Equine Diagnostic Applications of Real-Time Kinematics Precision GPS Systems

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Abstract

This study explores the potential of high-precision GPS systems in monitoring equine behavior and providing insights into horse health. This research addresses challenges in GPS accuracy during horse movement obtained by a Real-Time Kinematics (RTK) system. By recording positional data for extended periods the goal is to discover abnormalities that could signify underlying health concerns in the animal. The study involves a GPS-RTK system with radio communication, tested for accuracy, and equipped with an induction charging system to ensure that the rover can be charged without disrupting the waterproofing thus making the system weather-resistant. The PCB design and assembly, along with housing considerations, are detailed for a two-device system including an equine GPS rover and a base station.

1 Introduction

Horses have been one of the most important and versatile domesticated animals in human history and culture. They've served roles in transportation, agriculture, sport, and warfare. Consequently, understanding equine movement and health remains important to preserving these roles. This study aims to do this by employing a high-precision GPS module to monitor the horse's positional data over several hours. The collected data will be used to create models that can predict potential critical health issues that may come up in the future. One study utilized such a GPS module to distinguish between healthy dogs and those suffering from osteoarthritis, leading to earlier and more effective medical intervention [4]. This project aims to refine and expand on this approach by integrating GPS and IMU sensors into a single device, tailored for monitoring horses. The combined utilization of high-precision GPS technology and Inertial Measurement Units (IMUs) is expected to improve the monitoring and management of equine health and training, by providing detailed insights into their movement patterns over time. To achieve this, components provided by SparkFun Electronics, including a GPS module capable of 1 cm precision and an IMU, will be utilized.

2 Purpose & Background

2.1 GPS Background

The first system utilizing satellites to determine position on the planet was the Global Positioning System (GPS) developed by the United States Department of Defense in the 1970s. Since then the GPS has expanded rapidly and was made available for civilian use in the 1980s. 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 use data from many of these global navigation satellite systems (GNSS) and attain 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, such as the one used in this study, uses information from both bands to determine the location of the receiver. A GPS module calculates its range to the satellite through 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, one can find the distance the wave traveled to arrive at the module with the time it took to get there. However, when accounting for error, it can be seen that this is not the true range. What is measured is the 'pseudorange', which 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, refraction in the ionosphere and troposphere, satellite clock data, and error in the satellite ephemeral data [6]. This error can be mitigated through the use of a Real-Time Kinematic system (RTK). This system involves a static base station with a known position. The base station's position is found by collecting positional data over approximately 24 hours and then averaging it to find the best estimate for the true position. The base station is then used to generate messages that contain the positional information for the base station, the errors in the pseudoranges of the signal, and information carrier waves from the satellite under the Radio Technical Commission for Maritime Services (RTCM) protocol. 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. Measuring the phase of the signal the base station receives from the satellite as,

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

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. This integer ambiguity is what is left to be solved by the RTK algorithm. The values for x, y, and z used to calculate ρ are the system's coordinates in the Earth-centered, Earth-fixed (ECEF) coordinate system which calculates the position in terms of the center of mass of the Earth. 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. This is then replicated for every satellite the system can see. 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 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]. For the receiver, ρ corresponds to the pseudorange, and for the base station, it corresponds to the true range. This process assumes that the base station and rover are sufficiently close together ($\sim$ 20 km) so that the errors are the same for both systems and therefore canceled in this calculation. A diagram for this process can be seen in **Figure 1**.

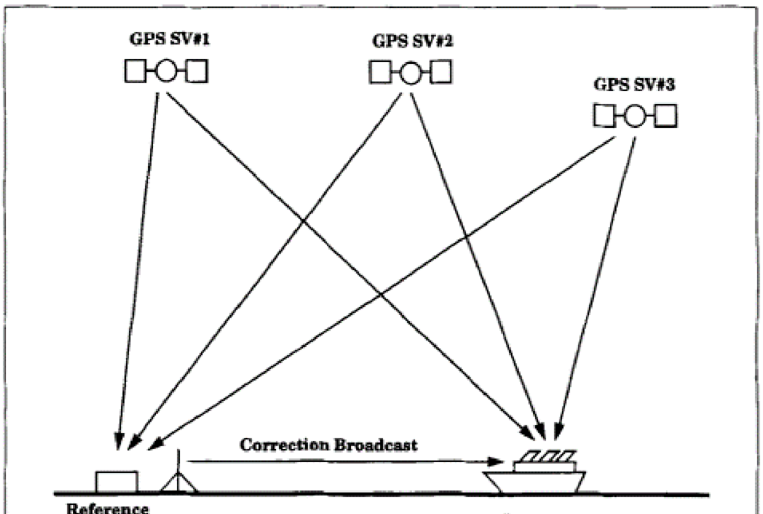


Figure 1: Visual example for an RTK system. Image adapted from [6].

Before the rover solves these integer ambiguities, it enters what is known as floating mode. The algorithm used to solve these ambiguities during floating mode depends on the device. Since the base station's position is known exactly once the integer ambiguities are determined, the rover's relative position to the base station can be determined from the phase difference. This is a simplified explanation of how the RTK algorithm works. One study describes a more complicated version, which involves other variables in the calculation such as the noise of the signal. However, it is still necessary to calculate the integer ambiguities to determine the relative position between the base station and the rover [7]. To solve these ambiguities the system must take data for a time that depends on the device's capabilities, 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 [7]. It is during this process that the rover uses the data the base station took about the error estimation between the pseudorange and the range for the base station. Once the rover solves these ambiguities it enters fixed mode and has a higher positional accuracy ($\sim$ 1cm) compared to a standard GPS. In fixed mode, the rover will determine its position in reference to the base station rather than purely referencing the satellites as in a traditional GPS. This process can also be done in post-processing instead of in real-time for a higher accuracy than real-time due to more data being available. However, for the purpose described above, real-time calculations are preferred.

Building upon this technical foundation, this study delves into the potential of GPS technology to monitor equine movements to provide valuable insights into the health and well-being of horses, bridging the gap between technology and equine management strategies.

2.2 Utilization of GPS and IMU Technology for Equine Health Diagnostics

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 [11]. Furthermore, employing GPS units to conduct investigations into racehorses has highlighted their effectiveness in providing precise measures of daily workload, offering valuable insights into horse training and its connection to injuries [10]. Understanding the correlation between GPS-monitored movement and injury risk could potentially lead to strategies for preventing injuries in equine management.

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 [13]. Additionally, the incorporation of IMUs has played a pivotal role in objective gait measurements, demonstrating effectiveness in identifying gait abnormalities and alerting owners to lameness and other diseases [14].

IMUs consist of both accelerometers and gyroscopes to measure the spatial and rotational movement of a system. The IMUs used in this study can detect movement in three spatial directions at the same time. This will allow the continuous measurement of the orientation of the device while it is on a horse. This measurement aims to catalog the subtle movements of the horse while walking or running and provide insights into the horse's natural behavior patterns. Once these patterns are observed the device would then be able to use these measurements to detect deviations that may indicate underlying health issues.

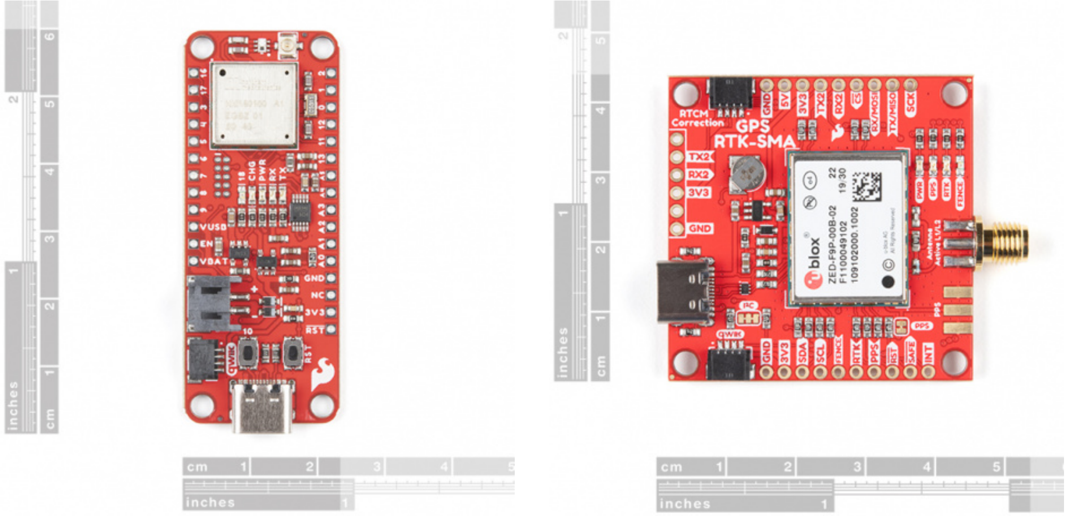
Recognizing the potential synergies between GPS and IMU systems, integrating these technologies could provide a comprehensive solution for monitoring behavioral changes in horses. This synergy, along with the precision of 1 cm capable of the GPS module, will be the main differentiator for the device and study compared to previous efforts. By harnessing the combined strengths of both systems, enhanced accuracy, reduced costs, and improved accessibility are anticipated. This study focuses on three primary applications for such a device: recovery monitoring, training enhancement, and illness detection. Initially, the device's effectiveness in monitoring recovery will be tested.

In collaboration with the University of Illinois College of Veterinary Medicine, the study will evaluate the device's ability to gather data during a horse's recovery from illness. This partnership will enable us to examine how such data can be used to track movement patterns during recovery phases and, inform strategies to improve the recovery process. The ultimate objective is to deepen the understanding of recovery strategies and contribute to the development of approaches that optimize equine health and well-being, setting this study apart through its precision and integrated approach.

This experiment will explore the hypothesis that RTK GPS monitors equipped with high-precision coordinate measurement capabilities can effectively identify nuanced movements associated with specific behaviors, enabling the detection of irregularities that may signify underlying health issues and recognize the potential of these systems in monitoring a horse's behavior during recovery from illness. To achieve the desired outcomes, this system will require the GPS module to maintain a precision to within a few centimeters to accurately monitor nuanced equine behaviors.

3 Experimental Setup

The system used for this study involves two GPS-RTK-SMA breakout boards provided by Sparkfun Electronics which include a u-blox ZED-F9P differential GPS 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 [16]. 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. LoRa is a wireless modulation technology derived from linear frequency modulation spread spectrum (CSS) technology to encode radio wave information by using linear frequency modulation pulses. LoRa modulation transmission has strong anti-interference ability and can be received from a long distance [1]. These boards are equipped with an NM180100 system from Northern Mechanics and a Semtech SX1262 LoRa transceiver. These components allow communication between each device over the LoRa frequency band (902 – 928 MHz in the U.S.). These boards can be seen in **Figure 2**.

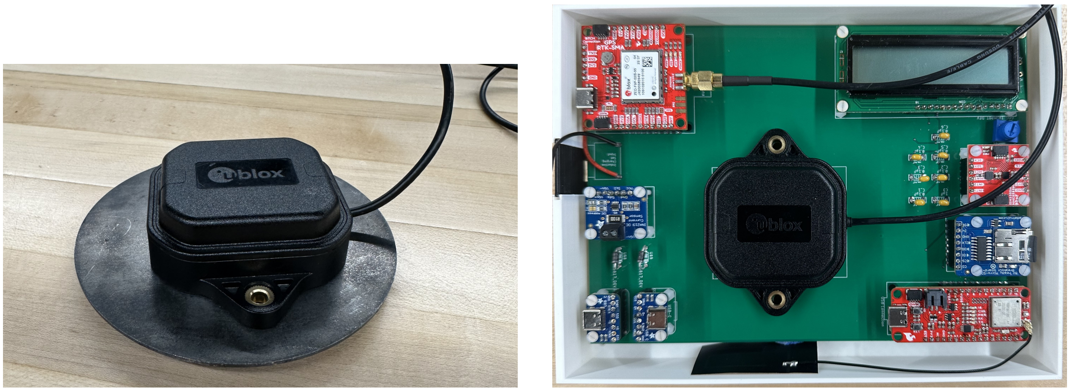


(a) Sparkfun LoRa Thing Plus - expLoRaBLE with scale for reference

(b) SparkFun GPS-RTK2 Board - ZED-F9P with scale for reference

Figure 2: Sparkfun Breakout Boards

The base station produces RTCM messages needed for RTK and transmits them over LoRa for the rover to receive. Each GPS board has an ANN-MB-00 GNSS multiband antenna capable of receiving both the L_1 and L_2 frequency bands. The GPS antenna also has the advantage of being waterproof in design, giving it much more flexibility in its mounting. Included with this is a metal grounding plate, attached to the bottom of the antenna which, due to its weight, will be subject to tests to determine its necessity for the system. A metal ground plane improves antenna performance as it shapes the radiation pattern of the antenna to reduce the signal in the direction below the antenna. 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 3a**



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

(b) Prototype Equine Rover Board. Note that the base station is made up of just the two Sparkfun breakout boards and antenna shown here.

Figure 3: Experimental Setup

The GPS board and the LoRa Thing Plus are connected via the I^2C communication protocol 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 the library that Sparkfun provides for the GPS board, and the RadioLib library to control the LoRa communication is used [9].

The Equine Rover system is also equipped with a SparkFun 6DoF IMU breakout board that will measure gyroscopic and acceleration data. These data in conjunction with the positional data will be used to develop a better idea of how a horse is moving throughout the day. This board can be seen in **Figure 4**.

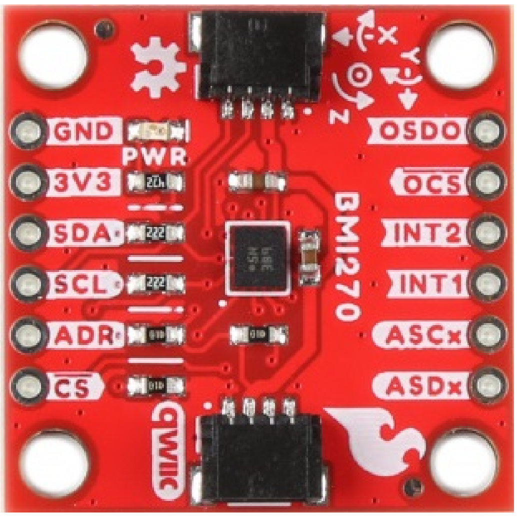


Figure 4: SparkFun 6DoF IMU Breakout - BMI270

For preliminary tests, the base station uses in 'Survey-In mode' where it determines its position for 1-2 minutes and then starts relaying RTCM messages to the rover. The system can transmit byte arrays with a maximum length of 256 bytes, which should be enough for most RTCM messages. As a fail-safe, the code constructs an RTCM message and sends the full message when either the next message starts, or the maximum message size is reached. The rover can dynamically adjust for the length of the received message. Once an RTCM message is received it is then sent to the GPS module for processing. The prototype for the equine rover can be seen in **Figure 3b**.

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 positional data for approximately 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. 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 Windows's Remote Access feature so the base station can be monitored and controlled. The rover will be powered via battery and charged via an induction system to ensure the ability to make the rover waterproof while on the horse.

The range of the radio antenna used to communicate between the base station and the rover will also be tested. The antenna that will be tested is the Wide Band 4G LTE Internal LoRa Antenna provided by Sparkfun Electronics, shown in **Figure 5**.

Figure 5: Wide Band 4G LTE Internal LoRa Antenna, image adapted from Sparkfun's product page [15].

4 PCB Design

4.1 Equine GPS Rover PCB Design

The PCB design for the equine GPS rover, which is shown in **Figure 6**, integrates two devices: the SparkFun GPS-RTK-SMA breakout board and a SparkFun LoRa Thing Plus expLoRaBLE board.

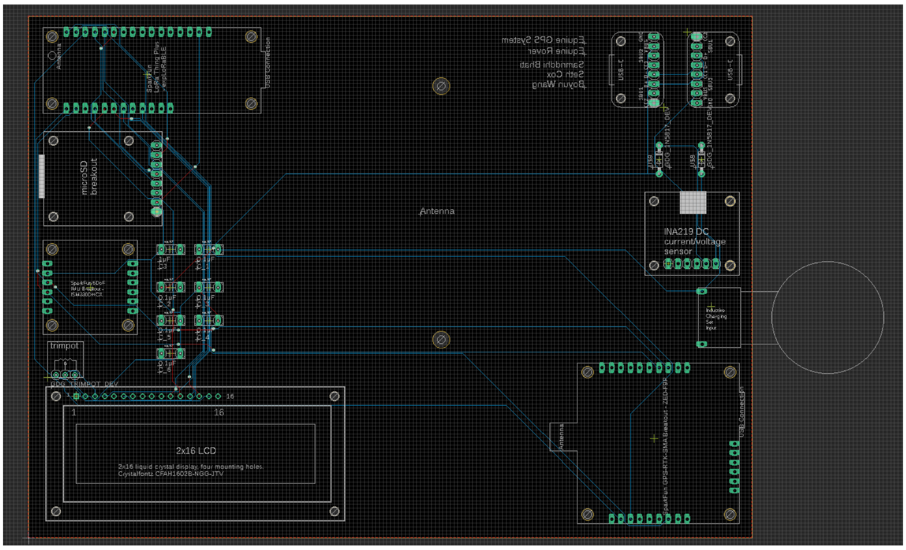


Figure 6: Equine GPS Rover PCB design with both Serial and I^2C connections, and including 5-Battery Box and inductive charging input set

One thing to consider when developing a PCB is the antenna installation orientation of the radio antenna and GPS antenna. Though those antennas are connected by cables, it is still one of the ways to save space for the PCB design and avoid damage of the antennas and cables. 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 I^2C, and the serial port to allow for 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. Also shown in this PCB are the batteries and inductive charger. These will give the device the ability to remain untethered when the Equine GPS Rover PCB board is out in the field. To maintain a waterproof seal, the method of induction charging to charge the device was adopted. The induction charging module is shown in the **Figure 7**.

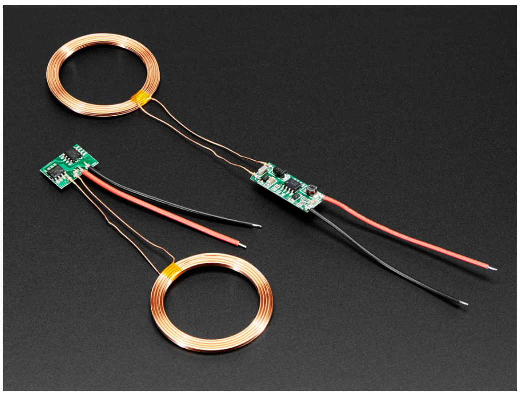


Figure 7: Inductive Charging Set Shown in the design of the PCB, image adapted from Adafruit's Product Page [2]

When the input charging coil, which is the half of the set equipped in the Equine Rover, 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, they can be 7mm apart. For a 10mA current, the distance between coils can reach half an inch (14.5mm). 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 Receiving Board PCB Design

The PCB design for the Receiving Board is shown in **Figure 8**. It integrates a 2x16 character LCD screen and a micro-SD card interface for data storage and retrieval, which is suitable for applications requiring visual feedback and external data recording. The layout includes the designated area for an antenna and USB connection. A

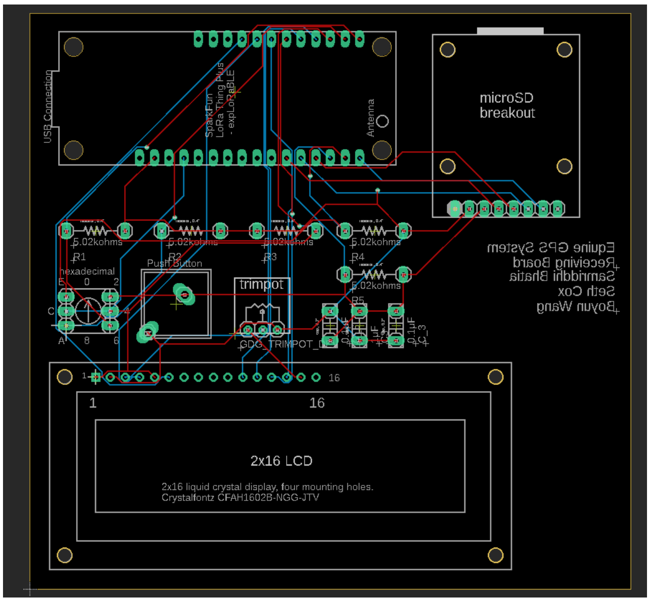


Figure 8: PCB design for the receiving Board

push button and hexadecimal rotary switch allow for control of the rover remotely via radio communication. In addition, another half of the induction charging set is included with this board.

4.3 Base Station PCB Design

The third PCB, shown in **Figure 9**, is that of the Base Station. In contrast to the rover, this system does not rely on a battery system for power. The base station requires a constant connection to an external Windows PC to utilize the u-center program used to directly monitor the GPS sensor. The base station also only requires the I^2C connection between the two Sparkfun breakout boards as the serial connection is not required for broadcasting the correction data.

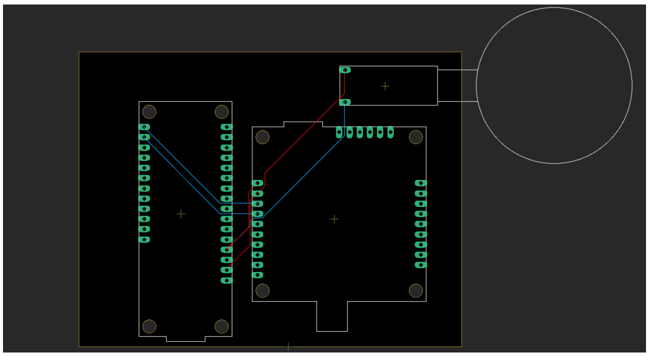


Figure 9: Base Station PCB design with only I^2C connections

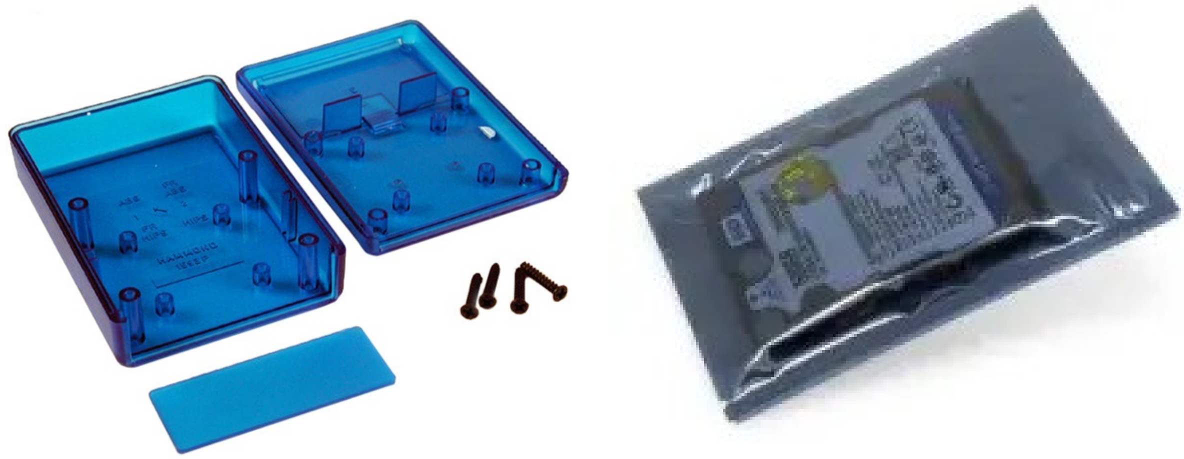
5 Housing Design & Setup

Durability is a critical consideration in designing the GPS base station and the equine GPS rover system. The device must be robust enough to endure various weather conditions, including rain and snow, particularly since it will be mounted on a horse. This demands the selection of high-quality, weather-resistant materials that can withstand the harsh elements and the dynamic movement of a horse. The design should feature a sturdy, waterproof enclosure to protect the sensitive electronic components from moisture and dirt ingress.

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. The waterproof scheme being considered is a resealable customized bag made of plastic and other materials that can be made waterproof. These concepts can be seen in **Figure 10**.



(a) Screwing Box for PCB. Image adapted from Digi-Key's product website [5].

(b) Sample waterproofing bag that could be used to protect the rover. Image adapted from Foshan Nicepak's product website [12].

Figure 10: Options for the waterproof enclosure for the Equine GPS Rover

5.1.2 Design selection criteria

The decision to use a waterproof case or bag for the GPS device depends on its durability and the comfort it provides to the horse. If the device causes discomfort, the horse may resist wearing it, which could ultimately lead to damage or destruction of the device through the horse rolling. 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 integration with the horse, is underway.

5.2 GPS Base Station

5.2.1 Assembly and Power Supply

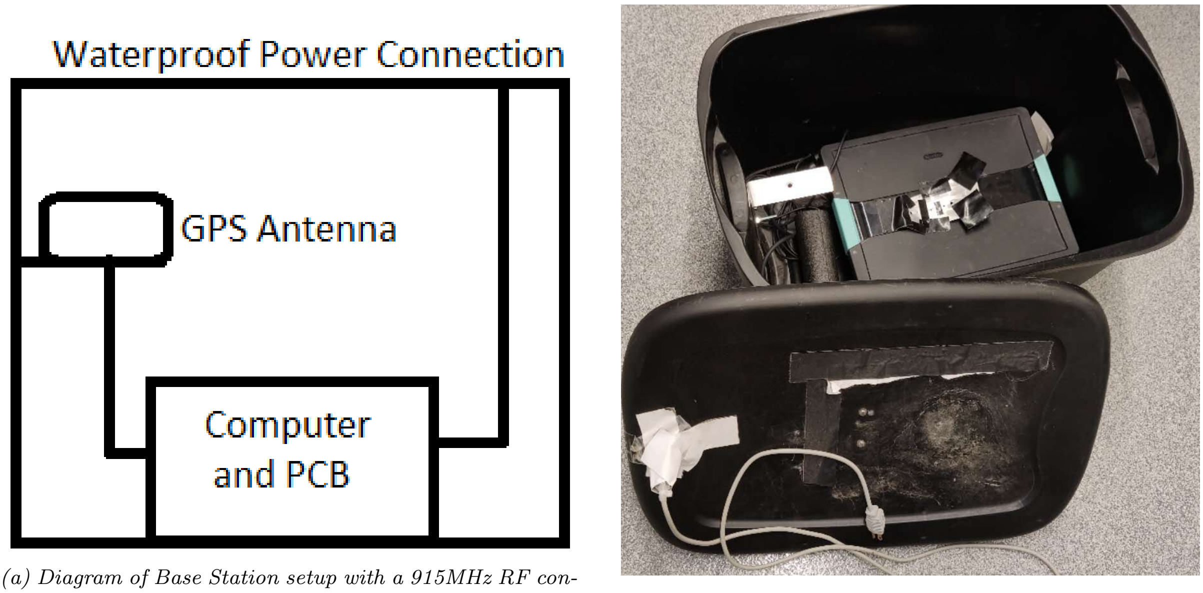
The PCB circuit board will be directly connected to a computer via USB. This will ensure the base station can maintain power over extended periods as well as allow the base station to be directly monitored for any operating issues.

5.2.2 External Casing

The base station 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 is important to reduce the impact of any factors that may interfere with the device. If the base station loses its signal for any reason such as a loss of power, the rover will no longer be able to perform RTK corrections. To accomplish this, the computer and PCB were placed in a small plastic box within a larger plastic container. Power was then run to the computer via a sealed connection to the outside. A diagram for this setup as well as the prototype is shown in **Figure 11**.

6 Data Acquisition and Procedure

Positional data can be acquired in two ways. The first is directly from the GPS module using the manufacturer u-blox's program, u-center [17]. This program can directly record and process the satellite data seen by the device. This method will be used when collecting data for around 24 hours 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 file sizes on the order of several gigabytes per day, which may become impractical in the field. The second method is recording the data to an SD card for exterior data analysis. Under the current configuration, the horizontal and vertical accuracy of the position measurement using the device's built-in accuracy methods are recorded. As mentioned earlier, the accuracy with and without the grounding plate, as well as the accuracy when the rover is moving and stationary are measured. 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



(a) Diagram of Base Station setup with a 915MHz RF connection

(b) Prototype Base Station

Figure 11: Diagram and prototype for the Base Station Enclosure.

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 while walking in circles approximately $1 - 2$ m from the base station. The area 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.

The next test for the device was to monitor the accuracy and position over a longer period. This was done by walking around with the device while it recorded its position along with gyroscopic, acceleration, and fix data in relation to the base station. The purpose of this test was to determine if trends are observed within the data corresponding to particular changes in movement which can then be used to determine what measurements will be useful to take on a horse.

Finally, a test was done by attaching the rover to a surcingle and mounting it onto a horse. This was done with the help of Professor Annette McCoy of the University of Illinois College of Veterinary Medicine. For this test, the rover was powered by a 10050 mAh battery and the horse was free to walk around with the guidance of Prof. McCoy. For over 15 minutes the horse walked around at varying speeds with the idea being the data should indicate this change in speed. At the end of the test, the horse laid down to see if the prototype could detect this as this is one of the indicators of potential illness in a horse. The rover, along with the horse, are shown in **Figure 12a**.

(a) GPS Rover Mounted to a surcingle and attached to a horse.

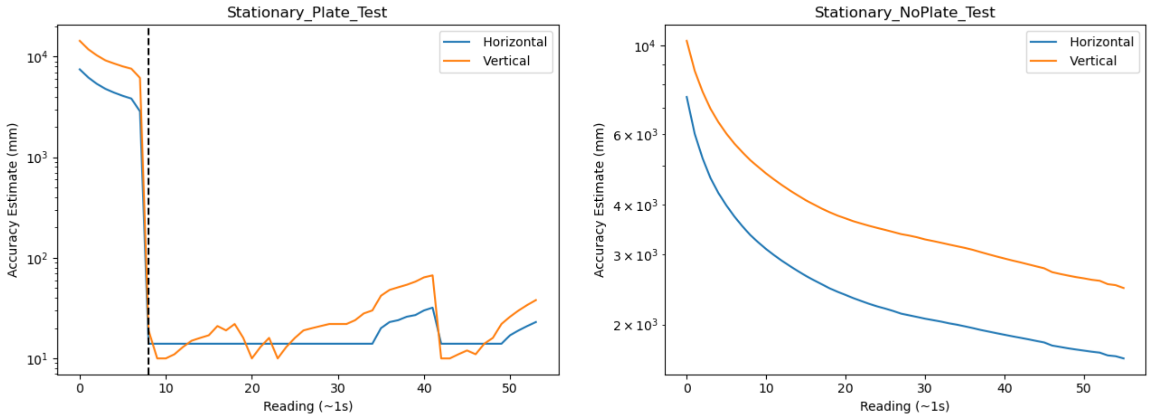
(b) GPS Rover Casing

Figure 12: Experimental setup for testing the Equine Rover on a horse.

To test the range of the radio antenna, a continuous radio broadcast was set up at ground level with the rover system continuously looking for the signal and reporting whenever a signal was found. The rover was then taken straight down the sidewalk from the broadcast location. This was done to minimize obstructions due to the environment. It was then recorded where the system was when it had not seen a signal for around 30 seconds.

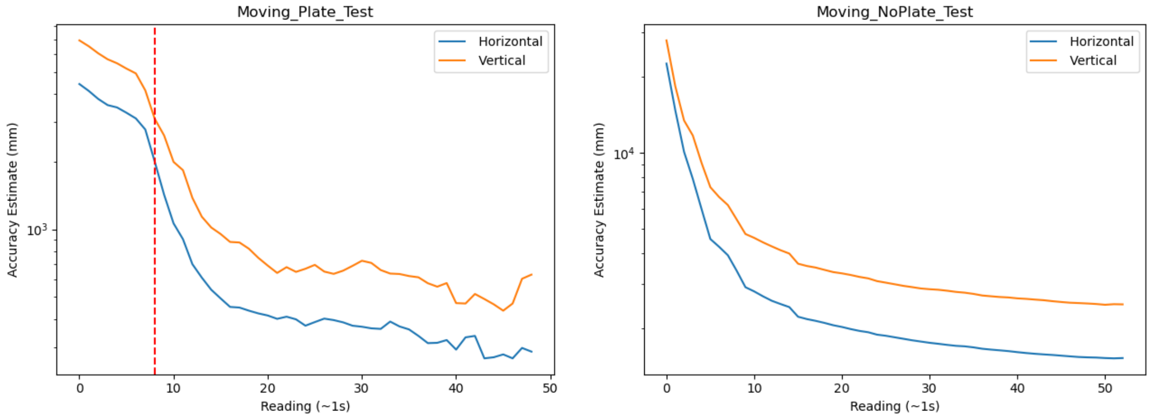
7 Results & Discussion

The results from the preliminary accuracy measurement are shown in **Figure 13**. Accuracy is estimated using the GPS module's onboard functions for horizontal and vertical accuracy. The preliminary accuracy measurements show that the grounding plate is 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. The ground plate improves the ability of the antenna to receive signals from GPS satellites, so it makes sense that it improves performance. Its weight was the primary reason for exploring omitting it from the design. It can also be seen that no matter the test the vertical accuracy is worse than the horizontal. This behaviour was expected according to SparkFun's documentation. While the results shown in **Figure 13a** indicate that this may not end up being a large issue, it is still something to consider as implementations for the system are developed. From this data, it can also be seen 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 did not visibly enter floating mode, which means it was able to find the integer ambiguities discussed previously quickly enough that it did not show up on measurements. This data has one troubling aspect, that being 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



(a) Semi-log plot of the Vertical and Horizontal Accuracy data using a stationary rover and a grounding plate.

(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.

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

Figure 13: Results from Preliminary accuracy measurement. The black and red vertical lines correspond to the fixed and floating RTK modes respectively. One reading corresponds to approximately 1s.

implementations of the final product. For instance, one 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 high speed will surely cause a significant issue. To test this accuracy over time, data was taken as the device was walked, at a typical walking pace, around the Loomis Laboratory of Physics, with the results shown in **Figure 14**.

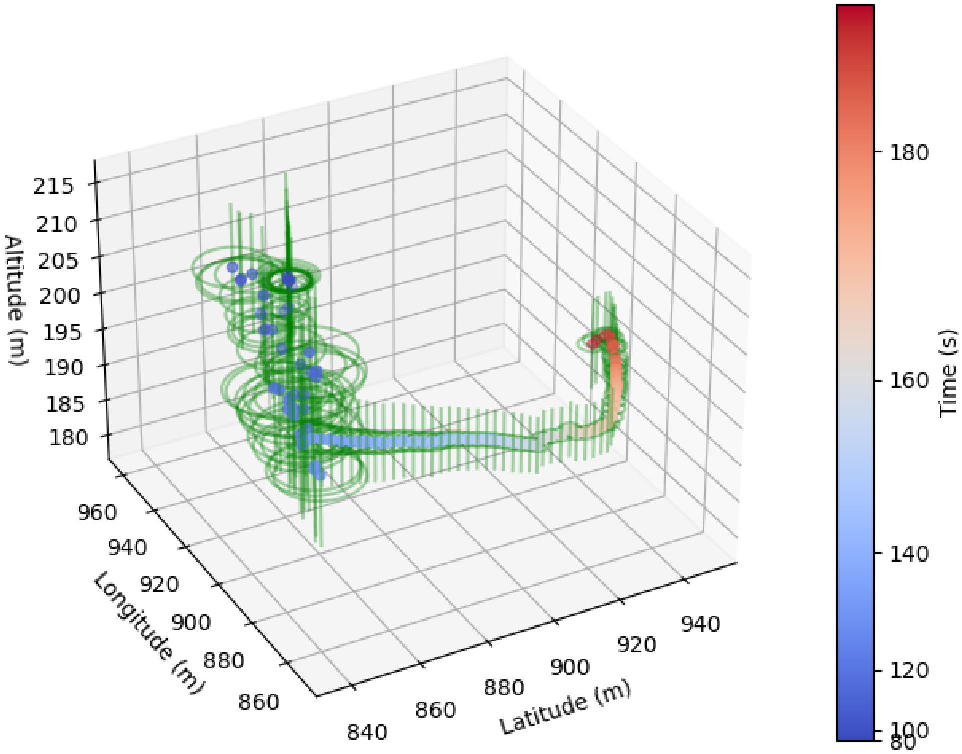
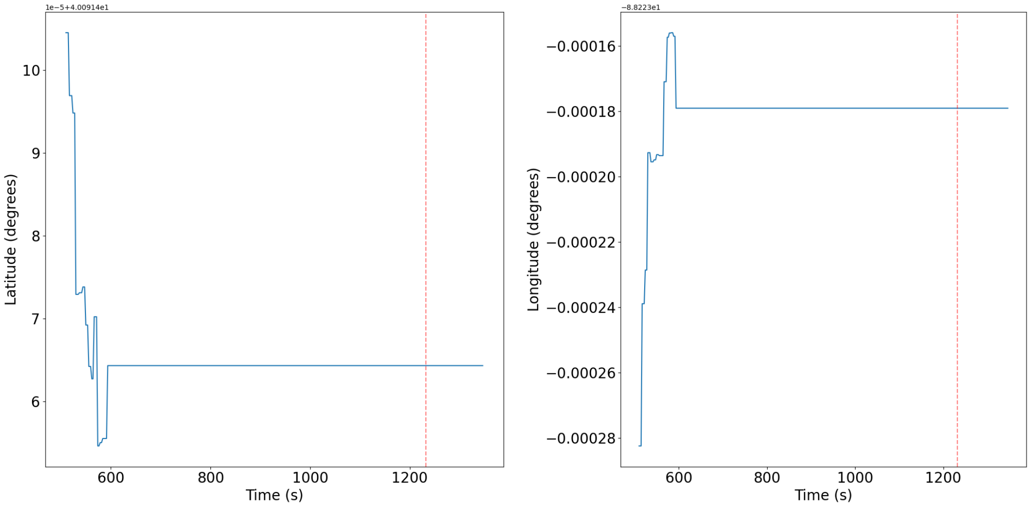


Figure 14: Positional data in Latitude/Longitude with horizontal error shown as circles and vertical error shown. Degrees Latitude/Longitude are converted to meters using the pyproj python library [18]. The time is shown as a gradient on the color of the points. Note the improved accuracy as time went on.

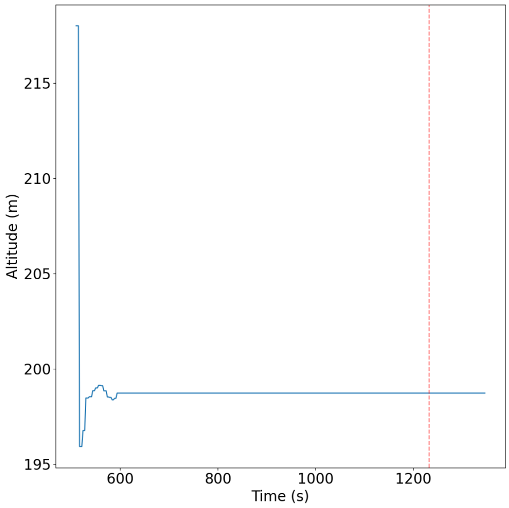
The points in this figure with large errors are when the device was first started and was in the process of turning on. As time goes on it is clear that the positional error gradually decreases with horizontal error at the end of the measurement being down to five meters while continuing to fall. The full set of data collected by both the GPS and IMU for this test can be seen in **Appendix A.1**.

One of the applications for the device is monitoring whether a horse is standing or not, so the accuracy of the altitude measurement is important to consider. Again, it can be seen that when the device is first started, the vertical error is extremely high, but after about a minute and a half, it falls to a much more consistent value of around five meters. While this error range is too high to reliably detect whether a horse is standing or not, observations during troubleshooting indicate that the error eventually falls to approximately 0.75 m, which is promising for the intended purpose. An important note for this data as well is that it was taken without correction data from the base station. The base station has proven difficult to reliably utilize which will have to be taken into consideration in the future if a fix is not found. Since the preliminary measurements were done, fixed mode has not been achieved and floating mode has only been briefly seen before it is lost. Reasons for this include interference due to other signals in the area or buildings obstructing communication between the rover and base station as well as the view that either of them has of the satellite constellation and potential hardware/software inconsistencies that were not realized at the time of testing.

Positional Data for the field test on the horse is shown in **Figure 15**.



(a) Latitude Plot for Test on Horse. *(b) Longitude Plot for Test on Horse.*



(c) Altitude Plot for Test on Horse.

Figure 15: Positional Data for Horse Test. Note the data goes constant after 2 minutes. Vertical red line signifies when the horse laid down.

While troubleshooting the base station, it had been observed that the GPS sensor would occasionally enter a 'Time-Only' mode. While in this mode the GPS module only solves for the time, not position. It is currently unknown why the device enters this mode as it happened at most once a day while troubleshooting for several hours. This mode causes the positional data to go constant and does not allow RTK corrections. Unfortunately, for the test on the horse, the device entered this mode after about 2 minutes, rendering the GPS data obtained largely useless. In an ideal scenario, the positional data from this run would show the speed up and slow down of the horse, as well as whether or not the horse was lying down or not. To do a predictive analysis of the horse's welfare it would be necessary to record data for several days to build up a database for the horse's typical movements. It would also be crucial to record the behavior of a horse with a health issue so that the difference between healthy and sick horses could be observed. As of the time of this writing, it is believed that this mode is a consistent enough issue to raise concern for the feasibility of the entire project. The data from the IMU, however, was not affected and the acceleration data can be seen in **Figure 16**.

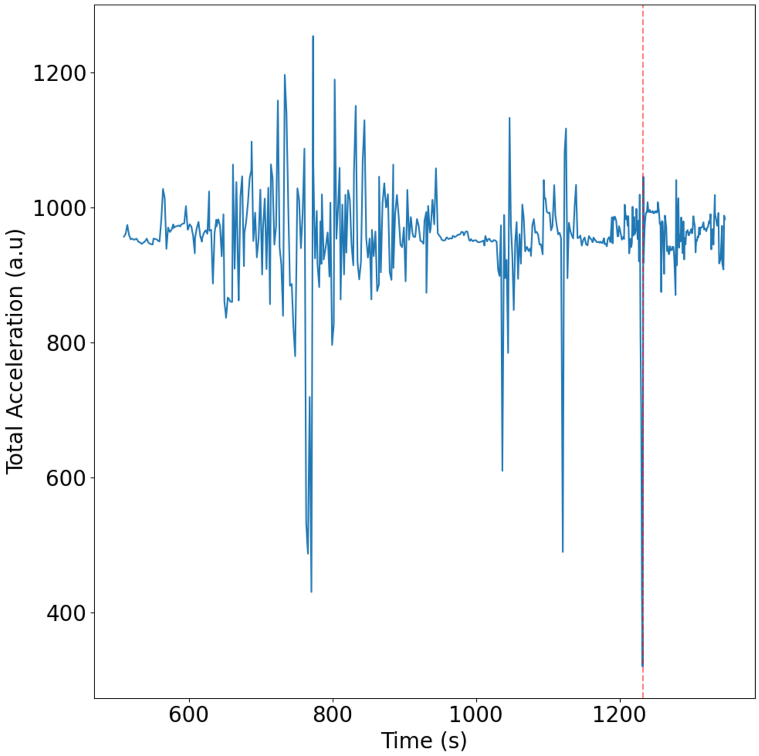


Figure 16: Acceleration of Horse during testing. Vertical red line signifies when the horse laid down.

From this figure times where the horse is speeding up and slowing down are clear. Also, a significant drop-off near the end of the data is seen, which is consistent with the horse lying down. The IMU was able to pick up on this behavior when the GPS failed, showing a clear reason to use the devices together. To see all of the data collected on this run, see **Appendix A.2**.

The measured range for the radio antenna was approximately 0.2 mi. This is too short for the desired purpose. To fix this new options for the radio antenna will have to be considered. In doing so balancing the range of the antenna with how protruding it will be to the design will be important. The current antenna was unobtrusive but has been shown to not provide the range needed. Other antennae may be able to provide that range but may need to stick out of the system inconveniently. A potential choice to test is shown in **Figure 17**.

Figure 17: 915MHz LoRa Antenna Omni 5dbi Gain SMA Male for ESP32 LoRa OLED Board + 15cm IPEX Extension Cable. Image adapted from gistgear product page [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 mode, testing the distance the rover can be from the base station and testing accuracy as a function of the distance from the base station. It must be decided what kind of positional data is gathered from the horse which will be determined by what aspect of the horse's movement is being monitored. Since the preliminary test determined that the grounding plate was necessary, lightweight options that can be used to achieve the desired accuracy must be considered. Possible options include a thin copper plate, cut to the parameters of the steel plate. The range of the radio antenna must also be improved as tests must be done over a larger area to gain insight into the behavior of grazing animals. The problem of the reliability of the base station is also important to fix moving forward as without it there are limits on the achievable accuracy.

Furthermore, the current design faces some challenges. Due to various conditions and design factors, the rover's size is too large for long-term placement on a horse. According to Prof. McCoy, the desired size would be about the size of a cell phone. This would allow safely mounting it to the horse and avoiding damage from the horse rolling or moving around naturally. The current design is more than twice this size. The prototype design has some elements that could be removed to save space which must be a consideration for the next iteration of the device. The horse did roll during the test, which the prototype survived. It was clear due to the plastic case breaking, however, that further precaution for this behavior would be necessary before continuing testing.

Another consideration is the method by which the rover is secured to the horse. For the field test, the rover was attached to the surcingle using zip ties through the sealed bag and the plastic shell. While this method was adequate for preliminary testing, it will be unsuitable for long-term use. Firstly,the waterproof bag surrounding the device had to be pierced to accommodate the use of zip ties, compromising the device's protection against moisture in the event of rain. The zip ties also do not provide a stable solution. There was enough give in the zip ties to allow for movement of the device while the horse was moving. With a desired 1 cm accuracy, this movement would cause observable deviation in measurements thereby skewing the results. The zip ties were also not strong enough to handle the horse rolling, indicating that a more robust attachment solution is needed for future applications.

The limitations of the prototype described previously make it inconclusive whether a system designed in such a way is feasible for the goals of the study. The GPS breakout board provided by SparkFun proved unreliable through the tests described in this study, even in controlled environments. Deploying this out in the field in an unmonitored test could introduce unforeseen issues, even if the current problems are resolved. While it was possible to observe sharp changes in movement such as turning or lying down using the data collected from the current prototype, it is not clear whether it would be possible to observe more nuanced changes in movement over time that would be necessary for a comprehensive gait analysis.

One approach for a functioning system would be to collect several data sets over multiple hours from a single horse and use machine learning or other data analysis tools to find trends in the data. These trends could be studied to detect deviations from normal behavior of a horse which could indicate the onset of an illness. Another approach could be to deploy multiple GPS and IMU sensors on different parts of the horse, enhancing the ability to detect nuanced behaviors by comparing the trends from different sensors. The current prototype is not ready for this phase of operation. The sensor currently in use was selected based on initial specifications, but it has proven to be less than ideal for the detailed and precise requirements of this study. Due to the large size and reduced functionality of this prototype, it is not ready to take the large data sets required for a true analysis of the behavior of the animal and the prediction of health issues before they occur.

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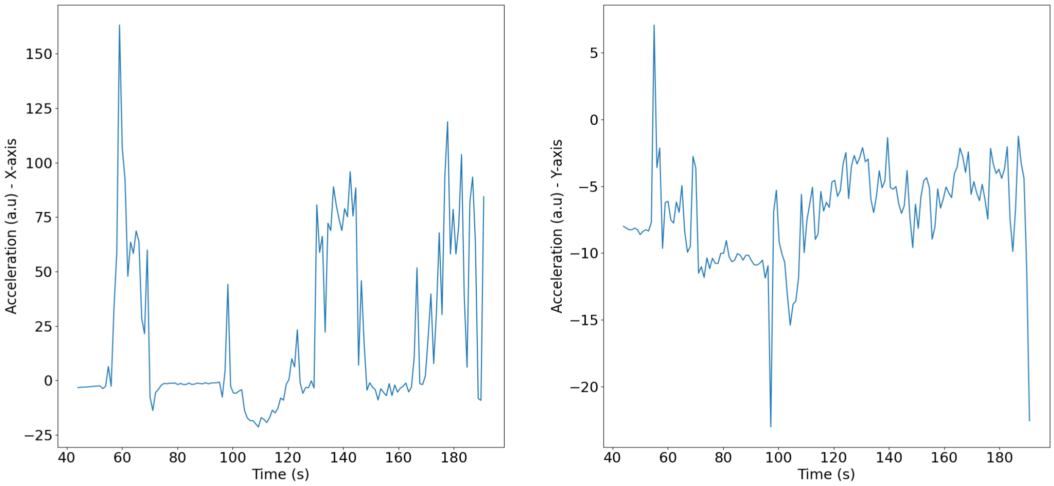
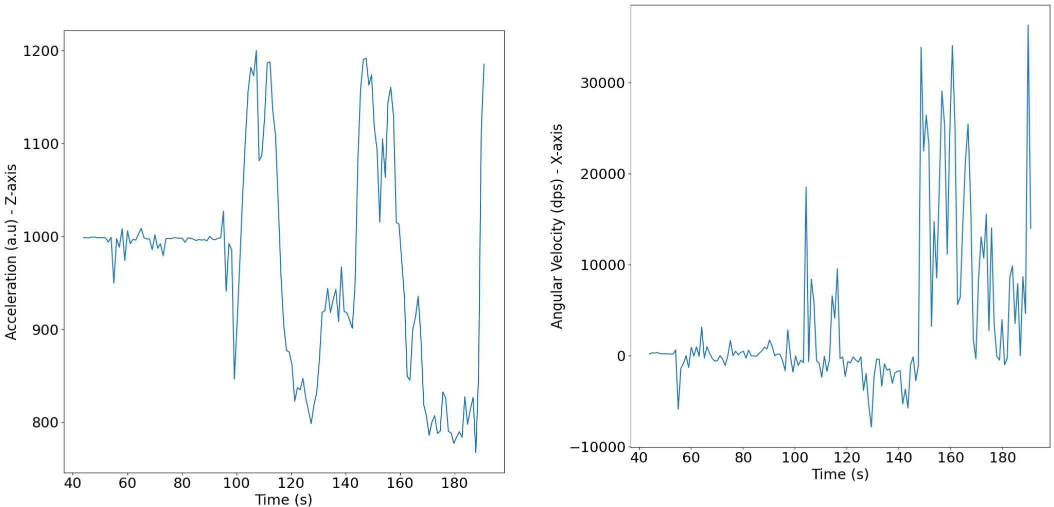
A Figures

A.1 Walking Test Data



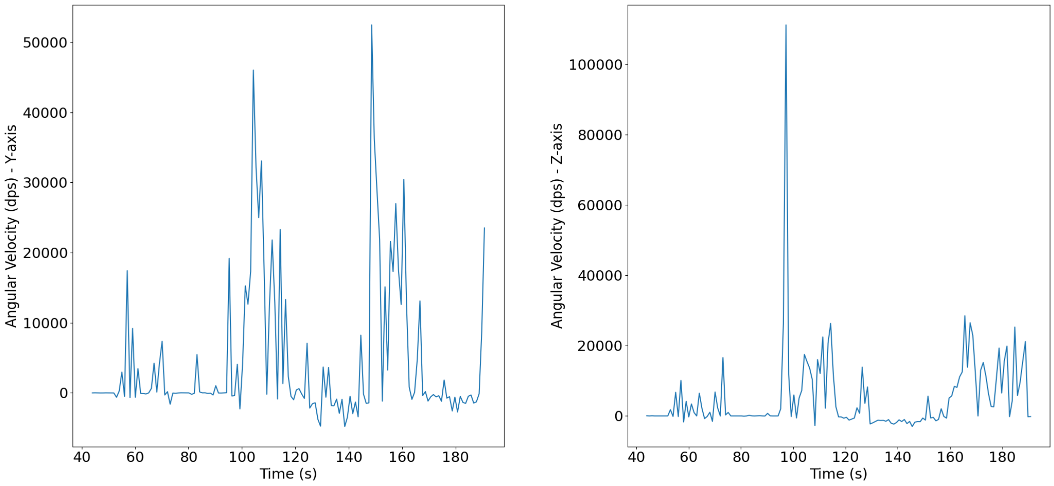
(a) X axis Acceleration Data from the walking test.

(b) Y axis Acceleration Data from the walking test.



(c) Z axis Acceleration Data from the walking test.

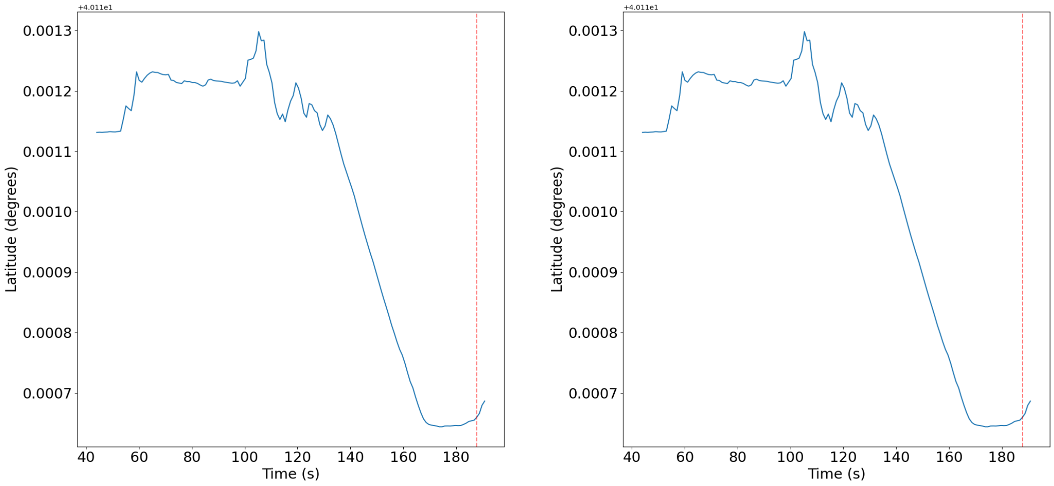
(d) Angular Velocity on the X-Axis Data from the walking test (dps).



(e) Angular Velocity on the Y-Axis from the walking test (dps).

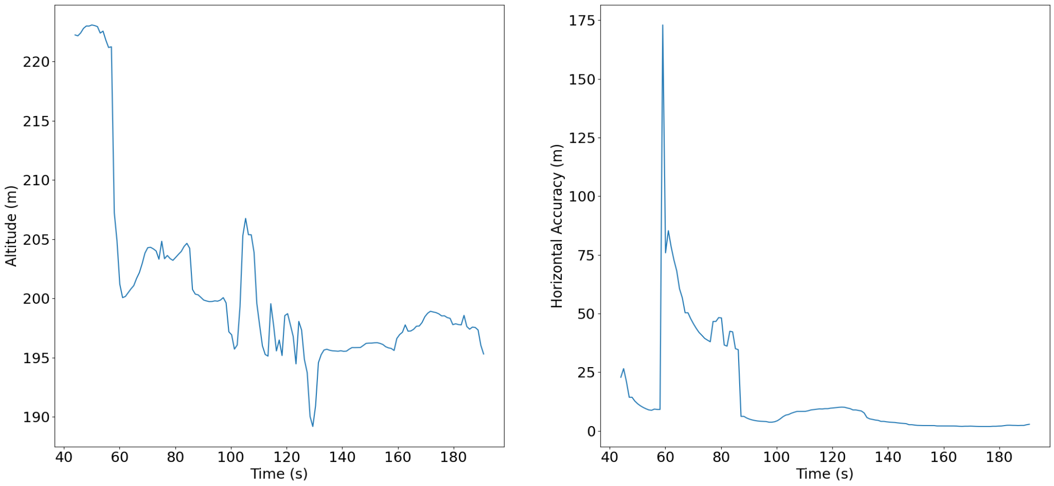
(f) Angular Velocity on the Z-Axis from the walking test (dps).

Table 1: Data Collected from IMU for walking test plotted versus time.



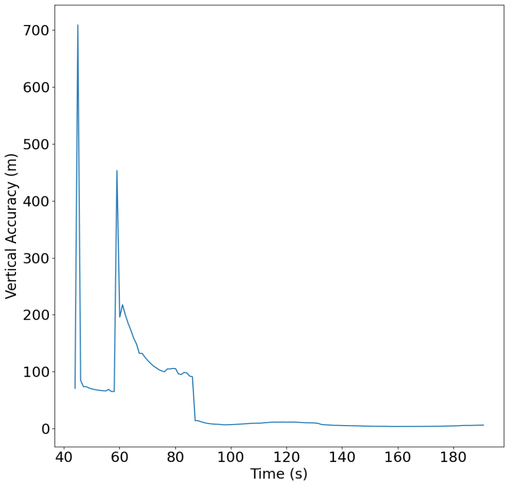
(a) Latitude for walking test.

(b) Longitude for walking test.



(c) Altitude for walking test.

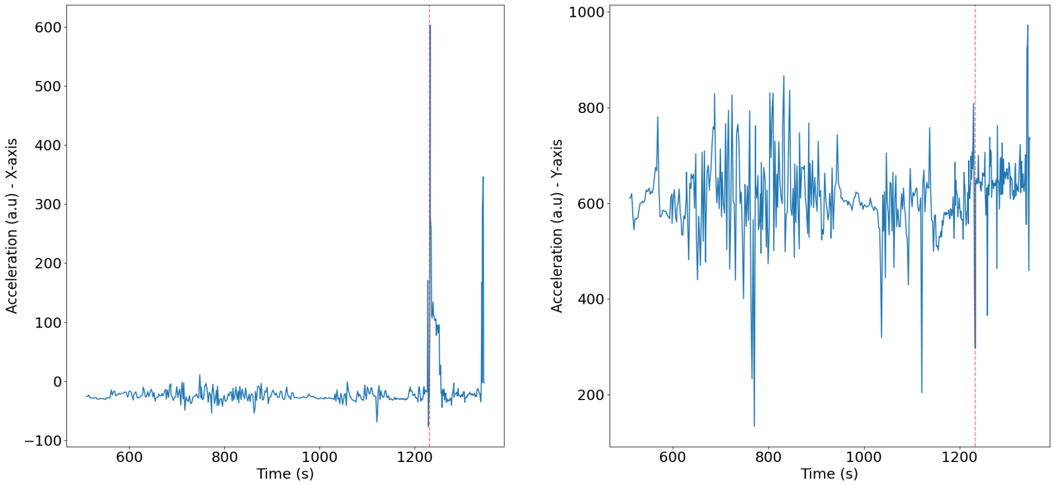
(d) Horizontal Accuracy for walking test (m).



(e) Vertical Accuracy for walking test (m).

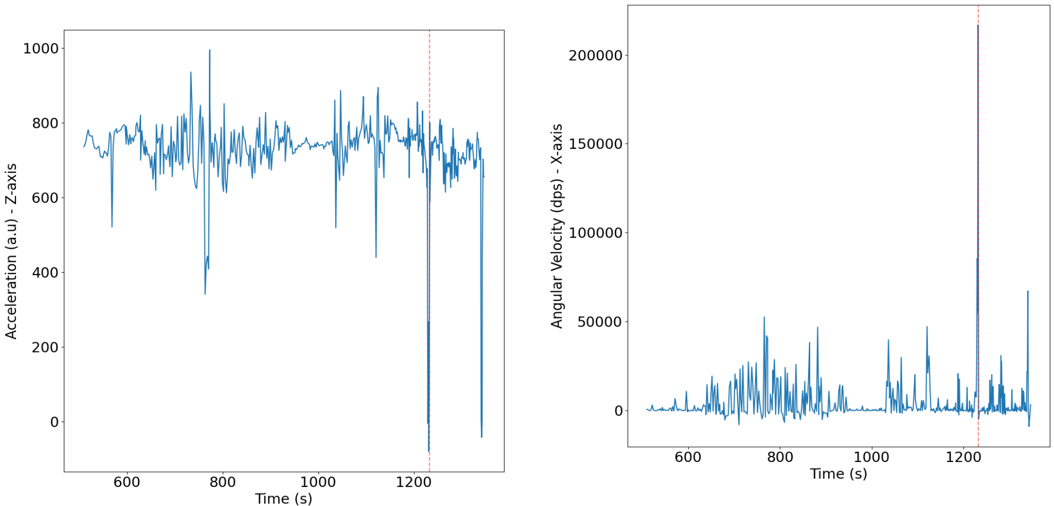
Table 2: GPS Data for walking test.

A.2 Horse Test Data



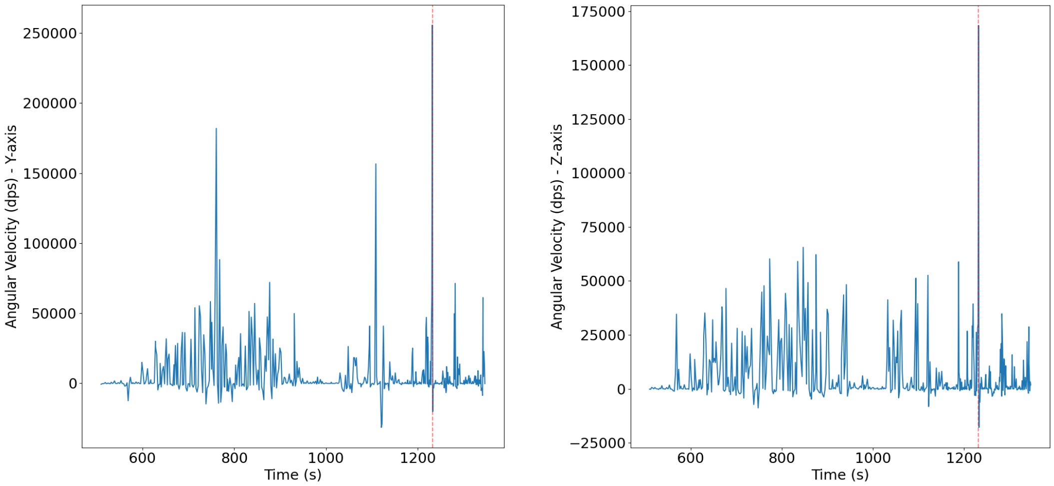
(a) X-axis Acceleration Data from horse test.

(b) Y-axis Acceleration Data from horse test.



(c) Z-axis Acceleration Data from horse test.

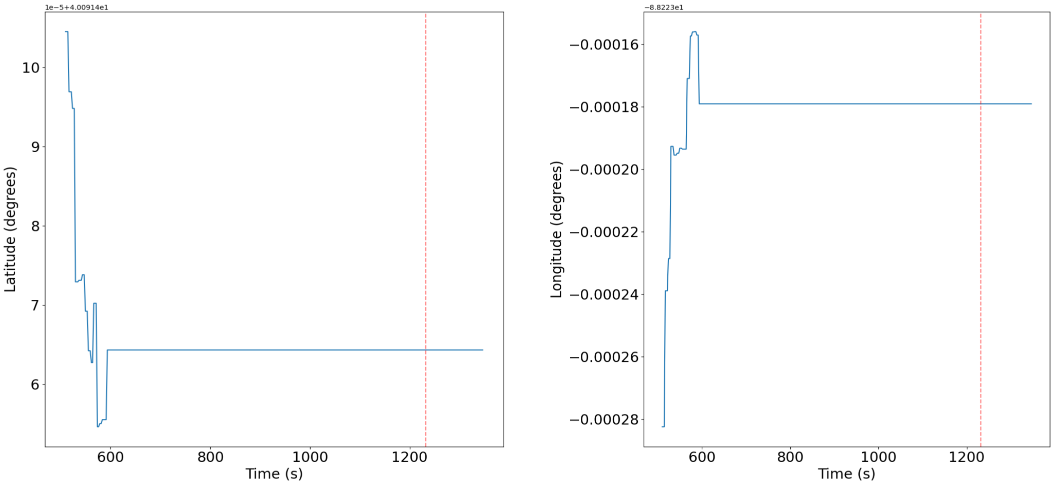
(d) Angular Velocity on the X-Axis from horse test (dps).



(e) Angular Velocity on the Y-Axis from horse test (dps).

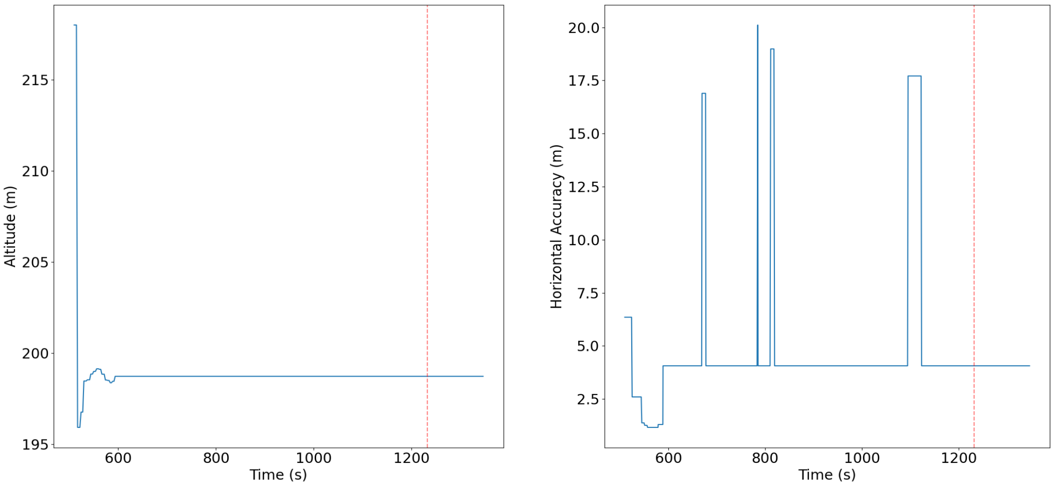
(f) Angular Velocity on the Z-Axis from horse test (dps).

Table 3: Data Collected from IMU for horse test plotted versus time. Vertical red line signifies when the horse laid down.



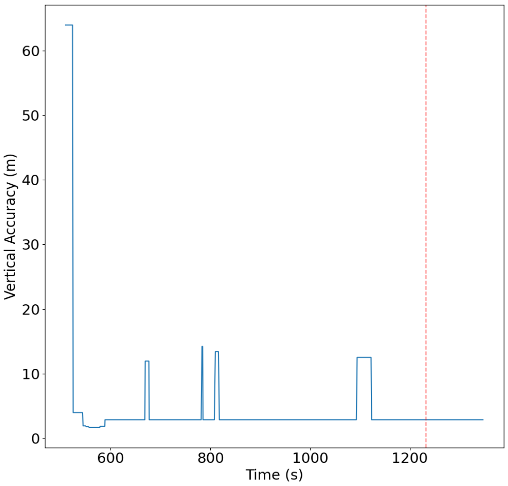
(a) Latitude for horse test.

(b) Longitude for horse test.



(c) Altitude for horse test.

(d) Horizontal Accuracy for horse test (m).



(e) Vertical Accuracy for horse test (m).

Table 4: GPS Data for horse test. Vertical red line signifies when the horse laid down.