Lunar Rover Communications

Moron System - A Beacon System for the Lunar Zebro

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Abstract

With the re-emerging interest in exploring the moon, different types of space machines are in development. A beacon system is an essential part of all remote and inaccessible systems. It is responsible for analysing the machine's health state and autonomously reporting unusual events. These systems save resources in the spacecraft and on costs associated with mission control operations.

In this work, a small and efficient beacon system is developed for the Lunar Zebro, a small rover design, developed by the TU Delft team, aiming to get new data from the moon. For this, different methodologies are proposed to continuously analyse its systems and report any abnormal behaviour, with all relevant and necessary information back to the control centre, allowing a faster diagnosis and corrective action. This will also help discover the cause of failure which can help deploy preventive measures in future missions and acts as a secondary mission for the Rover. In this work it is also presented all the systems engineering and processes for creating the system architecture, from operational modes, message structure and components chosen.

Finally, a PCB was designed and tests were performed using EVMs, proving the reliability of the system's architecture which also complies with the list of requirements. However, it was not possible to obtain all the results needed to declare this Beacon a finished project due to supply chain delays.

Keywords: Lunar Zebro, Beacon system, Failure reporting system, Space grade, Moon Earth communications, System design and architecture

1. Introduction

1.1. Motivation

The moon is still a huge source of knowledge for humans. With this in mind, a small group of students and researchers from TU Delft started exploring the possibility of sending a few robots to the moon. Lunar Zebro, the smallest and lightest luner rover, was born from this idea.

Having a new robot exploring the moon is a big step for TU Delft, however, this small machine needs to be able to survive extreme conditions in order to collect and transmit data back to Earth correctly.

In general, from an engineer's perspective and for the sake of the overall space mission, knowing the health state of the machine operated is crucial. To maintain the systems running as they should, anomalies and unexpected conditions must be detected as soon as possible, and a fast proper diagnosis is critical. This can be extremely challenging when it comes to a space machine. The fact that they are not easily accessible by a human augments those needs, since physical repairs are not possible, and reprogramming the device with new software is laborious most of the time. To simplify this task, a low-rate signal can be transmitted back to Earth with a few bits indicating the actual state of the main computer and the state of some mission-critical components such as power delivery systems and communication modules. It can make the difference between not knowing what is going on with the robot and having a quick and easy solution for the problem.

This can be achieved using a a separate and independent system, that continues to function even if the robot is no longer working as it should. This will allow the engineers to better understand the reason for the malfunction of the rover, preventing it from happening in a future version of the robot. Moreover, using this end of life ping from the Beacon, it is possible to conduct other experiments and use the system's data to plan future lunar missions better.

With all those advantages in mind, the need for an independent Beacon subsystem for the next lunar Zebro emerged, becoming one of the essential parts of the third version of the robot.

1.2. The Lunar Zebro

Developed by a team from TU Delft, the robot from Figure 1 will travel to the moon, and after the lander's deployment on previously defined spots in the south pole, the doors will open, and the Zebro will be sent out. His first task is to report back to Earth and walk out of the shadow to recharge its batteries [10].

The rover will explore the lunar surface for the first

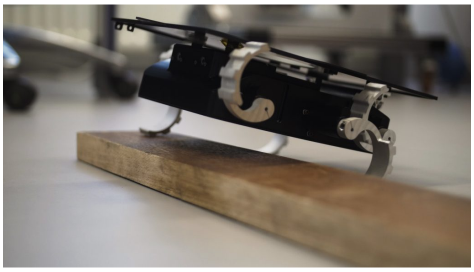


Figure 1: Lunar Zebro. Obtained from [10]

time and carry out ground imaging around the landing spot to study the effects of traditional landing on the lunar surface. Once this first mission is complete, the rover will walk as much distance as possible in order to test its resilience to the moon's adverse conditions, gathering information for the development of future missions [10].

Regarding the design of the robot, it is built with as few parts as possible to reduce size and weight. One of the most notable features is the asymmetrically aligned legs, which paired with a specially developed locomotion algorithm, maintains system stability while moving. It is also important to note that this design allows the rover to remove the upper layers of the lunar surface and collect information via its camera on how the depth of lunar regolith changes from one point to another. Additionally, these features will provide the first data towards studying this type of locomotion on lunar soil.

In the future, the Zebro's platform can be used not only for educational purposes but also for more ambitious projects with industry and institutional partners, like exploring Mars, creating a swarm of rovers on the moon, exploring different payloads and even creating a recording of cosmic radiation on the far side of the moon with the help of a swarm of Zebros retransmitting the data back to Earth [10].

1.3. State of the art

1.3.1 LIFELINE

The first study of a full-scale Beacon health monitoring system was conducted by the DOD in the nineties. LIFELINE was designed to become part of a constellation of different satellites, including the GPS constellation. The sub-system was prepared to do an onboard state assessment and send it as a 3-bit result combined with the spacecraft id and position state vector. However, the project stopped receiving funds and was never deployed due to concerns over operations and maintenance costs.[15][5]

1.3.2 JPL DS1 System

The next agency to show interest in Beacon monitoring was NASA, with the DS1 mission. To reduce the number of communications and the operation cost, JPL designed a system that was able to evaluate the state of the spacecraft in 2 bits and transmit this to Earth through four tones, described in Table 1, revealing how urgent data retrieving and ground control action was, concept summarized in Figure 2.

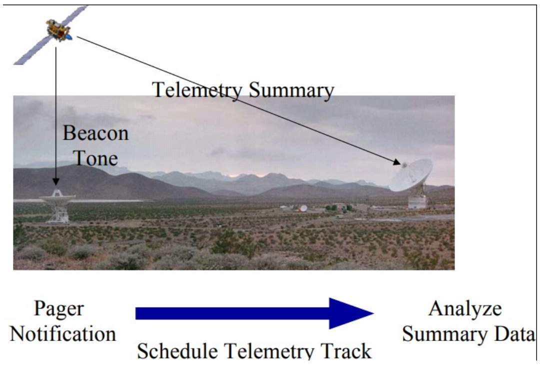


Figure 2: DS1 Beacon concept adapted from [4]

These tones were transmitted using phase modulation. Meaning that every tone appears around the carry frequency[14]. The carrier frequency is completely suppressed. The resulting downlink spectrum consists of tones at odd multiples of the subcarrier frequency above and below the carrier. Four pairs of tones are needed to represent the four possible messages[4].

Table 1: Tone's Meaning of JPL Beacon system for different spacecrafts [13].

RF state	DS-1	Europa Orbiter (Cruise Ops)	Europa Orbiter (Mapping Orbit)	Genesis
No Detection	Help	Ok	Ok	Help
Tone 1	OK	OK	OK	Collector Plate 1 OK
Tone 2	Downlink within 2 weeks	Downlink within 1 week	Downlink within 3 days	Collector Plate 2 OK
Tone 3	Downlink within 2 days	Downlink within 3 days	Downlink within 1 week	Collector Plate 3 OK
Tone 4	Urgent, downlink as soon as possible	Urgent, downlink as soon as possible	Urgent, downlink as soon as possible	Downlink within 1 week

To better analyse the spacecraft data, and reduce false alarm events and attribute priorities and different emergency level to different failures, JPL DS1 system was programmed using a new software subsystem, the ELMER.

The ELMER subsystem was used as a new way to detect out of ordinary results, since this is trained as a neural network and new adaptive alarm limits can be associated with failures. After detecting abnormal results, a data summary was created comprising only relevant engineering data for further mission control analysis. This subsystem was also responsible for assigning one of the 4 available tones, present in Table 1 to the message. This data was sent using the normal telemetry link after Beacon contact and command center contact with the spacecraft[4].

One of the advantages of this system is that it does not need Earth contact to send the Beacon system. This reduced risk in the missions since if something not normal is happening, the mission control is almost immediately notified, something that did not happen in previous spacecrafts. Besides this, as predicted, the cost associated with the mission using the Beacon were significantly reduced.

This particular system was implemented with minimal changes to several spacecrafts, due to it's proving effectiveness in cost and undetected failure reductions.

1.4. SAPPHIRE

Equally, in the late nineties, early two-thousands, the micro-satellite community started exploring the Beacon system idea with SAPPHIRE [9]. Also, using the two-bit, four tone code described in Table 2, the spacecraft internal computer would do a simple analysis of the systems onboard and report to Earth, minimizing the human resources allocated to the mission control of the project. The main difference from the JPL to this system was the usage of an amateur radio protocol (AX.25) to communicate the Beacon signals, allowing low-cost receiving stations back on Earth [7], facilitating continuous monitoring of the spacecraft health while standard mission data is downloading and processed by the command centre. This is possible since the Beacon signals are transmitted within one second. A disadvantage of this system is that the system runs in the main computer and not in a separate and independent system as in the DS1 system. This means that the Beacon is powered by the same systems of the satellite, not having an independent power source and processing unit in case of failure. Another difference to the JPL system is the usage of pulse modulation instead of the phase shift.

Table 2: SAPPHIRE Beacon modes and States[7] [8].

Beacon Mode	Vehicle Mode	Condition Represented	Operator Interpretation
Normal	Standard	Healthy	Continue currently planned operations
Abnormal	Standard	Out of limit telemetry	Respond within 30 hours
Critical	Safe	CPU Controlled Safe Mode	Respond immediately; onboard troubleshooting data available
Emergency	Safe	CPU Reset Induced Safe Mode	Respond immediately; onboard troubleshooting data available

1.4.1 GeneSat-1 System

Later, in 2006, the GeneSat-1 launched, carrying with it a new Beacon sub-system to test as a second life mission. Developed by NASA in partnership with Santa Clara University, the communications were only unilateral. Using the same amateur protocol as the SAPPHIRE (AX.25) and operating in the UHF band, a 64 bytes data package containing real-time payload temperature, bus time and solar panel current is sent back to Earth.[15]

Although automation on on-board detection was not present, and posterior analysis of the downloaded data was required to take appropriate action on the satellite's systems, the system proved to be effective and was further tested in 3 other small cube-sats.

The system has been operating since January of 2010 using four ground stations and successfully forwarding Beacon data to mission control. Part of the experiment was to determine the data frequency which the current Beacon monitoring network provides. Successful detection of various spacecraft and ground segments anomalies has shown that a frequency of ten packets per week is an acceptable number. However, having the power to control the number of packages seems useful, increasing the frequency of those during critical stages of the mission.

2. Architecture

2.1. Requirements

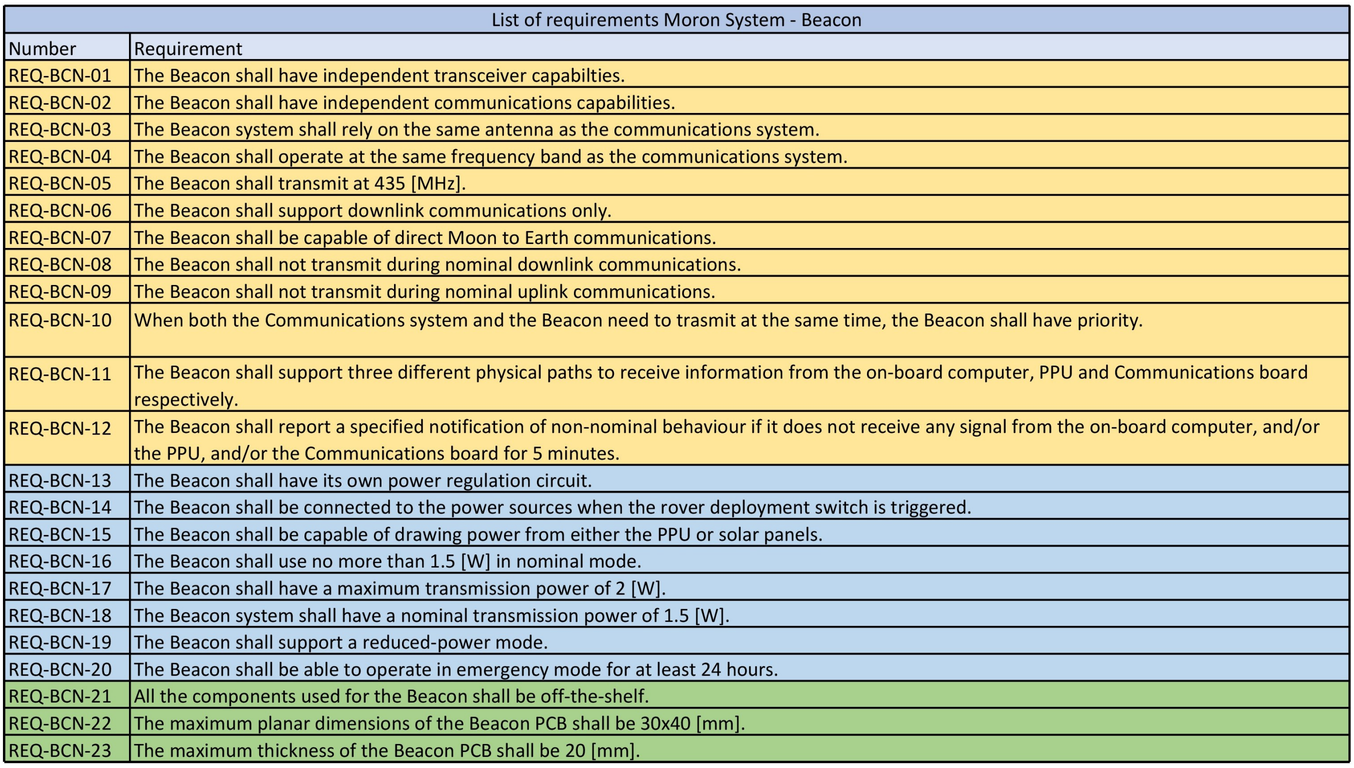
In order to design the system, a set of requirements is needed. This not only specifies the physical characteristics of the Beacon, such as size and weight but also more technical aspects like the use of the same antenna as the Coms-Board or the use of two independent power sources. Another point present in the requirements is the use of modes that describe the different behaviours of the Beacon in several distinct scenarios.

In this Beacon version, it is also specified that the Beacon should report the status of the ZPU (Zebro Processing Unit), PPU (Power Processing Unit), Coms-Board (Communications Board), battery and solar panels. The complete set of requirements is presented in Figure 3.

2.2. Modes of operation

To better describe the behaviour of the Beacon in several stages of the mission a set of modes of operation were developed. These describes not only what the Beacon should do but also the other systems that should report to the Beacon and the frequency of messages that the Beacon should send back to Earth.

In total six modes are specified namely No Power, Safe mode, Nominal mode, Alert mode, Night mode and Emer-



List of requirements Moron System - Beacon

Number	Requirement
REQ-BCN-01	The Beacon shall have independent transceiver capabilties.
REQ-BCN-02	The Beacon shall have independent communications capabilities.
REQ-BCN-03	The Beacon system shall rely on the same antenna as the communications system.
REQ-BCN-04	The Beacon shall operate at the same frequency band as the communications system.
REQ-BCN-05	The Beacon shall transmit at 435 [MHz].
REQ-BCN-06	The Beacon shall support downlink communications only.
REQ-BCN-07	The Beacon shall be capable of direct Moon to Earth communications.
REQ-BCN-08	The Beacon shall not transmit during nominal downlink communications.
REQ-BCN-09	The Beacon shall not transmit during nominal uplink communications.
REQ-BCN-10	When both the Communications system and the Beacon need to trasmit at the same time, the Beacon shall have priority.
REQ-BCN-11	The Beacon shall support three different physical paths to receive information from the on-board computer, PPU and Communications board respectively.
REQ-BCN-12	The Beacon shall report a specified notification of non-nominal behaviour if it does not receive any signal from the on-board computer, and/or the PPU, and/or the Communications board for 5 minutes.
REQ-BCN-13	The Beacon shall have its own power regulation circuit.
REQ-BCN-14	The Beacon shall be connected to the power sources when the rover deployment switch is triggered.
REQ-BCN-15	The Beacon shall be capable of drawing power from either the PPU or solar panels.
REQ-BCN-16	The Beacon shall use no more than 1.5 [W] in nominal mode.
REQ-BCN-17	The Beacon shall have a maximum transmission power of 2 [W].
REQ-BCN-18	The Beacon system shall have a nominal transmission power of 1.5 [W].
REQ-BCN-19	The Beacon shall support a reduced-power mode.
REQ-BCN-20	The Beacon shall be able to operate in emergency mode for at least 24 hours.
REQ-BCN-21	All the components used for the Beacon shall be off-the-shelf.
REQ-BCN-22	The maximum planar dimensions of the Beacon PCB shall be 30x40 [mm].
REQ-BCN-23	The maximum thickness of the Beacon PCB shall be 20 [mm].

Figure 3: List of system requirements for the Moron System.

gency mode.

2.2.1 No Power mode

This is the mode that the Beacon is when the rover is in transit. In reality, the Beacon does not receive any power in this mode, so nothing is expected. This mode ends when the rover is deployed.

2.2.2 Safe mode

In safe mode, the Beacon is waiting for all the other rover system to boot and report a successful boot. If all of them successfully boot, then it goes into Nominal mode. If for some reason, one or more systems do not report a successful boot in fifteen minutes, then the Beacon goes to Alert mode.

In this mode, the Beacon sends to Earth a message every minutes with all the systems that already had booted and the internal Beacon temperature.

2.2.3 Nominal Mode

In this mode, the Beacon does not report anything to Earth. In fact it is only listening for the suppressing messages from the other systems indicating that everything is operating correctly. Only if one or more systems fail this signals, then the Beacon transits to Alert mode. Alert Mode In alert mode one or more systems have fail to report their status. In this case, the Beacon sends a message every five minutes with the systems that have failed and that are operating correctly and also the internal temperature.

From this mode, if the system starts reporting again, then the Beacon goes to Nominal mode.

2.2.4 Night mode

In case the ZPU and the PPU signal the Beacon to enter night mode, then the Beacon starts operating in this mode until one of the systems signal the Beacon to leave the mode.

This mode is used during moon night and the main purpose is to save power. For that, the system is only reporting about the solar panels, battery and PPU once every twelve hours. In the messages the internal temperature is also sent.

2.2.5 Emergency mode

In emergency mode both Beacon power sources have failed. In this case the Beacon is only powered by its internal battery. To save power the Beacon only sends five messages spaced equally in 24 hours. This messages only have the temperature and a special predefined code that the ground segment can interpret as the Beacon in emergency mode.

2.3. Subsystems

The Beacon architecture is divided into three subsystems as seen in Figure 4.

2.3.1 Control Subsystem

The first one is a simple microcontroller responsible for receiving the different signals from the other rover systems and deciding in what mode the Beacon should operate.

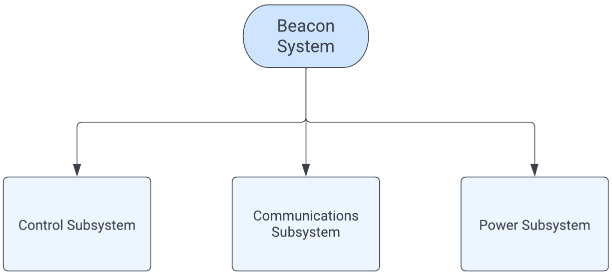


Figure 4: Beacon System schematic.

These also receive information from the power subsystem to understand the status of the different Beacon's power sources.

In addition, this subsystem has a temperature sensor and sends this information back to Earth using the communication subsystem.

Lastly, this subsystem is responsible for composing the different messages and relaying those to the communications subsystem.

2.3.2 Communications Subsystem

The task of this subsystem is only to send the information composed by the control subsystem back to the GS.

The subsystem is a transceiver responsible for transforming the message received from the control subsystem into a radio signal, using the correct frequency and modulation, in this case, OOK or FSK, and passing this to a power amplifier that increases the power of this signal so that the GS have better reception of the signal.

2.3.3 Power Subsystem

The power subsystem is responsible for independently generating the different voltage levels required by the other Beacon subsystems. It is also its job to analyse and report the status of the different power sources and decide from what power source the Beacon should be harvesting its energy at every given moment.

It is also this subsystem that is responsible for storing the energy needed for the Beacon when no power is provided to the Beacon.

2.4. Messages

2.4.1 Message structure

Depending on the Beacon's mode, different messages are sent to the GS differently spaced apart in time. In all modes, the message starts with a call sign comprised of 24 bits, followed by a 3-bit code indicating the mode of operation, described in Table 4.

After this, in most modes except in emergency and night, the message has three bits indicating the status of the three analysed Zebro systems and 2 bits indicating the status of the two power sources. In Table 3, is the association between the five bit code and the different fault that can occur. Lastly, it sends an integer with 9 bits with the temperature value rounded to the nearest integer. These give the Beacon the ability to send temperatures between -256 ºC and 255 ºC, as seen in Figure 5.

While in night mode, and since two of the three analysed systems are down, the 3-bit code indicating the status of the other systems becomes just one bit that represents the PPU status.

However, in emergency mode, the only information sent is the call sign and the 3-bit code indicating the mode to reduce the amount of power used to communicate to Earth.

With this, three different message structures are used, all present in Figure 5.

Table 3: Codes indicating the faulty system on Beacon's messages.

Bit Fault in	5	4	3	2	1
Solar Panel	X	X	X	X	1
Battery	X	X	X	1	X
ZPU	X	X	1	X	X
PPU	X	1	X	X	X
Coms System	1	X	X	X	X

Table 4: Codes representing the mode of operation on Beacon's messages.

Modes	Bit 3	Bit 2	Bit 1
Safe	0	0	0
Nominal	0	0	1
Night	0	1	0
Alert	0	1	1
Emergency	1	0	0

2.4.2 Message timings

The Table 5 is a summary table of the different timings of the messages in the several Beacon modes as well as the time requirements for relevant modes.

Table 5: Time between Beacon's messages.

Modes	Time between messages	Time requirements
Safe	1 minute	15 minutes maximum in this mode
Nominal	No messages	
Night	12 hours	
Alert	5 minutes	
Emergency	5 hours	Minimum 24 hours active

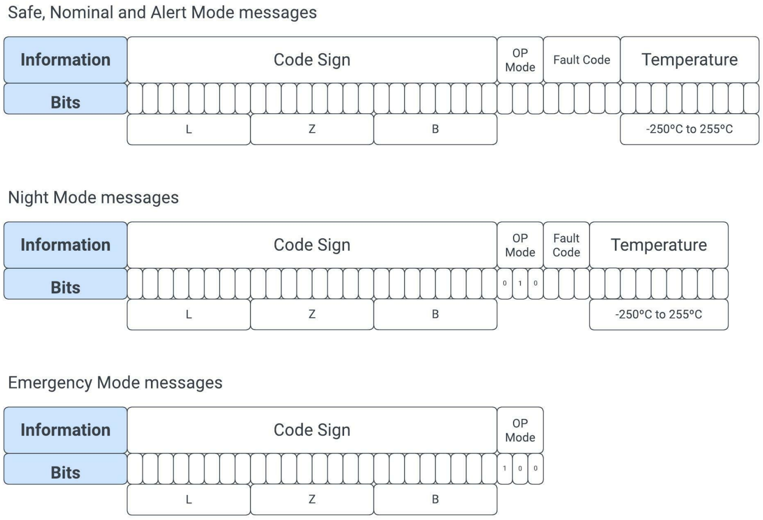


Figure 5: Beacon message format.

3. Board Design and Simulation

3.1. Control Subsystem

For this subsystem only two components are needed, a microprocessor and a temperature sensor. For the first one, the MSP430FR5969 from Texas Instruments is used, not only for the flight heritage and space-grade capabilities, but also because it is a low power microcontroler that meets all the necessary requirements described in the list below.

- At least four interrupt pins
- Low power mode available to be activated during the night and emergency modes to save as much battery as possible
- As less power consumption during nominal use as possible
- Working between 3.3 V or at 5 V DC.
- I^{2}C or OneWire Communication for temperature sensor
- SPI Communication for transceiver
- Built-in clock (real-time or relative)

Moreover, this component is already being used in other systems in the rover, making the adoption easier for the team. Lastly, the component has a real time clock that is going to facilitate the time counting between messages. All the information about the componet can be found on the datasheet in [12].

For the temperature sensor, a DS18B20 from Maxim is used, for its simplicity on implementation, the possibility of operating both at 3.3 V and 5 V. Another reason is the fact that the component has a built in low power mode that reduces the accuracy of the measurement but allows for a much lower power consumption [6]. Although this component does not have a space-grade version, the main purpose of the Beacon is not to send the temperature and this is the best cost-effective solution for getting the Beacon temperature.

3.2. Power subsystem

The objective of the power subsystem is to monitor both power sources of the Beacon and deliver the different voltage levels needed. According to the power budget calculations performed, the Beacon needs around 4 W while sending a message and 50 mW in idle state. These values can be seen in the power budget present in table 6.

For monitoring the souces, two LC4368 from Analog devices [1] are used. These components are going to protect the Beacon from undervoltage, overvoltage, and reverse current with a bi-direction circuit breaker. The acceptable values can be adjusted with the passive components connected to this components and these two LTC4368 are going to monitor both the solar panels and the battery and report to the microcontroler with the fault pin present in them.

For selecting the power source from which the Beacon should obtain its energy, a simple circuit using only passive components and a transistor was created. This circuit is present in Figure 6 and the simulation results for it are in Figure 7. The chosen transistor is the IRFL024ZTRPBF from Infineon, due to its Vgs of 4 V and a maximum Id current of 5.1 A.

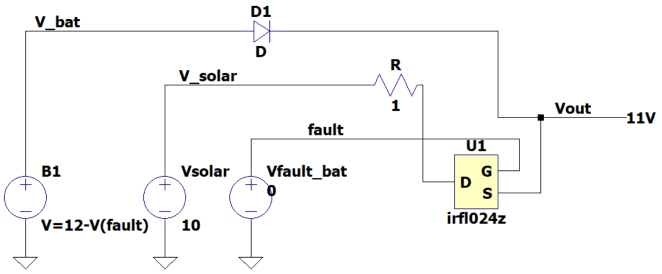


Figure 6: Power source switching circuit.

Table 6: Power budget for the Beacon System, with reference values from the datasheets [12], [6], [11], [3], [1].

System /Component	Supply voltage (V)	Load Current (mA)	Power consumption while sending message (W)	Power consumption in idle state (mW)
Detection Subsystem				
Microcontroler	3.3	7.28	0.024	1.19
Temperature Sensor	5	1	0.005	0.004
Coms Subsystem				
Transceiver	3.3	50	0.165	39.6
Power Amplifier	5	720	3.6	0.005
Power Subsystem				
Voltage Regulators	12		0.18	2.4
Total			3.974	43.199

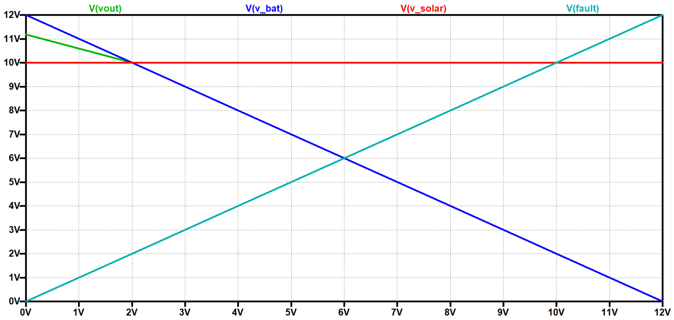


Figure 7: Power switching circuit simulation. In green the output voltage.

Lastly, for generating the different voltage levels, in this case, 3.3 V and 5 V, the LT1764-3.3 and the LT1764A both from Analog Devices [2] are used respectively. The first will generate a 3.3 V level and the second one is adjusted using external resistors to generate the 5 V. There were chosen due to their small size and weight when compared with other components and since each is able to output 3A, there is enough current for the Beacon to correctly operate.

3.3. Communication Subsystem

The first task to correctly choose the components for this subsystem is to do a link budget calculation, present in Figure 8. From this, it is possible to obtain the output power needed for the message to arrive directly from the moon to Earth. Using the parameters provided by the team and adapting the frequency for 435 MHz, the output power needed for sending the 41 bit message in one second is around 1 W. However, to have more link margin, it was decided that the output power should be 1.5 W minimum.

For getting the messages created, a transceiver from Texas Instruments, the CC1120 is used [11]. This component was chosen due to its ease of use, output power capable of saturating the power amplifier, it is space-grade and has space heritage and lastly because it is also used in the nominal communications board.

To get the minimum of 1.5 W of output power, a power amplifier is needed to amplify the signal. For that, the CMX901 from CMLMicro is used. This was chosen since it is one of only small and compact power amplifiers capable of generating the output needed, its space heritage and the fact that it will work in 3.3 V and 5 V. Above all, this amplifier proved very stable during testing.

Lastly in this subsystem, it was needed to do impedance matching between components. Not only the transceiver output needed to be matched to the power amplifier input, but also the amplifier output to the antenna. In the first case, the reference circuits provided by the manufactures of both components are used. However, in the second case a π shaped circuit are used.

3.4. PCB

With all the components picked out, the PCB was designed according with the manufacture rules and with the stack impedance provided by the manufacturer, in order to create the correct impedance lines between components described in Section 3.3.

In the top layer are all the components from the control and communication subsystems as well as most of the connection between them. Similarly, the components and connections of the power subsystem are in the bottom layer. The middle layers are used to create connections that cross each other and the second layer is also used as a ground plane to shield the communication subsystem from the power subsystem and to create the microstrip with 50 Ω between the antenna and the power amplifier.

In Figure 9 and Figure 10 it is possible to see a 3D rendering of the PCB with all the components.

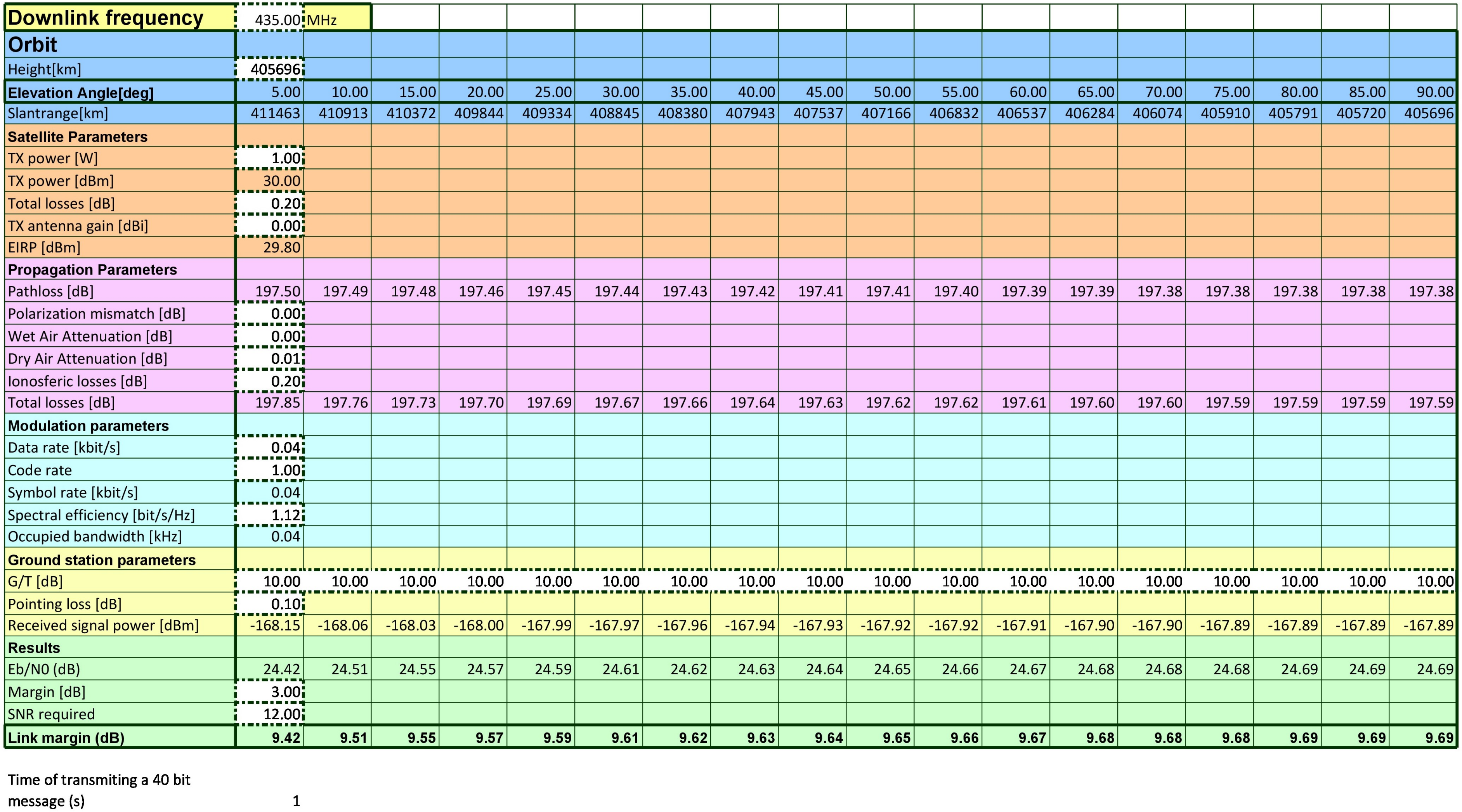
4. Results

4.1. Fail analysis of the system architecture

An important exercise to check the system architecture is to find the single point of failure that the system may have. This is especially important in a space system since there is no way of getting there to check what has failed.

In this architecture, several single points of failure were identified, and several solutions can be implemented in future versions to mitigate the problems that originate from any of these points.

The first and the one that most concerns the team is the antenna. Due to structural constraints, having a separate antenna dedicated exclusively to the Beacon is impossible. In addition, the antenna is folded during the space voyage between Earth and Moon. This system should be one of the first to be actuated and correctly unfold the antenna. If this system fails, there will be no communication from the rover since the antenna is not correctly positioned and of the correct size. Another point of failure is the combination of signals. The nominal communication and Beacon signals will be sent using the same antenna, so



Downlink frequency	435.00	MHz															
Orbit																	
Height[km]	405696																
Elevation Angle[deg]	5.00	10.00	15.00	20.00	25.00	30.00	35.00	40.00	45.00	50.00	55.00	60.00	65.00	70.00	75.00	80.00	85.00	90.00
Slantrange[km]	411463	410913	410372	409844	409334	408845	408380	407943	407537	407166	406832	406537	406284	406074	405910	405791	405720	405696
Satellite Parameters																		
TX power [W]	1.00																	
TX power [dBm]	30.00																	
Total losses [dB]	0.20																	
TX antenna gain [dBi]	0.00																	
EIRP [dBm]	29.80																	
Propagation Parameters																		
Pathloss [dB]	197.50	197.49	197.48	197.46	197.45	197.44	197.43	197.42	197.41	197.41	197.40	197.39	197.39	197.38	197.38	197.38	197.38	197.38
Polarization mismatch [dB]	0.00																	
Wet Air Attenuation [dB]	0.00																	
Dry Air Attenuation [dB]	0.01																	
Ionosferic losses [dB]	0.20																	
Total losses [dB]	197.85	197.76	197.73	197.70	197.69	197.67	197.66	197.64	197.63	197.62	197.62	197.61	197.60	197.60	197.59	197.59	197.59	197.59
Modulation parameters																		
Data rate [kbit/s]	0.04																	
Code rate	1.00																	
Symbol rate [kbit/s]	0.04																	
Spectral efficiency [bit/s/Hz]	1.12																	
Occupied bandwidth [kHz]	0.04																	
Ground station parameters																		
G/T [dB]	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00
Pointing loss [dB]	0.10																	
Received signal power [dBm]	-168.15	-168.06	-168.03	-168.00	-167.99	-167.97	-167.96	-167.94	-167.93	-167.92	-167.92	-167.91	-167.90	-167.90	-167.89	-167.89	-167.89	-167.89
Results																		
Eb/N0 (dB)	24.42	24.51	24.55	24.57	24.59	24.61	24.62	24.63	24.64	24.65	24.66	24.67	24.68	24.68	24.68	24.69	24.69	24.69
Margin [dB]	3.00																	
SNR required	12.00																	
Link margin (dB)	**9.42**	**9.51**	**9.55**	**9.57**	**9.59**	**9.61**	**9.62**	**9.63**	**9.64**	**9.65**	**9.66**	**9.67**	**9.68**	**9.68**	**9.68**	**9.69**	**9.69**	**9.69**

Time of transmiting a 40 bit message (s)	1

Figure 8: Beacon Link Budget Calculation with Power Amplifier.

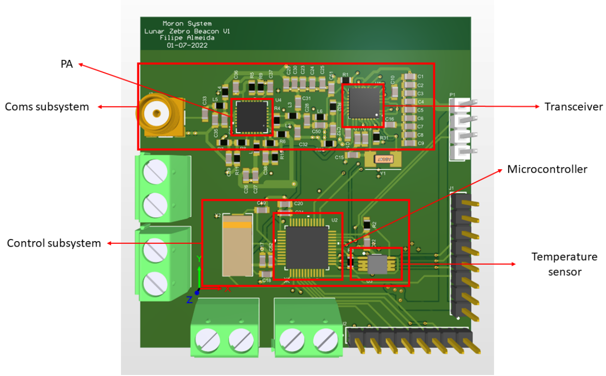


Figure 9: Beacon PCB 3D rendering of the top.

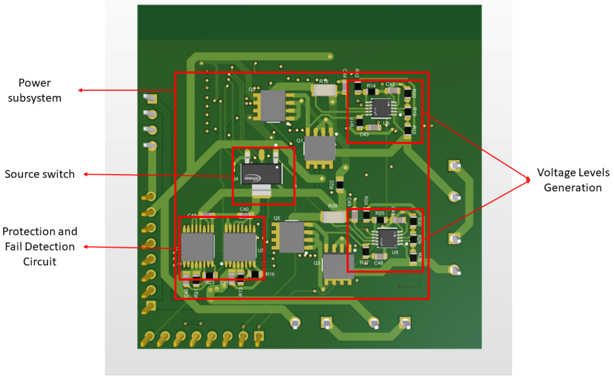


Figure 10: Beacon PCB 3D rendering of the bottom.

there is a need to operate the antenna using more than one transceiver. Since a signal combiner is too big and heavy to fit inside or outside the rover, a series of connections are made using a multiplexer. Zebro's communications board will control this multiplexer and, in case of failure, should prioritise the Beacon. However, since this is external to the Beacon, it is another possible point of failure. A solution for both problems is the implementation of a second antenna dedicated exclusively to the Beacon system.

Another point identified is that there is no way of individually cutting power to any Beacon component. This is important since there is no way to prevent the component from draining the battery from the rover in case of failure. A solution to this is adding extra circuits that allow the microcontroller from the Beacon to shut down the power to individual components.

In addition to this, the components on the Beacon are not redundant. This is important since this is a critical system. In this case, all the critical components except the temperature sensor should be duplicated. This measure was not considered in this version to reduce the size and weight of the system.

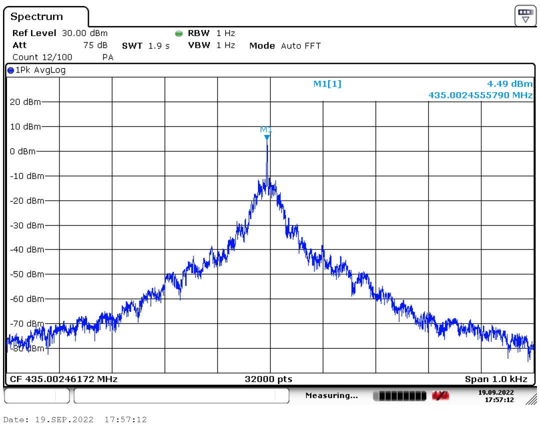
Lastly, in this first version of the Beacon, there is no energy accumulation system. Although it is a requirement, it was not fulfilled due to technical constrains such as space and weight, and therefore, the emergency mode will not be operational. Regarding the solution, an energy accumulation solution can be easily implemented in a future version of the Beacon.

4.2. Output spectrum

Although it was impossible to test the system using the EVM, a SDR can be used to simulate the transceiver.

For this purpose, an ADALM-PLUTO from Analog Devices was programmed to generate a random sequence of bits and transmit those using OOK modulation.

The PA's output spectrum when injecting the SDR signal is in Figure 11. Due to the low data rate, the side lobes are not noticeable.



Ref Level 30.00 dBm
Att 75 dB
SWT 1.9 s
RBW 1 Hz
VBW 1 Hz
Mode Auto FFT
Count 12/100
PA
1Pk AvgLog

CF 435.00246172 MHz
32000 pts
Span 1.0 kHz
Measuring...
19.09.2022
17:57:12

Date: 19.SEP.2022 17:57:12

Figure 11: Output spectrum of the PA for 41 bits in 1 second of transmission using OOK modulation.

5. Requirements analysis

To check if the architecture complies with the list of requirements, each requirement is checked in one of three ways. A requirement can be met through a design choice, and without the need for testing the system, through a set of tests performed on the Beacon system or only during general testing of the Zebro.

It is vital to notice that not all the tests were performed due to the challenges already explained throughout this document. However, it is also essential to notice that from, all the tests performed, only one requirement regarding the energy accumulation system was not accomplished.

6. Conclusions

6.1. Future work

Although the work of systems architecture and engineering of the Beacon system for the Lunar Zebro is done, the system can be further tested and improved.

The first and most important work that still needs to be done is assembling and testing the PCB and the entire system. It was impossible to obtain the components for populating the PCB due to manufacturing delays and no availability of components. With this next step, the system can finally be tested and prove effective for Zebro's mission.

Besides this, several points of failure were identified in this Beacon version that can be easily fixed.

Another important point is that this Beacon version needs to have an energy accumulation subsystem. This is also something that was not done due to time constraints and, therefore, can be done in the future.

From another perspective, other functionalities can make this Beacon more robust. Some examples are controlling the output power of the PA using the microcontroller, using the internal MSP430FR5969 and CC1120 temperature sensors to compare with the primary temperature sensor and having more temperature data points of the Beacon. Also, having adaptive power management inside the different modes of operation or even having more Zebro systems reporting their status to the Beacon. All this addition can make the Beacon more useful in the mission.

Finally, the Beacon needs a new PCB design using the connectors of the new Zebro version since those were changed.

For future missions and rovers, the final Beacon with all the improvements described above can be used in the Zebro and all kinds of space machines with zero to none adaptations.

6.2. Conclusion

The existing systems already working and deployed on several types of space machines were reviewed but proved too complex and too big in terms of volume and weight for Zebro. Therefore a new architecture for the system was made from the ground up. In order to simplify those Beacon systems, the new version is not responsible for identifying the failure. Instead, it relies on each system of the rover to report its own failure, passing this responsibility to the other systems.

This new architecture divides the Beacon into three subsystems, each responsible for one or more simple tasks. The control subsystem is responsible for receiving the messages from the other systems and, if necessary, drafting the message to send to Earth, the communication subsystem is responsible for sending the message, and the power subsystem is responsible for providing power to all the Beacon's components. This new Beacon was designed according to the system specifications, and modes of operation,in order to create a reliable Beacon for the Zebro and to prevent unnecessary messages.

Although not all the defined specifications were met due to time constraints and the PCB was not populated and tested due to delays in manufacturing time. However, the main objective of the work, in this case, was to design the first version of an independent system that report a failure of some other rover systems, capable of operating in adverse conditions, transmit back to Earth directly and in a size and weight compatible to the Zebro was achieved. Besides this, the system can also harvest its energy from the batteries and the solar panels, making it more reliable than the rover itself.

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