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The Design of a PocketQube Satellite Communication System

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Nomenclature

Variables and functions

V	Voltage
I	Current
R	Resistance

Acronyms and abbreviations

GS	Ground Station
PQ	PocketQube
LEO	Low Earth Orbit
LOS	Line-of-Sight
PCB	Printed Circuit Board
EPS	Energy Power System
TX	Transmit
RX	Receive
GPS	Global Positioning System
GNNS	Global Navigation Satellite System
IMU	Inertial Measurement Unit
SU	Stellenbosch University
PQSU	PocketQube Stellenbosch University
RF	Radio Frequency
IC	Integrated Circuit
PEC	Perfect Electrical Conductor
ASK	Amplitude Shift Keying
PSK	Phase Shift Keying
FSK	Frequency Shift Keying
QAM	Quadrature Amplitude Modulation
GFSK	Gaussian Frequency Shift Keying
GUI	Graphical User Application
EIRP	Equivalent isotropic radiated power

Abstract

English

The English abstract.

Afrikaans

Die Afrikaanse uittreksel.

1. Introduction

This project aims to design and implement a wireless communication system for a miniaturised satellite called a PocketQube (PQ). The PocketQube standard was created to define physical and electronic requirements for so-called ”nano satellites”. The goal of this is to allow for easy integration of various sub-modules into one physical enclosure. One common use-case of these satellites is to collect sensory information from the atmosphere. These can either be placed into orbit, are attached to a *high-altitude balloons* (e.g. a large, helium balloon). In this project, such a balloon will been provided by the department, and a communication system for this satellite balloon will be designed.

This project consists of the design of three sub-systems. The communication system to be designed will involve both a tracking ground station (GS), as well as a PQ ’unit’, that will use a custom link protocol. The general idea is that the GS will mechanically track the PQ while it communicates with it, enabling realtime data transmission and telemetry. An existing two-axis antenna mount has been provided for the GS, which a newly-designed PCB will be placed into. The GS will mechanically the balloon, allowing bi-directional wireless communication. The PQ unit should conform to the PQ standard and fit inside a provided housing. The third sub-system is the integration of a proprietary Radiosonde (atmospheric telemetry device) into the newly-designed communication system.

Literature will be consulted in order to investigate the various design approaches and decisions. Since the project focuses on system design and integration, a number of components and sub-modules will ultimately be combined to form the final system. Different electronic components and their specifications will be compared based on gathered project requirements. This will require trade-offs to be made, since the system design is limited in time, cost, form-factor and several other factors. This report documents the trade-offs and decisions made, with the goal of being of use to future designers of similar systems.

2. Problem

2.1 Overview

The requirements for this project are defined by analysing general, currently existing balloon-satellite systems, as well as taking into account the planned launch that this specific PocketQube will be used in, as shown in Figure 2.1. Further, the desired integration with the existing Radiosonde system (the iMet-54 device) is taken into account.

Generally, high-altitude balloons can drift to a height as much as 30 km above sea level [9]. For this project, the balloon is planned to be released from near Saldanha Bay (Western Cape, South Africa), where it will travel a maximum distance of around 200 km towards the Cederberg and land furthest in Worcester. From Cape Town, this is a maximum straight line distance of around 115 km.

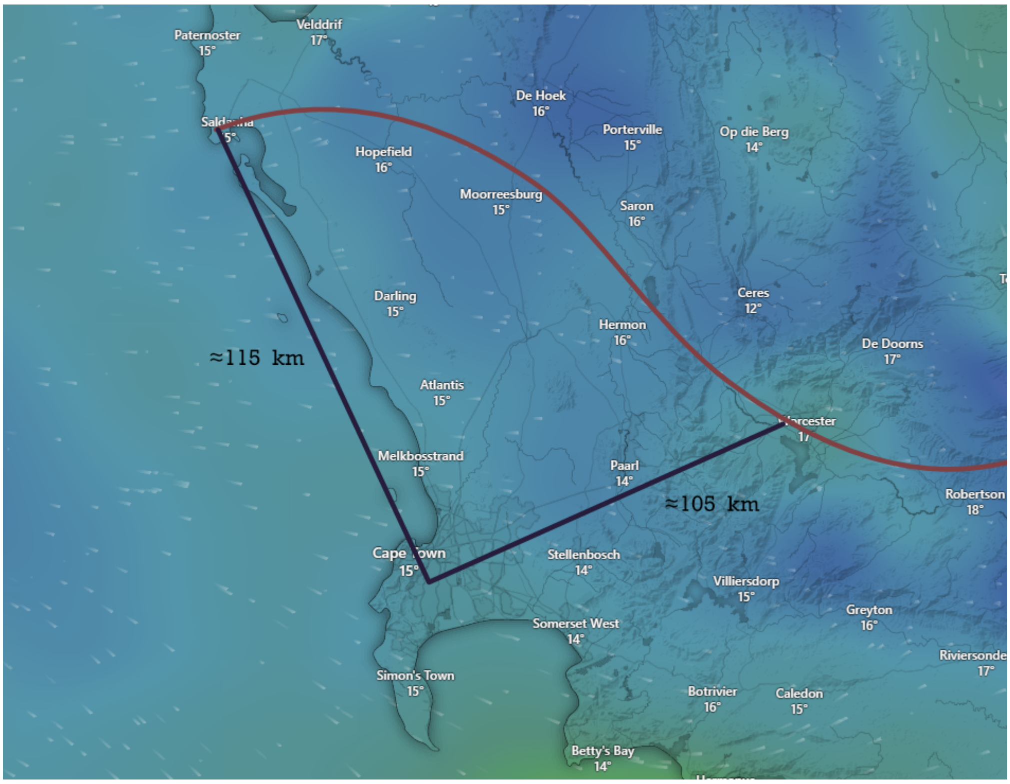

Figure 2.1: Balloon Path and Distances

2.2 Requirements

The general requirement of the system is that continuous, wireless communication should be established and maintained between the ground station and a balloon-satellite carrying a PocketQube payload. The antenna mount of an existing ground station has been provided. Further, communication with the existing Radiosonde should also be possible. From this information, and after supervisor consultation, slightly more specific user requirements are gathered and listed:

1. Wireless communication data between the GS and the PQ should be retrievable, as well as data from the priorietary Radiosonde.
2. The communication system should be capable of the range covered in Figure 2.1.
3. The PQ unit should conform to the *SU-modified* PQ9 standard (which has been provided), and integrate with other prototype units. This standard is hereby refered to as PQSU.
4. The PQ unit should remain operational for ”a few hours”.
5. The GS electronics should integrate into an existing antenna mount.

The system will undergo a *flight-readiness review* to determine if it has met the requirements before launch. To match the features of the existing, proprietary Radiosonde system [10], an additional requirement that the slant range should be no less than 250 km will be imposed. Further, although these are the minimum requirements for the Saldanha launch, choices could be made such that the communication system is even more general-purpose, and can potentially be used for low earth orbit (LEO) applications as well. In this case, the orbital height should be increased to between 160 km and 1000 km [11]. As the project progresses, if supporting such a distance will not significantly increase the time, complexity, or cost of the system, it could be catered for as an expansion to the core requirements.

2.3 Specifications

For specification definition, further calculations should be done. This will allow a list of more detailed, system-level specifications to be created. First, the required communication conditions (link distance, atmospheric effects etc.) are established. Then, power and voltage requirements are expanded on. Finally, system integration is considered.

Typicall balloon satellites reach a maximum height of around 30 km [9]. They rise at a vertical speed of around 20 km/h, and can travel horizontally as fast as 200 km/h when falling. However, a typical distance for such a balloon is 200 km, and therefore an average speed of around 100 km/h will be designed for given the average flight time of longer than 2 hours. At this height, a line-of-sight (LOS) calculator reveals that the horizon is around 600 km, meaning that the antenna could theoretically be placed on sea level. Further, the earth's curvature is found to be negligible at this distance, meaning pythagoras can be used to calculate an LOS distance of 120 km. If LEO heights are to be considered, the curvature of the earth should be taken into account. At a height of 160 km, an LOS distance of 1400 km is required, and at 1000 km, an LOS distance of around 3500 km is required. Since this is much further than the required slant range of 250 km, it will not be designed for initially. However, as mentioned, this could potentially be added as a project expansion.

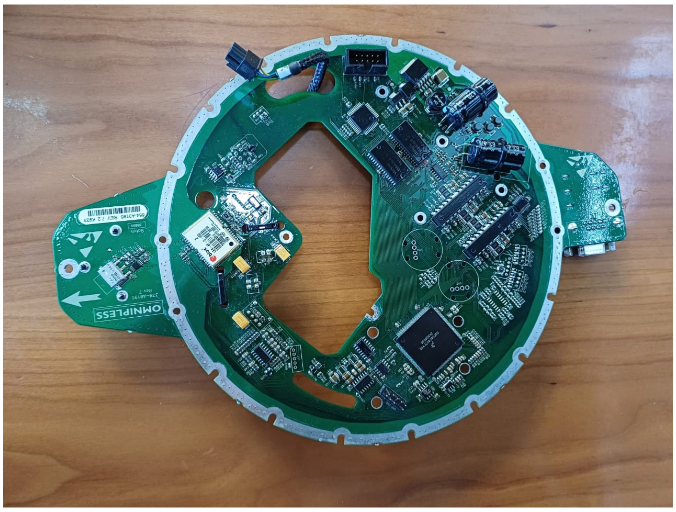

Figure 2.2: Existing Antenna Mount PCB

The PQ9 standard stipulates a 3V minimum bus voltage. This must therefore be used directly to power the PQ unit circuitry. As mentioned, the PQ unit will be integrated with other *prototype* units into a single PocketQube. Since this is a prototype launch, there is risk of the EPS malfunctioning. Further, a power connection is also needed during development for modularized testing. A simple on-board battery at least matching the standard's voltage, as well as a battery source selector, will therefore be included in the design. This can be used for testing and deployment, however this battery cell could potentially be removed if the EPS is found to meet the *flight-readiness* tests. It should be noted that high-altitude balloons generally remain air-bound for 2-3 hours, where they eventually pop.

Both designed PCBs integrate into the relevant systems. The PQ9 standard clearly defines the dimensions of such a PCB (e.g. 42 mm x 42 mm outer dimensions) and the design should conform to this. The old antenna mount made use of an existing circular PCB with mounting holes and two support ”wings”, as shown in 2.2. The new GS PCB should conform to this form factor. Lastly, the system should drive the existing stepper motors in the antenna mount.

Further investigation finally leads to the following general system-level specifications:

1. The system should be capable of a slant range of 250 km.

2. The system should be designed to operate at a data rate of 9600 baud at the specified range. This data rate is a typical satellite telemetry value as in [12].

3. The system should allow for iMet-54 Radiosonde data to be retreived, assuming that the priorietary protocol can be reverse-engineered. This data is GFSK modulated at a pre-selected frequency of between 402 to 405 MHz [13].

4. A single antenna should be used for both the custom and proprietary protocol on the GS, meaning the custom communication frequency should be as close to 405 MHz as possible (to minimize required antenna bandwidth).

5. The PQ unit should follow the PQSU standard, stipulating:

   - A 42 mm square outer PCB dimension
   - A 4 mm component height above, and 2 mm below.
   - A 20-pin header interface, catering for RS-485 and I2C communication, and providing 3.3 V and 5 V power lines.

6. The PQ unit should include a battery capable of lasting 4 hours at nominal current draw.

7. The GS should be capable of tracking the balloon at 110 km/h at a distance of 90 km away (10 % headroom).

8. The GS PCB connecting to the existing antenna mount, which has a diameter of 20 cm, with equi-spaced mounting holes, wings etc. as in Figure 2.2.

9. The GS should control two 4218S-15 bipolar stepper motors, which have a maximum current of 0.50 A per phase, each being driven at 24 V.

10. The GS should provide a USB-C connection to allow a PC to monitor the data in realtime. This should be capable of receiving all data from the link in realtime.

3. Background

3.1 PocketQube

The PocketQube standard is a fairly new set of protocols and specifications defining a modularized nano-satellite system. The term *modularized* in this context refers to the ability for different "modules" or PocketQube units, each with their own set functionality, to be connected to a common *backplane* and integrated seamlessly. *Integration* here refers to both the mechanical spacing of each module, as well as the electronic communication between the modules.

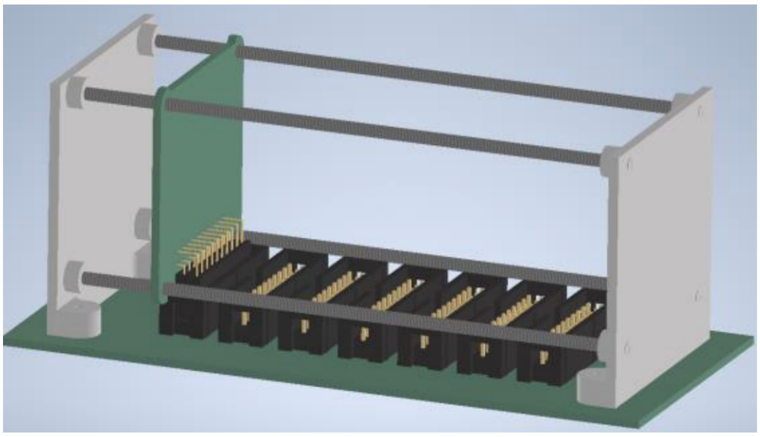

Figure 3.1: A PQSU Enclosure [1]

As an example, a PocketQube enclosure could contain three units: a communication module, a sensor pack, and a battery system. These modules can then be connected onto the backplane via headers, and placed inside a single enclosure, such as that in Figure 3.1. This "nano-satellite" can then be "launched" through any means.

3.2 Antenna Theory

This section covers a very brief review of different types of antennas in literature, as well as how to practical feed these antennas and a summary of their differing performance.

3.2.1 Types

There are various antenna types to consider for a satellite communication system. A highly-customized antenna design is out of the scope of this project, and therefore only common designs with tunable parameters, or existing designs in literature, will be considered. Ultimately, the following characteristics will be used to compare the various options:

- Radiation pattern (qualitative shape)
- Gain (relative to an *isotropic* source)
- Bandwidth (relative to resonant frequency)
- Beamwidth (width of *main lobe*)
- Dimensions

Half-Wavelength Dipole

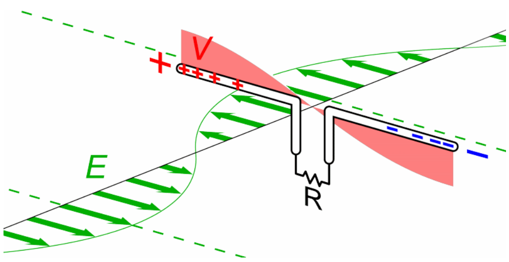

Figure 3.2: Dipole Antenna Illustration [2]

The half-wavelength (0.5λ) dipole anntenna is arguably the simplest and most common type of antenna. It consists of two conductive elements operating in opposite phase, as depicted in Figure 3.2. It is considered *omni-directional* i.e. it radiates relatively equally in all directions. Its gain is relatively low, at around 2.15 dBi [8]. Further, it does not radiate in the direction tangential to the conductor.

General Dipole

Dipole antennas can, in general, be any length. However, a change in length results in a change in the antenna's characteristics. In general, smaller antennas result in lower gain and lower efficiency, but a larger beamwidth at the resonant frequency. The obvious advantage of these designs is that the size of the dipole can be decreased. However, if size is a constraint, *monopole* antennas are generally employed.

Quarter-Wave Monopole

The working principle of a classic monopole antenna makes use of the electromagnetic theory of *imaging*. Essentially, if an infinite ground plane or Perfect Electrical Conductor (PEC) is placed below one half of a 0.5λ dipole antenna, then, since the PEC holds the constraint that the tangential electric field is zero across its boundary, an equal but opposite electromagnetic wave is ”induced” due to the incident wave. This wave ”appears” to have come from an equal but oppositely polarized ”image” source, hence removing the need for the second half of the dipole to be present.

These antennas are extremely useful when size is a constraint, however have the disadvantage of requiring a ground plane. A *whip* antenna is a form of monopole antenna designed to be flexible so that it does not break as easily, and often placed inside a plastic enclosure, as in Figure 3.3. [8]

Figure 3.3: Whip Antenna in Plastic Housing

Helical

Figure 3.4: Helical, Unidirectional Antenna

Helical antennas are coiled windings of wire, where the circumference of the coil has some relationship with the desired wavelength. Commonly, a circumference of $C = 1.0\lambda$ is used for *unidirectional* variants. In this case, a ground plane is required (referring to the theory of imaging in Section 3.2.1). The ground plane can also be *cupped* (i.e. extended as an open cylinder) for additional directivity [14]. *omni-directional* variants are also possible, having a circumference size much smaller than the operating wavelength, and not requiring a ground plane. [15]

When $C \approx \lambda$, the antenna is said to be operating in *axial mode*. Conversely, the antenna operates in *normal mode*. Figure 3.4 depicts a 21-turn antenna designed to operate in normal mode.

Helical antennas have several design parameters that influence the antennas characteristics, such as number of turns (n), wire width (wd), and spacing between turns (S). A spacing of $0.20\lambda < S < 0.25\lambda$ is recommended, however smaller spacings of $0.10\lambda < S < 0.20$ are commonly used [16]. They also are able to receive either linear or circularly polarized signals, making them more flexible. Lastly, since they can be designed with an arbitrarily small or large number of turns, their size is generally smaller than other unidirectional designs (e.g. yagi-uda antennas) due to their *circumference* being related to the wavelength.

Patch

A *patch* antenna (also collequially known as a *PCB* antenna) is simply a rectangular PCB trace sized correctly to allow for radiation. Typically, a simple square or rectangular shape can be used. They allow for small profiles at the cost of efficiency [8], and can be integrated onto a PCB using normal trace techniques.

Array

In general, multiple antennas can be combined in what is known as an *array* configuration. This allows complete manipulation of the design by manipulating the *constructive* and *destructive* interference of electromagnetic waves. This can allow for either an increase or decrease in directivity. Common variations of this concept reside in *Yagi-Uda* and *Patch Array* antennas. [8]

Yagi-Uda

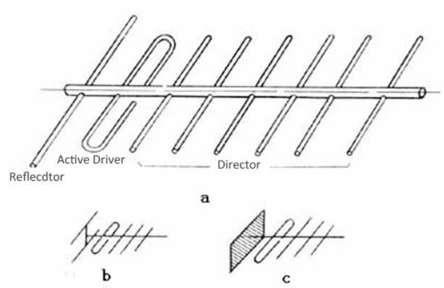

Figure 3.5: Yagi-Uda Antenna [3]

Although not strictly an antenna array, *Yagi-Uda* antennas are one of the most popular directive antennas. A given number of conductors are stacked in a specific configuration as show in Figure 3.5. This ultimately ”steers” the electromagnetic waves using the concept of interference. Only one of the conductors in the array is actually fed with the signal - the rest are merely *passive* elements used for increasing the directivity.

Microstrip

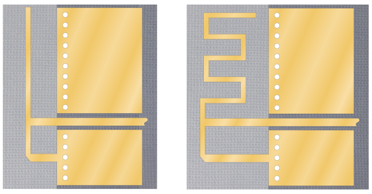

Figure 3.6: Inverted-F Microstrip Antennas [4]

Microstrip antennas generally refer to any planar, PCB antenna. They can be considered a generalization of a patch antenna. Many designs exist (which are often derived from non-planar antennas) and allow for a diverse selection of desired characteristics. A few examples include:

- A *patch array*, which has increased directivity.
- An *inverted-F* design, which has a small form factorer and a nearly 3D omni-directional radiation pattern.
- A *ring antenna*, which is unidirectional, and has an even smaller form factor than the inverted-F antenna [17].
- A *helical patch* antenna, which is simply a ”zig-zag” helix shape flattened onto a PCB.

Many variations on these designs exist, and the literature may be further consulted in the design phase. A multi-frequency inverted-F design is illustrated in Figure 3.6.

3.2.2 Feedline

In general, *feeding* an antenna is more complicated than simply connecting the supply’s positive an negative terminals to the antenna’s terminals. Generally, a $50\,\Omega$ system impedance is used in RF design. Since each antenna has a unique *input impedance* which is generally different from this value, it should be *match* appropriately for optimal performance. The most general, narrow-band technique for lower frequency is to employed a ”lumped element” matching circuit. The most common example of this is an L-section (e.g. a capacitor and inductor). A few specific techniques for some of the antennas in Section 3.2.1 are reviewed below.

Half-Wavelength Dipole

A dipole antenna has an input impedance of around 73 ohms, varying only due to the wire diameter used. A common method to reduce this impedance to 50 ohms is simply to reduce the length of the dipole. In this case, matched resonance occurs at between $0.42\,\Omega$ and $0.44\,\Omega$. [14]

Helical

The input impedance of a helical antenna varies between 100 to 200 ohms. A common method to reduce this impedance is for the first quarter turn of the helix to be in the form of a conductive strip, and for the pitch angle of this section to be close to zero or vary slowly [14]. The height above the ground plane can then be varied to match the antenna appropriately, with the following equation approximately providing an approximate $50\,\Omega$ match [14]:

$$h = \frac{w}{\frac{377}{\sqrt{\epsilon_r}Z_0} - 2}$$

3.2.3 Summary

The following table presents a general summary of the investigated antennas. A qualitative comparison of the results have been presented from consensus in the literature to aid in design. Note that a narrow beamwidth general corresponds to a unidirectional antenna (and wide for omni-directional) and therefore this has not been included.

Type	**Gain (dBi)**	**Radiation**	**Bandwidth**	**Size**
0.5λ Dipole	2.15	Omnidirectional	Medium	Medium
Monopole	1.76	Omnidirectional	Medium	Small
Helical	< 20	Either	Large (56%)	Small-Medium
Microstrip	< 10	Either	Small-Medium	Small
Yagi-Uda	< 40	Unidirectional	Small	Large

Table 3.1: Qualitative Comparison of Antenna Characteristics [8]

3.3 Telecommunication Theory

A review of the communication techniques used for wireless links is conducted below. Since it is already planned to use modular components in the hardware design stage, and most modules handle error correction, modulation, demodulation and more with little effort, only a brief overview is given.

3.3.1 Modulation Techniques

The *modulation* technique used over a communication link essentially refers to the method used to encode analog or digital information into an electrical voltage. ASK, FSK, PSK, and QAM are the most common techniques [18] [19]:

- *Amplitude Shift Keying* (ASK). This technique modulates the amplitude of the voltage to represent various bit levels.
- *Frequency Shift Keying* (FSK). This method changes the frequency of the signal to represent various signal levels. Commonly, *Gaussian-FSK* (GFSK) is used, which implements a smoothing filter. This decreased the bandwidth for similar throughput, making it comparable to the following techniques.
- *Phase Shift Keying* (PSK). This is often seen as a variantion of FSK, where the phase of the signal is varied instead of the frequency. It required complex synchronisation, and has lower spectral efficiency compared to QAM.
- *Quadrature Amplitude Modulation* (QAM). This method modulates both the amplitude and phase of a signal, allowing for a large number of signal levels. It has very high spectral efficiency, and is commonly used for higher cost systems.

loRa (”Long-Range”) is a relatively new technique which offers makes use of frequency-varying ”chirps” to modulation the incoming signal. It has been seen to drastically increase range capacity, while sacrificing bit rate. Its practical use has also been demonstrated in an existing PocketQube application in [20].

3.3.2 Link Budget

For any communication system, a ”link-level” design or *link budget* should be conducted. The goal of this design step is to determine the power requirements of the commuication system, taking into account transmitter power, antenna characteristics, receiver sensitivity, modulation technique, and any attenuation involved.

Free software *Python ”Link Budget”* is available which employs calculations from the ITU-R to easily compute attenutation due to path loss, atmospheric effects, and more for a given satellite link at a given distance. It will be used during the link budget design.

3.4 Satellite Tracking

There are various tracking methodologies used to track balloon satellites in order to maintain a wireless communication link from the ground. Ultimately, all of these methods provide a single output to a ground station system: the direction in which to ”steer” its antenna mount. Each method is compared and expanded on below.

3.4.1 Open-Loop

The simplest method to track a balloon satellite is using simple ”open-loop” control. In this method, information about the flight path of the balloon is fed into the system, and the ground station is simply pointed in that direction, with the ”hopes” of maintaining a connection. This information can simply be a pre-calculated, predicted path of travel, or a continuously re-estimated path based on continous weather data. *HABHug.org* is an organisation with a high-altitude path predictor [21].

An advantage of this method is its extreme simplicity in implementation. It has several disadvantages, however, including being vulnerable to prediction inaccuracies, as well as the difficulty experienced in re-acquiring the communication link once it is lost. Further, the ground station generally still a requires GPS receiver and IMU, however this could theoretically be excluded if it is to be placed in a fixed position.

3.4.2 GPS (Direct)

If an initial communication link can be estabilished between the satellite and ground station, *direct* GPS transmission can be added for positional feedback. This is a simple method of closing the loop, since the path data can be updated dynamically.

3.4.3 GPS (Relay)

If a link cannot be initially estabilished, a ”relay” method of GPS tracking can be used. The tracking functions in a four-step process, explained below and depicted in Figure 3.7:

1. The precise position of the payload and the ground station is determined using data received from GPS satellites.

2. The position is *relayed* to an external network (satellite or ground -based) using a radio transmitter.

3. The ground station receives the location from the external network (e.g. via the internet).

4. The ground station calculates the direction to point based on its own GPS location, and the GPS location of the payload.

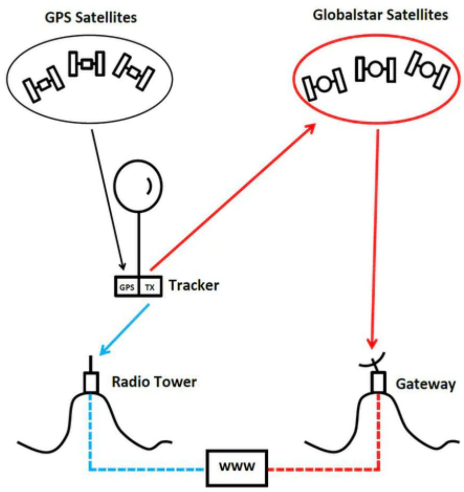

Figure 3.7: GPS Relay Tracking [5]

The major disadvantage of this method is the additional cost required. Since an antenna capable of communicating with one of the external networks is required, two antennas are needed if direct communication with a ground station is desired. Further, the cost of subscribing to an external network is generally high. This type of tracking works well if the satellite is physically close to the external network satellites, or if the ground station does not need to communicate in realtime, but merely needs access to location of the satellite (e.g. in a homemade cellphone balloon satellite launch).

3.4.4 Radio

Radio tracking can be done when the satellite itself transmits radio waves. Techniques which provide simple direction pointing make use of the electromagnetic signal strength to point the ground station correctly. To initially find the satellite, the entire sky can be scanned or an initial guess can be provided. From there, periodic *radius scanning* can be used to track the signal within a certain portion of the sky, or more advanced techniques such as *conical scanning* can be used.

3.5 PCB Design

Printed circuit board (PCB) design is considered a skill and art in and of itself. Since this project will require basic PCB design techniques related to simple circuits, as well as potentially RF circuits (depending on decisions made in the design process), an initial review of literature and techniques should be done. A very brief overview of the most relevant, core concepts is presented.

3.5.1 Layers

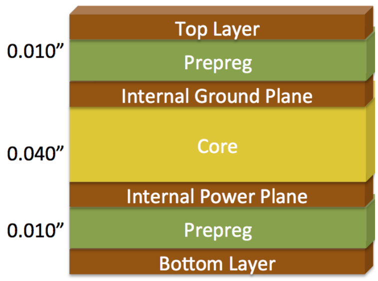

Figure 3.8: Common 4 Layer PCB Stackup [6]

A PCB is made up of multiple layers. 2-layer and 4-layer PCBs are considered the most common. For a 2-layer board, there are two layers of copper on both the top and bottom of the board. For 4-layer boards, 2 extra copper layers lie in between the outer layers and are therefore not exposed to air. These inner layers are general used for *ground planes* or *power planes*. The purpose of each layer and how they are distributed is called the PCB *stackup*. Figure 3.8 shows a common 4-layer PCB stackup. [22]

3.5.2 Traces

The traces connect various components on the different layers. They are created by removing the copper which surround them, resulting in a single conducting path. For digital design, generally only the thickness of the trace is important, and is determine by the current handling requirements of that signal. For radio frequency *RF* design, the type of material in between traces, distance between traces, thickness of the trace etc. should all be taken into account. This is due to the fact that they influence the *characteristic impedance* of the resulting *transmission lines*.

3.5.3 Vias

Vias are holes on boards that (generally) pass a signal from one layer to another. They allow for a circuit's components to be distributed across layers, therefore providing flexibile in laying traces. *Untented* (uncovered) vias can be soldered to for e.g. *through-hole* components, whereas *tented* vias are used to prevent the via from being soldered to [23]. *Stiching vias* are a large number of vias placed in a spaced-out pattern, which result in a stronger connection, allow for better thermal management, and reduce crosstalk and EMI [24].

3.5.4 Copper Pours

Copper pours are large areas of copper on a PCB. They are typically used for large exposed ground planes and power planes where power distribution or electrical shielding is necessary.

3.5.5 RF Design

The design of PCB circuits involving higher frequencies is significantly more complex. Not only is the layout of components more critical, but the length of traces, the placement of ground planes, and many complex considerations need to be made. Some of this process can be significantly simplified by making use of RF *modules*. These are typically isolated components with an RF *shield* providing a single functionality.

The following list encompasses a short summary of some considerations that *may* be applicable in this project. It should be noted that many of these points are *only* applicable if RF traces and RF ICs are designed directly (as opposed to using an RF module). This is known as a ”chip-down” design. The trade-off of using such modules will be made in the design phase.

- Ensure proper grounding with thick enough traces and V_{cc} bypas capacitors near RF integrated circuits. If the ground is not on the same layer as the IC, multiple vias should be used [25].

- If a high-frequency signal is to be routed on a trace longer than the frequency's critical length (taken to be $\frac{\lambda}{10}$ [26]), its characteristic impedance should either be *controlled* or *matched* appropriately. In other words, if two $50\,\Omega$ RF pins on two different ICs are to be connected together, either the trace itself should have a $50\,\Omega$ impedance, or impedance matching should be done so that the transition between characteristic impedances does not cause reflections. [25]

- Take care of *crosstalk* and electromagnetic *isolation*. Use *RF filters*, *RF shields* and *stitching vias* to minimize these effects.

- Keep RF lines as far as possible from each other, and route high-speed digital signals on a different layer from the RF lines entirely. Layers should be dedicated to a continuous ground plane and power plane - typically layers 2 and 3 for a 4-layer board, as shown in Figure 3.8. [27]

- Apply curved bending or *mitering* when transmission lines are required to change direction abruptly. [27]

4. System Design

4.1 Overview

This chapter encompasses the system-level design. The approach is to make design choices that allow for modularity with regards to component integration and testing. The specific details of the circuit design and interconnects will be not be discussed, however initial high-level design choices will be made. This include decisions for the overall system, the PocketQube unit, and the ground station unit.

4.2 High-Level System

There are various decisions to be made regarding the entire communication system. A complete high-level system block diagram illustrating the decisions discussed below is shown in Figure 4.1. Note that the yellow blocks are external (i.e. assumed to be available already).

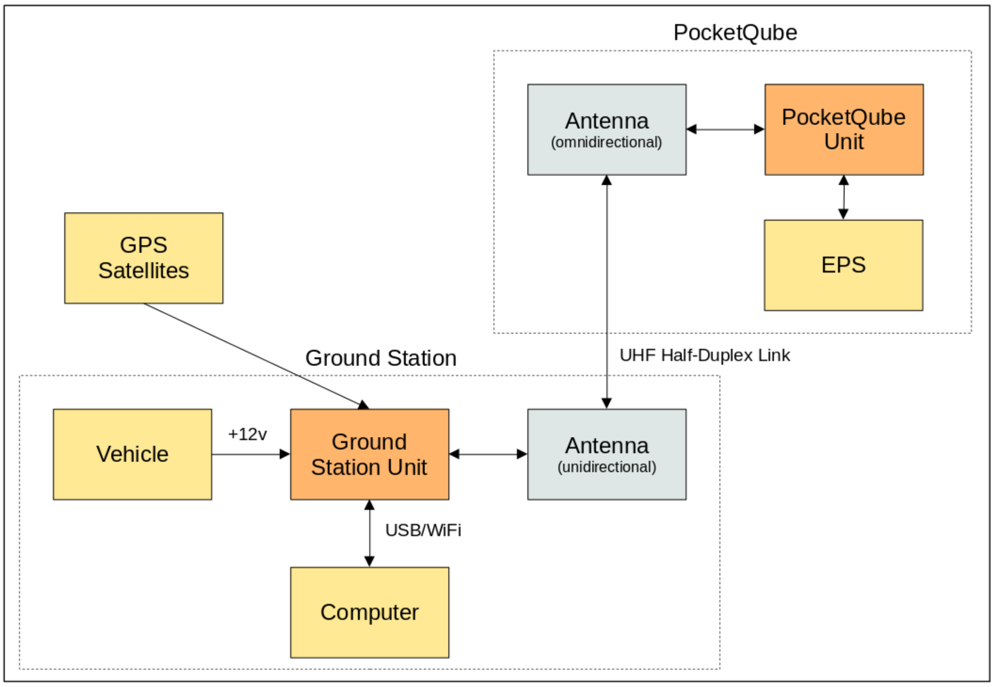

Figure 4.1: High-Level System Diagram

4.2.1 Methodology

Since a large number of sub-system are required on the ground-station, either *modules* or simple *reference designs* will be form the basic building blocks of the system. This will simplify the design process and integration. Only if no modules or designs are found to meet the system requirements, should a more custom solution be developed. The ground station will be powered via +12V from a nearby vehicle, and the PocketQube will be powered from an on-board EPS (another PQ unit). Both sub-systems should be designed such that testing without a vehicle/EPS is also possible.

4.2.2 Tracking

It is known that open-loop path-predicted tracking is adequate for high-altitude balloons. In this sense, the ground station requires at least a GPS connection, as well as some form of inertial measurement unit (IMU) for beem steering. The path data will be uploaded to the ground station via USB or WiFi and an external device, such as a laptop, personal computer or smartphone (referred to as the system's *computer* onwards). Further, this computer will be used to monitor the link and record the data. If longer-range communication is required, it will be desirable to have a second method of tracking other than path prediction. Either radio signal-strength tracking, or direct GPS tracking, may then be added.

4.2.3 Custom Protocol

Firstly, high-level decisions should be made regarding the custom communication protocol to be implemented. Half-duplex communication will be designed for, since full-duplex is unnecessary for this type of link. This is due to the nature of the link itself i.e. the command-response pattern used when receiving data from satellites.

For the given flight path, a goal of at least 9600 downlink baud rate will be designed for at the approximate 100 km range, as it is a relatively standard satellite downlink speed as mentioned. Both GFSK and LoRa techniques will be explored in the detailed design stage, since GFSK is well-estabilished and is considered suitable over such a range, but LoRa may have added noise immunity benefits. The 433 MHz amateur band (430 to 440 MHz) will be utilized.

4.2.4 Proprietary Protocol

The requirement to communicate with the existing Radiosonde should be considered. According to the iMet54's datasheet [13], it operates at a centre frequency of between 402 and 405 MHz, selected in 1 MHz increments. Ideally, for a simpler design, one antenna should be designed on the GS supporting both the custom and proprietary communication communication protocols. The feasibility of this will be investigated further in the antenna design stage.

4.2.5 Phased Design Plan

If very long-range communication is to be supported, a highly-directive antenna will most likely be needed and, as mentioned in Section 3.2, these antennas are usually large in size. Although the possibility of a high-gain design in the 400 to 500 MHz band will be investigated, it is probable that this may be limited by the size and weight constraints of the existing antenna mount. Given the above considerations, it was decided for the detailed design to follow a phased approach:

- **Phase 1:** The design of a single ground station antenna in the 400 to 500 MHz band, allowing for close-range testing of both the custom and proprietary protocols. Only open-loop tracking will be implemented.

- **Phase 2:** The addition of a physically smaller, high-gain 868 MHz band antenna for long-range custom protocol communication. Signal-strength tracking, as well as GPS on the satellite, may be added.

In this way, close-range system requirements are met in Phase 1, and longer range support can be added in Phase 2, if time allows. This phased-approach is also made possible due to the choice to use modular components, which easily allows e.g. a 433 MHz RF module to be swapped for an 868 MHz module, with minimal re-design.

4.3 Ground Station

A block diagram of the system components for the ground station is shown in Figure 4.2.

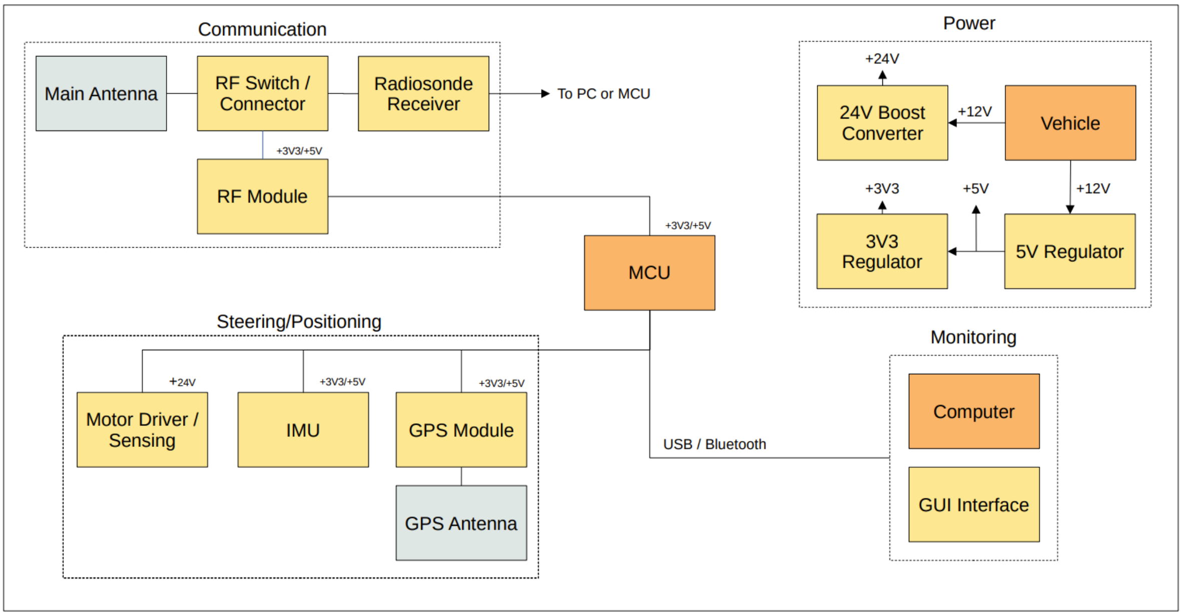

Figure 4.2: Groud Station System Diagram

4.3.1 Power

The power section consists of two linear regulators, as well as a boost converter. The existing antenna mount has two *NEMA 17 4218S-15* stepper motors, which will be used to steer the ground station in the direction of the satellite. These motors are ideally powered from +24V, and therefore a boost converter will be used to step up the voltage from the car's voltage of +12V. Further, +5V and +3V3 regulators will be ncl to power both the MCU and any other ICs, depending on the voltage level they require.

4.3.2 Communication

The communication section consists of the main antenna, as well as the RF control circuitry and connectors. The *RF Switch/Connector* is provided to allow the antenna to be shared between custom and the proprietary communication protocols. Initially, a connector will be used for prototyping. Then, if time allows, a dedicated RF switch will be included, which will allow for the MCU to control the antenna connection. Both the RF module and the Radiosonde receiver will connect through the RF switch/connector and to the antenna. The Radiosonde will either connect to the PC (if an SDR dongle is used) or to the MCU (if a dedicated receiver is used).

4.3.3 Steering and Position

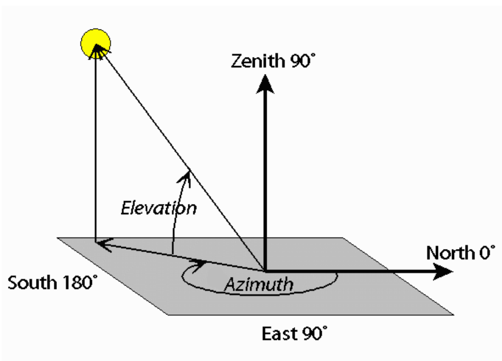

Figure 4.3: Azimuthal and Elevation Visualization [7]

Generally, the orientation of the ground station's antenna is described by both an azimuthal and an elevation angle, as in Figure 4.3. The resultant two angles should be controllable to a reasonable degree of accuracy, such that the antenna can point in a given direction.

The existing two-axis antenna mount is shown in Figure 4.4. Since the antenna platform moves relative to the base (where the PCB is mounted), this relative angle needs to be known. Two options to do this are considered:

1. *Open-loop.* The base's absolute orientation is measured in realtime, and the platform's relative orientation is pre-computed ("calibrated"); stored in firmware for each combination of stepper motor steps; and looked up in a table when needed.

2. *Closed-loop.* The platform's itself's absolute orientation is measured in realtime, and this information is fed back into the motor's control system to point the platform correctly.

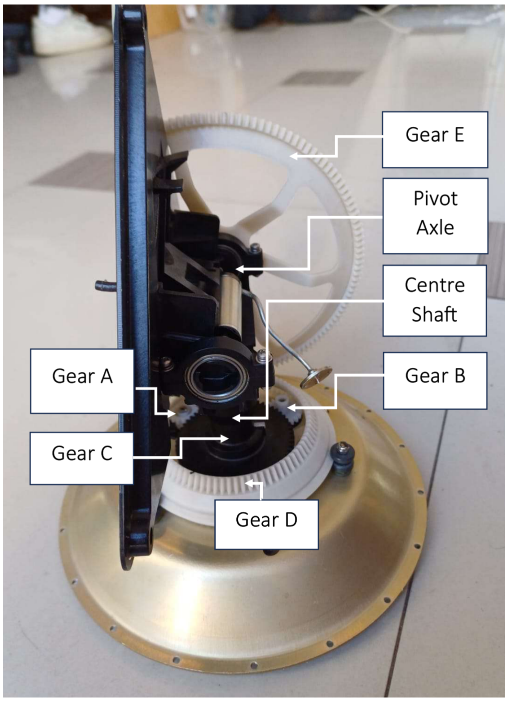

Figure 4.4: The Existing Antenna Mount

Relative orientation can be measured by an inertial measurement unit (IMU), which typically includes an accelerometer and gyroscope. If a magnetometer is included, absolute orientation can also be measured. This will be discussed further in the detailed design stage.

4.3.4 Monitoring

A laptop or PC will be used to monitor the connection. A Graphical User Application (GUI) will be implemented for ease-of-use. This should include the following functionality:

- Send specific commands to the satellite.
- Read sensor measurements of the satelite.
- Control the ground station orientation e.g. performing motor calibration etc.
- Set communication parameters e.g. output power and modulation parameters.
- Monitor communication link performance.

4.4 PocketQube Unit

A block diagram of the system components for the PocketQube unit is shown in Figure 4.5.

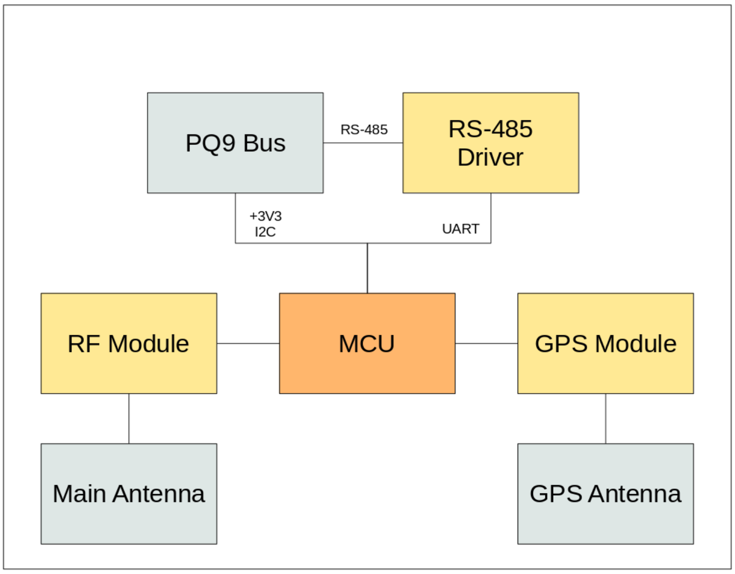

Figure 4.5: PocketQube Unit System Diagram

This unit is relatively simple in comparison to the ground station, and so the ground station should be considered a priority. The unit consists of an RF section, and a GPS section. The RF antenna should integrate well onto a typical PocketQube housing, as should the GPS antenna. The MCU should be capable of interfacing with the Stellenbosch PocketQube bus, which includes:

- A 3V3 line
- A 5V line
- An I2C bus
- An RS-485 bus

The MCU will pull directly from the +3V3 line, and will also communicate directly with the I2C bus. However, an RS-485 line transceiver should be included to cater for the RS-485 protocol, which will connect to the MCU via UART.

5. Detailed Design

5.1 Component Selection

The first step in the detailed design process is to select components for the various sub-systems. Components for both the ground station and PQ unit will be selected in one step, due to the overlapping research involved. Ideally, components should be readily available from local suppliers. Finally, through-hole components and breakout boards will mostly be used for the ground station, and surface mount components for the PQ unit.

5.1.1 Existing Components

The ground station has a number components which will be used without modification. As mentioned, two stepper motors are already mounted. These motors draw 0.50 A, and allow for up to $0.5\,\mathrm{N \cdot m}$ of torque [28]. The ground station also includes a small zero-sensing circuit for the azimuthal direction, which integrates a *H22A* optical switch [29] and a low-pass filter.

5.1.2 GPS

A GPS should be selected for the ground station, and possibly for the PQ unit. In order to cater for Phase 2, and for simplified system development, a GPS module will be chosen that is suitable for both the PQ unit and the GS. To estimate GPS accuracy, a 1 degree variation is used (since the beamwidth of a typical antenna is an order of magnitude larger). A distance of $100\,\mathrm{km}$ therefore results in a required accuracy of $2 \times 100000 \times \pi \times \frac{1}{360} \approx 2\,\mathrm{km}$, which is very large.

The NEO line of GPS modules from *u-blox* are very commonly used, and are quoted to have a 2.5 m accuracy, however there was limited availability of these modules from local supplies (e.g. the *NEO-6M*). Modules with similiar specifications from *Makerbase* were therefore considered, such as the *ATGM336H* and the *ATGM332D*. Since both of these advertise 2.5 m accuracy, active antenna support, and current consumption less than 100 mA, the ATGM332D-5N31 was chosen for its lower price.

5.1.3 IMU

In order to cater for either the ”open-loop” or the ”closed-loop” method as mentioned in Section 4.3.3, the ground station PCB should be designed such that either method can be implemented. This will allow for their performance to be contrasted if necessary.

To determine absolute azimuthal rotation, the ground station (either the base or the platform) should either be manually positioned to face north, or a magnetometer can be used. As seen in Section 5.1.2, only very primitive, low accuracy is required. *Sensor fusion* is the mathematical process of converting raw sensor data into meaningful orientation angles. This is critical for fast-moving systems, where the accelerometer suffers during fast movements, and the gyroscope suffers due to noise drift over time.

The *BNO055* is a 9-axis IMU which integrates an ARM Cortex-M0 to perform sensor fusion. It operates at 100 Hz, has 0.3 µT magnetic field resolution, and around 16 bit sensors. It, however, is very expensive (around R800). The *MPU-9250*, and the *MPU* line of IMU's in general, are seen as cheaper alternatives. Since the grouond station will be moving slowly, there is low requirement for complex sensor fusion algorithms. Since the MPU also has a 16-bit accelerometer, and only slightly lower magnetic field accuracy (0.6 µT), but is only around R150, it was selected.

5.1.4 RF Communication

The transciever for both the custom and proprietary protocol needs to be considered. There are a few options in this regard, listed from more to less specialized:

- Fully custom design. Here, all components are discretely designed using transistors, MCUs etc.
- Front-End Module (FEM). For this option, the FEM provides filters, a low-noise amplifier (LNA), antenna matching, and down-conversion. Then, a controller (e.g. FPGA or MCU) needs to be designed to perform modulation/demodulation functionality (the *modem*) and interface with the FEM.
- Dedicated Transciever. A transciever provides both the FEM functionality and the software modulation, however still requires RF techniques for matching, as well as an additional RF shield.
- Dedicated module. For this option, all functionality is provided in a dedicated modulate with an antenna and MCU interface. This is the easiest, but has little flexibility (e.g. since all matching is done internally, the frequency band is constrained).
- Software-defined radio. This is the most general option which are extremely general-purpose, but do not exercise the highest performance. They often can be connected to a computer via USB.

Custom Communication

For the custom protocol, a dedicated RF module will be used. Unfortunately, few modules exist that support 405 MHz for the proprietary protocol, meaning a dedicated module would be needed. The module for custom communication will therefore be chosen to be as close as possible in frequency to 405 MHz.

LoRa will be used, however since this technology is relatively new, GFSK will be used as a secondary technique. This is relatively simple, as many LoRa modules also offer GFSK as an option. Table 5.1 contrasts the two most common modules in the 433 MHz LoRa band which offer this feature. Most modules available are based on *Semtech* chipsets due to the company's patent on the technology, and so there is little variation in performance. The RA-02 is ultimately selected due to its availability and cost.

Name	RX Sensitivity	TX Sensitivity	Frequency
RA-02	-141 dBm	+17 dBm	410 to 525 MHz
RFM98	-148 dBm	+20 dBm	410 to 525 MHz

Table 5.1

Proprietary Communication

Since the proprietary communication protocol will require reverse-engineering, and the exact encoding and GFSK parameters are unknown, SDR will be utilized to allow for flexibility. Universal Radio Hacker (URH) (https://github.com/jopohl/urh) is software available to investigate wireless protocols using an SDR. For this development, an easy-to-use USB SDR can be employed to investigate the protocol. The "RTLSDR" is considered the standard, low-cost solution for this.

5.1.5 Stepper Motor Driver

The original PCB of the previous antenna mount system contained two A3972 ICs to drive the stepper motors. Although these could be de-soldered and used, it is favourable to use a newer supported IC with better capabilities, and in case of damage. From the driver and motor datasheets, the following specifications are realized:

- Dual DMOS Full-Bridge Output Configuration
- Bipolar PWM current control
- Micro-stepping (for smoother stepping)
- 0.5A, 24V

Very few drivers fit these exact specifications. The *A4970* is considered the follow-up version of the *A3972*, however is not available in a single pack. The L6219 driver is found to match these specifications and is readily available from a local supplier, and so will be selected.

5.1.6 Power Distribution

Both a 3.3V regulator and 5V regulator will be needed for the ground station power distribution. For this, the LD1117V33C and L7805CP will be used due to availability. A boost converter will also be needed to achieve the 24V motor drive voltage. A breakout board based on the XL6009 IC will be used from a local supplier.

5.1.7 Microcontroller

As discussed later, a general-purpose MCU will be needed both on the GS and the PQ. The three most popular frameworks/MCU types for this the ESP32, Arduino, and STM32.

The *ESP32-WROOM-32* is a commonly available ESP32 variant which has 32 GPIO pins, of which several can be used as an ADC input, SPI or I2C interface. This means that there are 23x GPIO available, enough for this project. Further, the ESP32 has the added benefit of WiFi and Bluetooth connectivity, which may allow “smart” features to be added to either devices in the future. The *ATMEGA328PB* is an MCU commonly used in small Arduino boards. It, however, has fewer pins than the ESP, and is also an 8-bit MCU, as opposed to the 32-bit ESP. It does, however, allow a supply voltage of as low as 1.8V. Finally, the common *STM32F411* MCU is a high-performance, ARM-Cortex board with highly accurate ADCs, up to 81 GPIOs, and a fast internal FPU.

Since the processing requirements for this project are not very high, and the ESP32 is a relatively high-performance MCU which satisfies the pin requirements and has added smart capabilities, it will be selected for the GS. For the PQ unit, an ATMEGA328PB will be used, due to its exceptionally low current consumption, and many fewer pins being needed for the PQ unit.

5.1.8 RS-485 Driver

Most RS-485 drivers come in a common 8-pin form factor. Due to having very little requirements (i.e. short range, no speed specifications) the *SN75179BDR* is selected due to its availability from local suppliers.

5.2 Ground Station PCB

5.2.1 Circuit Design

Since the ground station mainly consists of various sub-systems and components, ”typical application” circuits found in component datasheets were mostly employed. The final schematic is found in Appendix B.

Power

Current calculations should be done to ensure that the voltage regulators and the boost converters can provide enough power where necessary. A car socket can supply up to 10 A at +12 V (i.e. 120 W). The supply voltage, current consumption, and power consumption of the various system components is listed in Table 5.2. In all cases, maximum current is provided.

Component	Voltage	Current	Power
Motors	24 V	0.5 A (x4)	48 W
ESP32 Dev Board	5 V	120 mA	660 mW
RA-02	3.3 V	100 mA	330 mW
ATGM332D-5N31	3.3 V	25 mA	82.5 mW
MPU-9250	3.3 V	3.7 mA	12.21 mW

Table 5.2: Ground Station Component Power Consumption

Therefore, maximum consumption - even at full motor current draw - is only 50 W, and will not place heavy load on the car socket battery supply. The 3.3 V regulator should be able to supply around 130 mA, and the 5 V regulator around $120\,\text{mA} + (130\,\text{mA} \times \frac{3.3\,\text{V}}{5\,\text{V}}) \approx 210\,\text{mA}$. The LD1117CV can supply up to 800 mA, and the L7805CP up to 1.5 A, meaning the limitations are met.

The power section also includes selector jumpers to isolate it from the rest of the board. In this way, if a component is damaged during implementation, or if the power section is found to not be working, external power can be supplied appropriately.

Motor Drivers

The L6219 drivers require a reference voltage to set the maximum current. According to the datasheet [30], a peak current of $I_{max} = 10 \times \frac{V_{ref}}{R_s}$ in mA is used. Since the recommended value of $R_s = 1\,\Omega$ is being used, $I_{max} = 10 \times V_{ref}$ mA. Since the motors allow up to 500 mA per winding, a current value of $I_{max} = 475\,\text{mA}$ is chosen to prevent damaging the motors. Therefore, $V_{ref} = 4.75\,\text{V}$. This can be implemented with a voltage divider. Setting the upper resistor $R_1 = 1\,\text{k}\Omega$ results in $R_2 \approx 20\,\text{k}\Omega$, as shown in the schematic. The disadvantage of this method is that the maximum current cannot be controlled dynamically. The reference voltage can be replaced with a DAC from the MCU if more control is required.

Connectors

The RA-02 RF module states that not all data pins are necessary. A connector is provided for unused GPIO pins, the SPI, and the unused RF module pins, to allow for flexibility once the PCB is manufactured.

5.2.2 PCB Design

Stackup

A 2-layer stackup was decided on, so that the board could be manufactured in-house early on in the project (as the in-house PCB machine has a 2-layer limitation).

Final Design

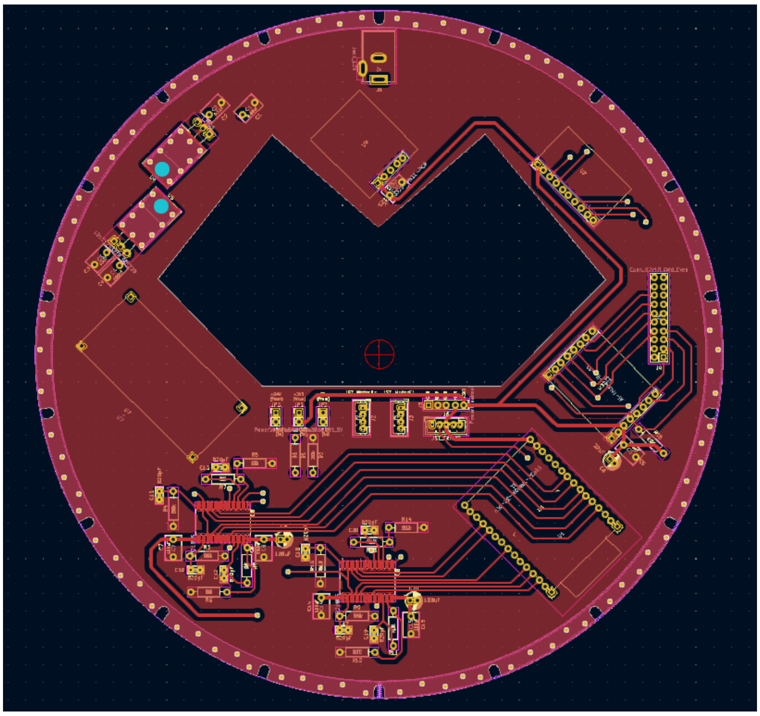

Figure 5.1: Ground Station PCB Design

The final PCB was designed in KiCAD. It was designed to have a compatible form factor as the previous antenna mount PCB i.e. with a 198 mm outer diameter, outer mounting holes, and holes for the stepper motors. The front layer of this design is shown in Figure 5.1. Female headers were used for most of the modules, since development boards were being used. Two PCB pours were exposed below the voltage regulators for added heat dissipation.

5.3 PocketQube Unit

5.3.1 Circuit Design

To design the PocketQube PCB, since no development boards were used, the Arduino Nano schematic in [31] was consulted as a reference design. It was decided to simply expose the relevant pins needed to flash the MCU, instead of integrating a USB connection directly, however this could be added for future iterations. The final circuit schematic can be found in Appendix C.

Power

The maximum power consumptions of the on-board components is found in Table 5.3. Since the power is provided by an external source, this is simply calculator as a figure of merit, and to allow for sizing of a battery for development purposes. Again, maximum current values are listed. A total maximum power consumption of around 600 mW is calculated.

Component	Current	Power (@ 3V3)
ATmega328	0.2 mA	0.66 mW
RA-02	100 mA	330 mW
ATGM332D-5N31	25 mA	82.5 mW
SN75179B	57 mA	188 mW

Table 5.3: PocketQube Unit Component Power Consumption

RF

Since the RA-02 RF module has a U.FL connector onboard, no considerations need to be taken with respect to impedance matching at the interface between the module and the antenna feed. However, the ATGM332D GPS module directly exposes its RF input via one of its SMD pins, meaning impedance matching may need to be done.

The higher L1 GPS band operates around 1575.42 MHz, which is a wavelength of $\frac{3e8}{1575.42e6} = 190\,\text{mm}$. As discussed in 3.5.5, the critical length is therefore around 19 mm. Since this is relatively large, if the trace length between the module and antenna interface is kept short than this, impedance matching will not strictly be necessary.

5.3.2 PCB Design

Stackup

It was decided to use a 2-layer board, due to the low component count. Although the impedance matching is not necessary for the GPS module, it is still desirable to control the trace impedance as much as possible. However, a 50-ohm trace on a 2-layer board is around

2.8 mm (determined using a microstrip impedance calculator), which is much larger than the pad sizes of the GPS module. Therefore, the trace was simply made as large and as short as possible.

Final Design

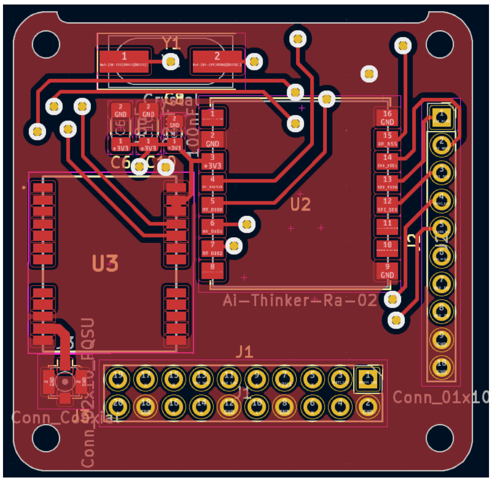

Figure 5.2: PocketQube Unit PCB Design (Front)

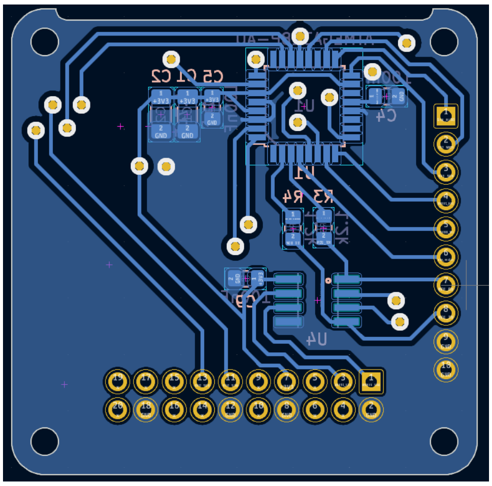

Figure 5.3: PocketQube Unit PCB Design (Back)

The final PCB was designed to conform to the PocketQube standard, as shown in Figures 5.2 and 5.3.

5.4 Link Budget

The link budget should now be conducted, as well as initial considerations for the ground station geo-location. This location will affect the range of elevation angles to accomodate, the distance to the horizon, as well as the free-space path loss.

If it is acceptable to estabilish the link a few minutes after the launch, Signal Hill in Cape Town is a viable location for the ground station, and is easily accessible. At its height of 350 m, communication with the balloon would move be available after the ballon reaches an altitude of 650 m. A maximum elevation angle of 13.5○ (to Worcester) should therefore be considered.

If communication with the satellite from the beginning of launch is necessary (e.g. for direct GPS tracking), then the ground station would need to be raised above sea level. Considering Cape Town as a location would require a height of around 1 km (measured to Saldanha Airfield), which is mostly impractical, unless accessibility into Table Mountain is granted. Therefore, a location scout would need to be conducted closer to the launch site. At 200 m altitude, the site could be up to 50 km away from launch. In this case, a maximum elevation angle of between 25○ and 30○ will need to be considered.

The *receiver sensitivity* is a value which denotes the minimum power level required at the receiver for successful communication. Depending on set parameters, the SX1278 quotes varying receiver sensitivity values. Notable configurations are listed in Table 5.4.

Description	Modulation	Parameters	Bit Rate	Sensitivity
Maximum Bit Rate	GFSK	62.5 kHz	250 000 bps	-92 dBm
High Bit Rate	GFSK	40 kHz	38400 bps	-109 dBm
Target Bit Rate ($\approx 9600 bps$)	GFSK	5 kHz	4800 bps	-115 dBm
-	LoRa	500 kHz, SF 8	10417 bps	-119 dBm
Maximum Sensitivity	LoRa	62.5 kHz, SF 12	24 bps	-147 dBm

Table 5.4: Notable SX1278 Configurations

The software mentioned in Section 3.3.2 was used to compute attenuation effects in the link budget, with Saldanha Airfield as the satellite location, and Signal Hill as the ground station location. All calculations were based on the RA-02's internal SX1278 chip and its specifications, half-wavelength dipoles as antennas, and worst-case impedance mismatch loss of 1.2 dBi (a VSWR 3:1, taken from the SX1278 datasheet). Then, the resultant margin will be analysed, and an appropriate directive antenna will be designed for the ground station to allow for increased margin and performance. The LoRa ”target bit rate” sensitivity value of -119 dBm is used in this budget.

Transmitter Power	17 dBm
Mismatch Loss	(1.2 dBi)
Transmission Line Loss	(0.1 dB)
Antenna Gain	2.15 dB
EIRP	**17.85 dBm**

Table 5.5: Link Budget - Satellite

Free space path loss (110 km)	125.9 dB
Atmospheric loss	0.22 dB
Scintillation loss	0.37 dB
Polarization Mismatch	3 dB
Total Loss	**129.49 dB**

Table 5.6: Link Budget - Channel

Antenna Gain	2.15 dBi
Transmission Line Loss	(0.1 dB)
Mismatch Loss	(1.2 dB)
Receiver Sensitivity	119 dBm
GS Sensitivity	**119.85 dBm**

Table 5.7: Link Budget - Ground Station

The final link budget therefore results in 17.85 dBm - 129.49 dB + 119.85 dBm = 8.21 dB of link margin. Although this is theoretically adequate, there are a few considerations to be made:

- The application note in [32] suggests a minimum link margin of 10 dB. It also further suggests a margin of above 20 dB for critical links.
- If a higher bit rate is required, e.g. 38.4 kbps, then the margin drops to -1.79 dB.
- If a longer range (e.g. for future projects) is required, free space path loss will drastically increase. For example, for a 250 km range, the loss becomes 133 dB, meaning the margin drops to only 1.11 dB.

To achieve the 10 dB recommended margin, an antenna with at least 1.79 dB additional gain (i.e. 3.94 dBi total) should be designed for the ground station. Then, if necessary, the 20 dB recommendation can be reached by lowering the bit rate.

5.5 Ground Station Antenna

5.5.1 Mechanical Considerations

The existing antennna mount is shown in Figure 4.4. Azimuthal and elevation stepper motors are connected directly through Gear A and B respectively. Gear A rotates the centre shaft to provide azimuthal steering, whereas Gear B rotates through Gear D and E to allow a change in elevation. The specifications in Table 5.8 were realized.

Component	Specification
Motor	200 full steps (per 360 degrees)
Gear A	15 teeth
Gear B	20 teeth
Gear C	60 teeth
Gear D	92 inner teeth, 80 outer teeth
Gear E	140 teeth (equivalent)

Table 5.8: Mount Component Specifications

The black plastic platform is triangular and has three mounting holes. The new ground station's antenna should therefore be mounted onto this platform. It is important to consider the forces/torques involved, as well as the stepper motor holding torques, in order to determine the maximum weight and acceptable form factor of the new antenna.

The azimuthal motor need not be considered, as all torques from the mount to its base are perpendicular to the central shaft, meaning it would only need to overcome static frictional forces to rotate the antenna, which are assumed to be negligible. The holding torque of the elevation motor, however, will constrain the antenna design. The holding torque of each motor is 0.25 Nm. The gearing ratio resulting from Gears B, D and E, results in an around 8x torque increase. This provides a holding torque of around 2 Nm at the pivot axle.

The centre of gravity of the antenna, as well as its weight, will affect the motor's ability to hold it in place. The horizontal distance between the pivot axle and the mount in the upright position is measured to be 40mm. Therefore, in the worst-case (when the mount is upright as in Figure 4.4) a planar antenna could weigh up to $\frac{2}{(9.8 \times 0.04)} = 5.1\,\text{kg}$. In general, the "mass-distance" product of the antenna (mass times distance of centre of gravity from mount) should not be more than $0.2\,\text{kg} \cdot \text{m}$. This should be strongly considered if a longer antenna is desired.

The physical dimensions of the antenna's ground plane is also constrained. If the mount's is raised adequately, the constraint will be imposed by the when the ground plane first makes contact with the mount's base. For a circular ground plane, this is around 360 mm diameter.

5.5.2 Theoretical Design

As discussed, the antenna should be capable of receiving from both the 405 MHz proprietary protocol, as well as the custom LoRa-based protocol in the amateur radio band of 430 to 440 MHz. A helical antenna is suggested, for the following reasons:

- Ability to increase gain arbitrarily by increasing the number of windings
- High fractional bandwidth of 56%, which may allow for a smaller antenna than other antenna types
- Ease of manufacture

The centre frequency f_c of the antenna should first be selected. With a fractional bandwidth of 56%, the inequality $f_c \times (1 - \frac{0.56}{2}) < 405\,\text{MHz}$ must hold. This gives an upper bound on the centre frequency of 562.5 MHz. A minimum ground plane diameter of no smaller than 0.5λ is recommended in [14], and 0.75λ into [33]. It is, however, probable that a ground plane as small as 0.5λ will adversely affect the radiation pattern near the end of the specified bandwidth.

Assuming the larger ground plane recommendation, the resulting ground plane diameter is $0.75 \times \frac{3e8}{562.5e6} = 400\,\text{mm}$, which is larger than the mechanical size constraint. Neverthless, $f_c = 550\,\text{MHz}$ is chosen as the initial centre frequency for simulations. Then, the ground plane should be decreased in size appropriately (towards $G_\lambda = 0.5$ i.e. $270\,\text{mm}$).

The design parameters for a helical antenna are f_c (centre frequency), n (number of turns), S (the spacing between turns), C (the circumference) and G (the ground plane diameter). Design formulae are provided in [14], and have been modified below to use relative values instead of absolute ones (i.e. S_λ and C_λ instead of S and C). Directivity, in dBi, is given by:

$$D_0 = 10\log(15 \cdot nS_\lambda \cdot C_\lambda)$$

C_λ is typically kept at 1.0, meaning the cirumference is equal to the operating wavelength. As mentioned, a gain of 4 dBi is required. However, a 3 dB bandwidth drop is estimated nearer to 400 MHz. Further, the effect of a smaller ground plane will likely decrease performance by an estimated minimum of at least 1 dB. Therefore, a centre-frequency gain of 8 dBi will be designed for. For this gain, the nS_λ product should equal around 0.45. Although the optimal value for S_λ is 0.23 [14], smaller values have been quoted to work [16] and are mechanically easier to construct. Therefore, choose $S_\lambda = 0.15$, and finally $n = 3$.

5.5.3 Simulation Design

Simulation of a helical antenna is well documented in literature, and therefore the parameters can be varied iteratively and integrated into the antenna design process. For this project, FEKO software is used. An initial model with the above parameters, a large ground plane ($G_\lambda \approx 1.0$), and a wire diameter of 2.5 mm (chosen due to availability) is simulated. The resulting radiation pattern at the centre frequency of $f = 550\,\text{MHz}$ is shown in Figure 5.4, with a maximum gain of around 9.5 dBi.

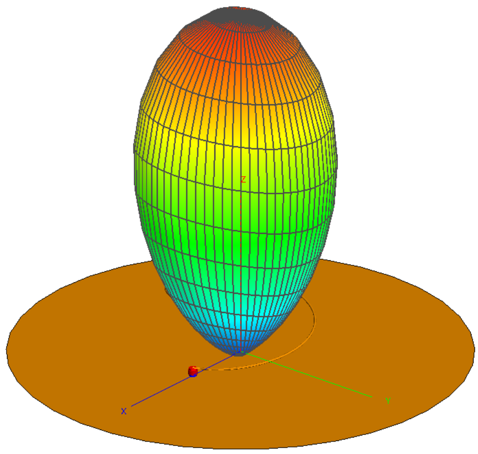

Figure 5.4: Initial Helical Antenna Radiation Pattern ($f = 550\,\text{MHz}$)

Most of the initial design is conducted around the lower frequency of $f = 405\,\text{MHz}$. The radiation patterns for $G_\lambda = 0.5$ and $G_\lambda = 0.7$ ($G = 273\,\text{mm}$ and $G = 382\,\text{mm}$) are shown in Figures 5.5 and 5.6 respectively. It is clear that the recommended value of $G_\lambda = 0.5$ from [14] will not work near this lower frequency, as shown by the morphed radiation pattern. The pattern is found to be acceptable at around $G_\lambda = 0.7$. However, after analysing the input impedance for this ground plane size (shown in Figure 5.7) it is clear that broadband matching would be difficult, due to the drastic change in impedance near the lower end of the spectrum.

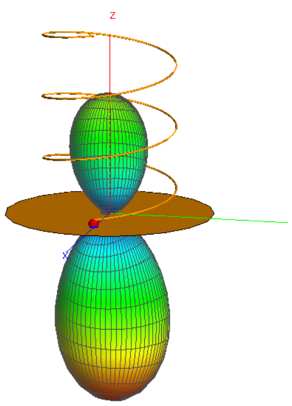

Figure 5.5: Helical Antenna Pattern at $f = 405\,\text{MHz}$ ($f_c = 550\,\text{MHz}$, $G_\lambda = 0.5$)

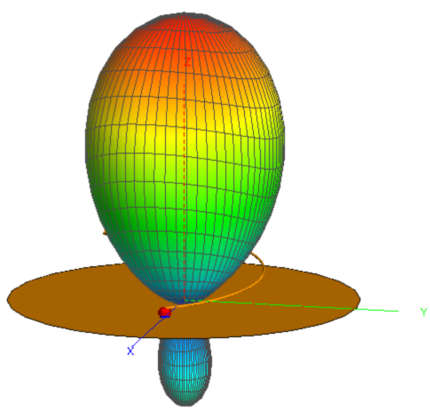

Figure 5.6: Helical Antenna Pattern at $f = 405\,\text{MHz}$ ($f_c = 550\,\text{MHz}$, $G_\lambda = 0.7$)

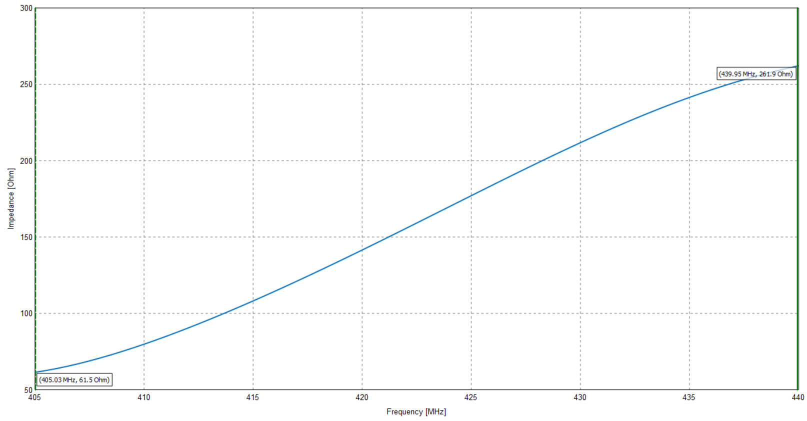

Figure 5.7: Helical Antenna Input Impedance ($f_c = 550\,\text{MHz}$, $G_\lambda = 0.7$)

The common amateur band frequency of 433 MHz is chosen for the LoRa communication link. In order to ease matching, a lower centre frequency should ideally be used, to move the input impedance at 405 MHz and at 433 MHz closer together. This will, however, require either a larger ground plane, or a cupped ground plane (discussed further on).

Unfortunately, FEKO does not allow for an optimization goal that depends on two frequencies. Therefore, an iterative approach was used to find the centre frequency which minimizes the difference between the two impedances. The resulting centre frequency was found to be around $f_c = 510\,\text{MHz}$ at $G_\lambda = 0.6$ ($\approx 350\,\text{mm}$), with a resultant input impedance close to $250\,\Omega$, as shown in Figure 5.8.

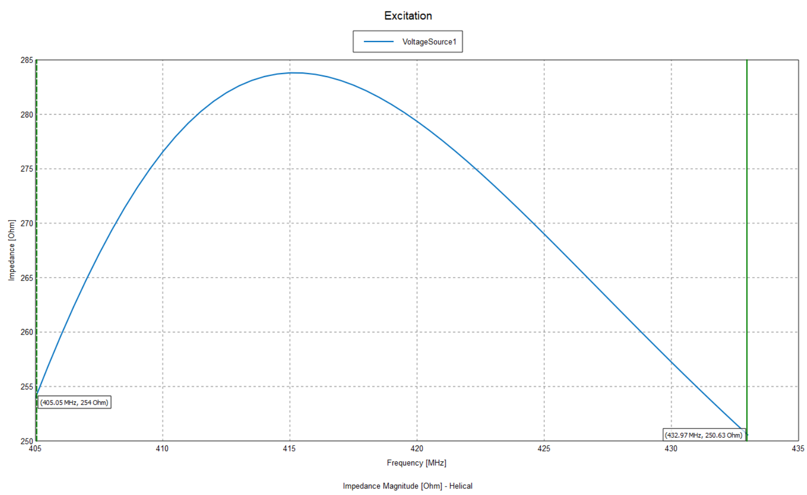

Figure 5.8: Helical Antenna Input Impedance ($f_c = 510\,\text{MHz}$, $G_\lambda = 0.6$)

Since the mount can support a larger weight than the 3 turn coil, it was decided to experiment with larger a turn count (i.e. $n = 4$), both for increased directivity/performance, and to potentially cater for manufacturing imperfections, such as a thin aluminium foil ground plane, and any diversions from the ideal helical shape. It was found that, for small ground plane diameters, the radiation pattern for $f = 405\,\text{MHz}$ was negatively affected as the number of turns increased. This is intuitive when referring to image theory, as the non-idealities due to the finitely-sized ground plane become more apparent as distance to the plane increases. It should be noted that the pattern at $f = 433\,\text{MHz}$ was not as badly affected.

The ground plane was therefore cupped, and the results observed. At $G_\lambda = 0.6$, a cup height equal to 1 helical turn was found to greatly improve the radiation pattern. This is shown in Figures 5.9 and 5.10.

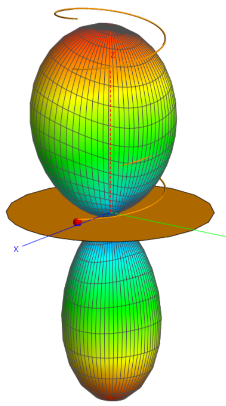

Figure 5.9: Helical Antenna Pattern without Cup ($G_\lambda = 0.6$, $f = 405\,\text{MHz}$)

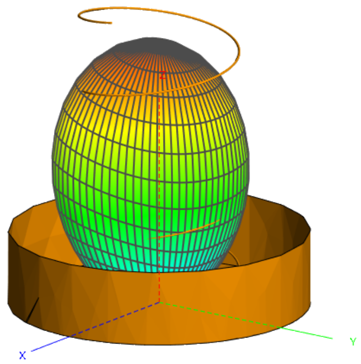

Figure 5.10: Helical Antenna Pattern with Cup ($G_\lambda = 0.6$, $f = 405\,\text{MHz}$)

It was therefore decided that the antenna would initially be built with a large ground plane and higher number of turns. Then, after measurement results and protocol implementation, the ground plane would be decreased appropriately to fit onto the mount. If time allows, a cup will then be added, to improve the pattern and antenna performance, and cater for the proprietary protocol. The final model parameters are then:

- $C_\lambda = 1.0 \therefore D = 187.1\,\text{mm}$
- $S_\lambda = 0.15 \therefore S = 88.2\,\text{mm}$
- $n = 4$
- $G_\lambda = 0.6 \therefore G = 350\,\text{mm}$

5.5.4 Matching

Impedance matching should be done if the helical antenna is to be fed by a $50\,\Omega$ coaxial cable. It was decided to match the antenna to the custom protocol's frequency of $f = 433\,\text{MHz}$ using the strip method mention in Section 3.2.2 for an uncupped ground plane. The FEKO model for this method is shown in Figure 5.11.

The strip is recommended to be relatively flat, and extend for approximately the first quarter turn. Its pitch angle was therefore chosen to be half that of the full helix, and it was chosen to extend for 0.15 turns. The unknown parameters for the strip are then its height above the ground plane (also the height of the coaxial pin), and its strip width. The FEKO optimizer was used to optimize these two parameters for a minimum return loss. The resulting

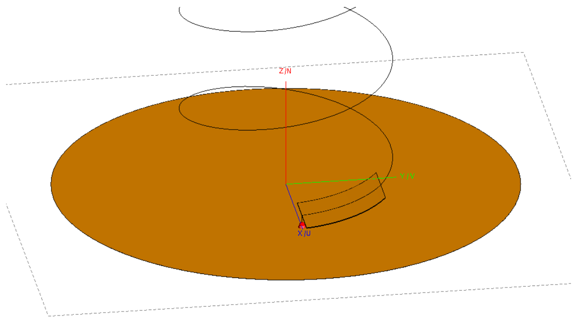

Figure 5.11: Helix Antenna Model with Matching Strip

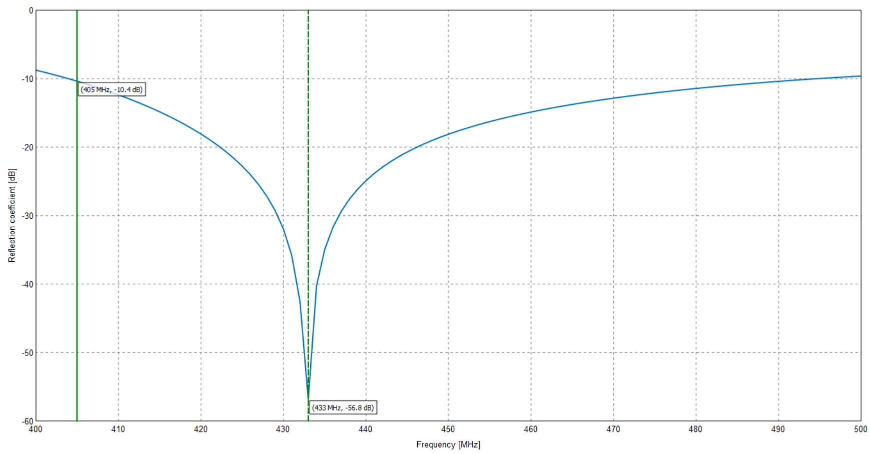

Figure 5.12: Helical Antenna Return Loss vs Frequency

return loss as a function of frequency is shown in Figure 5.12. The resultant mismatch loss is close to 0 dB at the target frequency, and 0.451 dB at 405 MHz.

The final antenna parameters are:

Parameter	Value
Diameter (D)	187.1 mm
Turn Spacing (S)	88.2 mm
No. of Turns (n)	4
Ground plane diameter (G)	> 350 mm
Strip height (sh)	19.4 mm
Strip width (sw)	77.7 mm
Strip length (sl)	13.2 mm
Cup height, if used (ch)	88.2 mm

Table 5.9: Helical Antenna Final Parameters

5.6 PocketQube Unit Antenna

5.6.1 Simulation Design and Matching

It was decided to use a simple half-wavelength dipole for the PQ unit, due to its omnidirectional radiation pattern and its extremely easy design and construction. The wavelength of interest is for the custom protocol i.e. $f = 433\,\text{MHz}$ or 693 mm. A simple 1.5 mm metal wire will be used due to its availability, with a small gap between the two sides of the dipole, and fed by a coaxial cable.

The design parameters for the dipole are L_λ (the total dipole length relative to lambda), F_{gap} (the gap distance of the feed), and F_{length}, the length of the feed. A fixed gap distance of $F_{\text{gap}} = 5\,\text{mm}$ is decided on, as it is assumed to not be critical if sufficiently small.

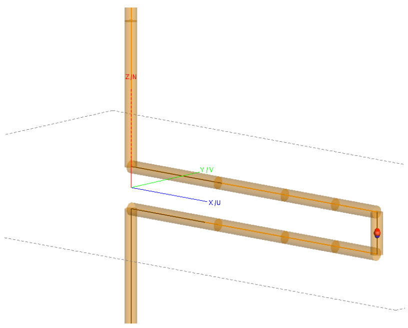

Figure 5.13: Dipole Model

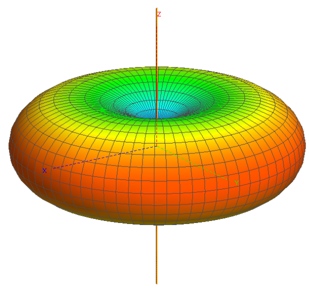

Figure 5.14: 0.45λ Dipole Radiation Pattern

The FEKO model in Figure 5.13 was used. The optimizer was used to calculate the optimal dipole length and feed length that would minimize the return loss for $f = 433\,\text{MHz}$ at a feed impedance of $50\,\Omega$. The resultant parameters are found to be $L_\lambda = 0.45$ ($L = 312\,\text{mm}$) and $F_{\text{length}} = 39.0\,\text{mm}$. The resultant radiation pattern of the dipole is shown in Figure 5.14, as well as the optimised return loss as a function of frequency in Figure 5.15.

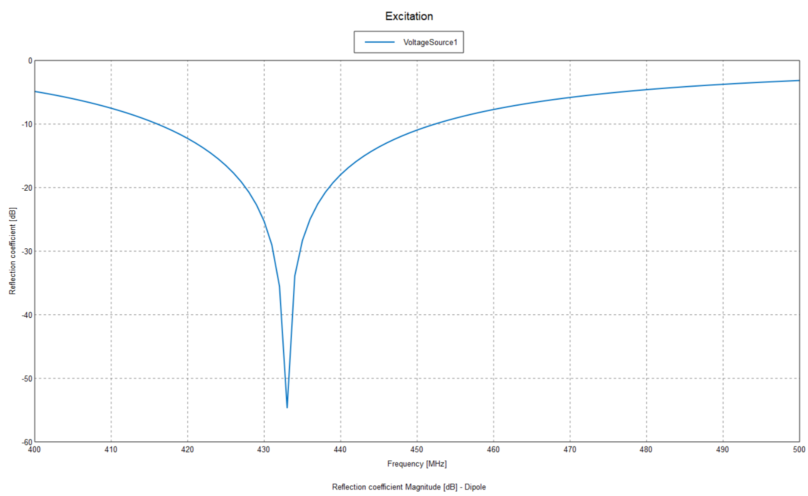

Figure 5.15: 0.45λ Dipole Return Loss vs Frequency

6. Conclusion

The conclusion

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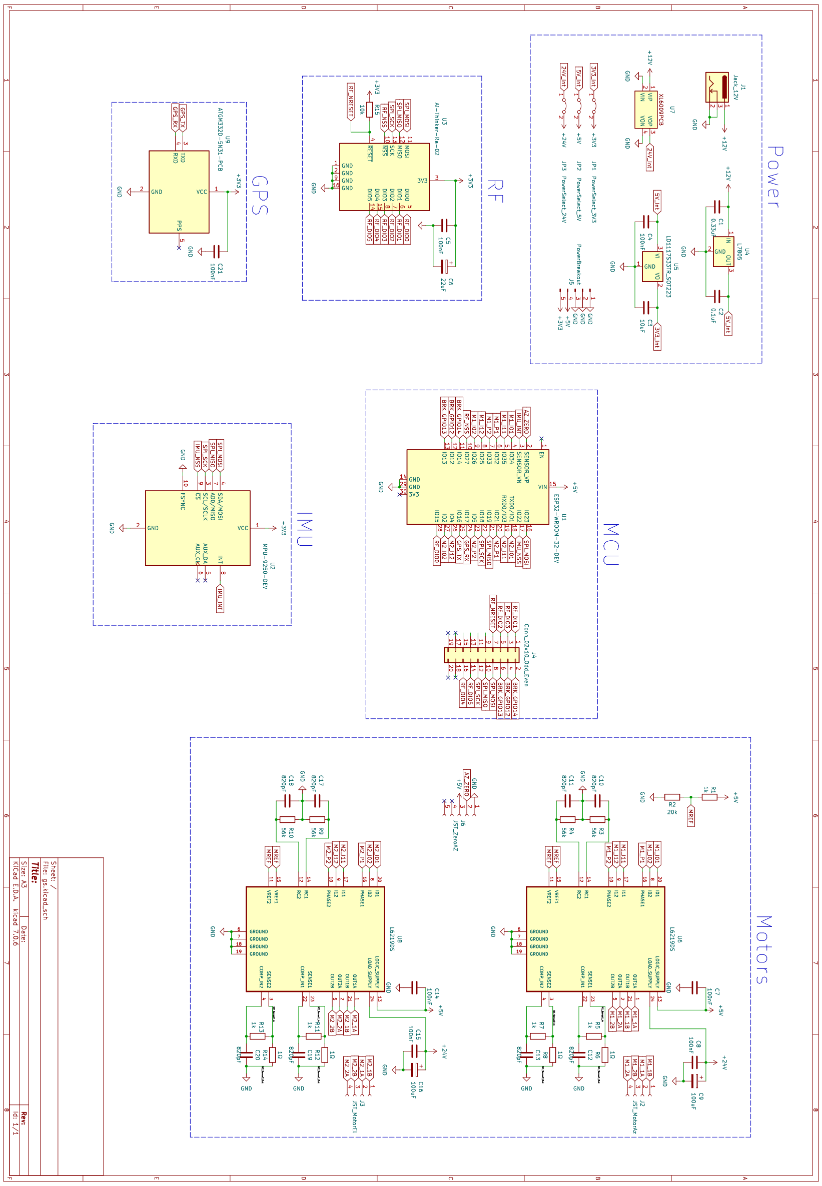
A. Appendix A

Week 01 (24/07 to 30/07): Problem formulation; requirements gathering Week 02 (31/07 to 06/08): Initial research; component selection Week 03 (07/08 to 13/08): System-level design; initial system layout; components ordered Week 04 (14/08 to 20/08): PCB design without traces; initial circuit design Week 05 (21/08 to 27/08): Component prototyping; Full PCB design; initial antenna design; Week 06 (28/08 to 03/09): Mechanical design; Custom protocol investigation; PCB ordered Week 07 (04/09 to 10/09): (Test week) Week 08 (11/09 to 17/09): Initial build Week 09 (18/09 to 24/09): Software design; initial testing Week 10 (25/09 to 01/10): Software design; debugging Week 11 (02/10 to 08/10): Reporting Week 12 (09/10 to 15/10): Design improvement Week 13 (16/10 to 22/10): Testing Week 14 (23/10 to 29/10): Reporting Week 15 (30/10 to 05/11):

B. Appendix B



C. Appendix C