MASTER'S THESIS

Telemetry, Tracking and Commanding subsystem for the CzechTechSat Pico satellite

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Master Thesis

Telemetry, Tracking and Commanding subsystem for the CzechTechSat Picosatellite

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A thesis submitted in fulfilment of the requirements for the degree of

Master of Science in Space Science and Technology

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I, Ning.Y, declare that this thesis titled, 'Telemetry, Tracking and Commanding subsystem for the CzechTechSat Picosatellite' and the work presented in it are my own.I worked out the presented Diploma thesis independently and I quoted all used materials (literature, projects, SW etc.) in the attached list. I confirm that:

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- Where I have consulted the published work of others, this is always clearly attributed.
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"Thanks to my solid academic training, today I can write hundreds of words on virtually any topic without possessing a shred of information, which is how I got a good job in journalism."

Dave Barry

CZECH TECHNICAL UNIVERSITY

Abstract

FEE in CTU
Department of Control Engineering

MSc in Electrical Engineering and Informatics-Control Engineering

Telemetry, Tracking and Commanding subsystem for the CzechTechSat PicoSatellite

by Ning YANG

The main goal of the thesis is to perform research, design, development and summary of achieved results of the Telemetry, Tracking and Commanding (TT&C) subsystem for the CzechTechSat CubeSat-class picosatellite. Consider different types of RF components, amplifiers, low noise preamplifiers, commercial telemetry modules and power consumption with respect to price, availability, reliability and simplicity of assembly. During design period the influence of the near-space and space environment shall be considered together with possible influence of ionizing and particle radiation background. Consider and implement the most convenient TT&C frequency plan for satellite communication allowed by the International Telecommunication Union (ITU). Determine the expected bandwidth with respect to real environment of the stratospheric balloon flight and Low Earth Orbit (LEO) spaceflight. Implement simple data transfer protocol. Summarize the test and achieved results.

Acknowledgements

All praise to my supervisor Jaroslav who really conduct and guide me through the whole one year SpaceMaster period in Czech Technical University. He brings me potential and courage to accomplish this work. After that I would like to thank my parents for their efforts, supports and prayers throughout my life and especially during my master studies in Europe. Without their encouragement, I cannot even imagine to complete my study endeavour.

It was my big honor to participate in the CzechTechCubeSat research group, we've done the Magnetic Levitation equipment last summer for attitude control and this year I carry on the work as my Master thesis in Measurement department of CTU and appreciate all the study experiences in Control department in Charles Campus.

At the end, I avail this opportunity to thank the SpaceMaster consortium for selecting me consequently providing me an opportunity to study in the three different european countries. I am genuinely grateful to Jaroslav and the development support all covered by CTU FEE internal grants, also the cooperation with the Observatory in Slovakia and Czech Republic.

Contents

List of Figures

Abbreviations

TT&C	**T**elemetry **T**racking **C**ommand
CTS	**C**zech **T**ech **S**at
MPPT	**M**aximum **P**ower **P**oint**T**racking
EPS	**E**lectrical **P**ower **S**upply
FRAM	**F**erroelectric **R**andom **A**ccess**M**mory
ITU	**I**nternational **T**elecommunication **U**nion
LEO	**L**ow **E**arth **O**rbit
SSO	**S**lectrical **P**ower **S**upply
FM	**F**requency **M**odulation
COTS	**C**ommercial **O**ff **T**he**S**helf
OBC	**O**n **B**oard **C**omputer
GS	**G**round **S**tation
GP	**G**round **P**lane
FHSS	**F**requency **H**opping **S**pread**S**pectrum
PLL	**P**hase **L**ocked **L**oop
AFC	**A**utomatic **F**requency **C**ontrol
RSSI	**R**eceived **S**ignal **S**trength**I**ndicator
ADC	**A**nalog **D**igital **C**onverter
LNA	**L**ow **N**oise **A**mplifier
LBW	**L**oop **B**and **W**idth
DCE	**D**ata **C**ircuit-terminating **E**quipment
DTE	**D**ata **T**erminating **E**quipment

Physical Constants

Speed of Light	c	$=$	$2.997\ 924\ 58 \times 10^{8}\ \mathrm{ms}^{-\mathrm{S}}$
Gravitational Constant of the Earth	μ	$=$	$398600.440 km^3/s^2$
J_2 term of Gravitational Field	J_2	$=$	$1.7555 \times 10^{10} km^5/s^2$
The ratio of a circle's circumference	π	$=$	3.14159265359

Symbols

a	distance	m
P	power	W (Js^{-1})
i	inclination of the orbit	$^\circ$C
ω	angular frequency	rads^{-1}
f	signal frequency	MHz
λ	signal wavelength	m
v	velocity of object	ms^{-1}
$\Delta\Omega$	angular precession per orbit	$rads$

Chapter 1

Introduction to Czech CubeSat

1.1 CzechTechSat

CzechTechSat(CTS), A Space-friendly CubeSat-class Picosatellite, has been developed under Czech Technical University for more than 2 years. A CubeSat is a type of miniaturized satellite for space research that usually has a volume of exactly one liter (10 cm cube), has a mass of no more than 1.33 kilograms. The CubeSat specification accomplishes several high-level goals. Simplification of the satellite's infrastructure makes it possible to design and produce a workable satellite at low cost.

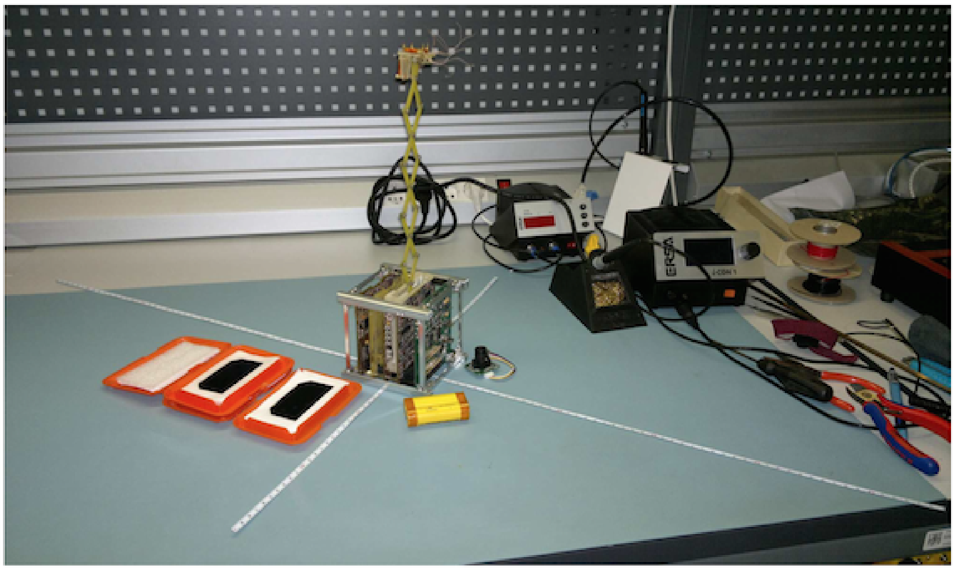

Figure 1.1: CzechTechSat

1.1.1 Scientific and Technical overview

CzechTechSat involves doubled cold redundant Onboard Computer with autonomous power arbiter, SiC JFET-based discrete Maximum Power Point Tracking (MPPT) regulator and power supply with Lithium batteries and triple junction solar cells, onboard Fluxgate Magnetometer with deployable scissor mechanism-based non-magnetic boom and PWM FRAM-based coherent demodulation, validate the onboard Attitude Determination and Control Subsystem and its control software and to test deployment of the wrapped strip dipole antennas for VHF/UHF in order to develop COTS-based subsystems for future scientific and academia activities with increased system reliability with respect to space environment (radiation, temperature range) at reduced cost. The Fig. 1.1 displays the CzechTechSat CubeSat Engineering Model in Clean Room at CTU FEE, excluding outer solar panels.

1.2 Subsystems Introduction of CzechTechSat

At its most fundamental level, the CubeSat can be defined as a discrete but scalable 1 kg, $100 \times 100 \times 100$ mm cuboid spacecraft unit; this is now commonly referred to as a 1U(nit) CubeSat. Whilst the form requirement of a 1U is likely to remain for launch interface reasons, strict adherence to the 1 kg mass requirement is already becoming redundant, allowing developers a greater freedom to create innovative payload packages. Overall the 6 subsystems have been introduced.

1.2.1 Electrical Power Supply(EPS)

Electrical Power Supply is the source of life to whole subsystems, this power that is delivered reliably and efficiently. The CzechTechSat CubeSat-Class Picosatellite programme addresses the development of electrical subsystems based on Lithium batteries and triple junction solar cells in Fig. 1.2 and SiC JFET-based discrete Maximum Power Point Tracking (MPPT) regulator to accomplish 3.3V and 5V power supply.

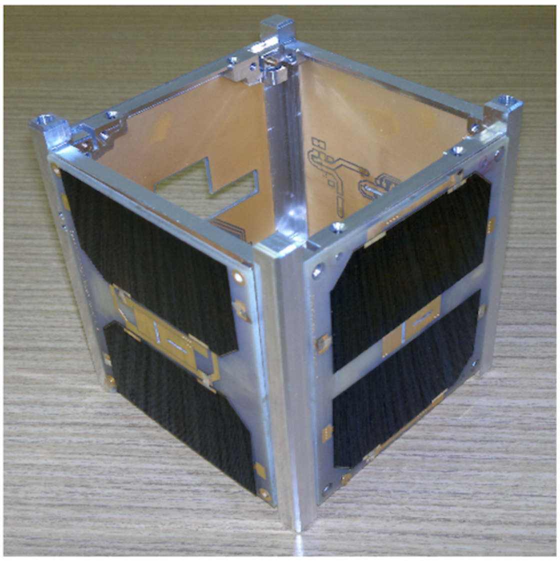

FIGURE 1.2: Solar Panels

1.2.2 Onboard Computer(OBC)

The Onboard Computer (OBC) implements among others the I/F to the onboard color cam and doubled triplet (Triple Modular Redundancy) of Flash memories ($2 \times\ 3 \times$ 2MB). We expect proper flight data storage (position estimation, time stamps, measured magnetic vectors from FGM, color images upon Telecommand request, onboard data handling between subsystems and Ground Station, housekeeping data collection and very rare takeover of the back-up part of OBC in case of Single Event Latchup caused by radiation).

1.2.3 Fluxgate Magnetometer(FGM)

The Fluxgate Magnetometer(FGM) scientific payload is designed to process analog data from CTU FEE, Dept. of Measurement originally designed and hand-made manufactured racetrack sensors with a noise down to 15 pT/Hz. The electronics is based on FRAM-stored PWM sampled sinewave and carefully selected and designed analog circuits with a goal to operate in harsh environment. Analog to digital converters (ADC) are interconnected to measure X, Y, Z components of outer geomagnetic vector also in case of failure of two of three ADC chips. Electrically deployable stainless steel spring-powered non-magnetic scissor boom has been selected and manufactured as a

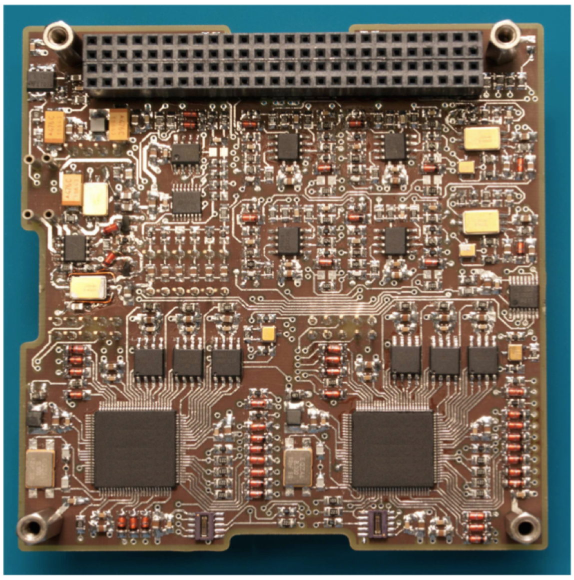

FIGURE 1.3: OBC

best trade-off between reliability, magnetic cleanliness, deployment mechanism complexity and cost. We expect proper functionality and magnetic field vector measurement, including monitoring of ADC status (failure detection) with respect to attitude (outer environment and operational conditions).

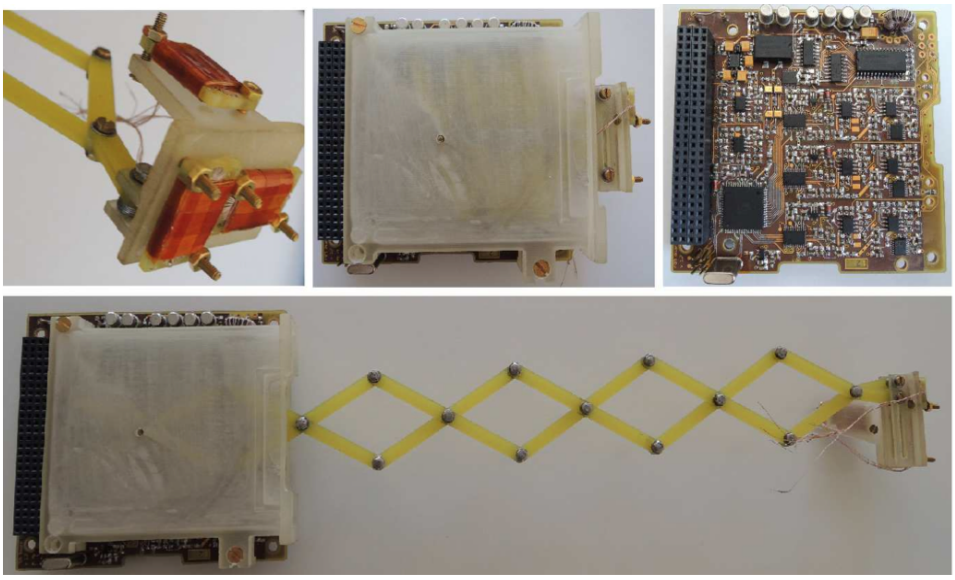

FIGURE 1.4: Fluxgate and Scissors boom

1.2.4 The Attitude Determination and Control Subsystem (ADCS)

The Attitude Determination and Control Subsystem (ADCS) board implements Kalman filter for attitude estimator based on 3 MEMS gyroscopes, each of them is SAR100 Single-Axis Gyro from sensonor, and 3-axis magnetometer HMC5883L. One Global Navigation Satellite System (GNSS) Unit integrated on the ADCS board and sets of 8 (on 2 plates) differential photodiode-based slot sun sensors under the solar panels boards are designed to support 2 axis determination on each plate which will realize the attitude estimation with a support of Real Time Clock implemented in the Onboard Computer. Two kinds of actuators have been selected: magnetic torquer rods and one reaction wheel mounted to be able to rotate the CubeSat hanging perpendicularly to ground surface. Magnetic torquer is passive magnetic stabilization, A permanent magnet will align the satellite with the local Earth magnetic field lines (as can be seen in the Appendix B). The magnetic field has been modeled in the Simulink environment based on the World Magnetic Model 2005 (WMM2005), which is approximately a dipole at low altitudes.The magnet torque, calculated in Modeling of the attitude determination and control system of the nanosatellite oufti-1 [?], has a value of 1E-5 Nm, which is far higher than the disturbing torques and ensures thus the expected orientation of the satellite.

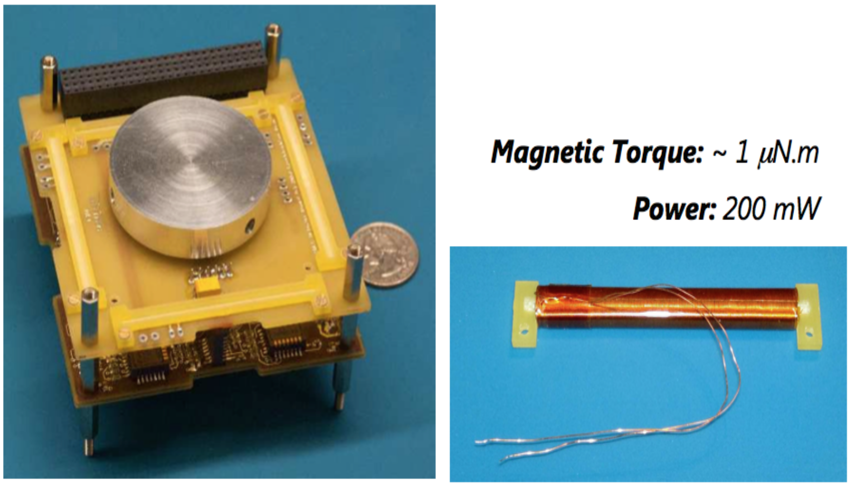

Figure 1.5: Reaction Wheel and Magnetic Torquer

1.2.5 Telecommunication Subsystem

Telecommunication subsystem might include TT&C board, Ground Station and Antenna assemble and deployment techniques. In the thesis, the TT&C board based on XBee868 module will be thoroughly introduced, also will be applied to Balloon flight for data transferring between the CubeSat and Ground Station. Ground plane antenna will be amounted on the CubeSat platform and Yagi antenna is used on Ground Station segment to realize the telecommunication. AT command will be utilized to configure

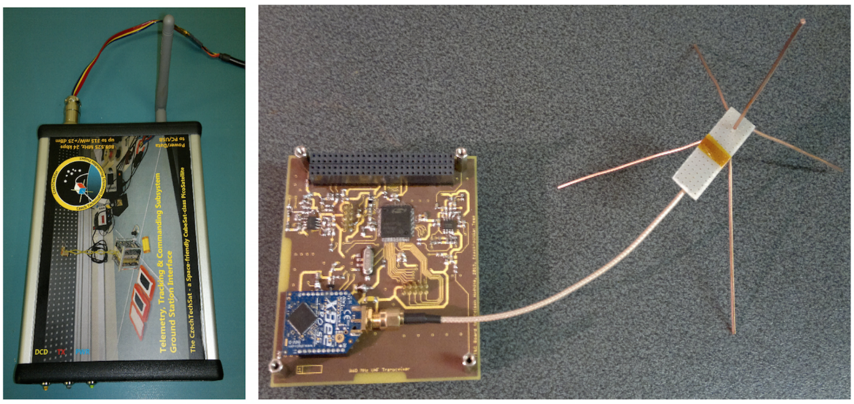

FIGURE 1.6: GS (Left) and Transmitter on Board(Right)

XBee868 module, transparent and API mode will be distinguished as well. Future more, upgraded board based on ADF7022 will be described by Low Noise Amplifier and Power Amplifier circuit design, plus AX.25 protocol will be introduced and present its pros/-cons. Antenna deployment strategy is designed in my Colleague Radovan Vlach's Master Thesis [?], the mechanical technique and design will be roughly introduced in this thesis, the deployment test and realization in Balloon flight video is attached in Appendix A.

1.2.6 Thermal control and Protection subsystem

This specific thermal board(Fig. 1.7) is designed for balloon flight purpose, since the atmospheric conditions during the long lasting flight are rather harsh in terms of low temperatures in contrary to the spaceflight (order of tens of seconds in the region with atmospheric pressure, humidity and low temperature), the CubeSat has to be thermally protected against the deep freezing.

To support the thermal control of the CubeSat, the electronic thermostat ready to deliver up to a maximum of 25 W has been developed. Heating system powered from 50 Wh vacuum-proof batteries has been designed to keep the internal temperature within the structure above $-10\,^{\circ}\mathrm{C}$ and switch off by sensor while reaches $-5\,^{\circ}\mathrm{C}$. Thermal control box will contain the auxiliary HD camera to deliver the flight video in total length of 3 hours.

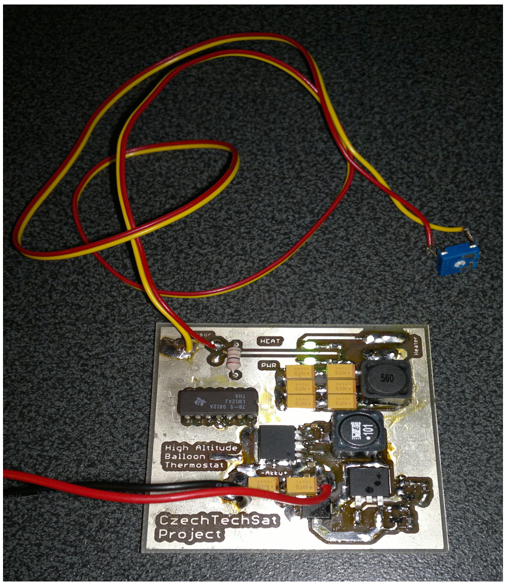

FIGURE 1.7: CTS Thermostat

Chapter 2

TT&C Board design for Balloon flight

FIGURE 2.1: Balloon Flight Set-up

The current TT&C Board is based on commercial component XBee868 as transceiver, and data processing is by micro-controller c8051f120. This present version is urgent to be built to test data transfer link functions because of the near stratospheric balloon flight associated with Czech Space Office. The overall Telecommunication system also include Ground Station construction and antenna implement and deployment on board technique. Fig. 2.3 displays the TT&C subsystems board with XBee868 module and Micro-controller. Second TT&C design were chosen and studied further to the point of design and simulation for future space flight, with one being fabricated and tested. The methods for the design and deployment of the antennas are described in this paper as well.

2.1 High Altitude balloon flight

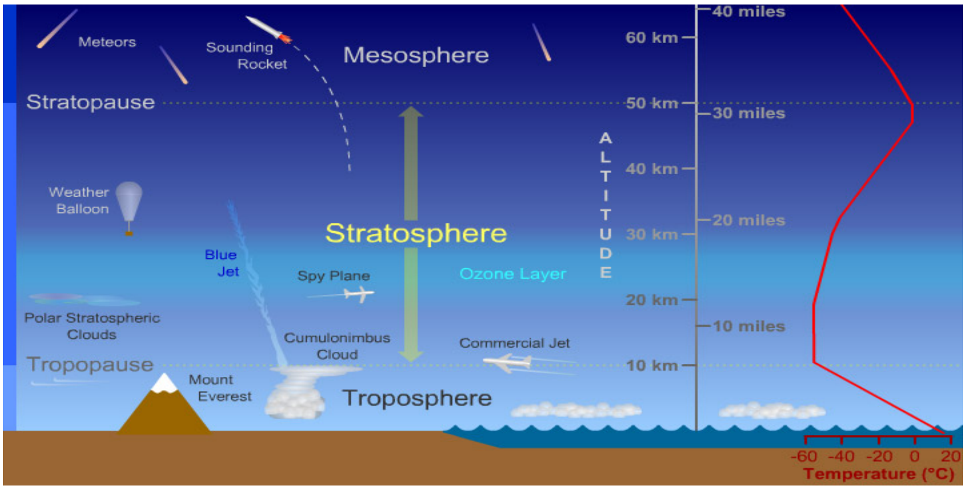

FIGURE 2.2: Stratosphere Balloon Flight

Czech Space Office Institution regularly launch most common type of high altitude balloons are weather balloons, which are unmanned balloons, usually Inflated with helium or hydrogen, that are released into the stratosphere. From the Fig. 2.2 it generally can attain as 60,000 feet in our case and the red curve shows the temperature according to altitude, it's approximately $-30\,°C$, depends on the wind speed, the internal temperature is rather unpredictable as well, therefore we have thermostat equipped. The balloon flight is being said "Today, this is the only way we have to get into the stratosphere quickly and economically" [**?**]. The other scientific purposes provide for students include use as a platform for experiments in the upper atmosphere. Modern balloons generally contain electronic equipment such as radio transmitters, cameras, or satellite navigation systems, such as GPS receivers. These balloons are launched into what is termed "near space"—the area of Earth's atmosphere where there is very little air, but where the remaining amount generates too much drag for satellites to remain in orbit. High altitude ballooning is a popular hobby for spacecraft testing teams which can assist the development of payloads [**?**].

2.1.1 Components selection

The XBee-PRO 868 modules [**?**] we use are long-range embedded RF modules providing end-point device connectivity for European applications. Supporting RF line-of-sight distances up to 80 km, these modules are ideal for challenging wireless environments where RF penetration and transmission distance are critical to the application. Only for use in EUROPE. SMA-RP Version, Fig. 2.3 displays the XBee Module, and the Schematic diagram of this TT&C board is attached in Appendix C. Also, a low-power

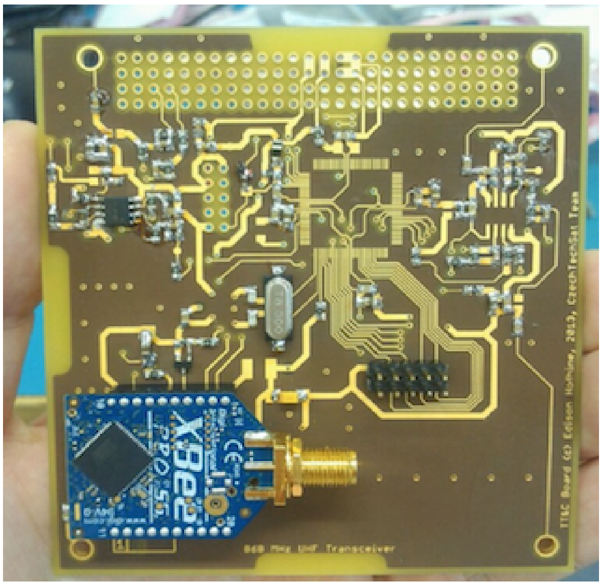

FIGURE 2.3: XBee module

satellite beacon was proposed as a way of identifying the satellite. When satellites pass overhead, they usually broadcast a simple acknowledge code message that functions as an identifier. Using a separate, low-power beacon would free up the primary transceiver to focus on its data transmission priorities, and allow for constant beacon identification, which was not possible with the relatively high power consumption of the primary transceiver.With this in mind, communication components were selected with the following requirements:

- The primary transceiver must be capable of communicating through line of sight with another node in the network, as well as a ground station that is around 40 km away as edge requirement.
- The frequency of the transceiver should be in one of the amateur radio bands, allocated for amateur satellite use.
- The antenna for the transceiver should be implementable and deployable, resonate at the correct frequency, and must have enough gain with omni-directionality to communicate with a ground station.

- The primary transceiver must be capable of transmitting a complete data stream in an allotted time.
- The TT&C beacon should be a simple acknowledge code message that consists of an identifying call sign and some simple satellite health telemetry data. The data must be transmitted with a low-power transmitter that can be on at all times if necessary (In our balloon flight, we intend to transmit data during the whole mission).

2.1.2 Link Budget

A link budget [**?**] is the accounting of all of the gains and losses from the transmitter, through the medium (free space, cable, waveguide, fiber, etc.) to the receiver in a telecommunication system. It accounts for the attenuation of the transmitted signal due to propagation, as well as the antenna gains, feedline and miscellaneous losses. Randomly varying channel gains such as fading are taken into account by adding some margin depending on the anticipated severity of its effects. All the effective factors related to link budget are:

- Transmit Power output of XBee Module is 25dBm
- A whip antenna is an antenna consisting of a single straight flexible wire or rod. And the The quarter wavelength Ground Plane Antenna is extremely famous too. The bottom end of the attenna is connected to the radio transmitter(XBee868) has 3 dB loss.
- Free-space path loss (FSPL) is the loss in signal strength of an electromagnetic wave that would result from a line-of-sight path through free space (usually air), with no obstacles nearby to cause reflection or diffraction. It does not include factors such as the gain of the antennas used at the transmitter and receiver, nor any loss associated with hardware imperfections.

$$FSPL = (\frac{4\pi d}{\lambda})^2 = (\frac{4\pi df}{c})^2$$

where: λ is the signal wavelength(in meters), f is the signal frequency(in meters), d is the distance from the transmitter(in meters), c is the speed of light in a vacuum, $2.99792458 \times 10^8 m/s$. Free-space path loss in decibels:

$$FSPL(dB) = 10\log_{10}((\frac{4\pi df}{c})^2 = 20\log 10(d) + 20\log_{10}(f) - 147.55$$

- A Yagi-Uda array, commonly known simply as a Yagi antenna, is a directional antenna consisting of a driven element (typically a dipole or folded dipole) as transmitting and receiving antenna of ground station subsystem. Due to radio communication limits, the transmitting gain must below 23dB.
- The receiver sensitivity of XBee module is -112 dBm.
- The transmitter point must be constrained below one watt as amateur radio safety concern. In the uplink calculation, assume Yagi antenna has 23dB full gain, the XBee868 module has to be 4dBm in order to keep 27dBm (1 Watt).

Sort out all the above influences, the rough estimation of ideal link budget at frequency 868 Mhz is:

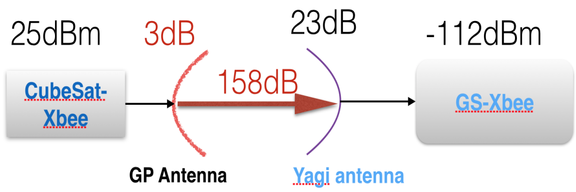

FIGURE 2.4: Downlink power consumption

Downlink: Equivalent to 2180 km approximately as 158 dB FreeSpaceLoss

$$P_{CubeSatXBeeTX}(25dBm) - L_{Ant}(3dB) - L_{FSL}(158dB) = G_{Yagi}(23dB) + P_{GSXBeeRX}(-112dBm)$$

uplink: Reachable to 240 km as 138 dB FreeSpaceLoss

$$P_{GSXBeeRX}(4dBm) + G_{Ant}(23dB) - L_{FSL}(138dB) = G_{Ant}(-3dB) + P_{CubeSatXBeeRX}(-112dBm),$$

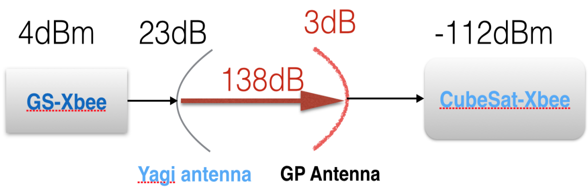

FIGURE 2.5: Uplink power consumption

2.2 Ground Station

2.2.1 Ground Station subsystem

Ground station subsystem is designed merely for ballon flight purpose. As mentioned above, the commercial XBee868 component is transceiver and Atmega128 plays the role as data processor, the PCB board design shows in Fig. 2.6 and its Schematic diagram is attached in Appendix D. The programming part utilize interrupt function, whatever micro-controller receives from XBee868, which will deliver the data to the Laptop via Serial Port and display on the Hyperterminal.

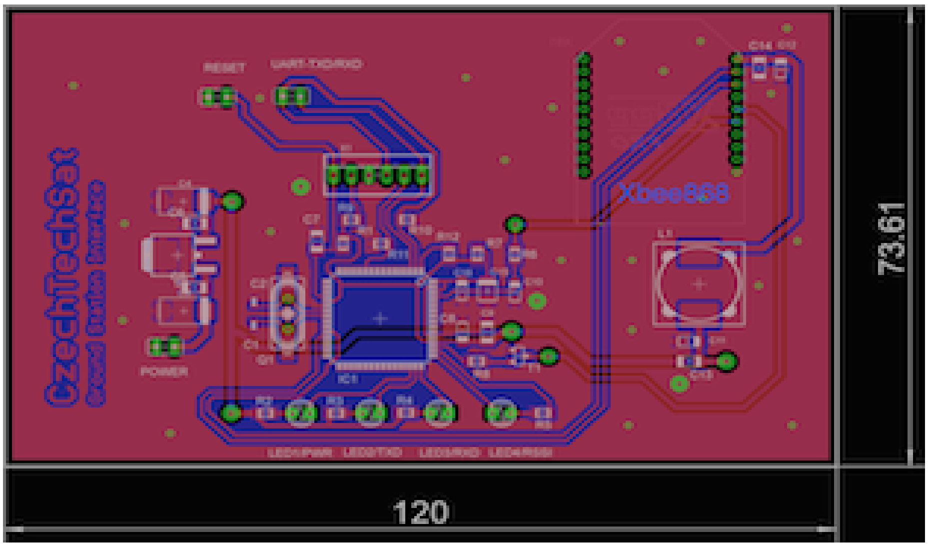

FIGURE 2.6: PCB board of GS

2.2.2 Doppler shift concern

Given the key role played by the frequency shift due to the Doppler effect, we provide a quick review of the Doppler-shift formula. It is assume that a wave with frequency $f_{tx}$is transmitted from the Tx platform (earth or satellite). If the relative velocity between the Tx platform and the Rx platform is $\dot{r}$, the frequency f_{rx} of the received wave is given by:

$$f_{rx} = f_{tx}\sqrt{\frac{c - \dot{r}}{c + \dot{r}}}$$

where c is the velocity of electromagnetic wave, equals to light speed. This formula is often written approximately as:

$$f_{rx} = f_{tx}(1 + \frac{\Delta v}{c})$$

So the change in frequency is $\Delta f = \frac{\Delta v}{c} f_{tx}$, imagine the wind speed is more or less 10 knots per hour, which equals to 5 meters per sec, plug in the number in the equation, we will obtain 0.0145 Hz difference. Turns out we can ignore this doppler shift compensation.

2.2.3 Telemetry and Telecommand

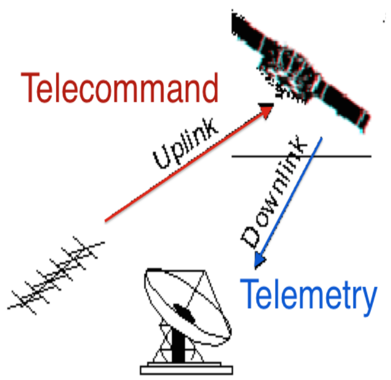

FIGURE 2.7: Uplink and Downlink

Telemetry, Tracking and command is in charge of Satellite-To-Ground communications. The process of sending information towards the spacecraft is called uplink or forward link and the opposite process is called downlink or return link. Uplink consists of commands and ranging tones where as downlink consists of status telemetry, ranging tones and even may include payload data. Dipole antenna is mounted on the CubeSat and Yagi antenna is applied to the Groundstation segment are the main components of a basic communication subsystem. The subsystem can provide us with the coherence between uplink and downlink signals, and because of the low speed balloon flight, the Doppler shifts can neglected in the data link transfer. The communication subsystem is sized by data rate, allowable error rate, communication path length, and RF frequency.The TT&C subsystem functions are [**?**]:

- Controlling of spacecraft by the operator on earth (One axis control in our case).
- Receive the uplink commands, process and send them to other subsystems for implication.
- Receive the downlink commands from subsystems, process and transmit them to earth.
- Inform constantly about the spacecraft position.

When the ground station wants to retrieve this information, or simply give instructions to the satellite network, a reliable link must be created between satellite and ground station that is sufficient for ranges of about 30km in our case the balloon flight.

The Fig. 2.8 shows the TT&C link test between two mountains 30km away and no data loss.

FIGURE 2.8: Link Test

Chapter 3

Upgraded TT&C Board design for future Space flight

3.1 TT&C Tranceiver Selection

In Space Flight mission, CubeSat is planning to be launched into Sun synchronous orbit with 600 km altitude and inclination around 98°, as data telecommunication, we assigned VHF 145 MHz and UHF 435 MHz for uplink and downlink relatively.

The consideration in hardware transceiver selection, we strongly seek for ADF7022 [**?**], which is a low power, highly integrated 2FSK/3FSK/4FSK transceiver. It is designed to operate in the narrow-band, license-free ISM bands and licensed bands in the 80 MHz to 650 MHz and 862 MHz to 940 MHz frequency ranges. It has both Gaussian and raised cosine data filtering options to improve spectral efficiency for narrow-band applications. Fig. 3.1 hows the ADF7022 Functional Block Diagram.

It is suitable for circuit applications targeted at European ETSI-EN 300-220, the Japanese ARIB STD-T67, the Chinese Short Range Device regulations, and the North American FCC Part 15, Part 90, and Part 95 regulatory standards. A complete transceiver can be built using a small number of external discrete components, making the ADF7022 very suitable for price-sensitive and area-sensitive applications.

The transmit section contains a voltage controlled oscillator (VCO) and a low noise fractional-N PLL with output resolution of $<$ 1 ppm. This frequency-agile PLL allows

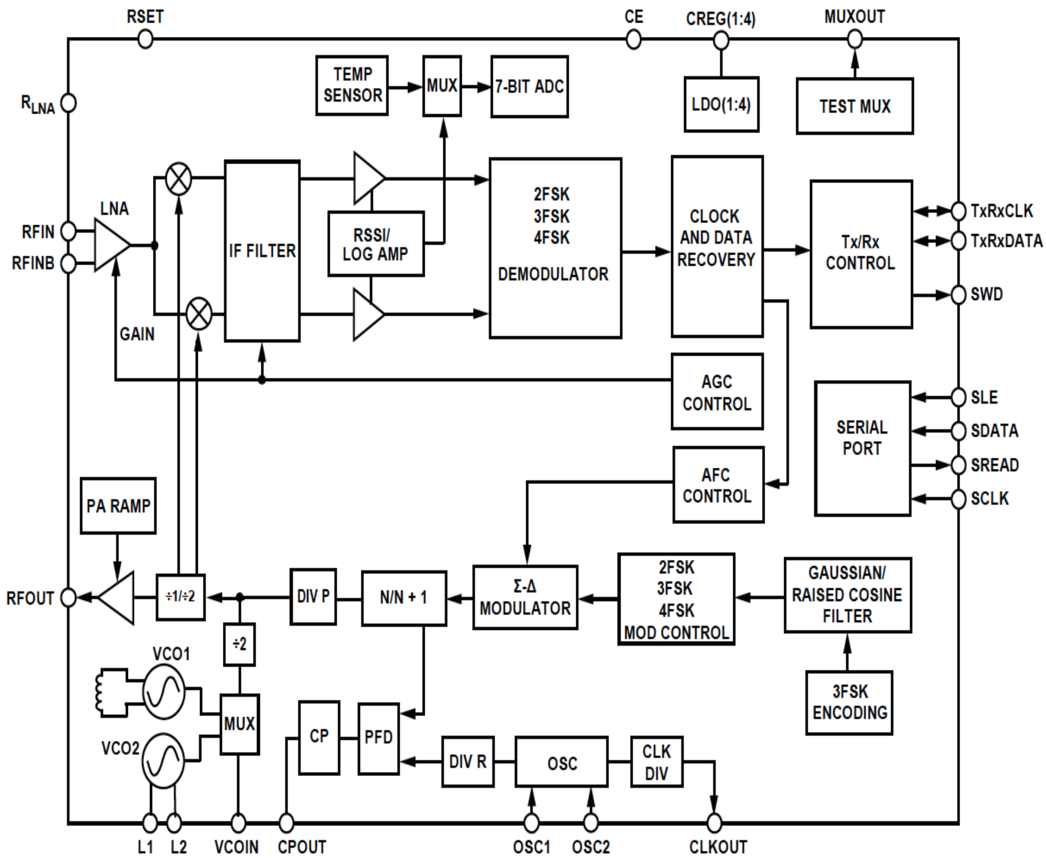

FIGURE 3.1: Functional Block Diagram

the ADF7022 to be used in frequency hopping spread spectrum (FHSS) systems. The VCO operates at twice the fundamental frequency to reduce spurious emissions and frequency pulling problems. The transmitter output power is programmable in 63 steps from -16 dBm to +13 dBm and has an automatic power ramp control to prevent spectral splatter and help meet regulatory standards. The transceiver RF frequency, channel spacing, and modulation are programmable using a simple 3-wire interface. The device operates with a power supply range of 2.3 V to 3.6 V and can be powered down when not in use.

A low IF architecture is used in the receiver (100 kHz), minimizing power consumption and the external component count while avoiding interference problems at low frequencies. The IF filter has programmable bandwidths of 12.5 kHz, 18.75 kHz, and 25 kHz. The ADF7022 supports a wide variety of programmable features including Rx linearity, sensitivity, and IF bandwidth, allowing the user to trade off receiver sensitivity and selectivity against current consumption, depending on the application. The receiver also features a patent-pending automatic frequency control (AFC) loop with programmable pull-in range, allowing the PLL to track out the frequency error in the incoming signal.

An on-chip ADC provides readback of an integrated temperature sensor, an external analog input, the battery voltage, and the RSSI signal, which provides savings on an ADC in some applications. The temperature sensor is accurate to $\pm 10\,^{\circ}$Cover the full operating temperature range of - $40\,^{\circ}$C to $+85\,^{\circ}$C. This accuracy can be improved by doing a 1-point calibration at room temperature and storing the result in memory.

3.2 Low Noise Amplifier in Reception

145MHz very high frequency bandwidth will be applied on transiting to CubeSat, in the reception side, low noise filter and amplifier is neccesary to be developed to separate desired radio frequency signal from all the other signals picked up by the antenna and enhance the detected signal magnitude. The LNA schematic circuit is attached in the Appendix E. Inside ADF, we use Phase locked loop method to convert to Intermediate frequency signal from a modulated carrier wave. A couple of ADF segments will be described as following.

3.2.1 Reference Input of Frequency Synthesizer

The on-board crystal oscillator circuitry (see Fig. 3.2) can use a quartz crystal as the PLL reference. Using a quartz crystal with a frequency tolerance of $\leq$10 ppm for narrow-band applications is recommended. It is possible to use a quartz crystal with >10 ppm tolerance, but to comply with the absolute frequency error specifications of narrow-band regulations, compensation for the frequency error of the crystal is necessary.

The oscillator circuit is enabled by setting $R1\_DB12$ high. It is enabled by default on power-up and is disabled by bringing CE low. Errors in the crystal can be corrected by using the automatic frequency control feature or by adjusting the fractional-N value (see the N Counter section).

Two parallel resonant capacitors are required for oscillation at the correct frequency. Their values are dependent upon the crystal specification. They should be chosen to make sure that the series value of capacitance added to the PCB track capacitance

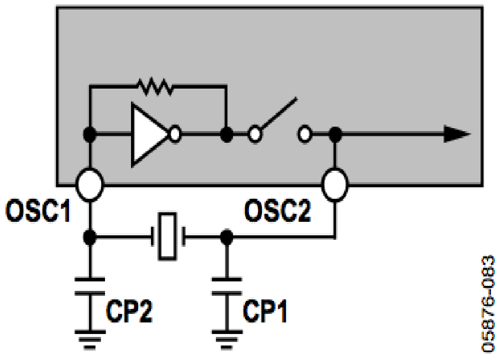

FIGURE 3.2: Oscillator Circuit on the ADF7022

adds up to the specified load capacitance of the crystal, usually 12 pF to 20 pF. Track capacitance values vary from 2 pF to 5 pF, depending on board layout. When possible, choose capacitors that have a very low temperature coefficient to ensure stable frequency operation over all conditions.

3.2.2 R counter

The 3-bit R counter divides the reference input frequency by an integer of 1 to 7. The divided-down signal is presented as the reference clock to the phase frequency detector (PFD). The divide ratio is set in $R1\_DB[4:6]$. Maximizing the PFD frequency reduces the N value. This reduces the noise multiplied at a rate of 20 log(N) to the output and reduces occurrences of spurious components. Register 1 defaults to R = 1 on power-up.

$$PFD[Hz] = XTAL/R$$

3.2.3 Loop Filter

The loop filter integrates the current pulses from the charge pump to form a voltage that tunes the output of the VCO to the desired frequency. It also attenuates spurious levels generated by the PLL. A typical loop filter design is shown in Fig. 3.3.

The loop should be designed so that the loop bandwidth (LBW) is approximately 100 kHz. This provides a good compromise between in-band phase noise and out-of-band spurious rejection. Widening the LBW excessively reduces the time spent jumping

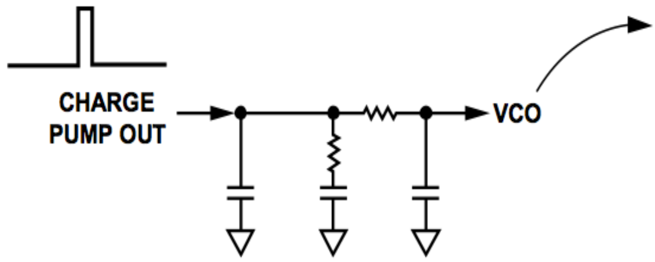

FIGURE 3.3: Oscillator Circuit on the ADF7022

between frequencies, but it can cause insufficient spurious attenuation. Narrow-loop bandwidths can result in the loop taking long periods to attain lock and can also result in a higher level of power falling into the adjacent channel. The loop filter design on the EVAL-ADF7022DBX should be used for optimum performance.

3.2.4 N Counter

The feedback divider in the ADF7022 PLL consists of an 8-bit integer counter and a 15-bit fractional_N divider. The integer counter is the standard pulse-swallow type that is common in PLLs. This sets the minimum integer divide value to 23. The fractional divide value provides very fine resolution at the output, where the output frequency of the PLL is calculated as:

$$f_{OUT} = \frac{XTAL}{R} \times (Integer\_N + \frac{Fractional\_N}{2^{15}})$$

When RF_ DIVIDE_BY_2 (see the Voltage Controlled Oscillator (VOC) section) is selected, this formula becomes:

$$f_{OUT} = \frac{XTAL}{R} \times 0.5 \times (Integer\_N + \frac{Fractional\_N}{2^{15}})$$

The combination of the integer _N (maximum =225) and the fractional _N (maximum = 32,768/32,768) give a maximum N divider of 255+1. Therefore, the minimum usable PFS is :

$$PFS_{MIN}[Hz] = \frac{MaximumRequiredOutputFrequency}{255 + 1}$$

For example, when operating in the European 868 MHz to 870 MHz band, PDF_{MIN} equals 3.4 MHz.

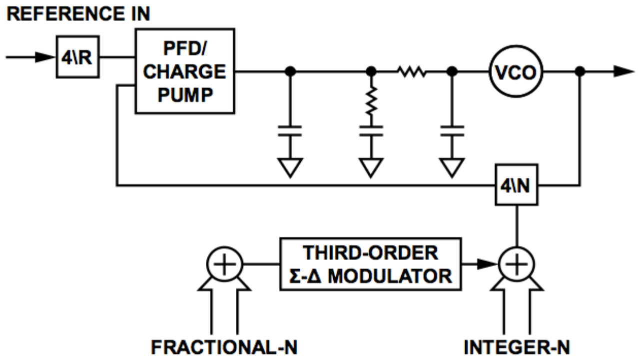

FIGURE 3.4: Fractional-N PLL

3.2.5 Voltage Controlled Oscillator (VCO)

The ADF7022 contains two VCO cores. The first VCO, the internal inductor VCO, uses an internal LC tank and supports 862 MHz to 950 MHz and 431 MHz to 475 MHz operating bands. The second VCO, the external inductor VCO, uses an external inductor as part of its LC tank and supports the RF operating band of 80 MHz to 650 MHz.

To minimize spurious emissions, both VCOs operate at twice the RF frequency. The VCO signal is then divided by 2 inside the synthesizer loop, giving the required frequency for the transmitter and the required local oscillator (LO) frequency for the receiver. A further divide-by-2 is performed outside the synthesizer loop to allow operation in the 431 MHz to 475 MHz band (internal inductor VCO) and 80 MHz to 325 MHz band (external inductor VCO).

The VCO needs an external 22 nF capacitor between the CVCO pin and the regulator (CREG1) to reduce internal noise.

3.2.6 Internal Inductor VCO

To select the internal inductor VCO,which is the default setting in regisgter.the minimum bias current setting under all conditions when using the internal inductor VCO is 0x8.The

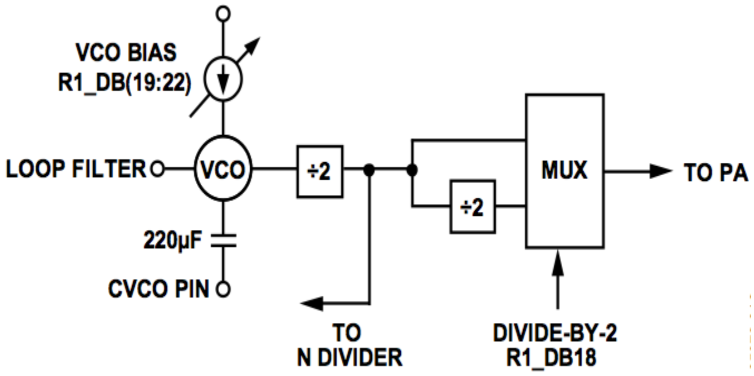

FIGURE 3.5: Voltage Controlled Oscillator (VCO)

VCO should be re-centered, depending on the required frequency of operation, This is detailed in Fig. 3.6.

RF Frequency Output (MHz)	VCO to Be Used	RF Divide by 2	Register Settings (VCO_INDUCTOR) R1_DB25	(RF_DIVIDE_BY_2) R1_DB18	(VCO_ADJUST) R1_DB[23:24]	(VCO_BIAS) R1_DB[19:22]
900 to 950	Internal L	No	0	0	11	8
862 to 900	Internal L	No	0	0	00	8
450 to 470	Internal L	Yes	0	1	11	8
431 to 450	Internal L	Yes	0	1	00	8
450 to 650	External L	No	1	0	XX	4
200 to 450	External L	No	1	0	XX	3
80 to 200	External L	Yes	1	1	XX	2

FIGURE 3.6: RF Output Frequency Ranges for Internal and External Inductor VCOs and Required Register Settings

3.2.7 External Inductor VCO

When using the external inductor VCO, the center frequency of the VCO is set by the internal varactor capacitance and the combined inductance of the external chip inductor, bond wire, and PCB track. The external inductor is connected between the L2 and L1 pins.

A plot of the VCO operating frequency vs. total external inductance (chip inductor + PCB track) is shown in Fig. 3.7.

As extended observation, when the frequency drops to 145MHz which is the uplink frequency bandwidth, the external inductance would end up with 47 nH approximately.

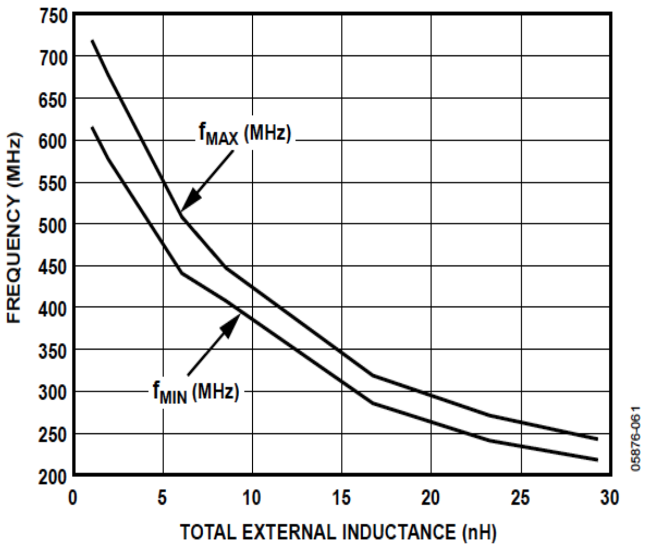

FIGURE 3.7: Direct RF Output vs. Total External Inductance

The inductance for a PCB track using FR4 material is approxi- mately 0.57 nH/mm. This should be subtracted from the total value to determine the correct chip inductor value.

3.3 Power Amplifier in Transmition

3.3.1 RF Output stage

he power amplifier (PA) of the ADF7022 is based on a single- ended, controlled current, open-drain amplifier that has been designed to deliver up to 13 dBm into a 50 Ω load at a maximum frequency of 950 MHz.

The PA output current and consequently, the output power, are programmable over a wide range. The PA configuration is shown in Fig. 3.8. The output power is set using R2_DB[13:18].

The PA is equipped with over-voltage protection, which makes it robust in severe mismatch conditions. Depending on the application, users can design a matching network for the PA to exhibit optimum efficiency at the desired radiated output power level for a wide range of antennas, such as loop or monopole antennas. See the LNA/PA Matching section for more information.

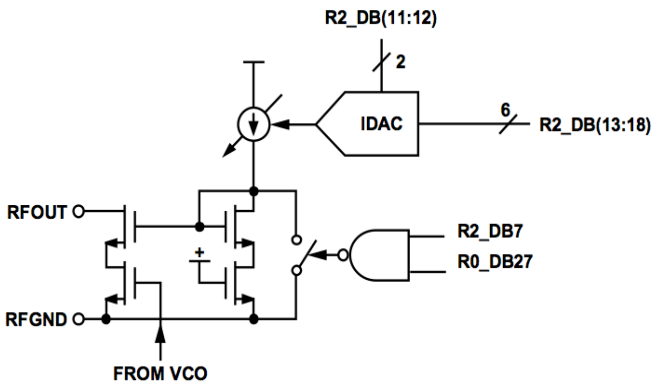

FIGURE 3.8: PA Configuration

3.3.2 PA Ramping

When the PA is switched on or off quickly, its changing input impedance momentarily disturbs the VCO output frequency. This process is called VCO pulling, and it manifests as spectral splatter or spurs in the output spectrum around the desired carrier frequency. Some radio emissions regulations place limits on these PA transient-induced spurs. By gradually ramping the PA on and off, PA transient spurs are minimized.

The ADF7022 has built-in PA ramping configurability. As Fig. 3.9 illustrates, there are eight ramp rate settings, defined as a certain number of PA setting codes per one data bit period. The PA steps through each of its 64 code levels but at different speeds for each setting. The ramp rate is set by configuring R2_DB[8:10].

If the PA is enabled/disabled by PA_ENABLE (R2_DB7), it ramps up at the programmed rate but turns off hard. If the PA is enabled/disabled by Tx/Rx (R0_DB27), it ramps up and down at the programmed rate.

3.3.3 PA Bias Currents

The PA_BIAS bits (R2_DB[11:12]) facilitate an adjustment of the PA bias current to further extend the output power control range, if necessary. If this feature is not required, the default value of 9 μA is recommended. If output power of greater than 10 dBm is required, a PA bias setting of 11 μA is recommended. The output stage is powered down by resetting R2_DB7.

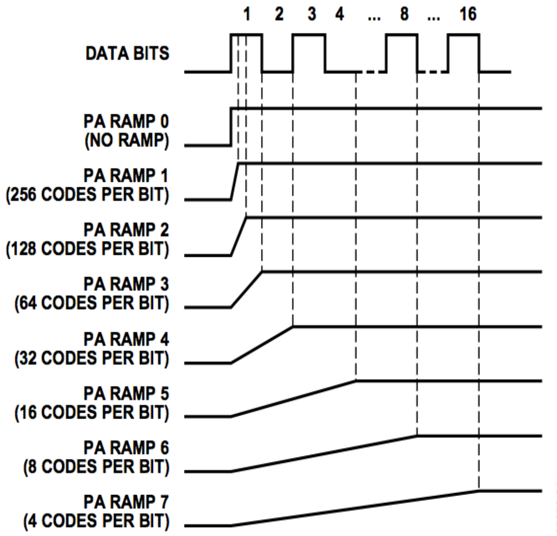

FIGURE 3.9: PA Ramping Settings

3.4 AX.25 Link-Layer Protocol Specification

AX.25 is a data link layer protocol derived from the AX.25 protocol suite and designed for use by amateur radio operators. It is used extensively on amateur packet radio networks. In the future space flight, this world-wide verified protocol will be considered in our TT&C subsystem. In this section, a short introduction of AX.25 protocol will be interpreted.

3.4.1 Scope and Field of Operation

In order to provide a mechanism for the reliable transport of data between two signaling terminals, it is necessary to define a protocol that can accept and deliver data over a variety of types of communications links. The AX.25 [**?**] Link-Layer Protocol is designed to provide this service, independent of any other level that may or may not exist.

As defined, this protocol will work equally well in either half- or full-duplex Amateur Radio environments.

It works equally well for direct connections between two individual amateur packet radio stations, or between an individual station and a multi-port controller.

It permits the establishment of more than one link-layer connection per device, if the device is so capable.

It also permits self-connections. A self-connection occurs when a device establishes a link to itself using its own address for both the source and destination of the frame.

Most link-layer protocols assume that one primary (or master) device (generally called a DCE, or data circuit-terminating equipment) is connected to one or more secondary (or slave) device(s) (usually called a DTE, or data terminating equipment). This type of unbalanced operation is not practical in a shared-RF Amateur Radio environment. Instead, AX.25 assumes that both ends of the link are of the same class, thereby eliminating the two different classes of devices.

3.4.2 Frame Structure

Link layer packet radio transmissions are sent in small blocks of data, called frames [**?**]. there are three general types of AX.25 frames:

- Information frame (I frame).
- Supervisory frame (S frame).
- Unnumbered frame (U frame).

Each frame is made up of several smaller groups, called fields. Fig. 3.10 and 3.11 shows the two basic types of frames. Note that the first bit to be transmitted is on the left side.Each field is made up of an integral number of octets (or bytes), and serves a specific function as outlined below.

First Bit Sent				
Flag	Address	Control	FCS	Flag
01111110	112/560 Bits	8 Bits	16 Bits	01111110

FIGURE 3.10: U and S frame construction

Each field is made up of an integral number of octets (8-bit byte of binary data) and serves the specific function outlined below.All fields except the Frame Check Sequence (FCS) are transmitted low-order bit first. FCS is transmitted bit 15 first.

First Bit Sent						
Flag	Address	Control	PID	Info.	FCS	Flag
01111110	112/560 Bits	8 Bits	8 Bits	N*8 Bits	16 Bits	01111110

FIGURE 3.11: Information frame construction

3.4.3 Flag Field

The flag field is one octet long. Since the flag is used to delimit frames, it occurs at both the beginning and end of each frame. Two frames may share one flag, which would denote the end of the first frame, and the start of the next frame. A flag consists of a zero followed by six ones followed by another zero, or 01111110 (7E hex).

3.4.4 Address Field

The address field is used to identify both the source of the frame and its destination. In addition, the address field contains the command/response information and facilities for level 2 repeater operation.

3.4.5 Control Field

The control field identifies the type of frame being sent. The control fields in AX.25 are modeled after the ISO HDLC balanced operation control fields.

Fig. 3.12 and 3.13 illustrate the basic format of the control field associated with each of these three types of frames.

The control field can be one or two octets long and may use sequence numbers to maintain link integrity. These sequence numbers may be three-bit (modulo 8) or seven-bit (modulo 128) integers.

where:

- Bit 0 is the first bit sent and bit 7 (or bit 15 for modulo 128) is the last bit sent of the control field.

Control Field Type	Control-Field Bits 15 14 13 12 11 10 9	8	7 6 5 4 3 2 1	0
I Frame	N(R)	P	N(S)	0
S Frame	N(R)	P/F	0 0 0 0 S S 0	1

FIGURE 3.12: Control-field formats (modulo 8)

Control Field Type	Control-Field Bits 7 6 5	4	3 2 1	0
I Frame	N(R)	P	N(S)	0
S Frame	N(R)	P/F	S S 0	1
U Frame	M M M	P/F	M M 1	1

FIGURE 3.13: Control-field formats (modulo 128)

- N(S) is the send sequence number (bit 1 is the LSB).
- N(R) is the receive sequence number [bit 5 (or bit 9 for modulo 128) is the LSB].
- The "S" bits are the supervisory function bits.
- The "M" bits are the unnumbered frame modifier bits.
- The P/F bit is the Poll/Final bit. The P/F bit is used in all types of frames. The P/F bit is also used in a command (poll) mode to request an immediate reply to a frame. The reply to this poll is indicated by setting the response (final) bit in the appropriate frame. Only one outstanding poll condition per direction is allowed at a time.

3.4.6 PID Filed

The Protocol Identifier (PID) field shall appear in information frames (I and UI) only. It identifies what kind of layer 3 protocol, if any, is in use. The PID itself is not included as part of the octet count of the information field. The encoding of the PID is as follows:

HEX	MSB LSB	Translation
0x01	00000001	ISO 8208/CCITT X.25 PLP
0x06	00000110	Compressed TCP/IP packet. Van Jacobson (RFC 1144)
0x07	00000111	Uncompressed TCP/IP packet. Van Jacobson (RFC 1144)
0x08	00001000	Segmentation fragment
**	yy01yyyy	AX.25 layer 3 implemented.
**	yy10yyyy	AX.25 layer 3 implemented.
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 implemented.
0xFF	11111111	Escape character. Next octet contains more Level 3 protocol information.

FIGURE 3.14: PID Field

Note: All forms of yy11yyyy and yy00yyyy other than those listed above are reserved at this time for future level 3 protocols. The assignment of these formats is up to amateur agreement. It is recommended that the creators of level 3 protocols contact the ARRL Ad Hoc Committee on Digital Communications for suggested encodings.

3.4.7 Information Filed

The information field is used to convey user data from one end of the link to the other. I fields are allowed in only three types of frames: the I frame, the UI frame, and the FRMR frame. The I field can be up to 256 octets long, and shall contain an integral number of octets. These constraints apply prior to the insertion of zero bits as specified in Bit Stuffing, below. Any information in the I field shall be passed along the link transparently, except for the zero-bit insertion (Bit Stuffing) necessary to prevent flags from accidentally appearing in the I field.

3.4.8 Bit Stuffing

In order to assure that the flag bit sequence mentioned above doesn't appear accidentally anywhere else in a frame, the sending station shall monitor the bit sequence for a group of five or more contiguous one bits. Any time five contiguous one bits are sent the sending station shall insert a zero bit after the fifth one bit. During frame reception, any time five contiguous one bits are received, a zero bit immediately following five one bits shall be discarded.

3.4.9 Frame Check Sequence

The frame-check sequence (FCS) is a sixteen-bit number calculated by both the sender and receiver of a frame. It is used to insure that the frame was not corrupted by the medium used to get the frame from the sender to the receiver. It shall be calculated in accordance with ISO 3309 (HDLC) Recommendations.

With the exception of the FCS field, all fields of an AX.25 frame shall be sent with each octet's least-significant bit first. The FCS shall be sent most-significant bit first.Any frame consisting of less than 136 bits (including the opening and closing flags), not bounded by opening and closing flags, or not octet aligned (an integral number of octets), shall be considered an invalid frame by the link layer.If a frame must be prematurely aborted, at least fifteen contiguous ones shall be sent with no bit stuffing added.Whenever it is necessary for a DXE to keep its transmitter on while not actually sending frames, the time between frames should be filled with contiguous flags.

3.5 Sun-sychronous Orbit for Space Flight

The space mission is planed to be launched by Chinese Rocket Long March 2-D into sun-synchronous orbit (sometimes called a heliosynchronous orbit). is a geocentric orbit which combines altitude and inclination in such a way that an object on that orbit ascends or descends over any given Earth latitude at the same local mean solar time.

3.5.1 Orbital elements of Sun-synchronous orbit

A satellite in sun-synchronous orbit [**?**] might ascend across the equator twelve times a day each time at approximately 15:00 mean local time. This is achieved by having the osculating orbital plane precess (rotate) approximately one degree each day with respect to the celestial sphere, eastward, to keep pace with the Earth's movement around the Sun. Fig. 3.15 showing the orientation of a sun-synchronous orbit (Green) in four points of the year. A non-sun-synchronous orbit (Magenta) is also shown for reference.

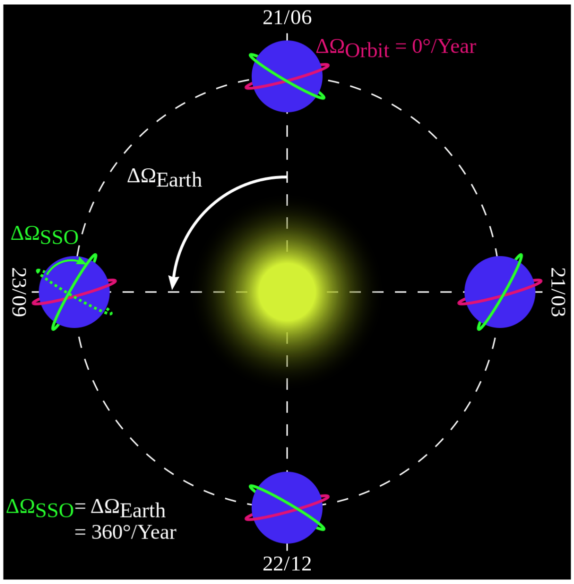

FIGURE 3.15: Sun Synchronous Orbit

The uniformity of Sun angle is achieved by tuning the inclination to the altitude of the orbit (details in section "Technical details") such that the extra mass near the equator causes the orbital plane of the spacecraft to precess with the desired rate: the plane of the orbit is not fixed in space relative to the distant stars, but rotates slowly about the Earth's axis. Typical sun-synchronous orbits are about 600-800 km in altitude, with periods in the 96 to 100 minute range, and inclinations of around 98°

Special cases of the sun-synchronous orbit are the noon/midnight orbit, where the local mean solar time of passage for equatorial longitudes is around noon or midnight, and the dawn/dusk orbit, where the local mean solar time of passage for equatorial longitudes is around sunrise or sunset, so that the satellite rides the terminator between day and night. Riding the terminator is useful for active radar satellites as the satellites' solar panels can always see the Sun, without being shadowed by the Earth. It is also useful for some satellites with passive instruments which need to limit the Sun's influence on the measurements, as it is possible to always point the instruments towards the night side of the Earth.

3.5.2 Technical discription

Equation of the article Orbital perturbation analysis (Spaccraft)gives the angular precession per orbit around an oblate planet as:

$$\Delta\Omega = -2\pi \frac{J_2}{\mu p^2} \frac{3}{2} \cos i$$

where:

- J_2 is the coefficient for the second zonal term ($1.7555 \times 10^{10} km^5/s^2$) related to the oblateness of the earth (see Geopotential model).
- μ is the gravitational constant of the Earth ($398600.440 km^3/s^2$).
- p is the semi-latus rectum of the orbit.
- i is the inclination of the orbit to the equator.

An orbit will be sun-synchronous when the precession rate,ρ, equals the mean motion of the Earth about the Sun which is 360° per tropical year(1.99106×10^{-7} radians/s), so we must set $\Delta\Omega/P = \rho$ where P is barbital period.

As the orbital period of a spacecraft is $2\pi a\sqrt{\frac{a}{\mu}}$(where a is the semi-major axis of the orbit) and as $p \sim a$ for a circular or almost circular orbit it follows that:

$$\rho \sim -\frac{3J_2 \cos i}{2a^{7/2}\mu^{1/2}} = -(360^\circ) \times (a/12352km)^{-7/2} \cos i$$

we can get:

$$\cos i \sim -\frac{\rho\sqrt{\mu}}{\frac{3}{2}J_2} a^{\frac{7}{2}} = -(a/12352km)^{\frac{7}{2}} = -(P/3.795hrs)^{\frac{7}{3}}$$

As an example, for a=7200 km (the spacecraft about 800 km over the Earth surface) one gets with this formula a sun-synchronous inclination of 98.696 deg.

I used Satellite Took Kit to simulate the sun-synchronous orbit, the Fig. 3.16 displays the 3D (left) and 2D (right) graphic of sun-synchronous orbit which also shows the ground track on the earth, the orbital elements to be set as:

- Altitude: 798 km.
- Inclination: 98.574 degrees.
- Period: 100.7 min, 14 orbit/day.
- Semi-Major Axis (a): 7176.07 km = 7176070 m.
- Eccentricity (e): 0.001251477.
- perigee = a×(1 - e) = 7167089.313 m.

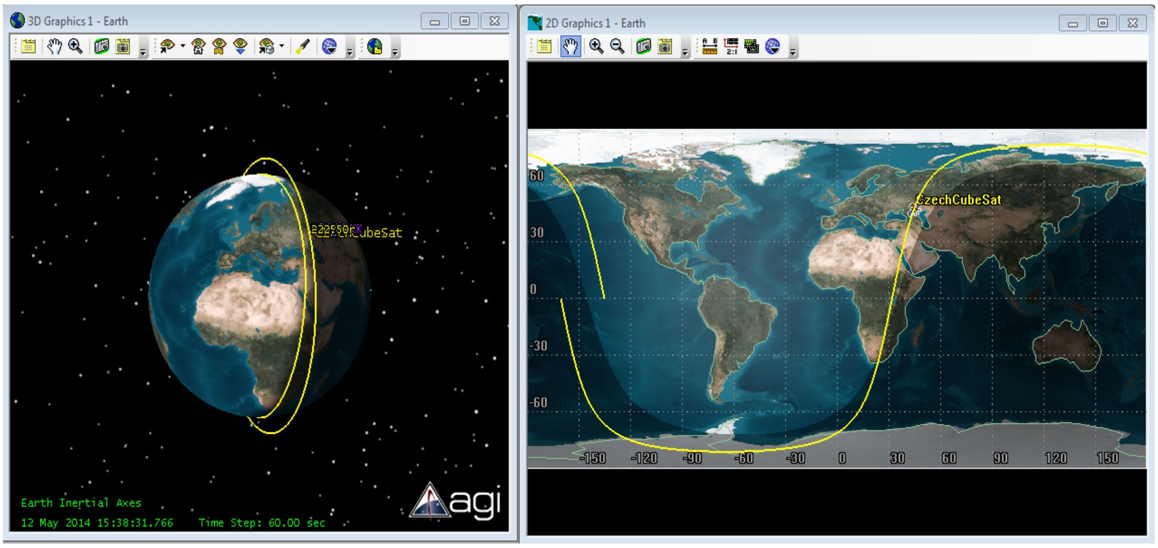

FIGURE 3.16: 3D (left) and 2D (right) graphic of sun-synchronous orbit

Chapter 4

Radio frequency and data transfer

4.1 Data transfer on XBee module

The XBee-PRO 868 RF Modules [?] were engineered to support the unique needs of low-cost, low-power wireless sensor networks. Our 868 MHz 500 mW long-range module which supports proprietary point-to-point and star, for use in Europe.

The XBee module provides a serial interface to an RF link. The XBee module can convert serial data to RF data that can be sent to any device in an RF network. In addition to RF data communication devices, the XBee module provides a software interface for interacting with a variety of peripheral functions, including I/O sampling, commissioning and management devices.

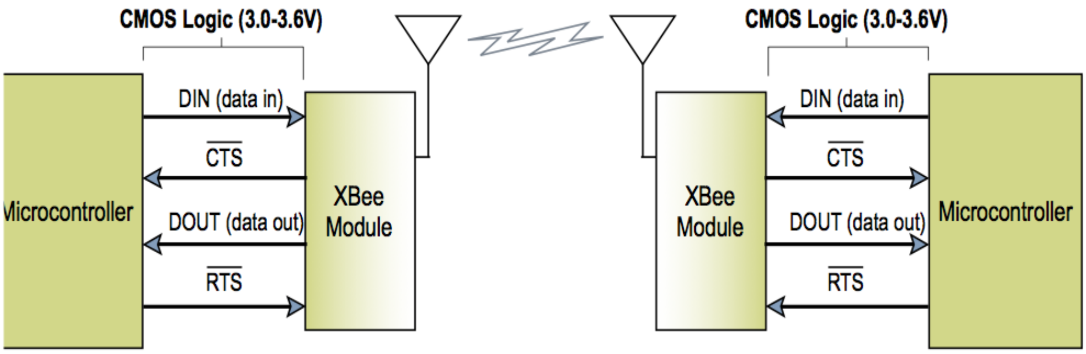

Figure 4.1: System Data Flow Diagram in a UART-interfaced environment

4.1.1 UART Data Flow

Devices that have a UART interface can connect directly to the pins of the RF module as shown in the Fig. 4.1.

4.1.2 Serial Buffers

The XBee-PRO modules maintain buffers to collect received serial and RF data, which is illustrated in the figure below. The serial receive buffer collects incoming serial characters and holds them until they can be processed. The serial transmit buffer collects data that is received via the RF link that will be transmitted out the UART.

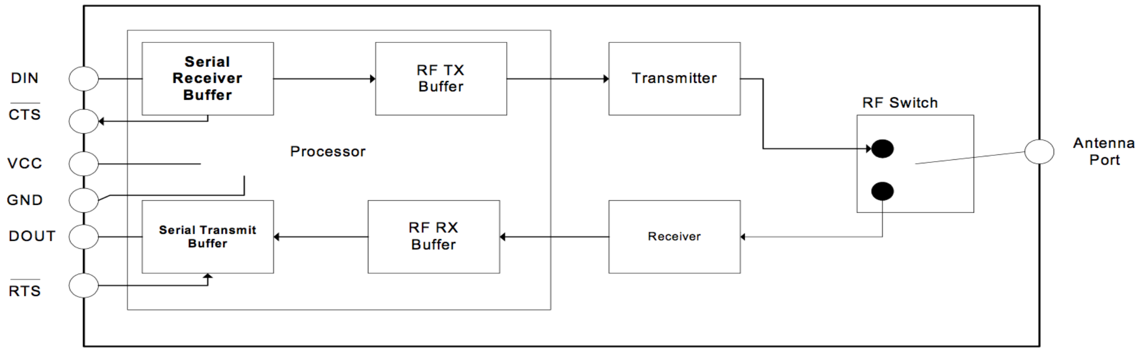

FIGURE 4.2: Internal Data Flow Diagram

4.1.3 Serial Flow Control

The $\overline{RTS}$ and $\overline{CTS}$ module pins can be used to provide $\overline{RTS}$ and/or $\overline{CTS}$ flow control. $\overline{CTS}$ flow control provides an indication to the host to stop sending serial data to the module. $\overline{RTS}$ flow control allows the host to signal the module to not send data in the serial transmit buffer out the UART. $\overline{RTS}$ and $\overline{CTS}$ flow control are enabled using the D6 and D7 commands.

4.1.3.1 $\overline{CTS}$ Flow Control

If $\overline{CTS}$flow control is enabled (D7 command), when the serial receive buffer is filled with FT bytes, the module de-asserts $\overline{CTS}$ (sets it high) to signal to the host device to stop sending serial data. $\overline{CTS}$ is re-asserted when less than FT - 16 bytes are in the UART receive buffer. (See command description for the FT command.)

4.1.3.2 $\overline{RTS}$ Flow Control

If $\overline{RTS}$ flow control is enabled (D6 command), data in the serial transmit buffer will not be sent out the DOUT pin as long as $\overline{RTS}$ is de-asserted (set high). The host device should not de-assert $\overline{RTS}$ for long periods of time to avoid filling the serial transmit buffer. If an RF data packet is received, and the serial transmit buffer does not have enough space for all of the data bytes, the entire RF data packet will be discarded.

4.1.4 Serial Interface Protocols

The XBee modules support both transparent and API (Application Programming Interface) serial interfaces. We will operate in transparent mode, the modules act as a serial line replacement. All UART data received through the DIN pin is queued up for RF transmission. When RF data is received, the data is sent out through the DOUT pin. The module configuration parameters are configured using the AT command mode interface.

Data is buffered in the serial receive buffer until one of the following causes the data to be packetized and transmitted:

- No serial characters are received for the amount of time determined by the RO (Packetization Time- out) parameter. If RO = 0, packetization begins when a character is received.
- The Command Mode Sequence (GT + CC + GT) is received. Any character buffered in the serial receive buffer before the sequence is transmitted.
- he maximum number of characters that will fit in an RF packet is received.

4.2 Operation of XBee module

The XBee supports both an AT and an API (Application Programming Interface) mode for sending and receiving data at your controller. Both have their advantages.

In AT Mode, also called Transparent Mode, just the message data itself is sent to the module and received by the controller. The protocol link between the two is transparent to the end user and it appears to be a nearly direct serial link between the nodes as illustrated previously in Fig. 4.3. This mode allows simple transmission and reception of serial data. AT Commands are used to configure the XBee.

In API Mode, we are not using while as needed to be mentioned here, the programmer packages the data with needed information, such as destination address, type of packet, and checksum value. Also, the receiving node accepts the data with information such as source address, type of packet, signal strength, and checksum value. The advantages are the user can build a packet that includes important data, such as destination address, and that the receiving node can pull from the packet information such as source address of the data. While more programming intensive, API Mode allows the user greater flexibility and increased reliability in some cases.

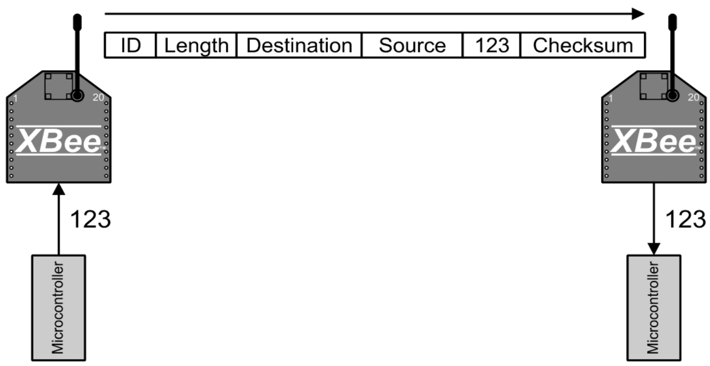

FIGURE 4.3: IPackaging Data for Delivery

4.2.1 Idle Mode

When not receiving or transmitting data, the RF module is in Idle Mode. During Idle Mode, the RF module is checking for valid RF data. The module shifts into the other modes of operation under the following conditions:

- Transmit Mode (Serial data in the serial receive buffer is ready to be packetized).
- Receive Mode (Valid RF data is received through the antenna).
- Command Mode (Command Mode Sequence is issued).

- Sleep Mode (A device is configured for sleep)

4.2.2 Transmit Mode

When serial data is received and is ready for packetization, the RF module will exit Idle Mode and attempt to transmit the data. The destination address determines which node(s) will receive the data. We are using broadcast in transmitting mode.

4.2.3 Receive Mode

If a valid RF packet is received, the data is transferred to the serial transmit buffer.

4.2.4 Command Mode

To Enter AT Command Mode, have to send the 3-character command sequence "+++" and observe guard times before and after the command characters. Default AT Command Mode Sequence (for transition to Command Mode):

- No characters sent for one second [GT (Guard Times) parameter = 0x3E8].
- Input three plus characters ("+++") within one second [CC (Command Sequence Character) parameter = 0x2B.].
- No characters sent for one second [GT (Guard Times) parameter = 0x3E8].

Once the AT command mode sequence has been issued, the module sends an "OK\r" out the DOUT pin. The "OK\r" characters can be delayed if the module has not finished transmitting received serial data.

4.2.5 Sleep Mode

Sleep modes allow the RF module to enter states of low power consumption when not in use. The XBee RF Modules support both pin sleep (sleep mode entered on pin transition) and cyclic sleep (Module sleeps for a fixed time).

4.2.6 Duty cycle

The duty cycle of this radio is 10 % averaged over the period of one hour. (six minutes). Meaning, if the next transmission will push the running average duty cycle over the 10% limit, the module will not transmit until enough time has elapsed to stay under the duty cycle.

Because of heat restraints in the module, a 10% duty cycle over the period of 1 second will be enforced after the measured temperature of the module rises above 60 degrees Celsius.

To overcome the Duty cycle, one method is to re-set XBee868 software, however, this usage must be assure the hardware component is under critical temperature in safety concern issues.

4.3 Initialize XBee module

Using Programmed micro-controller send AT command via UART to configure the XBee868 module.

4.3.1 The AT command set

The AT command set (Attached in Appendix F), also known as the Hayes command set, was originally developed for use with the Hayes modems in the 1980s. Many modern dialup modems are still based around this standard. The term AT command comes from the use of the ASCII characters AT to notify the host modem that a command will follow. These characters are sent before each command and were originally used as an abbreviation for the word attention.

When command mode has been entered, the command mode timer is started (CT command), and the module is able to receive AT commands on the DIN pin. All of the parameter values in the sequence can be modified to reflect user preferences. Send AT commands and parameters using the syntax shown below.

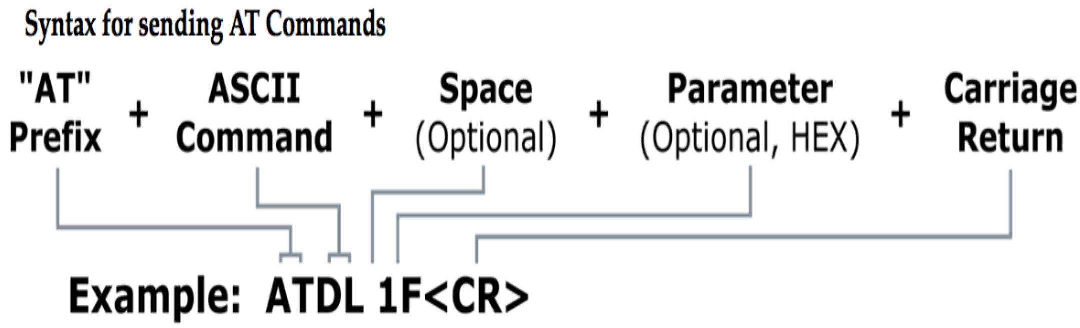

FIGURE 4.4: AT command syntax

4.3.2 XBee868 Addressing

For most applications, using the default settings will work best. We would test the connection both in broadcast and unicast configuration and have similar performance. As suggested by Digi technician, only using two radios, a broadcast is much easier to configure. A broadcast is DH=0, DL=FFFF, this is also the default configuration.

Broadcast:

- Configure DH = 0, DL=FFFF.
- Data is sent to all remote nodes.
- Data is actually sent 1+MT times (default would be 1+3).
- No acknowledgements are received, so the data is sent multiple times in the hopes that at least one will get through.
- RF traffic is consistant, we always know how many transmissions are made.

A Broadcast message is a message that will be received by all modules on any given ID. In 802.15.4 a Broadcast message is sent only once and not repeated, so there is no guarantee of any given node receiving the message. In order to send a Broadcast message set the DH=0x0 and the DL=0xFFFF. With these settings all XBee modules within range of the broadcasting node will receive the message.

The disadvantage of doing this configuration would be data reliability. But if our concern is telemetry data, it might be more beneficial to have instantaneous data (so that we know exactly what the balloon's status is) with a high amount of loss rather than receiving a unicast frame that might be a few seconds old because it was being retried so many times.

Unicast:

- Configure DH+DL = remote SH+SL.
- Data is sent to that remote address exclusively.
- If there is a failure, the radio will retry up to RR times (default is 10).
- If operating in API mode, you will receive an ACK frame back indicating success or failure in data transmission.
- Unicast has the potential of producing the highest amount of RF traffic.

A Unicast message is a more reliable method for delivering data. A Unicast message is sent from one module to any other module based on the module's addressing. If the message is properly received the receiving radio will send back an acknowledgment or ACK. If the transmitting module doesn't receive an ACK it will attempt MAC level retires (3 MAC level retires for every transmission for a total of 4 attempts) until it receives an ACK. This greatly increases the probability of getting the data through to the destination.

4.3.3 Flow control

The XB 868 uses a pool of memory to allocate to buffers and tables. The actual size is dynamic and it can grow to fit the given task at any one instant. The 868 is restricted to the 10% usage rule per channel, depending on your data usage that might appear to be unlimited. However it is not. The actual though put depends on how many channels you have assigned to be used at once and the baud rate of your transmissions. I've been strongly suggested the usage of Flow Control as the real data rate is highly dynamic. Hence we set up the Baud rate is 96000 bps and the XBee module keeps transmitting once it receives the data from OBC.

4.3.4 RSSI

RSSI (Received signal strength indication) indicators, which is possible to measure the received signal strength on a device using the DB command. DB returns the RSSI value (measured in -dBm) of the last received packet.

The DB value can be determined in hardware using the RSSI/PWM module pin (pin 6). If the RSSI PWM functionality is enabled (P0 command), when the module receives data, the RSSI PWM is set to a value based on the RSSI of the received packet. This pin could potentially be connected to an LED to indicate if the link is stable or not.

Chapter 5

Balloon Flight test and Antenna deployment

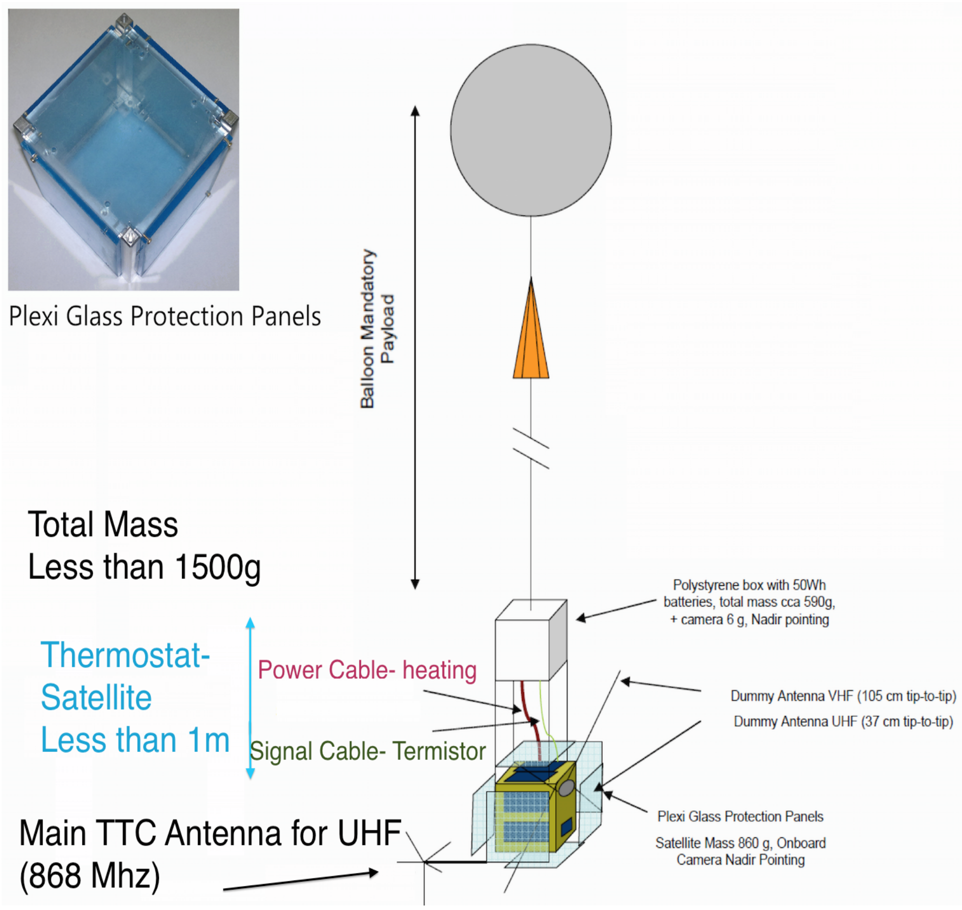

Figure 5.1: Ballon Flight

The first development steps of the CzechCubeSat project will be derived from the results of the stratospheric maiden flight test and subsystems' behavior. We expect telecommand-synchronized schedule for onboard data acquisition from the sensors (ADCS, EPS, OBC, and Color Camera). To characterize unexpected errors on the each board including solar panels.

Fig. 5.1 explains the model of structure for the balloon flight mission, the total mass has to be below 1500g, including the CubeSat and extra battery boxes segment (thermostat) and the Plexi glass protection to avoid solar panels contamination. The launch spot took place at 31st, May, in Partizanske of Slovakia. Detailed Balloon flight will be described in the end of this chapter. For telecommunication purpose, several antennas have to be introduced to achieve this technique.

5.1 Antennas Selection

During the whole projects period, two design phases have been introduced. One for ballon flight and eventual space flight for another. In terms of safety and reliability as first test experiment, we intend to implement ground plane antenna on the balloon platform attached with CubeSat. As usual, Yagi antenna will be assembled with ground station segment. For the future goal, two dipole antennas have to be applied to $TT\&C$ board, where as 145 MHz for uplink and 435 MHz for downlink purpose.

5.1.1 Dipole Antenna

In space flight telecommunication, we choose dipole antenna [**?**] or doublet, the simplest and most widely used class of antenna.It consists of two identical conductive elements such as metal wires, which are usually bilaterally symmetrical. The driving current from the transmitter is applied, or for receiving antennas the output signal to the receiver is taken, between the two halves of the antenna. Each side of the feed-line to the transmitter or receiver is connected to one of the conductors.

A simple dipole antenna can be used for improved FM broadcast signals. A dipole is basically a length of conductor (wire) split into two portions and signal is taken off at the split. It has a nominal 3 dB gain over an isotropic source and is directional, tending to favor signals broadside to the wire. The dipole is customarily an electrical half wavelength of wire at the frequency of interest, which shows in the Fig. 5.2, since the impedance under this condition is theoretically 72 ohms resistive and is a good match to a 50-75 ohm source or load generally presented by interfacing equipment such as receivers and transmitters designed to work into this range of impedances.

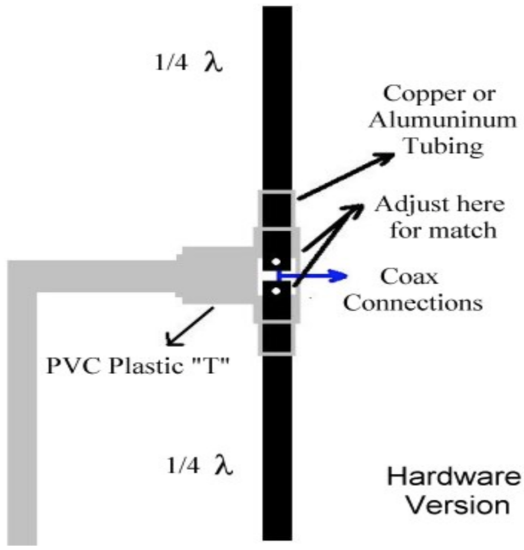

Figure 5.2: Dipole Antenna calculation

As the theory explained, the uplink frequency is chosen 145 Mhz VHF, so a quarter wavelength and the same as one leg of dipole is 49.2 cm long with 75 Ohm impedance together, while each leg of downlink dipole with 435 Mhz UHF is 16.46 cm long and having 50 Ohm impedance.

5.1.2 Ground Plane Antenna

In electrical engineering, a ground plane is an electrically conductive surface, usually connected to electrical ground. The term has two different meanings in separate areas of electrical engineering. In antenna theory, a ground plane is a conducting surface large in comparison to the wavelength, such as the Earth, which is connected to the transmitter's ground wire and serves as a reflecting surface for radio waves. In printed circuit boards, a ground plane is a large area of copper foil on the board which is

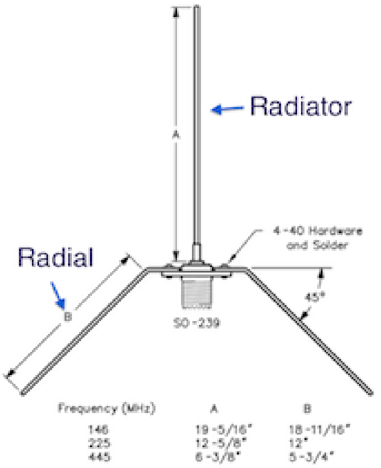

FIGURE 5.3: Ground Plane Antenna Display

connected to the power supply ground terminal and serves as a return path for current from different components on the board.

The quarter wavelength (extremely famous and very well described) GP Antenna (the Ground Plane Antenna) for 868 MHz (nadir pointing from balloon) will be done by 86mm thick and strong copper wire, tin and soldering station. Attached with SMA-R connector and UHF cable to the XBee on the CubeSat.

The display shows as Fig. 5.3. The Radiator should be made from grass rod, or copper wire, something you can easily solder into the center connector. The radials are mounted with screws and nuts soldering is not practical. Space the Radials evenly to form an X if looked down upon from the top. Bend the radials down at a 45° angle. The radials should be about 5% longer than the driven element. This isn't really very critical, so if you make them 90.3mm long, the antenna will work just fine.

5.1.3 Yagi Antenna

A Yagi-Uda array, commonly known simply as a Yagi antenna, is a directional antenna consisting of a driven element (typically a dipole or folded dipole) and additional parasitic elements (usually a so-called reflector and one or more directors). The reflector element is slightly longer (typically 5% longer) than the driven dipole, whereas the so-called directors are a little shorter. We select the 23 dB gain Yagi antenna in the ground station in order to achieve a very substantial long distance communication.

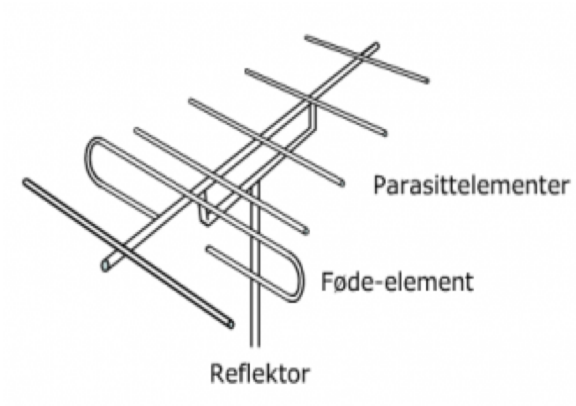

FIGURE 5.4: Yagi Antenna

Highly directional antennas such as the Yagi-Uda are commonly referred to as "beam antennas" due to their high gain. However, the Yagi-Uda design only achieves this high gain over a rather narrow bandwidth, making it useful for specific communications bands. Amateur radio operators frequently employ these on HF, VHF, and UHF bands, In the balloon flight, we intend to point Yagi antenna at long distance object in order to receive the highest RF power.

5.2 Antenna Deployment technique for the Space Flight

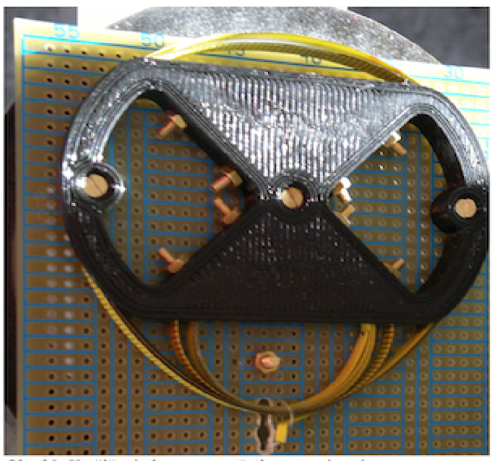

FIGURE 5.5: Antenna Holder

In the space flight mission, two amateur radio frequencies bandwidth will be used in uplink and downlink scheme (435 and 145 MHz respectively). Hence, two pairs of Dipo antenna will be mounted on the CubeSat, the meanwhile, antenna deployment technique has to be accomplished as well.

Fig. 5.5 interprets the optimal method for the antenna deployment. We will place this holder on one plate of CubeSat, the width of strip antenna is 3mm and suitable space for implementation is necessary to be considered, which means we have to compact other hardware and payload to save this space.

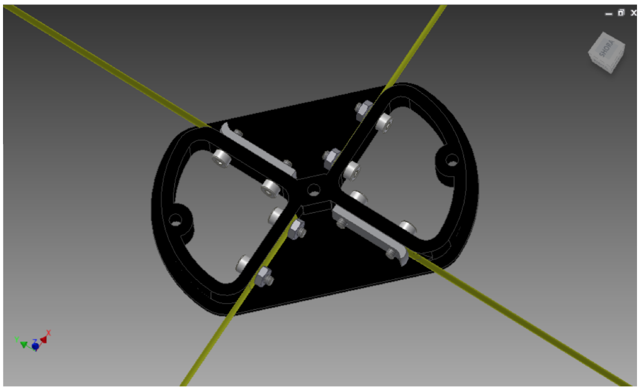

FIGURE 5.6: Antenna Deployment

The holder is facing towards one plate of CuteSat, and solar panel can be attached to its back side as well. The shorter strips are twisted in one side and the longer ones cover around them and ultimately locked by the temperature-sensitive wire and locked by heating resister. The resister will generate amount of heat after applying amount of current and will break the wire to deploy four antennas. Fig. 5.6 gives the 3-D model after deployment, and the Dual Band CubeSat Antenna Deployment Test video can be found on YouTube. Also, you will find more detailed discussion and technical data information from my colleague's master thesis [**?**].

5.3 Balloon Flight Test

The CzechTechSat 1U CubeSat including the MOSFET-free Space-grade Electrical Power Supply, Onboard Computer, Attitude Determination and Control Subsystem including Slot Sun Sensors, Magnetometer, 3-axis Gyroscopes, Magnetorquers and Reaction Wheel, World's First Low Power CubeSat GPS Receiver, Triple Junction Solar cells and Deployable VHF/UHF antenna has been launched into stratosphere on May 31,

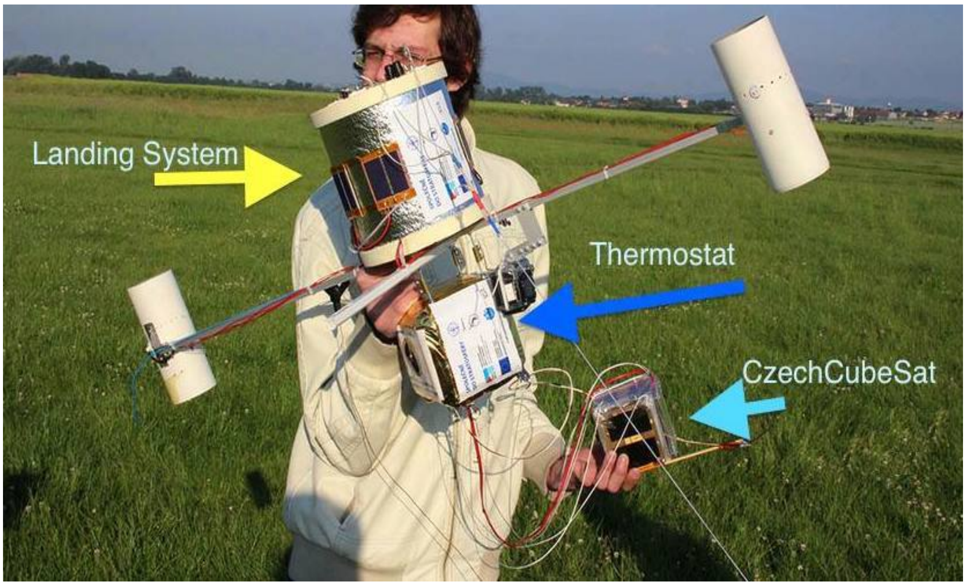

FIGURE 5.7: Ballon Flight Platform

2014 from the Partizanske Airport, west Slovakia. The video describes first seconds of the flight, liftoff of the 3.5 kg gondola. The flight was jointly organized with the Observatory in Valasske Mezirici, Observatory in Partizanske and the Czech Technical University, Faculty of Electrical Engineering, Dept. of Measurement / Space Lab.

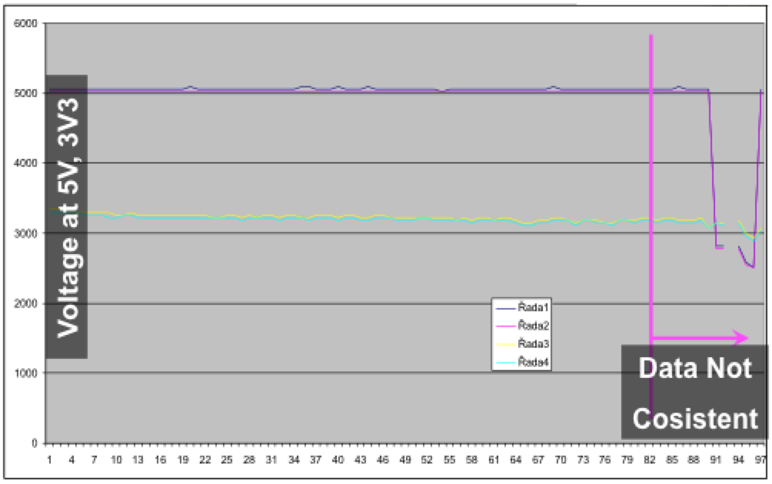

FIGURE 5.8: Power Supply before the Antenna Deployment

Fig. 5.7 is the pre-launch image, shows the landing system and our project thermostat and CzechCubeSat. The Launching video has been captured on electrically modified (stratospheric conditions protection) E-flite EFC-720 digital camera + 32 GB MicroSD card.

Fig. 5.8 interprets the voltages from EPS before the antenna deployment, it's obvious the power supply is all stable just right after the heating system consume lots of power from EPS and we can see the voltage drop in the end of this plots on both 5 V supply and little wobble on 3.3 V curve. Because of this, OBC was switched off due to low power supply and restarted again, unfortunately we lost all the data prior to this time point.

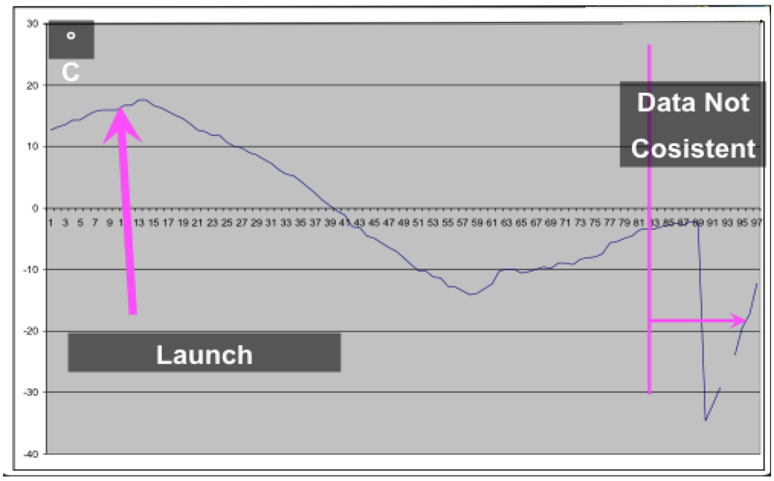

FIGURE 5.9: Temperature before the Antenna Deployment

Together with the stage of CTS climbing gave the temperature where inside the CubeSat was determined as $-14\,°C/-2\,°C$ and stabilized by internal thermostat.

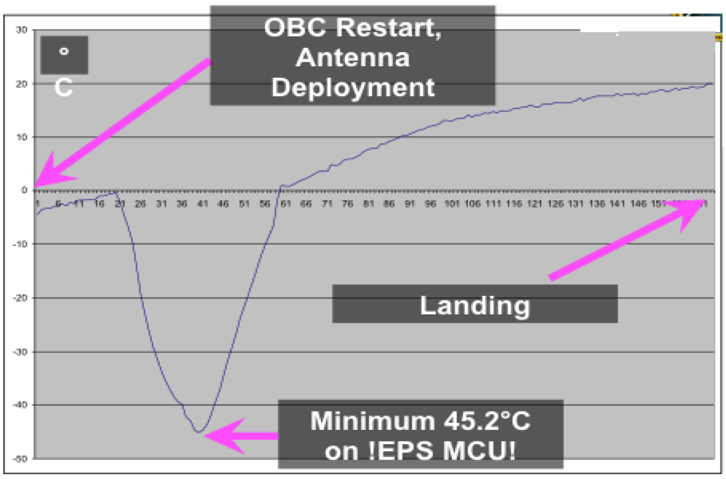

FIGURE 5.10: Temperature after the Antenna Deployment

Fig. 5.9 shows the temperature before the antenna deployment, as beginning the temperature sensor on the Micro-controller give approximately $12\,°C$ and increase a bit because we were holding the unit in hand, after launching and along with the altitude ascent, the temperature decreased till −14 °C and Thermostat started working and heating the CubeSat while up to −2 °C then switched off.

After antenna deployment, Fig. 5.10 tells the temperature on Micro-controller sensor went down to −45.2 °C and system all working well. Clearly the deployment really cause much power supply consumption.

The most significant test is the dipole antenna deployment, in this video you can hear the squelch opened immediately after the antenna was released, Fig. 5.11 is the snapshot of the CzechTechSat Dual Band Antenna was deployed upon Telecommand at the altitude of 28200 meters / 92500 ft. after the release the Telemetry data on the mobile ground station showed the full deployment status was successful via extra pins header.

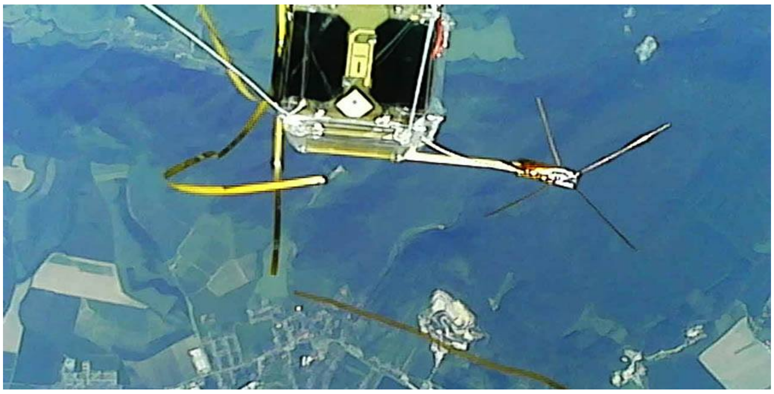

FIGURE 5.11: Dipole Antenna Antenna Deployment

The final landing approach was quite lucky too as it ascended on the tree branches, fully protected our CubeSat. And ultimately we received 376 kB of telemetry data through the TT&C board.

The full video links will be attached in the Appendix A.

Chapter 6

Conclusion and Future Development

6.1 Conclusion

It was my big honor to participate in the CzechTechCubeSat research group, we've done the Magnetic Levitation equipment last summer for attitude control and this year I've been working on the TT&C subsystem design as my Master thesis.

With the time constrains I won't finalize the advanced TT&C board, also the bandwidth registration issue. Regarding to the robust performance and functionality of each subsystem on the CubeSat for the future Space Flight, we will have chance to test in Balloon Flight mission. In a short aim, we decide to construct simple version TT&C board by using XBee-PRO 868 commercial component as transceiver, which can support RF line-of-sight distance up to 80 km and only for use in Europe with free-registered 868 MHz frequency.

To set up the XBee868 module, I applied AT transparent mode, which allows simple transmission and reception of serial data. AT command is for XBee configuration. The big disadvantage of this module is the duty cycle (10 min per hour), in order to consume the least RF power I chose broadcast address scheme and put Broadcast Multi-Transmit as zero so only to send actually data once. I didn't use flow control since XBee uses a pool of memory to allocate to buffers and tables, the actual size is dynamic and it can grow to fit the given task at any one instant. The Baud rate is 9600 bps. I kept most features as default value as it's already optimal. Duty cycle and Received signal strength indication can be written from Diagnostics AT Command, nevertheless, to enter the Command Mode, the process takes at least 3 seconds and won't be efficient, we use Analog-To-Digital function of Micro-controller to read out from RSSI/PWM module pin from XBee868. Due to the single bandwidth, we implemented the quarter wavelength Ground Plane antenna on the CubeSat. Because lack of SMA-R connector, the handmade GP antenna with a soldering board and duct tape instead,which works pretty well in the test. Total output of +25 dBm is sufficient to keep the link connected during the whole flight.

My colleague designed the Ground Station segment, which used the XBee868 as transceiver also connected with 23 dB Yagi anttenna. The most critical task is to program the data processor. We used interrupt function of micro-controller, whatever the data XBee received all send back to Laptop via UART and parse the data. The stratospheric flight was organized in co-operation with the Observatory in Valasske Mezirici, Observatory in Partizanske and the Czech Technical University, Faculty of Electrical Engineering, Dept. of Measurement / Space Lab. During the flight we received 376 kB telemetry data, which including the battery status, altitude condition, internal temperature and realized one telecommand control to release the dipole antenna, we measured extra pin header and the status showed the deployment was successful too.

I already started designing updated TT&C board with Eagle Cad software. Low Noise Amplifier is already done for reception. The future task is to draw the power amplifier circuit on the schematic board for transmission purpose. Also to initialize the ADF transceiver and to implement suitable protocol for telecommunication. The meantime, registration for the 145 and 435 MHz dual bandwidth has to be accomplished as well.

6.2 Space Flight

The first Space-friendly spacecraft is assumed to be launched into space onboard the Long March 2-D launch vehicle in the autumn 2015.

The Long March 2D, also known as the Chang Zheng (as Chinese) 2D, CZ-2D and LM-2D, is a Chinese orbital carrier rocket, which can launch Payloads of up to 3,500

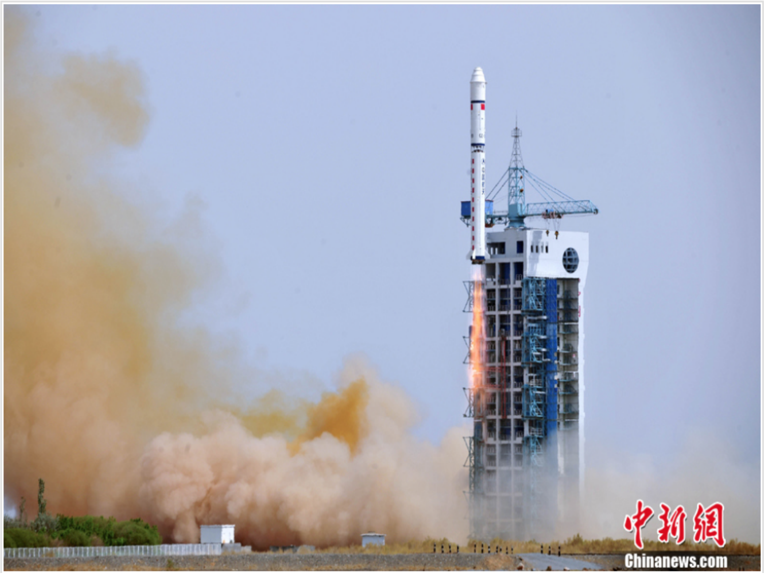

FIGURE 6.1: Long March 2-D

Kilograms to Low Earth Orbit and has a SSO capability of up to 1,300kg. The CZ-2D Launcher was developed by the Shanghai Academy of Spaceflight Technology and is capable of delivering payloads into a variety of Orbits, including Low Earth Orbit and Sun Synchronous Orbit.

Appendix A: The CzechCubeSat Project Channel

– ADCS Test in MagLev:

www.youtube.com/watch?v=3e2RwD_UHxQ

(Please notice the underline when copy the link)

– Dual Band CubeSat Antenna Deployment Test:

https://www.youtube.com/watch?v=nuWM5EsRmnU

– 33 km / 108k ft CzechTechSat Stratospheric Balloon Test Flight - Launch Video:

https://www.youtube.com/watch?v=9i2wwzpiKXo

– Full Video (1 of 11) - CzechTechSat Stratospheric Balloon Test Flight - Liftoff:

https://www.youtube.com/watch?v=agK2hc2f3Go

– Full Video (2 of 11) - CzechTechSat Stratospheric Balloon Test Flight - Climbing:

https://www.youtube.com/watch?v=bkqIPC8xs9k

– Full Video (3 of 11) - CzechTechSat Stratospheric Balloon Test Flight - Climbing:

https://www.youtube.com/watch?v=2T_E8gwtL14

(Please notice the underline when copy the link)

– Full Video (4 of 11) - CzechTechSat Stratospheric Balloon Test Flight - Climbing:

https://www.youtube.com/watch?v=ge_evfUE1Vk

(Please notice the underline when copy the link)

– Full Video (5 of 11) - CzechTechSat Stratospheric Balloon Test Flight - Climbin:

https://www.youtube.com/watch?v=-GEoh85B1hQ

– Full Video (6 of 11) - CzechTechSat Stratospheric Balloon Test Flight - Climbin:

https://www.youtube.com/watch?v=BEE7lfi3daQ

– **Full Video (7 of 11) - Successful CzechTechSat Antenna Deployment at 28,2 km / 92.5k ft:**
https://www.youtube.com/watch?v=ouUdCifjCek

– **Full Video (8 of 11) - Operation with Deployed Antenna & Climbing to the Top Altitude:**
https://www.youtube.com/watch?v=rBN5icwJuc4

– **Full Video (9 of 11) - Free Fall CzechTechSat Re-Entry from the Edge of Space 33 km / 108k ft:**
https://www.youtube.com/watch?v=Upcje_iw01Y *(Please notice the underline when copy the link)*

– **Full Video (10 of 11) - CzechTechSat Parachute Re-Entry from the Edge of Space 33 km / 108k ft:**
https://www.youtube.com/watch?v=6aEsS3EOqcE

– **Full Video (11 of 11) - Successfull CzechTechSat Final Approach & Landing:**
https://www.youtube.com/watch?v=4pRQ8stFd0E

Appendix B: Magnetic Field Lines of the Earth

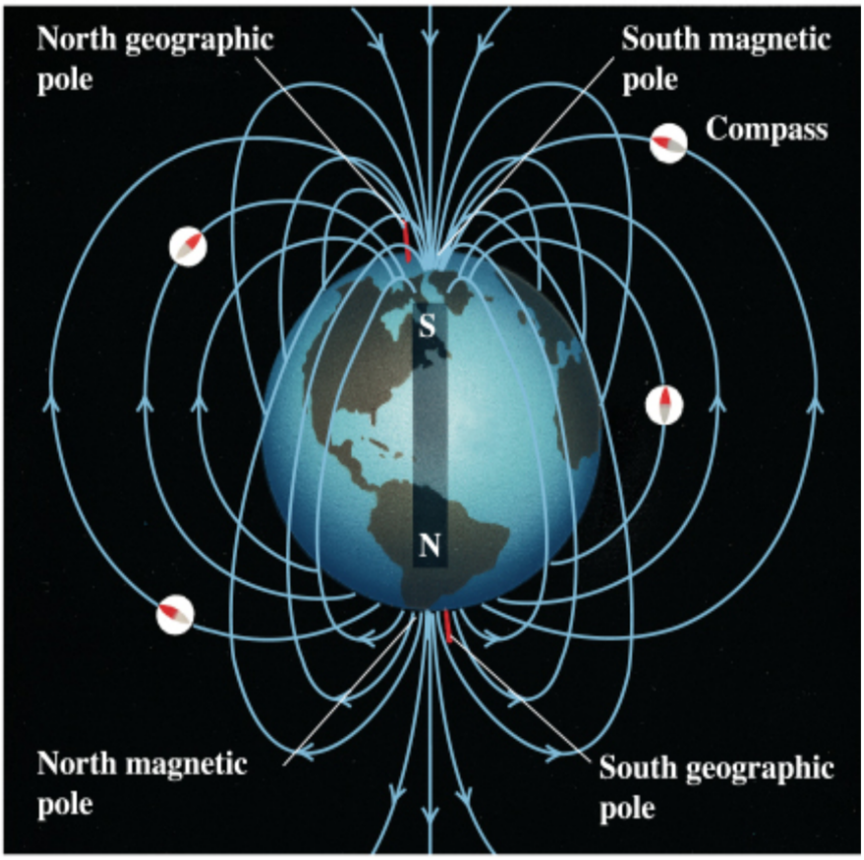

Figure 2: Earth Magnetic Field

Appendix C: Schematic Diagram of TT&C Board based on XBee868

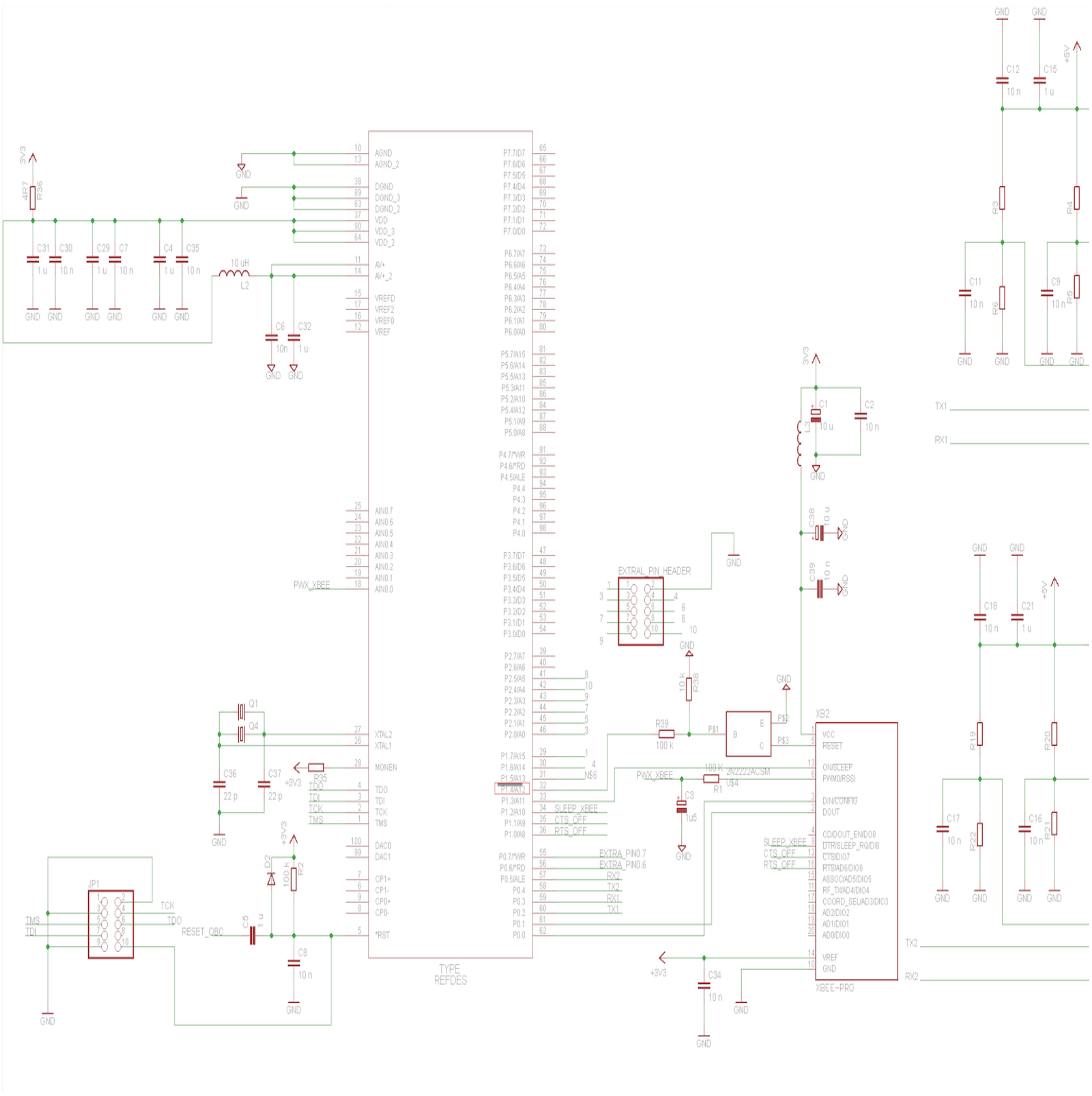

FIGURE 3: XBee Module part 1

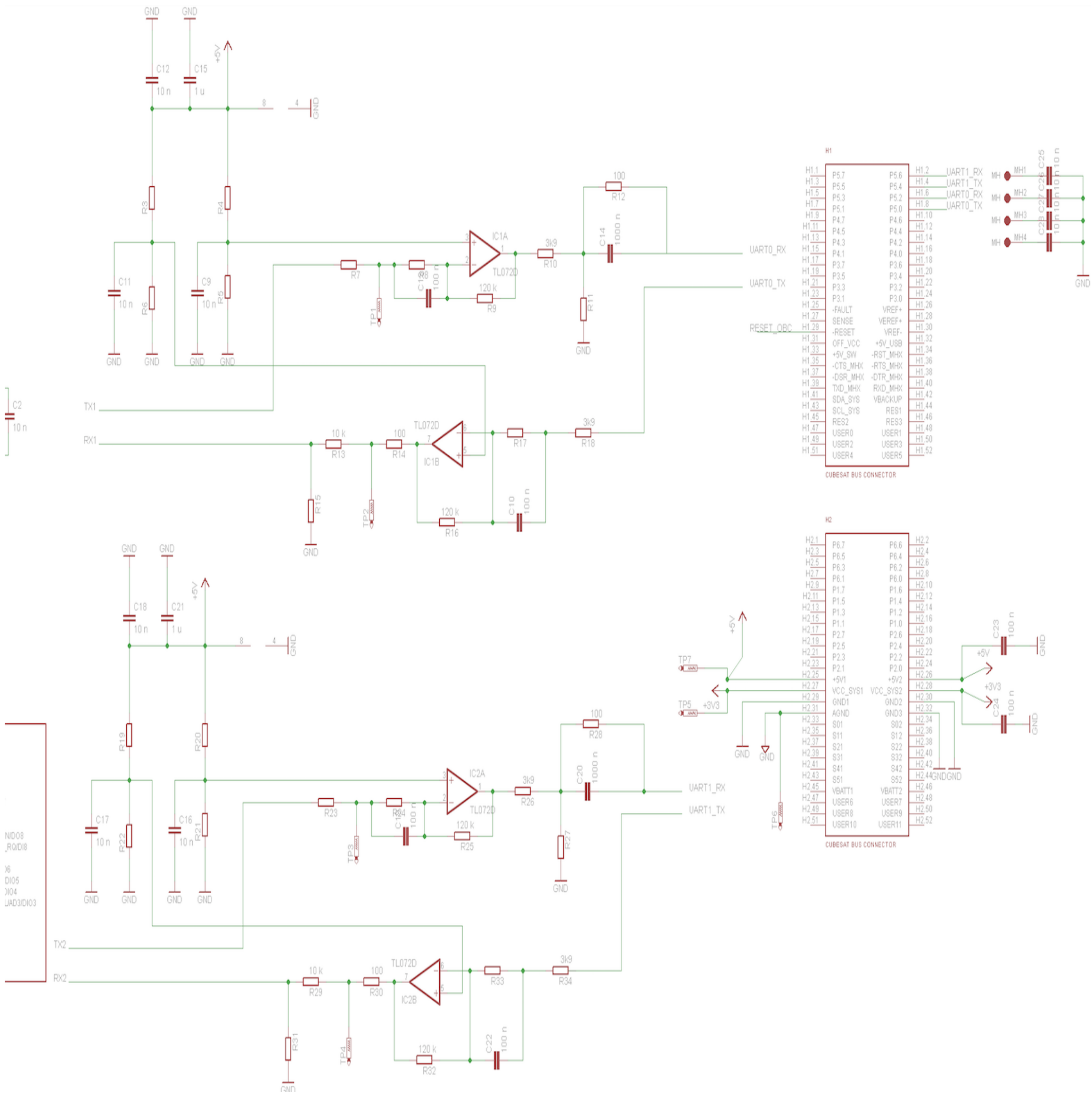

FIGURE 4: XBee Module part 2

Appendix D: Schematic Diagram of GS

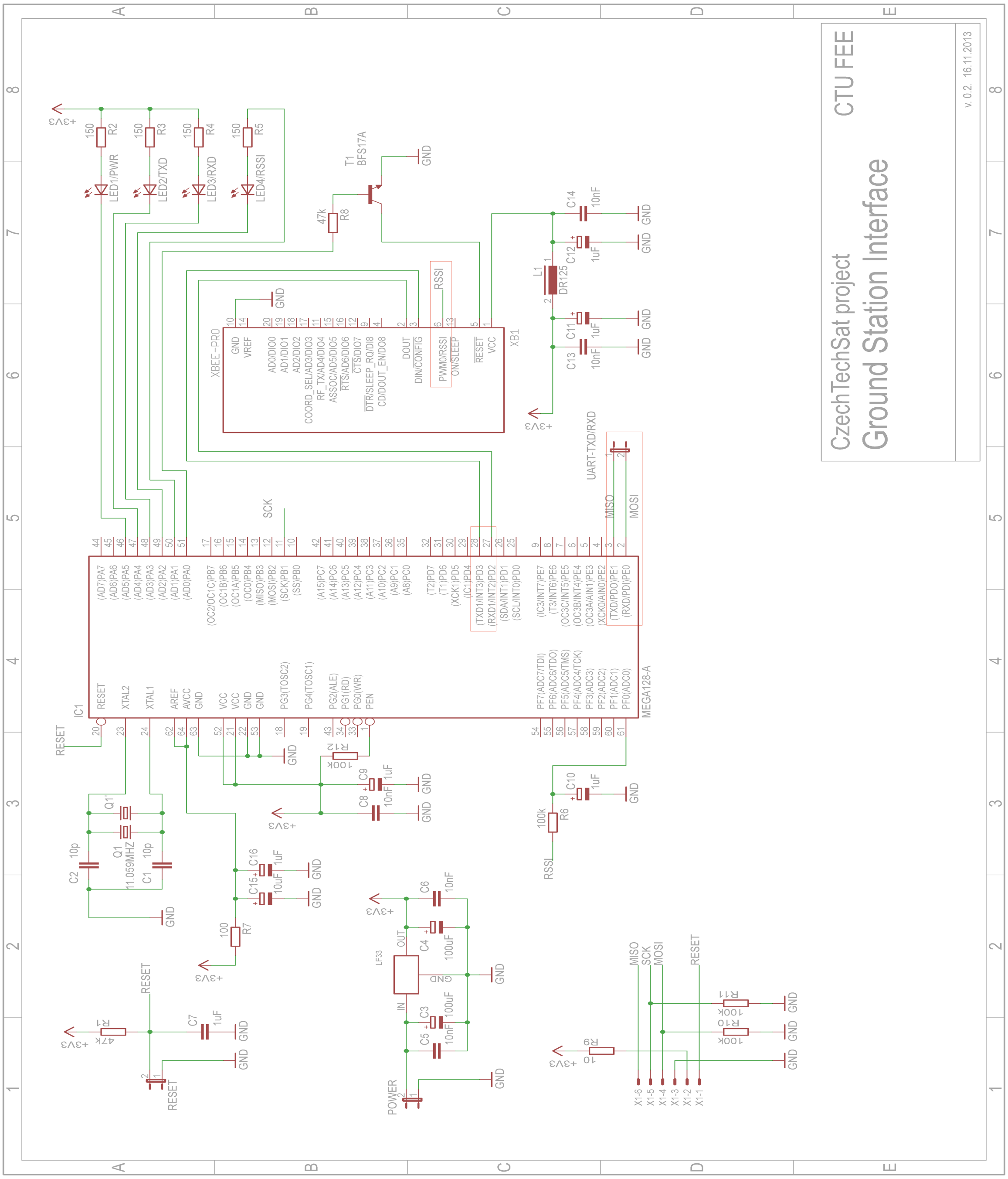

FIGURE 5: Schematic Diagram of GS

Appendix E: Low Noise Amplifier Schematic Board

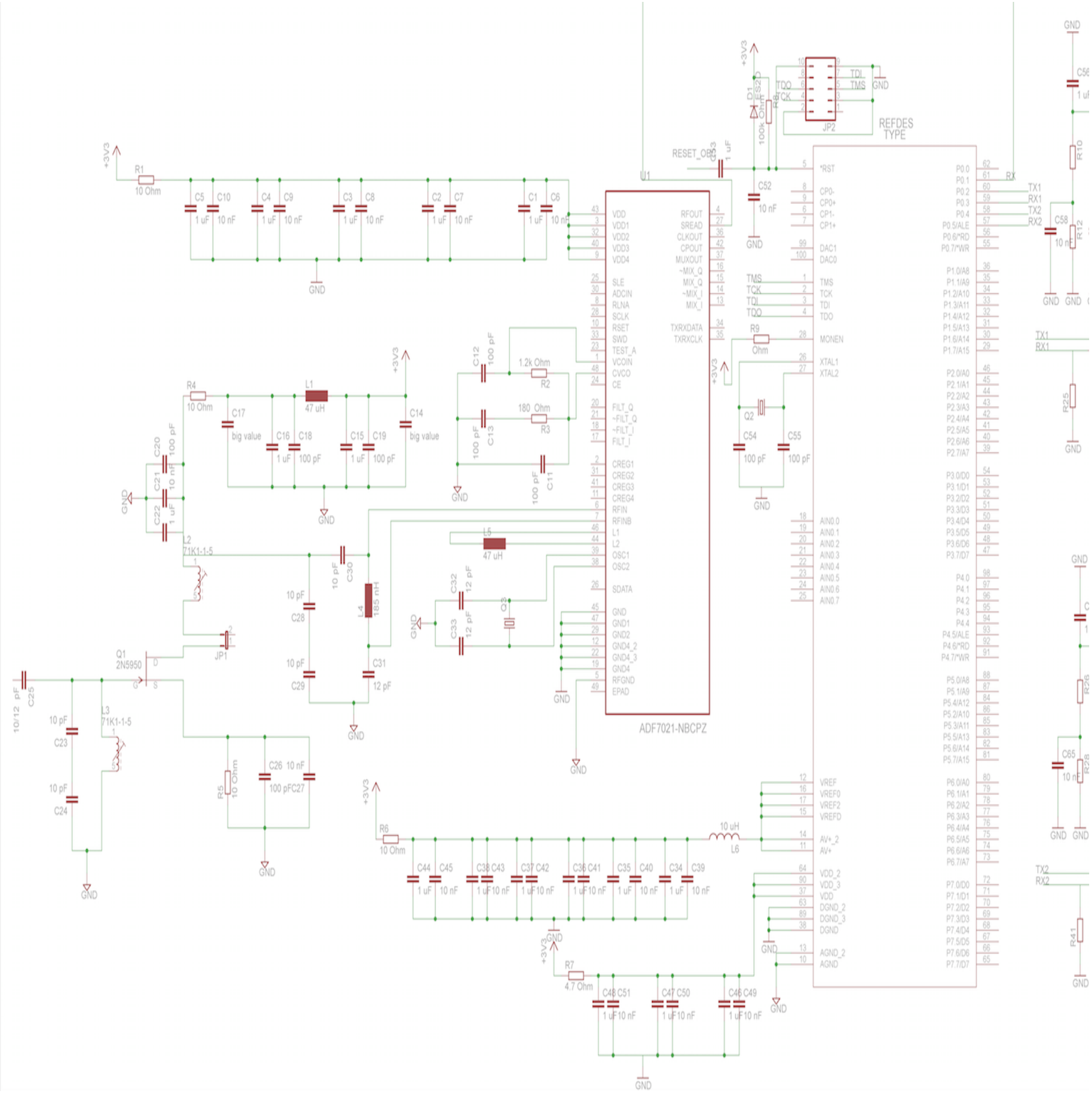

FIGURE 6: LNA part 1

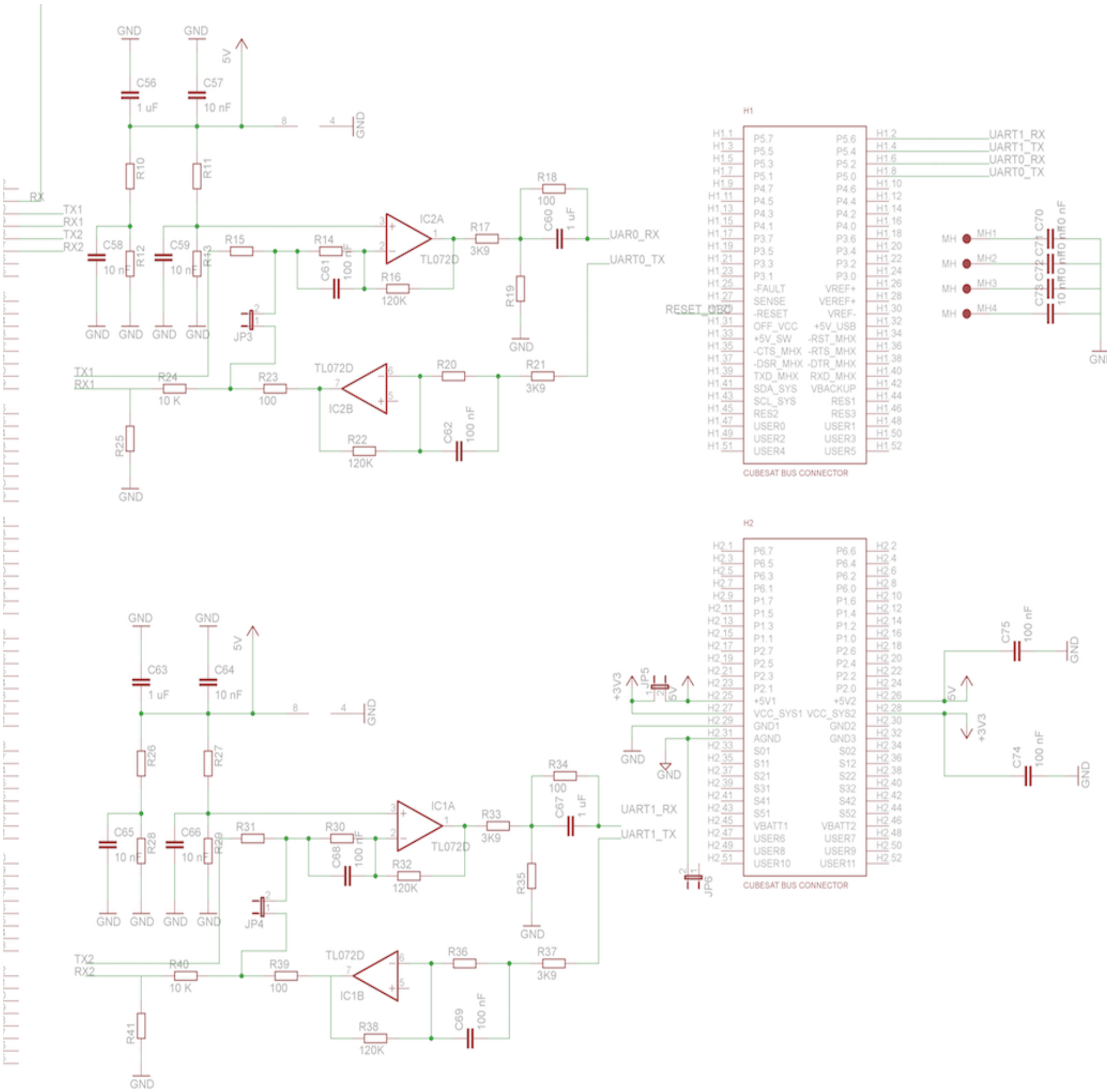

Figure 7: LNA part 2

Appendix F: AT Commands

AT Command Options

AT Command Options Commands

AT Command	Name and Description	Parameter Range	Default
CT	**Command Mode Timeout.** Set/Read the period of inactivity (no valid commands received) after which the RF module automatically exits AT Command Mode and returns to Idle Mode.	2-0x1770	0x64 (100d)
CN	**Exit Command Mode.** Explicitly exit the module from AT Command Mode.	--	--
GT	**Guard Times**. Set required period of silence before and after the Command Sequence Characters of the AT Command Mode Sequence (GT + CC + GT). The period of silence is used to prevent inadvertent entrance into AT Command Mode.	0 to 0xFFFF	0x3E8 (1000d)
CC	**Command Character**. Set or read the character to be used between guard times of the AT Command Mode Sequence. The AT Command Mode Sequence causes the radio modem to enter Command Mode (from Idle Mode).	0 - 0xFF	0x2B

Figure 8: AT Command Options

Addressing

Addressing Commands

AT Command	Name and Description	Parameter Range	Default
DH	**Destination Address High**. Set/Get the upper 32 bits of the 64-bit destination address. When combined with DL, it defines the destination address used for transmission.	0 to 0xFFFFFFFF	0
DL	**Destination Address Low**. Set/Get the lower 32 bits of the 64-bit destination address. When combined with DH, DL defines the destination address used for transmission.	0 to 0xFFFFFFFF	0x0000FFFF
DD	**Device Type Identifier.** Stores a device type value. This value can be used to differentiate multiple XBee-based products.	0-0xFFFFFFFF [read only]	0x40000
SH	**Serial Number High**. Read high 32 bits of the RF module's unique IEEE 64-bit address. 64-bit source address is always enabled. This value is read-only and it never changes	0-0xFFFFFFFF	Factory
SL	**Serial Number Low**. Read low 32 bits of the RF module's unique IEEE 64-bit address. 64-bit source address is always enabled. This is read only and it is also the serial number of the node..	0-0xFFFFFFFF	Factory
SE	**Source Endpoint**. Set/read the application layer source endpoint value. This value will be used as the source endpoint for all data transmissions. The default value 0xE8 (Data endpoint) is the Digi data endpoint	0-0xFF	0xE8
DE	**Destination Endpoint**. Set/read application layer destination ID value. This value will be used as the destination endpoint for all data transmissions. The default value (0xE8) is the Digi data endpoint.	0-0xFF	0xE8

Figure 9: Addressing Commands

Special

Special Commands

AT Command	Name and Description	Parameter Range	Default
WR	**Write**. Write parameter values to non-volatile memory so that parameter modifications persist through subsequent resets. Note: Once WR is issued, no additional characters should be sent to the module until after the "OK\r" response is received.	--	--
RE	**Restore Defaults**. Restore module parameters to factory defaults.	--	--
FR	**Software Reset**. Reset module. Responds immediately with an "OK" then performs a reset 100ms later.	--	--
AC	**Apply Changes**. Immediately applies new settings without exiting command mode.	--	--
R1	**Restore Compiled**. Restore module parameters to compiled defaults.	--	--
VL	**Version Long**. Shows detailed version information including application build date and time.	--	--

Figure 10: Diagnostics Commands

Diagnostics

Diagnostics Commands

AT Command	Name and Description	Parameter Range	Default
VR	**Firmware Version**. Read firmware version of the module.	0 - 0xFFFFFFFF [read-only]	Firmware-set
HV	**Hardware Version**. Read hardware version of the module.	0 - 0xFFFF [read-only]	Factory-set
CK	**Configuration Code**. Read the configuration code associated with the current AT command configuration.The code returned can be used as a quick check to determine if a node has been configured as desired.	0-0xFFFFFFFF	n/a
ER	**RF Errors**. Read the number of times a packet was received which contained integrity errors of some sort. When the value reaches 0xFFFF, it stays there.	n/a	n/a
GD	**Good packets**. Read the number of good frames with valid MAC headers that are received on the RF interface. When the value reaches 0xFFFF, it stays there.	n/a	n/a
RP	**RSSI PWM timer**. Set or read the time that the RSSI output (indicating signal strength) will remain active after the last reception. Time units are measured in tenths of seconds	1 to 0xff	0x20 = 3.2 seconds
TR	**Transmission Errors**. Read the number of MAC frames that exhaust MAC retries without ever receiving a MAC acknowledgement message from the adjacent node. When the value reaches 0xffff, it stays there.	n/a	n/a
TP	**Temperature.** Read module temperature in Celsius. Negatives temperatures can be returned.	0xff74 to 0x0258	n/a
DB	**Received Signal Strength.** This command reports the received signal strength of the last received RF data packet. The DB command only indicates the signal strength of the last hop. It does not provide an accurate quality measurement for a multihop link. The DB command value is measured in -dBm. For example if DB returns 0x60, then the RSSI of the last packet received was -96dBm.	n/a	n/a
DC	**Duty Cycle**. Returns a current usage percentage of the 10% duty cycle. This is measured over the period of 1 hour. For example, if the radio had averaged 2% duty cycle, then this would return 20%	0 - 0x64	-
RC	**RSSI for channel**. Reads the dBm level of the designated channel.	0	n/a
R#	**Reset number**. Tells the reason for the last module reset. 0 = Power up reset 2 = Watchdog reset 3 = Software reset 4 = Reset line reset 5 = Brownout reset	n/a	0
TA	**Transmit Acknowlegement Errors**. Incremented once for each failed ack retry.	0 - 0xFFFF	0
%V	**Supply Voltage.** Reads the voltage on the Vcc pin in mV. Read module voltage in millivolts.	0-0x/F00	n/a

Figure 11: Diagnostics Commands

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