Project ELSA: Europa Lander for Science Acquisition

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Jupiter's moon Europa is of great interest to the scientific community as evidence suggests there may be a deep liquid water ocean beneath its icy surface. To investigate the surface and subsurface, future missions to Europa will require the use of landers and/or surface probes to measure surface characteristics and investigate the potentially unique subsurface conditions beneath the ice. Ball Aerospace has begun to explore the feasibility of conducting an exploration with several small, relatively inexpensive probes as an alternative to a large and costly lander. Our team of nine undergraduate students has designed and constructed a compact, low-cost, spherical probe, which can collect, store, and transmit scientific data relevant to the study of Europa. The goal of our project was to develop and construct a TRL 4 prototype over the course of 8 months, while keeping the cost under $5000. The development focused on data collection, FPGA software development, and system integration while neglecting environmental elements, such as temperature, radiation, and shocks. Two relevant scientific instruments, a triaxial magnetometer and a Geiger counter, were selected and integrated with an avionics package, which is centered on FPGA-based command and data handling (C&DH). The FPGA is integrated with a transceiver to communicate over RF to a ground station, simulating a Europa orbiter. In order to provide the capability to observe magnetic field and radiation variations during one complete orbit of Europa about Jupiter (85 Earth hours), an independent power system was developed and integrated to sustain the probe through its entire mission of 100 hours. The power system, avionics package, science instruments, and transceiver are mounted to a custom-designed structure, contained within a 25.4 centimeter diameter sphere. The prototype collects data for a total of 100 hours, and transmits that data in 8 minute simulated passes, demonstrating the feasibility of using small, cost effective probes to explore the surface of Europa or other planetary bodies.

Nomenclature

FPGA	=	Field Programmable Gate Array	
bps	=	bits per second	
TRL	=	Technology Readiness Level	
C&DH	=	Command and Data Handling	
UHF	=	Ultra High Frequency	
BASiX	=	Binary Asteroid in-Situ Explorer	
STK	=	Systems Tool Kit	
CPM	=	Counts Per Minute	
ASCII	=	American Standard Code for Information Interchange	
SRAM	=	Static Random Access Memory	
RAM	=	Random Access Memory	
SPI	=	Serial Peripheral Interface	
CR	=	Current/(5.2×# batteries)	(unitless)

I. Introduction

Europa, one of Jupiter's four Galilean moons, is believed to have a sizable ocean up to 100 km below its icy surface[1]. NASA has identified Europa as a high priority target in the search for life within our solar system, because of this potential ocean. Spacecraft that have already been sent through the Jovian system have revealed that Europa has one of the smoothest surfaces in the Solar System and has few impact craters which indicates a young and geologically active surface[2]. Photographs of Europa show many large streaks along its surface called lineae. These lineae are suspected to be the result of tidal flexing on Europa's surface as it orbits Jupiter[3]. In 2013 the Hubble Space Telescope spotted significant plumes of water spouting from the surface, which further suggests that bodies of water exist under the ice. If an ocean does indeed exist, it would be one of the most hospitable places in our Solar System for simple extraterrestrial life. Project ELSA (Europa Lander for Science Acquisition) will provide a stepping stone for future missions exploring Europa by demonstrating the feasibility of collecting relevant data from the surface of Europa within a relatively low cost, low mass, and low volume spherical landing probe, called the NeoPod.

The concept of deploying these small, low cost probes to investigate the surface of an astronomical body is rooted in other missions that have been investigated by Ball Aerospace. Previous projects done in conjunction with students from the University of Colorado investigated similar spherical probe systems to deploy to the surface of an asteroid. The student-led TIRESIAS (2013-2014) project developed a fully integrated pod as a building block for the Binary Asteroid in-Situ Explorer (BASiX) mission[4]. The concept for the BASiX mission was to deploy multiple pods to the surface of an asteroid from an orbiter. Once on the surface, one probe carrying an explosive payload would be detonated while other probes measured the vibrational effect. TIRESIAS demonstrated that vibrational data could be collected and transmitted through their communications system with a standalone pod. Ball Aerospace hopes to extend this concept to the study of Europa by providing an alternative to a large and expensive lander often conceived for a Europa mission.

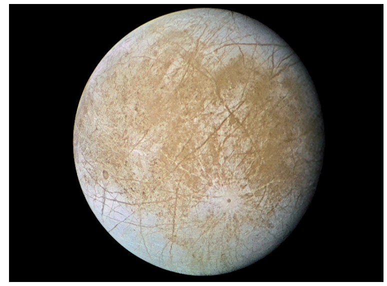


Figure 1. Image from orbit around Europa

Because of their similarities, a few basic aspects of the TIRESIAS project were re-purposed and integrated into the NeoPod design. The NeoPod has the same outer structure consisting of the aluminum sphere outer casing. The previously developed patch antennas will also be reused in the NeoPod design. However, a significant portion of the project is new and had to be updated or redesigned to fit the Europa specific requirements or to improve flight readiness. Most significant is the payload package, which had to utilize sensors, that if flight-grade, would be capable of collecting meaningful science from the surface of Europa. In the TIRESIAS project, avionics were handled using a simple Arduino micro-controller.

For this iteration, Ball Aerospace requested the use of a flight-ready avionics board with a Field Programmable Gate Array (FPGA). The communications system architecture was improved by using a transceiver chip instead of a separate transmitter and receiver package. The power system had to be overhauled to accommodate the longer mission lifetime requirements of 100 hours. And finally, a new internal mounting structure was developed to support the components. With the completion of this project, science data will be collected, processed, and transmitted from the probe, which is a critical step forward to eventually sending scientific probes to Europa.

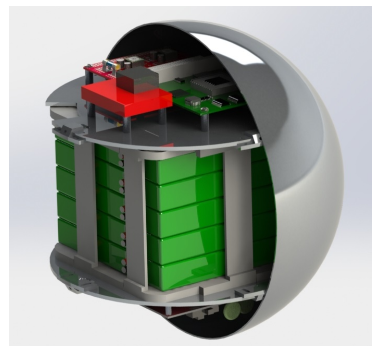


Figure 2. NeoPod Design Assembly (one hemisphere removed)

II. Design Objectives

This project was driven by three key functional requirements, i) to maximize collection of scientific data relevant to Europa, ii) to have the capability to remotely transmit the data and iii) to fit within specific mission constraints provided by the customer, such as strict weight and volume requirements. The first functional requirement comes from the need to demonstrate that high value science can be done from this kind of platform. While this probe was constructed in a lab environment, future iterations will benefit from the feasibility it demonstrates by collecting scientific data similar to what would be collected on the surface of Europa. The second functional requirement comes from the need to transmit the data once it has been collected. Since the probes will not be physically collected at the end of mission, it is crucial that the NeoPod be able to communicate wirelessly to a simulated orbiter. The overall mission includes a spacecraft orbiting Europa, which is used to collect data from the NeoPod and later transmit back to Earth. As it takes Europa 85 hours to rotate about Jupiter, the mission was designed to survive a full 100 hours. To determine how much data could be collected and sent from the probe from the surface of Europa during this mission, a software simulation of the Europa orbiter was created in Systems Tool Kit (STK). The mission parameters for the Europa orbiter were provided by JPL (95° inclination, 126 minute period, 0 eccentricity, 12° mask angle on probe). Since the orbiter is in a nearly polar orbit, different longitude locations were simulated for the NeoPod probe to rest on the surface which influenced total contact time with the orbiter over 100 hours. Below is a table illustrating the simulated total amount of data that can be transmitted from each latitude of Europa.

Transmitted Mission Data at Different Latitudes Over 100 Hour Period				
Latitude Location (deg South)	Total Pass Time (s)	Transmit Rate (kbps)	Maximum Data (MB)	Maximum Transmittable Data Including 25% Margin (MB)
0	2198	128	40	30
20	2094	128	38	29
45	3010	128	55	41
60	4146	128	76	57
75	10149	128	186	139
90	21942	128	401	301

Table 1. STK Scenario Data Return

Since the total amount of data return is maximized when the probe is placed at the poles of Europa, the team chose to use this scenario as a design driver. Placing the NeoPod at the poles also functions as a worst case scenario for the power subsystem as the avionics and communications subsystems will perform more computations and tasks over the mission lifetime. The team took these restrictions into mind when designing the communications timeline for the mission by including a realistic, limited window in which it is possible to transmit data. The final two key derived requirements, which flowed from the use of the orbiter, were that the NeoPod shall have a maximum data rate of 128 kbps and that upon command, the NeoPod will begin sending stored data. The team has designed a small Earth-based ground station to simulate this orbiter, which will be used for all testing. The final functional requirement was that the NeoPod needed to fit within existing mission architecture previously designed by Ball Aerospace. These include having a total mass of less than 10 kg, and the ability to completely enclose the entire system within a 25 cm diameter sphere. They also include the use and integration of a Ball Aerospace-designed field programmable gate array (FPGA) in the system to regulate sensor input, store received data, and handle commands and integration with the communications system. The communications system in turn must include a Ball Aerospace-provided patch antenna which lays flush with the exterior of the spherical probe.

The highest levels of success map directly to these key functional and derived requirements. The top level success for payload was to have two distinct sensors that generate data sent to the avionics board for storage and transmission. For the avionics to be successful, it must be able to handle and store data from sensors. It must also be able to begin transmission of data upon command reception from the ground station for a total of 8 minutes. The communications system, which includes the ground station, must be able to receive commands over RF as well as transmit data in a packetized form at a maximum of 128 kbps. The ground station must be able to receive this data and then store it in such a way that it can be accessed post-mission. The power system must supply 3.3 V and 5 V lines to the entire system for the entire 100 hour mission and must be contained within the small, spherical probe. Finally the structure itself must be designed to integrate all NeoPod components and must not exceed 10 kg and a 25 cm diameter. As an overall system, the top level of success was to demonstrate the full 100 hour mission with a fully integrated sphere in a lab environment.

The most critical project elements (CPEs) to achieve these levels of success were the avionics hardware integration and FPGA software development; two-way communication between NeoPod and ground station while sending multiple data types; designing a lightweight, small power system that can supply power for 100 hours; and integrating the entire system into a 25 centimeter diameter spherical shell. The first CPE, related to FPGA hardware and software development, was the biggest challenge for the project, as none of the team had FPGA experience before beginning the project, and thus had to learn how to code an FPGA, as well as develop software needed for the project in an incredibly limited schedule with little margin. The communication system was difficult, because the team did not have significant experience in RF, and had to develop a ground station before any communications testing could be accomplished. The power system was difficult due to the limited space in the sphere itself, and a custom printed circuit board (PCB) as well as circuit design had to be developed in order to provide adequate power for the 100 hour mission. The team was also concerned about fully integrating into the sphere, as the mass and volume requirements were very strict, and for full system success, the NeoPod had to operate as a closed-sphere contained system.

III. Design Methodology

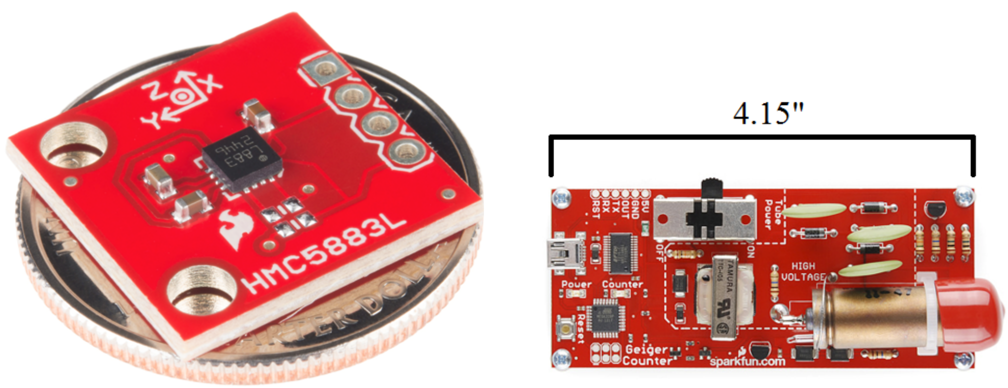
A. Payload

A trade study was conducted early in the project to identify relevant and realistic sensors for the payload package. While the sensors were not required to be flight grade components, it was important for the fidelity of the data collection, storage, and transmission path that the sensors collect data relevant to the study of Europa. Research showed that there were several categories of science exploration worth investigating from the surface: Ice Shell and Ocean Characterization, Surface Environment and Composition Characterization, and Surface Geology [5]. Within these categories were anywhere between 1 and 6 different sensor options. A trade study was used to decide upon a sensor that would best fit the needs of mission. Each sensor type was evaluated on its science value, cost , availability, complexity, size, and mass. Extra weight was given to complexity, because the project focus was on the data path and not on the data from the sensor itself, and size, which was important in fitting within the small structure.

The full trade study resulted in the selection of a magnetometer and Geiger counter as the sensors of choice for this mission. Each had their own advantages that led to the decision to use them, but one of the major factors for both sensors was their availability from a local electronics supplier, Sparkfun. The magnetometer was chosen because in a real Europa mission, observations of the change in the magnetic field during a full orbit would either confirm or reject the hypothesis of a large ocean beneath the surface. If it exists, the ocean would generate a specific magnetic signature as Europa moves through Jupiters orbit that would not be there otherwise. The magnetometer was also one of the smallest sensors investigated and uses a simple I2C interface for the integration with the Avionics Board.

Sensor	Sensitivity	Range	Resolution
Magnetometer	1370 LSb/Gauss	$\pm$8 Gauss	0.73 mG/LSb
Geiger Counter	18 cps/mR/hr	100 cpm	1 cpm

Table 2. Sensor Specifications



a) Sparkfun Triaxial Magnetometer. This inexpensive magnetometer uses an I2C interface when connected with the Avionics System. It is capable of recording 3 axis magnetic field values at .75 - 75 HZ

b) Sparkfun Geiger Counter. The Geiger counter can detect alpha, beta, and gamma radiation. It registers a single count every time one of the particles interacts with the Geiger tube the counter will output a single bit high voltage, which is read by the Avionics System

Figure 3. Scientific Instruments Chosen as the Payload

First, the magnetometer was selected for its large relevance to the dynamic magnetic field on Europa. These changes come from a variety of factors such as Europa's movement through Jupiter's Van Allen Belts and induced fields caused by the conductivity of Europa's interior. By taking measurements of this variable magnetic field environment, researchers would be able to more accurately characterize Europa's interior, which has long been suspected of containing a large ocean. Magnetic field fluctuations from this induction are expected to be around 2.5 mG, which, for a table-top version of the mission could be detected by the 0.73 mG/LSb resolution of the selected sensor[6]. However, in reality, a different sensor would be selected to survive space environmental conditions.

The Geiger counter was chosen because of the value of having radiation measurements from the surface. The radiation environment on the surface will be intense and poses a hazard for future manned or unmanned exploration missions. This environment consists of largely electron radiation, also known as Beta particles, which the selected Geiger counter is able to detect. Having radiation measurements on the surface would improve knowledge of conditions there, making the success of future missions more likely. The specific Geiger counter that was chosen came ready for connection and has a simple interface. Anytime the Geiger counter is hit by a radioactive particle the sensor outputs a single bit that can be read by the Avionics Board. The data can be collected and put out in counts per minute (CPM).

Two other sensors, temperature and pressure sensors, also scored well in the trade study but were ultimately ruled out. They would have been easier to integrate into the payload, but would have provided significantly less scientific value than the magnetometer and Geiger counter.

B. Avionics

The avionics subsystem serves as the connective glue between each of the subsystems. It provides processing and data storage for the sensor packages. Additionally, it responds to commands and initiates data transmission periods. Because of the desire to further the technology readiness of the mission concept, an FPGA driven avionics board was provided by Ball Aerospace. During design, the Ball avionics board was a long lead item. In order to reduce this risk, an FPGA development board with the same family of FPGA was procured (donated by Microsemi). This board served as a learning aid in the development phase, as well as a contingency plan in the event the Ball board was defective or behind schedule. Because FPGA programming was new to the ELSA team, this became a critical project element. Designing for an FPGA is drastically different than designing software for a microcontroller. An FPGA is a method of describing logic hardware, where everything executes in parallel rather than sequentially as is the case with microprocessors. With this difference in mind, there are three main tasks that the avionics system must accomplish. First, data must be collected from the sensor packages and processed into a data format. Second, the data must be written to and read from memory. Third, data must be passed to and from the communication system. All FPGA software was written Verilog HDL. A high level flowchart of the software design is shown below in Figure 4.

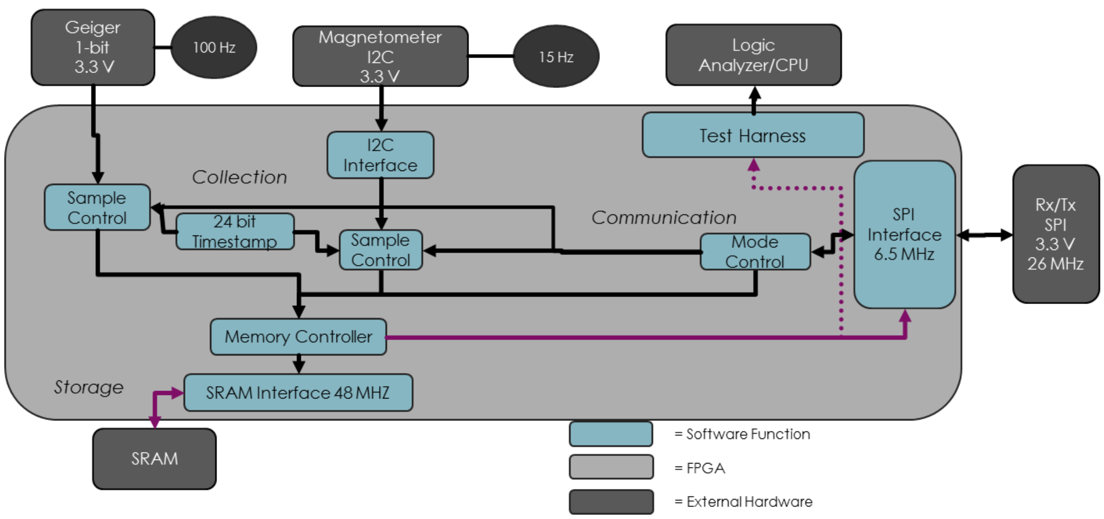


Figure 4. High level flowchart of Verilog software modules contained in FPGA design. Data from the instruments is packaged into a uniquely identifiable 10 byte data point in the sample control modules. The data points are passed to the memory controller to be saved in SRAM. The SPI interface and mode control modules configure the transceiver to the correct state, as well as respond to commands. Upon receiving the transmit command, data is read from memory and sent to the transceiver.

While all of the software functions are executed in parallel, it is most natural to follow the path of data as it comes into the system. The Geiger counter outputs one logic line that would go high when a radiation event was detected. The FPGA simply monitors this line to count the number of radiation events. Every minute the number of counts is output to be stored in memory. The magnetometer outputs 3 vectors of twos complement data. For both the Geiger counter and magnetometer, a 10-byte data packet is formed for each unique data point. Each point consists of an 8-bit ASCII identifier ('G' for Geiger, 'M' for Magnetometer), a 24-bit timestamp, and 48 bits of data. A 24-bit timestamp was chosen as opposed to a standard 32-bit timestamp to reduce the total amount of data transmission. A timestamp resolution of 10 Hz was sufficient and would be encapsulated by 24 bits over the 100-hour mission timeline.

In order to save data for later transmission, an SRAM interface was developed. Additionally, a memory controller was developed to handle the scheduling of simultaneous read and write requests, as well as to keep track of read and write addresses. The use of SRAM allowed for small read and write times that would not limit the data rate of the communications system. However, due to the volatile nature of RAM, the system is required to remain powered at all times.

The avionics system also controls the transceiver over an SPI interface. Upon power up, the FPGA configures the transceiver to the proper communications protocol and puts it into a continuous receive state. Upon receiving an ASCII ’T’ from the ground station, an 8 minute pass timer begins. The transceiver is put into transmit mode while data is read from memory and sent to the transceiver. When the 8 minute timer expires, the transceiver is sent back into continuous receive mode. This cycle repeats throughout the entire mission lifetime, and is simultaneous to the data processing and storage modules.

C. Communications and Ground Station

The communication system serves to initiate and complete the data transmission cycle, effectively wrapping around the entire mission concept. The communication system operates wirelessly via RF and is split into two separate subsystems: Ground Station & NeoPod. The Ground Station acts as an analog to an orbiting satellite and does not have any weight or volume restrictions. In order to fit within the mission architecture the Ground Station must receive and save data as well as transmit commands via RF to the NeoPod. Due to the unique spherical shape of the Neopod, it requires a non-traditional antenna that can function in many orientations. Ball Aerospace provided the shell structure with a low-profile patch antenna mounted to it, and the antenna had been tested and proven to work in two separate bands with center frequencies of 437.5 and 401.5 MHz. Along with having frequency restrictions, the NeoPod portion of the communication system is required to operate on very little power in order to reduce the strain on the power system requirement to operate for 100 hours. The Texas Instruments CC1101 transceiver was identified as a capable element to include in the design because its power draw is on the order of milliamps and has heritage with University of Colorado Aerospace Engineering Sciences department faculty. The CC1101 is configurable and has the ability to change its center frequency in increments of slightly more than 400 Hz allowing it to be set near the center frequency of 437.5 MHz. Within the mission architecture the transceiver is responsible for packetizing and wirelessly transmitting data from the NeoPod to the Ground Station. Inside the NeoPod, the CC1101 is commanded, configured and sent data by the Avionics system via the SPI interface. On start up the internal registers of the transceiver are configured to the correct center frequency, channel width, data rate, and packet structure. The Ground Station transceiver uses a program called SmartRF Studio to configure the correct registers on the CC1101. SmartRF Studio has Perl scripting functionality that interfaces with all SmartRF Studio commands. Test scripts were written in order to automate command and data reception periods. In the test scripts that simulate a normal satellite pass, the Ground Station first switches from an idle state to transmit mode then transmits an ASCII ”T” to the NeoPod, signaling that the NeoPod needs to switch to transmit mode. The Ground Station switches to ’receive’ mode and the NeoPod begins transmitting its stored data at 100 kbps in 50 byte packets. Once data has been received from the Ground Station, the data packets are passed to another software developed by Ball Aerospace called COSMOS. The data is routed from the Perl script directly to COSMOS via TCP/IP connection. The COSMOS software allows for easy packet decomposition and real time data display which is the motivation behind using the program. COSMOS looks for ”G” or ”M” headers in the data packets to identify unique data points based on the data point structure discussed above. Once a 50 byte packet is parsed, COSMOS stores and plots the data in real time. After data has been sent for 8 minutes, the avionics system switches back to receive mode and awaits another command from the Ground Station which will be sent at the start of the next pass. The process repeats until all passes are completed.

D. Power

One of the requirements of the system is that the NeoPod must be able to record data for one orbital period of Europa around Jupiter. Based on this, it was determined that the mission timeline would be 100 hours. This would provide enough time to record all of the necessary data and transmit it up to the orbiter. First it was determined what power source should be used. Many spacecraft and rovers use solar panels to collect and store energy; however, since Jupiter 5.2 AU from the sun, the solar power available is less than 4% that at the Earth or just over 50 Watts per square meter, not enough for solar panels to be a viable option. Another possible option was a radioisotope thermoelectric generator such as those used by deep space vehicles such as those in the Voyager program. However, these systems are too heavy and take up too much space to fit within the mission parameters of a small probe. Additionally, the radioactive fuel needed to power these systems is extremely dangerous, expensive, and difficult to obtain. For these reasons, it was decided to use batteries as the power source for the project.

Since volume and mass are limited in the design, it was important that the batteries be as efficient as possible. It was decided that lithium polymer (Lipo), 11.1 V batteries with a capacity of 5.2 Amp-hours (Ah) were the best choice because they are rechargeable, efficient, and relatively easy to obtain. There is an increased level of risk in using Lipo batteries, as they can be unstable and dangerous if they are not treated with care. In order to mitigate these risks, steps were taken to characterize the behavior of these batteries in order to create accurate models. For example, the voltage output by Lipo batteries gradually decreases over time, before dropping off sharply at the end of the batteries' lifespan. If the battery voltage drops below 9 V, the potential for critical failure increases greatly. In order to avoid this, a margin was applied that ensured the battery voltage does not fall below 10.5 V. Based off these models, it was found that this occurs at about 85% of the battery capacity so we used this as our working capacity moving forward.

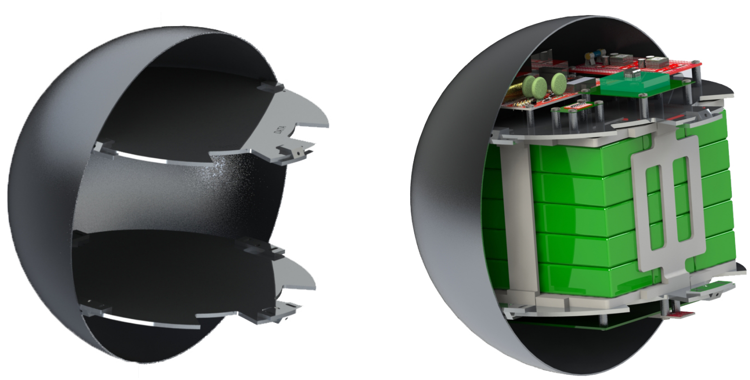
In order to determine the number of batteries needed, a power budget was developed for the entire 100-hour mission. Each system was assumed to operate at maximum power for the duration of the mission. Margin was applied in addition to this. It was determined that 15 batteries would be needed to ensure that all systems would be powered. All of these batteries are connected in parallel to form a single power source. This ensures that no system will run out of power before the others. The voltage from the batteries is conditioned using a series of switching DC voltage converters to efficiently, at 90%, step the voltage down to 5 V and 3.3 V sources. These regulators are designed to output constant voltage with low ripple effects through a range of input voltages. Additionally, a low voltage cutoff switch is used to protect the batteries from dipping below 9.5V. Together, the power system is capable of providing appropriate voltage and current values to all other systems for the duration of the mission.

E. Structure

The NeoPod structure is used to house all components in a single assembly to increase the flight readiness of the system. In order to determine how the physical structure would need to be designed, the requirements surrounding the physical integration needed to be examined. These requirements specify that the entire system must be contained within a sphere with a diameter of 25 cm or less and have a mass less than 10 kg in order to fit within the mission parameters (physical size and mass restrictions of orbiter). Due to the timeline of this project, the structural design did not have any requirements to fulfill regarding load testing or modeling surviving an impact on Europa.

In order to fit all circuit boards, science instruments and batteries into the NeoPod, the team designed a simple internal structure to house all of these components within the sphere. The design consists of two circular shelves with four clips on each shelf, mounted parallel to one another within the sphere. This design allows for all subsystem circuit boards and science payloads to be mounted to exterior of the plates while leaving a substantial amount of room between the plates for batteries. The circular plates also include cut outs in order to distribute wires throughout the system Figure 5a is a visual of the internal structure.

The team was also given two halves of an existing external shell from the TIRESIAS project (25.4 cm external diameter) which was used in the structural design. Another consideration for the internal structure was the necessity for housing the Lipo batteries contained in the center of the NeoPod. To reduce weight and manufacturing time, a 3D printed structure enclosed on all sides was created to meet this need. The 3D printed structure screws into both the top and bottom plates, making the shelves and the battery case one integrated unit. All subsystems and components were modeled in SolidWorks to verify that this system would fit within a sphere of this size. Figure 5b is a representation of the NeoPod with one side of the sphere hidden showing how all components and internal structure physically integrate together.



a) NeoPod Internal Structure

b) NeoPod Assembly, one side of the sphere is hidden to allow a view of the internal assembly

Figure 5. NeoPod Structural Assembly

Another function of the physical structure was to dissipate heat generated by the entire system. In order to determine the extent of the thermal dissipation needed, a worst case thermal model was developed in which all power supplied to a component was treated as heat output. In Solidworks, a transient thermal simulation was run to steady state which provided an initial estimate of temperatures predicted throughout the mission lifetime. Temperatures of the batteries and temperatures on most subsystem circuit boards were monitored over time and it was discovered that all components stayed under their maximum operating temperatures even at steady state. Figure 6 is a graph that shows the SolidWorks Simulation results. The margin represented by the green portion of the bars, is the difference between the modeled temperature and the maximum temperature provided by the component specification sheets.

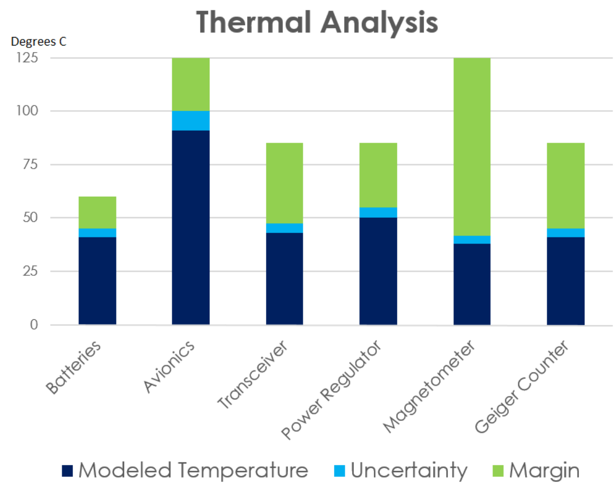


Figure 6. Thermal Modeling Results. The height of the bar signifies the maximum operating temperature for each subsystem while blue signifies the modeled temperature

As better estimates of current draw and power consumption are known, the thermal model will be updated to reflect these changes. Currently, the FPGA is modeled to be using all logic gates and running at full power which is not realistic. Better software and hardware estimates should further reduce the steady state temperatures predicted in this model.

IV. Design Testing and Result

A. System Design

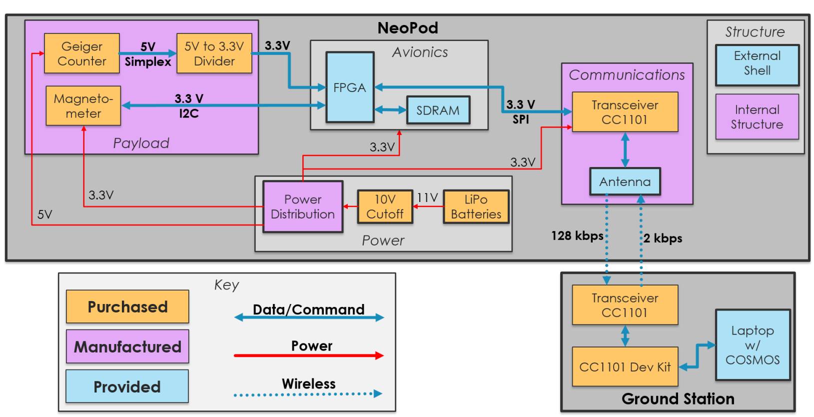


Figure 7. NeoPod System Functional Block Diagram. The system consists of four key subsystems, payload, avionics, communications, and a power distribution system. There is also an manufactured internal structure, mounted to an external shell provided by Ball Aerospace. The Ground Station is separate from the system, and will be used for testing in a lab environment.

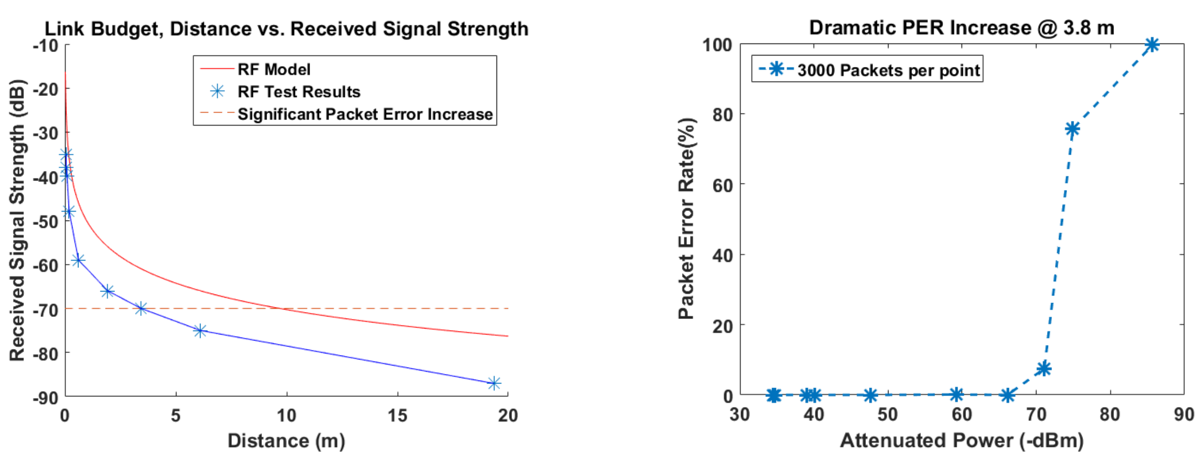
Figure 7 is a functional block diagram representative of the entire NeoPod system. As seen the NeoPod is broken into four key subsystems: payload, avionics, communications, and a power system, each of which are contained within the ball. The payload sensors are mounted on team designed printed circuit boards, which also contains a step-down voltage converter for the Geiger counter for integration with the avionics system. The avionics system consists of an FPGA mounted on a board, which was provided by Microsemi and uses SRAM as its storage method. The team developed all software needed for the board to function correctly. The communications subsystem consists of a CC1101 transceiver chip, purchased from Texas Instruments, and a curved patch antenna, mounted to the exterior of the sphere, both provided by Ball Aerospace. The communications system handles the majority of the packetization for the data. The avionics and communications subsystem are integrated using an SPI interface. The system is powered using fifteen lithium-ion batteries connected in parallel at 11 volts. A team designed power distribution board allows for all components in the system to be powered at either 3.3 or 5 volts. These subsystems are mounted to two circular shelves, which use brackets to mount to the external sphere. The batteries are located in a 3-D printed battery case, which is mounted between the two shelves. The 25 centimeter external shell is then closed, and all subsystems are contained. The ground station consists of a second CC1101 transceiver chip, as well as the included development kit, both provided by Texas Instruments. This is connected over USB to a laptop computer, which uses COSMOS, a data processing software, to send commands and save data.

B. System Testing and Expected Results

The NeoPod design is currently being tested for functionality and performance. The testing process consists of 3 testing stages:

1) Individual subsystem testing
2) Avionics subsystem testing
3) System integration testing

The first stage is individual subsystem testing. The individual subsystem tests consists of binary component tests and a communication RF link test. These tests have been successfully completed. The purpose of the binary component tests was to verify that purchased components, such as the Geiger counter and magnetometer, function as specified, and for the team to gain experience in their operation. The purpose of the communication RF link test was to evaluate the signal strength and packet error rate when transmitting data packets over varying distances. This test was performed in a lab environment, using combinations of additional attenuations to simulate distance. Over the course of the test, ten differing attenuations representing distance were tested, with three trials of 1000 packets sent at each attenuation. The results of the RF link test, shown in Figure 8b, shown that while the curve of the test results matched the model quite well. However, there was a 10 dB offset consistently over the course of the test. The team believes the reason for this to be the environment of the lab, and unknown constant degradation of the signal during the test. In the operating zone of 0 to 3.8 meters, there were 3 packet errors out of 21000 10-bit packets sent. This equates to a 0.0001 percent packet error rate within the operating test environment. Once outside this environment the packet error rate jumped up to almost 100 percent loss.



a) Link Budget Test Results

b) Packet Error Rate Test Results

Figure 8. Results from RF Link Test, compared to model and shown with measured packet error rate. The first graph shows received signal strength over distance, simulated by increasing attenuation. During the test it was discovered that the operating zone in the lab environment was 0 to 3.8 meters, resulting in a 0.0001 % PER.

The second stage is avionics integration testing. The avionics integration tests consist of binary tests wherein the power board, payload sensors, and communications subsystem are each individually tested in conjunction with the avionics board to make sure that the avionics system interfaces correctly with the other subsystems. At the time of writing, the NeoPod is undergoing this stage of testing.

An example of one of these tests is the integration of the Geiger counter with the avionics subsystem. The single digital line between the two systems was connected and both were powered to desired voltages. The number of radiation counts outputted from the avionics system was compared to the number of counts seen on the Geiger counter, which were observed by an on-board LED, and confirmed to match. Furthermore, the overhead identifier byte (ASCII 'G'), and time-stamp bytes were present as expected.

Once the avionics integration tests are complete, the NeoPod will enter the third testing stage, system integration testing. The system integration tests consist of two flat-sat tests and a fully integrated test. The first flat-sat test will be a two-hour binary test of all subsystems minus the structure and batteries; a power supply will be used in place of the batteries. The purpose of this test is to verify that all subsystems work together to produce a complete data path from the payload sensors to the ground station.

The second flat-sat test will be a 6-hour test that incorporates the batteries. The purpose of this test is to evaluate battery performance and to increase confidence that the batteries will sustain the system for at least a 100 hour mission lifetime. Battery voltage and current readings will be logged throughout the test at 5 minute intervals and 1 second intervals respectively. The current measurements will be used to confirm the 0.6 Amp estimate that was used to develop the battery discharge model, and the voltage measurements will be compared against the power model (shown in Figure 9) to evaluate initial battery performance.

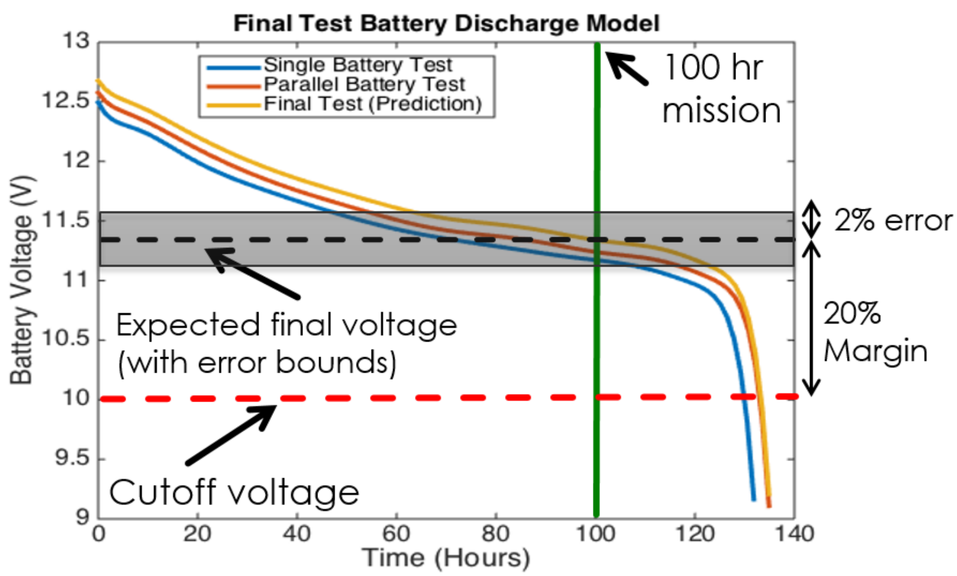


Figure 9. Voltage curves for the one and two battery discharge tests (parallel battery test), as well as the predicted discharge curve for the final test. The one and two battery discharge curves were obtained by discharging the batteries at 0.38CR 0.19CR respectively. The discharge curves were then expanded horizontally according to our expected current draw and battery capacity for the final test. The model discharge curve for the final test, which is expected to have a current discharge at 0.0077CR, was obtained by: 1) analyzing change in Voltage vs. change in CR for our batteries and for other well characterized Lipo batteries, 2) determining the ratio of voltage change of our batteries compared to the well characterized batteries, 3) extrapolating the ratio of expected voltage change from .19CR to .0077CR, and 4) applying the ratio of voltage change to the parallel battery discharge profile.

Following the flat-sat test with batteries, the full NeoPod system will be integrated. The purpose of the full integration test is to validate the power requirement that the system will function for a 100 hour mission lifetime and to validate structure requirements that the NeoPod will weigh less than 10 kg and be contained within a 25 cm diameter sphere. The final battery voltage is expected to be 11.35 +/- .2 Volts (see Figure 9). At the completion of this test, all requirements will have been verified and the project will be completed. This test is expected to run for a total of 100 hours, and incorporates 47 simulated communications passes over the course of the test, one every 120 minutes.

V. Conclusion

Upon successful completion of the testing plan, the ELSA team will have shown that the NeoPod is capable of collecting, storing, and transmitting data for the entirety of the 100-hour mission. These were the key objectives that needed to be demonstrated by the completed system. Important to this is the verification of the communication and battery life models and validation of all the requirements. As seen above, the communications test results are quite close to the model, other than a slight offset, and demonstrate that data can be sent with a minimal packet error rate of 0.0001 percent. The power model, once tested over 100 hours, will show the capability of keeping a system this small powered without any recharge for a full 100 hours. If these probes are to collect data on the surface of Europa they must be able to operate for that long. The fully integrated system test will show how closely the design matched these models to fulfill requirements.

It is by meeting or exceeding these objectives that the overall concept of sending small and inexpensive probes to Europa is further validated and future teams can build on the progress to improve the system and advance its maturity and viability for a real Europa mission. This can potentially present a unique and novel alternative to the large landers in use today.

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