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ESTCube-1 satellite beacon

Master's Thesis in Computer Engineering (30 ECTS)

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1 Table of Contents

2 List of acronyms

Acronyms and abbreviations that are used in this document:

- ADC – Analog digital converter
- ADCS – Attitude and Determination Control subsystem
- CAM – Camera subsystem
- COM – Communications subsystem
- CDHS – Command and Data Handling subsystem
- CW – Continuous wave modulation
- dBi – Antenna gain increase compared to isotropic radiator
- Eb / N0 – Bit energy to noise ratio
- EIRP – Effective isotropic radiated power
- ESAIL - Electric Solar Wind Sail
- EPS – Electrical Power subsystem
- FEC – Forward error correction
- Flash – Flash memory
- FSK – Frequency shift keying
- GS – Ground station
- IARU – International Amateur Radio Union
- I^2C – Inter-integrated circuit
- IF – Intermediate frequency
- ITU – International Telecommunication Union
- JT4 – 4 level narrowband FSK with FEC encoding
- LEO – Low Earth orbit
- MCU – Microcontroller unit
- PCB – Printed circuit board
- RAM – Random access memory
- RF – Radio frequency
- TBD – To be decided in the next satellite development phase
- TCS – Thermal Control subsystem
- UHF – Ultra high frequency range
- WPM – Words per minute, one word-unit equals 5 characters

3 Introduction

ESTCube-1 shall be the first Estonian satellite to be launched in 2012. The mission has innovative scientific and educational objectives.

The goal of ESTCube-1 satellite is to successfully deploy a single 10 meter long Hoytether structure in low Earth orbit using centrifugal force. The successful tether deployment is needed to demonstrate critical technologies for a full-scale Electric Solar Wind Sail (ESAIL) test mission in the future.

The concept of ESAIL has potential to become one of the most efficient space propulsion technologies. It is based on the interaction between the positively charged particles in the solar wind with the positively charged tether net deployed from a satellite. Each tether is a four-fold Hoytether structure so it can be made very light but the whole structure shall retain the durability that is needed in a space environment. The concept was proposed by Pekka Janhunen from Finnish Meteorological Institute in 2006 [1].

ESTCube-1 is being developed by students from the University of Tartu and Tallinn University of Technology in tight cooperation with international partners from Finland (Finnish Meteorological Institute, University of Helsinki, Jyväskylä University) and Germany (DLR Bremen).

ESTCube-1 communications subsystem (COM) is responsible for the communication between a ground station (GS) and the spacecraft. It can receive telecommands from the GS for setting different operating modes and requests to transmit data. There are two different types of downlink transmission modes:

- LPTM - Low Power Transmission Mode (Beacon)
- HPTM - High Power Transmission Mode (Data)

The beacon is used for tracking the satellite and to get a simple overview of the satellite's status. The beacon data contains a small subset of telemetry data that is transmitted periodically in Morse code.

The HPTM is used for transmitting large amounts of mission data. This consists of telemetry data from each subsystem and the experiment data, for example a picture taken by the camera. HPTM is turned on only after receiving a certain telecommand.

The main goals of the current work were to:

- Analyze other CubeSat projects beacon implementations
- Analyze requirements for ESTCube-1 beacon
- Determine optimal parameters for ESTCube-1 beacon:
    - Output power
    - Transmission period
    - Modulation
    - Beacon data
    - Operating frequency
- Propose a beacon design for ESTCube-1
- Analyze operational risks of the beacon design
- Develop beacon radio frequency (RF) electronics prototype
- Measure the output parameters of the prototype
    - Signal purity
    - Signal strength
    - On / off signal ratio

The work consists of ten Chapters. In Chapter 4, an overview of other CubeSat projects beacon implementations is given to see different solutions that are currently operational on orbit. Chapter 5 describes ESTCube-1 satellite in more detail with focus on COM subsystem.

Chapter 6 analyzes requirements for developing a satellite beacon. Based on that analysis a beacon design is proposed in Chapter 7. Chapters 6 and 7 form the main body of the work. Chapter 8 describes the beacon radio frequency electronics prototype development and measurement analysis.

In Chapter 9, the results of this work are discussed and future activities are proposed. In Chapter 10, most important of these results are concluded and the completion of goals is assessed.

4 Overview of other CubeSat projects and their beacon implementations

Large majority of other CubeSat projects have implemented a radio beacon on-board their satellite in addition to the primary downlink channel. Four case studies of different CubeSat beacon implementations have been made, overview is given in four following subsections. Main objective of these case studies is to analyze the technical parameters such as modulation, output power and transmission speed and the contents of beacon data.

4.1 Compass-1

Compass-1 is Aachen University's first satellite, it was launched in the spring of 2008 [2].

Technical details of Compass-1 beacon are:

- Frequency band: 70 cm (437.275 MHz)
- Output power: 100 mW
- Transmission speed: 15 words per minute (WPM)
- Transmission mode: Continuous wave modulation (CW)
- Transmission start interval of:
  - 3 minutes in normal operating mode
  - 8 minutes in power save mode

Satellite orbital parameters are:

- Sun-synchronous polar orbit
- Height 630 km
- Inclination 98°

Beacon data contains:

- Satellite name
- Solar cells voltage
- Solar panel current
- EPS reset counter
- Power level
- Heater active
- Powersafe counter
- Emergency mode counter
- Battery voltage
- Battery current
- Battery temperature

4.2 XI-IV

XI-IV was built by University of Tokyo, it was launched it was launched with the first batch of CubeSats in 2003 [3].

Technical details of XI-IV beacon are:

- Frequency band: 70 cm (436.8475 MHz)
- Output power: 100 mW
- Transmission speed: 50 WPM
- Transmission mode: CW
- Transmission interval: continuous

Satellite orbital parameters are:

- Sun-synchronous polar orbit
- Height 830 km
- Inclination 98^{o}

Beacon data contains:

- Web site address of University of Tokyo
- Time information
- General status information
- On-board computer status
- COM hardware status
- Received signal strength indicator
- Battery voltage
- Information about solar panels
- Battery temperature

4.3 XI-V

XI-V was built by University of Tokyo, it was launched it was launched with the second batch of CubeSats in 2005 [3].

Technical details of XI-V beacon are:

- Frequency band: 70 cm (437.465 MHz)
- Output power: 80 mW
- Transmission speed: 50 WPM
- Transmission mode: CW
- Transmission interval: continuous

Satellite orbital parameters are:

- Sun-synchronous polar orbit
- Height 700 km
- Inclination 98°

Beacon data contains:

- Satellite name
- Time information
- Different status information, for example:
  - Charge status
  - On-board computer survival status
  - Data sending status
- Received signal strength indicator
- Battery voltage
- Solar array voltage
- Battery temperature
- Solar array current
- Solar array temperature
- FM transmitter temperature
- Configurable message from on-board computer

4.4 Cute-1

Cute-1 was built by Tokyo Institute of Technology in Japan, it was launched with the first batch of CubeSats in 2003 [4].

Technical details of Cute-1 beacon are:

- Frequency band: 70 cm (436.8375 MHz)
- Output power: 100 mW
- Transmission speed: 50 WPM
- Transmission mode: CW
- Transmission interval: continuous

Satellite orbital parameters are:

- Sun-synchronous polar orbit
- Height 830 km
- Inclination 98°

Beacon data contains:

- Satellite name
- Receiver S-meter reading
- Solar panel voltage
- Battery voltage
- Battery current
- Different status information, for example:
    - FM transmitter status, transmission protocol, packet interval
    - Operating mode
    - Memory status
    - Experiment status
    - Antenna deployment status
    - Sun sensor power status
    - Sun sensor operating mode
- Sun sensor information
- Battery temperature
- COM subsystem temperature

5 Overview of ESTCube-1 satellite

ESTCube-1 shall be designed according to the CubeSat standard. It shall be a single unit CubeSat with dimensions 100 x 100 x 113.5 mm^3 and mass up to 1.33 kg [5].

The satellite body consists of the main frame and side panels that are attached to the main frame. All 6 side panels shall have solar cells and one side panel shall include the antenna deployment system. PCBs for different subsystems are fixed inside the main frame.

Satellite is divided into the following subsystems:

- Structure (STR) subsystem, which offers a mechanical structure for the satellite. All other subsystems are attached to the structure.
- Attitude Determination and Control System (ADCS), which stabilizes the satellite in orbit, maintains the required side towards Earth. During the tether experiment, ADCS starts and maintains the satellite rotation.
- Electrical Power System (EPS) generates power with side-mounted solar panels, stores it in the Li-Ion or Li-Polymer batteries and distributes power according to different subsystems needs.
- Thermal Control System (TCS) on ESTCube-1 shall be a passive system. Different paints and coatings are used to provide fixed temperature range on-board the satellite.

- Communications System (COM) is responsible for the communication between a ground station (GS) and the spacecraft.
- Command and Data Handling System (CDHS) is the data- and telecommand administration system of ESTCube-1. CDHS is responsible for taking autonomous decisions to control the satellite.
- Payload (PL) subsystem includes the essential hardware and instruments needed for the tether experiment, the most essential one being the tether itself.
- Camera (CAM) subsystem is responsible for Earth surface imaging for educational and public outreach purposes and tether deployment verification as a part of the primary payload mission.

Different microcontrollers on-board the satellite are shown on Figure 1.

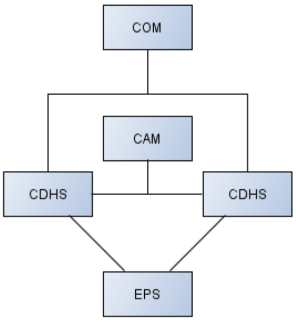


Figure 1: Different microcontrollers on-board ESTCube-1.

The satellite shall operate in two amateur radio bands:

- Uplinks in 2 m band (145 – 146 MHz)
- Downlinks in 70 cm band (435 – 438 MHz)

The satellite shall have two uplink channels; both the primary and secondary uplink channels are used only for telecommands.

The uplink channels shall operate on a different band (2 m) from the downlink channel (70 cm) so a full duplex connection would be possible to implement. That means the satellite can receive commands even if it is transmitting data at the same time. This enables telecommand stations to turn off satellite transmitters in the presence of an active transmission. For example during telemetry or beacon transmission.

The two uplink channels use separate receivers which are connected to different microcontrollers:

- Primary uplink receiver is connected to COM subsystem microcontroller. Telecommands received by the COM microcontroller are sent directly to the satellite main microcontroller (CDHS subsystem) for execution.
- Secondary uplink receiver is connected to the EPS subsystem microcontroller. Telecommands received by the EPS microcontroller are executed directly on the EPS microcontroller. The EPS microcontroller can also forward commands to CDHS microcontroller.

The EPS microcontroller is also responsible for power distribution in the satellite - it can turn power for different subsystems electronics on and off.

Uplink and downlink channels shall use a separate quarter-wave monopole antenna, which are mounted in parallel with each other and on the opposite side from the tether (Figure 2) [5].

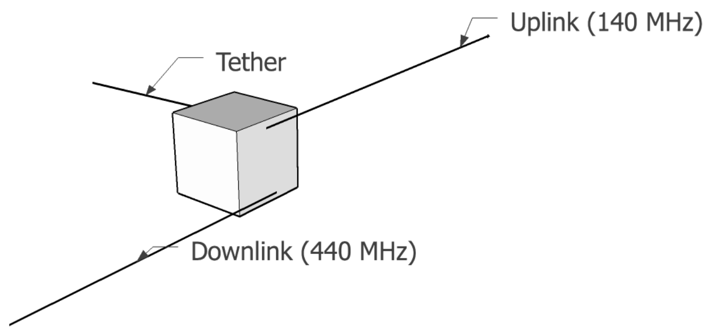
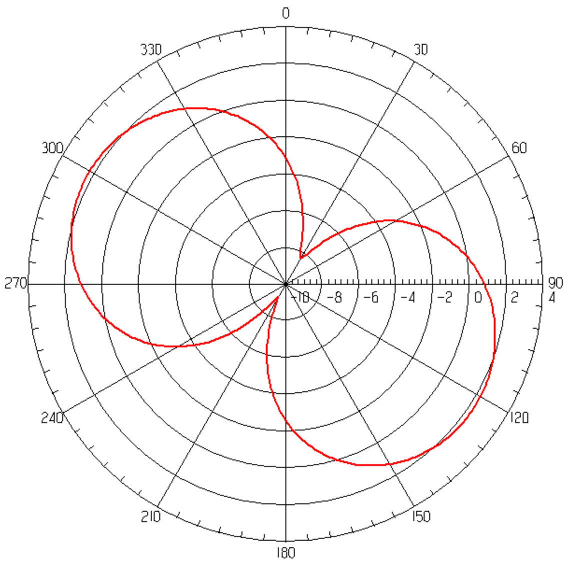


Figure 2: Antenna layout on ESTCube-1 in relation to the tether.

Primary downlink parameters:

- Frequency band: 435-438 MHz
- Output power:
    - Typical 0.5 W
    - Maximum 1.0 W
- Modulations:
    - FSK / GFSK 1200 – 19200 bps
    - MSK / GMSK 1200 – 19200 bps
- Associated antenna:
    - 70 cm quarter wave monopole
    - Simulated radiation patterns for Φ = 0 [6]:
        - Figure 3 – without the tether
        - Figure 4 – with the tether
    - Simulated radiation patterns for Θ = 90 [6]:
        - Figure 5 – without the tether
        - Figure 6 – with the tether



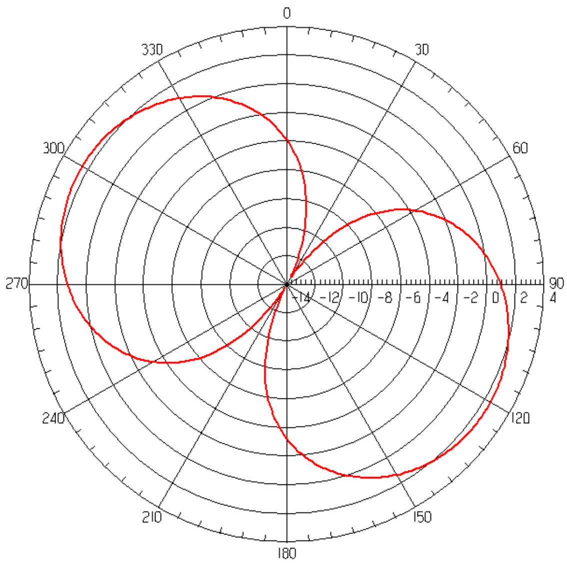
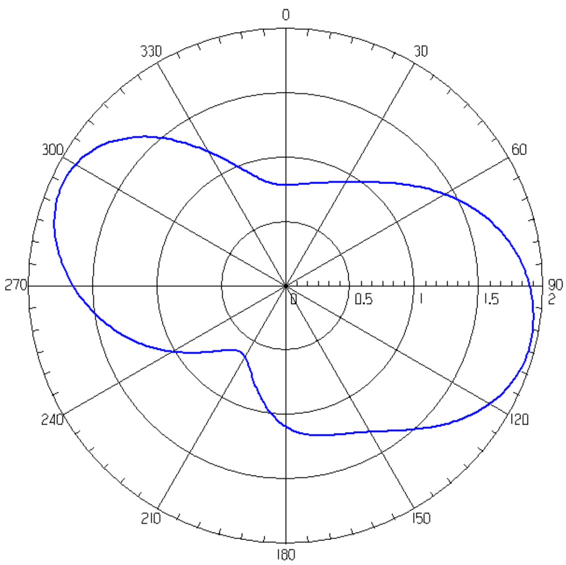


Figure 3: Simulation of 70 cm monopole antenna radiation pattern, Φ = 0 without the tether. [6]

Figure 4: Simulation of 70 cm monopole antenna radiation pattern, Φ = 0 with the tether. [6]



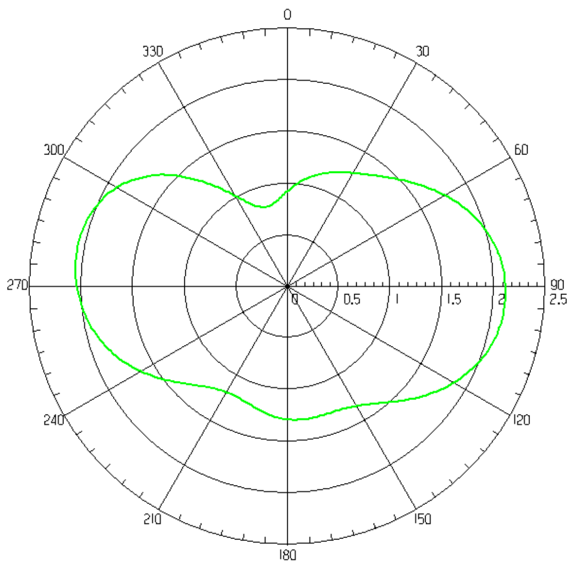


Figure 5: Simulation of 70 cm monopole antenna radiation pattern, Θ = 90 without the tether. [6]

Figure 6: Simulation of 0 cm monopole antenna radiation pattern, Θ = 90 with the tether. [6]

Preliminary radiation patterns for 70 cm monopole antenna show that the antenna gain is about 2.79 dB [6].

6 Beacon development

Beacon is a periodically activated RF transmitter which purpose is to give a simple overview of the satellite's status. The beacon signal could also be used for tracking the satellite.

Beacon operates as a backup downlink for any mission-critical telemetry data.

It shall operate on a fixed dedicated RF frequency in the UHF amateur radio frequency band (435-438 MHz). The exact beacon frequency shall be allocated by the International Amateur Radio Union (IARU) frequency coordination authorities.

The primary transmission mode of the beacon should be CW (Morse code). There is an optional 4-level narrowband FSK with FEC encoding (JT4) transmission in consideration but its implementation has not been decided yet.

6.1 Requirements

Functional requirements for the beacon are:

- To periodically transmit basic telemetry data
- Operate as a backup downlink for any mission critical telemetry data
- Experiment progress shall be verifiable by using data transmitted by the beacon alone
- Beacon data should provide enough information for satellite debugging in emergency situations

Environmental requirements related to the planned orbit are:

- In low Earth orbit (LEO) the satellites movement is relatively rapid and therefore the Doppler effect causes a noticeable frequency shift as the satellite approaches the GS and moves away. The GS needs to tune uplink and downlink frequencies according to this frequency shift [7 pp. 34, 45].
- Faraday effect is a phenomenon which causes rotation of the polarization angle of a linearly polarized wave. Using a circularly polarized antenna at the GS the impact of the Faraday effect can be minimized [7 pp. 84-85].

Requirements based on the CubeSat Design Specification are [8]:

- All deployables such as booms, antennas and solar panels shall wait to deploy a minimum of 30 minutes after the CubeSat's deployment switch(es) are activated from P-POD ejection.
- RF transmitters greater than 1 mW shall wait to transmit at least 30 minutes after the CubeSat's deployment switch(es) are activated from P-POD ejection.
- Operators shall obtain and provide documentation of proper licenses for use of radio frequencies. For amateur radio frequency use, this requires a proof of frequency coordination by the International Amateur Radio Union (IARU).

Requirements based on IARU frequency coordination are [9]:

- Satellite operators must be able to turn off all satellite transmitters immediately in case of interference.

Requirements based on Estonian laws are:

- Amateur radio callsign for the satellite must consist of the associated GS callsign, where a slash "/S" is added to the end [10].

Planned orbit for ESTCube-1 is a circular, near-polar low Earth orbit with height of 500 – 900 km.

Orbital parameters are:

- Apogee: 500 – 900 km
- Perigee: 500 – 900 km
- Inclination: 97 – 99°
- Period: 90 – 100 minutes

Minimum requirements for the GS to ensure a successful communication link are:

- Transmission capability on 2 m amateur radio band with:
  - Minimum transceiver output power of 20 W.
  - Circularly polarized 2 m antenna with a minimum of 12 dBi gain (antenna gain increase compared to isotropic antenna).
- Receiving capability on 70 cm amateur radio band with:
  - Circularly polarized 70 cm antenna with a minimum of 16 dBi gain.
- Antenna rotation of at least:
  - 360° in azimuth.
  - 90° in elevation.
  - Frequency tuning to compensate for the Doppler shift.

6.2 Transmission period

Beacon transmission period is the time between two consecutive transmission starting times. Beacon transmission length is the time it takes the beacon to transmit all of the beacon data. Beacon transmission period and length are described on Figure 7.

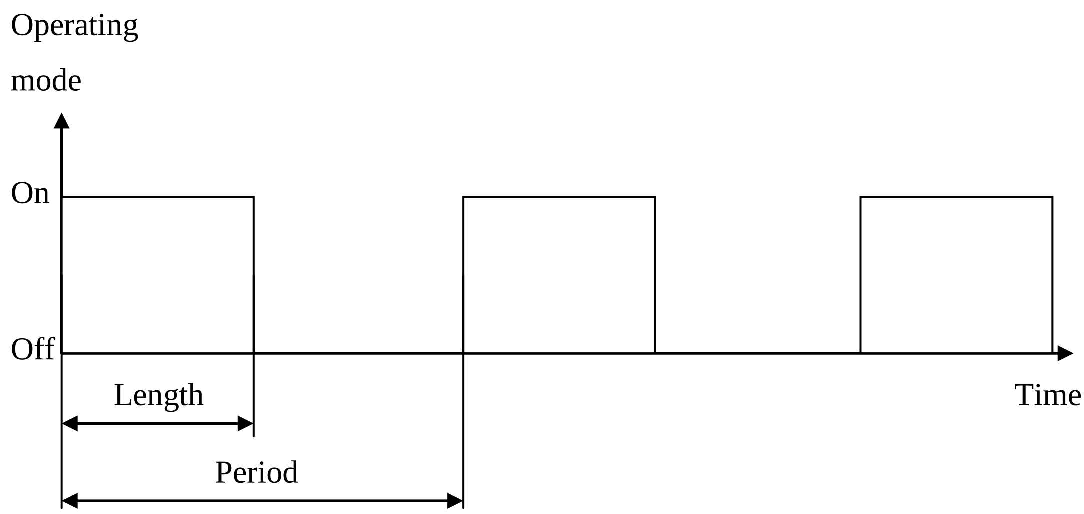


Figure 7: Beacon transmission period and transmission length.

Orbital simulations were made to determine the average number of ESTCube-1 visible passes per day from Tartu University satellite ground station [11]. AGI STK simulation software was used [12] for simulating satellite passes for two different orbit heights (Figure 8):

- 500 km
- 900 km

Simulation time period was 24 hours and a minimum elevation angle of 4° from the horizon is required for the line of sight with the satellite.

Complete results of the simulations are included Appendix A: Orbital simulations.

Average number of passes per day for different orbit heights is shown in Table 1.

A minimum of two beacon transmissions during one pass are needed for reliable reception by human operators. In CW if some characters are missed or not heard correctly then it is common to wait for the next transmission to verify these characters. Usually two transmissions are sufficient to verify transmission reception.

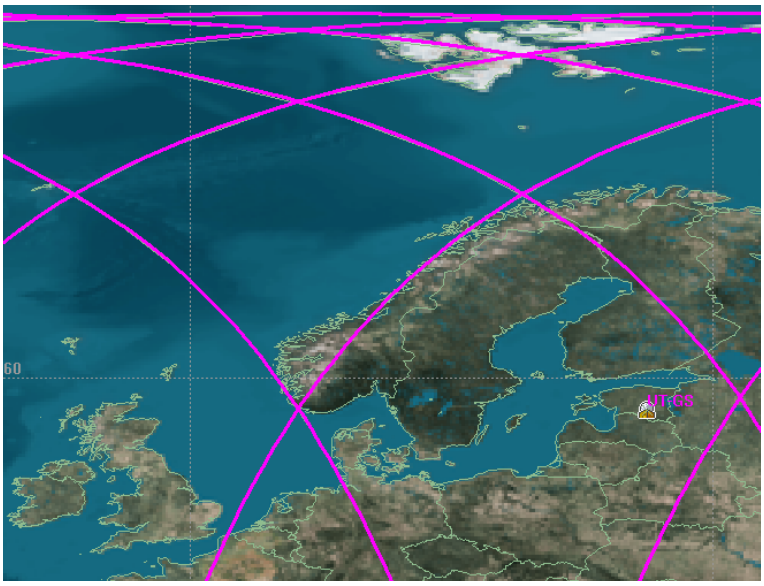


Figure 8: Simulated satellite ground tracks near Tartu University satellite ground station. Orbit height is 900 km and simulation time period is 24 hours.

Table 1: Average number of visible satellite passes per day with different orbit heights.

Duration (minutes)	Number of passes (orbit height is 500 km)	Number of passes (orbit height is 900 km)
1 – 6	2	1
6 – 9	3	2
9 – 12	2	3
Over 12	0	4

The beacon should have a configurable period and by default two different periods should be used for the following cases:

- In normal operating mode, a 3 minute period should be sufficient to receive at least 2 beacon transmissions during 90 % of the passes.
- Low power operating mode, a longer beacon period is needed to conserve more power. Considering that reducing power usage is higher priority that to receive 2 beacon transmissions during a pass, a 5 minute period is proposed. This should be sufficient to receive at least 1 beacon transmission during 90 % of the passes.

Both operating modes may include different amount of data, which affects the transmission length.

6.3 Beacon data

The beacon data format is configurable by commands received from a ground station via primary or secondary uplink receiver. Beacon data is a subset of all of the telemetry data that is gathered by CDHS. All of the telemetry data is included in Appendix B: Proposed telemetry data.

Beacon data contains:

- Satellite identificator, this could be either satellite name (“ESTCube-1”) or callsign (most likely "ES5EC/S").
- Mission-critical telemetry data. Sensors that are absolutely vital to estimate the mission success, e.g. gyro sensor reading to verify the change in satellite rotational speed. These sensors are connected directly to the EPS microcontroller so that sensor readings can be transmitted even if CDHS microcontroller fails.
- Other telemetry data. Rest of the sensors included in beacon data. This data is mostly needed to observe satellite health status. The data from these sensors are gathered by CDHS microcontroller and sent to EPS microcontroller.

Unmodulated carrier signal for satellite range or orbital parameters measurements. This can be optionally activated.

Table 2 shows proposed contents of beacon data for different subsystems and shows which microcontroller is responsible for reading the sensor data.

Table 2: Proposed contents of beacon data for different subsystems. For each component a more thorough description is added. Measured by shows which microcontroller is connected to this component.

Sub-system	Component	Data description	Measured by
EPS	Solar panels	Average solar panel power output	EPS
	Batteries	Battery voltage	EPS
		Average current (sign value)	EPS
		Battery temperature	EPS
	Microcontroller	Operation phase	EPS
		Firmware version	EPS
		Failure mode	EPS
	Power lines	Main power bus voltage	EPS
		Converter status	EPS
	Calculated	Average power usage of the satellite	EPS
		Payload power usage	EPS
	Other	CDHS processor switch	EPS
ADCS	Sensors	Magnetometer reading	CDHS
		Magnetometer status	CDHS
		Gyro sensor reading	CDHS
		Gyro sensor status	CDHS
		Sun sensor status	CDHS
	Coils	Coil driver status	CDHS
	Other	Operating mode	CDHS
		Failure mode	CDHS
CDHS	Microcontroller	Firmware version	CDHS
		Reset counter	CDHS
		Other subsystem check	CDHS
		Operating mode	CDHS
		Failure mode	CDHS
	Real time clock	Satellite time	CDHS
COM	RF power measuring unit	Transmission forward power	COM
		Transmission reflected power	COM
	Microcontroller	Satellite identificator	COM
		Operating mode	COM
		Failure mode	COM
TCS	Temperature sensor	Average satellite temperature	CDHS

Sub-system	Component	Data description	Measured by
Payload	Motor	Reel turning	CDHS
		Launch lock status	CDHS
		Reel lock status	CDHS
		Failure mode	CDHS
		Motor position (step counter)	CDHS
		Motor temperature	CDHS
	Electron gun modules	Module current	CDHS
		Module status	CDHS
	Tether	Tether voltage	CDHS
		Tether current	CDHS
		Supply voltage	CDHS

6.4 Modulations

Beacon shall be in telegraph Morse and in JT4 [5]. JT4 is a 4-level narrowband frequency shift keying (FSK) with forward error correction (FEC) encoding (JT4) transmission. JT-4 modulation is continually getting more widespread, it would attract more radio amateurs to tracking and listening to ESTCube-1. Implementing JT-4 is under consideration but the primary operating mode of the beacon shall be CW Morse.

6.4.1 CW

In case of CW, a signal to noise ratio (SNR) above 6 dB is needed for machine decoding, for decoding by human ear about 0…3 dB is needed in 200 – 500 Hz bandwidth radio channel. CW is usually transmitted as incoherent OOK

A suitable transfer speed for Morse is 17 WPM as demonstrated by Compass-1 satellite (see section 4.1 Compass-1), 1 word-unit is 5 characters, one character is 7 bits. This results in transfer speed of 10 bits per second [13].

A bit error rate (BER) of 10^{-3} can be used for beacon, this results in one erroneous bit in every 1000 bits.

Required Eb/N0 for CW for BER 10^{-3} is about 11 dB [14].

6.4.2 JT-4

JT-4 uses four tones carrying two bits per symbol, one bit is sync sent as a pseudo-random code, the other is a data bit [13]. This enables SNR required for decoding JT-4 to be just above -15 dB in 2.4 kHz bandwidth.

Data transfer speed for JT-4 is 8.8 bits per second.

Required Eb/N0 for JT-4 is -1…1 dB [13].

6.4.3 Unmodulated carrier signal

Unmodulated carrier signal should be used for satellite range or orbital parameters measurements. This can be optionally activated.

6.5 Link budgets

Link budgets are used to determine the required transmit power for the communication link. Link budget accounts for all the gains and losses in transmission channel. Resulting link margin shows how much additional attenuation the system could tolerate between the transmitter and the receiver before the signal is too weak to receive.

A link budget calculator was used for two different orbit heights [15]:

- 500 km, shown in Table 3
- 900 km, shown in Table 4

For each orbit height, link margin was calculated in two satellite positions, in zenith and on the horizon, for CW and JT-4 transmission modes.

Equations (1) to (6) are used for calculations in link budgets in Table 3 and Table 4.

Effective isotropic radiated power (EIRP) can be calculated using the following equation

$$EIRP = P_{tx} + G_{tx}, \tag{1}$$

where P_{tx} is transmit power in dBW and G_{tx} is transmit antenna gain in dBi.

Free space loss (FSL) can be calculated using the following equation

$$FSL = 20\log\left(\frac{4 \times \pi \times d \times f}{c}\right), \tag{2}$$

where d is distance in meters, f is frequency in Hertz and c is speed of light in m/s.

Receiver figure of merit (G/T) can be calculated using the following equation

$$G/T = G_{rx} - 10\log(t_0), \tag{3}$$

where G_{rx} is receive antenna gain in dBi.

Boltzmann's constant can be calculated using the following equation

$$k = 10\log(1.38 \times 10^{-23}) \tag{4}$$

Final signal to noise ratio for the communication channel can be calculated using the following equation

$$Final\ E_b/N_0 = EIRP + G/T - L - 10\log(rb) - k, \tag{5}$$

where EIRP is the effective isotropic radiated power in dBW, G/T is the receiver figure of merit in dB/K, L is the total signal loss in channel in dB, rb is the bit rate in bits per second and k is the Boltzmann's constant in dB.

Link margin can be calculated using the following equation

$$Link\ margin = Final\ {}^{E_b}/_{N_0} - Required\ {}^{E_b}/_{N_0}, \qquad (6)$$

where Final E_b/N_0 is communication channel total SNR in dB and required E_b/N_0 is the SNR required for chosen modulation in dB.

Based on the calculated link budgets 100 mW transmit power is sufficient in CW mode when the satellite is in zenith (link margins of 26.85 and 21.74 dB) and barely sufficient when the satellite is close to the horizon (link margins of 2.53 and -0.05 dB). Link margins in JT-4 mode are even higher.

Since CW shall be the main operating mode and link margins are higher when the elevation angle during the satellite pass is over 4°, we can conclude that 100 mW transmit power is sufficient for beacon normal operating mode.

In case the real signal losses are higher than estimated in the link budgets, a higher maximum transmit power should be considered when applying for the beacon operating frequency. 500 mW transmit power should be sufficient for maximum transmit power.

Table 3: Beacon link budget for orbit height of 500 km.

Parameter	Value (Zenith)	Value (Horizon)	Unit
Transmitter			
Transmit power (P_{tx})	0.1		W
	-10		dBW
Frequency (f)	437		MHz
Transmit antenna gain (G_{tx})	2.79		dBi
Effective Isotropic Radiated Power (EIRP)	-7,21		dBW
Channel			
Range (d)	500	2600	km
Free Space Loss (FSL)	139.29	153.61	dB
Signal fade margin	20	30	dB
Other losses	3	3	dB
Total loss (L)	162.29	186.61	dB
Receiver			
Receive antenna gain (G_{rx})	16.15		dBi
System noise temperature (t_0)	550		K
Receiver figure of merit (G/T)	-11.25		dB/K
General – CW modulation			
Bit rate (rb)	10		bps
Boltzmann's constant (k)	-228.60		dB
Final E_b/N_0	37.85	13.53	dB
Required E_b/N_0 for given modulation and coding	11		dB
Link margin	26.85	2.53	dB
General – JT4 modulation			
Bit rate (rb)	8.8		bps
Boltzmann's constant (k)	-228.60		dB
Final E_b/N_0	38.40	14.08	dB
Required E_b/N_0 for given modulation and coding	0		dB
Link margin	38.40	14.08	dB

Table 4: Beacon link budget for orbit height of 900 km.

Parameter	Value (Zenith)	Value (Horizon)	Unit
Transmitter			
Transmit power (P_{tx})	0.1		W
	-10		dBW
Frequency (f)	437		MHz
Transmit antenna gain (G_{tx})	2.79		dBi
Effective Isotropic Radiated Power (EIRP)	-7,21		dBW
Channel			
Range (d)	900	3500	km
Free Space Loss (FSL)	144.40	156.19	dB
Signal fade margin	20	30	dB
Other losses	3	3	dB
Total loss (L)	167.40	189.19	dB
Receiver			
Receive antenna gain (G_{rx})	16.15		dBi
System noise temperature (t_0)	550		K
Receiver figure of merit (G/T)	-11.25		dB/K
General – CW modulation			
Bit rate (rb)	10		bps
Boltzmann's constant (k)	-228.60		dB
Final E_b/N_0	32.74	10.95	dB
Required E_b/N_0 for given modulation and coding	11		dB
Link margin	21.74	-0.05	dB
General – JT4 modulation			
Bit rate (rb)	8.8		bps
Boltzmann's constant (k)	-228.60		dB
Final E_b/N_0	33.30	11.50	dB
Required E_b/N_0 for given modulation and coding	0		dB
Link margin	33.30	11.50	dB

7 Beacon design layout

ESTCube-1 beacon shall share the final RF output stage with the primary downlink channel on 70 cm band. The final RF output stage consists of a RF power amplifier, power measuring unit and 70 cm antenna.

This will keep the overall satellite design simpler but introduces a risk of the beacon and the primary downlink trying to transmit at the same time. The concurrent use of RF output stage shall be prevented on the software level.

Beacon shall be controlled by EPS microcontroller to reduce the risks of losing satellite transmission capability. Since EPS microcontroller is responsible for power distribution on-board the satellite, a large amount of beacon data is already gathered by EPS microcontroller. In addition, the secondary uplink channel shall also be controlled by EPS microcontroller. This enables GS to control the beacon even if primary uplink and downlink in the COM subsystem are not responding.

The hardware for beacon shall be located on COM PCB, to simplify the PCB design for RF electronics and to reduce signal losses.

Beacon output frequency needs to have long-term stability and precision. In space conditions frequency drift due to the temperature changes need to be considered as well. To correspond to these requirements a voltage controlled crystal oscillator should be used in combination with a temperature sensor. This enables frequency tuning to compensate for short term temperature changes as well as to long term component aging [16].

Beacon shall use an intermediate frequency, which is equal to output frequency divided by 4. The output frequency range is 435 – 438 MHz, until an exact frequency is allocated for the beacon, an estimation of intermediate frequency of 109 MHz is used.

Output frequency shall be generated with the use of frequency multipliers.

A band-pass filter should also be used before the signal is forwarded to final RF output stage.

Necessary signal amplification for 100 mW transmit power shall be done in the RF power amplifier. Amplifier output RF power needs to be measured to adjust the amplification.

Proposed beacon design layout is shown in Figure 9.

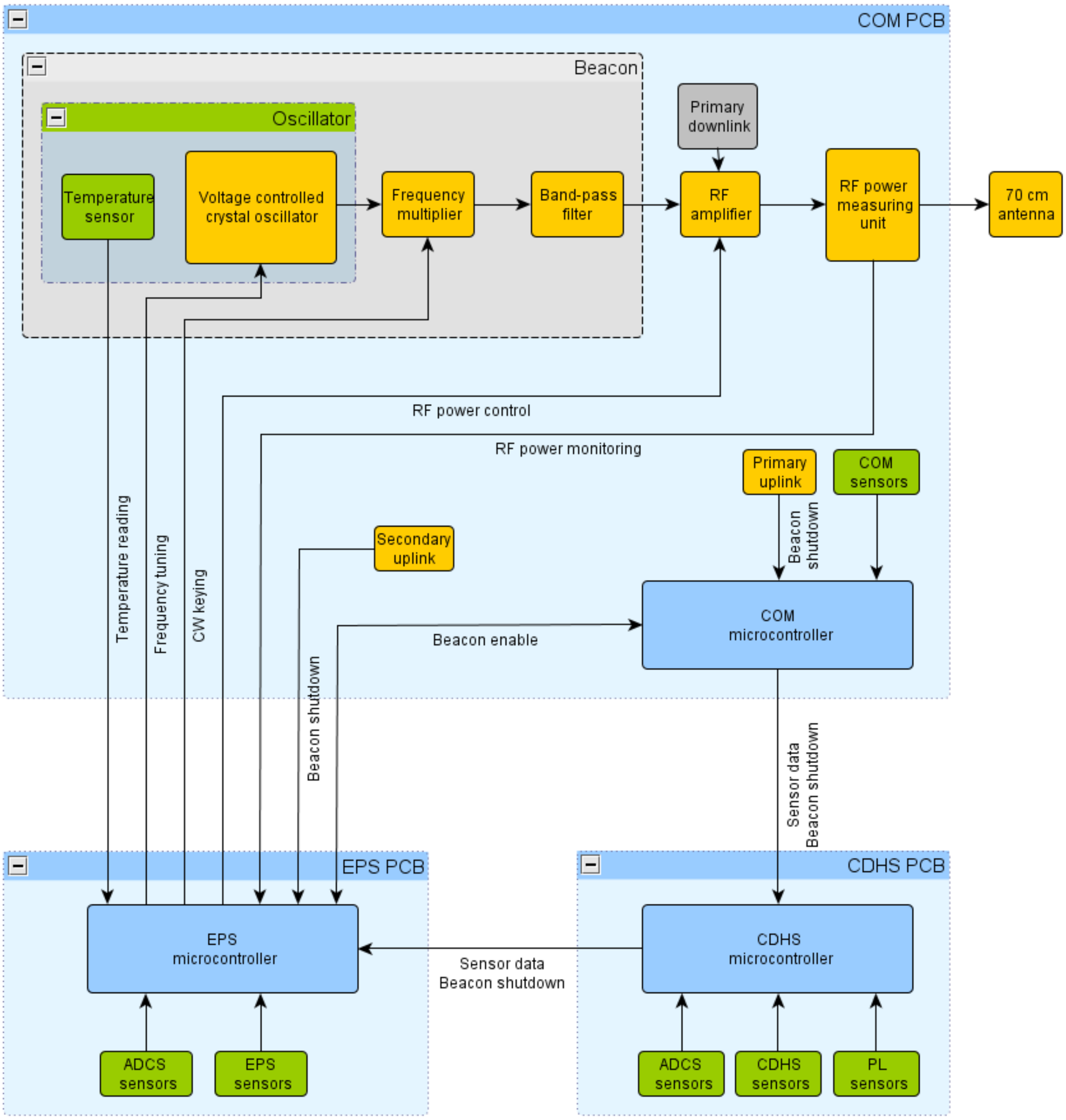


Figure 9: Beacon design layout showing beacon components on COM PCB, beacon control interfaces for EPS microcontroller and beacon related subsystems, which can receive and forward beacon control commands from the ground (e.g. beacon shutdown).

7.1 Beacon software

Beacon software process shall run on EPS microcontroller. It is responsible for periodically asking CHDS for new beacon data, which is then coded into Morse and transmitted. Figure 10 shows the software process flowchart.

If the downlink final stage is in use a delay timer is used, after which beacon process shall resume its normal operation.

It shall be possible to command the beacon process to reload its configuration file without having to restart the beacon process.

It shall be possible to turn the beacon process off by a command.

The beacon data content, transmission and period mode are configurable with commands received from a ground station via primary or secondary uplink receiver.

There are a few sensors that are connected directly to EPS microcontroller. The data from these sensors are gathered directly by EPS microcontroller and sent to CDHS as telemetry information. In case the CDHS microcontrollers fail, the beacon process should be able to send available telemetry data from EPS directly.

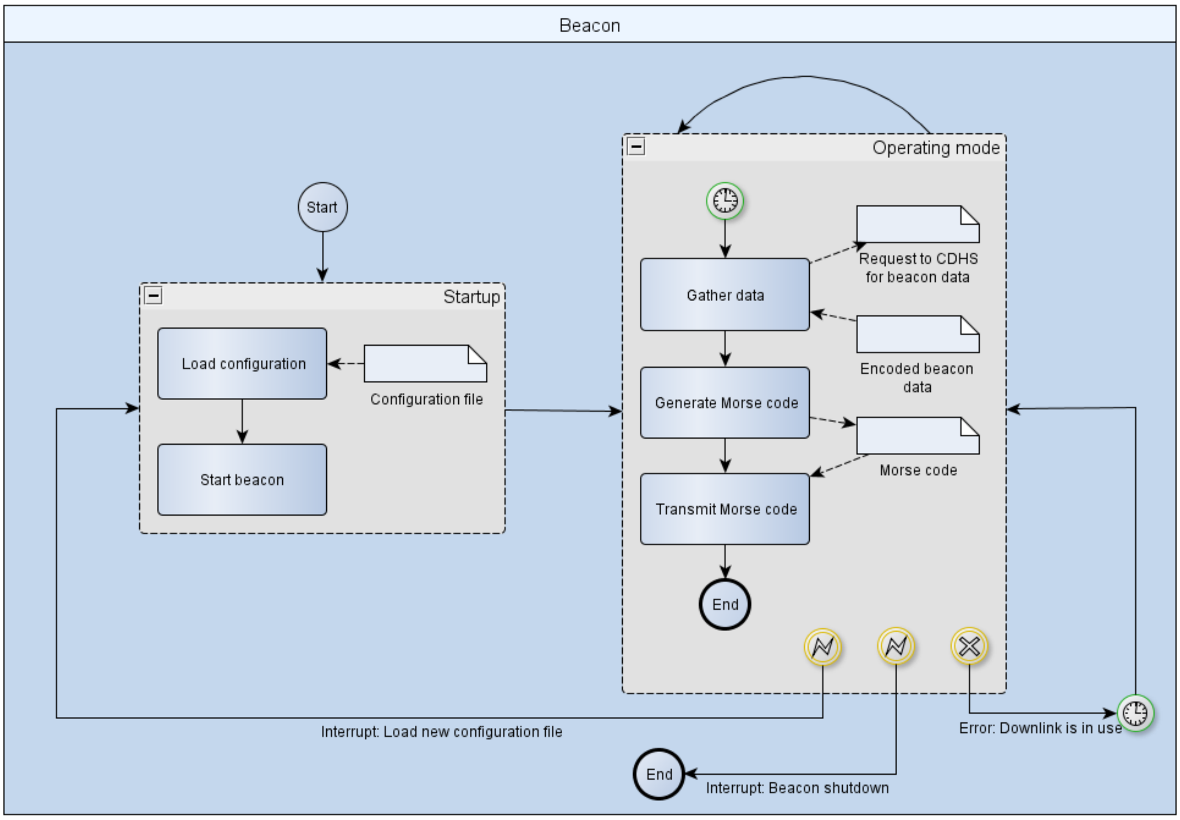


Figure 10: Beacon software flowchart. Different operating modes, beacon data and beacon period can be changed with a configuration file. In operating mode, the beacon process periodically asks for beacon data from CDHS, received data is coded into Morse and transmitted. Different interrupts and errors can result in a delay, configuration file reload or beacon shutdown.

7.2 Risk analysis

Operational risks are considered to be hard risks, these will mostly occur during the satellite operating in the orbit. The hard risk matrix for satellite beacon is shown in Table 5 and the associated list of risks with action plans for risk mitigation is shown in Table 6.

A risk index is assigned to each risk based on its severity and likelihood. Risk indexes are categorized as [17]:

- 4E, 5D, 5E – very high risk, these are unacceptable, if a risk mitigation plan not reduce the risk then a major redesign of the system is required.
- 3E, 4D, 5C – high risk, also unacceptable
- 2E, 3D, 4C, 5B – medium risk – unacceptable
- 1D, 1E, 2C, 2D, 3B, 3C, 4B, 5A – low risk, acceptable
- 1A, 1B, 1C, 2A, 2B, 3A, 4A – very low risk - acceptable, does not require any mitigation plan

Table 5: Risk matrix showing hard risks that can occur during beacon operation.

Severity		A	B	C	D	E
	5	RF interference	EPS fails			
	4		CDHS fails	Configuration fails		
	3		Low power; COM fails	Old beacon data		
	2			Software bugs		
	1			Packet loss	Low transmit power	
		A	**B**	**C**	**D**	**E**
		Likelihood				

Table 6: Beacon risk mitigation.

Risk name	Type	Scenario	Action for mitigation
Packet loss	C1	Erroneous bits in beacon transmission result in useless packet	None, a new beacon data packet shall be transmitted with next transmission period
Configuration fails	C4	Configuration file is corrupted and beacon process is not able to start or starting results in unexpected behavior	A new configuration file needs to be uploaded during next pass; beacon should be turned off until then
Low transmit power	D1	Beacon transmit power is insufficient for receiving beacon signal	Beacon transmit power shall be increased by a command sent from the GS, up to 500 mW transmit power can be used
Low power	B3	Available power on the satellite is critically low	Beacon switches to low power operating mode, ground control shall debug the satellite using beacon data
RF interference	A5	On-board RF interference disturbs beacon operation or distorts beacon output signal	Possible on-board RF interferences should be eliminated during testing. If this occurs after launch, then the interfering component needs to be identified and turned off for the duration of beacon transmission in the future.
Software bugs	C2	Bugs in beacon software result in unexpected operating behaviour	Bugs should be fixed on the ground and a new firmware image uploaded to the satellite
EPS fails	B5	EPS subsystem failure	It needs to be ensured that beacon electronics are also turned off, otherwise beacon might disturb the use of downlink stage by COM
CDHS fails	B4	CDHS subsystem failure	Beacon is still able to transmit data from sensors that are

			connected directly to EPS
COM fails	B3	COM subsystem failure	It needs to be ensured that downlink final stage is still available, separate electrical power controls are needed for beacon, downlink final stage and rest of COM subsystem
Old beacon data	C3	CDHS is unable to gather new data for some parts of beacon data	Beacon should keep transmitting the last known data for these parts of beacon data, but it should be indicated in the transmitted data

7.3 Radio frequency allocation

The frequency coordination process involving IARU, National Amateur Radio Society (Eesti Raadioamatööride Ühing) and National Telecommunications Regulatory Authority (Tehnilise Järelvalve Amet) was started. The exact beacon transmit frequency shall be allocated by IARU frequency coordination authorities.

Beacon radio frequency allocation plan is shown in Table 7. It includes available frequency range for satellite communications in associated amateur radio bands, proposed modulations, bit rates and corresponding International Telecommunication Union (ITU) emission designators. [18] The typical output power is based on link budget calculations.

Table 7: Beacon radio frequency allocation plan.

<table>
<tr><th rowspan="2">Radio band</th><th rowspan="2">Abbre-viation</th><th rowspan="2">Frequency range</th><th rowspan="2">Modu-lation</th><th rowspan="2">Bit rate (bps)</th><th rowspan="2">ITU emission designator</th><th colspan="2">Output power</th><th rowspan="2">Associated antenna</th></tr>
<tr><th>Typ. (W)</th><th>Max. (W)</th></tr>
<tr><td rowspan="2">70 cm</td><td rowspan="2">UHF</td><td rowspan="2">435 - 438</td><td>CW</td><td>10</td><td>100HA1A</td><td rowspan="2">0.1</td><td rowspan="2">0.5</td><td rowspan="2">70 cm monopole</td></tr>
<tr><td>JT4</td><td>8.8</td><td>2k00F1D</td></tr>
</table>

8 Prototyping and testing

Beacon radio frequency electronics prototype was developed with primary goal to test the transmission chain, which outputs unmodulated carrier wave that shall be used for CW with a Morse key.

The developed prototype supports testing of:

- Digital-analogue converter (DAC) for oscillator frequency tuning
- Current measurement unit
- Analogue-digital converter (ADC) which includes a temperature sensor

Prototype includes input interfaces

- Power supply
- Frequency tuning
- CW keying
- Signal output for RF amplifier
- I^2C interface for ADC and DAC

The goal of this work is to develop and test circuit for:

- Oscillating circuit which will use intermediate frequency of 109 MHz
- Two frequency multiplier stages which multiply the oscillating circuit frequency up to 438 MHz
- Band-pass filter which limits harmonics
- Buffer stage which is controlled by keyer

Beacon RF prototype layout is shown in Figure 11.

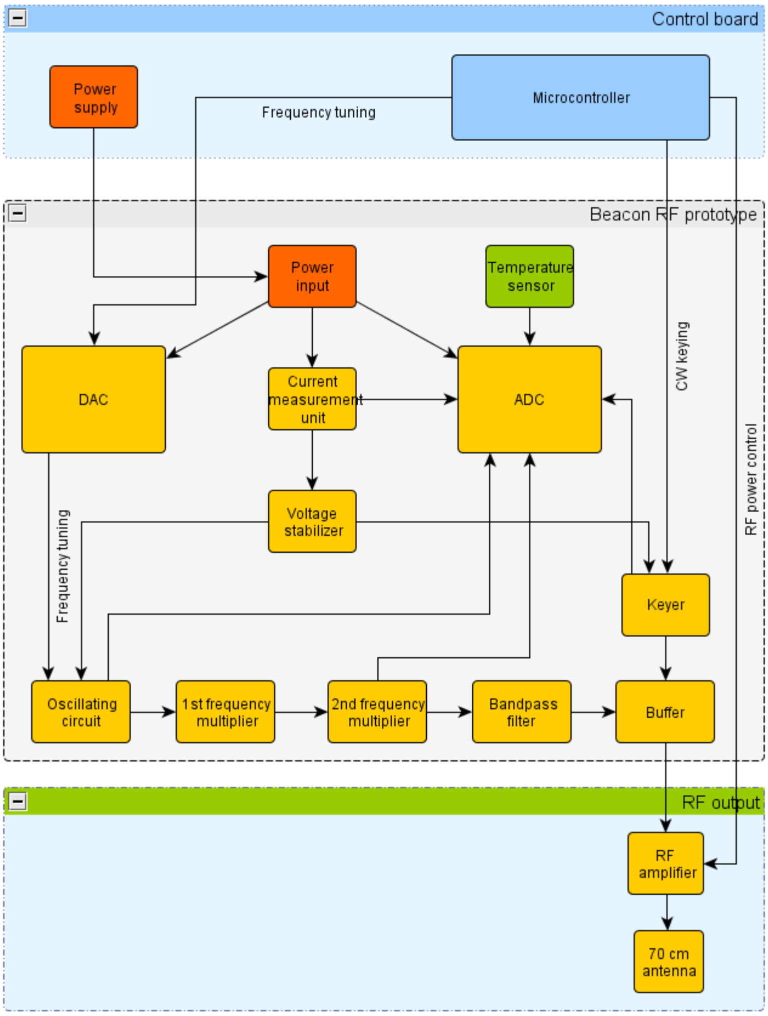


Figure 11: Beacon prototype design layout.

8.1 Prototype implementation proposal

Design rules for the prototype were:

- 2 layer PCB board
- Board size of 100 x 55 mm^2
- Copper coated PCB
- LPKF Protomat milling
- SMD components are used, except for pinheaders, SMB connector and quartz crystal

Rules for PCB layout design:

- Isolation – 0.3 mm
- Spacing – 0.254 mm
- Width – 0.4 mm
- Hole diameters – 3.2 mm
- Via drill holes – 0.6 mm

General recommendations to follow:

- Other side under the band-pass filter should be kept clear
- As much ground area should be designed around the filter as possible
- There should be no long wire track under RF electronics
- All RF components should be placed as close together as possible
- Screw holes do not need to be isolated from the ground plane
- A ground via should be near every conductor to ground connection
- A ground via should be near every transistor to ground connection
- Ground vias with regular steps should be used on board edges to prevent board edge RF radiation
- Temperature sensor should be as close to the crystal as possible
- For every chip, a capacitor should be used for de-coupling the supply voltage

Component selection for the prototype:

- Resistors – size 0603
- Capacitors (10 uF) – 0603

- Capacitors (all others) – 0805
- Inductors – 0805
- Transistors – SOT23
- Coaxial connector - SMB
- Filter – 5CHT (Toko) [19]
- Voltage regulator chip – SOT25
- Voltage measurement chip – UMAX8 (MAX4712) [20]
- ADC – TSSOP (AD7417) [21]
- DAC – MSOP8 (LTC1663) [22]
- Trimmer capacitor – Murata TZB4-B type [23]
- Varicap diode – SOT23
- Crystal oscillator– 5th overtone, frequency = 109 MHz
- External connectors – Pinheader

For oscillating circuit a Butler crystal oscillator circuit was used [24]. The beacon RF prototype schematics are shown in Figure 12.

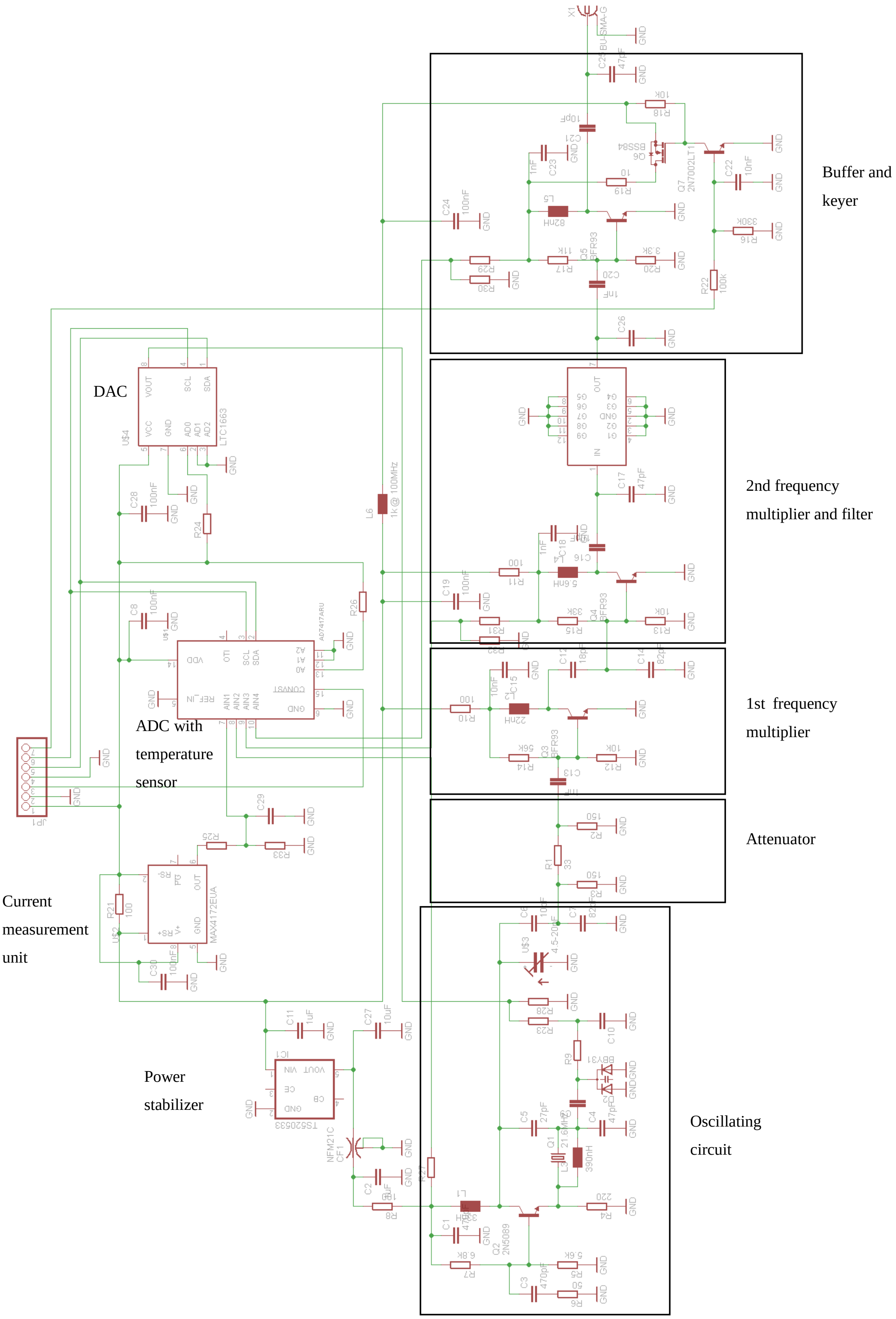


Figure 12: Schematics of beacon radio frequency electronics prototype.

Beacon RF prototype PCB layout is shown in Figure 13 (top side) and Figure 14 (bottom side).

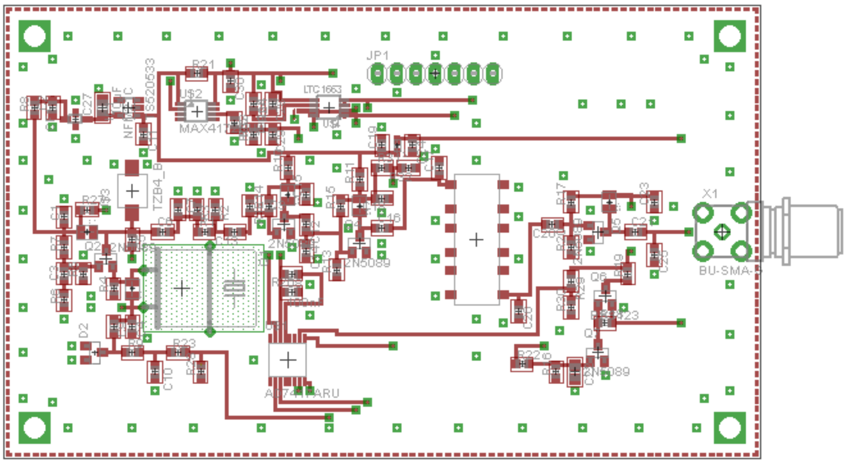


Figure 13: Top side of the beacon prototype PCB layout.

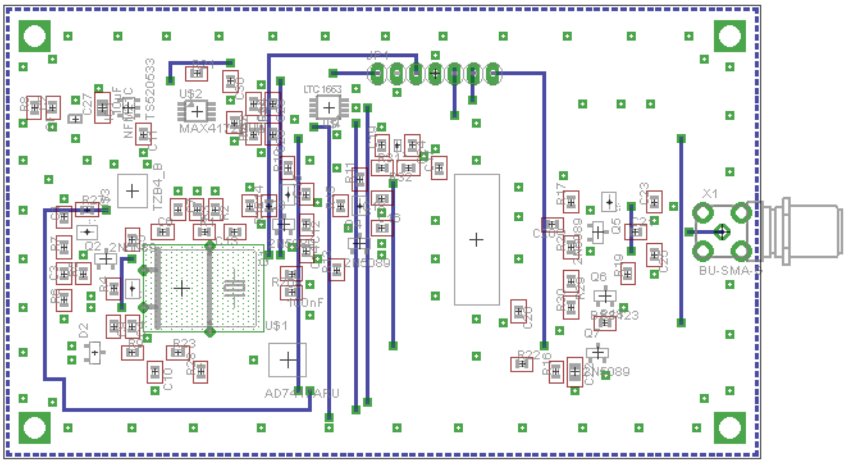


Figure 14: Bottom side of the beacon prototype PCB layout.

8.2 Simulations

Preliminary parameters for components in resonant circuits were simulated with PSpice software for the following stages [25]:

- Oscillating circuit
- 1st frequency multiplier
- 2nd frequency multiplier and the buffer stage

8.2.1 Oscillating circuit

Preliminary values for circuit components were determined experimentally with the simulation software. Figure 15 shows the circuit with suitable values to tune the circuit resonance around to 109 MHz. The crystal oscillator was replaced by a 330 Ω resistor.

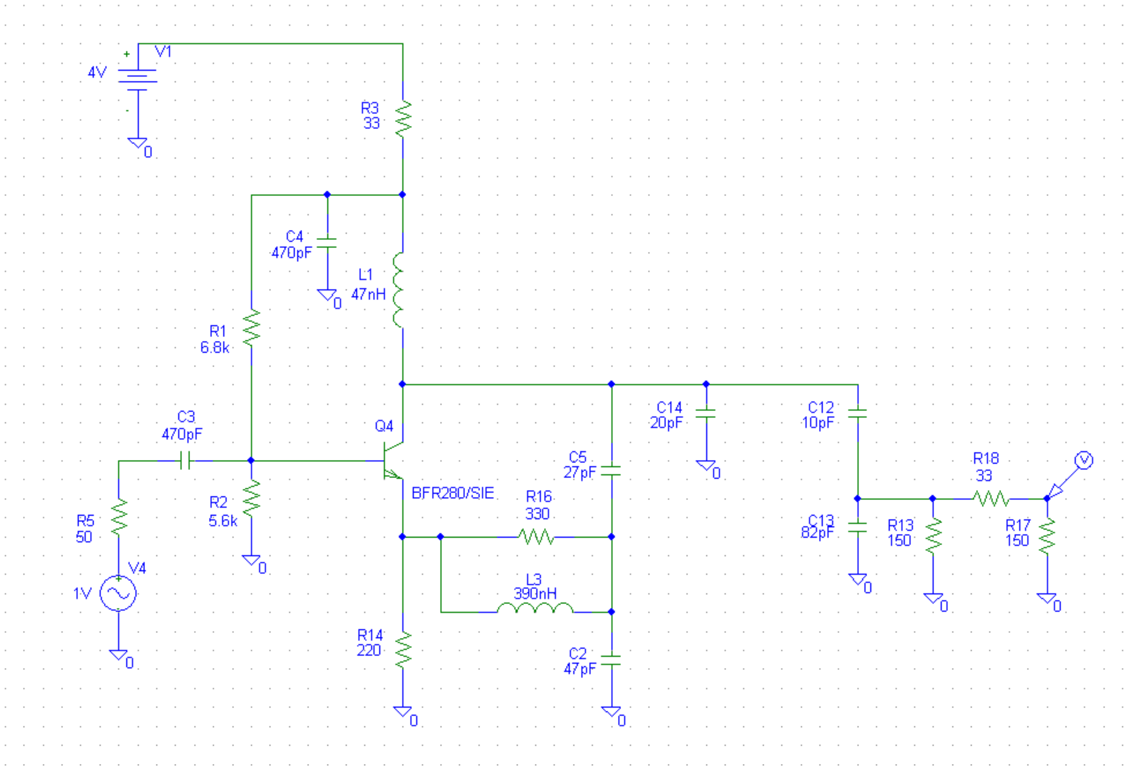


Figure 15: PSpice schematic for oscillating circuit showing experimental values for tuning the circuit resonance.

Forward voltage gain measurement simulation is shown on Figure 16. Peak gain is around 109 MHz.

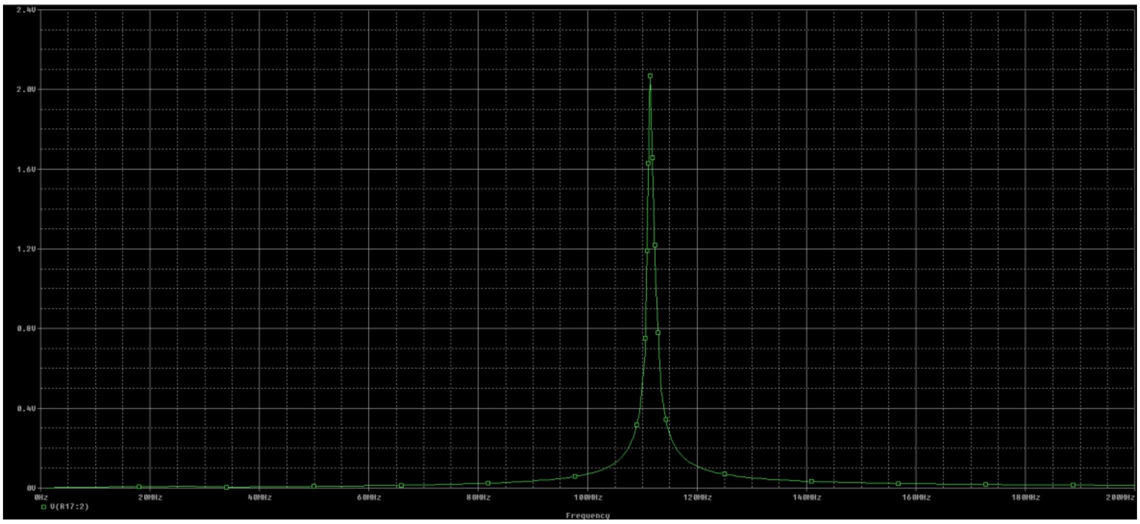


Figure 16: PSpice simulation results for forward voltage gain of the quartz oscillator circuit. Horizontal axis shows signal frequency from 0…200 MHz and vertical axis shows signal voltage gain from 0…2.4 V.

8.2.2 1st frequency multiplier

Preliminary values for circuit components were determined experimentally with the simulation software. Figure 17 shows the circuit with suitable values to tune the circuit resonance around to 218 MHz. A 5 pF capacitor was added to compensate for PCB parasitic capacitance.

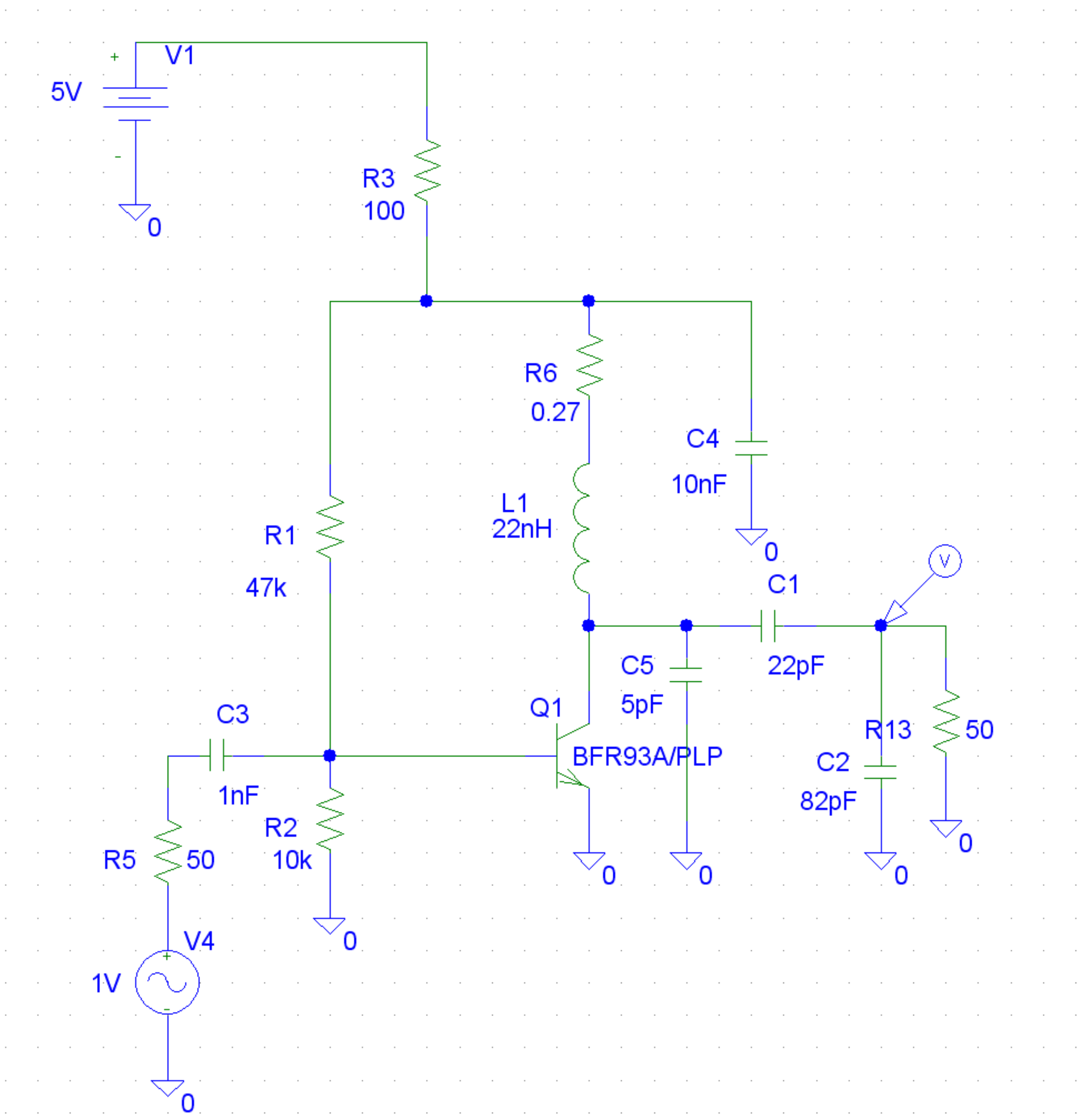


Figure 17: PSpice schematic for 1st frequency multiplier showing experimental values for tuning the circuit resonance.

Forward voltage gain measurement simulation is shown on Figure 18. Peak gain is around 218 MHz. Simulation shows that 109 MHz signal should be suppressed quite well.

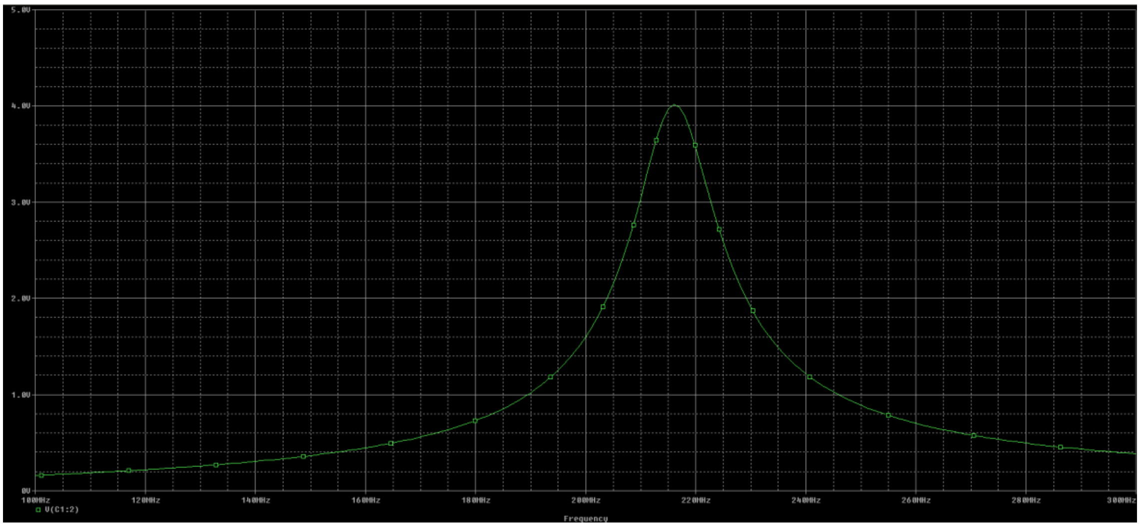


Figure 18: PSpice simulation results for forward voltage gain of the 1st frequency multiplier circuit. Horizontal axis shows signal frequency from 100…300 MHz and vertical axis shows signal voltage gain from 0…5.0 V.

8.2.3 2nd frequency multiplier and buffer

Preliminary values for circuit components were determined experimentally with the simulation software. Figure 19 shows the circuit with suitable values to tune the circuit resonance around to 432 MHz. A 3 pF capacitor was added to compensate for PCB parasitic capacitance. The same values can be used for the buffer circuit in the final stage.

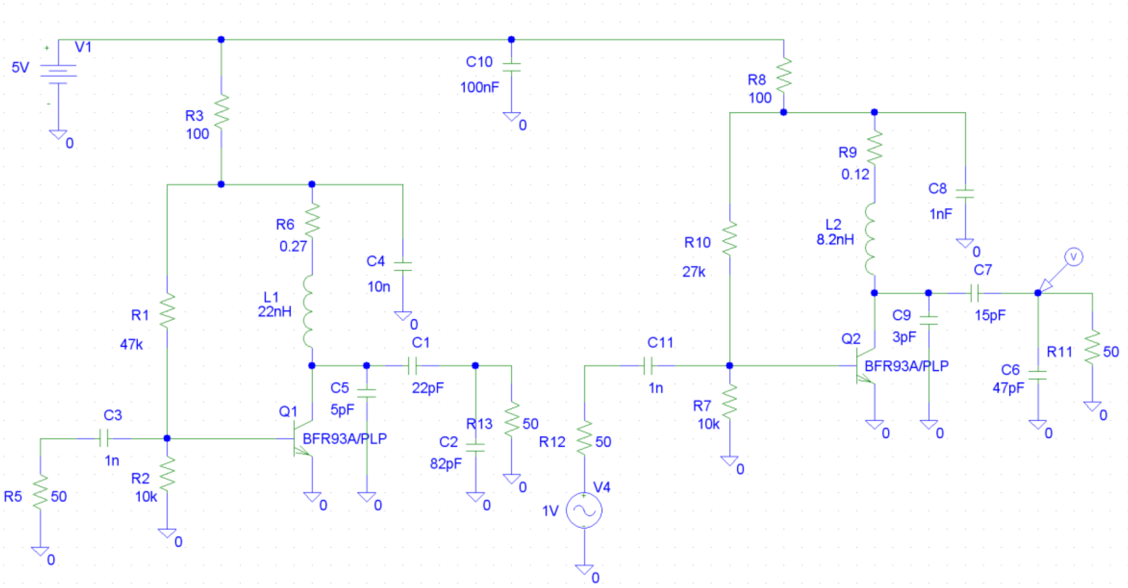


Figure 19: PSpice schematic for 2nd frequency multiplier showing experimental values for tuning the circuit resonance. The 1st frequency multiplier is present on the left side of the schematic, the 2nd frequency multiplier on the right side.

Forward voltage gain measurement simulation is shown on Figure 20. Peak gain is around 430 MHz. Simulation shows that 218 MHz signal should be suppressed quite well.

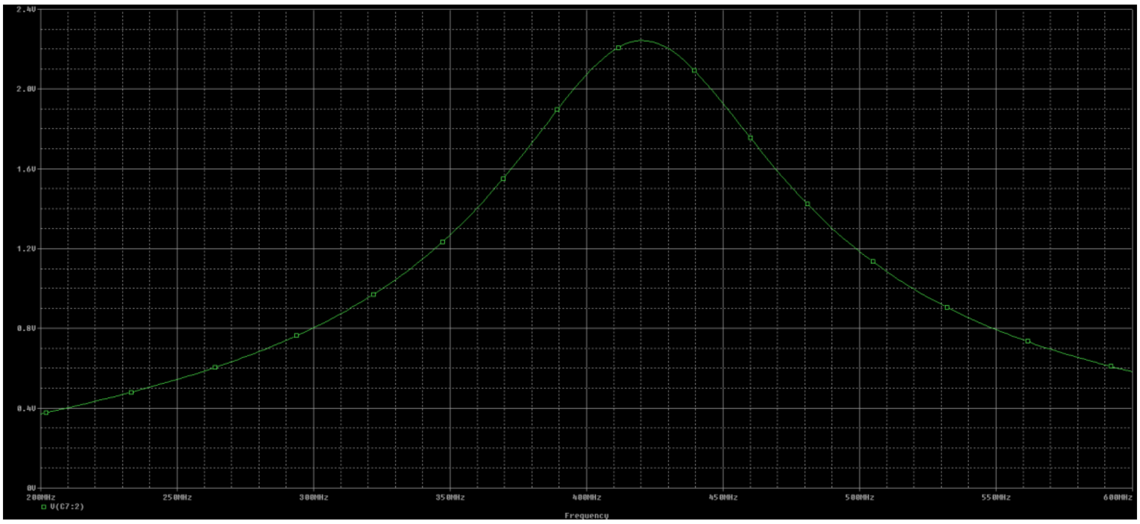


Figure 20: PSpice simulation results for forward voltage gain of the 2nd frequency multiplier circuit. Horizontal axis shows signal frequency from 200…600 MHz and vertical axis shows signal voltage gain from 0…2.4 V.

8.3 Measurements and testing

For tuning different resonant circuits, forward gain needs to be measured. This is needed for the following cases:

- 1st frequency multiplier separately
- Filter separately
- 2nd frequency multiplier with filter
- Quartz oscillator

When multiple stages are tested together, the frequency spectrum analysis is done. This is needed for the following cases:

- Both frequency multipliers with filter and buffer stage
- Transmission chain as a whole

In addition, frequency spectrum of the quartz oscillator needs to be measured.

The on / off keying signal ratio and signal to noise ratio for the whole transmission chain need to be measured.

Additional technical parameters that are needed:

- Prototype board mass
- Power consumption for on / off keying

8.3.1 1st frequency multiplier

1st frequency multiplier was tuned to twice the 109 MHz. Using the parameters from simulation resulted in maximum gain at 181 MHz, which is shown on Figure 21. This suggested a parasitic capacitance of about 5 pF.

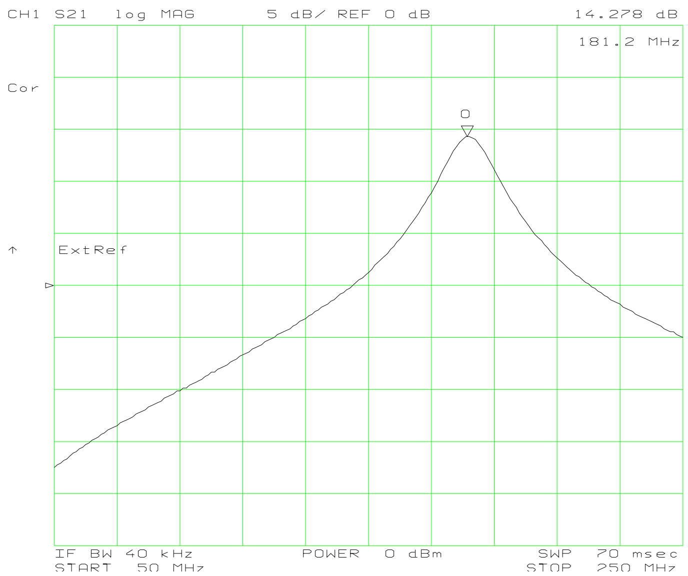


Figure 21: 1st frequency multiplier forward gain measurement suggests a 5pF parasitic capacitance in the circuit. Horizontal axis shows signal frequency from 50…250 MHz and vertical axis shows signal strength in logarithmic scale from -25…25 dB.

The simulation was compensated for the parasitic capacitance and new values were found for the components in the circuit. Measurements with the new components resulted in peak gain at ~220 MHz, shown on Figure 22. This result is quite good for the preliminary tuning of the 1st frequency multiplier. Ratio to signal strength at 109 MHz is -23.8 dB.

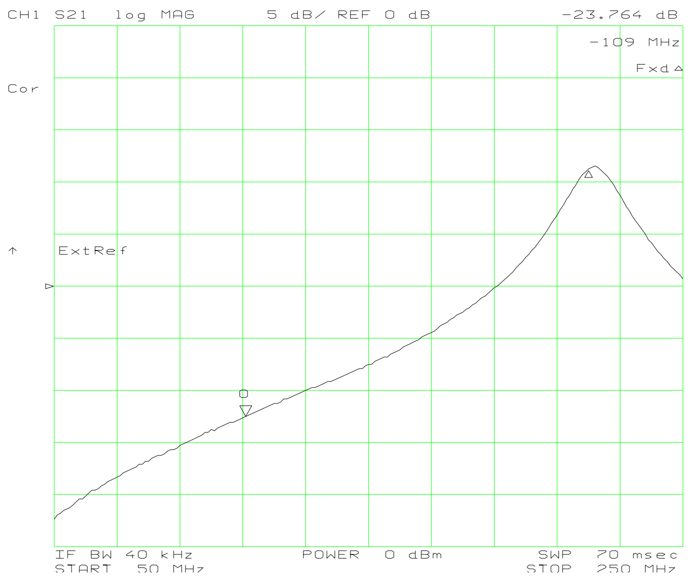


Figure 22: 1st frequency multiplier forward gain measurement with corrected values to compensate for 5 pF parasitic capacitance. Ratio to the 109 MHz is also shown. Horizontal axis shows signal frequency from 50…250 MHz and vertical axis shows signal strength in logarithmic scale from -25…25 dB.

8.3.2 Filter

Filter parameters were measured separately before connecting the filter to the 2nd frequency multiplier output. Figure 23 shows filter forward gain when it is tuned around 438 – 440 MHz.

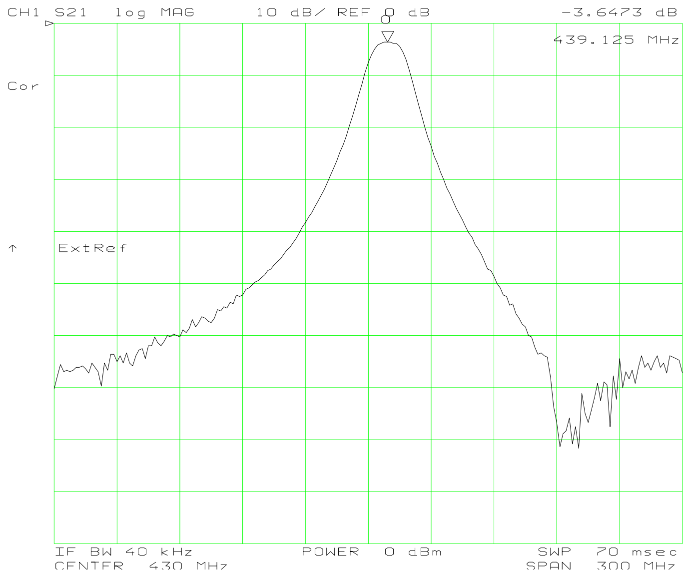


Figure 23: Filter forward gain measurement. Filter is tuned to 438-440 MHz. Horizontal axis shows signal frequency from 280…580 MHz and vertical axis shows signal strength in logarithmic scale from -100…0 dB.

8.3.3 2nd frequency multiplier and filter

2nd frequency multiplier was tuned to four times the 109 MHz, using the parameters from simulation. Figure 24 shows that maximum gain is about 9.5 dB with 10 dB reference value around 433 MHz. This frequency is suitable for using the beacon on the ground and therefore can be used when testing.

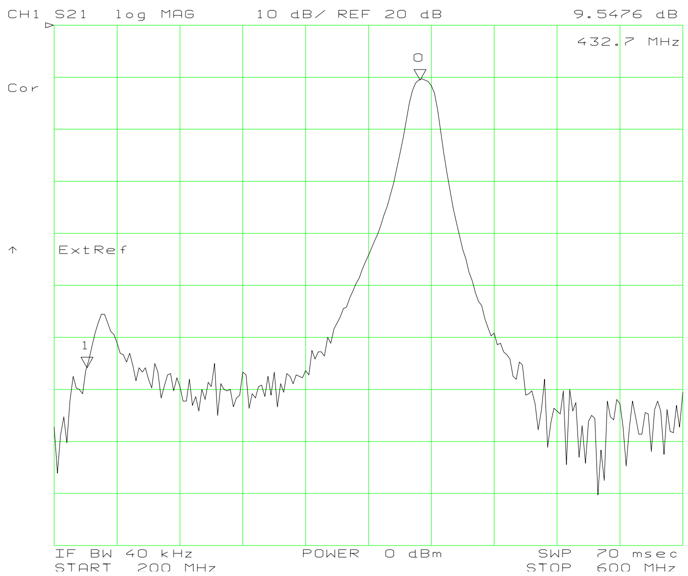


Figure 24: 2nd frequency multiplier forward gain measurement. The peak is around 433 MHz and next peak is around 220 MHz. Horizontal axis shows signal frequency from 200…600 MHz and vertical axis shows signal strength in logarithmic scale from -80…20 dB.

For spectrum analysis a signal generator was connected to 2nd frequency multiplier input. Input signal parameters were:

- Frequency 108 MHz
- Signal strength -8.8 dBm

Frequency spectrum was measured from the filter output. Figure 25 shows that a strong lower frequency harmonic is present around 220 MHz and a weaker harmonic around 330 MHz.

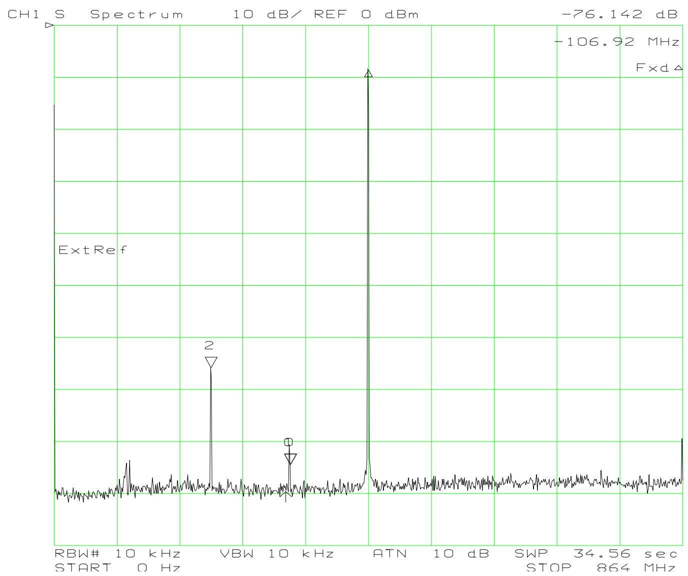


Figure 25: Frequency spectrum measured from filter output. Input signal is connected to 2nd frequency multiplier. Frequency range is shown on horizontal axis from 0…864 MHz, signal strength is shown on the vertical axis from -100…0 dB. Attenuator value is 10 dBm.

8.3.4 Frequency multipliers with filter and final stage

For spectrum analysis of both frequency multipliers and final stage together a signal generator was connected to 1st frequency multiplier input. Input signal parameters were:

- Frequency 108 MHz
- Signal strength -8.8 dBm

Morse key was turned on and measurements were made from final stage output. Figure 26 shows that signal strength on 431 MHz is -65.3 dB, this is lower than expected and suggests that buffer resonant circuit is tuned to much higher frequency compared with simulation results. In addition a higher frequency harmonic appears to be around 2* 430 MHz.

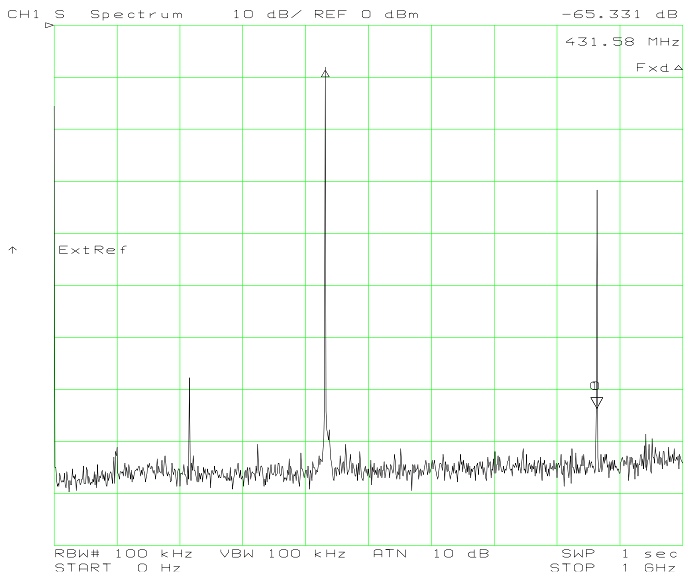


Figure 26: Frequency spectrum measured from final stage output. Input signal is connected to 1st frequency multiplier. Frequency range is shown on horizontal axis from 0…1000 MHz, signal strength is shown on the vertical axis from -100…0 dB. Attenuator value is 10 dBm.

Circuit parameters were adjusted and new measurements are shown on Figure 28 with Morse key on. Now the output signal strength is around 9 dB and the higher order harmonic around 2 * 430 MHz is being suppressed.

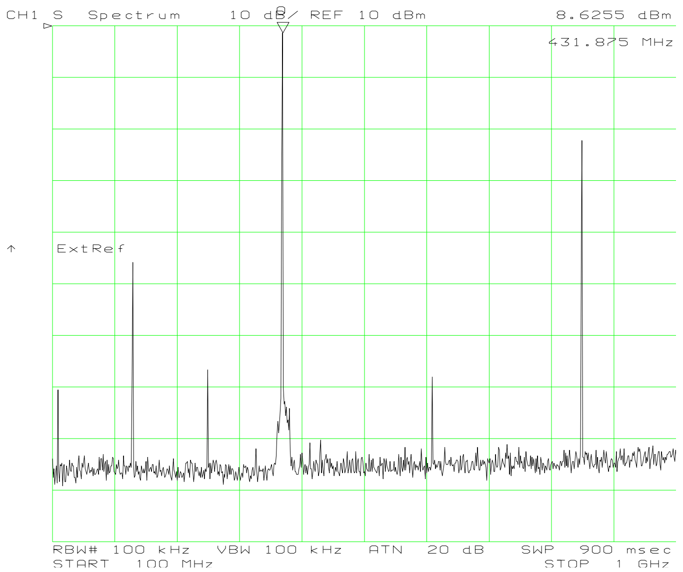


Figure 27: Frequency spectrum measured from final stage output. Morse key is on. Input signal is connected to 1st frequency multiplier. Frequency range is shown on horizontal axis from 100…1000 MHz, signal strength is shown on the vertical axis from -90…10 dB. Attenuator value is 20 dBm.

Figure 27 shows frequency spectrum with Morse key turned off. One higher order harmonic around 2 * 430 MHz is present and output signal strength is -20.3 dB.

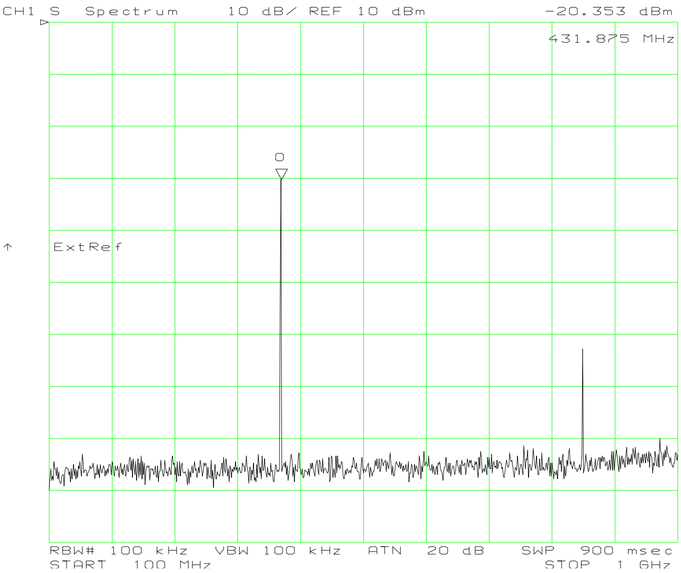


Figure 28: Frequency spectrum measured from final stage output. Morse key is off. Input signal is connected to 1st frequency multiplier. Frequency range is shown on horizontal axis from 100…1000 MHz, signal strength is shown on the vertical axis from -90…10 dB. Attenuator value is 20 dBm.

8.3.5 Quartz oscillator

Quartz capacity was measured to be 4.7 pF so a resonator of 370 nH should be suitable to connect in parallel with the quartz.

Quartz oscillator resonant circuit forward power peak gain can be tuned from 98.3 MHz to 120.7 MHz with a trimmer capacitor. Figure 29 shows the circuit tuned to the lowest possible frequency and Figure 30 shows the circuit tuned to the highest possible frequency.

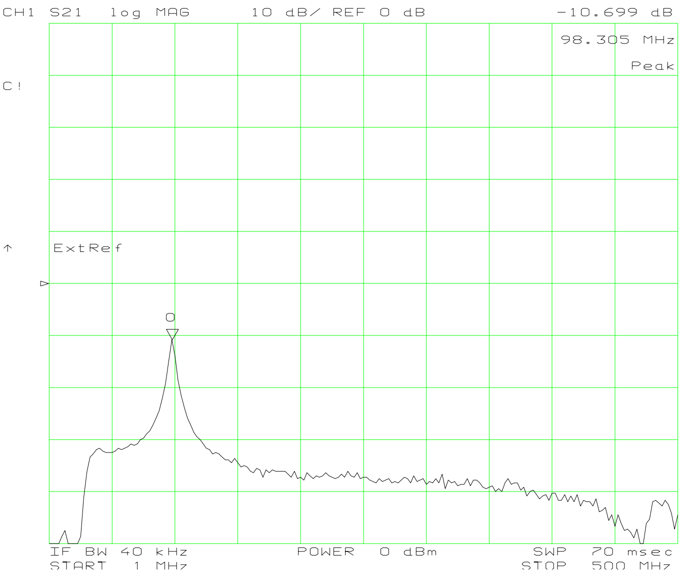


Figure 29: Quartz oscillator resonant circuit forward gain measurement. Circuit is tuned with a trimmer capacitor to the lowest possible frequency. Horizontal axis shows signal frequency from 1…500 MHz and vertical axis shows signal strength in logarithmic scale from -100…0 dB.

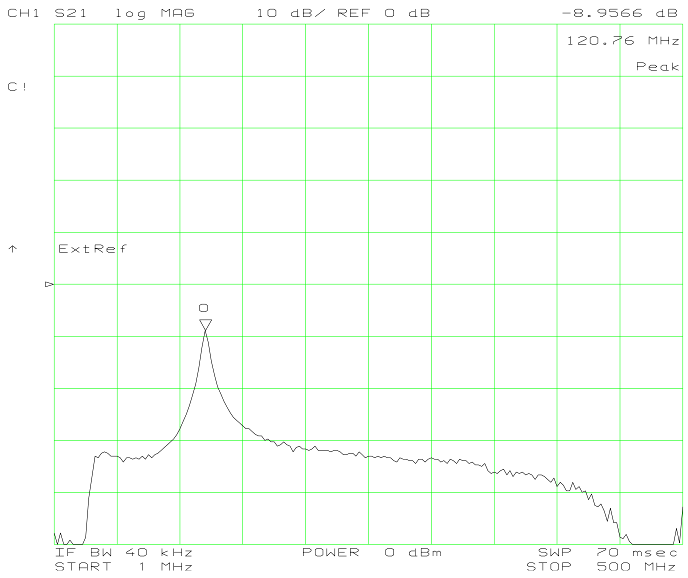


Figure 30: Quartz oscillator resonant circuit forward gain measurement. Circuit is tuned with a trimmer capacitor to the highest possible frequency. Horizontal axis shows signal frequency from 1…500 MHz and vertical axis shows signal strength in logarithmic scale from -100…0 dB.

The output spectrum of quartz oscillator circuit is shown on Figure 31. The presence of lower order harmonics should be noted.

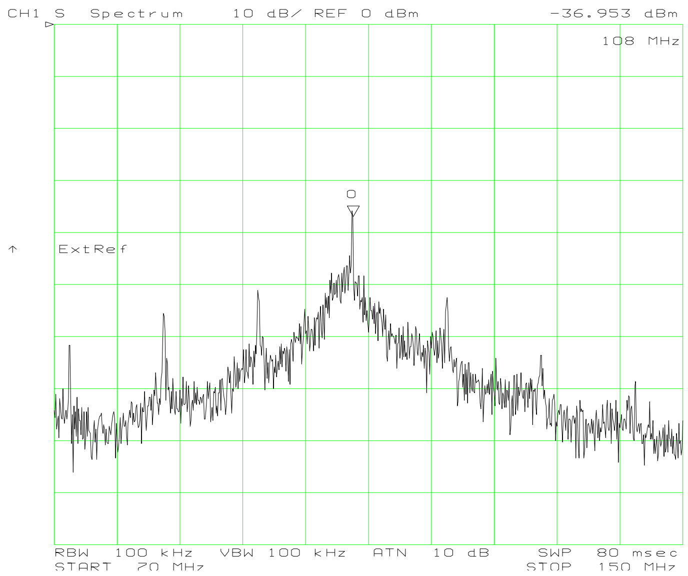


Figure 31: Frequency spectrum of quartz oscillator circuit output. Frequency range is shown on horizontal axis from 70…150 MHz, signal strength is shown on the vertical axis from -100…0 dB. Attenuator value is 10 dBm.

8.3.6 Transmission chain as a whole

The output spectrum of the whole transmission chain is shown on Figure 32. Signal strength at 431 MHz is 8.9 dBm.

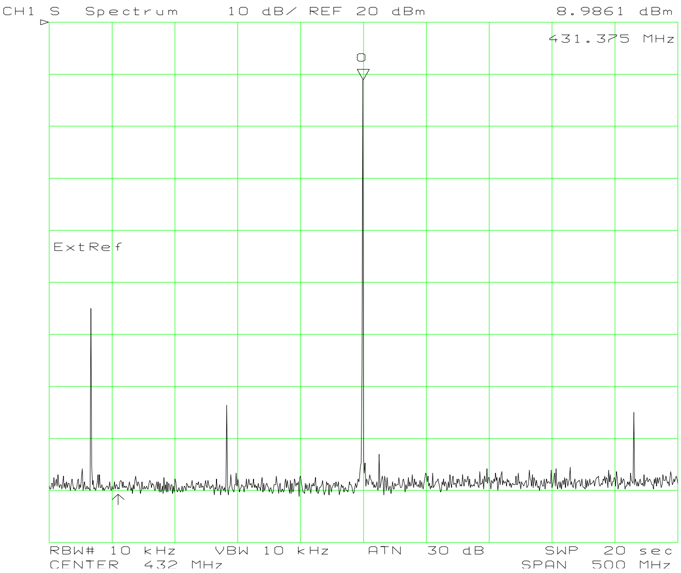


Figure 32: Frequency spectrum of the whole transmission chain. Frequency range is shown on horizontal axis from 182…682 MHz, signal strength is shown on the vertical axis from -80…20 dB. Attenuator value is 30 dBm.

Signal strength ratio measurement for on / off keying is shown on Figure 33. The ratio is -28 dB.

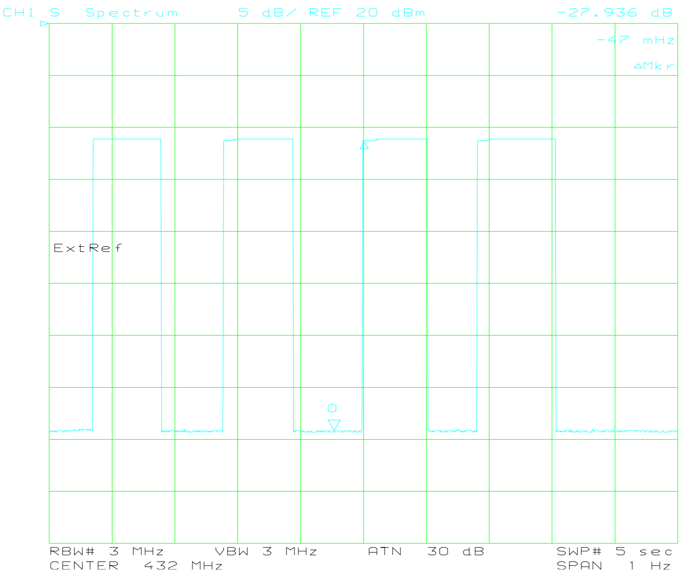


Figure 33: Signal strength change during on / off keying, captured with spectrum analyzer. Frequency range is shown on horizontal axis, it is centered to 432 MHz with 1 Hz span, signal strength on the vertical axis is from -30…20 dB. Attenuator value is 20 dBm.

8.3.7 Technical parameters

Additional technical parameters that were measured:

- Mass of the prototype PBC with components is 18 g.
- Current when the Morse key is off is 11 mA with 5.0 V supply voltage.
- Current when the Morse key is on is 25 mA with 5.0 V supply voltage.

9 Discussion

9.1 Technical parameters

Based on the measured technical parameters of the prototype we can estimate the beacon electrical power usage as shown in Table 8. An estimation of average current is when Morse key is on for 50% of the time. For average power estimation, a transmission length of 1 minute was used.

Table 8: Estimated beacon power usage during different operating modes.

Beacon period	Voltage (V)	Current (mA)			Power (mW)	
		Key off	Key on	Average	Average	Peak
3 minutes	5.0	11	25	18	30	125
5 minutes	5.0	11	25	18	18	125

Beacon mass can be estimated to be one third of the prototype mass because the heaviest component – SMB connector is not used and the free space on the prototype board suggests that components can be placed together on a smaller board area.

9.2 Quartz oscillator output signal

In a proper 3rd of 5th overtone quartz oscillator only higher order harmonics are present in frequency spectrum. This was not the case with current quartz oscillator where the crystal base frequency harmonics were present below 109 MHz. Adding an inductor in parallel with the crystal did not seem to affect this. This suggests that the problem lies in the quartz crystal, to verify that a different quartz crystal in similar frequency is needed.

9.3 Improving Morse on / off keying signal strength ratio

In the current prototype, the signal strength ratio of on / off keying was about 30 dB, which is to be expected when the keying controls only one stage of the transmission chain. To further improve the on / off keying signal ratio, the keying circuit should control an earlier stage, for example keying the 2nd frequency multiplier stage should give an additional 30 dB signal strength ratio.

9.4 Improving output signal frequency spectrum

To achieve a better SNR, somewhat can be done by tuning each stage of the transmission chain more accurately. To suppress the twice the 109 MHz harmonic in transmission chain output, an additional band-pass filter could be added after the final stage.

9.5 PCB design

To enable the design of large ground areas around filter components a 4 layer PCB is recommended for the COM PCB. In the current prototype, a compromise was made and a signal wire was placed directly under the filter to keep the length of the wire optimal.

Supply voltage de-coupling capacitors can be doubled to reduce the risk of cold solder joints.

Supply voltage de-coupling capacitors should be placed as close to the related inductors as possible to reduce the parasitic capacitance of the circuit. This should result in schematic simulations corresponding to the prototype circuit more accurately.

10 Conclusion

All goals defined for this thesis were fully completed.

The main goals of the work were to analyze requirements for the beacon, based on the analysis, propose a beacon design for ESTCube-1 and to develop a radio frequency electronics prototype of the beacon. This involved the analysis of other CubeSat projects beacon implementations.

The most important results of this work are:

- Based on beacon link budgets a 100 mW transmit power is sufficient for reliable communications between the ESTCube-1 and a ground station with minimum requirements.
- Beacon transmission periods were proposed:
    - 3 minute period for normal operating conditions would enable the ground station to receive at least 2 beacon transmissions during most of the visible passes.
    - 5 minute period can be used in low power operating mode, this should conserve power and still enable the ground station to receive at least 1 beacon transmission during most of the visible passes and at least 2 transmissions during half of the visible passes.
- Beacon shall use CW Morse transmission mode with transmission speed of 17 words per minute. The implementation of JT-4 modulation is also feasible.
- As a subset of satellite telemetry data, the preliminary contents of the beacon data were determined.
- The frequency coordination process involving IARU, ERAU and TJA was started. The exact beacon transmit frequency shall be allocated by IARU frequency coordination authorities.
- Based on the requirements analysis, ESTCube-1 beacon design was proposed and a radio frequency electronics prototype was developed. The concept of this radio frequency electronics was proved to work. To achieve better on / off keying signal ratio and signal to noise ratio a partial redesign of the prototype is needed.

Recommended future steps based on the work are:

- Based on beacon data, different data encoding schemes should be analyzed and a solution for ESTCube-1 beacon proposed.
- Based on the radio frequency electronics prototype the oscillator frequency compensation should be tested.
- Using the same prototype board, the following beacon components should be tested:
  - Analogue-digital converter
  - Digital-analogue converter
  - Current measurement unit
  - Temperature sensor
- Beacon software prototype should be developed.

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12 ESTCube-1 satelliidi raadiomajakas

Urmas Kvell

Kokkuvõte

Eesti tudengisatelliidi ESTCube-1 missiooniks on elektrilise päikesepurje tehnoloogia esimeste komponentide katsetamine kosmoses [1]. ESTCube-1 põhineb CubeSat standardil, mis seab raadiomajaka arendamisele teatavad nõuded [8]. Satelliit planeeritakse orbiidile viia aastal 2012.

Satelliidi sidesüsteem kasutab amatöörraadioside sagedusalasid:

- 145 – 146 MHz vastuvõtukanaliteks
- 435 – 438 MHz saatmiskanaliteks

Erinevaid saatmiskanaleid on kokku kaks:

- Raadiomajakas – edastab perioodiliselt olulisemaid telemeetriaandmeid, mille abil on võimalik saada ülevaade satelliidi peal toimuvast. Raadiomajaka signaali kasutatakse ka satelliidi jälgimiseks ülelennu ajal.
- Põhiline saatmiskanal – saadab vastava käsu peale kõik teatud ajaperioodil kogutud telemeetriaandmed.

Kõik käesolevale magistritööle seatud eesmärgid täideti. Töö peamine eesmärk oli analüüsida Eesti Tudengisatelliidi ESTCube-1 raadiomajaka ehitamiseks vajalikke nõudeid ja analüüsile tuginedes pakkuda välja raadiomajaka põhimõtteline ehitus ja tarkvaralahendus ning arendada välja raadiomajaka esimene raadiosageduselektroonika prototüüp. Töö käigus analüüsiti ka teiste CubeSat standardile vastavate satelliitide raadiomajakate teostust.

Töö olulisemad tulemused ja järeldused on:

- Sidekanali analüüs näitas, et 100 mW saatmisvõimsus on piisav, et tagada edukas side miinimumnõudeid täitva baasjaama ja satelliidi vahel.
- Tavaolukorras piisab kasutada 3 minutilist raadiomajaka saatmisperioodi, see võimaldab vastu võtta vähemalt 2 sideseanssi enamuste ülelendude jooksul.

- Madala energiatarbe olukorras piisab kasutada 5 minutilist raadiomajaka saatmisperioodi, see võimaldab vastu võtta vähemalt ühe sideseansi enamuste ülelendude jooksul ning vähemalt 2 sideseanssi pooltel ülelendudel.
- Majakas kasutab info edastamiseks Morse koodi, kiirusega 17 sõna minutis, lisavõimalusena saab kasutusele võtta JT-4 tüüpi modulatsiooni.
- Raadiomaja täpne saatesagedus määratakse Rahvusvahelise Amatöörraadioside Liidu (ingl. k. *International Amateur Radio Union*) poolt. Saatesageduse koordineerimisega on veel seotud Eesti Raadioamatööride Ühing ja Tehnilise Järelevalve Amet, kellega on samuti läbirääkimisi alustatud.
- Tuginedes nõuete analüüsile pakuti välja ESTCube-1 raadiomajaka põhimõtteline ehitus- ja tarkvaraskeem, analüüsiti raadiomajaka töö käigus tekkida võivaid riske ning koostati raadiosageduselektroonika prototüüp. Prototüübi põhjal tuvastati, et selline elektroonikalahendus põhimõtteliselt töötab, kuid parema Morse tastimise dünaamika või signaal-müra suhte jaoks oleks vaja prototüüp osaliselt ümber disainida.

Tuginedes käesoleva töö tulemustele on soovitatav järgmiste sammudena teha:

- Raadiomajaka andmete tabeli põhjal uurida ja välja töötada andmete kodeerimise lahendus.
- Testida ostsillaatori sageduse kompenseerimist.
- Prototüübi põhjal testida järgnevaid raadiomajaka osi:
    - Analoog-digitaal muundi
    - Digitaal-analoog muundi
    - Voolutarbe mõõtja
    - Temperatuuri andur
- Koostada raadiomajaka tarkvaralahenduse prototüüp.

Appendix A: Orbital simulations

Orbital simulations were made to determine the number of visible passes from Tartu University satellite ground station and the length of these passes [11]. Simulation software was AGI STK [12].

Parameters for the ground station were:

- Latitude 58.25°
- Longitude 26.45°
- Line of sight is needed for communication
- Minimum elevation angle for line of sight is 4° from the horizon

Satellite orbits were Sun-synchronous near-polar orbits with inclination of 97°. Simulations were made for two different orbit heights:

- 500 km – Table 9
- 900 km – Table 10

Simulation time period was 24 hours.

Table 9: Orbital simulation for visible passes over Tartu University satellite ground station. Simulation time period was 24 h. Orbit height was 500 km.

Pass nr.	Start time (UTCG)	Stop time (UTCG)	Duration (seconds)	Duration (minutes)
1	1 Jul 2007 12:26:34.010	1 Jul 2007 12:34:34.536	480.526	8.0
2	1 Jul 2007 18:36:54.578	1 Jul 2007 18:38:36.366	101.788	1.7
3	1 Jul 2007 20:06:04.650	1 Jul 2007 20:14:29.201	504.551	8.4
4	1 Jul 2007 21:38:57.088	1 Jul 2007 21:48:38.189	581.102	9.7
5	1 Jul 2007 23:15:18.622	1 Jul 2007 23:21:28.455	369.834	6.2
6	2 Jul 2007 09:01:01.004	2 Jul 2007 09:06:26.506	325.502	5.4
7	2 Jul 2007 10:33:36.733	2 Jul 2007 10:43:13.913	577.180	9.6
Statistics				
Minimum duration			101.788	1.7
Maximum duration			581.102	9.7
Mean duration			420.069	7.0
Total duration			2940.482	49.0

Table 10: Orbital simulation for visible passes over Tartu University satellite ground station. Simulation time period was 24 h. Orbit height was 900 km.

Pass nr.	Start time (UTCG)	Stop time (UTCG)	Duration (seconds)	Duration (minutes)
1	1 Jul 2007 12:26:33.715	1 Jul 2007 12:39:48.148	794.432	13.2
2	1 Jul 2007 14:08:33.884	1 Jul 2007 14:18:20.855	586.971	9.8
3	1 Jul 2007 15:49:40.170	1 Jul 2007 15:56:03.218	383.048	6.4
4	1 Jul 2007 17:28:05.583	1 Jul 2007 17:36:04.495	478.912	8.0
5	1 Jul 2007 19:05:57.129	1 Jul 2007 19:17:52.008	714.879	11.9
6	1 Jul 2007 20:45:43.795	1 Jul 2007 20:59:55.582	851.788	14.2
7	1 Jul 2007 22:28:24.157	1 Jul 2007 22:41:40.829	796.673	13.3
8	2 Jul 2007 00:16:08.591	2 Jul 2007 00:21:23.192	314.601	5.2
9	2 Jul 2007 09:06:36.769	2 Jul 2007 09:18:04.075	687.306	11.5
10	2 Jul 2007 10:47:59.468	2 Jul 2007 11:02:17.001	857.533	14.3
Statistics				
Minimum duration			314.601	5.2
Maximum duration			857.533	14.3
Mean duration			646.614	10.8
Total duration			6466.142	107.8

Appendix B: Proposed telemetry data

Beacon contains a subset of satellite telemetry data, which is shown in Table 11.

There are two distinguished types of telemetry data:

- Monitoring data – old data shall be automatically deleted after a certain time period, for example 48 hours.
- Experiment data – a subset of monitoring data, which is stored separately during the experiment. This data shall be preserved until manually deleted from on-board memory.

Table 11: Proposed telemetry data for ESTCube-1.

Sub-system	Component	Data description	Measured by	Data type
EPS	6 Solar panels	Solar panel voltage	EPS	Monitoring
		Solar panel current	EPS	
		Solar panel temperature	EPS	
	2 Batteries	Battery voltage	EPS	Experiment
		Battery temperature	EPS	
		Battery discharge current	EPS	Monitoring
		Battery converter temperature	EPS	
		Battery charge current	EPS	
	Microcontroller	Operation phase	EPS	Experiment
		Firmware version	EPS	
		Failure mode	EPS	
		Zombie check	EPS	Monitoring
		Active sensors	EPS	
	Power lines	Main power bus voltage	EPS	Experiment
		Power bus current	EPS	Monitoring
		Converter status	EPS	Experiment
		Converter temperature	EPS	Monitoring
	Other	Antenna deployment	EPS	
		CDHS processor switch	EPS	Experiment
	Calculated	Power budget	EPS	Experiment
		Satellite direction based on solar panels	EPS	Monitoring

Sub-system	Component	Data description	Measured by	Data type
ADCS	Sensors	Magnetometer reading	CDHS	Experiment
		Magnetometer status	CDHS	
		Gyro sensor reading	CDHS	
		Gyro sensor status	CDHS	
		Sun sensor reading	CDHS	Monitoring
		Sun sensor status	CDHS	
	Coils	Coil current direction	CDHS	Monitoring
		Coil activation time	CDHS	
		Coil driver status	CDHS	
	Other	Operating mode	CDHS	Experiment
		Failure mode	CDHS	
CDHS	Real time clock	Satellite time	CDHS	Experiment
	Microcontroller	Operating mode	CDHS	Experiment
		Failure mode	CDHS	
		Reset counter	CDHS	
		System error log	CDHS	
		Other subsystem check	CDHS	
		Microcontroller core temperature	CDHS	Monitoring
		Percentage of free memory	CDHS	
		Percentage of average resources used	CDHS	
		Percentage of RAM used	CDHS	
		Percentage of Flash used	CDHS	
		Firmware version	CDHS	
COM	RF power measuring unit	Transmission forward power	COM	Monitoring
		Transmission reflected power	COM	
	Temperature sensor	RF power amplifier temperature	COM	
	Microcontroller	Satellite identificator	COM	
		Operating mode	COM	
		Failure mode	COM	
TCS	Temperature sensors	Satellite temperature	CDHS	Monitoring
CAM	Camera module	RAW pictures	CAM	Experiment
	Microcontroller	Firmware version	CAM	Monitoring

Sub-system	Component	Data description	Measured by	Data type
CAM		Failure mode	CAM	Monitoring
Payload	Motor	Reel turning	CDHS	Experiment
		Launch lock status	CDHS	
		Reel lock status	CDHS	
		Failure mode	CDHS	
		Motor position (step counter)	CDHS	
		Motor temperature	CDHS	
	Electron gun modules	Module current	CDHS	
		Module status	CDHS	
	Tether	Tether voltage	CDHS	
		Tether current	CDHS	
		Supply voltage	CDHS	