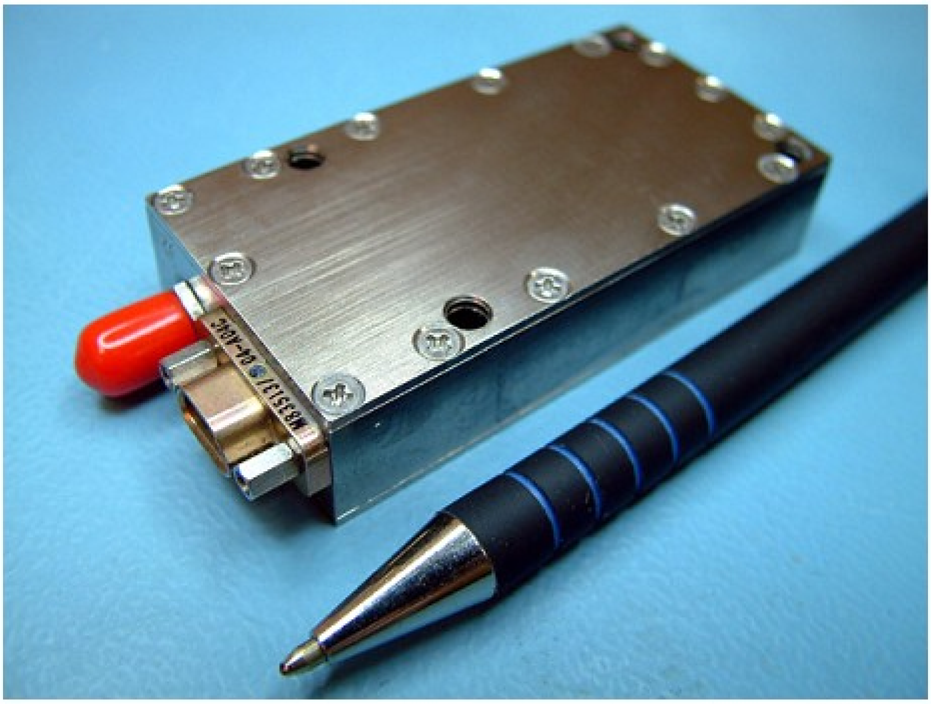

Figure 8.4 : SpaceQuest TX-2400 S-band transceiver

Some of the important technical properties of TX-2400 [131] are:

- 2000 to 2400 Mhz frequency range
- 200 gr weight for 2.5 W model
- 8 to 32 VDC
- 800 mA maximum for 2.5 W RF output
- 68mm x 35mm x 15 mm
- 2.5 W, 5 W, and 10 W options

Limited explanations in technical properties make it a bit hard to analyse this model. The strong points of this transceiver are different power options, being space-qualified, possibly ability to implement specific protocols with the help of a TNC, and the ability to be tracked worldwide such as amateur radio operators. The weak points are high power consumption, relatively high weight, and high price tag, which is $25000. If not aimed worldwide tracking, then this model is not a feasible option.

8.2.3 CubeSatShop.com & NanoCom transceivers

ISIS, or Innovative Solutions in Space is a company that specializes in the miniaturization of satellite systems with particular emphasis on the design and development of subsystems for micro and nanosatellites. The company provides several subsystems of cubesats and payloads, as well as ground station components and a full station, launch adapters and miscancellaneous things.

TXS S-band transmitter [127] is sold by cubesatshop.com, which is the shopping platform of ISIS [132].

Figure 8.5 : TSX transmitter sold by ISIS

As it is only a transmitter, only downlink is possible with this device. This necessiates the use of other communication elements for uplink. Some of the important properties of TSX are:

- 2100 to 2500 Mhz frequency range
- BPSK, QPSK, and for lower data rates GMSK modulation schemes
- 38.4 kbps data rate
- Up to 500 mW output power
- 70 gr weight
- 90mm x 96mm x 25 mm dimension (PC/104 compatible)
- Less than 3.5 W power consumption

The strong points of this transceiver are:

- Different modulation schemes, and possibility to change the modulation scheme in-flight.

- PC/104 form factor allowing easy integration
- I2C data interface, allowing easy integration
- Allows tracking by other ground stations and amateur radio operators

The weak points of this transceiver are:

- High power consumption (3.5 W consumption for 0.5 W output power)
- Relatively high price, though less than SpaceQuest transceivers

8.2.4 Other ready transceivers & modems

There are other transceivers for S-band. For example, Astrodev is planning to produce two options in the future [133].

9. ITU-pSAT II GROUND STATION

The ground station will consists of an UHF and an S-band system. Although it is nearly certain that, there will be uplink and downlink on the UHF band, the situation for S-band is not certain. There may or may not be downlink on S-band depending on the transceiver selection on the satellite.

9.1 Ground Station Hardware

Ground station hardware will consist of UHF band Yagi-Uda antennas, S-band dish antenna, a base to support these antennas, a rotator controller, an UHF capable transceiver, an S-band capable transceiver or receiver depending on the communication subsystem architecture of the satellite, computer interface cards/parts, and of course cables and connectors. In addition to these parts, some extra parts can be used for enhancing reliability of the system, accuracy of pointing etc.

9.1.1 UHF band antennas

Most, if not all, of the ground stations use Yagi-Uda antennas for communicating on the UHF band. For higher gain, generally additional antennas with the same types are used. By using an antenna array instead of one antenna, the gain may be increased. Doubling the number of arrays gives a gain that is close to 3 dB, although imperfections may reduce this value. Also, increasing the number of antennas can make the array more susceptible to winds and decrease mechanical löp.

9.1.2 S-band antennas

For higher frequencies than UHF bands, an antenna with higher gains is needed because of the increasing free space path loss. Generally, dish antenna is used for these frequencies. They have a gain in the range of 30 dB.

9.1.3 VHF/UHF capable transceiver

The transceiver will be used in UHF uplink and downlink. There are requirements for ITU-pSAT II mission, and possible requirements for future missions. Although it is not necessary to fulfil all of the requirements, some are critical, and some are good to have around. These are given below:

- Must have transmit and receive functions in 2m and 70cm bands.
- Transmit and receive functions on 23cm and 13cm will be a bonus.
- High transmit power. The transmit power of the transceivers vary from 50 to 100W. Also lower values for several types of unwanted signal transmission.
- High sensitivity and better selectibility.
- Ability to work on two different bands simultaneously (may be unofficially called cross-band full duplex communication).
- Capable of transmitting digital data with high baud rate. High baud rate generally means 9600 baud.
- Capable of FSK/MSK/GMSK modulation. Most of the ready communication subsystems on the satellites uses these modulation techniques.

There are few tabletop transceivers and several portable transceivers for use in ground station. Although portable transceivers have reduced capabilities, such as lower output power, they are still used in some ground stations.

9.1.3.1 ICOM IC-910H

ICOM IC-910H is a popular transceiver that is used in a lot of ground station. It works in 2m and 70cm bands, and can use these two bands simultaneously for a variety of modes. With the addition of UX-910 module, it can also work in 23 cm band, and with a downconverter AG-2400, it can receive signals at 13cm band.

Figure 9.1 : Front view of ICOM IC-910H.

It supports 9600 baud packet operation in both main and sub bands simultaneously. So, with two optional modules mentioned above, transmitting from three bands and receiving from four bands are possible, provided that the two bands used in send and receive are not the same bands. As it does not have a built-in TNC, a separate TNC or software TNC is needed [134]. It is possible to control this rig with a PC using CT-17 module (CI-V level converter) [135] or some other company's products such as RigBlaster. During the typing time of this thesis IC-910 is out of production, and a newer model IC-9100 is not on sale yet. Some sites still sell it, and it has a price about 1700$ [136].

9.1.3.2 ICOM IC-7000

It is the only amateur tabletop HF/VHF/UHF transceiver produced by ICOM. It has the same receive sensitivity capabilities with IC-910H. It can receive on two bands.

Figure 9.2 : ICOM IC-7000.

It has the same connections for digital data, and uses GMSK modulation for 9600 baud. Low output power makes this transceiver undesirable for our satellite operations [137].

9.1.3.3 ICOM IC-9100

ICOM's new model is not approved by F.C.C yet. It provides better sensitivity and selection on several modes, more modulation schemes, and can also support 23cm band with the same way as IC-910H by using UX-9100 module, however there is no such support for 13cm band. It also has a D-STAR (Digital Smart Technologies for Amateur Radio) support that allows more than 9600 baud data rate [138].

Figure 9.3 : ICOM IC-9100 is not in production yet.

A price that is similar to IC-910H may be expected from IC-9100 transceiver.

9.1.3.4 ICOM IC-208H

IC-208H is one of the portable models by ICOM for 2m and 70cm bands. It has a good level of output power among portable models, however it is still below tabletop ones. This transceiver can use only one band at a time, however, considering price [139], one of them is still a cheap option.

Figure 9.4 : ICOM IC-208H is a portable transceiver.

A TNC can be connected to IC-208H, and it supports both 1200 baud and 9600 baud rates. It supports G3RUH and GMSK modulation schemes on 9600 baud rate [140]. It is a feasible option for low budget, or a backup transceiver.

9.1.3.5 ICOM IC-880H and IC-2820H

These two transceivers have similar output power and sensitivity to ICOM IC-208H. A main difference is the ability to use D-STAR with its separately sold module. However, it does not have a huge advantage over using a TNC, because D-STAR is capable of 950bps data rate for these bands [141].

Figure 9.5 : ICOM IC-880H.

Modulations, connection types, data rates are the same with ICOM IC-208H. IC-2820H has a diversity function, which is only useful if there is two separate antenna systems for the same band [142][143].

Figure 9.6 : ICOM IC-2820H.

With D-STAR not a useful option within this bands, these two transceivers are not good options.

9.1.3.6 Kenwood TS-2000 series

Kenwood TS-2000 series transceiver is one of the most suitable transceivers for satellite tracking. It can use HF, 50MHz band, 144 Mhz band, and 440MHz band. In addition to these bands, TS-2000X model can use 1200MHz band. This transceiver has an output power of up to 100W on HF, 6m, and 2m bands, up to 50W on UHF band, and up to 10W on 23cm band [144].

Figure 9.7 : Kenwood TS-2000 Series.

One of the main advantages of this transceiver is a built-in TNC. This TNC conforms to the AX.25 protocol. It has 9600 bps capacity. This transceiver also allows an external TNC (or software TNC), which can be connected to its ACC2 connector. The transceiver can be connected to a computer via RS-232 cable. With this connection, it is possible to control both transceiver and the built-in TNC. However, it is not possible to control them simultaneously, thus making the internal TNC unusable [145].

Depending on the models, this transceiver has a price in the range of 1380-2000$ [146].

9.1.3.7 Comparison of the transceivers and final selection

After reviewing several specifications of the transceivers, only three of them can be considered as the most feasible alternatives. Considering that ICOM IC-9100 is not in sale in the writing time of this thesis, only two transceivers remain for selection. These are ICOM IC-910H and Kenwood TS-2000 series, because of their high output power, digital data support (TNC support), HRD compatibility, with better characteristics in uplink and downlink. The transceiver selection requires a deeper inspection of these two devices. The advantages of these two over each other are given below:

Advantages of TS-2000X over ICOM IC-910H:

- Internal TNC. With this TNC, there is no need to create audio signals outside of the transceiver. Also, digital data can be taken directly from the transceiver.
- RS-232C port on the transceiver. With it, it is possible to control the rig without additional hardware. It is also possible to send data to the internal TNC without additional hardware. Internal TNC can be controlled only by this port.
- Slightly better uplink and downlink characteristics than ICOM.
- Additional FSK support for Kenwood.

However, some issues in the transceiver makes us unable to use all of these advantages. First of all, with the RS-232 port, either the rig is controlled, or TNC is used. As the communication with satellite requires continuous data flow in both ways, and the frequency needs to be changed continuously due to the Doppler effect, a compromise is needed. It can use additional TNC (software or hardware) by its data port, so RS-232 port must be used for controlling the rig only, which renders the internal TNC unnecessary. Also, additional TNC requires additional hardware. In the final configuration, there is a need for one additional hardware.

Advantages of IC-910H over TS-2000X:

- Ability to uplink in two bands simultaneously. It is not clear if there will be uplink in two bands simultaneously for ITU-pSAT II, but it provides more flexibility for future projects.
- More output power at 70cm band. This is a big plus.
- More ground stations use ICOM than Kenwood, which means more information about implementation is available.
- It is cheaper even with additional hardware.

ICOM IC-910H's advantages outweight Kenwood TS-2000X's advantages. IC-910H is out of production, however there are still places that sell this rig. So, it is a more logical solution. If a seller cannot be bought, TS-2000X is still a good choice.

Using IC-910H requires two additional hardware. One of these are for controlling the rig (changing frequency, modulation etc.), and the other is for using a software TNC. For controlling the rig, a CT-17 from ICOM, or a product from RigBlaster is needed. Considering the price and the capabilities of the devices, a RigBlaster Plus II from West Mountain Radio is a good choice [147].

Figure 9.8 : Front and back view of the RigBlaster Plus II.

Another requirement for ICOM is a data jack for taking the audio signals from the sound card of PC to the 6-pin jack of the transceiver. For this, there is a product from West Mountain Radio, which is called Data Jack [148]. With it, it is possible to use software TNC on PC.

Figure 9.9 : RigBlaster Data Jack.

With these rig and two interface hardwares, the system looks like to the picture given below:

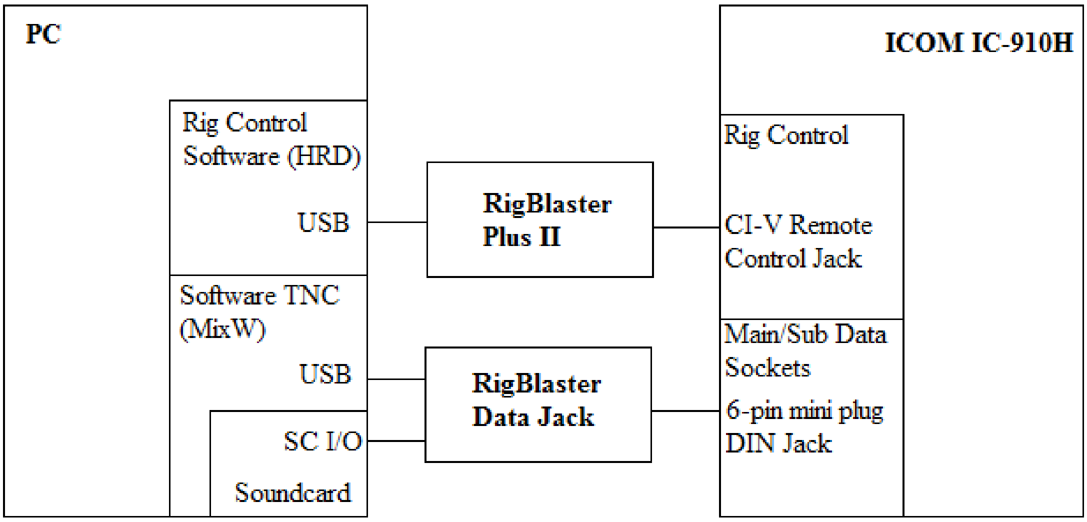

Figure 9.10 : PC and transceiver connections for rig control and TNC.

9.2 Ground Station Software

There are mainly three types of software for controlling the ground station. These are radio control software, rotator control software, and digital mode software.

Radio control software is used for controlling the radio. Its main aim is to change the radio parameters in real time, with the most important factor being the Doppler effect. For changing the frequency, the program must either use TLE datas and time (usually time on the PC), or somehow get these information from another program. Radio control software's radio support is an important factor for determining which radio to buy. Fortunately, most of the radio control software support both ICOM IC-910H and Kenwood TS-2000, which were described before.

Rotor control software is used for changing the direction of the antennas by controlling the antenna rotators. Rotor control softwares must also use TLE datas and time, or get these information from another program. Similar to radio control software, rotor control software must support the most popular rotators.

Digital mode software are used for converting visualised signals into meaningful data. These softwares must especially support basic modulation types, such as BPSK, QPSK, FSK, GMSK etc. The results from these programs will be used in mission specific programs, which is not determined in the writing time of this thesis.

Also there are some other programs that do not directly interfere with external hardware. These are either used for passing the necessary information to the software that directly interferes with external hardware, or used for demonstration purposes.

As most of the software interacts with each other, the most robust was is to use just one computer, although more PC can be used for redundancy purposes. Also, as most of the programs are written for Windows OS, a computer with Windows 7 will be used.

9.2.1 HamRadioDeluxe

This program is written by a radio amateur with callsign HB9DRV (Simon Brown), with the support of another radio amateur PH1PH (Peter Halpin). The programs that are called HRD Suite include the main program Ham Radio Deluxe, HRD Satellite Tracking, HRD Rotator, Digital Master 780, and HRD Logbook. In the writing time of this thesis, there were v4.0 and v5.0 as beta. The main difference of v5.0 from v4.0 is that, these programs are standalone programs instead of modules to the main program. The descriptions of these programs (or modules, depending on the version) are given below.

Ham Radio Deluxe: This program is used for controlling the radio. The program has a built-in logbook, internet explorer style favorites, integrated DX cluster, customizable band layouts, satellite tracking interface, and scanning functions. This program supports several radios, including ICOM IC-910H and Kenwood TS-2000, but not Yaesu FTM-350R, which may have been another option for ground station. This program can be integrated with HRD Satellite Tracking program, and can change the frequency for compensating against the Doppler shift.

Figure 9.11 : Main window of the Ham Radio Deluxe.

HRD Satellite Tracking: This program takes the TLE datas of the satellites, and calculates the orbital position of these satellites. Also, given the frequencies of these satellites, it can calculate the communication frequency which is different from the transceiver frequency on the satellite due to Doppler shift.

This program is connected to Ham Radio Deluxe using TCP/IP, including the localhost if HRD is in the same computer. With this connection established, Satellite Tracker can be used for changing and tuning several options either manually or automatically on the radio via HRD Deluxe.

It can also communicate with HRD Rotator using Dynamic Data Exchange (DDE). HRD Rotator uses the values provided by HRD Satellite Tracking for controlling the antenna.

With these properties, HRD Satellite tracking has the ability to be the main control program for controlling the radio and antenna rotators by using other HRD programs as software interfaces.

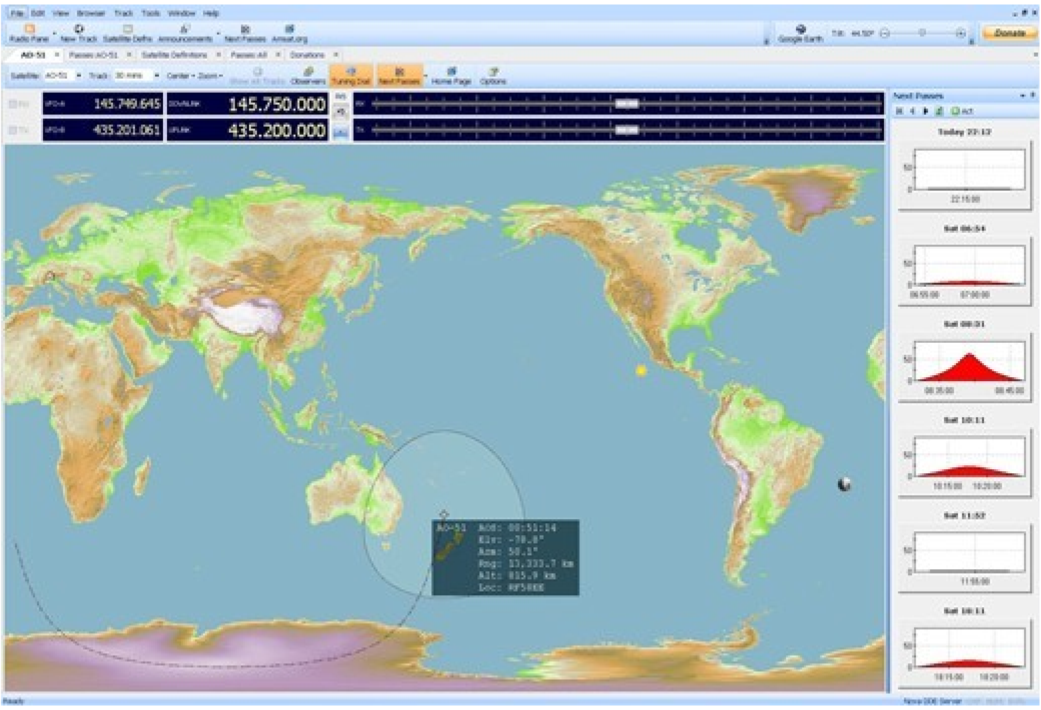

Figure 9.12 : HRD Satellite Tracker.

HRD Rotator: HRD Rotator is used for tracking the satellites, and uses the azimuth and elevation values that are provided by HRD Satellite Tracking program. It can also connect to Nova and Orbitron programs for controlling the rotators. HRD Rotator supports many rotators including the Yaesu rotators.

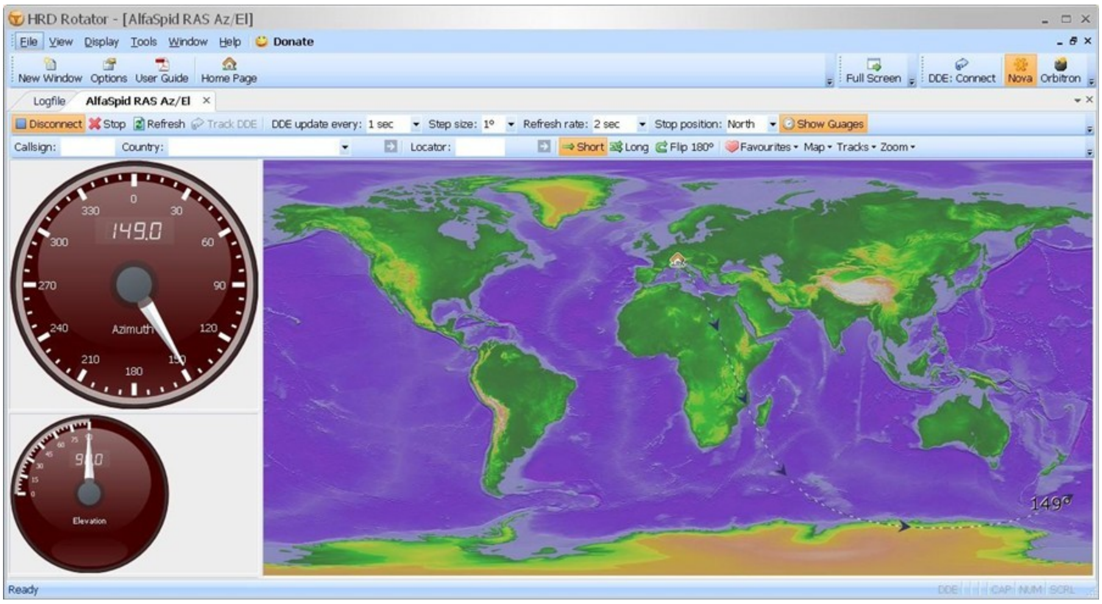

Figure 9.13 : HRD Rotator.

Digital Master 780: This program is a multi-mode digital software program. It supports most of the digital modes, including BPKS, QPSK, CW, MCW, RTTY, MFSK, Olivia, DominoEX, Throb, MT63, Hell, WJTS with their variants. This program is one of the options for software TNC [149].

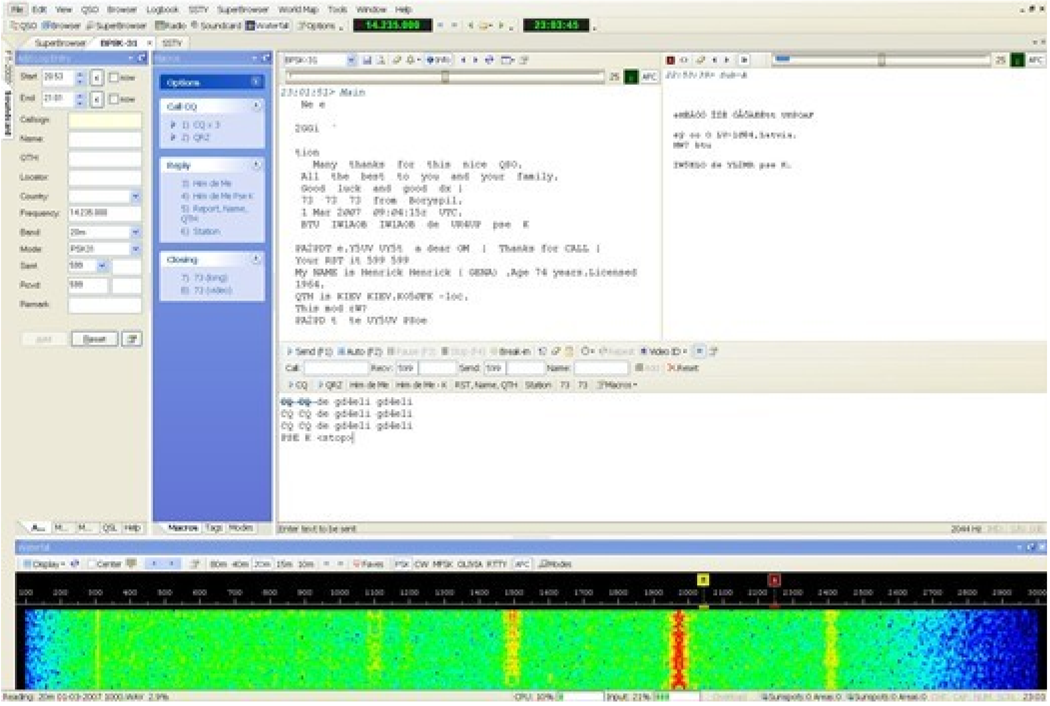

Figure 9.14 : Digital Master 780.

As all of these programs are part of Ham Radio Deluxe suite, fewer problems should be expected in terms of compatibility with each other. However, in some forums [150], it is implied that some of the programs in this suite, especially DM780, are overly complicated, which may necessiate use of other programs for some of the functions. On the other hand, this suite can be used in demo mode without the need of actual radio or rotators.

9.2.2 SatPC32 and WiSat32

SatPC32 and its sister program WiSat32 are created by a radio amateur, whose callsign is DK1TB (Erich Eichmann). The subprograms WinAOS, and WinListen is included in the main package, and DDESat32 can be installed separately.

SatPC32: This program calculates the tracks of earth orbiting satellites. For the calculations, SGP4/SDP4 models are used. Along with calculating the orbits of the satellites, and presenting them in a graphical output, SatPC32 is able to steer the antennas and control the radios with included Doppler correction. Besides the ability to control the rotators and radio, SatPC32 constantly sends DDE datas, allowing other programs to receive antenna positions, frequencies and modes.

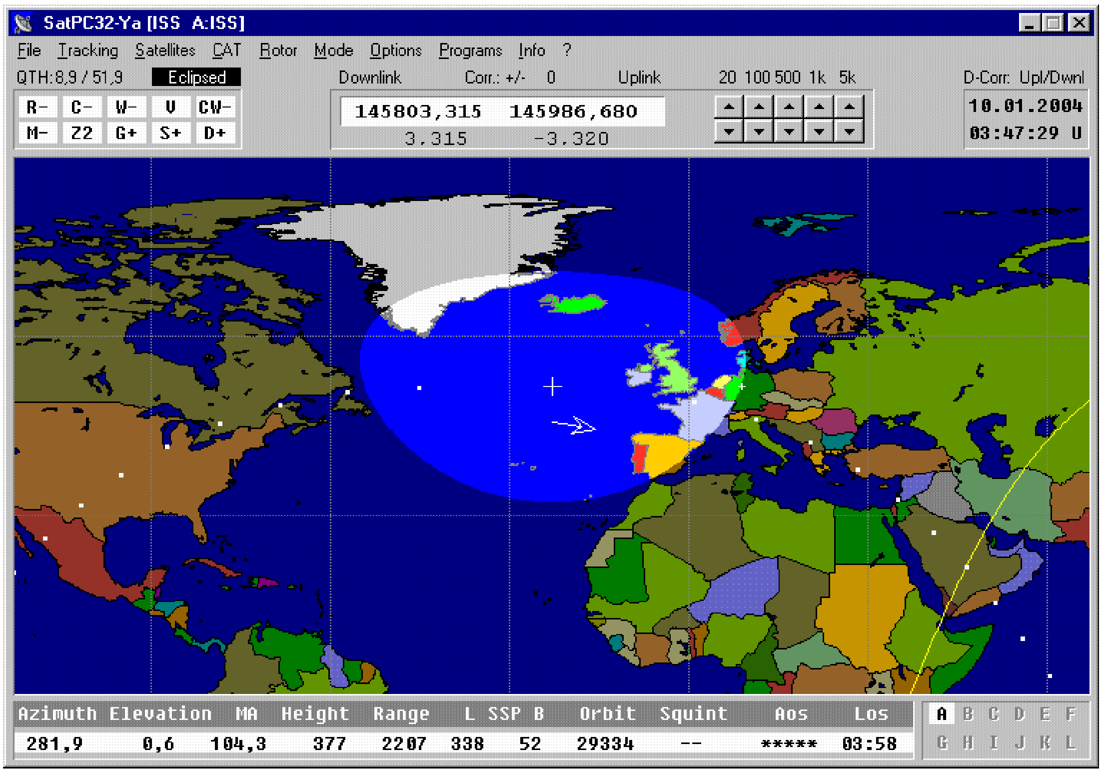

Figure 9.15 : SatPC32 main window.

WiSat32: This program has the same functions with SatPC32, but lacks graphical interface.

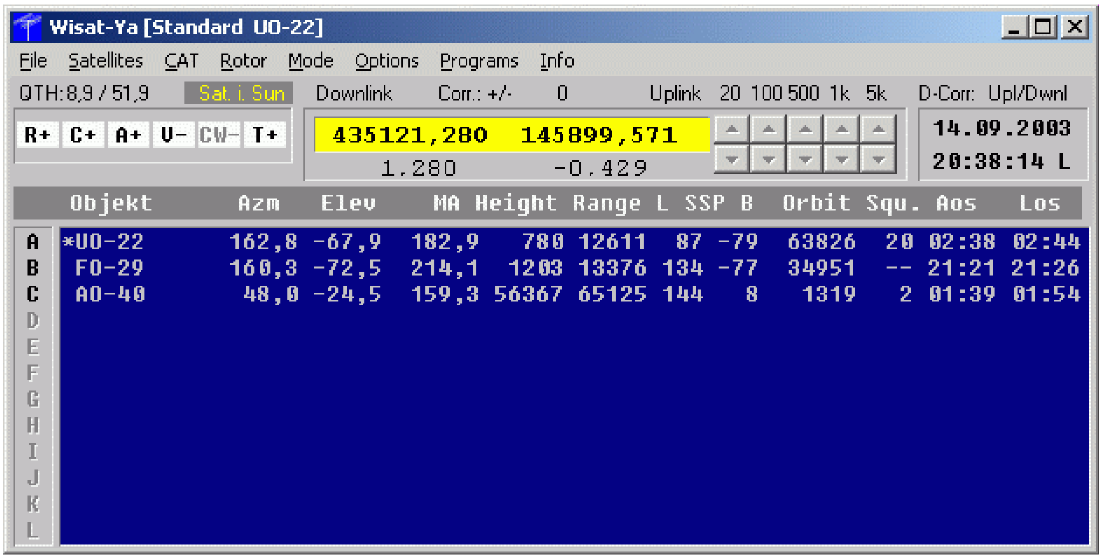

Figure 9.16 : WiSat32 lacks the GUI that SatPC32 has.

WinAOS and WinListen: These two programs read the source files that contain Keplerian data in the AMSAT or Nasa-2-Line format. WinAOS shows the results of several satellites, whike WinListen show the results of specific satellites and multiple observers if there are more than one.

DDESat32: This program takes the outputs of SatPC32 or WiSat32, and converts them to the protocols of the connected rotor and cat interfaces, and outputs them to the hardware.

SatPC32 and WiSat32 lacks things including automatic update of Keplerian Data, and time synchronization. However, in comparison to HRD Suite, SatPC32 uses less memory from each of the modules of HRD Suite, which may provide useful depending on the PC.

Demo version of the program does not store ground station coordinates, and it has to be entered at every run [151].

9.2.3 MixW

MixW is a multi mode software with digital functions. It supports CW, BPSK31, QPSK31, BPSK63&125, MFSK, RTTY, FSK31, Packet, Pactor RX/TX, Amtor TX/RX, Hellschreiber, FAX, SSTV, THROB, and MT63 [152]. It also supports multimode TNCs if hardware TNC is used [153]. In the figure, telemetry values from HO-59 is taken [154].

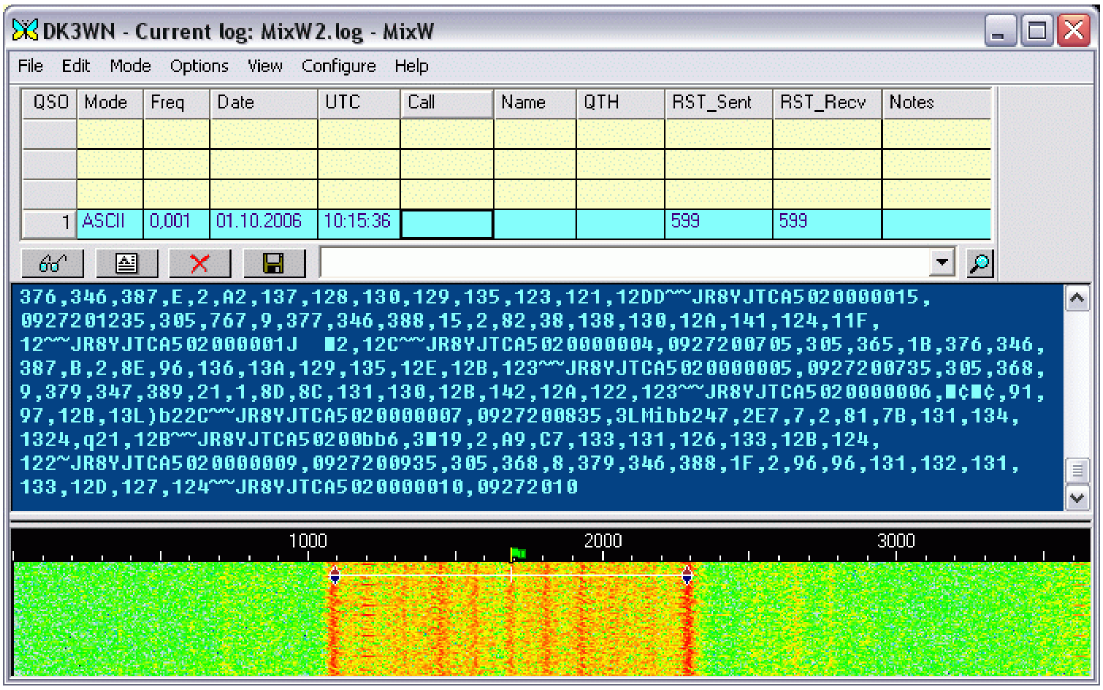

Figure 9.17 : MixW taking data from HITSAT-OSCAR 59.

MixW is one of the popular digital mode program, so the support of the community should be higher than other not well known programs. The program is shareware, and can be registered for $50.

9.2.4 Fldigi

Fldigi is a digital modem program written by a radio amateur with callsign W1HKJ. It supports many modulations such as PSK-500. Fldigi supports several OS such as Windows XP/Vista, Linux, OSX, and Free-BSD [155].

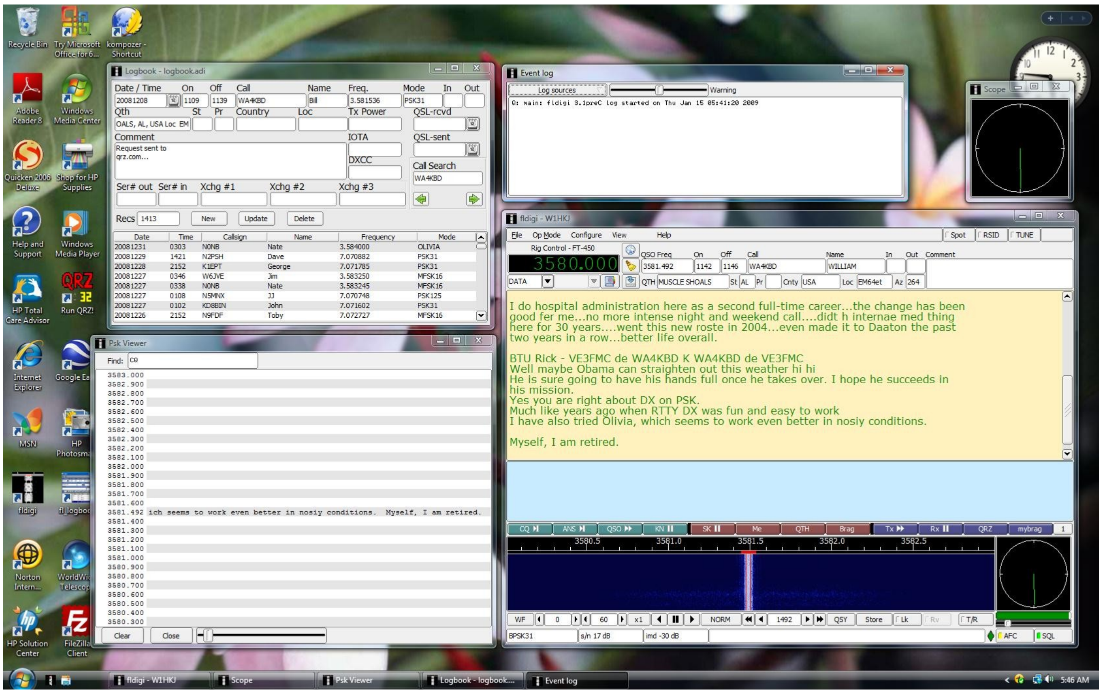

Figure 9.18 : Fldigi on Windows Vista

The good points of this program are that, it is light on computer resources, supports several operating systems, has a slick interface.

According to digital mode users, this program is one of the best digital mode program if not the best. The reasons are that, it supports several operating systems, has a lean interface, is light on computer resources, has a better decoding ability in weaker signals than other programs, and so on [156]. Fldigi is a freeware program.

9.2.5 MultiPSK

MultiPSK is another digital mode program. It supports several phase shift keying, on-off keying, frequency shift keying, multi frequency shift keying modes, as well as several other modes [157].

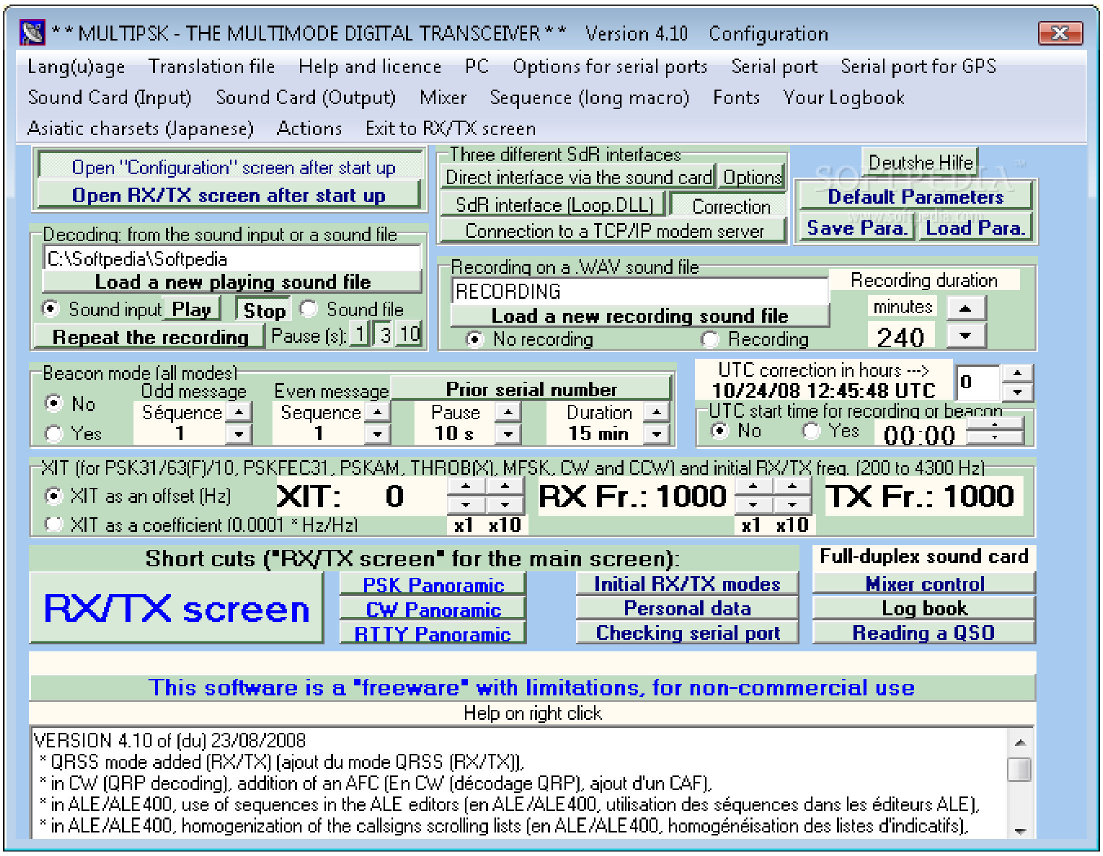

Figure 9.19 : MultiPSK.

This program is a highly rated program alongside fldigi, despite its poor layout [158].

9.2.6 NOVA

Nova is a satellite tracking and antenna rotator program. It supports a variety of rotator interfaces. This program has some specific properties such as controlling the antennas with a joystick, automatic time setting via the internet (changes system clock time too), listing of the satellite passes with more advanced options (such as, the time interval when a satellite can be seen by two observers), etc. It has a scheduling program useful for automatization of the ground station. With this scheduling program, multiple passes of the multiple satellites can be arranged with appropriate priorities for each satellite [159].

The demo version does not save the settings between runs. Registered version costs about $60.

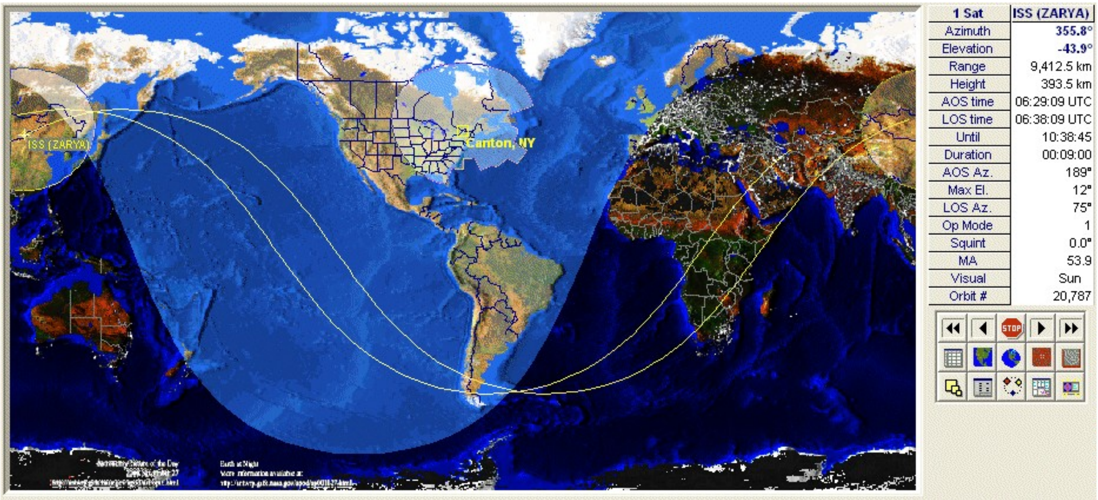

Figure 9.20 : NOVA Interface.

9.2.7 Orbitron

Orbitron is a satellite tracking program. This program can give the orbital positions of the satellites, and can calculate the azimuth and elevation, and Doppler shift. It has radio and rotor control support like HRD Satellite Tracker, albeit a simpler one. Another feature of the program is to predict future passes of the satellites. The main advantages of the program are simplicity, ease of use, and being light on computer resources. As a result, it is good to have this program, even if it is just for demonstration purposes [160].

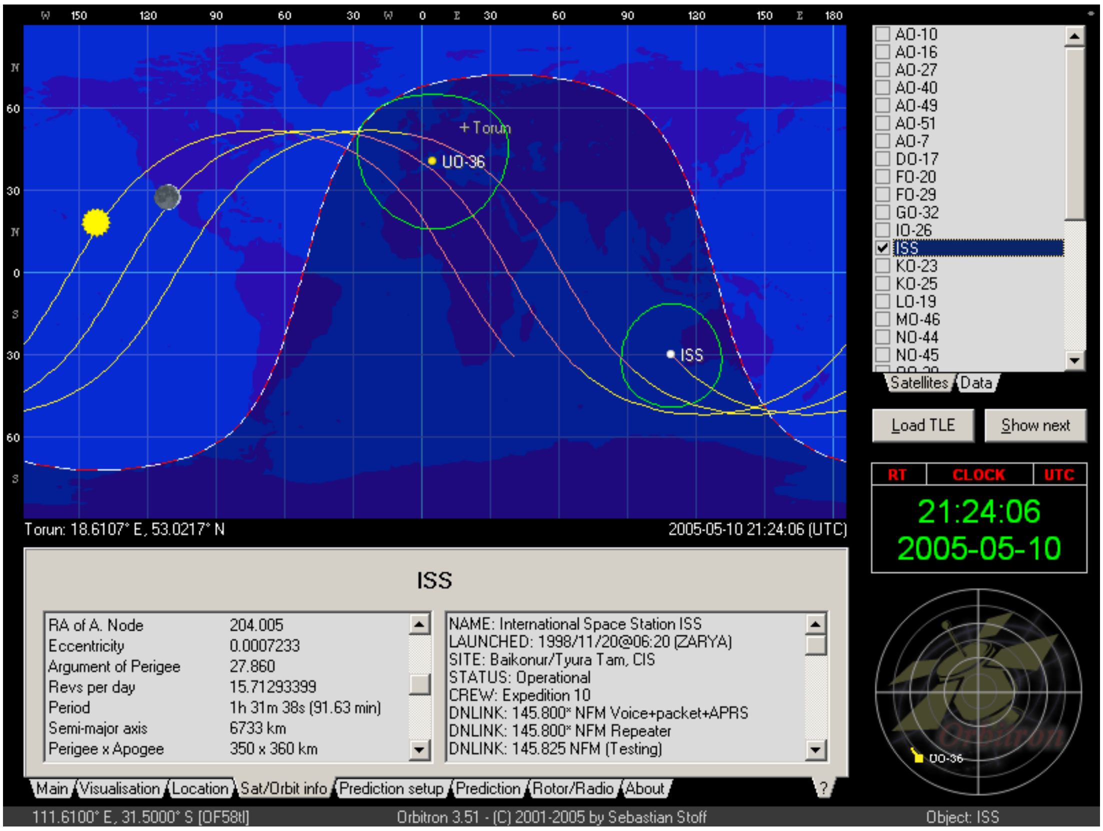

Figure 9.21 : Orbitron showing the positions of the three satellites simultaneously.

9.2.8 Predict

Predict is a multi-user satellite tracking and orbital prediction program. It gives information to users and client applications through a variety of ways. These are system console, command line, network socket, and audio speech. It can give various orbital position and velocity information, as well as the Doppler shift, and also can be used for controlling azimuth and elevation of the antenna rotators.

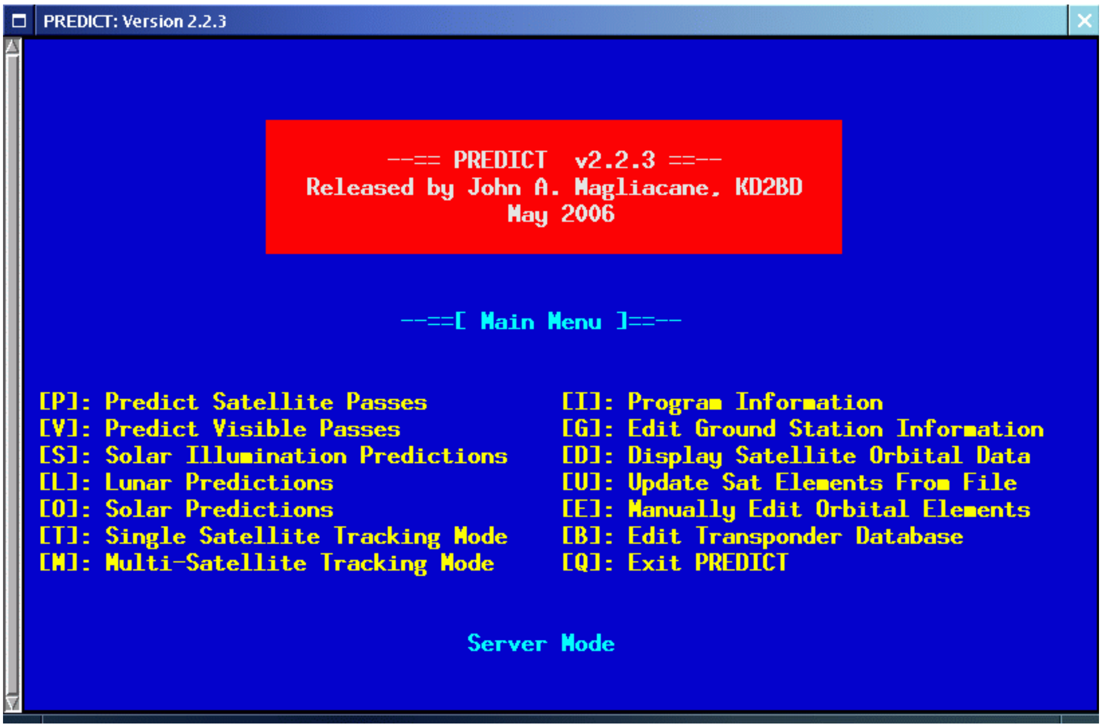

Figure 9.22 : PREDICT Menu.

The program itself lacks a graphical user interface. However, there are some client applications written that takes information from PREDICT using UDP communications protocol [161].

While there are programs such as SatPC32 and HRD, using PREDICT is not the first option. However, when a need for creating a custom GUI occurs in the future, this program is a good place to start.

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APPENDICES

APPENDIX A.1 : CubeSat Launches [27].

APPENDIX A.1

Table A.1 : CubeSat Launches.

Name	Type	Organization	Launch Date	Rocket	Status	Additional Notes
CanX-1	1U	UTIAS	30/06/03 14:15	Rokot/Briz-KM	Failed	No signal
DTUsat-1	1U	DTU	30/06/03 14:15	Rokot/Briz-KM	Failed	No signal
AAU Cubesat	1U	Aalborg University	30/06/03 14:15	Rokot/Briz-KM	Failed	Battery problems
QuakeSat	3U	Stanford University	30/06/03 14:15	Rokot/Briz-KM	Active	N/A
CUTE-1	1U	Tokyo Institue of Technology	30/06/03 14:15	Rokot/Briz-KM	Active	N/A
Cubesat XI-IV	1U	University of Tokyo	30/06/03 14:15	Rokot/Briz-KM	Active	N/A
Cubesat XI-V	1U	University of Tokyo	27/10/05 14:15	Kosmos-3M	Active	N/A
NCUBE-2	1U	ARR/NSC	27/10/05 14:15	Kosmos-3M	Failed	No signal
UWE-1	1U	University of Würzburg	27/10/05 14:15	Kosmos-3M	Failed	Contact lost
CUTE 1.7 + APD	2U	Tokyo Institue of Technology	21/02/06 21:28	JAXA M-V #8	Active	N/A
SACRED	1U	University of Arizona	26/07/06 19:43	Dnepr-1	Failed	Launch Failure
ION	2U	University of Illionis	26/07/06 19:43	Dnepr-1	Failed	Launch Failure
Rincon 1	1U	University of Arizona	26/07/06 19:43	Dnepr-1	Failed	Launch Failure
ICE Cube 1	1U	Cornell University	26/07/06 19:43	Dnepr-1	Failed	Launch Failure
KUTESat	1U	Uniersity of Kansas	26/07/06 19:43	Dnepr-1	Failed	Launch Failure
NCUBE-1	1U	ARR/NSC	26/07/06 19:43	Dnepr-1	Failed	Launch Failure
HAUSAT-1	1U	Hankuk Aviation University	26/07/06 19:43	Dnepr-1	Failed	Launch Failure
SEEDS-1	1U	Nihon University	26/07/06 19:43	Dnepr-1	Failed	Launch Failure
CP-2	1U	California Polytechnic University	26/07/06 19:43	Dnepr-1	Failed	Launch Failure

AeroCube 1	1U	Aerospace Corporation	26/07/06 19:43	Dnepr-1	Failed	Launch Failure
MEROPE	1U	Montana State University	26/07/06 19:43	Dnepr-1	Failed	Launch Failure
Mea Huaka'i	1U	University of Hawaii	26/07/06 19:43	Dnepr-1	Failed	Launch Failure
ICE Cube 2	1U	Cornell University	26/07/06 19:43	Dnepr-1	Failed	Launch Failure
CP-1	1U	California Polytechnic University	26/07/06 19:43	Dnepr-1	Failed	Launch Failure
GeneSat-1	3U	NASA/Santa Clara University	16/12/06 12:00	Minotaur	Active	N/A
CSTB1	1U	Boeing	17/04/07 06:46	Dnepr-1	Active	N/A
AeroCube 2	1U	Aerospace Corporation	17/04/07 06:46	Dnepr-1	Failed	Solar Converter Error
CP-4	1U	California Polytechnic University	17/04/07 06:46	Dnepr-1	Active	N/A
Libertad-1	1U	Sergio Arboleda University	17/04/07 06:46	Dnepr-1	Success	Deactivated 09/05/2007
CAPE-1	1U	University of Louisiana at Lafayette	17/04/07 06:46	Dnepr-1	Active	N/A
CP-3	1U	California Polytechnic University	17/04/07 06:46	Dnepr-1	Active	N/A
MAST	1U	Tethers Unlimited	17/04/07 06:46	Dnepr-1	Active	N/A
Cute-1.7 + APD II	1U	Tokyo Institue of Technology	28/04/08 03:53	PSLV-CA	Active	N/A
COMPASS-1	1U	FH Aachen	28/04/08 03:53	PSLV-CA	Active	N/A
AAUSAT-II	1U	University of Aalborg	28/04/08 03:53	PSLV-CA	Active	N/A
Delfi-C^3	3U	Delft University of Technology	28/04/08 03:53	PSLV-CA	Active	N/A
CanX-2	3U	University of Toronto	28/04/08 03:53	PSLV-CA	Active	N/A
SEEDS-2	1U	Nihon University	28/04/08 03:53	PSLV-CA	Active	N/A
PREsat	3U	NASA	03/08/08 03:34	Falcon 1	Failed	Launch Failure
NanoSail-D	3U	NASA	03/08/08 03:34	Falcon 1	Failed	Launch Failure

PharmaSat	3U	NASA Ames, Santa Clara University, UTMB	19/05/09 23:55	Minotaur I	Active	N/A
CP-6	1U	California Polytechnic University	19/05/09 23:55	Minotaur I	N/A	N/A
HawkSat I	1U	HISS	19/05/09 23:55	Minotaur I	N/A	N/A
AeroCube 3	1U	Aerospace Corporation	19/05/09 23:55	Minotaur I	N/A	N/A
SwissCube-1	1U	Ecole Polytechnique Fédérale de Lausanne	23/10/09 06:21	PSLV-CA	Active	N/A
BeeSat	1U	Technisch Universtat Berlin	23/10/09 06:21	PSLV-CA	Active	N/A
UWE-2	1U	Universtat Würzburg	23/10/09 06:21	PSLV-CA	Active	N/A
ITU-pSat1	1U	Istanbul Technical University	23/10/09 06:21	PSLV-CA	Active	N/A
Hayato	1U	Kagoshima University	20/05/10 21:58	H-IIA 202	Failed	N/A
Waseda-SAT2	1U	Waseda University	20/05/10 21:58	H-IIA 202	Unclear	N/A
Negai	1U	Soka University	20/05/10 21:58	H-IIA 202	Success	N/A
Tlsat-1	1U	SUPSI	12/07/10 03:53	PSLV-CA	Active	N/A
StudSat	1U	StudSat	12/07/10 03:53	PSLV-CA	Active	N/A
KySat-1	1U	Kentucky Space	22/11/10	Taurus-XL	Awaiting Launch	N/A
Hermes	1U	University of Colorado at Boulder	22/11/10	Taurus-XL	Awaiting Launch	N/A
Explorer-1'	1U	Montana State University - Bozeman	22/11/10	Taurus XL	Awaiting Launch	N/A
MaSat-1	1U	Budapest University of Technology and Economics	2010 (planned)	N/A	Awaiting Launch	N/A
CHASQUI-I	1U	Universidad Nacional de Ingenieria (Peru)	2010 (planned)	N/A	N/A	N/A
ICUBE-I	1U	Institue of Space Technology (Pakistan)	2011 (planned)	N/A	N/A	N/A

UAPSAT	1U	University Alas Peruanas (Peru)	2011 (planned)	N/A	N/A	N/A

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