Equine Diagnostic Applications of Real-Time Kinematics Precision GPS systems

Samriddhi Bhatia, Seth Cox, Boyun Wang

December 2023

Abstract

The study explores the potential of high-precision GPS systems in monitoring equine behaviour and providing insights into horse health. The research will address challenges in GPS system accuracy during horse movement by introducing Real-Time Kinematics (RTK) system. By recording positional data for extended periods of time we hope to discover abnormalities that could signify underlying health concerns in the animal. The study involves a GPS-RTK system with LoRa communication, tested for accuracy, and equipped with induction charging system to ensure weather resistance. The PCB design and assembly, along with housing considerations, are detailed for both the equine GPS rover and the base station. Additional testing is essential to assess the feasibility of the equipment and discuss the types of data most valuable for comprehending the horse behaviour.

1 Introduction

Horses have been one of the most important and versatile domesticated animals in human history. From transportation to agriculture to warfare to entertainment and more, no animal has the same resume as the horse. With this in mind, the need to continue developing new ways to monitor the health of these animals is evident. Our hope is to do this by using a high-precision GPS module to monitor the horse's positional data over large periods of time. Using this data we hope to be able to model and predict potential health issues before they become a large enough issue to endanger the life of the horse. In a paper from Herlin et Al, they show that such a system can have positive impacts on the health of an animal [1]. They used such a device to raise alarm when the animals' behavior deviated from the observed normal. We hope to replicate such as system. To do this we will be utilizing components provided to us by Sparkfun Electronics which include a GPS module capable of 1 cm precision. Significant care will go into the data collection and analysis so that we may learn as much as possible while also providing as little as possible discomfort for the horse.

2 Purpose & Background

The first system utilizing satellites to determine the position of something on the planet was the Global Positioning System (GPS) developed by the United States Department of Defense in the 1970s. Since then the GPS system has expanded rapidly adding more satellites and being made available for civilian use in the 1980s. Other systems have also been launched by other countries the main ones being the Global Navigation Satellite System (GLONASS) developed by the Soviet Union and operated by modern-day Russia, Galileo operated by the European Union, and BeiDou operated by China. Most modern-day systems that use 'GPS' signals to determine position actually use data from many of these global navigation satellite systems (GNSS) in order to have access to more satellites and therefore more accurate positioning.

GNSS satellites broadcast signals on two different frequencies denoted L_1 and L_2, which correspond to 1575.42 MHz and 1227.60 MHz respectively. A multi-band differential GPS system, such as the one described in this paper uses information from both bands to determine the location of the receiver. A GPS module calculates its range to the satellite through a process called trilateration. This is done by measuring the time difference between the time the signal leaves the satellite, which is contained in the message the satellite sends, and the time the signal arrives at the GPS module, which is calculated using the GPS module's internal clock. Using the speed of light as the speed of the carrier wave, finding the distance the wave traveled to arrive at the module with the time it took to get there is trivial. However, when accounting for error, it can be seen that this is not the true range. What is actually measured is the 'pseudorange' and is equal to the true range plus some offset that comes from the error. Error is introduced in this process in the form of atmospheric delays, specifically in the ionosphere and troposphere, satellite clock data, and error in the satellite ephemeral data [2]. This error can be mitigated through the use of a Real-Time Kinematic system (RTK). This system involves the use of a static base station with a known position that is used to generate correction messages under the Radio Technical Commission for Maritime Services (RTCM) protocol that are then sent to a rover system which will use the correction data to improve its own accuracy. An RTCM message typically contains the positional information for the base station, information about the errors in the pseudoranges of the signal, and information about the phase of the carrier wave. The base station calculates the phase difference via an algorithm known as double difference processing. This is done by calculating the difference in phase of the signals that reach the base station and the rover. We start by measuring the phase of the signal the base station receives from the satellite which can be equated to

$$\phi_{\text{base },i} = \frac{2\pi}{\lambda}\left[\rho_i - N_i\lambda + \epsilon_\phi + I_i - T_i + c\left(b_{\text{sat },i} - b_{\text{base }}\right)\right], \tag{1}$$

where $\rho_i = \sqrt{\left(x_{\text{base }} - x_{\text{sat },i}\right)^2 + \left(y_{\text{base }} - y_{\text{sat },i}\right)^2 + \left(z_{\text{base }} - z_{\text{sat },i}\right)^2}$, the distance from satellite i, ϵ_ϕ accounts for any noise originating from the system itself, I_i refers to the ionospheric error for satellite i, T_i refers to the tropospheric error for satellite i, c refers to the speed of light in m/s, $b_{sat,i/base}$ refers to the clock biases of both the base station and satellite i, λ refers to the wavelength of the signal and N_i refers to the integer ambiguity of the signal from satellite i. The values for x, y, and z used to calculate ρ are the system's coordinates in the ECEF coordinate system which calculates the position in terms of the center of mass of the Earth. The phase of the carrier signal is measured for 2 satellites and is then sent to the rover system which also takes a phase measurement for those same two satellites. The rover then finds the difference between the phase measurements as,

$$\Delta\Phi = \frac{2\pi}{\lambda}\left(\rho_{rec,1} - \rho_{base,1} - \rho_{rec,2} + \rho_{base,2} - \lambda\left(N_{rec,1} - N_{base,1} - N_{rec,2} + N_{base,2}\right)\right), \tag{2}$$

where ρ refers to the distance from the satellite to the receiver/base station, λ refers to the wavelength of the signal N refers to the integer ambiguity of the wavelength which must be solved in order to determine the relative position of the rover. The integer subscript refers to which satellite the signal originated from. Equations 1 and 2 are adapted from an article by Mauricio Andrada [3]. ρ for the receiver is the pseudorange and for the base station it is the true range. This process assumes that the base station and rover are sufficiently close together so that the error from ionospheric and tropospheric refraction, satellite clock differences, and satellite ephemeral data errors are all the same for both systems and therefore are removed in this calculation. Once the rover gets to this point it enters what is known as floating mode, where it tries to solve the integer ambiguities. Since we know the base station's position exactly (or as close to exactly as possible) once we determine the integer ambiguities we can then determine the rover's relative position to the base station from the phase difference. This is a simplified explanation of how the RTK algorithm works; Yanming Feng and Jinling Wang describe a more complicated version in their paper which involves other variables in the calculation such as the noise of the signal however the result being the need to calculate the integer ambiguities to determine the relative position between the base station and the rover is the same [4]. To solve these ambiguities the system must take data for a sufficiently long enough time to perform a statistical analysis of the parameters to produce the correct values. Methods for this include the Least-squares ambiguity decorrelation adjustment (LAMBDA) method and the Minima Search (LMS) method. It is during this process that the rover uses the data the base station took about the error estimation between the pseudorange and range for the base station. The efficiency of an RTK system to solve these ambiguities is one of the most important aspects of the quality of the device. Once the rover solves these ambiguities it enters fixed mode and has a significantly higher positional accuracy compared to a standard GPS system. This process can also be done in post-processing instead of in real-time for higher accuracy however for the purpose described above real-time calculations are preferred.

Building upon this technical foundation, we delve into the potential of GPS technology to not only monitor equine movements but also provide valuable insights into the health and well-being of horses, bridging the gap between technology and equine management strategies.

While the exploration of equine behaviors through daily movements has been relatively limited, existing studies have shed light on the potential consequences of sedentary lifestyles in domesticated horses when compared to their feral counterparts [5]. This sedentary behavior may contribute to various health concerns and issues related to hoof quality, particularly due to restricted movement within paddocks or stables from an early age. Furthermore, investigations into racehorses employing GPS units have highlighted their effectiveness in providing precise measures of daily workload, offering valuable insights into horse training and its connection to injuries [6]. Understanding the correlation between GPS-monitored movement and injury risk could potentially lead to strategies for preventing injuries in equine management.

The utilization of GPS technology has become widespread in the equine industry for assessing various facets of performance, including exercise and competition speed, behavior and locomotion, as well as overall fitness [7].

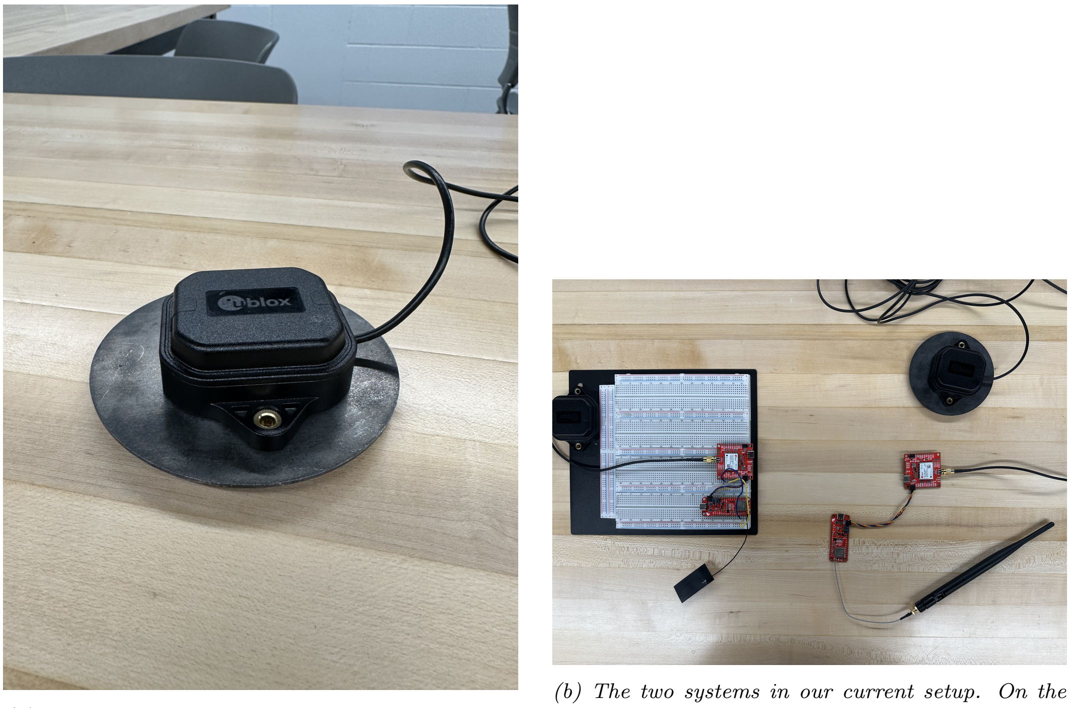
In parallel, the historical evolution of equine behavior analysis from the 1870s, often referred to as the "golden age" of equine gait analysis initiated by Muybridge and Marey, has progressed to the point where age, disease, injury, and fatigue can be detected through the analysis of health changes and sport performance [8]. The incorporation of Inertial Measurement Units (IMUs) has played a pivotal role in objective gait measurements, demonstrating effectiveness in identifying gait abnormalities and alerting owners to lameness and other diseases [9].

Recognizing the potential synergies between GPS monitoring and IMU systems, the integration of these technologies could offer a comprehensive solution for detecting behavioral changes and pasture usage in horses. By combining the strengths of both systems, there is potential for enhanced accuracy, reduced costs, and increased accessibility. This integration becomes particularly pertinent in addressing the overarching question: How can the use of a GPS collar indicate behavioral changes in horses?

The experiment will explore the hypothesis that GPS monitors can effectively identify nuanced movements associated with specific behaviors, enabling the detection of irregularities that may signify underlying health issues or environmental concerns within the pasture. Importantly, this research also recognizes the potential of these systems in monitoring a horse's behavior during recovery from illness. The ability to track the horse's movements and behavior post-illness will provide valuable data for assessing the effectiveness of recovery strategies and ensuring the well-being of the horse as it returns to its normal activities.

3 Experimental Setup

Our system involves two GPS-RTK-SMA Breakout boards provided by Sparkfun Electronics which include a u-blox ZED-F9P differential GPS system capable of producing and handling the RTCM messages needed for RTK fixing. These boards are specified to have a 1 cm horizontal accuracy when using the RTK system [10]. One board is used to set up the base station, which will stay in a static position, and one is used as the rover, which will eventually go on the horse. Connected to each of these boards is one LoRa Thing Plus - expLoRaBLE board also provided by Sparkfun Electronics. These boards are equipped with an NM180100 system from Northern Mechanics and a Semtech SX1262 LoRa transceiver. This allows us to communicate with each device over the LoRa frequency band ($902 - 928$ MHz in the U.S.). With this, the base station will produce the RTCM messages needed for RTK and transmit them over LoRa for the rover to receive. Each GPS board has an ANN-MB-00 GNSS multiband antenna which is capable of receiving both the L_1 and L_2 frequency bands. This antenna also has the advantage of being intrinsically waterproof, giving it much more flexibility in its mounting. Included with this antennae is a metal grounding plate which, due to its weight, will be subject to tests to determine whether it is necessary for our system. These tests will be done by measuring the accuracy of the system with and without the grounding plate. The antenna with its grounding plate can be seen in **Figure 1a**



(a) ANN-MB-00 GNSS multiband antenna. Note the steel grounding plate. This adds approximately 0.4211 lbs *to the system*

(b) The two systems in our current setup. On the left is the rover and on the right is the base station. Note the extra connection over the serial port on the rover.

Figure 1: Experimental Setup

The GPS board and the LoRa Thing Plus are connected via i2c for both the base station and the rover, with the rover having an additional connection via the serial port for piping the incoming RTCM messages over to the GPS module. Controlling each system will be done via the Arduino IDE where we use the library that Sparkfun provides for the GPS board, and the RadioLib library developed by Jan Gromeš to control the LoRa communication [11].

For preliminary tests, the base station will be used in 'Survey-In mode' where it determines its own position over a period of 1-2 minutes and then starts relaying RTCM messages. The system is able to transmit up to 256 length byte arrays at a time, which should be enough for most RTCM messages. As a fail-safe, the code constructs a byte array of the RTCM data and sends the full array when either the next message starts, or the maximum array size is reached. The receiving code is able to dynamically adjust for the difference in received byte arrays. Once an RTCM message is received it is then sent to the GPS module for processing. Our current setup can be seen in **Figure 1b**. For later tests and to achieve the highest possible positional accuracy, the base station will be placed on the roof of the Loomis Laboratory of Physics to maintain a clear view of the sky as well as to remain undisturbed. Once on the roof, the base station will collect data for up to 24 hours where the data will then be post-processed to obtain millimeter accuracy coordinates for the antenna. Post-processing is handled by the Canadian Spatial Reference System Precise Point Positioning Service. Once the permanent base station is installed, further tests into the accuracy and range of the measurements can be done. The base station will require its own computer to monitor the system and provide power. Each system requires 3.3 V of power so for the base station this will come directly from the computer the system is hooked up to. Since the base station will be on the roof of Loomis, which is not free to access for the public, this computer will be accessed via Window's Remote Access feature so in the event the code controlling the base station needs to be changed, we will be free to do so. The rover will be powered via battery and charged via an induction system to ensure our ability to make the rover waterproof while on the horse.

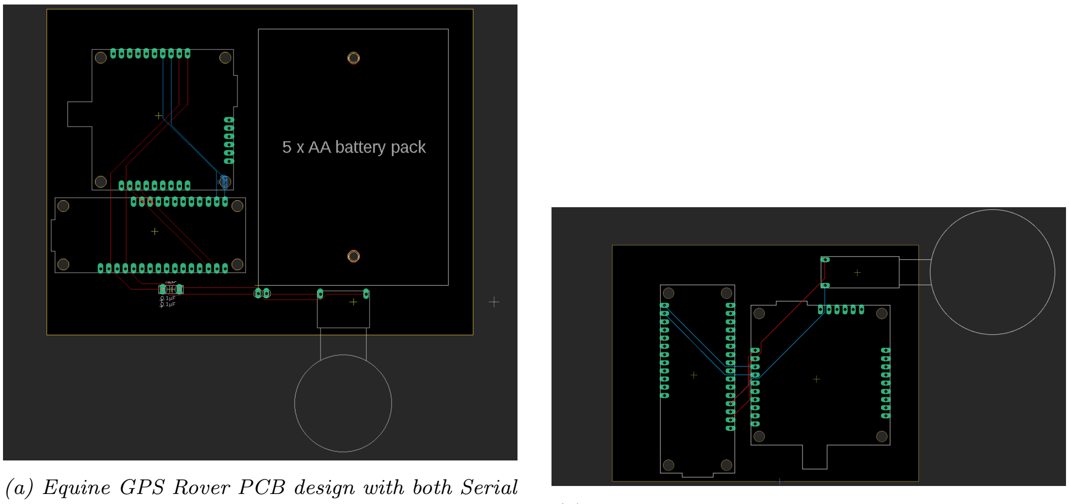
Another thing that we will test will be the range of the radio antenna used to communicate between the base station and the rover. The antenna that will be tested is the Wide Band 4G LTE Internal LoRa Antenna provided by Sparkfun Electronics, shown in **Figure 2**.

Figure 2: Wide Band 4G LTE Internal LoRa Antenna, image adapted from Sparkfun's product page [12].

4 PCB Design

4.1 Equine GPS Rover PCB Design

Our PCB design for the equine GPS rover, which is shown in **Figure 3a**, integrates two devices: the SparkFun GPS-RTK-SMA Breakout board and a SparkFun LoRa Thing Plus expLoRaBLE board.
The main thing to consider when developing the PCB was the orientation of the antenna mounts for both the radio antenna and the GPS antenna. These need to be facing outward to allow the most maneuverability when deciding where to mount these devices. The GPS module and the expLoRaBLE board are connected via both I2C and the Serial port to allow easy communication between the two devices as well as to provide a channel for the expLoRaBLE board to send the RTCM messages it receives from the base station over. Also shown in this PCB are the batteries and inductive charger. These will be what give the device the ability to remain untethered when out in the field. Considering the waterproof problem of the product, we adopted the method



(a) Equine GPS Rover PCB design with both Serial and I2C connections, and including 5-Battery Box and inductive charging input set

(b) PCB design with only I2C connection, and including inductive charging output set

Figure 3: PCB Design

of induction charging to charge the device without having to break the waterproof seal that the components are stored inside. The induction charging module is shown in the **Figure 4**.

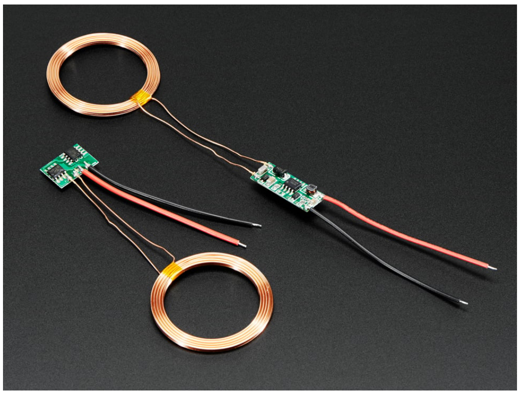


Figure 4: Inductive Charging Set Shown in the design of the PCB, image adapted from Adafruit's Product Page [13]

When the input half is powered by 9V to 12V DC, it provides 5V DC output from the output half. If the coils are 2 or 3 mm apart, about 500mA of current can be consumed. If you only need 100 or 200mA, it can be 7mm apart. For a 10mA current, the distance between coils can reach half an inch (12.5mm). Moreover, any non-ferrous metal/non-conductive material (such as air, wood, leather, plastic, paper, or glass) can be used between the two coils without affecting the efficiency of the charging system. The coils need to be coaxial to get the best power transmission. The large module is used for the input end, which supplies power to the coil via a USB connection. The small module is placed on the equine GPS rover to charge the battery.

4.2 Base Station PCB Design

The second PCB, shown in **Figure 3b**, is that of the Base Station. In contrast to the rover, this system does not rely on a battery system for power, therefore the battery shown previously is removed from the PCB design. The other end of the inductive charger is included. This leads to a smaller and more compact design for the components of the base station.

In a word, assuming that our product design is waterproof enough, the USB power supply can always be used in the scene of the Reference Base Station, and the PCB design does not need an external battery pack, thus simplifying the previous design. This change reflects the concern for desktop or fixed applications, in which the motherboard can keep the connection with the computer and get power directly from the USB connection without a separate power supply.

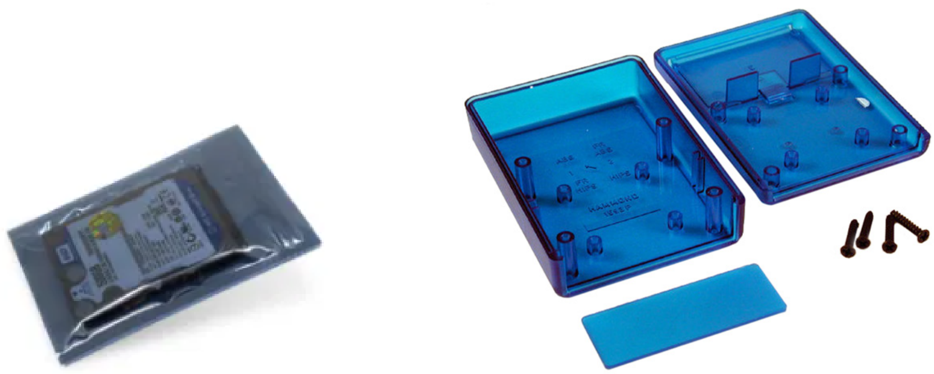
5 Housing Design & Setup

When designing our GPS base station and our wearable GPS rover system we must consider the function of our device, will what we build be able to do what we want it to do, as well as its durability, will the device be able to survive being mounted on a horse and will it survive the elements such as rain or snow?

5.1 Equine GPS Rover

5.1.1 PCB housing

The PCB circuit board will be wrapped in a small waterproof container, which is fixed on the horse's neck. This design emphasizes both protecting the device from bad weather and making the horse feel comfortable. Two waterproof schemes are being considered. The first is a custom-sized waterproof case with screws to ensure waterproof sealing. Our second idea is a customized bag made of carbon fiber and other materials that can be made waterproof, anti-corrosive, and mildew-proof. The concepts can be seen in **Figure 5**. Since the GPS antenna is waterproof itself, for both designs it can be made as external to the enclosure as needed in order to maintain signal strength.



(a) Sealing PCB Bag. Image adapted from Digi-Key's product page [14].

(b) Screwing Box for PCB. Image adapted from Foshan Nicepak's product website [15].

Figure 5: Options for the waterproof enclosure for the Equine GPS Rover

5.1.2 Design selection criteria

The choice of a waterproof case or waterproof bag will depend on their durability and comfort to the horse. The design is still in the initial stage, and the consideration of climate variability, such as how the equipment works at low temperatures and the horse's acceptance of wearing the equipment, is underway.

5.2 GPS Base Station

5.2.1 Assembly and Power Supply

We will be taking the PCB circuit board and connecting it directly to a computer via USB. This will ensure the base station can maintain power over extended periods of time as well as allow the base station to be directly monitored for any operating issues. We hope to build a system analogous to the one shown by Sparkfun in their base station tutorial that can be seen in **Figure 6** [16].

Figure 6: The SparkFun RTK Base Station complete with an NTRIP internet connection and a 915MHz RF connection

5.2.2 External Casing

The system will be placed inside a waterproof casing to protect the components from weather conditions and other environmental factors. Since the base station must be out in the open and left undisturbed it's important to reduce any factors that can interfere with it. If the base station loses its signal for any reason the rover will no longer be able to perform RTK corrections.

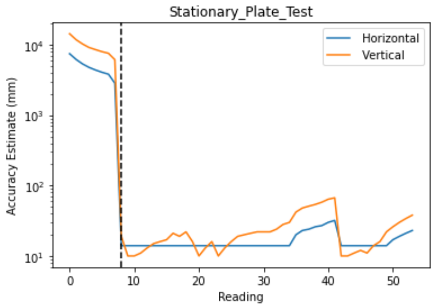
6 Data Acquisition and Procedure

Data can be acquired in one of two ways. The first is directly from the GPS module using the u-blox program, u-center. This method will be used when collecting data over a significant period of time to determine the position of the base station. The reason for this is that data taken over this long of a period can result in large file sizes, so being able to utilize the hard drive of the accompanying PC is convenient, and with the ability to remotely access said PC it provides no downsides. The second method is via the Arduino IDE. As our current tests have not had us separate the rover from a computer yet, nor have they required us to save large data sets, using the serial monitor is sufficient to acquire the data. Methods we have discussed in the future to save the data from the rover would be to either save the data to a micro SD card attached to the rover or send the data over LoRa to a third board that will be able to store and analyze it. Under the current configuration, we test the horizontal and vertical accuracy of the position measurement using the device's built-in accuracy methods. As mentioned earlier, we test the accuracy with and without the grounding plate, as well as the accuracy when the rover is moving and stationary. For each test, the base station was left undisturbed. For the tests where the rover was stationary, the rover was placed around 1 m away from the base station. In between each test, the rover was powered down so that RTCM data from previous tests would not influence the data at all. For the moving tests, the rover was held by one of us while walking in circles approximately $1 - 2$ m from the base station. The area we moved in was the same for each test to avoid any effects from the direction the RTCM data was broadcast over. Each test was done over a minute-long period resulting in about 60 data points.

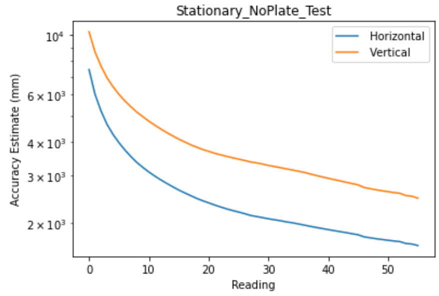
To test the range of the radio antenna, we set up the base station to continuously broadcast a signal and have the rover system continuously be looking for a signal and report whenever it finds one. We then take the rover and walk down the street with it, making note of where the system is when it hasn't seen a signal after around 30 seconds.

7 Results & Discussion

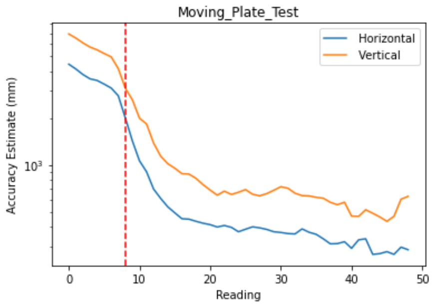
The results from our preliminary accuracy measurement can be seen in **Figure 7**.



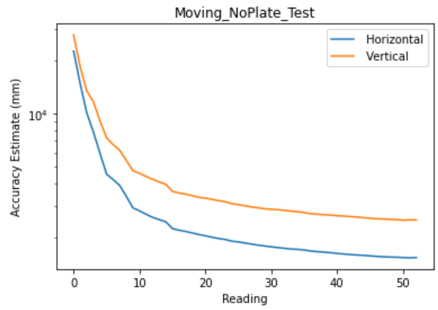
(a) Semi-log plot of the Vertical and Horizontal Accuracy data using a stationary rover and a grounding plate. The vertical black line corresponds to the rover entering 'fixed' RTK mode.



(b) Semi-log plot of the Vertical and Horizontal Accuracy data using a stationary rover and no grounding plate.



(c) Semi-log plot of the Vertical and Horizontal Accuracy data using a moving rover and a grounding plate. The vertical red line corresponds to the rover entering 'floating' RTK mode.



(d) Semi-log plot of the Vertical and Horizontal Accuracy data using a moving rover and no grounding plate.

Figure 7: Results from Preliminary accuracy measurement.

Our preliminary accuracy measurements show that the grounding plate is clearly necessary, as without it the system never enters any RTK mode, and the accuracy remains in the order of hundreds of millimeters instead of the desired 10 mm. We also see that no matter the test the vertical accuracy is worse than the horizontal. While the results shown in **Figure 7a** indicate that this may not end up being a large issue, it is still something to consider as we develop implementations for our system. From this data, we can also see that the time it took the system to enter fixed RTK mode was approximately 10 seconds. This is a promising result as it is rather quick and the system also didn't visibly enter floating mode, which means it was able to find the integer ambiguities described above quickly enough that it did not show up on measurements. This data does have one troubling aspect, that being that when the rover was moving the system did not successfully enter fixed RTK mode. This could be a huge issue for the viability of the current form of the project as horses are not stationary animals, they move around often. While the accuracy measurements from this test do not indicate that such data is completely unusable, it does place serious limitations on the potential implementations of the final product. For instance, one big potential use for an Equine RTK Positioning system outside of veterinary medicine is in the field of horse racing. If the movement of a human walking was enough to throw the accuracy off the desired value, a horse galloping at maximum speed will surely cause a significant issue. Moving forward, once we have the permanent base station installed on the roof of Loomis, we would like to continue these tests, specifically to see if the movement of the rover is as much of an issue as this data suggests.

The measured range for the radio antenna was approximately 0.2 mi. This is clearly not a great range, especially if we're hoping to put this device on a farm that can span large distances. To fix this we will have to look at new options for the radio antenna. In doing so we will have to balance the range of the antenna with how protruding it will be to the design. The current antenna was very sleek but has shown to not provide the range we need. Other antennae may be able to provide that range but may need to stick out of the system in an inconvenient way. A potential alternative choice we will need to test is shown in **Figure 8**.

Future tests include monitoring the time it takes the rover to enter fixed mode after moving, seeing if the rover will enter fixed mode while moving on a longer timescale, seeing if there is a maximum velocity that the rover can move while maintaining fixed, testing the distance the rover can be from the base station and testing accuracy as a function of the distance from the base station. We have to figure out what kind of positional data

Figure 8: 915MHz LoRa Antenna Omni 5dbi Gain SMA Male for ESP32 LoRa OLED Board + 15cm IPEX Extension Cable. Image adapted from gistgear product page [17]

we would like to gather from the horse which will be determined by what aspect of the horse's movement we are trying to monitor. We also need to determine what material would be best to use for the grounding plate. Since this test determined that the grounding plate was necessary we must see if there are lightweight options that we can use to achieve our desired accuracy since the weight of the provided plate is a little too much to comfortably place on a horse for several hours. We also must determine how long we want the rover device to be on the horse as that will determine the size of the battery that we must attach to it. We also must determine a solution for the range of the radio antenna.

References

[1] Anders Herlin, Emma Brunberg, Jan Hultgren, Niclas Högberg, Anna Rydberg, and Anna Skarin. Animal welfare implications of digital tools for monitoring and management of cattle and sheep on pasture. *Animals (Basel)*, 11(3), March 2021.

[2] Per K. Enge. The global positioning system: Signals, measurements, and performance. *International Journal of Wireless Information Networks*, 1(2):83–105, Apr 1994.

[3] Mauricio Andrada. Real-time kinetics (rtk), Sep 2020.

[4] Yanming Feng and Jinling Wang. GPS RTK performance characteristics and analysis. *Positioning*, 01No.13:8, 2008.

[5] BA Hampson, JM Morton, PC Mills, MG Trotter, DW Lamb, and CC Pollitt. Monitoring distances travelled by horses using GPS tracking collars. *Australian Veterinary Journal*, 88(5):176–181, April 2010.

[6] J K Kingston, G M Soppet, C W Rogers, and E C Firth. Use of a global positioning and heart rate monitoring system to assess training load in a group of thoroughbred racehorses. *Equine Vet J Suppl*, (36):106–109, August 2006.

[7] Arno Lindner and Anna Brand. Global positioning system–determined and stopwatch-determined running speeds of horses differ. *Journal of Equine Veterinary Science*, 84:102871, 2020.

[8] Rolf Moe-Nilssen and Jorunn Helbostad. Interstride trunk acceleration variability but not step width variability can differentiate between fit and frail older adults. *Gait posture*, 21:164–70, 02 2005.

[9] Thilo Pfau, Thomas H. Witte, and Alan M. Wilson. A method for deriving displacement data during cyclical movement using an inertial sensor. *Journal of Experimental Biology*, 208(13):2503–2514, July 2005.

[10] u-blox. *ZED-F9P-02B High precision GNSS module*, 2023. Rev. 3.

[11] Jan Gromeš. RadioLib. https://github.com/jgromes/RadioLib, 2023. [Online; accessed 9-Sep-2023].

[12] Shenzhen XinLisheng Hardware Electronics Co., Ltd. *2G 3G 4G LTE full band FPC Internal Antenna*, 2023.

[13] adafruit. *Inductive Charging Set - 5V @ 500mA max*, 2023.

[14] digiKey. *1593PTBU*, 2023.

[15] Made-in-China. *Custom ESD Logo Printed 2-Side Sealing Anti-Static Vacuum Clear Plastic Bag for PCB Packaging*, 2023.

[16] NATE. *How to Build a DIY GNSS Reference Station*, 2023.

[17] Gistear. *915MHz LoRa Antenna Omni 5dbi Gain SMA Male for ESP32 LoRa OLED Board + 15cm IPEX Extension Cable 2 Pcs*, 2023.