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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

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.

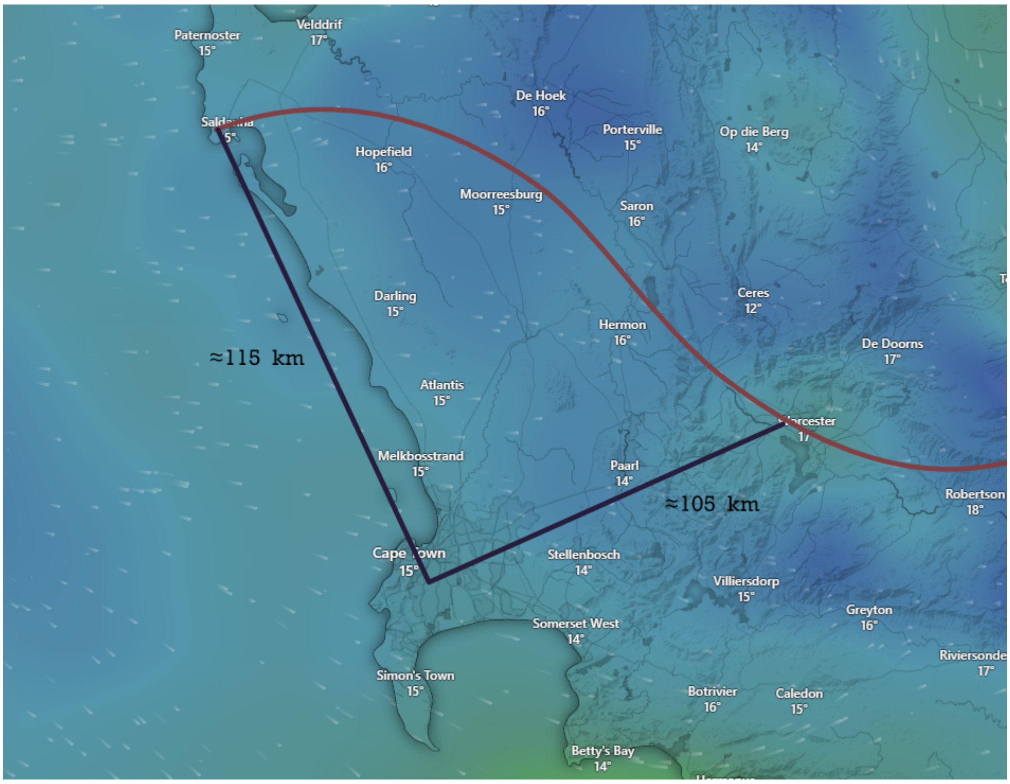

Figure 2.1: Balloon Path and Distances

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.

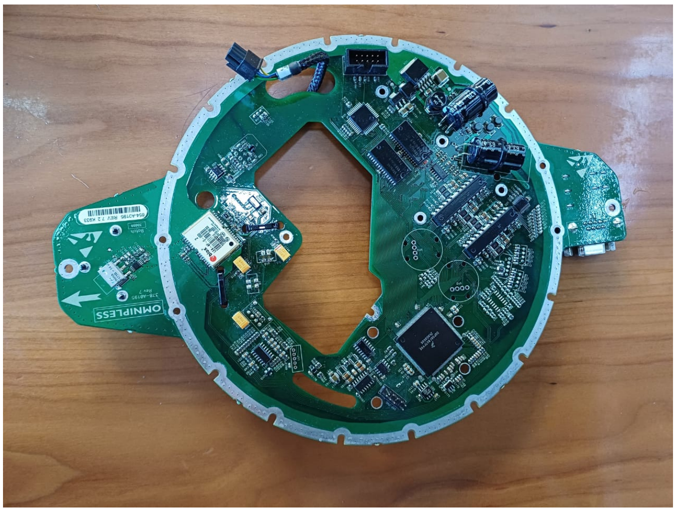

Figure 2.2: Existing Antenna Mount PCB

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.

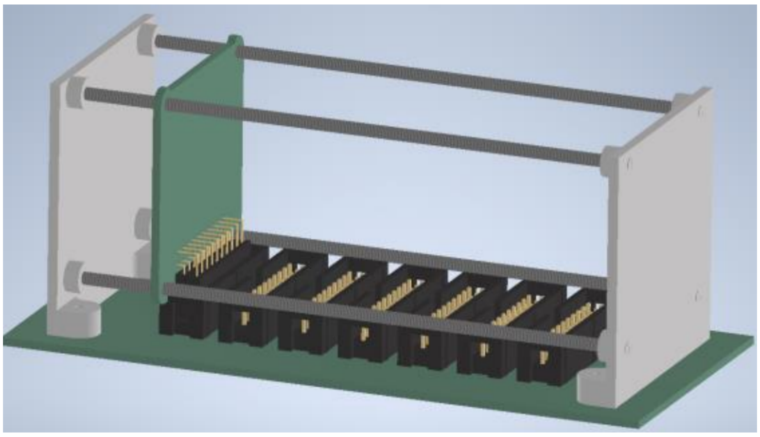

Figure 3.1: A PQSU Enclosure [1]

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

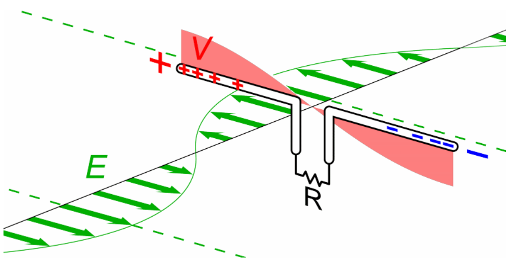

Figure 3.2: Dipole Antenna Illustration [2]

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

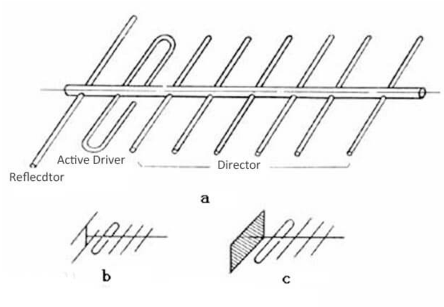

Figure 3.5: Yagi-Uda Antenna [3]

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

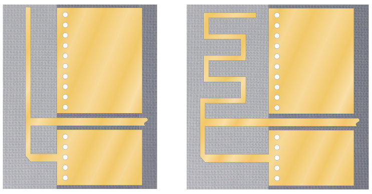

Figure 3.6: Inverted-F Microstrip Antennas [4]

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 Feeding

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 Ω 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. A few techniques for the most common 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 Ω and 0.44 Ω. [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 Ω 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	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. The following techniques are commonly used in satelllite communication:

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 [18].

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.

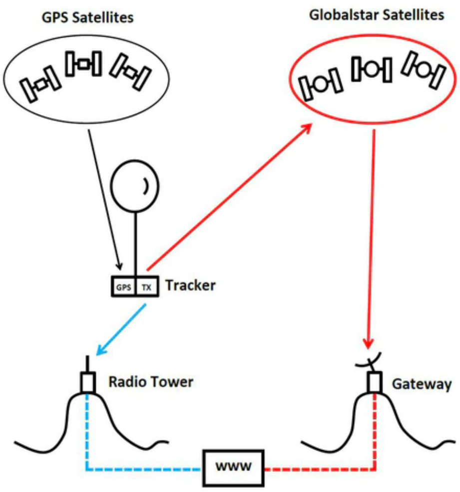

Figure 3.7: GPS Relay Tracking [5]

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

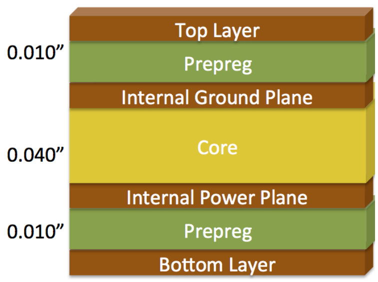

Figure 3.8: Common 4 Layer PCB Stackup [6]

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. [19]

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 [20]. *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 [21].

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 [22].
- If a high-frequency signal is to be routed on a trace, 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. [22]
- 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. [23]
- Apply curved bending or *mitering* when transmission lines are required to change direction abruptly. [23]

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).

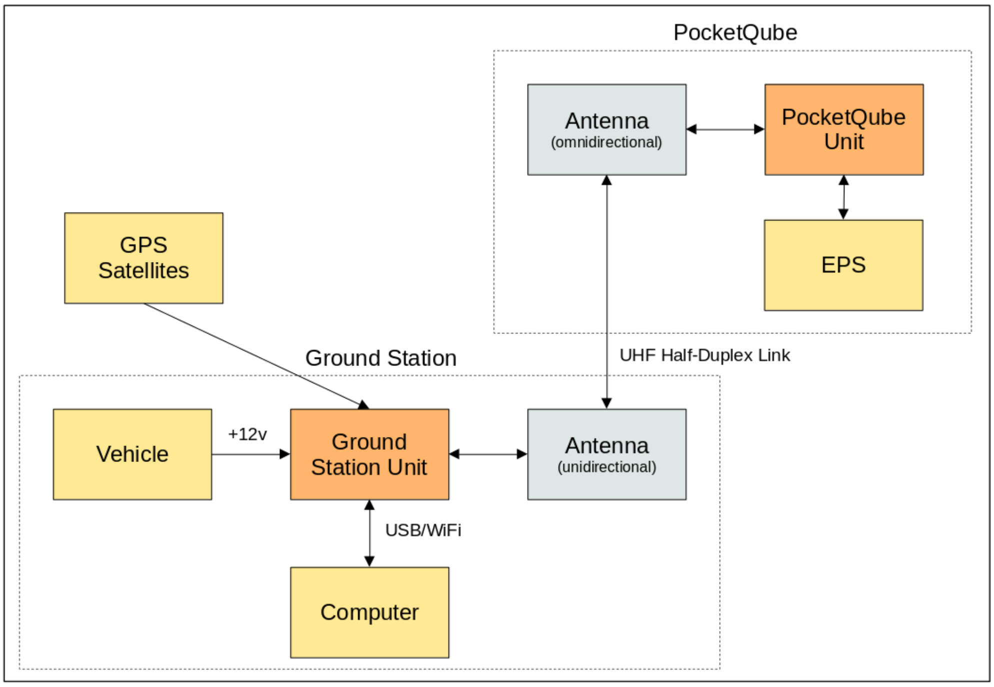

Figure 4.1: Complete High-Level Diagram of Communication System

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 know 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 intertial 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.

The modulation technique should be selected next. There are several common options to be considered: Gaussian Frequency-Shift Keying (GFSK) is commonly used in satellite links due to its amplitude noise immunity, low bandwidth and high throughput. LoRa (Long-Range) technology is a relatively new modulation technique which uses frequency-varying ”chirp” signals to provide ultra long-range communication, with a lower

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.

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, as there is little reason to separate the two process. Ideally, components should be readily available from local suppliers.

5.1.1 Existing Components

The ground station has a number components which will be used without modification. Two *NEMA 17 4218S-15* stepper motors will be used to ultimately steer the ground station (i.e. in elevation and azimuthal directions as shown in Figure 5.1). These motors draw 0.50 A and allow for up to $0.5\,\mathrm{N} \cdot \mathrm{m}$ of torque [24].

The ground station also includes a small zero-sensing circuit for the azimuthal direction, which integrates a *H22A* optical switch [25] and a low-pass filter.

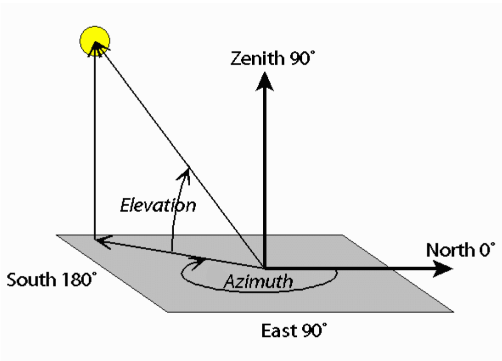

Figure 5.1: Azimuthal and Elevation Visualization [7]

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 km therefore results in a required accuracy of $2 \times 100000 \times \pi \times \frac{1}{360} \approx 2\,\text{km}$, 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

Generally, the ground station's orientation can be described by azimuthal and elevation angles as in Figure 5.1. The ground station requires absolute azimuth angle measurement data, as well as elevation angle/tilt data, in order to orientate itself with respect to its surroundings. To determine absolute azimuthal rotation, the ground station should either be manually positioned to face north, or a magnetometer can be used. An accelerometer can be used to determine tilt rotation.

The above sensors, as well as a gyroscope, are typically packaged into an *intertial measurement unit* (IMU). 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 $0.3\,\mu\text{T}$ 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 ($0.6\,\mu\text{T}$), but is only around R150, it was selected.

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):