17th March 2023

Dr. Mike Hegedus and ENSC 405W Instructional Team
School of Engineering Science
Simon Fraser University
8888 University Dr.
Burnaby, BC, V5A 1S6

Re: ENSC 405W Design Specifications

Dear Dr. Hegedus and instructional team,

Gamma Insights is a team committed to providing an alternate method of groundwater level detection that allows for unmanned, long-term monitoring in remote locations. We have prepared this design specifications document to describe the implementation of our system in hardware, firmware, and software. The document will detail the design specifications needed to satisfy the terms laid out in Gamma Insight's revised Requirements Specifications document (version 2.0), and specify which specifications pertain to the Proof-of-Concept, Prototype, and Production phases of the Hy-dar system.

Hy-dar uses Ground-Penetrating Radar to detect how far the level of the water table is below the Earth's surface, recording its measurements over time. The system is self-powered by mounted solar panels, robust to outdoor conditions, can be installed and left unattended for multiple seasons at a time, and is able to be uninstalled and relocated. Further, our solution does not require the extensive drilling, licensing, or specialized equipment other methods of water table measurement rely on, reducing cost and logistical concerns. These factors make the Hy-dar system ideal for teams with limited resources and studies in remote wilderness locations or environmentally sensitive areas. This price constraint and need for a robust, weatherproof, and low-power system result in some careful design choices and alternative designs.

Enclosed, you will find design specifications for the different subsystems of Hy-dar, including block diagrams, state diagrams, example components, power plots, a test plan appendix, and a detailed appendix of alternative designs. The choices listed are not final, as there are many variables which have not yet been fixed, and certain components have been discovered to be unavailable or out of the project's price range. However, they do represent our first proposed design for the project at the current time. The design alternatives are being seriously considered in tandem to this as a backup.

For any questions or concerns, please contact our Chief Communications Officer, Michael Ungureanu, at mungureanu@sfu.ca.

Sincerely,

M.U.

Michael Ungureanu
Chief Communications Officer

Gamma Insights (Company #06)

Design Specification

Hy-dar

Authors:

Michael Ungureanu, Chief Communications Officer (mungureanu@sfu.ca)
Joanna Giannopoulos, Co-Chief Technical Officer (jgiannop@sfu.ca)
Joanna Li, Co-Chief Technical Officer (joanna_li_5@sfu.ca)
Nick Polyzygopoulos, Chief Financial Officer (npolyzog@sfu.ca)
Tyler Bailey, Chief Information Officer (tyler_bailey@sfu.ca)
Basil Giannopoulos, Chief Operations Officer (bgiannop@sfu.ca)

Contact:

Michael Ungureanu
mungureanu@sfu.ca

Submitted to:

Dr. Mike Hegedus and ENSC 405W Teaching Team
School of Engineering Science
Simon Fraser University

Issue Date:

March 17, 2023

Abstract

The Hy-dar system provides researchers and resource management groups with an alternative for groundwater monitoring in remote environments. To accomplish this, a ground penetrating radar system is supported by a power and processing system designed to survive in remote environments. In this document, the design aspects of the Hy-dar groundwater monitoring system are explained, distinguished with Proof-of-Concept, Prototype, and product phases of design. Design specifications covered will include mechanical, electrical, and software specifications. Each of these sections is split into further subsections where more detailed design information is given. Reasoning for major design choices will be explained in the Alternative Designs Appendix, along with alternatives explored during specification selection. A Test Plan Appendix is also included, describing some key tests that will be performed to validate components of the system.

Hy-dar offers an important alternative for groundwater monitoring in remote environments, allowing for a better understanding of the groundwater table.

Contents

Table of Figures

Table of Tables

Table of Equations

Glossary

Acronym	Definition
ADC	Analog to Digital Converter
GPR	Ground Penetrating Radar
IP	Ingress Protection
PWM	Pulse Width Modulation
SOC	State of Charge: A value expressing the remaining charge in a battery pack as a percentage.
CMP	Common Mid-Point
ETS	Equivalent Time Sampling
GWT	Ground Water Table
EFN	Environmental Flow Needs
GRRG	Groundwater Resources Research Group
EMF	Electromagnetic Field
TX	Transmit
RX	Receive
UWB	Ultra Wide-Band
OTS	Off The Shelf
RF	Radio Frequency
BPF	Band-Pass Filter
VGA	Variable Gain Amplifier

1. Introduction

1.1 Background

Ground Water Table (GWT) level is an important feature of the environment, both ecologically and geologically. Short term changes to GWT level reflect weather events and can help predict floods or droughts, while long term variation can map the changing climate. B.C.’s Environmental Flow Needs (EFN) policies also demonstrate the value of GWT level data, for the purpose of monitoring ecosystem health [1]. But, measuring GWT level in remote and sensitive environments is a challenging process, as the most common method in B.C. involves drilling wells [2], an expensive and disruptive process. Dr. Diana Allen of SFU’s Groundwater Resources Research Group (GRRG) has expressed interest in a low-impact and portable system that would allow researchers to autonomously monitor GWT level in remote areas [3], contrary to existing well-based sensors.

1.2 Hy-dar System Overview

Gamma Insights plans to meet these needs via the development of the Hy-dar system, a non-disruptive, unmanned system utilizing Ground Penetrating Radar (GPR) to measure GWT level in remote environments over long periods of time. The Hy-dar system is comprised of 3 main subsystems: the power module, the radar module, and the processor module. The processing system (including signal processing, data storage, and timing control) is encapsulated in a rectangular orange enclosure (Figure 1 below) with the system battery (green) and power circuitry from the solar panel. The radar module is made up of the transmit and receive antennas and their circuitry, and are also each enclosed; however, they are not shown as the antenna design, including shape and size, is still being finalized. Lastly, the final component of the power module, the solar panel, is mounted on a post anchored to the ground.

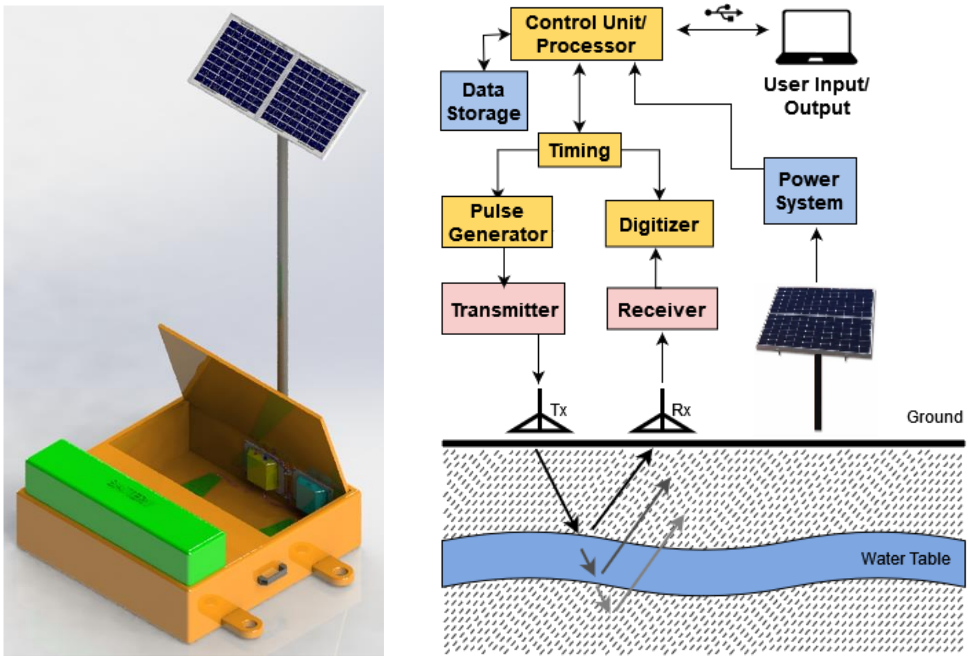


Figure 1 - CAD Model (right) and Block Diagram (left) of the Prototype Hy-dar System

1.3 Challenges

The Hy-dar system, and particularly the radar system, is quite complex. Some high-level challenges that have been encountered during the design process are as follows:

- Lack of or limited Off The Shelf (OTS) components available that meet the needs of the system.
- High cost of components required for the system, specifically high-performance components, Ultra Wide-Band (UWB) components and components with very fast (order of nanosecond) response time and sampling rates.
- Manufacturability and design of components that cannot be purchased OTS
    - Desired quality may not be achievable in the allotted time.
- Dependencies within the system:
    - Failure or non-completion of one stage of the system may make it difficult to demo other stages of the system.
    - Uncertainties in design of one aspect of the system may prevent the finalization of design of other aspects of the system.
- Component testing and validation
    - Characterizing and testing components that have been manufactured by the team is time-consuming, and requires equipment we may not have access to
    - It is difficult to compare the performance of components built by Gamma Insights (i.e. antennas, pulse-generator) to other components being used in similar GPR systems, as many GPR systems use proprietary antennas and electronics.

1.4 Feedback

Many of the challenges mentioned above related to one main point of feedback from the teaching team: concern over the challenge level of the project and the high-performance radar that would be needed to meet the requirements outlined in the Requirements Specification. This feedback was duly considered, and large changes were made to the Requirements Specification that reduced the radar performance requirements significantly. Additionally, the decision was made to pivot focus from producing a high-quality radar to instead producing a superficially functional radar that will provide enough functionality for demonstration. This will give more time and resources towards developing the rest of the system to an appropriate level.

1.5 Product Stage Classifications

The following convention will be used to distinguish design specifications for different stages of the product development:

Character	Development Stage
A	Proof of Concept (PoC)
B	Engineering Prototype
C	Production Version

Table 1 - Product Stage Classifications

2. Hy-dar Design

2.1 Mechanical Design Specifications

There are three major physical sections of the Hy-dar system: the electronics boxes (which contain the system battery, receive antenna, transmit antenna, and system processor as ‘transmit box’ and ‘receive box’), the power module and the stabilization system (guy-wires and anchoring). While the electronics boxes and stabilization system are common to both PoC and Prototype designs, the power module will be different. The PoC ‘s power module is wall-powered and simply uses an AC-DC converter and cabling, while the Prototype’s power module is solar-powered and uses a solar panel, mounting pole and cabling.

Table 2 below lists the hardware requirements for the construction of the Hy-dar system:

Design Specification ID	Description	Possible Changes to Future Designs	Related Requirement Specification(s)
D 2.1.1 - B	Antenna enclosures are moderately tough, rigid, and has a friction-fit or latching lid. It is made of water-resistant, non-corrosive, non-conductive material.	Number of enclosures may change depending on the size and distance between antennas	R 2.3.1 – A R 2.3.2 – B R 2.3.3 – B
D 2.1.2 - B	Electronics enclosure is moderately tough, rigid, and has a friction-fit or latching lid. It is made of a water-resistant, non-corrosive material.	Electronics may be placed into the Receive Antenna’s enclosure (as shown in CAD models)	R 2.3.1 – A R 2.3.2 – B R 2.3.3 – B
D 2.1.2 – C	All enclosures are made of impact-resistant plastic and rated to IP67 for protection against water and dust ingress. Exterior materials will be rated for use between -40°C to 85°C.		R 2.3.3 – B R 2.3.7 – C R 2.3.8 - C R 2.6.2 – B
D 2.1.3 – B	Enclosures will have maximum dimensions of 50cm x 50cm x 50cm, but will fully encapsulate the components within and be large enough as to be physically difficult for animals to consume due to size/shape.	A decal describing the system may be added in non-toxic paint.	R 2.6.5 – B
D 2.1.3 - C	Enclosure will be able to accommodate extra batteries added by the user (up to double to initial battery capacity)	An internal shelf/rack to may be added to the enclosure.	R 2.2.9 - C
D 2.1.4 - B	The solar panel mounting beam will be 1-3m tall and less than 50lbs in weight.	Further restrictions on the height and weight may be defined once a solar panel is chosen.	R 2.1.2 – B
D 2.1.4 - C	The mounting beam will be lightweight, collapsible, and rated to 100km/h windspeeds. It will be strong enough to potentially bear both a solar panel and a user-supplied satellite communication system.		R 2.1.7 – C R 2.3.6 – C R 2.5.8 – C

D 2.1.5 – B	The mounting beam will anchor into the ground with a helical pile (or similar) and be stabilized with a trio of radial guy wires anchored with pegs or cams	A tripod mount may be used if the solar panel is light and the tripod is cost-effective.	R 2.3.4 – B R 2.6.1 - A R 2.6.7 – B
D 2.1.6 – B	Sensitive electronic components will be shielded from EMF, and metallic guy wires will have “Johnny Ball” style insulators installed along their length to prevent coupling with the antennas.	Stainless steel guy wires may be swapped for a non-conductive material if a strong, low-cost option can be found.	R 2.1.8 – B
D 2.1.7 – B	Enclosure doors will be lockable via key lock and have handles or grab-bars on the sides.	If an enclosure without handles is used, additional handles may need to be added.	R 2.1.2 – B R 2.3.5 – B
D 2.1.8 - B	The physical system will be split into 4 packages when disassembled: the enclosure (with antennas, GPR and electronic components carried with), the solar panel (in a carrying case), the mounting beam, and helical pile and stabilizing guy-wires (in a carrying case).	The 4 packages may be packaged in a specific way for easy setup/take down and balanced weight distribution in the future.	R 2.1.2 – B R 2.5.5 – B R 2.6.1 – A

Table 2 - Mechanical Design Specifications

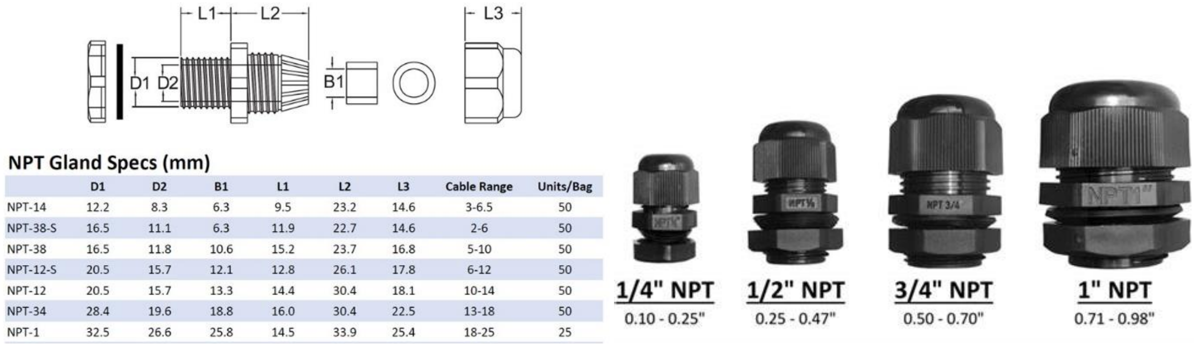
Ideally, the enclosure will be impact-resistant, IP67 rated fibreglass, such as the black models shown in Figure 2 [4] available from McMaster-Carr or orange model from another vendor [5] in a variety of dimensions. These enclosures will be modified with the removal of excess foam, addition of waterproof ports/cable glands, anchoring brackets and high-visibility non-toxic exterior paint. Thermal insulation can be added to protect interior components (ex: battery) during the winter season if needed.

Figure 2 - Examples of a lockable enclosure rated to IP67

However, the Prototype version must only be water-resistant, not IP67 rated, so the more cost-effective ($17) lockable dry box [6] in Figure 3 below will be used, allowing us to test out modifications with little financial investment in this early stage. If needed, an internal shelf will be added to utilize space effectively with batteries in the bottom half of the dry box and circuitry hosted in the upper half.

Figure 3 - Weatherproof Lockable Dry Box (29.5cm x 13cm x 18.1cm)

Holes would be drilled into the dry box and fitted with nylon cable glands (Figure 4) to provide ports for cabling to/from the power and antenna module to pass through [6] [7] [8]. These cable glands are robust, waterproof, and rated down to -40°C. They create a seal around the cables as they are tightened, come in a variety of sizes, and as many can be added as needed.



NPT Gland Specs (mm)

	D1	D2	B1	L1	L2	L3	Cable Range	Units/Bag
NPT-14	12.2	8.3	6.3	9.5	23.2	14.6	3-6.5	50
NPT-38-S	16.5	11.1	6.3	11.9	22.7	14.6	2-6	50
NPT-38	16.5	11.8	10.6	15.2	23.7	16.8	5-10	50
NPT-12-S	20.5	15.7	12.1	12.8	26.1	17.8	6-12	50
NPT-12	20.5	15.7	13.3	14.4	30.4	18.1	10-14	50
NPT-34	28.4	19.6	18.8	16.0	30.4	22.5	13-18	50
NPT-1	32.5	26.6	25.8	14.5	33.9	25.4	18-25	25

Figure 4 - Nylon Cable Glands for cable feedthrough to/from enclosures

The anchoring and stabilization of the PoC phase will be implemented with L-brackets [9] and heavy-duty tent pegs as in Figure 5 [10]. The L-brackets will be screwed into the enclosure and sealed from both sides with epoxy to mitigate water entry, and the pegs will fasten the brackets to the ground to prevent the enclosures from being moved by animals or weather conditions. Alternate tent pegs are discussed in the Alternative Design appendix, but the pegs shown in Figure 5 will be sufficient for PoC due to the controlled/known soil texture used for demonstration. Further, heavy-duty tent pegs are low-cost, and highly available which makes repair and replacement of lost or warped tent pegs easy for users.

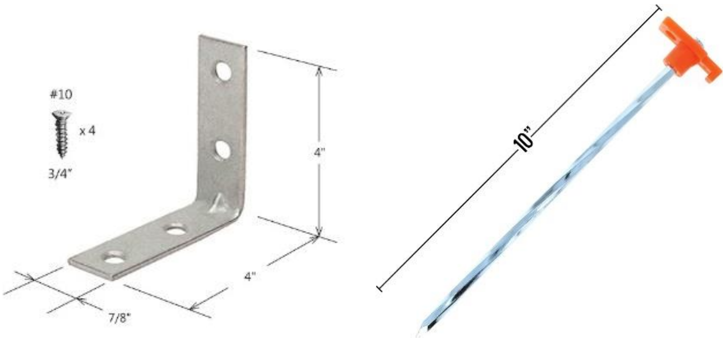


Figure 5 - Angle Brackets and Heavy-Duty Pegs for Securing Enclosures

For the Prototype phase, the solar panel mounting post will be anchored with a helical pile (shown in Figure 6 below) and 3 radially arranged stainless steel guy wires that peg into the earth, shown in Figure 8 [11] [12] [13] [14] [15]. Different styles of helical pile (square, round) can be used depending on the shape of mounting post chosen. Low cost, easy install, reasonable strength, and high availability lead us to plan to use a wooden or aluminum post for our Prototype phase, but ideally a material that is both light and nonconductive, like fiberglass, would be used in the Production phase. The helical piles allow "no dig" installation in most cases, as they can be screwed into most soil by hand, and the pegs can be driven in with a mallet.

Figure 6 - Helical Pile anchor for square (left) or round (right) posts

In particularly hard or rocky soil, some digging may be needed to start the pile installation, but it will be less than 2 ft in depth and possible to do without power equipment. Alternate anchoring options for environments with extremely loose/sandy or rocky terrain are discussed in the alternatives design appendix. Additionally, measures will be taken to mitigate electromagnetic field (EMF) interference between system components. For example, insulating balls will be used to break up the stainless steel guy wires such that section length does not match quarter wavelength multiples of the transmission wavelength, and antenna to guy-wire coupling is minimized. The antenna enclosures will be non-conductive, minimizing the distortion of antenna radiation patterns by the enclosure, and local shielding will be added to particularly sensitive electronic components to prevent EMF interference.

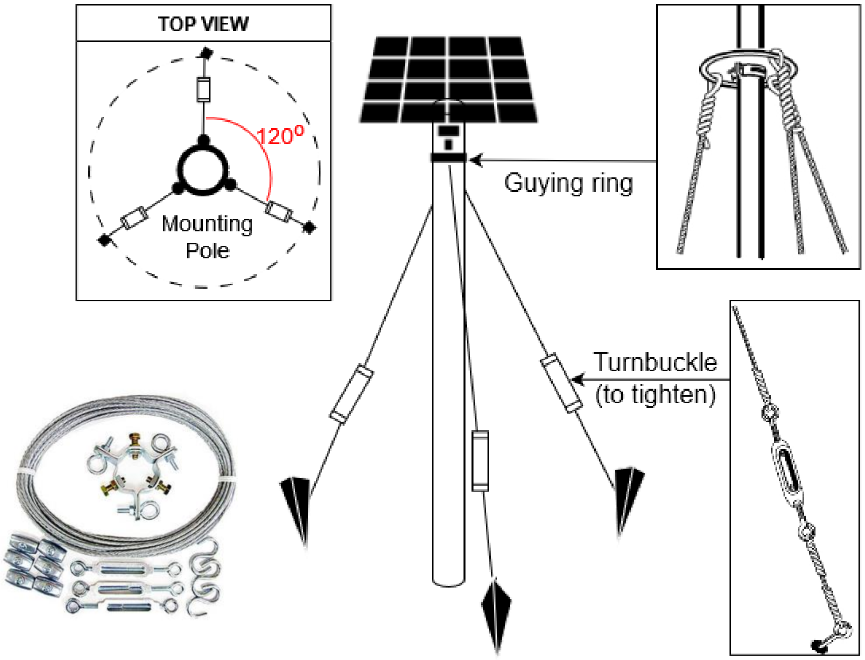


Figure 7 – Guy Wire Components and 3-Way Guy Wire Stabilization Diagram

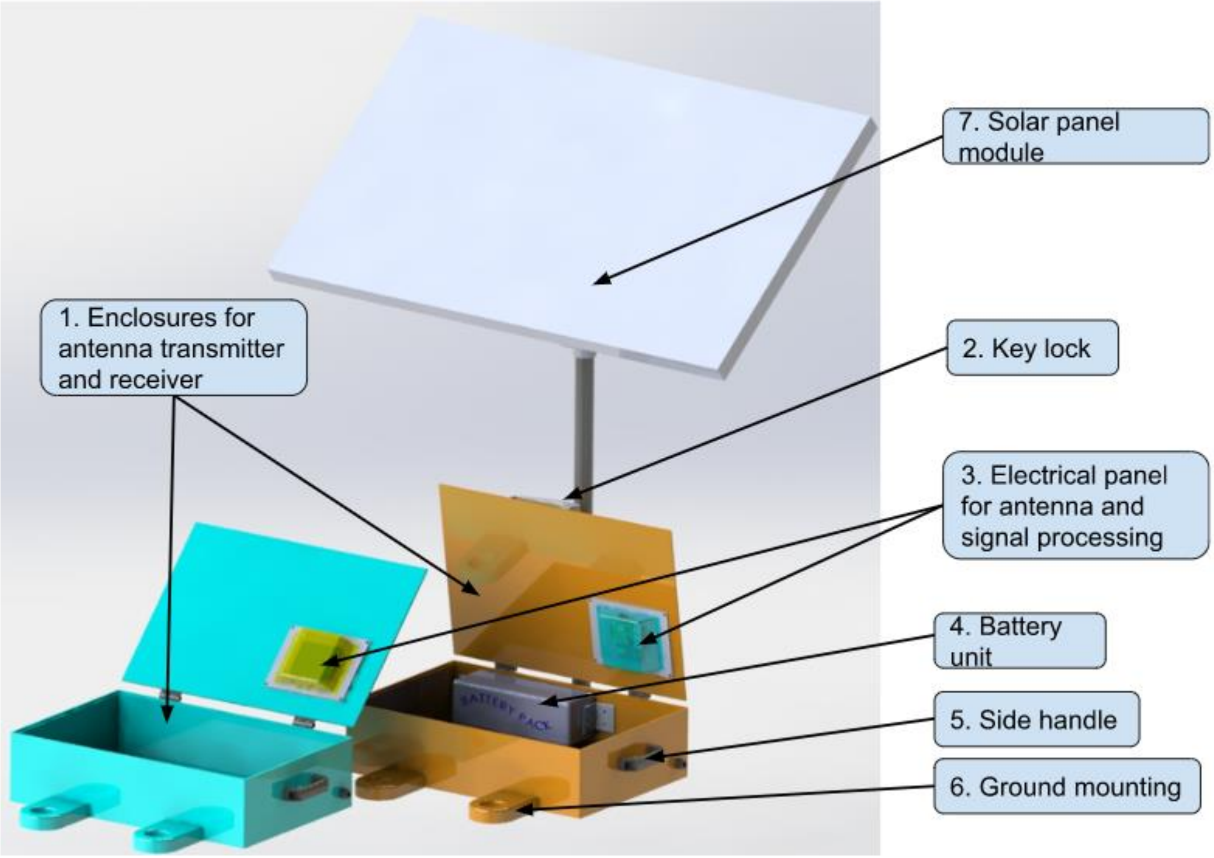


Figure 8 - Hy-dar system mechanical parts

Table 3 describes the numbered items seen in CAD diagrams below, Figures 9 to 16.

Item number	Description	Figure number for dimensions
1	Enclosures for the antenna transmitter and receiver, blue enclosure is for the transmitter, and the orange enclosure is for the receiver, with battery unit mounted inside.	Figure 9
2	Key lock for accessing the enclosures	Figure 10
3	Cyan electrical panel for the receiver and signal processing circuitry. Yellow electrical panel for the transmitter circuitry.	Figure 11 and 12
4	Battery unit for supplying power to the system.	Figure 13
5	Side handle	Figure 14
6	Ground mounting to stabilize the enclosures	Figure 15
7	Solar panel	Figure 16

Table 3 - Items in CAD Diagrams

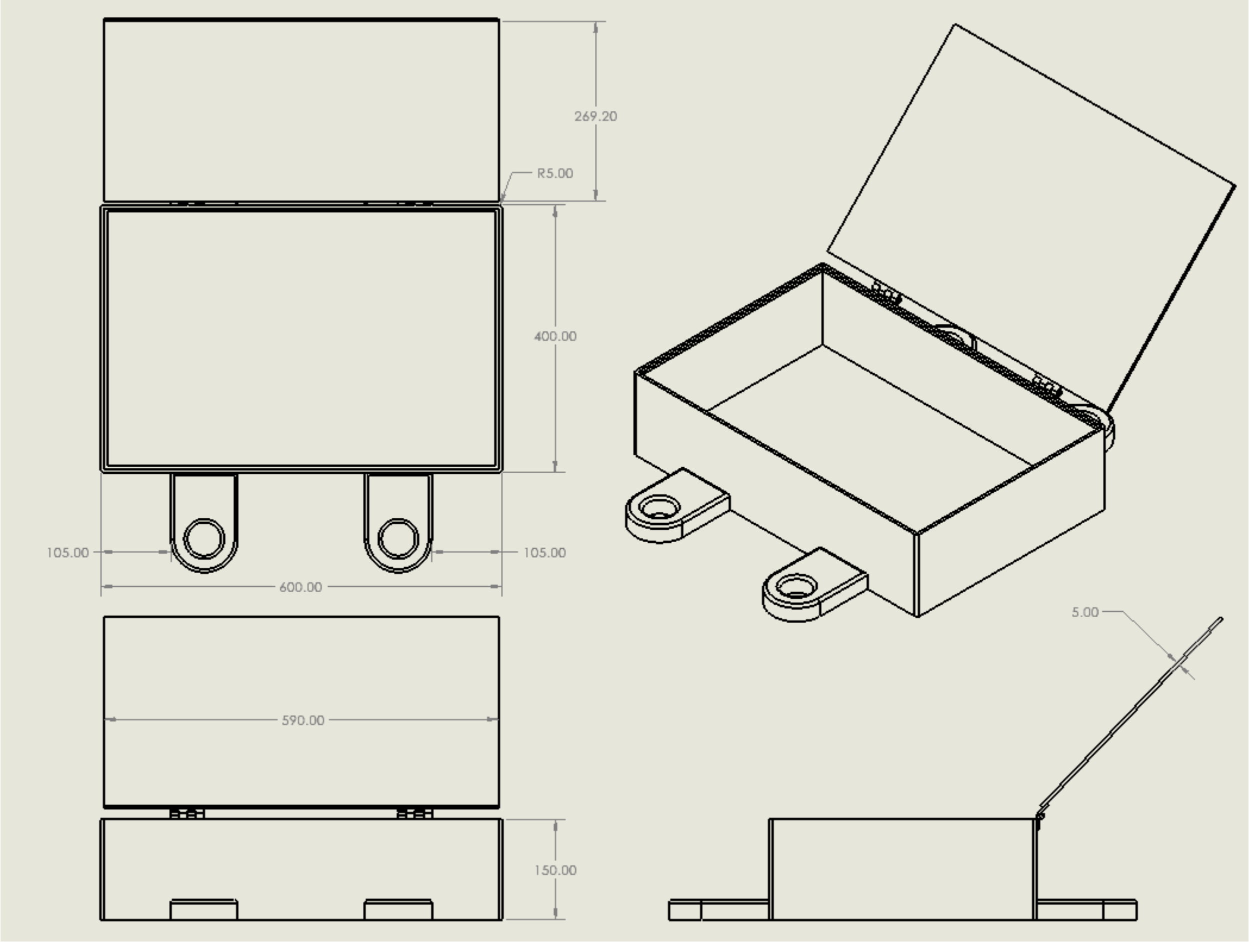


Figure 9 - Enclosure Dimension Unit in mm.

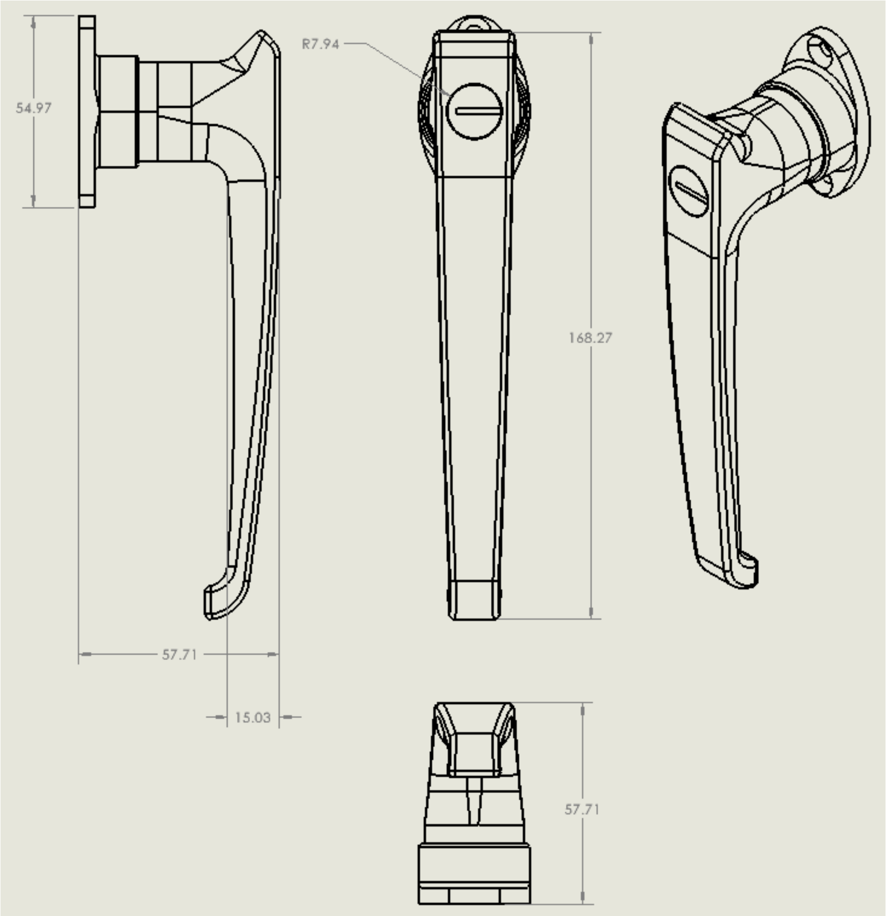


Figure 10 - Key Lock Dimension, Unit in mm

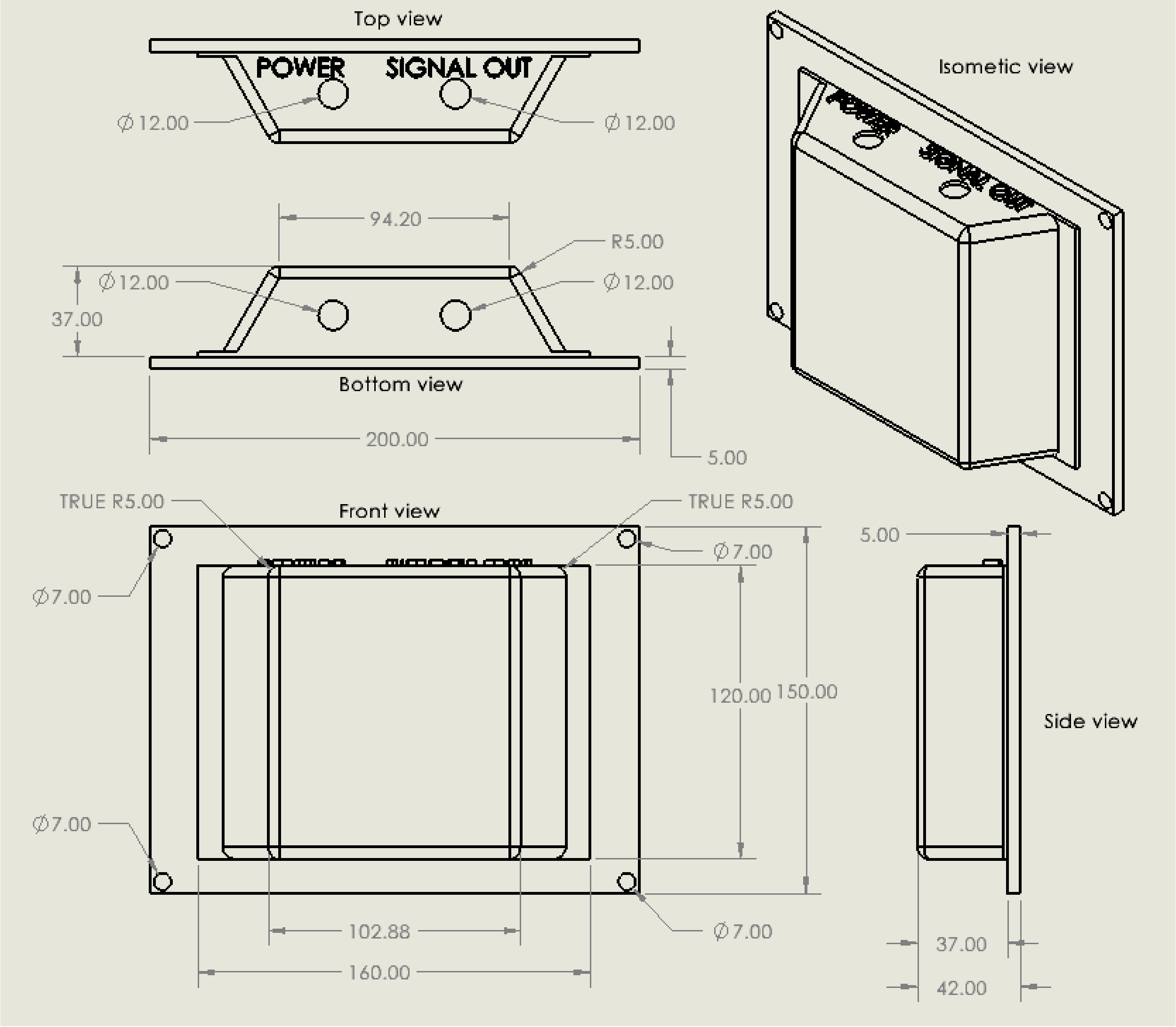


Figure 11- Antenna Transmitter Electrical Panel, Unit in mm

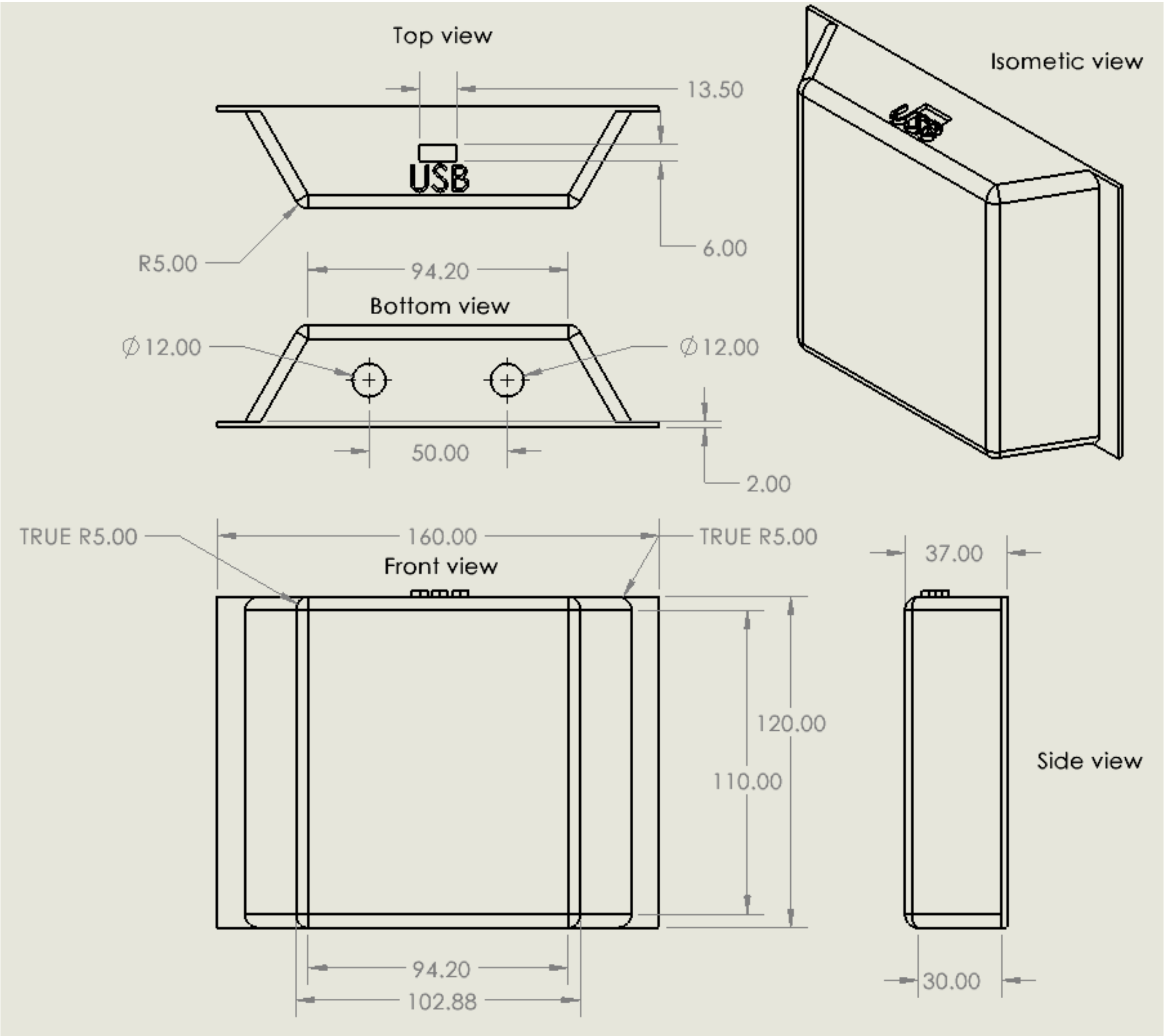


Figure 12 - Signal Processing Unit Electrical Panel, Enit in mm

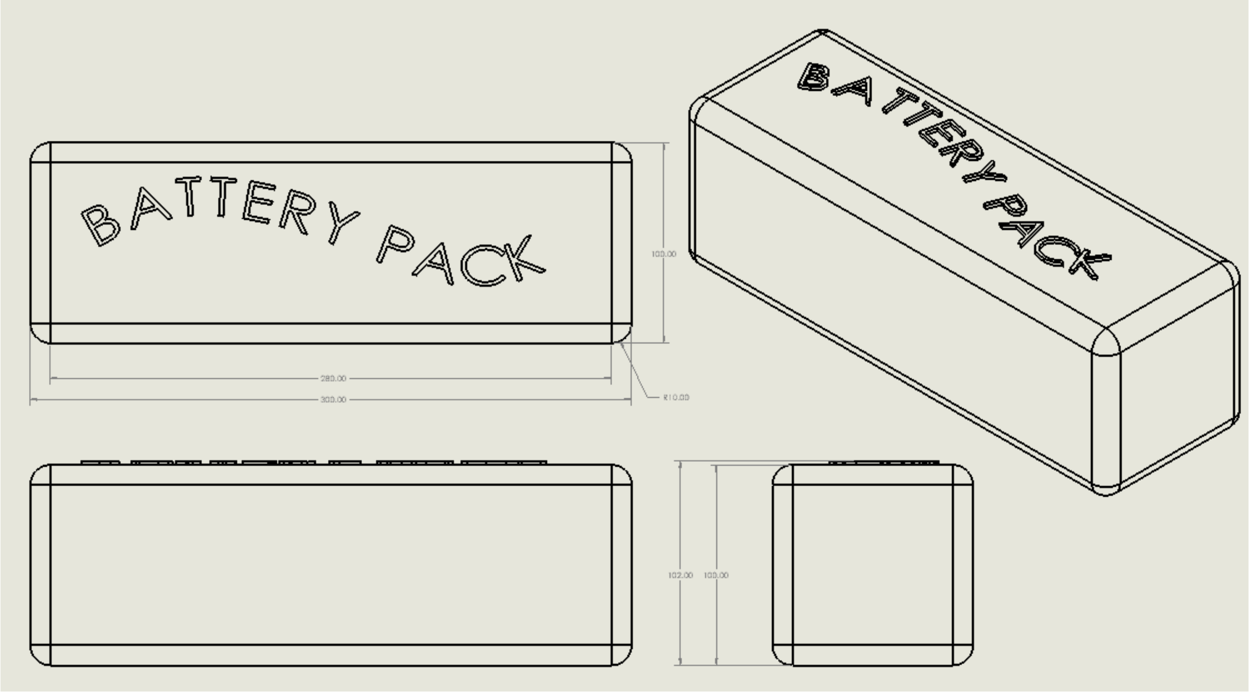


Figure 13 - Battery Unit Dimensions, Unit in mm

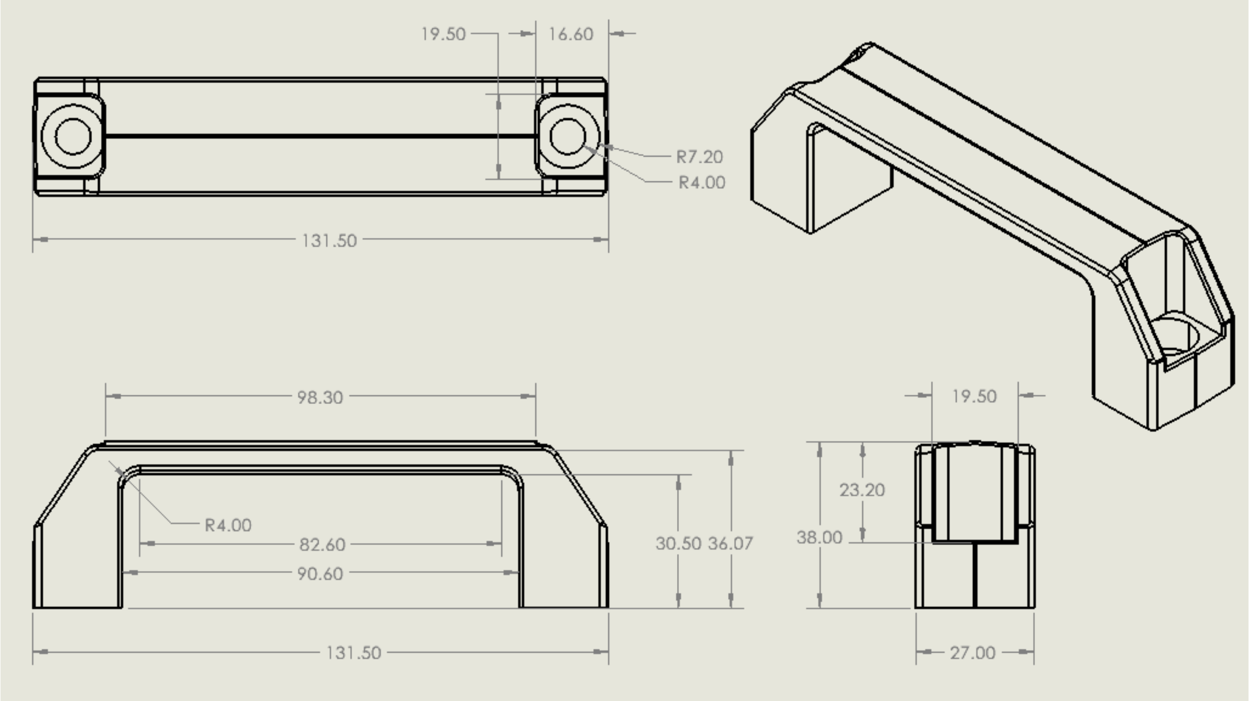


Figure 14 - Side Handle Dimensions, Unit in mm

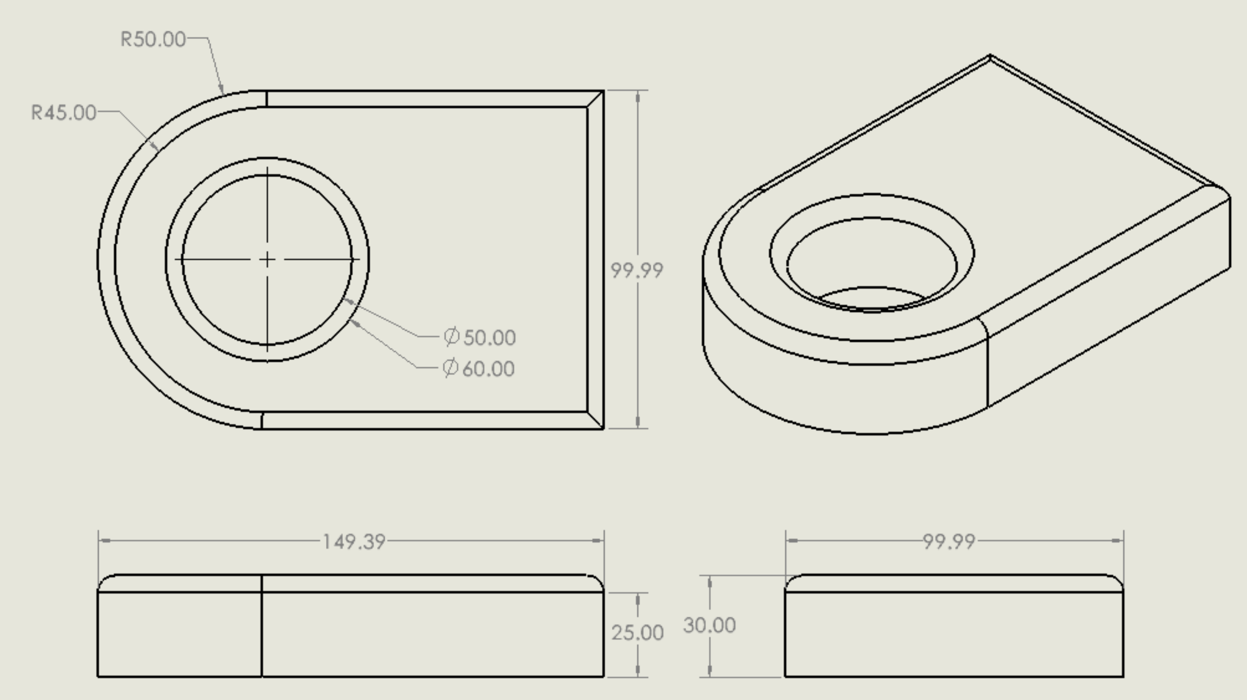


Figure 15 - Ground Mounting Dimensions, Unit in mm

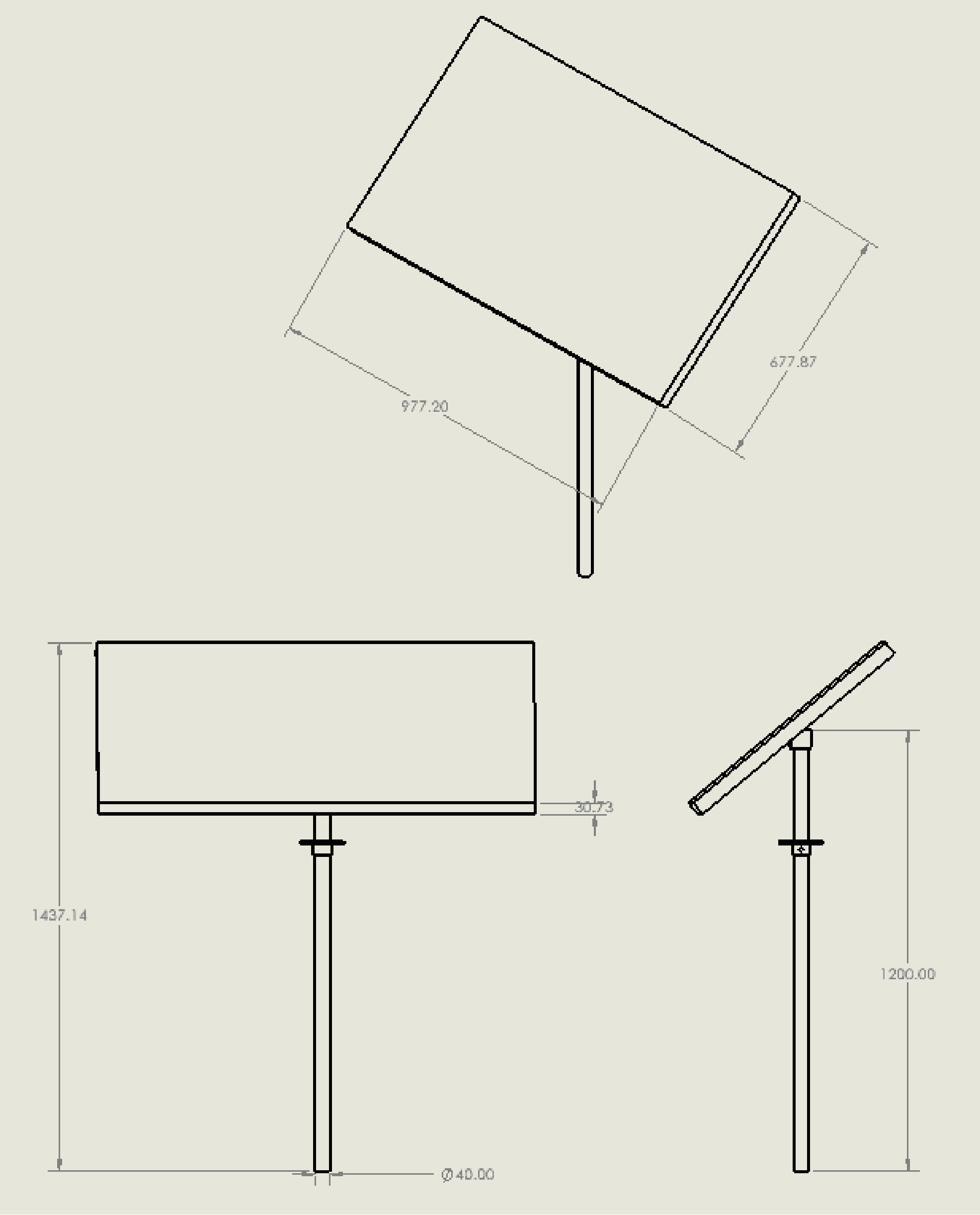


Figure 16 - Solar Panel Dimensions, Unit in mm

2.2 Electrical Design Specifications

2.2.1 Radar

Table 4 gives the electrical specifications of Hydar's radar subsystem.

Design Specification ID	Description	Possible Changes to Future Designs	Related requirement Specification(s)
D 2.2.1 – A	The system uses impulse radar.		Req 2.2.3 – B
D 2.2.2 – A	The pulse generator is capable of producing pulses of 1-2 ns pulse width and greater.		Req 2.1.3 – A
D 2.2.3 – A	The radar system supports an RF bandwidth between 400 MHz – 500 MHz.		Req 2.1.3 – A
D 2.2.4 – A	The radar system operates at an RF center frequency no less then 400 MHz and no greater than 500 MHz.		Req 2.1.1 – A
D 2.2.5 – A	The characteristic impedance of all transmission lines in the radar system is 50 Ohms.		Req 2.1.8 - B
D 2.2.6 – A	The transmit circuit will output a signal with power between 10 - 17dBm.	Transmit signal power will increase for the Prototype (B) based on achievable depth of penetration.	Req 2.1.1 – A
D 2.2.7 – A	The receiver front end can withstand an input power of at least 0 dBm.	Can upgrade receiver front end components in the future to withstand higher input powers.	Req 2.1.1 – A
D 2.2.8 – B	Digitizer is capable of digitizing an analog signal with a maximum frequency of 500 MHz.		Req 2.1.3 – A Req 2.4.2 – A
D 2.2.9 – A	The radar system has two antennas, one for RX and one for TX.		Req 2.1.1 – A Req 2.1.3 – A
D 2.2.10 – A	Antenna isolation is between 10 - 17 dB, dependant on the	For the Prototype (B), this value will increase	Req 2.1.1 – A Req 2.1.3 – A

	transmit signal power and the max. receiver input power.	based on increases in transmit signal power.	
D 2.2.11 – A	The antennas will be manufactured out of copper tape and a dielectric substrate or aluminium sheet metal.	Resistive loading may be added in the future to reduce the ring-down time of the impulse response.	Req 2.1.1 – A Req 2.1.3 – A
D 2.2.12 – A	Each antenna should have a foot print no larger than 0.5m x 0.5m.		Req 2.1.2 – B

Table 4 - Radar Subsystem Electrical Design Specifications

The Hy-dar radar subsystem will operate at a centre frequency between 400MHz and 500MHz, with an operational bandwidth between 400MHz and 500MHz. It will utilize impulse radar to transmit a signal into the earth and detect the reflections of this signal. Impulse radar is a radar method wherein the system emits a short time domain pulse, followed by a pause. During this pause, the system is said to be in the “receiving time” [16]. Received signals, or echoes, occur as the waves which were reflected off objects or interfaces return to the receiver. The time delay between transmission and an echo translates into a distance to this object or interface based on the wave velocity in the medium. The overall radar system is comprised of two main paths. First, the transmit path, composed of pulse generator, transmitter, and antenna. Second, an identical but separate antenna, a receiver, and a digitizer compose the receive path. A block diagram visualizes this architecture in Figure 15.

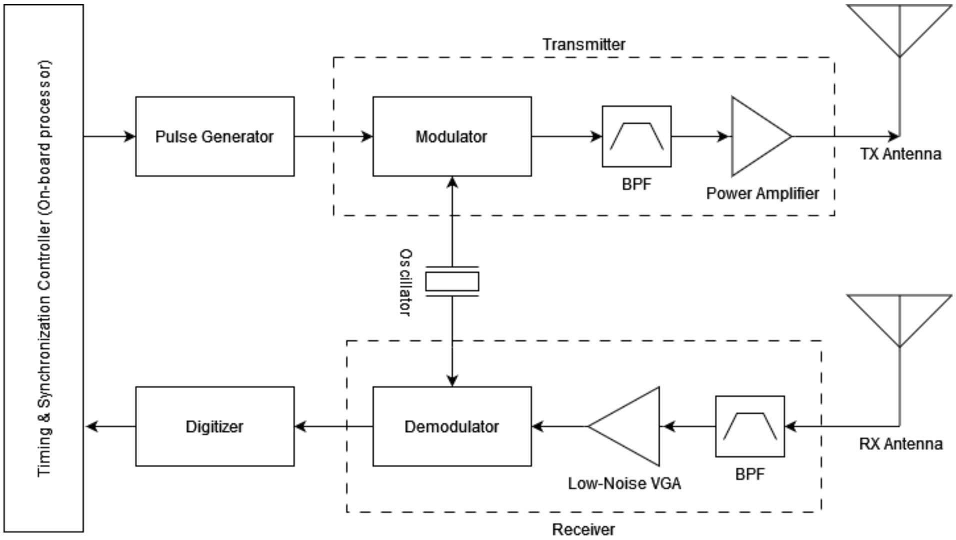


Figure 15 - Radar System Block Diagram

2.2.1.1 – Transmitter

Impulse radar necessitates the creation of short time domain impulses. The Hy-dar system requires a bandwidth of 400-500MHz, and bandwidth is inversely related to pulse width [17], so a pulse of 1ns relates to a bandwidth of 1GHz, while 2ns relates to a bandwidth of 500GHz. Thus, the Hy-dar system will generate a pulse of 1-2ns, and this is done with the pulse generator shown in Figure 10. This circuit employs the avalanche breakdown of an NPN transistor to achieve this short pulse width, in which the emitter voltage increases very rapidly once the breakdown conditions have been met. For Hy-dar's pulse generator, the avalanche breakdown occurs once the trigger source reaches 5V. Once this voltage is met, the transistor goes into avalanche breakdown, and the storage capacitor discharges creating the pulse. This pulse amplitude is controlled by the impedances at the collector and base of the transistor. An increase in impedance at the base of the transistor, in the shape defining impedance, further limits the ripple after the initial pulse. The exact values of the components in Figure 16 will be adjusted to the specific transistor, as avalanche breakdown behaviour is specific to each transistor.

This time-domain pulse produced by the pulse generator is a baseband signal. To be able to propagate this signal, it must be shifted to a higher frequency, which is done by mixing the baseband signal with a with a carrier frequency. This is done as part of the modulator in the transmitter section of Figure 15. It is important to note that due to radar not transmitting information, the modulator will not be encoding any information into the signal and will only be mixing the baseband pulse with the carrier frequency. Once the signal has been mixed, it will be passed through a bandpass filter to remove any out of band harmonics that may have been introduced by the mixer.

Ideally, the Hy-dar system would transmit at an incredibly high power to achieve an increased depth of penetration. Realistically, the output power is constrained by what the circuit components can handle and what level of amplification can be provided at the output. While the pulse generator can produce relatively high-power pulses, components such as mixers typically have maximum input power requirements, for example 50mW, or just under 17dBm [18] [19], which limits the power level of the pulse that is generated. Thus, the bulk of the transmit power must be provided by a power amplifier situated just before the antenna. For the PoC a high transmit power is not required as large depths do not need to be reached during the demonstration, and thus no power amplifier will be used.

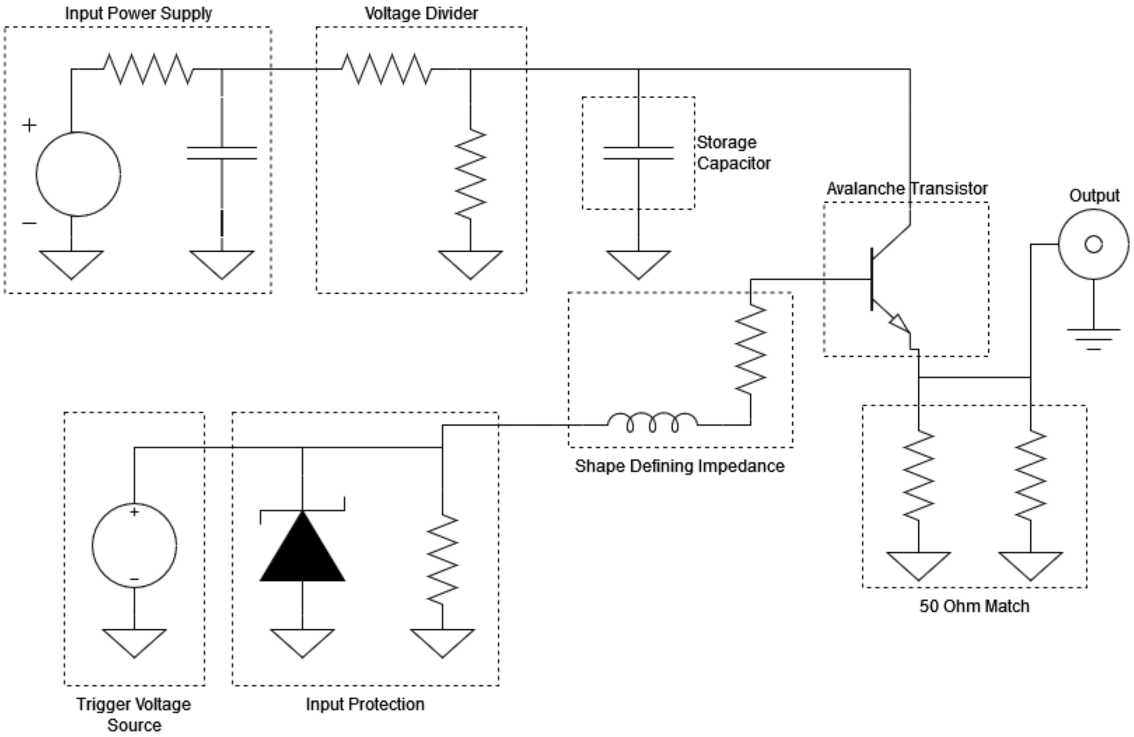


Figure 16 - Pulse Generator Schematic

2.2.1.2 – Receiver

The receiver of the Hy-dar radar subsystem is comprised of three main components, a band-pass filter, a low-noise variable gain amplifier, and a demodulator. Each of these components should be able to withstand an input power of 0dBm, with potential to source components that can withstand higher input powers in the future. The band-pass filter attenuates any signals outside of the bandwidth of the system, preventing any high power out of band signals from saturating the receiver. The variable gain amplifier amplifies the received signal with a settable gain. This component will be used to implement automatic gain control in the receiver, an important feature as the reflections returning to the receiver may have a wide range of powers. Automatic gain control ensures that the system can sufficiently amplify low-power reflections, while preventing excessive amplification of high-power reflections that could lead to receiver saturation. This amplifier should also be low noise, to improve the sensitivity of the receiver and allow the detection of lower power reflections from deeper interfaces. Lastly, the demodulator takes the received signal and frequency shifts it back into a baseband signal before passing the signal to the digitizer. Converting back to a baseband signal is key as this lowers the maximum frequency of the signal, thus reducing the necessary sampling rate of the digitizer.

2.2.1.3 – Digitizer and Timing & Synchronization Controller (On-Board Processor)

The purpose of the digitizer is to convert the analog input data to digital data, so that the on-board processor will be able to calculate the reflection depth from the collected data. The bandwidth of the radar system is at maximum 500MHz, so by Nyquist Theorem which states that a periodic signal must be sampled at more than twice the highest frequency component of the signal, the sampling rate of the digitizer should be at minimum 1GS/s. Since this is a theoretical minimum and not necessarily realistic, the digitizer should sample at a rate of at least 4 times the highest frequency component, or 2 GS/s.

For the PoC, an oscilloscope will be used to visualize the received signal. For the engineering prototype, the digitizer will be separated into three main parts: high frequency Analog to Digital Convertor (ADC), JESD204 serial interface, and the logic device.

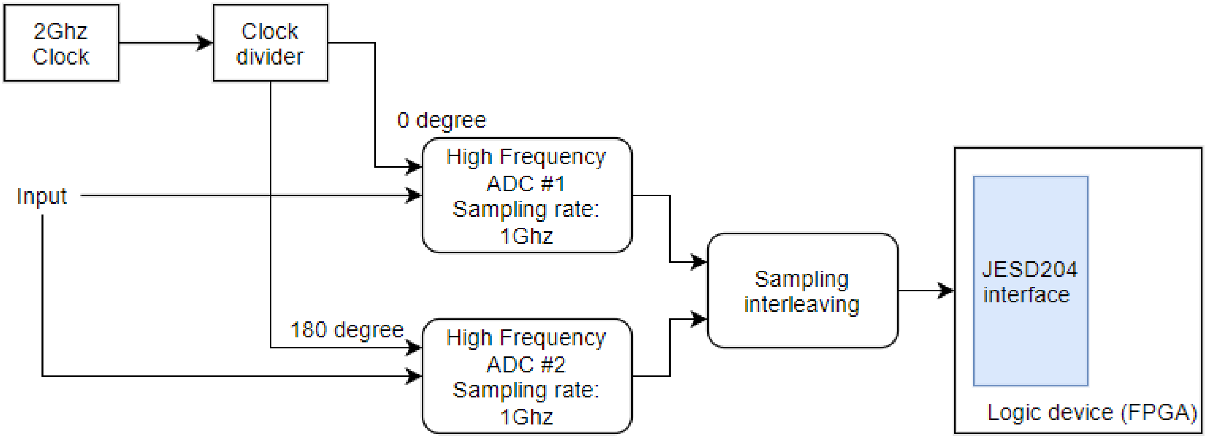


Figure 17 - Block diagram for the digitizer

Since the required sampling rate for the ADC is 2GS/s, in order to find a reasonable priced yet powerful enough ADC, a method called “Time Interleaving” will be applied. By using two identical ADCs, the sampling rate is doubled. Time interleaving design requires to offset the second ADC to 180 degrees so the system can sample on rising edge and falling edge. This is shown in Figure 18.

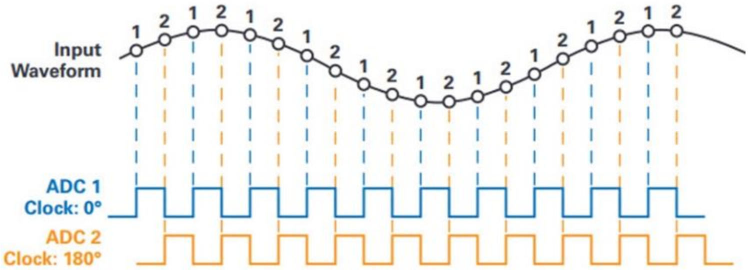


Figure 18 - Time Interleaving Sampling

2.2.1.4 – Antennas

The Hy-dar system will include two antennas used to transmit the impulse signal and receive the returning reflections. Because these two antennas will be spatially close, cross-coupling must be considered and managed. Considering that the receiver front end can safely withstand at least 0dB of signal power, the two antennas must have an isolation between 10 and 17 dB, depending on the transmit pulse power of the PoC system. An empirical analysis of the isolation levels will have to be conducted once the antennas are built, but a consultation on the topic with Professor Chris Hynes gives some confidence that such isolation levels are achievable for the PoC [20]. Since the PoC system will be operated at a lower power then the prototype, antenna isolation will need to be improved for the prototype version of the system. Improved antenna isolation can be achieved through multiple methods, such as using more directive antennas, introducing a cavity shield to the antenna design, orthogonally polarizing the two antennas, and increasing the antenna spacing [21].

The Hy-dar antennas will operate with a bandwidth between 400MHz and 500MHz, ensuring that the antennas can transmit and receive the full bandwidth of the transmit pulse and returning reflections. The center frequency of this bandwidth will be the same as the rest of the system (between 400MHz and 500MHz) for a similar reason: to accurately transmit the modulated pulse signal. Each antenna will be lightweight and not exceed dimensions of 0.5mx0.5mx0.5m to ensure that the full system remains portable. 2 main antenna types have been identified that can meet these requirements, the Bow-tie and Vivaldi antenna. Both exhibit wideband properties and are planar in at least one dimension, an important factor for both portability and manufacturability. The main two differences between these types are directivity and dispersion, with the Vivaldi being more directive but also more dispersive then a Bow-tie. Higher directivity is desired as this improves the isolation between the transmit (TX) and receive (RX) antenna and is also more power efficient then a more omni-directional pattern. But lower dispersion is also desired, as a more dispersive antenna will have an impulse response with a longer ring-down time due to high dispersion causing the conversion of the impulse signal into chirps [22]. A shorter ring-down time is desired as a long ring-down period may conceal reflections at shallow depths, depending on the difference between the power levels of the reflection of interest and the power level of the ringing. As such, both types of antennas will be manufactured, and empirical analysis will determine the optimal choice for the Hy-dar system. To support low-cost, fast manufacturing and ability to quickly iterate antenna design without sacrificing conductivity and therefore antenna performance, the antennas for the PoC will be constructed out of copper tape and a dielectric substrate, or aluminium sheet metal if the physical features are simple enough. For the prototype the antenna will be made of sheet aluminium due to the cheap cost, decent conductivity, and corrosion resistance of aluminium. The addition of resistive loading to reduce ring-down time [23] will also be investigated for the prototype. The general physical forms of these two antenna types are shown in Figure 19. Exact dimensions will be determined later in the design process.

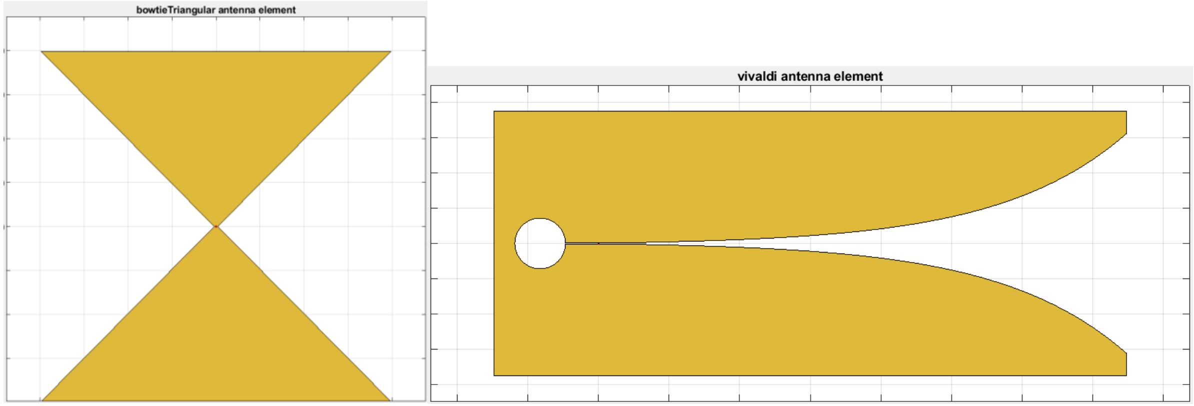


Figure 19 - Bow-tie Antenna (Left) and Vivaldi Antenna (Right)

2.2.2 Power

Table 5 gives the electrical specifications for the Hy-dar power subsystem.

Design Specification ID	Description	Possible Changes to Future Designs	Related requirement Specification(s)
D 2.2.13 – A	The system will be powered by a bench power supply.	Integrate DC wall adapter	R 2.2.1 – A
D 2.2.14 – B	The system will employ a passive switching mechanism to allow for a 12V, 10A DC wall adapter input.	Current rating decrease Use active switching mechanism	R 2.2.1 – A R 2.2.6 – B
D 2.2.15 – A	Various stages of filtering will be applied to all power inputs.		R 2.2.2 – A
D 2.2.16 – B	A 10-30Ah lithium iron phosphate battery pack will power the Hy-dar system year round for measurement intervals up to 1 per hour.	Increase in battery capacity	R 2.2.3 – B
D 2.2.17 – B	The charge controller should allow the battery to operate without an input supply present.		R 2.2.5 – B
D 2.2.18 – B	The system will employ a battery management system (BMS) to prevent operation when the battery cannot safely operate.		R 2.6.6 – B R 2.6.8 – C R 2.6.10 – C
D 2.2.19 – B	A non-acid-based battery chemistry will be utilized in the system.		R 2.6.2 – B
D 2.2.20 – B	A 50-100W monocrystalline solar panel will power the Hy-dar in remote deployments for year-round use.		

D 2.2.21 – B	An in-line current sensor will be used to supply data to a SOC estimation algorithm.		R 2.2.7 - B
D 2.2.22 – B	Standard ¼” ring connectors will be used to ensure replacement batteries of the same package type are supported.		R 2.2.8 – B
D 2.2.23 – B	Modular battery capacity will be supported by a PWM solar charge controller.		R 2.2.9 – C
D 2.2.24 – C	The power system will employ a heating solution to ensure the batteries can safely charge in below freezing conditions.	Utilize a battery pack which supports charging in freezing temperatures.	R 2.3.7 – C

Table 5 - Power Subsystem Electrical Design Specifications

A high-level of the described power system for the Hy-dar’s engineering prototype is detailed below in Figure 20.

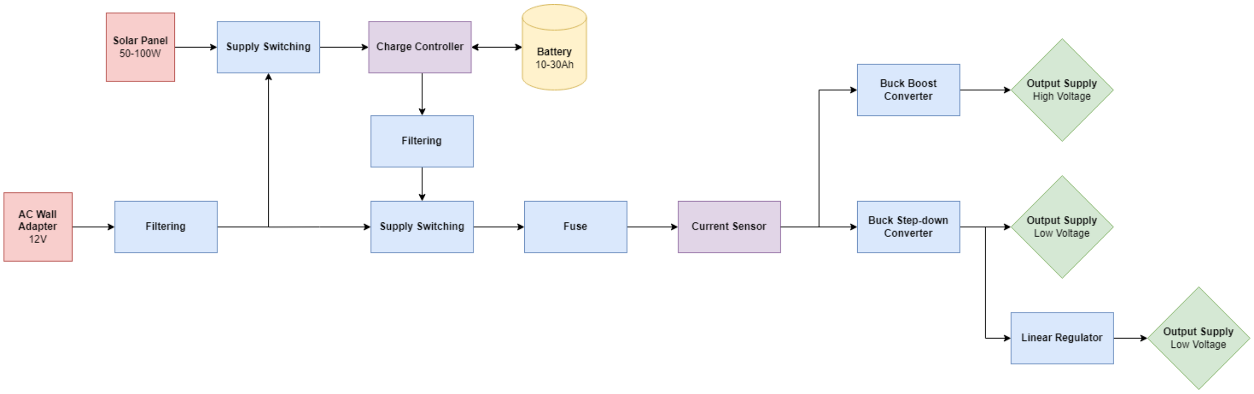


Figure 20 - High level diagram of power system

For the Hy-dar proof of concept, a simple bench power supply will be used to demonstrate that the GPR system is capable of basic operation. However, for future revisions of the system a 12V 10A AC-DC wall adapter will support the operation of the device and charging of the battery as a secondary supply (see Figure 20). This feature allows technicians to prepare the system prior to deployment without needing to setup the self-sufficient supply interface or charge the battery in the field during installation.

Figure 21 - A 12V 10A DC wall adapter [24]

The primary power supply for the Hy-dar will be a 50-100W monocrystalline solar panel which will charge the lithium iron phosphate battery pack. Although this battery chemistry supports discharging at below freezing temperatures as required by the Hy-dar in some remote deployments, an active heating system is required by the production version to support charging at temperatures below 0 °C. A PWM solar charge controller such as the SOLPERK HC-F10A will coordinate the charging of the battery pack using the solar source as other options are too expensive for this use-case. As development of the Hy-dar continues, these power specifications will be narrowed based on measured values to ensure the system is self-sufficient for year-round operation in southwestern British Columbia with a maximum supported measurement interval of 1 per hour. In addition, the selected battery has an integrated BMS which eliminates the need for an on-board solution.

Figure 22 - ROCKSOLAR 12-10 LiFePO4 battery [25] (left) and the SOLPERK HC-F10A solar charge controller [26] (right).

When in use, the grid-based supply will be favoured over the battery pack supply to conserve the battery supply. The proposed solution to achieve this is by using passive supply prioritization implemented by series diodes at both sources which will favour the source operating at the highest voltage potential and effectively implement a passive OR-ring prioritization network.

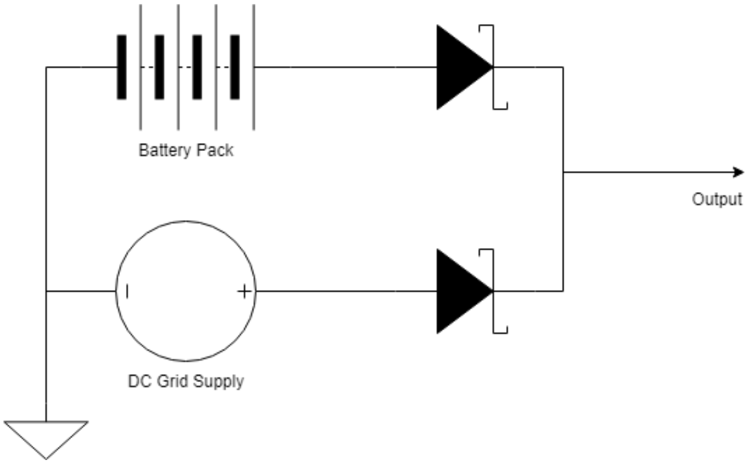


Figure 23 - Supply prioritization example.

After supply prioritization occurs, an in-line Hall-effect current sensor such as the TMCS1107 will measure the current draw of the system in order to estimate the SOC of the battery pack over time. Additionally, switching regulators will be used to either step up the 12V input voltage to those required by the GPR components, and to step the voltage down to 5V for the digital components used by the signal processing and data management modules. For any further voltage regulation linear regulators will be utilized if the voltage difference is within several volts.

2.2.3 Data Management

In the Hy-dar system, the receive signal will be collected, processed, and stored. When the signal processing is finished, the on-board processor will store the data as a text file and write the file to an SD card. During the data writing and transferring process, any kind of unscheduled power losses might lead to data corruption and losses. Having a holdup capacitor can make sure the processor is able to finish the data collecting and transferring process by providing a short amount of holdup time. During this short amount of holdup time, the processor will be able to finish the cycle and safely finish all the requested operations, therefore, data losses and corruption can be efficiently eliminated.

Table 6 outlines the electrical design specifications for the data management.

Design Specification ID	**Description**	**Possible Changes to Future Designs**	**Related requirement Specification(s)**
D 2.2.3 – B	A holdup capacitor will be included to supply power when the main power supply is cut-off	Manufacture of the capacitor	Req 2.2.4 – B
D 2.2.3 – B	Protection for the external storage (SD card) will prevent data loss	Better and faster external memory	Req 2.2.4 – B

Table 6 - Data Management Electrical Design Specifications

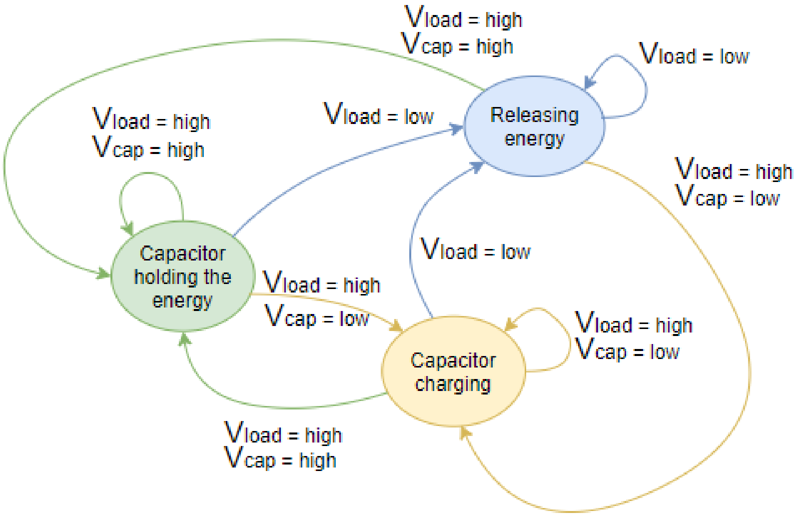


Figure 24 - Charging State Diagram [27]

The holdup capacitor will charge itself when the power is on and will keep charging until full charge is reached. When the main power is suddenly cut-off, the holdup capacitor will release its energy, which is used to supply the load circuitry.

A schematic of this circuit and formula for calculating holdup capacitance is shown below:

where $p = power,\ t = time, V_H = high\ voltage\ threshold, and\ V_L = low\ voltage\ threshold$

$$C = \frac{2pt}{{V_H}^2 - {V_L}^2}$$

Equation 1

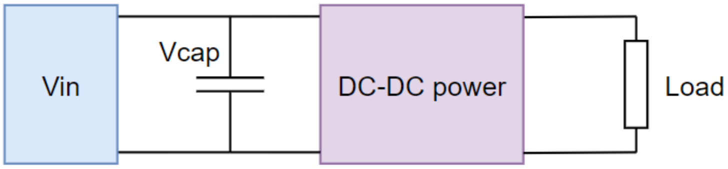


Figure 25 - Power Schematic

Voltage response during power up operation, normal operation, and power down operation is shown in the plots below:

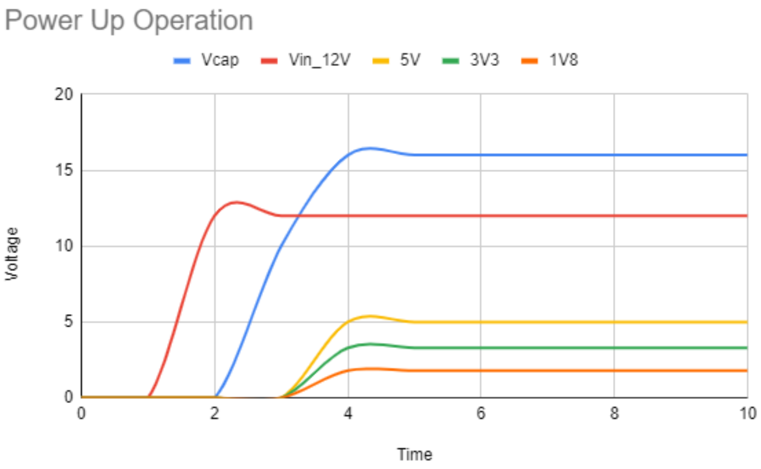


Figure 26 - Power Up Operation

Normal operation:

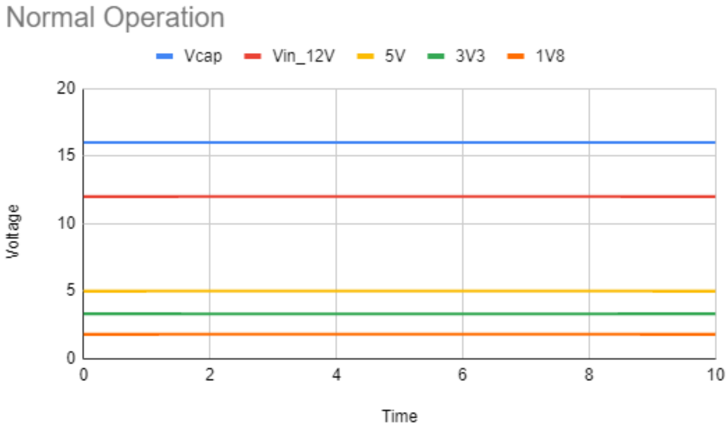


Figure 27 - Normal Operation

Power down operation:

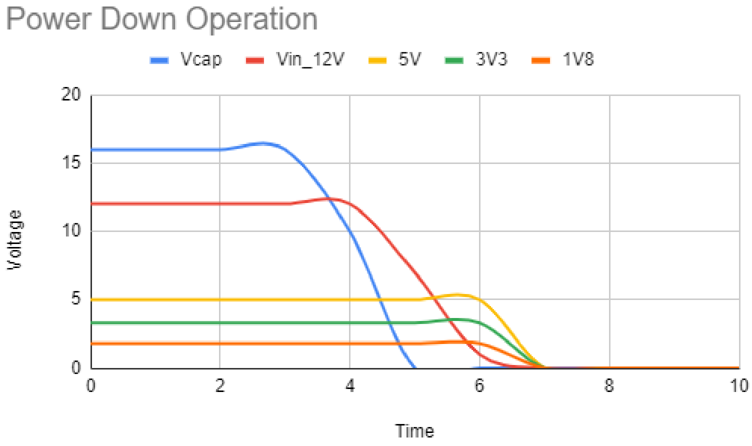


Figure 28 - Power Down Operation

2.3 Software Design Specifications

2.3.1 Overall Software Design

The software and firmware involved in the project include two main parts: the microcontroller firmware which runs on the Hy-dar system microcontroller, and the Hy-dar software interface which runs on the user's laptop or tablet device. Design of both these two parts centers around the idea of being able to control and monitor the microcontroller functioning by sending commands from the laptop via the software interface (and USB connection). However, when the microcontroller is disconnected, it can operate independently in a standalone mode.

Table 7 outlines the operation states the Hy-dar system will follow.

State	Description	Prompt low power mode?
Initialized	System successfully initialized and ready to pair, measure, or calibrate (?)	Yes
Not Initialized	Default system state on initial power up	Yes
Scanning	System is completing a scan	No
Sleep	System in between scans	Yes
Charging	System is unable to scan due to battery charge up.	Yes
Transferring	System is currently transferring data.	No
Error	System encountered an error.	Yes

Table 7 - Operation States

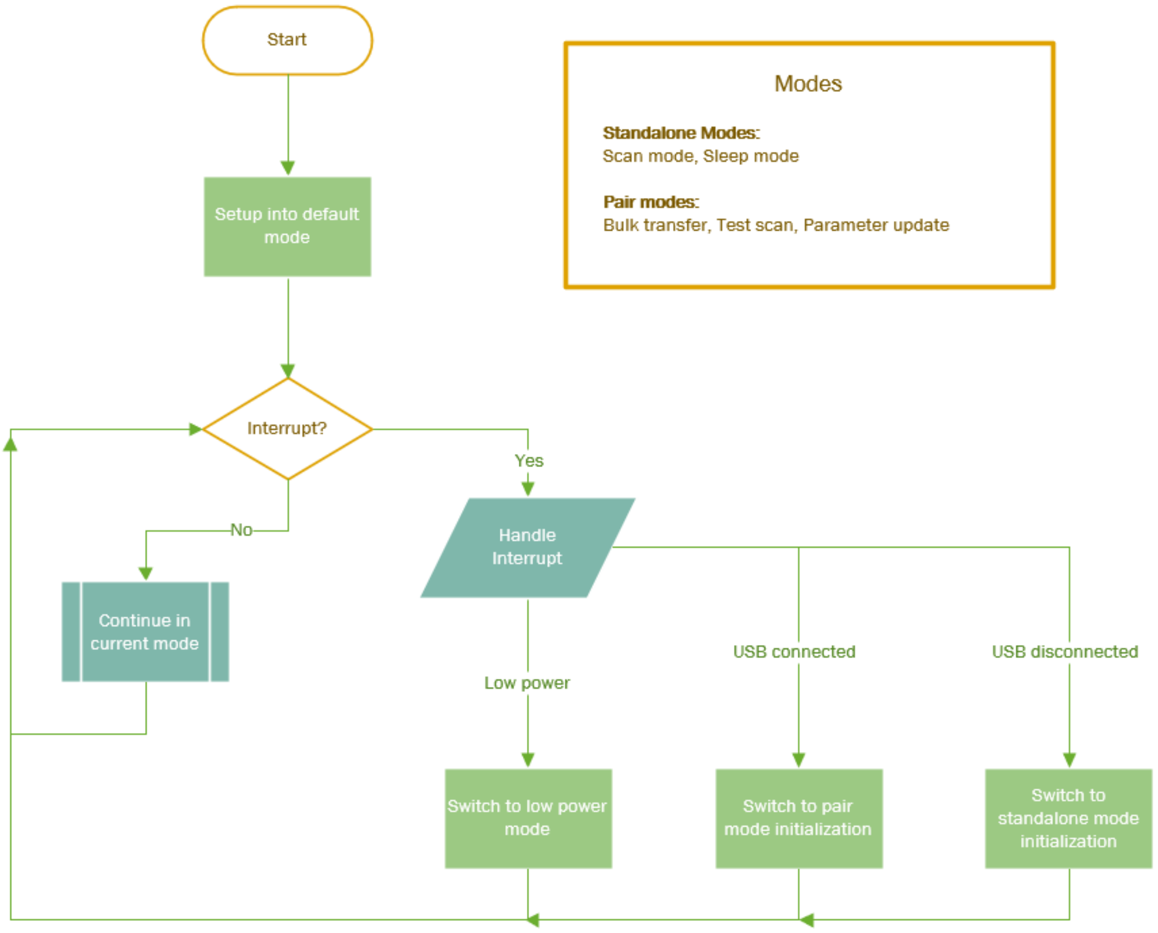


Figure 29 - General Operation State Diagram

Table 8 outlines the overall software design specifications for the Hy-dar system.

Design Specification ID	**Description**	**Possible Changes to Future Designs**	**Related requirement Specification(s)**
2.3.1.1 - B	The Hy-dar microcontroller starts up in the mode of the last known mode (loaded from memory).		Req 2.4.1 – A
2.3.1.2 - B	The Hy-dar microcontroller firmware recognizes when it is connected to an external device (laptop) via USB and goes into paired mode.		Req 2.5.1 – A
2.3.1.3 - B	The Hy-dar microcontroller in paired mode will allow for updating the parameters used for scans by overwriting the parameter values stored in Hy-dar device memory (when it		Req 2.5.6 – B

	receives the “update parameters” command).		
2.3.1.4 - B	The Hy-dar microcontroller in paired mode will allow for transferring all saved scan data from the Hy-dar device memory to the external laptop (when it receives the “bulk transfer” command).		Req 2.4.1 – A
2.3.1.5 - B	Hy-dar micro-controller paired mode will allow for performing a sample scan - a scan is performed, and the data is immediately sent to the laptop (starts when it receives the “start sample scan” command, stops using the “stop sample scan” command).		Req 2.5.2 – B
2.3.1.6 - B	Hy-dar micro-controller paired mode will allow for starting and stopping continuous scanning using “start measurement” and “stop measurement” commands.		Req 2.4.1 – A
2.3.1.7 - B	The Hy-dar micro-controller firmware recognizes when it is disconnected from an external device (laptop) via USB and goes into standalone mode.		Req 2.4.1 – A
2.3.1.8 - B	Hy-dar micro-controller standalone mode will either make the device idle (if scanning was configured to OFF with the “stop measurement” command while previously in paired mode) or will perform periodic scanning based on the set scan parameters and enter sleep mode when idle (if scanning was previously configured to ON with the “start measurement” command while previously in paired mode).		Req 2.4.4 – B
2.3.1.9 - B	The Hy-dar micro-controller can be interrupted by the power system in case it needs to put the device into sleep mode.		Req 2.4.1 – A
2.3.1.10 - B	The Hy-dar Software Interface displays the connection status of the laptop to the Hy-dar microcontroller.		Req 2.5.1 – A
2.3.1.11 - B	The Hy-dar Software Interface (Laptop interface) contains commands that can be sent to the Hy-dar microcontroller by clicking a button on the GUI: “bulk data transfer,” “start sample scan”, “stop sample scan”, “update parameters”,	Instead of GUI buttons, a console input command could be used if there isn’t enough time to build the GUI	Req 2.5.1 – A Req 2.5.2 – B

	“start measurement”, “stop measurement”.		
2.3.1.12 - B	The Hy-dar microcontroller will send acknowledgement (ack) to the Hy-dar Software Interface (Laptop) when a valid command is received (a command compatible with the microcontroller mode and status).		Req 2.4.1 – A
2.3.1.13 - B	The Hy-dar microcontroller will send negative acknowledgement (nack) to the Hy-dar Software Interface (Laptop) when an invalid command is received (a command incompatible with the microcontroller mode or status, or an unknown command).		Req 2.4.1 – A
2.3.1.14 - B	The Hy-dar Software Interface (Laptop interface) will report to the user via notification that a command was successful when it received an ack from the Hy-dar microcontroller within a small-time window. If it does not receive an ack in time, or receives a nack, it will report that the command was unsuccessful via notification.	Instead of GUI notifications, a console output message could be used if there isn’t enough time to build the GUI	Req 2.4.1 – A
2.3.1.15 - B	The Hy-dar microcontroller firmware logs actions to internal memory (scan time stamps, power status with time stamps, etc.)		Req 2.4.1 – A

Table 8- Software Design Specifications

2.3.2 Data Management

Table 9 includes the design specifications for the data management subsystem software.

Design Specification ID	Description	Possible Changes to Future Designs	Related requirement Specification(s)
D 2.3.2.1 – A	The system uses a SD card as the external memory for data storage, with storage larger than 256Gb	A larger size of SD card may be used	
D 2.3.2.2 – B	The reading and writing directory will be verified every read or write operation, and log an error code if issues are encountered		

Table 9 – Data Management Specifications

A state diagram showing the process for storing data to the SD card is shown in Figure 30.

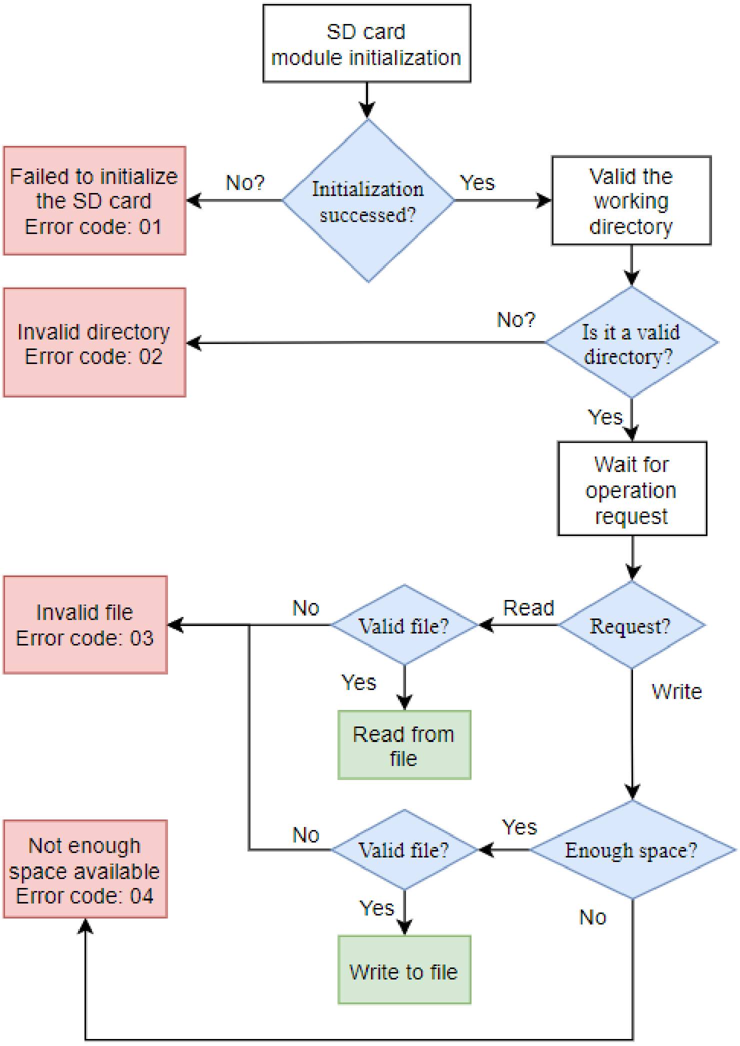


Figure 30 - Data Management State Diagram

2.3.3 Signal Processing

Various signal processing techniques are performed on the raw data (a time domain waveform of received signal reflections), in order to analyse the data to infer the water table depth. The techniques are discussed below. Table 10 outlines the necessary specifications for these processes.

Design Specification ID	**Description**	**Possible Changes to Future Designs**	**Related requirement Specification(s)**
2.3.3.1 – A	Software will perform spline interpolation on the received time domain waveform when necessary.		Req 2.4.2 – A

2.3.3.2 – A	Software will perform dewow filtering provided in the R package RGPR.		Req 2.4.2 – A
2.3.3.3 – A	Software will implement a bandpass filter to use on the data, with pass region of approximately 100-700MHz		Req 2.4.2 – A
2.3.3.4 – A	Software will support the Common Midpoint survey (CMP) technique in order to obtain the average propagation velocity of the subsurface (using R package RGPR).	The use of hyperbolic velocity analysis may be added based on further investigation	Req 2.4.2 – A

Table 10 – Signal Processing Specifications

2.3.3.1 Overview

GPR data is often classified as scans: "A scans" also known as "single traces" represent the received radar signal in the time domain for a given location. Most GPR systems are mobile with positional encoding, allowing the user to take multiple A-scans over different locations, stitching them together into what are called "B scans" [28]. Since the Hy-dar system is stationary, we are solely interested in representing the received data as A scans (single traces). This makes the signal processing easier than many existing systems, removing the need for spatial metadata and the issues that arise from spatial data collection. There is still the need for basic signal processing of each trace to ensure it is more easily interpretable. This signal processing can be used by importing the raw data (csv or similar) into an environment with convenient data processing capabilities such as MATLAB, Octave, or R. It is the intention of Gamma Insights to use open source or free software in order to suit the target audience of primarily research institutions, and to keep costs low. Therefore, the R package is chosen as companion software for signal processing tasks.

2.3.3.2 Trace Correction

A common issue arising in trace data is clipping of the initial signal (non-reflected signal) due to receiver saturation caused by antenna ground coupling. This is problematic if the initial signal is used for normalising the reflected waves, which is often performed. In order to mitigate the clipping issue, spline interpolation can be used. Since interpolation can distort the signal if misused, one of the methods used commonly in literature for GPR applications will be implemented [29].

2.3.3.3 De-Wow

Another well known issue with raw GPR data is the presence of a decaying low frequency DC bias in the received waveform, caused by receiver saturation by early arrival signals and/or the proximity of the antennas creating inductive coupling [30]. Removing this undesired bias component by "dewow" filtering can be accomplished in software with DC subtraction possibly followed by a median filter with a short filter window [29] [31]. The R package RGPR also supports dewowing as a built-in function [32] [33].

2.3.3.4 Band Pass Filtering

A band pass filter will be used in order to remove noise at frequencies above or below the signal bandwidth. The pass band region will be centered to the peak signal frequency with a bandwidth of about 1.5 times its value (if peak frequency is 400 MHz, the pass band region is between 100-700 MHz) [29] [31].

2.3.3.5 Velocity Analysis & Depth Conversion

From the processed data, which represents the received signal (reflections of the output pulse), the depth of the water table can be inferred by measuring the time delay of the reflection. The time domain signal can be converted to a depth scale for analysis. In order to do this, there must first be an estimation of the average subsurface velocity, either with common mid-point surveys (CMPs) or hyperbolic velocity analysis. These techniques are implemented in commercial software packages and also RGPR [34] [35]. This process is done during the initial setup of the device in the field, in order to get the average propagation velocity of the subsurface. Using CMP, the antennas would be moved by hand in successive scans [29] [31]. In the Hy-dar system software, the CMP survey will be implemented with the help of the RGPR package.

With a depth scale, the water table can be monitored. However, signal reflections can also occur due to soil composition boundaries, buried rocks and organic matter. Therefore, it is important to keep the data without too much processing for plotting and potential altering of the processing steps, so that the user can make their own interpretations. Since the soil composition is unlikely to change significantly in the time intervals used whereas the water table is expected to change, it should be possible to discern the (depth) movement of the water table by looking at changes in the signal data from different scans.

2.3.4 Power Management

Table 11 gives the software specifications for the Hy-dar power management mechanism.

Design Specification ID	**Description**	**Possible Changes to Future Designs**	**Related requirement Specification(s)**
D 2.3.4.1 – B	Estimation of the battery pack's SOC will use the coulomb counting method.	SOC inference algorithm	R 2.2.7 – B
D 2.3.4.2 – B	System will use MOSFETs to cut power to radar signal processing components when not writing/transferring data or completing a measurement.		R 2.2.4 – B
D 2.3.4.3 – B	If a power failure occurs, the system will not start taking measurements again until the battery reaches a SOC of 20%.	SOC threshold change	R 2.2.3 – B R 2.2.4 – B
D 2.3.4.4 – C	BMS communicates faults to data management controller.		

Table 11 - Power Management Specifications

In order for the Hy-dar system to communicate its battery capacity and measurement capabilities to technicians, a means of inferring the SOC of the battery pack is necessary. As defined in section 2.2.2, this will be achieved using a current sensor integrated into the power system. The measurements collected by the sensor will supply the coulomb counting algorithm which will infer the battery pack's SOC over time. Additionally, this SOC reading will be used to determine if that system is operational if the system were unexpectedly shut-down due to power loss. Figure 31 displays the proposed operation and state determination of the power management system.

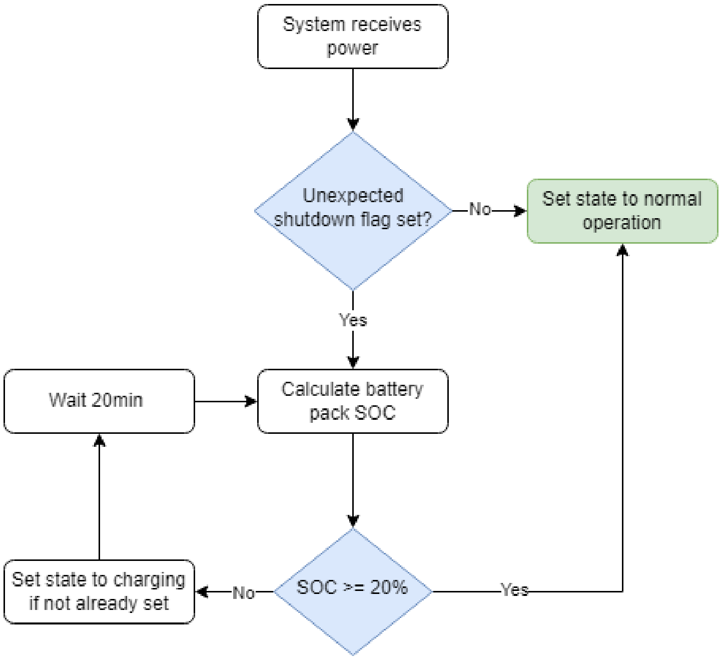


Figure 31 - Power management system flowchart

In addition to monitoring the battery pack, the power management system will also be responsible for managing a low power state where all power intensive sub-modules such as the GPR transmitter and receiver are powered off until the next time a measurement is requested. This will be implemented using p-channel MOSFETs in-line with the supply voltages for each sub-module which does not implement its own internal low power mode. This is detailed at a high-level in Figure 32 below.

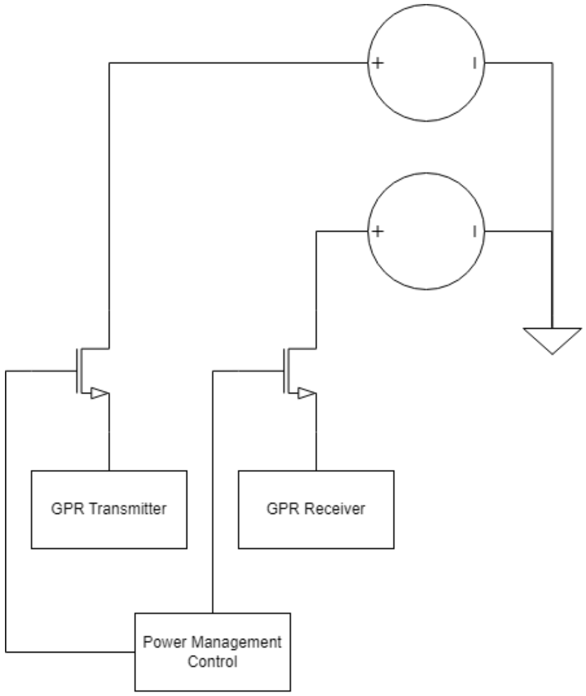


Figure 32 - Low power mode high-level implementation

3. Conclusion

Gamma Insights aims to simplify unmanned GWT level monitoring in remote and sensitive environments with the Hy-dar system. This document outlines the design specifications that will ensure that the system performance meets its requirements for Hy-dar's subsystems, including the mechanical, electrical, and software specifications. The mechanical specifications will ensure the durability of the Hy-dar system, allowing it to operate for extended periods in remote environments. The electrical specifications will guarantee the ability to create and transmit a radar pulse, as well as receive and store the data from this transmission. These specifications also include details on power storage and generation for the whole system, permitting it to operate without external power supply in the Engineering Prototype stage. Finally, the software specifications present the requirements needed to adequately process, error-correct and present the data collected from Hy-dar's GPR. Combined, these specifications define an affordable and non-invasive method for autonomous monitoring of GWT levels in British Columbia.

Though this project faces many challenges, Gamma Insights is optimistic that the design alternatives, combined with implementing feedback from TA Usman Ahmed, will help us reach an acceptable product. Usman recommended that the team produce a back-up plan in the scenario that a working radar cannot be produced despite the changes in scope discussed earlier. The team has come up with 3 possible back-ups, the first being to ask the Earth Sciences Department if the team could rent their PulseEkko GPR system for raw data collection. This data could then be used to showcase the functionality of other aspects of the system, such as the signal processing. Concerns with this option are the potential rental cost, as well as simply getting the permissions to use the device. Another option would be to find sample raw GPR data online that could be used in a similar manner, or alternatively use the GPR simulation software GPRmax to produce raw GPR data. Concerns with this option are that the data found or produced may not be representative of the data the Hy-dar system would theoretically produce. The last option would be to attempt to recreate a GPR receive signal using electronic equipment such as function generator or vector network analyzer, but again this may not be entirely representative of a real receive signal. Each of these alternative plans will be explored in tandem with the continued development of the radar system. Regardless of the results, it will be a valuable learning experience and highlight the areas of growth needed to achieve this technology in the future.

Design Alternatives Appendix

1. Mechanical Design Choices

Because the exact dimensions of our antenna and battery system are still unknown, choosing a suitably sized enclosure is difficult, necessitating some flexibility in design and several backup options. Luckily, multiple vendors have been identified that carry the proposed "briefcase-style" enclosure in a wide variety of sizes, and two other pre-fabricated container types exist that can be adapted to act as substitute enclosures: dry boxes, typically used for fishing or marine applications, and aluminum or ABS outdoor electrical junction boxes. While these two alternates have their downsides, as aluminum cannot be used to enclose the antenna without disrupting their radiation pattern and ABS junction boxes are typically not rated up to IP67 and mostly available in smaller sizes, they can be further modified to meet our needs reasonably well. When an electrical box enclosure is chosen, extra space will be selected so that if the system requires more battery storage than expected, there will be enough space to store additional batteries are needed to sustain the system.

Another design choice that had to be made was choosing the balance between cost-effectiveness and minimizing the number of metallic components of the system. Due to interaction of metallic components with the antenna's radiative pattern, the large antenna/electronics box enclosures will be plastic-based and non-conductive. However, most brackets and tent pegs available on the market are metallic, and could cause reflections near the surface of the earth that may partially obscure the water table's signal reflection, or may alter the antenna's radiative pattern. Metal brackets and pegs were chosen for their high availability, low cost and reasonable strength/robustness, with the assumption that they may be small enough and distant enough from the antennas to be insignificant. However, we will not be certain of this until we have been able to test the system. If the metallic pegs and brackets are determined to be an issue, an alternative is fiberglass brackets [36], which are more expensive but non-conductive, light, and corrosion-resistant, and rugged plastic tent pegs. While this is unlikely to be necessary, the fiberglass L-brackets can also be glued on to avoid metal screws. Similarly, the mounting pole for the solar panel can be made of fibreglass or rugged/reinforced plastic if an aluminum mounting pole has an undesirable effects.

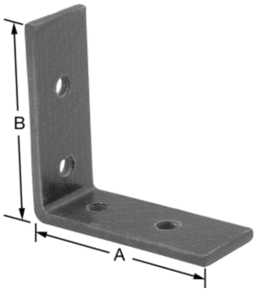


Figure 33 - Fiberglass Angle brackets, A = B = 4 inches [36]

Lastly, the diversity of outdoor environments the Hy-dar may be exposed to requires widely applicable system anchors and stabilization, leading to a number of design options. Though heavy-duty tent pegs were chosen as the primary option due to their effectiveness in Southwest BC, where most soil is medium-soft and moist, other terrain may necessitate other choices. In environments with loose sand or solid rock substrates, pegs are not effective: the sand is too loose to hold them and solid rock cannot be penetrated with pegs. A good alternative is using a tripod mount for the solar panel and a terrain-specific anchoring for the stainless steel guy wires [37]. For example, in a cliff/rock-face environment, cams, which are typically used for rock-climbing, can be used to anchor the stainless steel guy wires [38]. In rocky soil, arrow-head anchors are more effective and easier to drive in, as well as being small and light [39]. In sandy soil, wide plastic stakes are preferred. However, these specialized pegs are a more difficult to find and a bit more expensive, and cams in particular are very expensive compared to tent pegs [38]. Gamma Insights doesn't include every type of anchoring with the Hy-dar system, but does provide stainless steel guy wires that can be attached to any of these options so that users may bring their own specialized stakes for the environment they plan to do monitoring in. In all environments, sandbags can be additionally used to further weigh down the enclosures and tripod base for further stability.

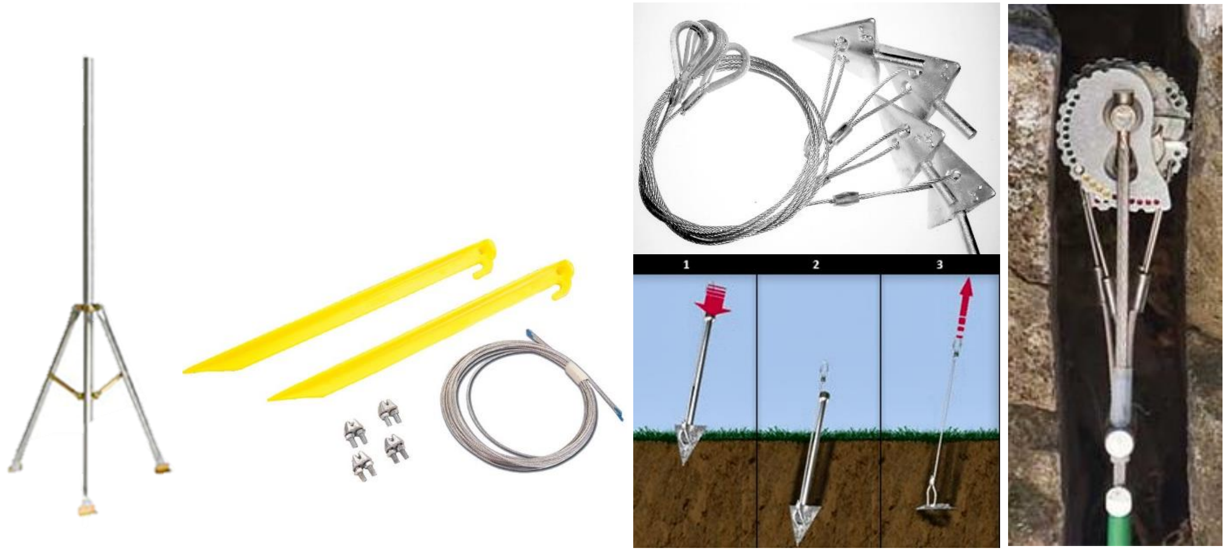


Figure 34 - Tripod (far left) and guy-wire anchors for alternate environments: sand stakes (center left), arrowhead anchors (center right) and cams (right)

2. Electrical Design Choices

2.1 Radar

For the overall radar design there were two major design choices to make: the frequency and bandwidth of operation, and the radar type.

Frequency and bandwidth were determined based on the desired depth and resolution of the system as described in requirement Req 2.1.1 – A, "The system should be able to detect water table levels between 30cm up to at least 1-5 meters", and Req 2.1.3 – A, "The system should be able to measure water table depth to a resolution of 10 - 30 centimetres". In the case of the Hy-dar system, only vertical or "range"/"radial" resolution is of interest, with higher resolutions being achieved by wider bandwidths [23]. This relationship is theoretically described by the Equation 1.27 from "Ground Penetrating Radar: Theory and Applications", 1st ed. [23]:

$$\Delta r \geq \frac{W_v}{4}$$

Equation 2

Where Wv is the half amplitude width of the pulse. Realistically this relation "must account for frequency-selective dispersion of the system, antenna, ground, and target" [23] and thus a more realistic range resolution equation is:

$$R_{res} = \frac{1.39c}{2B\sqrt{\varepsilon_r}}$$

Equation 3

Where 1.39 is empirically determined, c is speed of light, B is the system bandwidth, and ε_r is the relative permittivity of the soil. This equation represents the worst-case, so actual measurements will either have equal or better range resolution, but not worse [23]. These two equations are used to plot best-case range resolution vs. relative permittivity in Figure 29, and worst-case range resolution vs. relative permittivity in Figure 28. Each trace represents a different bandwidth, showing which minimum bandwidth is needed to meet the resolution requirement.

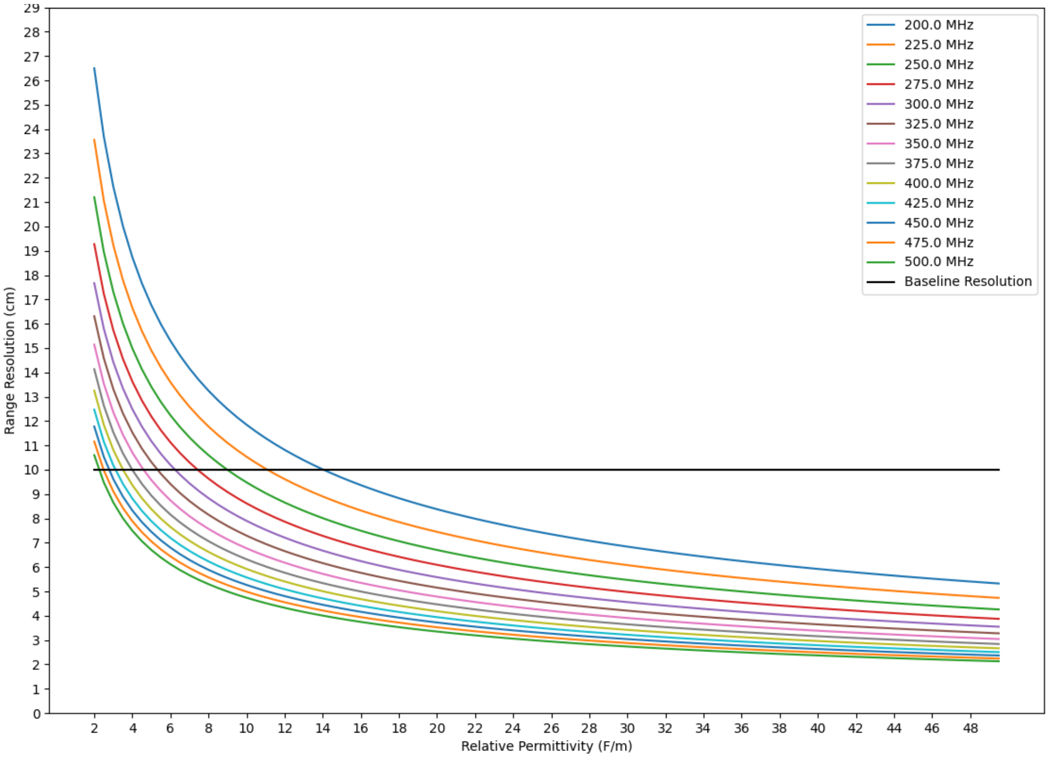


Figure 35 - Best-Case Range Resolution vs. Relative Permittivity and Bandwidth. Derived From [23] pp. 15, Equation 1.27

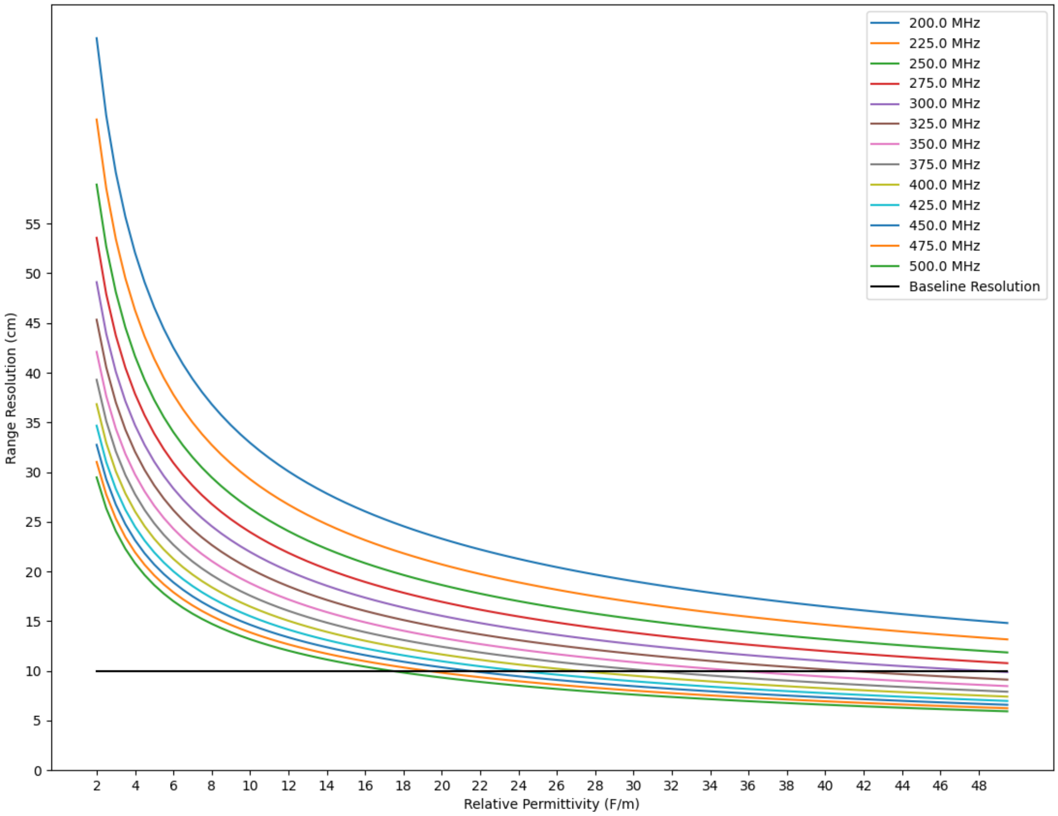


Figure 36 - Worst-Case Range Resolution vs. Relative Permittivity and Bandwidth. Derived From [23] pp. 78, Equation 3.3

From the worst-case plot a bandwidth of 400 MHz has been identified as the minimum required to achieve the minimum resolution requirement of 30cm across all permittivities. Permittivities of different ground and soil types can very anywhere between 3 and 40 F/m [40], so the full scale is considered. While bandwidth could be further increased, the improvement in resolution beyond 500 MHz becomes negligible and components such as antennas become difficult to produce with wider bandwidths, so the benefits do not outweigh the costs of increasing the bandwidth significantly. Thus, acceptable bandwidths for the system are defined between 400MHz and 500MHz.

Achievable depth is affected by the frequency of operation of the system, with lower frequency systems allowing for greater detection depths due to lower signal attenuation rate [23]. As such, it is best to keep center frequency as low as possible while still having room for the required bandwidth discussed above. Practically, this is typically achieved by setting the center frequency equal to bandwidth [23], which is the rule of thumb the Hy-dar system will follow as well. Achieving the resolution requirement was prioritized over achieving the depth requirement due to resolution being easier to test and demonstration on a benchtop indoors, while proving a maximum depth would have required a test/demonstration setup of that maximum depth (> 1m) which is somewhat unfeasible.

The second major design choice for the radar subsystem was the radar method to be used. The method for generating the transmitted signal has affects on the power consumption, the component selection, and the increased computing power required to interpret the received signal.

In general, Continuous Wave (CW) systems are more complex. A CW radar system transmits a signal continuously, and different variations exist. The method that was considered as an alternative was Frequency Modulated CW radar (FMCW). One transmission in the FMCW scheme involves varying the frequency across the bandwidth. The time echo of a specific frequency can be calculated, as in impulse radar systems, however it requires separating the frequencies on the receiver. This method of transmission has increased power requirements, as the transmission period is longer (or continuous). FMCW systems require performing a Fourier transform to calculate the difference in frequencies from the transmission to the received signal. This requires more complex computing, which in turn necessitates a more complex processor. Finally, it requires more power, as this calculation it done continuously, and is more power intensive of a calculation than the simple time-difference needed for an impulse system.

A key difference between the Hy-dar system and other radar systems is that Hy-dar is not interested in the speed of movement of the target. In a typical radar system, the echo is frequency shifted because of the movement of the target. Observing the frequency shift can give insight into the speed with which the target is moving relative to the radar system. The Hy-dar system will not report the rate of change of the water table, but rather the position of the water table at the time of measurement. The rate of change can be inferred from the change of position over time. If the Hy-dar system does not measure the frequency shift, it can have less complex computing, however doing so relies only on the time of receiving the echoes. For Hy-dar to rely only on time delays of echoes, a shorter transmission is more desirable as this dictates the minimum distance the radar system can detect an echo from. Impulse radar allows for a short transmission, which reduces the minimum distance in accordance to the depth of penetration requirements.

FMCW allows for an increased lateral resolution in mobile systems, as the frequency changes over time while the device is moving meaning a specific frequency is transmitted at a specific location. Due to the large planar nature of the water table, as well as the stationary nature of the Hy-dar device, this lateral resolution is not required, and a less complex system can be used. These factors are why impulse radar is preferred over FMCW radar for the Hy-dar system.

2.1.1 Antennas

For the system antennas, two major design decisions were made. The first was to have two antennas instead of just one. This decision was made to ensure requirement R 2.1.1 was met, which states that the system must be able to detect the water table to a minimum depth of 30cm. GPR pulse reflections arrive at the receiver at a time after the transmit pulse that is in the order of tens of nanoseconds [23], and even less for shallow reflections. In order to use a single antenna, a switch with an ultra-fast, less then 1 ns switching time would be required so that the switching process would not interfere with the pulse reflections being received. A switch with these sorts of speeds was simply too expensive and difficult to source, so the decision was made to use two separate antennas, one solely for TX and one for RX, which removed the need for a switch at all.

The second major design decision was to manufacture the systems antennas as opposed to buying them. This decision was made due to the unavailability of antennas on the market that both met the desired specifications and were also affordable for the team. Additionally, Professor Chris Hynes was consulted on this design choice and confirmed that manufacturing our own antennas was the more viable option.

2.1.2 Equivalent Time Sampling

An alternative to the digitizer design proposed is to use equivalent-time sampling (ETS), which is used to sample high frequency repetitive signals with a lower sampling rate (i.e. slower ADC). This means multiple output radar pulses are needed, where each output pulse is delayed appropriately in order to allow for most detectable reflections to be received. ETS is done by taking samples at different period multiples plus a variable offset, and reconstructing the waveform from these multiple acquisitions. This design option was rejected due to the unavailability of a critical component – the digitally programmable delay generator (AD9500).

2.2 Power

2.3.1 Battery Pack

The Hy-dar system's battery pack acts as a buffer between its photovoltaic power source when operating in the field and allows the device to maintain operation year-round. An important characteristic of the battery is its cell chemistry as this determines the power capabilities, size, cycle count and degradation modes [41]. Generally, lithium-based battery chemistries significantly outperform other cell types in terms of specific energy, or their energy content per unit mass. This quality comes with a trade-off as lithium cells are less thermally stable and require proper battery management systems to operate safely. With this considered, lithium cells are still popular choices for use in off-grid solar systems, particularly lithium iron phosphate (LiFePO4) cells due to their high cycle count and little maintenance [42]. Additionally, lithium cells have no risk of leaching harmful chemicals into the environment which is a concern for lead-acid batteries which could taint the sustainability of a remotely deployed off-grid system. For these reasons, the Hy-dar will implement a LiFePO4-based battery pack to support its photovoltaic supply to meet requirement R 2.2.3 and 2.2.6.

Table 12 describes battery cell chemistry performance parameters.

Parameter	**Lead Acid**	**NiCd**	**NiMH**	**LiFePO4**
Specific Energy (Wh/kg)	30-50	45-80	60-120	90-120
Lifecycle (80% discharge)	200-300	1000	300-500	1000-2000
Fast charge time	8-16h	1h	2-4h	1h or less
Overcharge tolerance	High	Moderate	Low	Low
Self discharge/month (room temp.)	5%	20%	30%	<10%
Charge Temperature	-20 to 50°C	0 to 45°C	0 to 45°C	0 to 45°C
Discharge Temperature	-20 to 50°C	-20 to 65°C	-20 to 65°C	-20 to 60°C
Maintenance	3-6 months	30-60 days	60-90 days	None
Safety	Thermally stable	Thermally stable, fuse protection common	Thermally stable, fuse protection common	Protection circuit required

Table 12 - Battery cell chemistry performance parameters [41].

In addition to the decision of which cell types the Hy-dar's power supply will implement, a capacity of 10-30Ah was determined. Since the Hy-dar is still in the early stages of prototype development, measurements of the data management and radar power consumptions cannot currently be determined. However, early simulations based on yearly weather forecasts, similar radar implementations and current sourced parts allow for early simulations of battery usage throughout the year. The estimated system parameters detailed in Table 13 were used to calculate the capacity of various batteries over time using hourly solar power data provided by the U.S. Department of Energy [43] and one measurement per hour taking and estimated 5 minutes to complete.

Sub-system	Description of Components	Power Estimation
Consumption during measurement		
Transmitter	Pulse generator, Power Amplifier	2W [44]
Receiver	Digitizer, VGA, signal processor	6W [44]
Data/Power Management	Controller, current sensor	2W
Consumption while idle		
Power Management	Controller, current sensor	1W

Table 13 - Estimated system parameters.

The figures below depict the results of running the simulation using varying solar panel power ratings in Vancouver, BC; Vancouver is where the Hy-dar's engineering prototype will be tested and data suggests that it is has one of the lowest totals of bright sunlight per year in BC [45]. It is evident that at the beginning and end of the year (November to January) that due to a lack of sunlight the battery entirely drains on multiple occasions. Increasing the power output of the solar panel mitigates multiple occurrences of this however an increase in battery capacity in required to completely alleviate this issue to allow a system with the parameters detailed above to collect data year-round and meet requirement R 2.2.3.

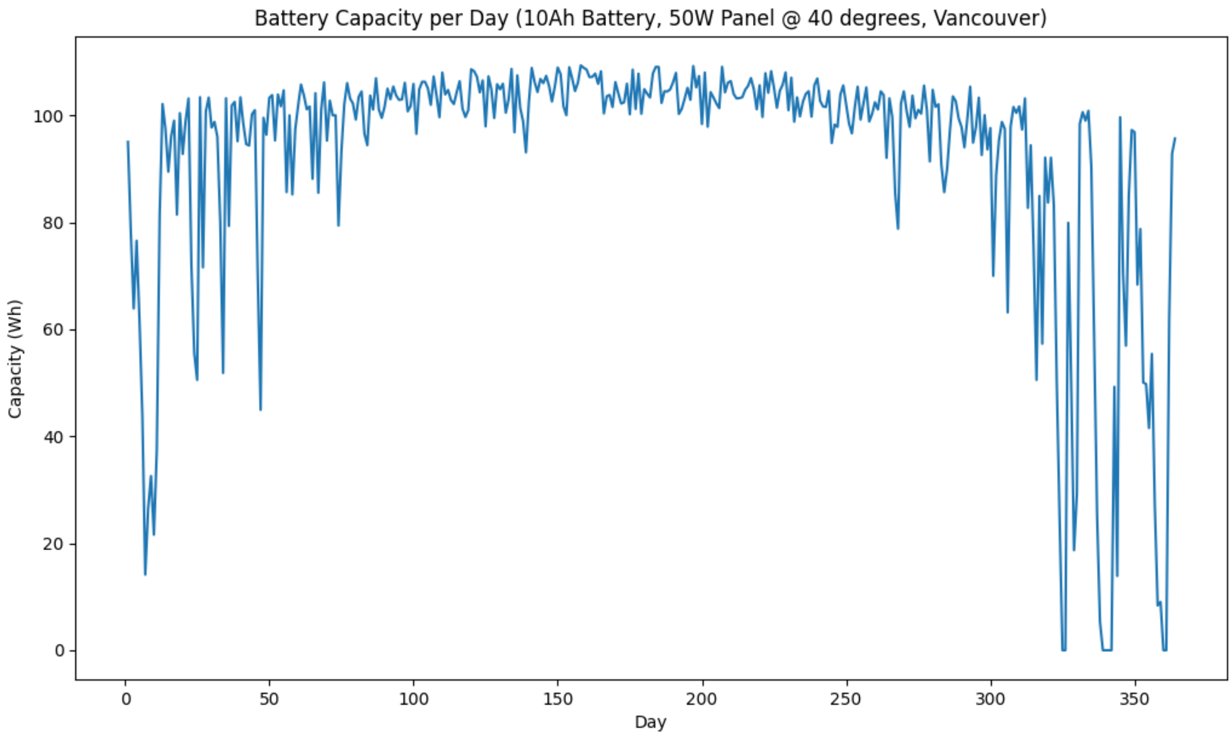


Figure 37 - Simulated results using a 10Ah battery and 50W solar panel in Vancouver, BC.

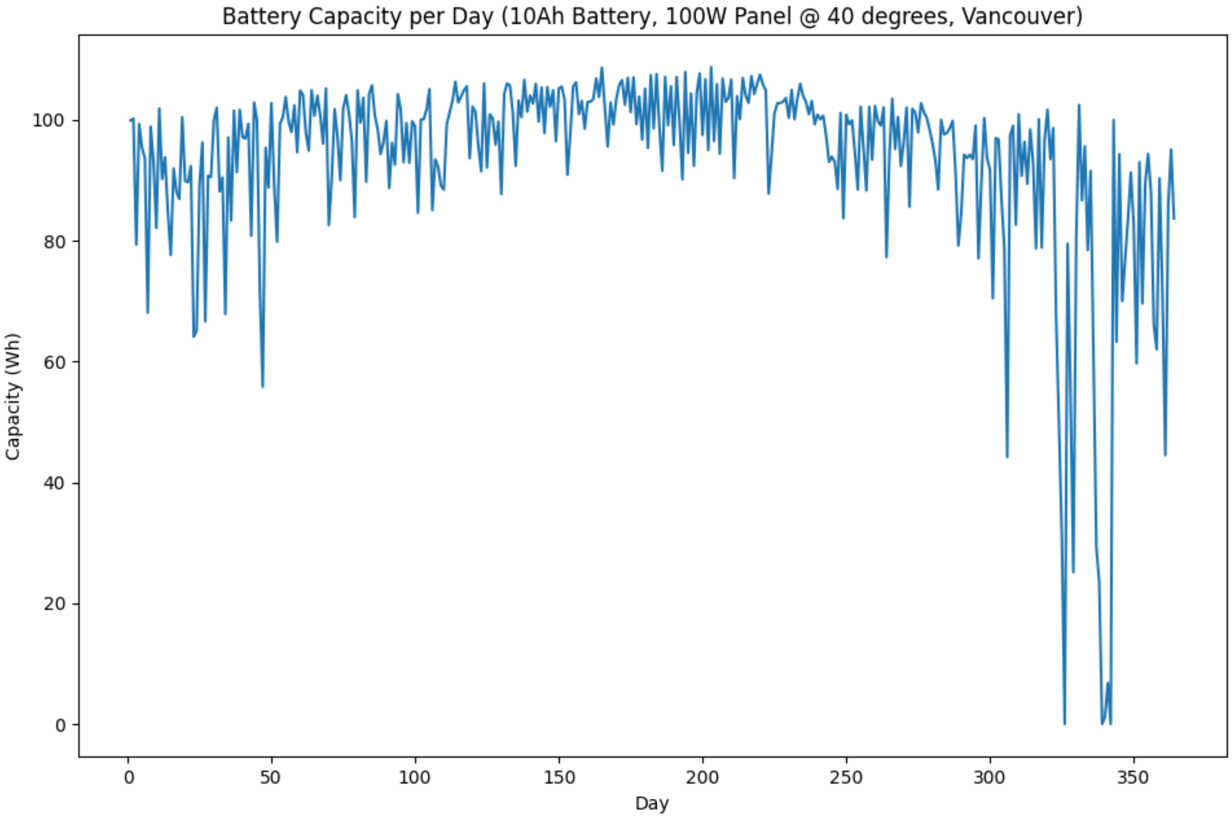


Figure 38 - Simulated results using a 10Ah battery and 100W solar panel in Vancouver, BC.

By increasing the capacity of the battery to 30Ah, in ideal circumstances the system will have an up-time of 100% throughout the year as detailed in Figure 33. As a result, the limits of the battery capacity were determined to be within 10 and 30Ah when considering the popularly manufactured sizes of lithium iron phosphate battery packs. It is worth noting that these initial projections are highly speculative and empirical results are required to accurately determine the capacity of the Hy-dar's battery. Additionally, battery charging rates in cold temperatures should be considered when optimizing the battery capacity size.

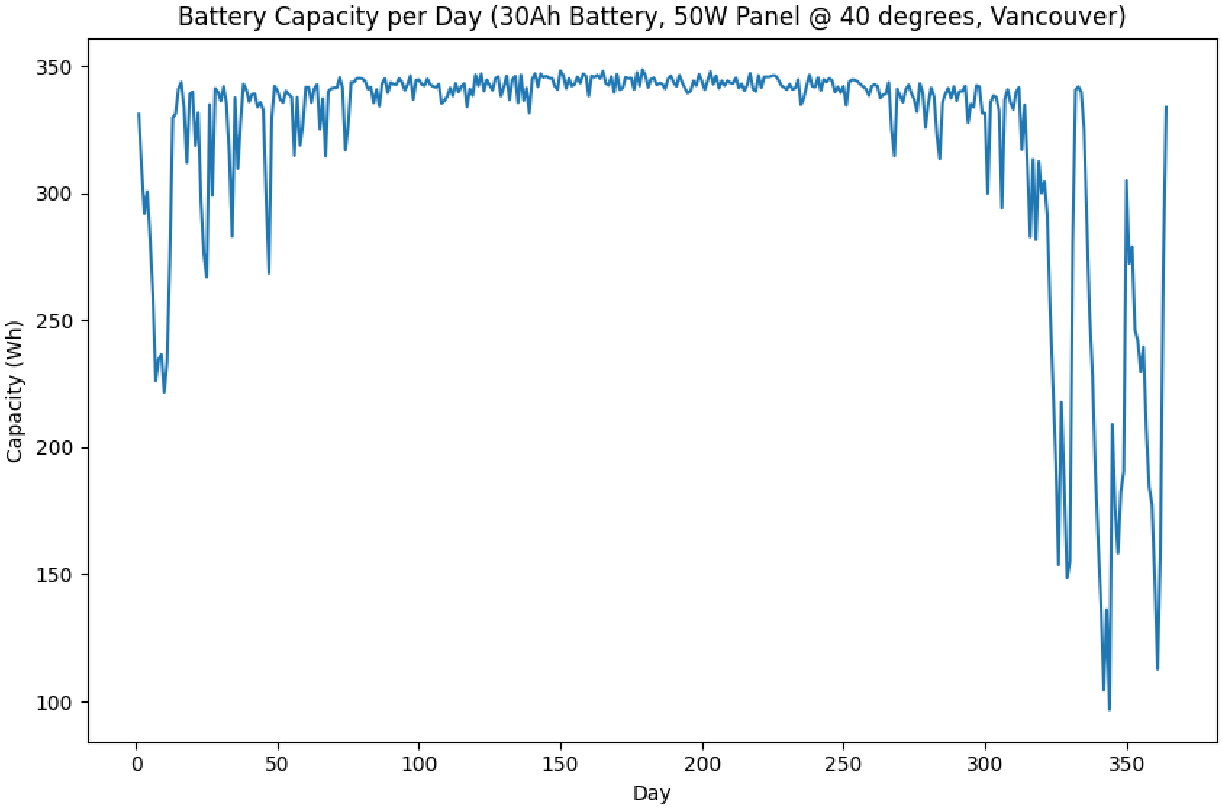


Figure 39 - Simulated results using a 30Ah battery and 50W solar panel in Vancouver, BC.

An alternative to purchasing a manufactured battery pack at a potentially unnecessary capacity would be to build one from scratch using lithium iron phosphate cells and a standalone BMS. For the engineering prototype this option is not favourable due to safety concerns however is not completely ruled out.

2.3.2 Power Inputs

As mentioned, the Hy-dar will support a grid-based wall outlet supply through the use of a 12V 10A AC-DC adapter supply; this decision allows the team to focus efforts on the more complex aspects of the system while still meeting requirement R 2.2.1 and 2.2.6. Rectifying the AC signal off-board simplifies the power system, and since this supply is intended to facilitate testing and charging of the system prior to deployment, additional circuitry without regular use was deemed unnecessary. The specified electrical parameters are derived from the capabilities of the determined 12 V battery pack and the notion that lithium iron phosphate cells can safely charge at c rates between 0.3 and 1C [46].

$$I_{charge} = C_r \times E$$

Equation 4

where I_{charge} is the charge current in amps, C_r is the c rate, and E is the energy capacity of the battery pack in amp hours.

Given the proposed battery capacity limits of 10 and 30Ah, a charge rate of 10A ensures that a battery pack of any size within this range can be charged without incurring any additional damage to the cells.

In addition to the secondary grid-based power supply, the Hy-dar will employ solar power as its primary source of power during deployment. Although many renewable energy sources are available, the flexibility, size, cost and up-time of photovoltaic sources are unmatched for this use case [47]. For example, although wind supplies are a favourable alternative, the conditions required for operation are much less predicable than solar radiation, along with their high cost and would prove insufficient for operation of the Hy-dar system [48]. Additionally, the specific photovoltaic source employed by the Hy-dar's power system is a monocrystalline solar panel. There are several other types of solar photovoltaic cells, those most desirable for use in such a system being polycrystalline and thin-film panels. The main factors considered when evaluating the various solar cell options were efficiency, cost, and weather resistance. Although it is the most expensive of the short listed options, a monocrystalline solar panel was chosen mostly due to its high efficiency and weather resistance as these are required to meet R 2.2.3, 2.3.7 and 2.6.4. Table 14 below details these parameters across the panel options commercially available.

Panel Type	**Monocrystalline**	**Polycrystalline**	**Thin-film**
Efficiency	20%	17%	15%
Cost	\$1.50/W	\$1.00/W	\$0.70/W
Weather Resistance	High	Moderate	Low

Table 14 - Comparison of solar panel types [48]

Additionally, the proposed size range of the monocrystalline solar panels of 50-100W was determined by consulting yearly solar data as used to determine the battery capacity in section 2.3.1 [43]. The rating of a solar panel is determined by its average expected power generation for 1 hour of operations in ideal circumstances [41]. In general, solar panel are manufactured in sizes with increments of 50-100W depending on the size, and with high granularity in lower power panels such as 10 and 30W. Figure 40 details the estimated hourly power production of a 50W solar panel in Vancouver BC. It is evident that at the beginning and ends of a year, the solar panel often produces less thana fifth of its rated power. As described in section 2.3.1, the Hy-dar is estimated to consume 10W of power while completing a measurement, which raises concerns for using a solar panel any smaller than 50W when considering unaccounted for losses.

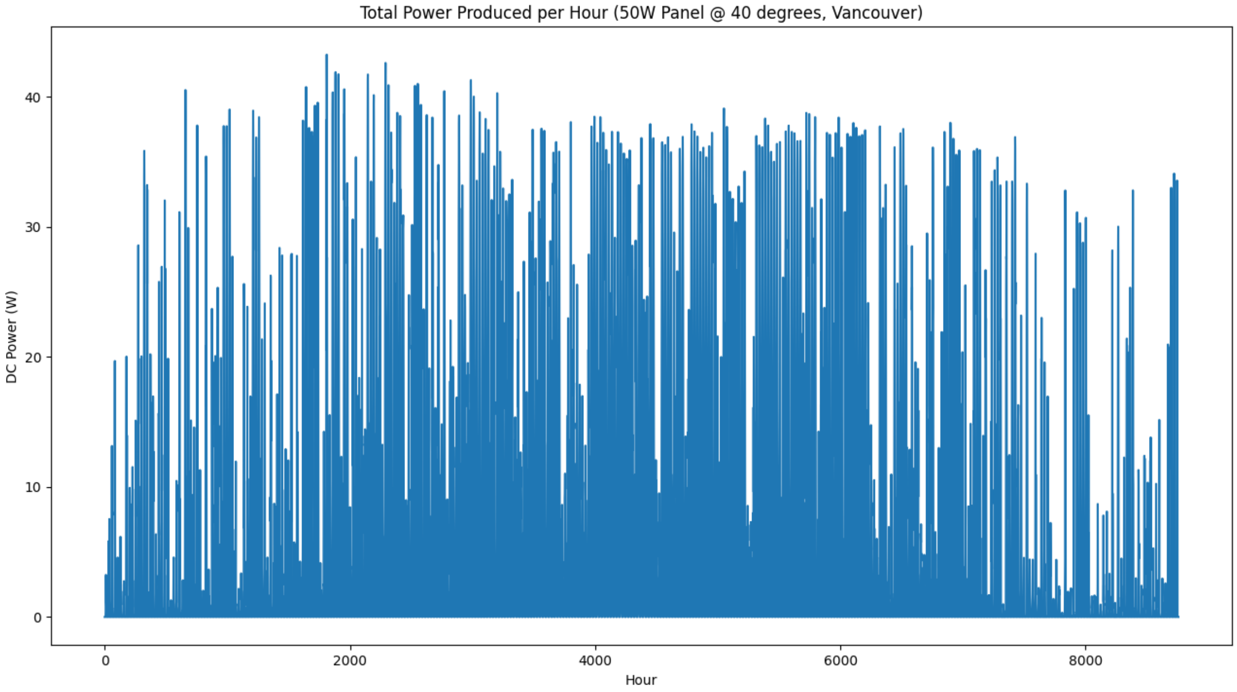


Figure 40 - Yearly estimated power generation of a 50W solar panel in Vancouver BC.

Due to the inability to make measurements of the Hy-dar at its current stage in development, the solar panel power will be optimized at a later date when detailed power consumption parameters are available.

2.3 Data Management

For data management, the alternative plan is to use an external memory drive to store data. Although the external memory drive is faster and comes with various sizes, it is essentially adding another component to generate energy inside the electrical panel. SD card is small and lightweight, since the data transfer process does not require a high speed, therefore, Hy-dar system will use 256Gb of SD card as the first choice memory component.

On the other hand, there are a lot more options to purchase a holdup capacitor. Ideally we are looking for a capacitor that has more than $1000uf$ capacitance, therefore, finding an alternative is not going to be difficult.

Test Plan Appendix

1. Mechanical Sub-systems

Table 15 outlines the test plan for the mechanical subsystems.

Test	Procedure	Expected Result
Installation Testing	- Determine installation and uninstallation time of 2 users setting up the system - Record challenges experienced by the users - Record use (or lack thereof) of manual - Record any unexpected user interactions with the system	Installation or uninstallation should take a maximum of 4 hours A minimum of 2 users should be able to install the system Users can safely install the system using the tools and PPE recommended
Robustness Testing	- After setting up the system, bump or walk into it lightly - Apply continuous manual vibration to the system for 10min - Use a spring-scale to measure the amount of force needed to pull out a guy-wire from its position pegged to the ground - Record results	System should remain secure under mild to moderate bumps and collisions Vibration should no dislodge enclosures from their place on the ground
(Non-destructive) Environmental Testing:	- Replace electronics components with an absorbent material, such as paper - Leave system outside for a period of 12 hours in a rainy and windy weather conditions - Monitor the system for signs of water seepage, instability/tilting, or damage - Inspect paper and inside of enclosures after test for dampness	Enclosures should not permit any liquid to pass to the inside The system should remain standing and stable throughout the 12 hour period No damage should be sustained by the system
Shock Hazards Testing	- Use a voltmeter to determine if any sections of the system are live when they should be grounded, and pose a hazard - Record results and correct grounding if necessary	There should be no live surfaces that the user could come into contact with during normal operation while the system is on.
Security Testing	- User will attempt to unlock the enclosure without the key (user may jiggle the lock, tug on it, twist it etc.) - Records results	The user should be unable to open the lock without use of specialized tools or excessive force.

Table 15 - Mechanical Subsystem Test Plan

2. Electrical Sub-systems

2.1 Radar Subsystem Test Plan

Table 16 specifies the radar subsystem test plan.

Test	Procedure	Expected Result
Pulse Generator Pulse Width Test	- Power Pulse generator with 10V, increase in steps of 15V up to 100V. - Trigger pulse generator by varying trigger voltage from 0V to 5V - Measure pulse output on oscilloscope capable of at least 2GS/s (one sample every .5ns) to capture a 2ns pulse	Each transistor will demonstrate a different avalanche breakdown behaviour. An ideal transistor will exhibit pulse length 2ns or less.
Transmit Signal Mixing Test	- Connect oscilloscope in place of transmit antenna, cycle pulse generator as in test above while connected to the rest of the transmit path. - Connect spectrum analyzer in place of transmit antenna and repeat	Signal should appear as baseband pulse modulated by the carrier frequency and have a center frequency between 400 and 500MHz
Antenna Isolation Test	- Connect both antennas to a Vector Network Analyzer - Ensure that the antennas are spatially separated at the same distance they would be in the product - Measure S12 parameter over frequency	S12 should be at minimum less then -10dB, and ideally less then -20dB over the desired frequency band.
Antenna Bandwidth Test	- Connect antenna to Vector Network Analyzer - Measure S11 parameter over frequency	S11 should be less then -10 dB over the desired frequency band.

Table 16 - Radar Subsystem Test Plan

2.2 Power Sub-system Test Plan

Table 17 outlines the power subsystem test plan.

Test	Procedure	Expected Result
Wall adapter supply isolation test	- Ensure no loads are attached to the power supply - Plug in a 12V DC wall adapter - Use a multimeter to probe the input of the charge controller and output of the switching network	12V is measured at the input of the charge controller and output of the switching network
Solar supply isolation test	- Ensure no loads are attached to the power supply - Plug in the solar/battery supply - Use a multimeter to probe the input of the battery and output of the switching network	12V is measured at the input of the battery and output of the switching network
Supply prioritization test	- Ensure that both a 12V DC wall adapter and solar/battery system is attached to the system	The voltage being supplied to the battery and system is that of the wall adapter

	- Measure the average voltages of both inputs using an oscilloscope channel for each	

Table 17 - Power Subsystem Test Plan

3. Software Sub-systems

Table 18 details the software subsystems test plan.

Test	Procedure	Expected Result
Unit Testing	- Determine edge case inputs (input "extrema") for all functions - Apply these input extrema to the corresponding function - Record results	Function should not throw any unrecoverable errors that could result in system failure/shutdown.
Command Testing	- Send sequence of all commands from software interface to microcontroller - Try sending commands while the controller is busy - Try sending illegal commands	Each function should execute the desired operation (if legal) on the microcontroller. Results can be checked by retrieving stored data.
Signal Processing Testing	- Manually alter input data to the signal processing companion software to edge case inputs - Record results	Companion software should not throw any unrecoverable errors that could result in system failure/shutdown.
SOC measurement testing	- Fully charge the battery pack using a wall supply - Insert an ammeter in the circuit to monitor the current over time - Use an external inverter to plug in an AC heater or high load device to drain the battery - Monitor the calculated SOC over time and the current being output by the battery's BMS	The ammeter should indicate that 0 current is being drawn from the battery when the SOC reaches 0%.

Table 18 - Software Subsystem Test Plan

References

[1] M. of E. and C. C. Strategy, “Environmental Flow Needs - Province of British Columbia,” https://www2.gov.bc.ca/gov/content/environment/air-land-water/water/water-licensing-rights/water-policies/environmental-flow-needs (accessed Jan. 25, 2023)

[2] Ministry of Environment and Climate Change, “Monitoring Aquifers: Provincial Groundwater Observation Well Network - Province of British Columbia,” https://www2.gov.bc.ca/gov/content/environment/air-land-water/water/groundwater-wells-aquifers/groundwater-observation-well-network (accessed Jan. 25, 2023).

[3] D. Allen, “Ground-Water Measurement -- Engineering Capstone Idea,” Jan. 25, 2023.

[4] McMaster-Carr, “Plastic Protective Storage Case with Foam”, https://www.mcmaster.com/6409A66/ (accessed March 12, 2023)

[5] Monoprice, “Weatherproof Hard Case”, Amazon.ca, https://www.amazon.com/Monoprice-Weatherproof-Shockproof-Hard-Case/dp/B07XSJVK2M/ref=sr_1_9?keywords=Heavy%2BDuty%2BStorage%2BContainers%2BWaterproof&qid=1677698098&sr=8-9&th=1 (accessed March 1, 2023)

[6] MAKERELE, “Outdoor Electrical Box”, Amazon.ca https://www.amazon.ca/MAKERELE-Electrical-Weatherproof-400300170mm-Electronics/dp/B08PNQDD3F/ref=sr_1_10?crid=3LN8S7290KECF&keywords=IP67%2Blarge%2Belectrical%2Bbox&qid=1678856117&sprefix=ip67%2Blarge%2Belectrical%2Bbox%2B%2Caps%2C133&sr=8-10&th=1 (accessed March 14th, 2023)

[7] Cable Glands Direct, “NPT Cable Glands: NPT-114”, https://cableglandsdirect.com/product/npt-114-22-32mm-cable-range/ (accessed March 15th, 2023)

[8] Difvan, “NPT Cable Gland”, https://www.difvan.com/npt-cable-gland/ (accessed March 15th, 2023)

[9] Lowes, “RELIABILT 4-in x 0.875-in x 4-in Galvanized Steel Corner Brace” , https://www.lowes.com/pd/ReliaBilt-RB-4-IN-GALV-CORNER-BRACE-4-CT/5001634687 (accessed March 15th, 2023)

[10] ASR Outdoor, “Heavy Duty Tent Pegs – Orange”, Amazon.com, https://www.amazon.com/ASR-Outdoor-Piece-Heavy-Duty/dp/B01COB9U0S (accessed March 15th, 2023)

[11] Weatherables, “No Dig Installation Instructions”, https://www.weatherables.com/media/wysiwyg/NoDigAnchorInstallationInstructions.jpg (accessed March 15, 2023)

[12] Onestopoutdoor.com, “Premium Galvanized No Dig Ground Anchor - Round Post & Flag Pole Base Ground Mount - Screw in Post Stake, 21" Inch Long”, https://onestopoutdoor.com/products/premium-galvanized-no-dig-ground-anchor-round-post-flag-pole-base-ground-mount-screw-in-post-stake-21-inch-long (accessed March 15, 2023)

[13] Test Equipment Depot, “Guy Wire Kit MGWA”, https://www.testequipmentdepot.com/onset/accessories/mounting/guy-wire-kit-mgwa.htm (accessed March 15, 2023)

[14] ChannelMaster, “How to Install and Select Guy Wires”, https://support.channelmaster.com/hc/en-us/articles/200383685-How-To-Install-and-Select-Guy-Wires-CM-9081- (accessed March 15, 2023)

[15] Ropes and Poles. “Engineering for Scouts 3: Analysing structures”, http://ropesandpoles.blogspot.com/2013/08/engineering-for-scouts-3-analysing.html (accessed March 15, 2023)

[16] “Radartutorial,” Radartutorial.eu, 2023. https://www.radartutorial.eu/02.basics/Pulse%20Radar.en.html (accessed Mar. 17, 2023).

[18] Mini Circuits, “Coaxial Frequency Mixer,” ZEM-2B+ datasheet Rev B., Available: https://www.minicircuits.com/pdfs/ZEM-2B+.pdf

[19] Mini Circuits, “Surface Mount Frequency Mixer,” ADE-2ASK+ datasheet Rev B., Available: https://www.minicircuits.com/pdfs/ADE-2ASK+.pdf

[20] C. Hynes, “Capstone Project - Antenna Suggestions,” Mar. 14, 2023.

[21] X. Shang, B. Yuan, Y. Gu, W. Shi, and J. Qi, “A New Method for Improving Isolation of GPR Antenna,” 2022 Photonics & Electromagnetics Research Symposium (PIERS). IEEE, Apr. 25, 2022. doi: 10.1109/piers55526.2022.9793166.

[22] H. G. Schantz, “Introduction to ultra-wideband antennas,” IEEE Conference on Ultra Wideband Systems and Technologies, 2003. IEEE. doi: 10.1109/uwbst.2003.1267792.

[23] H. M. Jol, *Ground penetrating radar: theory and applications*, 1st ed. Amsterdam, Netherlands Oxford, UK: Elsevier Science, 2009.

[24] COOLM, “12V 10A Power Supply”, amazon.com. https://www.amazon.ca/COOLM-Adapter-100-240V-Charger-Lighting/dp/B07FFKL7CR (accessed March 16th, 2023)

[25] ROCKSOLAR, “12V 10Ah Lithium Deep Cycle LiFePO4 Battery with BMS System.” amazon.com. https://www.amazon.ca/ROCKSOLAR-12V-10Ah-Battery-flashers/dp/B0B323S49T/ (accessed Mar. 16, 2023)

[26] SOLPERK, “10A Solar Charge Controller Waterproof Solar Panel Controller 12V/24V PWM.” amazon.ca. https://www.amazon.ca/SOLPERK-Controller-Waterproof-Intelligent-Regulator/dp/B0946MWYPK (accessed Mar. 16, 2023).

[27] “High-Voltage Energy Storage: The Key to Efficient Holdup”, Jean Picard. https://www.ti.com/download/trng/docs/seminar/Topic_5_Picard.pdf

[28] “Introductory (2D) models — gprMax User Guide.” https://docs.gprmax.com/en/latest/examples_simple_2D.html (accessed Mar. 17, 2023).

[29] H. M. Jol, *Ground penetrating radar: theory and applications*, 1st ed. Amsterdam, Netherlands Oxford, UK: Elsevier Science, 2009.

[30] C. Rowell, "GEOPHYSICAL ANALYSIS OF STRUCTURES AND FLOW GEOMETRY OF THE BLUE DRAGON LAVA FLOW, IDAHO, USA," May 2011.

[31] A. Benedetto, F. Tosti, L. Bianchini Ciampoli, and F. D'Amico, "An overview of ground-penetrating radar signal processing techniques for road inspections," *Signal Processing*, vol. 132, pp. 201–209, Mar. 2017, doi: 10.1016/j.sigpro.2016.05.016.

[32] E. Huber and G. Hans, "RGPR — An open-source package to process and visualize GPR data," in *2018 17th International Conference on Ground Penetrating Radar (GPR)*, Jun. 2018, pp. 1–4. doi: 10.1109/ICGPR.2018.8441658.

[33] "dewow: Trace dewowing in emanuelhuber/RGPR: Ground-penetrating radar (GPR) data visualisation, processing and delineation." https://rdrr.io/github/emanuelhuber/RGPR/man/dewow.html (accessed Mar. 17, 2023).

[34] "CMPAnalysis-methods: Velocity Analysis of CMP Gather in emanuelhuber/RGPR: Ground-penetrating radar (GPR) data visualisation, processing and delineation." https://rdrr.io/github/emanuelhuber/RGPR/man/CMPAnalysis-methods.html (accessed Mar. 17, 2023).

[35] "CMPhyperbolas: Returns hyperbolas associated with Vrms velociies in emanuelhuber/RGPR: Ground-penetrating radar (GPR) data visualisation, processing and delineation." https://rdrr.io/github/emanuelhuber/RGPR/man/CMPhyperbolas.html (accessed Mar. 17, 2023).

[36] McMaster, "Fiberglass 4" Corner Bracket", https://www.mcmaster.com/33125T112/ (accessed March 15, 2023)

[37] Test Equipment Depot, "Onset M-TPA-KIT: 13' Water Level Data Logger Starter Kit", https://www.testequipmentdepot.com/onset/measurement-kits/hobo-water-level-deluxe-data-logger-kit-kitdu20012.htm (accessed March 15, 2023)

[38] Schaer, B. "Best Climbing Cams", ABC of Rock Climbing, Nov. 2020. https://www.abc-of-rockclimbing.com/best-climbing-cams/ (accessed March 15, 2023)

[39] MILSPEC Anchors, "Ground Anchors: 3'' Earth Anchor Kit W/Drive Rod", milspecanchors.com (accessed March 15 2023)

[40] P. 527: Electrical characteristics of the surface of the Earth," *www.itu.int*. https://www.itu.int/rec/R-REC-P.527-6-202109-I/en (accessed Mar. 18, 2023).

[41] R. Satpathy and V. Pamuru, "Off-grid solar photovoltaic systems," in *Solar PV Power: Design, Manufacturing and Applications from Sand to Systems*, 2nd ed. London: Elsevier, 2021, ch. 7, pp. 270-285.

[42] Lithium Hub, "Off Grid Solar Batteries: What Types are Best?." lithiumhub.com. https://lithiumhub.com/off-grid-solar-batteries-what-types-best/ (accessed Mar. 16, 2023).

[43] Office of Energy Efficiency and Renewable Energy, "PVWatts Calculator." U.S. Department of Energy. https://pvwatts.nrel.gov/pvwatts.php (accessed Mar. 14, 2023).

[44] Sensors & Software, “pulseEkko Specifications.” sensoft.ca. https://www.sensoft.ca/products/pulseekkopro/specification/ (accessed Mar. 15, 2023).

[45] Environment Canada, “Climate Normals and Averages,” climate.weather.gc.ca. https://climate.weather.gc.ca/climate_normals/station_select_1981_2010_e.html?searchType=stnProv&lstProvince=BC (accessed Mar 15. 2023).

[46] Canbat, “Charging Lithium Iron Phosphate Batteries (LiFePO4),” canbat.com. https://www.canbat.com/how-to-charge-lifepo4-batteries/ (accessed Mar. 16, 2023).

[47] United Nations, “What is renewable energy?.” un.org. https://www.un.org/en/climatechange/what-is-renewable-energy (accessed Mar. 16, 2023).

[48] Wind Energy Technologies Office, “Advantages and Challenges of Wind Energy.” energy.gov. https://www.energy.gov/eere/wind/advantages-and-challenges-wind-energy (accessed Mar. 16, 2023).

[49] Aurora Solar, “Comprehensive Guide to Solar Panel Types.” aurorasolar.com. https://aurorasolar.com/blog/solar-panel-types-guide/ (accessed Mar. 15, 2023).