PRELIMINARY RESULTS OF A LOW-COST GPS-BASED GLACIER MONITORING SYSTEM: TRAPRIDGE GLACIER, YUKON TERRITORY, CANADA.

by

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Abstract

A low-cost GPS system has been designed and built at the University of British Columbia, and is specifically designed to operate in the harsh conditions typical of glaciated environments. Two GPS prototypes were deployed on the Trapridge Glacier research site in the Yukon Territory, Canada. Results from 2002–2003 are post-processed, and comparisons with net movement estimates of Trapridge Glacier derived using traditional surveying methods are made. Results indicate that the GPS derived net movement estimates are in agreement with those of a traditional optical survey. A least-squares estimate is used to fit a two-velocity linear model to Trapridge Glacier, showing that the glacier exhibits a summer/spring velocity of $17.6 \text{ m a}^{-1}$, and a winter velocity mode of between $0.0–6.9 \text{ m a}^{-1}$. Experience from this field season is analyzed, and recommendations for the future development of the GPS system are discussed. Design and fabrication details, as well as detailed circuit board, schematics and part lists for the prototype units are provided.
Acknowledgements

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# Table of Contents

Abstract ii

Acknowledgements iii

List of Figures viii

List of Tables x

Chapter 1 Introduction 1

1.1 Thesis overview . . . . . . . . . . . . . . . . . . . . . . . . . . . 2

Chapter 2 Literature Review 4

2.1 GPS surveys on Svalbard glaciers, Norway . . . . . . . . . . . . 4
2.2 Comparison of ice velocities derived from satellite images and GPS 5
2.3 Precise point positioning using IGS orbit products . . . . . . . . . 6
2.4 Low-cost GPS volcano deformation monitoring . . . . . . . . . . . 7
2.5 Automated motion and stream measurements . . . . . . . . . . . . . 8
2.6 General text books . . . . . . . . . . . . . . . . . . . . . . . . . . 9

Chapter 3 Study Area 10

3.1 Trapridge Glacier environment . . . . . . . . . . . . . . . . . . . 11
3.1.1 Temperature . . . . . . . . . . . . . . . . . . . . . . . . . . . 11
Chapter 4  GPS Theory  
4.1 GPS satellite signals  
4.1.1 Selective availability  
4.2 Positioning concepts  
4.2.1 Differential carrier phase tracking  
4.2.2 Pseudo-range positioning  
4.3 Error sources in GPS positioning  
4.3.1 Satellite errors  
4.3.2 Propagation errors  
4.3.3 Receiver errors  
4.4 GPS surveying considerations  
4.4.1 Visible satellites  
4.4.2 Elevation cutoff mask  

Chapter 5  GPS Prototype  
5.1 Hardware  
5.1.1 GPS receivers and antennas  
5.1.2 Power supply  
5.1.3 Microprocessor and memory  
5.1.4 Environmental enclosures and mounting hardware  
5.2 GPS prototype operation
Chapter 6 Results

6.1 Receiver status and data collected ........................................... 34
   6.1.1 02GPS02 ......................................................... 35
   6.1.2 02GPS03 ......................................................... 35
   6.1.3 Damage to the prototypes .............................................. 35
6.2 Unprocessed GPS positions .................................................... 36
6.3 Post-Processed results .......................................................... 39
   6.3.1 Net glacier movement from GPS survey ............................... 41
6.4 Net glacier movement from optical survey .................................. 41
6.5 Annual velocity model for Trapridge Glacier .............................. 42

Chapter 7 Conclusions ................................................................. 44

Chapter 8 Recommendations for Further Work ................................ 46
8.1 GPS survey improvements and recommendations .......................... 46
   8.1.1 Processing software .................................................. 47
8.2 Hardware improvements and recommendations ............................ 48
   8.2.1 Memory storage and transfer ...................................... 48
   8.2.2 PCB design and component selection ................................ 49
   8.2.3 PCB layout and mounting ......................................... 50
   8.2.4 Measurement of battery voltage and temperature ................. 51
8.3 Software improvements and recommendations ............................ 51

Appendix A Visible Satellites at Trapridge Glacier .......................... 53
   A.1 Trapridge Glacier ....................................................... 53
   A.2 North pole and Equator ............................................... 54
# List of Figures

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.1</td>
<td>Trapridge Glacier study area</td>
<td>10</td>
</tr>
<tr>
<td>3.2</td>
<td>Trapridge Glacier location</td>
<td>11</td>
</tr>
<tr>
<td>3.3</td>
<td>1999 temperature, logger #12603</td>
<td>12</td>
</tr>
<tr>
<td>3.4</td>
<td>1999 battery voltage, logger #12603</td>
<td>13</td>
</tr>
<tr>
<td>3.5</td>
<td>Trapridge Glacier bulge evolution, 1980–1988</td>
<td>15</td>
</tr>
<tr>
<td>4.1</td>
<td>Differential GPS</td>
<td>19</td>
</tr>
<tr>
<td>4.2</td>
<td>GPS standalone pseudo-range positioning</td>
<td>20</td>
</tr>
<tr>
<td>4.3</td>
<td>GPS satellite orbits</td>
<td>25</td>
</tr>
<tr>
<td>5.1</td>
<td>UBC prototype GPS receiver units</td>
<td>27</td>
</tr>
<tr>
<td>5.2</td>
<td>2002 and 2003 GPS units</td>
<td>28</td>
</tr>
<tr>
<td>5.3</td>
<td>GPS prototype operation flowchart</td>
<td>32</td>
</tr>
<tr>
<td>6.1</td>
<td>Position of 2002 GPS receivers</td>
<td>34</td>
</tr>
<tr>
<td>6.2</td>
<td>Damage sustained by 02GPS02</td>
<td>36</td>
</tr>
<tr>
<td>6.3</td>
<td>02GPS02 unprocessed data</td>
<td>37</td>
</tr>
<tr>
<td>6.4</td>
<td>02GPS03 unprocessed data</td>
<td>38</td>
</tr>
<tr>
<td>6.5</td>
<td>GPS data from September 5, 2002</td>
<td>39</td>
</tr>
<tr>
<td>6.6</td>
<td>02GPS03 post-processed results</td>
<td>40</td>
</tr>
</tbody>
</table>
List of Tables

4.1 Error sources in GPS surveying ........................................ 22
4.2 GPS error sources and RMS effect on position ...................... 22
6.1 2002-2003 GPS displacement ........................................... 41
6.2 2002-2003 survey displacements ....................................... 42
7.1 Comparison of GPS and optical net movement ....................... 44
C.1 Trapridge pseudo-UTM coordinates .................................. 64
C.2 Trapridge WGS-84 coordinates .......................................... 64
C.3 Difference between Trapridge and WGS-84 ......................... 64
D.1 Electrical component list for the 2003 GPS prototype. .............. 66
D.2 Other components for the 2003 GPS prototype. ...................... 66
1. Introduction

Traditionally, surveying done in glaciated environments have tracked glacier movement through optical measurements. Theodolites and laser–range finders are typically used to determine the distance and bering to survey prisms mounted atop flow–maker poles inserted along a glaciers surface. Although accurate, this method is logistically expensive, having to deal with the cost of a surveyor, placement of survey prisms, and expensive surveying equipment. This method of optical surveying is incapable of operating in weather conditions with poor visibility, and is often limited to studying glacier movement during warmer months of the year; as colder periods can be quite inhospitable. Large glaciers and ice sheets are also difficult to survey optically, as the areas of interest may not all be visible from a single location. Some methods have been developed to track glacier movement during the winter, such as using cameras to photograph flow–marker poles during the winter months Harrison et al. (1989).

The Navstar Global Positioning System (GPS) has revolutionized the way in which surveying is done in the scientific community. A constellation of 24 orbiting satellites allows the precise determination of geographic coordinates anywhere on the planet, and has opened up new possibilities for tracking of glacial movement. GPS systems have been involved in glacier research for several years (Eiken et al., 1997, Frezzotti et al., 1998). The GPS systems typically deployed have been able to achieve centimeter accuracy, and have provided a robust method of tracking glacier movement. However, such systems can cost over $20,000 USD per installation site. The risk of damaging expensive GPS equipment has often resulted in shorter, campaign style surveys being undertaken to study glaciers; not often are continuous movement records obtained. The need for a low–cost
movement monitoring system is not restricted to glaciology. A low-cost volcano deformation system is developed by Janssen et al. (2002), with an installation cost of $3000 USD per site.

The goal of this project was to develop a low-cost GPS receiver system using inexpensive, off-the-shelf electronic components, and to demonstrate the feasibility of such low-cost systems to operate year-round in difficult glaciated environments. The resulting design will be available to the scientific community for further development, and incorporation into research projects.

The GPS system described in this thesis presents an inexpensive way to track year-round glacial movement at an installation cost of approximately $500 USD per site. These GPS systems can then be installed on the glaciers’ surface and used to track year-round movement. This will allow several sites on the glacier surface to be monitored autonomously throughout the year.

1.1 Thesis overview

This thesis discusses the design and fabrication of a prototype GPS deployed on the Trapridge Glacier in July 2002. Data collected from July 2002 to July 2003 is processed and compared with net movement measurements made from an optical survey. GPS prototypes made in 2003 are also discussed, however no data from these units is analyzed. A variety of scientific research papers are reviewed in Chapter 2. Papers dealing with both GPS theory, and those dealing with the application of GPS to specific research projects in both glaciology and volcanology are discussed. Chapter 3 outlines the environmental climate of the Trapridge Glacier, and details how the environment creates difficulties in employing an automated GPS system. The geological setting and physical geography
of Trapridge Glacier are also discussed. The basic concepts of GPS system are reviewed in Chapter 4. The theory of determining a geographic position from satellite signals is discussed. Various aspects of the GPS surveying system such as error sources and the effects of the satellite constellation geometry are also examined. Chapter 5 reviews the design of the GPS prototypes developed at the University of British Columbia, and overviews the components selected for the device. The operating methodology for the devices is also discussed. Results obtained from the GPS prototypes survey of Trapridge Glacier from July 2002 until July 2003 are discussed in Chapter 6. A summary of how the GPS prototypes preformed during the winter is made, and data collected by two GPS prototypes installed on the glacier during this period is processed and the net movement of Trapridge Glacier is estimated. A comparison of the net movement amounts derived from GPS surveying and optical surveying is made, and a GPS derived annual velocity model for Trapridge Glacier is proposed. Recommendations for Further work outlines directions for future research and development of the low-cost GPS system, and improvements in the survey setup. A detailed part list, schematic, and circuit board from the 2003 GPS prototype are provided in the appendix.
2. Literature Review

Although the papers discussed in this chapter deal mainly with more expensive dual-frequency geodetic grade GPS receiver systems, and involve analysis of the carrier-phase observation, they serve to outline the processing strategies and methodologies employed in GPS surveying. They also provide some background into the application of GPS surveys in harsh climatic environments which are the norm for glaciology.

2.1 GPS surveys on Svalbard glaciers, Norway

A multi-year GPS survey was undertaken on several of the glaciers in Svalbard, a territory of Norway. Traditional surveying methods were difficult to apply on the large glaciers of Svalbard, roughly 80 km in length. GPS was used to create surface profiles and to monitor several stationary sites (Eiken et al., 1997). Data was collected over a four year period from 1991 to 1995 using dual frequency GPS receivers. Static GPS sites were drilled into the glacier surface, while profiles were generated using snowmobile mounted GPS receivers. The static locations collected between 1 to 2 hours of data at a time and were able to track elevation changes over the four year period. Resulting accuracies were under 1 centimeter. Eiken et al. concludes that GPS is a suitable replacement for traditional surveying techniques used to measure glacier mass balance. They also conclude that with long enough collection periods and advanced software processing, the difficulties of GPS surveying in high northern latitudes can be overcome provided that more than five satellites are visible for long periods of time.
2.2 Comparison of ice velocities derived from satellite images and GPS

Ice motion estimates are crucial for determining the mass balance of the Antarctic ice sheet, yet logistical problems and challenging environmental conditions make surveying of Antarctica’s ice sheets and glaciers difficult. It has been shown that ice velocities can be inferred from synthetic aperture radar (SAR) satellite images, but there has been very little comparison with SAR results to GPS or traditional optical surveys. Multi-year GPS data has been used to compare Antarctic ice-sheet velocities derived from GPS surveying and SAR images (Frezzotti et al., 1998). Inferring the velocity from SAR images requires tracking features on the ice surface which are large enough to be visible in the SAR images. The Drygalski Ice Tongue was monitored using 73 points; the velocity tracked using the Landsat–1 multispectral scanner and Landsat thematic mapper. Using these images, the average velocity of the Drygalski Ice Tongue was found to be 700 m a$^{-1}$. GPS measurements made at various times between 1989 and 1994 were used to determine average ice velocities at similar points in time of those in the SAR images.

Comparison of similar points using both the GPS and SAR derived average ice velocities were found to agree to within 15–20 m a$^{-1}$ on the average, with differences of up to 70 m a$^{-1}$ at some locations. Frezzotti et al. conclude that estimated errors of ± 15–20 m a$^{-1}$ for SAR velocities could be quite large for small outlet glaciers exhibiting velocities of 100–200 m a$^{-1}$, but are of less significance for most of the major outlet glaciers in Antarctica with velocities of 400–1000 m a$^{-1}$. This suggests that although ice velocities can be inferred from
satellite images on large, fast moving glaciers, for smaller non-Antarctic glaciers
exhibiting flow velocities of 10–30 m a\(^{-1}\) it may be difficult or impossible to obtain
estimates of movement from satellite images alone.

### 2.3 Precise point positioning using IGS orbit products

As part of the procedure to determine the receiver’s geographic coordinates, the
GPS satellite positions in space must be known with a high level of accuracy.
These positions are transmitted continually by each satellite, but small pertur-
bations into the satellite orbits can be introduced. It is also required that all the
GPS satellites be synchronized to the same time system. Although atomic clocks
on board the satellites keep time to a very high degree of accuracy, there is still
a small clock drift between the different satellites. To synchronize all satellites
to a common time system all satellite clocks get updated at regular intervals
from ground stations. The International GPS Service (IGS) tracks all satellites
and publishes accurate descriptions of the satellite positions and clock drift free
through the internet.

Users in the GPS and geodetic communities have adopted as common pro-
cedure the use of IGS orbital products to achieve sub-centimeter to sub-millimeter
accuracy. This currently applies differential positioning concepts in which the ob-
servations from a minimum of two receivers are combined; the unknown receiver
position is then determined relative to a fixed reference station. This method is
popular and has been successfully applied in various applications. A significant
drawback of differential positioning is that it requires all observations be synchro-
nized between all receiving stations. A method has been outlined to make use
of the IGS final orbital products\footnote{IGS orbit products are released at several periods after the initial satellite observation is made with increasing accuracy. The final orbital product is the most accurate, and is normally available within two weeks of the observation date. http://igscb.jpl.nasa.gov/.} to perform corrections to undifferentiated dual frequency pseudo-range and carrier phase observations at a stand-alone location (Heroux et al., 2001). In doing so, they achieve centimeter level accuracy at a static location without the hindrance of a base station. However, to achieve such a high degree of accuracy it is necessary to apply various correction terms to the data. These include solid earth tides, ocean loading, and variations of the Earth rotation parameters (such as pole position and precession). The paper demonstrates the feasibility of using single site GPS measurements to obtain accurate geographic position estimates with centimeter scale accuracy using undifferentiated GPS observations. This paper also serves to highlight the importance of post-processing GPS data with information such as the IGS final orbits.

### 2.4 Low-cost GPS volcano deformation monitoring

Accurate knowledge of the deformation of volcanos is necessary for both predictive and scientific information about active volcanos. However, the harsh and sometimes dangerous environments of active volcanos do not make them good candidates for traditional surveying methods. Autonomous GPS sites constantly measuring the active deformation would be an ideal solution. A low cost GPS system was placed in Indonesia and evaluated as a system for remote volcano deformation monitoring (Janssen et al., 2002). A method of combining high accuracy geodetic GPS receivers along a perimeter of the volcano combined with low cost single frequency GPS receivers placed on the volcano is outlined in the paper.
The low cost single frequency GPS receivers were placed at various positions on the volcano and transmitted data to a base station through a VHF radio connection for processing. The outer GPS network was used to generate correction terms which were applied to the observations from the inner network on the volcano. The systems used 8086 PC based systems which ran a DOS based operating system and used 12 V batteries charged by solar panels. The base station was powered by an AC power system with an uninterrupted power supply. An installation cost of $3000 USD per site was achieved for the entire survey.

However, it was found that the PC based systems suffered from memory leaks, and that the DOS based software eventually stopped working due to memory loss. A microchip based system was recommended to replace the PC system as it has more capabilities for real time operations. Environmental problems were also an issue for the survey. Sulphur gas from the volcano seriously corroded the units, while strong winds destroyed one observation site. It was found that high level of noise attributed to ionospheric phenomenon prevented successful post-processing of the inner GPS network data and thus no information about the volcano deformation could be inferred from the GPS data (Janssen et al., 2002).

2.5 Automated motion and stream measurements

To attempt to reconstruct year–long glacier motion from the Fels and Black Rapids glaciers in Alaska, an automated method for taking pictures of survey poles was developed (Harrison et al., 1989). This novel method involved focusing photographic cameras at survey poles and automatically exposing the film at set time intervals using a mechanical device. This method was highly susceptible to
weather and visibility. This serves to highlight the lengths to which glaciologists were willing to go to recover year round movement records of the glaciers they were studying.

2.6 General text books

There exist several excellent textbooks on the topic of GPS data processing and methodologies that develop the theoretical models of GPS positioning and some of the logistical and methodological practices of GPS surveying techniques. Both Hoffmann-Wellenhof et al. (1997) and Leick (1995) both go into great detail on mathematical models of positioning.
3. Study Area

Figure 3.1: Trapridge Glacier, shown from the east. Photograph taken July 27, 2003

Trapridge Glacier is a small surge-type glacier located in the Steele Valley within the St. Elias mountain range, Yukon Territory, Canada. The glacier has an average ice thickness of 60 meters, and covers an area of approximately 4 square kilometers. During the past decade, Trapridge Glacier has exhibited average flow rates of 30 m a\(^{-1}\) (Kavanaugh, 2000). Trapridge Glacier last surged sometime during the 1940’s, and has been host to a variety of research projects in glaciology since 1969. Although Trapridge Glacier is surrounded by mountains, none appear above 10 degrees on the horizon, thus the visibility of available GPS satellites is not impeded. The central region of the glacier, highlighted in Figure 3.1, contains the bulk of the instruments which measure the conditions on the glacier, as well as the GPS receivers discussed in this study.
3.1 Trapridge Glacier environment

Trapridge Glacier exhibits the harsh environmental conditions which are typical of glaciated regions at high latitudes. To successfully mount a GPS surveying campaign on the glacier surface, it is important to have an expectation of the environmental conditions of the area. This precursory information will be used to predict the stress on electrical components, power consumption needs, and general robustness of any GPS system placed on the glacier.

3.1.1 Temperature

Temperatures at the glacier surface are monitored year round by sensors located within Campbell Scientific data loggers. Figure 3.3 shows the yearly temperature from 1999, collected from a data logger on the glacier surface. It is evident that the glacier experiences sub-zero temperatures throughout most of the year, and has a minimum daily temperature of around $-20^\circ C$ for nearly half of the year. It should be anticipated that the winter temperatures will drop below $-40^\circ C$, and
summer temperatures will rise above 25°C within the Hoffman enclosures.

![Temperature graph]

**Figure 3.3:** 1999 maximum and minimum daily temperature as recorded on the surface of Trapridge Glacier from within a Hoffman environmental enclosure. Data logger #12603.

Because these temperatures are measured within an environmental enclosure, it should be anticipated that the conditions outside the enclosure will likely be more severe, which may pose problems for GPS antennas mounted outside the Hoffman enclosure. Electrical components selected for use in the GPS unit should have, at a minimum, an operating temperature specification of –40°C.

### 3.1.2 Solar energy intensity

A qualitative estimate for the intensity of solar energy received throughout the year at Trapridge Glacier can be made through the battery voltages of data loggers deployed along the surface of the glacier. Each data logger is equipped with a 6.5 Amp–hour lead-acid battery, which is continuously charged by a solar panel. Figure 3.4 displays the battery voltage throughout 1999 as recorded from a data logger situated on the surface of the glacier. During the summer months, with ample solar energy, the data loggers do not draw enough current to pull the battery voltage down.
However, when there is little or no solar energy during the winter months, the battery voltage begins to drop. Figure 3.4 shows that from mid-November to June the area is receiving little solar energy, and the minimum daily battery voltage drops to under 11 V. Figure 3.4 also shows that for a short period in late December the maximum battery voltage dips down to below 11 volts; coinciding with the coldest part of the 1999 winter. This suggests that during this period there was essentially no solar energy. To be feasible with such a limited energy budget throughout most of the year, all electrical components will need to consume very small amounts of power.

3.2 Geological setting

The geology of the region is originally described in Sharp, R. P. (1943), and is also discussed in Stone (1993). Bedrock near the Glacier consists of highly fractured basalts and low-grade metamorphic carbonates. Two bedrock ridges are exposed immediately below the terminus of the glacier. Aligned nearly parallel to the
direction of ice flow, these ridges are being overridden by the glacier as it advances. A poorly sorted alluvium deposit lies in the depression between these two bedrock ridges, and is deeply cut by a network of stream channels.

3.2.1 Trapridge Glacier physical geography

Trapridge itself is composed of ice in the subpolar thermal regime, meaning that only the ice near the ice–bed interface of the glacier is below its melting temperature (Flowers, 2000). This temperate basal ice is bounded by a margin of cold ice at subfreezing temperatures (Stone, 1993). The glacier spans an elevation range of approximately 2300–2800 m, with an equilibrium-line altitude between 2400–2450 m (Flowers, 2000). Basal heat melts the ice near the ice–bed interface, allowing subglacial water to exist. In the last decade, Trapridge Glacier has seen annual movement on the order of 30 m, with 90% of this movement being accounted for by a combination of sliding and deformation from a saturated sediment layer, 0.3–0.5 m thick, situated underneath the glacier (Blake, 1992). A medial moraine, shown in Figure 3.1 carries debris from granitic intrusions in the headwalls of the glacier. The moraine gets pulled below the glacier surface near the center of the glacier, and emerges approximately 300 meters down glacier where it travels downwards and falls off the toe of the glacier.

A prominent feature of Trapridge Glacier is the large bulging toe, terminating in a vertical ice cliff; shown in Figure 3.1. The growth of this wave-like bulge from 1980 to 1988 is shown in Figure 3.5. However, the terminus of the glacier has more recently found to be stable or slightly advancing (Flowers, 2000). The development of wave-like bulges appears to be common for sub-polar surge-type glaciers and is thought to be precursory to the glacier entering a surging
phase (Clarke et al., 1991). Various photographs and written accounts have pinpointed the last surge event of Trapridge Glacier to have taken place sometime between 1941 and 1949. Comparison with arial photographs taken in 1951 show the glacier advanced more than 1 km from its position in 1941 (Stone, 1993).

3.3 Current research at Trapridge Glacier

Research has been conducted on Trapridge Glacier since 1969 and has been led by Dr. Garry K. C. Clarke at the University of British Columbia. A variety of sensors have been placed on the glacier surface, within the ice, and along the ice-bed interface which allow the physical conditions of the glacier to be monitored year-round. Because of the unique nature of the research, most of the sensors are designed and fabricated by researchers at the University of British Columbia. During the summer months, an extensive field research campaign is undertaken on the glacier to collect the data measured by all the sensors, to preform maintenance on current sensors, and to install new ones.

![Figure 3.5: Trapridge Glacier surface profiles from 1980 to 1988, showing development of the prominent bulge at the glaciers terminus (Clarke et al., 1991). Image source http://www.geop.ubc.ca/Glaciology/bulge.html](http://www.geop.ubc.ca/Glaciology/bulge.html)

As part of this research, traditional optical surveying techniques are used to track the position of a fixed array of dozens of poles embedded in the glacier surface. Measurements on this array are taken each year to track the surface
motion of the glacier. Profiles are also surveyed on the glacier surface, allowing the annual geometric changes of the glaciers surface to be tracked (Figure 3.5).

Surveying of the glacier geometry is only undertaken for a few weeks during each field research season. Because of this, there is little information to correlate glacier movement with mechanical phenomenon observed at the various sensors on the glacier throughout the year. A GPS surveying system operating year round on the glacier surface may be capable of capturing specific episodic motion events throughout the year.
4. GPS Theory

The Navstar Global Positioning System (GPS) consists of a satellite constellation of 24 satellites and 4 backup satellites. The satellites orbit with a period of 12.06 hours at a distance of approximately 20,200 km above the Earth’s surface with a speed of roughly 3.87 km s\(^{-1}\). This satellite constellation allows the determination of a precise geographic location anywhere on the planet in all weather conditions. The GPS satellite constellation is owned and operated by the United States Department of Defence, and use is provided free for civilian users. The intention of this chapter is to provide a basic understanding of how the GPS system works and how a geographic position is determined from the measurement of satellite signals.

4.1 GPS satellite signals

GPS satellites continuously broadcast two microwave carrier signals, denoted the L1 (1575.42 MHz) and L2 (1227.6 MHz) signals. Modulated onto this signal is a complex combination of current satellite orbit position (ephemeris), Keplerian elements describing the satellite orbit, and time. Through various techniques of signal processing, the time difference between the GPS satellite clock can be determined (Hofmann-Wellenhof et al., 1997). To speed up the acquisition of satellite signals by receiver units, each GPS satellite transmits information about the health and position of all satellites within the satellite constellation network, known as the almanac. Because of the amount of data involved, it can take up to 12.5 minutes to download the entire almanac.
4.1.1 Selective availability

The U.S. Military, worried about the potential use of GPS by enemy forces, incorporated an intentional degradation of the non-military signal by adding errors to both the satellite ephemeris and clocks, known as Selective Availability (S/A). Various methods of post-processing can be applied to eliminate S/A, but these rely on measuring the signal with two or more receivers at the same time. Luckily, the U.S. Military disabled S/A in May 2000 and has no intention of re-activating it in the future.

4.2 Positioning concepts

Various methods of determining the unknown geographic coordinates of the receiver can be used depending on the information collected by the receiver. Two common methods of position determination are known as pseudo-range positioning and differential carrier phase tracking. These methods can be used with a combination of various mathematical positioning models to determine the unknown geographic coordinates of the receiver.

4.2.1 Differential carrier phase tracking

Carrier Phase Tracking is accomplished by tracking the fractional phase of the L1 or L2 carrier signals as they arrive at two or more GPS receivers at the same time. The fractional phase of the L1 or L2 carrier signals arriving from multiple satellites is tracked over time, and is used to infer the distance to each satellite. Because the GPS satellites are such far distances away from the receivers, the signals at two receiver locations contain essentially the same errors induced from signal propagation through the ionosphere and troposphere. By differencing the
observations, of the multiple receivers, several of the error terms are removed. This differential procedure can be done using a single frequency, or using both the L1 or L2 frequencies (dual frequency). Dual frequency differential carrier phase tracking has yielded accurate geographic positions on the millimeter scale when properly processed.

Figure 4.1: Differential GPS requires that the satellite is observed by two or more receivers at the same instant of time.

High quality survey grade GPS equipment and advanced processing software is required for differential carrier phase positioning, making this method of positioning expensive and cumbersome. Figure 4.1 displays a common difficulty when attempting to perform a differential GPS survey: because the GPS receivers are at two different locations, it is possible that all satellites are not simultaneously visible to both receiving sites. The mathematical positioning equations for this method are outside the scope of this thesis, however the topic is thoroughly treated in both Hoffmann-Wellenhof et al. (1997) and Leick (1995).
4.2.2 Pseudo-range positioning

Pseudo-range positioning relies on determining the amount of time it takes for the signal to propagate from the satellite to the receiver. This transmission time is then used to determine the geometrical distance from the receiver to the satellite, as depicted in Figure 4.2.

![Figure 4.2: Standalone pseudo-range positioning relies on having an estimate of the geometric distances between the satellite and the receiver.](image)

Each GPS satellite transmits a unique pseudo-random signal modulated onto the L1 carrier frequency, known as the coarse acquisition (C/A) code. Each GPS receiver contains a copy of the C/A code for each satellite. By correlating the signal received from the satellite with the one contained within the receiver an estimation of the transmission time can be made.

Once a propagation time estimate is obtained, the geometric distance between the GPS receiver antenna and the transmitting satellite can be estimated. The pseudo-range is the apparent propagation time multiplied by the speed of light in a vacuum. Since the satellite and receiver clocks are not synchronized to the same time frame, there is an unknown timing error known as the clock bias.
The pseudo-range differs from the actual geometrical distance by the clock bias, propagation delays and other errors including relativistic and doppler effects. The pseudo-range for the \( j \)th satellite can be expressed as

\[
P_j = \rho_j + c\delta t_j + T_{trop} + T_{ion} + T_{rel} + \epsilon
\]  

(4.1)

where \( P_j \) is the measured pseudo-range, \( \rho_j \) is the exact geometric distance between the receiver and the \( j \)th satellite, \( c \) is the speed of light in a vacuum, \( \delta t \) is the unknown clock bias, \( T_{trop} \) is the signal path delay due to the troposphere, \( T_{ion} \) is the signal path delay due to the ionosphere, \( T_{rel} \) is the signal delay due to relativistic errors due to the high satellite velocity and \( \epsilon \) is an estimate of the noise. A non-linear equation relates the geometric distance between the \( j \)th satellite, and the unknown positions of the receiver (equation 4.2).

\[
\rho_j = \sqrt{(X_j - X)^2 + (Y_j - Y)^2 + (Z_j - Z)^2}
\]  

(4.2)

where \((X, Y, Z)\) are the three unknown coordinates of the GPS receiver and \((X_j, Y_j, Z_j)\) are the known coordinates of the GPS satellite as transmitted in the ephemeris. A minimum of four satellites must be observed to solve for the 3 unknown receiver coordinates, and receiver clock bias term. This system of non-linear equations can be linearized using a Taylor series expansion, and then solved in an iterative fashion. A detailed derivation of this iterative pseudo-range positioning solution is provided in Appendix B.
4.3 Error sources in GPS positioning

<table>
<thead>
<tr>
<th>Error Source</th>
<th>Effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>Satellite</td>
<td>Clock bias</td>
</tr>
<tr>
<td></td>
<td>Orbital errors</td>
</tr>
<tr>
<td>Signal Propagation</td>
<td>Ionospheric refraction</td>
</tr>
<tr>
<td></td>
<td>Tropospheric refraction</td>
</tr>
<tr>
<td>Receiver</td>
<td>Antenna phase center variation</td>
</tr>
<tr>
<td></td>
<td>Clock bias</td>
</tr>
<tr>
<td></td>
<td>Multipath</td>
</tr>
</tbody>
</table>

Table 4.1: Sources of error in GPS surveying, (Hoffman-Wellenhof, 1997).

There are three main error sources in GPS positioning: the satellite, signal propagation, and the receiver. Table 4.1 summarizes the error sources, and their effect. These errors effect the resulting position to varying degrees, and are summarized in Table 4.2.

<table>
<thead>
<tr>
<th>Error Source</th>
<th>RMS Error (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ionosphere</td>
<td>7.0</td>
</tr>
<tr>
<td>Troposphere</td>
<td>0.7</td>
</tr>
<tr>
<td>Clock &amp; Ephemeris</td>
<td>3.6</td>
</tr>
<tr>
<td>Receiver Noise</td>
<td>1.5</td>
</tr>
<tr>
<td>Multipath</td>
<td>1.2</td>
</tr>
</tbody>
</table>

Table 4.2: Error sources and their RMS error effect on the determined geographic coordinates of the receiver (Langely, 1997.)

4.3.1 Satellite errors

The satellite coordinates used in determining the geographic coordinates of the receiver are transmitted on the L1 and L2 frequencies along with parameters describing the satellites orbit, and time. The orbit along which the satellite will travel must be known ahead of time. External effects on the satellite, such as solar radiation pressure, can shift it out of its predicted orbit by as much as 20 m,
with RMS (root-mean-square) errors of 5 m (Langely, 2000). Each GPS satellite contains four atomic clocks to ensure that a stable timing system is maintained. Although these clocks are extremely accurate, they can drift slightly resulting in each satellite's clock not being synchronized to one another. These errors in the satellite's orbital position and clocks can result in errors of 1–5 m in the resulting geographic position.

A network of ground based GPS monitoring stations is operated by a variety of research and military groups across the globe. The International GPS Service (IGS) uses data collected by these sites to determine the true orbital path and an estimate of the clock drift for each satellite. These are offered at no cost to the GPS community on a variety of time scales. The most accurate are the IGS final orbits, and are available for download over the internet two weeks after the observation date.

Currently the IGS final orbits have an accuracy of 3–5 cm in the orbital position of the satellite and an accuracy of 0.1–0.2 nanoseconds on the satellite clock drift (Heroux et al., 2001). A substantial improvement in the accuracy of the geographic receiver coordinates can be made by re-calculating the receiver coordinates with the new satellite orbit and clock drift.

### 4.3.2 Propagation errors

GPS satellite signals experience various propagation delays as they travel through the Earth’s atmosphere. These errors are mainly due to the ionosphere and to the troposphere. The ionosphere is located from approximately 50 km–1000 km above the surface, while the troposphere begins at the surface of the Earth and extends to an altitude of 14 km. Satellites having low elevations with respect to
the horizon have higher ionospheric and tropospheric noise components because
of the greater amount of time spent travelling through these two layers. The
ionosphere is most active in a region extending approximately 20° on either side
of the magnetic equator, with high frequency scintillations experienced both in
this region, and over the poles (Janssen et al., 2002). Dual-frequency GPS re-
ceivers are able to remove this ionospheric effect by using a linear combination
of measurements on both frequencies (Janssen et al., 2002).

4.3.3 **Receiver errors**

The distance measured by the GPS receiver is the distance between the physical
phase centers of the GPS receiver and the GPS satellite. However the phase center
of the GPS receiver is unstable, and will change with the changing direction of
the satellite signal (Mader et al., 2002). Phase center variations can be accounted
for by modelling the response of the satellite antenna. The effect of phase center
variation is quite small and is not taken into account for our GPS prototypes.

A significant amount of receiver error can be generated through a process
known as multipath. Multipath is where GPS signals are reflected from surfaces,
such as the ground surface, or buildings, near the receiver and directed towards
the antenna. Because the signal has travelled along a longer path, it appears
that the satellite is further away than it actually is. Because ice is relatively
transparent to electro-magnetic waves, it is likely that multipath errors will not
be a concern for glacial GPS work.

GPS receivers contain inexpensive quartz oscillators which control the re-
ceiver clocks. By using a relatively inaccurate time keeping method there is an
inherent inaccuracy of the receiver clock resulting in positioning errors. Although
the unknown clock drift is taken into account and solved for in the iterative solution method, it can still incorporate large errors into the resulting position.

4.4 GPS surveying considerations

4.4.1 Visible satellites

The GPS satellite constellation consists of six orbital planes inclined at 55° many degrees. This configuration allows for maximum coverage over the continental United States and Europe and ensures that at least 6 satellites are visible from anywhere on the planet. In order to solve the positioning equations, four or more GPS satellites must be visible to the GPS receiver. For higher latitudes, the geometry of the satellite constellation can create difficulty in having enough satellites in view for long periods of time, as the satellites appear low on the horizon. This also makes the satellite orbits susceptible to being blocked by high topography, which can be especially troublesome if the GPS receivers are situated in valleys.

![Figure 4.3: GPS satellite orbits. The orbital planes of the satellites do not pass directly over the poles.](image-url)
4.4.2 Elevation cutoff mask

To prevent large errors from the ionospheric and tropospheric delays, satellites below a certain cutoff elevation are usually excluded from being used in the positioning solution. While this methodology can easily be applied for most GPS surveys, closer to the poles it becomes a problem. At the poles, fewer satellites will have a high elevation at any given time. This often results in fewer than four satellites located above the cutoff elevation, and will require the incorporation of satellites low in the horizon into the solution. For this thesis satellites at angle of 15° with respect to the horizon are not incorporated into the solution.
5. GPS Prototype

A specialized GPS receiver system to track glacier motion has been designed and built at the University of British Columbia, and has been operating at the Trapridge Glacier research site since July 2002. This chapter will discuss the design and operation of the GPS prototypes and review their main components.

![GPS receiver units](image)

*Figure 5.1: The GPS receiver units, designed and built at the University of British Columbia, have been operating on Trapridge Glacier since July 2002.*

From the beginning, the goal of the project was to develop a low-cost GPS system which is suitable for harsh glacier environment and capable of tracking glacier motion. The first prototypes were designed and built in the summer of 2002, and two units (displayed in Figure 5.1) were installed on Trapridge glacier. In the summer of 2003, a new design was implemented that made use of dif-
ifferent components, as well as a printed circuit board (PCB). A comparison of the 2002 and 2003 prototypes showing their installation in Hoffman enclosures is presented in Figure 5.2. It is clear that the incorporation of a PCB made the devices easier to handle, install, and transport since there are significantly fewer loose wires connecting the various components. The 2002 and 2003 prototypes share the same basic design and operation; the only changes being in the various electrical components selected. The final cost of the GPS prototypes is approximately $500 USD; this includes solar panels, Hoffman enclosures, and electrical components.

5.1 Hardware

Figure 5.2: On the left is the 2002 GPS receiver prototype, on the right is the 2003 GPS receiver prototype. The decision to use a printed circuit board made it much easier to operate on the units in the field.

In Chapter 3 it is determined that all components used in the GPS prototype must be able to operate at temperatures as low as −40°C, and consume very little power. The following sections will discuss the various components used
in the prototypes and outline some of their operating specifications. A detailed schematic, PCB layout and part list for the 2003 prototype can be found in the appendix.

5.1.1 GPS receivers and antennas

The GPS receivers handle all aspects of decoding and tracking the satellite signals. Low power Trimble Lassen SP GPS receivers were selected for the 2002 prototypes, while Garmin 15L GPS receivers were selected for the 2003 models. Both of these GPS receivers record pseudo-range and carrier phase data on the L1 frequency, and output the data through a serial data connection. The normal operating power consumption of these receivers is less than 100 mA, and both have operating specifications of –40°C.

Skymaster II GPS antennas were selected for the 2002 unit, while Mighty Mouse II antennas were used in 2003. These antennas both offered 28 dB of signal gain, which serves to increase the signal–to–noise ratio. Both antennas are encased in a sturdy environmental packaging and have a –40°C operating temperature specification. The Skymaster II antennas used 12 mA of current, while the Mighty Mouse II draws only 5.0 mA.

5.1.2 Power supply

All aspects of the GPS prototypes are powered by 12 V 6.5 Amp-hour lead acid batteries. The batteries are continuously charged by 15 Watt solar panels. Power from the solar panel is regulated to ensure that the batteries are not over charged and to ensure that no large voltage spikes are sent to the battery. This battery and solar panel configuration has been in use at Trapridge glacier for nearly a
decade and has proved reliable for use with data loggers. Since all components in the GPS system are powered at 3.3 V, two integrated-circuit voltage regulators are used to step down the 12 V battery to 3.3 V and supply power to the electronic components. One power supply is used to provide power to the microcontroller, while the other is used to provide power to the GPS and memory. This regulator can be switched on and off by the microcontroller to turn on or off the peripherals.

5.1.3 Microprocessor and memory

The microprocessor is the brain of the device. It controls all aspects of the device operation including timing, powering the peripherals, communication between the GPS and memory, and communication between the GPS device and a personal computer. The environmental constraints of the systems required a microprocessor with extremely low power consumption and a relatively low operating temperature. Z-World Rabbit microprocessors were selected to operate the 2002 GPS prototypes, while Texas Instruments MSP430 microprocessor was selected for the 2003 GPS units and are recommended for future versions of the GPS devices. Both of the Z-World and Texas Instruments microprocessors operate with very little power and at –40° C. The Texas Instruments MSP430 uses only 250 µA of current when operating, and 1.6 µA in low power mode. An external quartz oscillator was used to ensure that accurate timing was kept over a wide range of temperature conditions.

Both microprocessors contain onboard flash memory, which is used to store programs and data. The C computer language was used to write the software which operates the devices. This enabled the software to be written and debugged on a personal computer, and then transferred to the devices where it is written
into the flash memory. The use of C allowed various software components from
the first prototype to be re-used on the second prototype, and will allow the GPS
system to be easily ported to different microprocessor architectures and future
systems.

Atmel data flash cards were used in both 2002 and 2003. In 2002, 4
megabyte cards were used and increased to 8 megabytes in 2003. These flash
memory cards contain no moving parts, and can retain their memory when there
is no power; providing a robust system for storing the data. The cards also satisfy
the environmental operating specifications needed for work on the glacier.

5.1.4 Environmental enclosures and mounting hardware

With the exception of the GPS antennas, all components are mounted within
Hoffman environmental enclosures. These enclosures have proved reliable for
housing electronic components and have been used regularly for the Trapridge
Glacier field research.

To suspend the GPS receivers above the glacier surface, two inch diameter
steel pipes were drilled several meters into the glacier surface. Approximately
one meter is left outside of the ice surface to allow the Hoffman box and solar
panel to be mounted and to elevate it above the snow level. The solar panel is
mounted facing southeast towards a topographic low-point, ensuring the panels
obtain the maximum amount of solar energy.

5.2 GPS prototype operation

The basic operation of the GPS devices follows the flow chart in Figure 5.3. Once
powered up, the device tracks GPS satellites until it acquires enough satellites to
determine its position. All information measured by the GPS about the estimated positioning, and signals received from the satellite is then stored in the flash memory. The limiting factors for the amount of data collected by the devices each day is the available power and the amount of memory storage space available. For 2002 the devices were programmed to recorded 2 minutes of satellite observation data each day. This amount was increased to 5 minutes for the 2003 prototypes.

![Flowchart](image.png)

**Figure 5.3: Flowchart for the GPS device operation. It is programmed to power on and collect GPS data each day, then return to low power mode until awoken by an internal alarm.**

As part of the transmitted ephemeris, the satellites send the current time GPS time\(^1\). The device then sets its internal clock to match GPS time, as well as an alarm to wake itself up the next day. All peripherals with the exception of the microprocessor are then turned off. The microprocessor enters a low power mode; only operating the internal clock and checking the wake-up alarm. The alarm set to wake-up the devices was set for 3 pm each day. This time was chosen because

\(^1\)GPS time is synchronized to Coordinate Universal Time (UTC), with the exception that no leap seconds are inserted to synchronize it to the irregular rotation of the Earth. Currently GPS time is ahead of UTC by 13 seconds
it would be at a warm time of the day and the battery would have acquired the most of the power it would receive through solar energy that day. Once powered up, the operation repeats itself. Should the device be unable to track satellites, it sets the wake-up alarm based on its current clock and enters the low power mode. It will repeat this cycle each day until a satellite lock is acquired.

Because each GPS device on the glacier synchronizes its internal clock to match the GPS constellation time, they will each be powering up at the same time every day and should track the same satellites over the same time period. This methodology will potentially allow for differential post-processing to be applied to the data collected by the GPS receivers located on the glacier.
6. Results

Two GPS devices, denoted 02GPS02 and 02GPS03\(^1\), were deployed on Trapridge glacier in July 2002 and left to operate throughout the winter. The two GPS prototypes were separated by a distance of \(\sim 150\) meters along a line roughly parallel with the direction of glacier flow; their positions on the glacier are shown in Figure 6.1. In July 2003 these units were re-visited and their data was collected.

![Figure 6.1: Initial installation positions of 02GPS02 and 02GPS03 on Trapridge Glacier. The two units were installed along a line roughly parallel to the direction of glacier flow.](image)

6.1 Receiver status and data collected

Upon inspection in July 2003, both GPS receivers were found to be intact, having survived the winter on Trapridge Glacier. Device 02GPS03 was operating perfectly when tested, while 02GPS02 had suffered from a battery failure sometime during the winter.

\(^1\)Convention in Trapridge Glacier research is to name sensors placed on the glacier YYXXNN, where YY is the two digit year, XXX denotes the type of sensor, and NN is a two digit identifier.
6.1.1 02GPS02

Unit 02GPS02 collected a total of 62 days of data from July 21st, 2002, until December 3rd, 2002, at which time it suffered a battery failure. In the 2003 field season, it was discovered that the SunSaver solar regulators used to charge the batteries required a large amount of power to perform their internal operations. Should the battery voltage drop below a certain level, the regulator would no longer operate and the battery would die completely. Upon replacing the battery, unit 02GPS02 was found to be fully operational.

6.1.2 02GPS03

Unit 02GPS03 collected a total of 118 days of data from July 11th, 2002, until January 5th, 2003. Unit 02GPS03 was found to have a fully charged battery and to be fully operational when tested, yet it stopped collecting data on January 5th 2003. Since approximately 1 megabyte of its 4 megabyte card was used, it is likely that its failure was due to a software bug. Since no record is kept of when the device wakes-up, it is unclear whether 02GPS03 was operational on any days between January and July 2003, or if it remained dormant during this period.

6.1.3 Damage to the prototypes

Although both devices were operational upon inspection, 02GPS03 was found to be tipped at a large angle, with its mounting pole being bent. This was most likely due to strong winds experienced sometime during the winter. 02GPS02 was found to have sustained damage to its Hoffman enclosure, as shown in Figure 6.2, where a threaded screw hole was ripped from the sturdy Hoffman enclosure. These damages illustrate the extreme conditions experienced by the receivers face
during the winter months on Trapridge Glacier. It is unclear whether the events leading to the damage of the two devices is related to periods where they do not collect data.

6.2 Unprocessed GPS positions

The GPS receivers determine their geographic coordinates automatically as they track the satellites. This positioning is recorded in a data file along with the the raw satellite information. The positions determined by 02GPS02 and 02GPS03 is presented in Figures 6.3 and 6.4 respectively. Since geographic coordinates are determined by the GPS receivers once every 5 seconds, for 2 minutes each day that they collected, the results in Figures 6.3 and 6.4 are the average position for each day. Both receivers continued to operate throughout July 2003. Unfortunately, an error resulted in the data collected by 02GPS02 to be lost, so only the results from 02GPS03 show results from the summer of 2003.

Both 02GPS02 and 02GPS03 show large gaps in their recorded data, and both failed to collect data during the month of November. Because there is
no record of when the devices wake-up, it is unclear whether the devices awoke during these periods, or if they remained dormant. Possible causes for these gaps may be a failure to adequately acquire a lock on the satellite signals, insufficient battery voltage, or a software malfunction.

The geographic locations determined by both GPS devices show a large amount of scatter. From July–August 02GPS02 appeared to collect data with an expected amount of scatter, on the order of ±10 m. 02GPS02 then remains dormant for 2.5 months, during which time it collects no data. The device then begins to collect data in October. Positions determined by 02GPS02 from October–December, exhibits an extreme, showing variations of over 1000 m from the mean (Figure 6.3). The poor quality of data collected by 02GPS02 in the later part of the year after a period of being dormant may be caused by damage to the GPS antenna, damage to the GPS receiver, or a low battery. Because there is no data

Figure 6.3: Unprocessed geographic coordinates from 02GPS02. Easting and Northing values have been subtracted from the mean.
from the summer of 2003 for this device, it is unclear whether this GPS device continued to collect data with a higher than expected amount of error. Positions determined by 02GPS03 from July–January 2003 exhibit scatter on the horizontal positions on the order of ±10 m. Data was collected by 02GPS03 in July of 2003, and exhibits similar amounts of scatter. A definite movement trend can be seen in the horizontal coordinates for 02GPS03. The Easting coordinate increases on the order of 10–15 m, and the horizontal component shows very little movement trend. This matches the general movement trends observed on Trapridge Glacier, as discussed in Chapter 3.
6.3 Post-Processed results

GPS data collected by both receivers was post-processed using the Rhino Post-Processor PLUS (Rhino) software package, available from US Positioning Group\(^2\). The C/A code derived pseudorange positions were re-processed using IGS Final orbits. Although carrier phase data was recorded by the GPS receivers, the two minute observation length did not provide enough data to process the carrier phase, and was not used in determining the post-processed positions. Because the record from 02GPS02 does not contain very much data, and exhibits a large amount of scatter, only the post-processed results of 02GPS03 will be analyzed.

\[ \text{Figure 6.5: Post–processed GPS data collected September 5, 2002. The reported error on the position, and horizontal coordinates subtracted from the mean.} \]

An additional processing step was done to remove coordinates which had high estimated errors on their latitude and longitude. Figure 6.5 shows an example of the estimated errors in the easting, northing and elevation component,

\(^2\)Rhino Post-Processor PLUS available at [http://www.uspositioning.com](http://www.uspositioning.com)
along with the horizontal coordinates for data collected on September 5, 2003 using 02GPS03. Coordinates exhibiting high error estimates were not included in the calculation of the average daily position. This essentially removes the data points that were collected right when the GPS obtained a satellite lock. Figure 6.5 shows that using points with error estimates of less than 1.0 m Easting and 1.6 m Northing, obtains an average position which differs by 2.5 m Easting, and 7.0 m Northing is obtained than by using all the positions determined by the GPS that day.

\[ \text{Figure 6.6: Post-processed geographic coordinates from 02GPS03. Easting and Northing values have been subtracted from the mean.} \]

The results of post-processed data, shown in Figure 6.6, show some improvement in the derived easting coordinate for 02GPS03, and negligible improvement for the northing and elevation. It is likely that not long enough observation periods were collected each day by the GPS devices for post-processing with IGS final orbital ephemeris to result in significant improvements of the resulting
geographic positions.

Although the Rhino software is not explicit in how it produces its error estimate, it is likely a combination of the satellite geometry and the amount of scatter present in the data. It appears under-estimate the amount of error present in the data. For most days of GPS observations, errors determined by Rhino for the easting and northing components usually reach as low as ~0.5 m. By looking at the resultant averages in Figure 6.6, it is clear that the overall positioning error is on the order of ±5 m in the Easting, and ±10 m for the Northing.

6.3.1 Net glacier movement from GPS survey

An estimate of the net glacier movement was made by subtracting the results from July 2002 and July 2003 of the GPS data. The post-processed data from 02GPS03 was used. The resulting net movement estimate is summarized in Table 6.1.

<table>
<thead>
<tr>
<th>ID</th>
<th>East(m)</th>
<th>North(m)</th>
<th>Elev.(m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>R26C20</td>
<td>12.1</td>
<td>2.90</td>
<td>-5.05</td>
</tr>
</tbody>
</table>

Table 6.1: 2002-2003 net movement of Trapridge Glacier using a least-squares estimate from the post-processed results of 02GPS03.

6.4 Net glacier movement from optical survey

A traditional optical survey using a theodolite and laser range finder was undertaken by Jessica Logher in 2002 and 2003 as part of the Trapridge Glacier field research. Survey prisms are placed atop marker poles embedded in the glaciers surface. These poles remain embedded in the glaciers surface year-round, and allows the net annual glacier movement to be determined. Two survey prisms
close to the GPS sites were selected. By subtracting their coordinates from 2003 to 2002 the net glacial movement for the year (Table 6.2).

<table>
<thead>
<tr>
<th>ID</th>
<th>East(m)</th>
<th>North(m)</th>
<th>Elev.(m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>R26C20</td>
<td>11.74</td>
<td>1.89</td>
<td>-3.62</td>
</tr>
<tr>
<td>R32C20</td>
<td>12.11</td>
<td>2.10</td>
<td>-1.28</td>
</tr>
</tbody>
</table>

Table 6.2: 2002-2003 displacements as measured by the optical survey.

Horizontal displacements at both survey targets are similar, and show movement on the order of 12 meters East, and 2 meters North. The discrepancy in the elevations taken at the two points may be due to melting experienced by the flow poles causing one of them to sink further into the ice than the other, and deformation of the survey poles by wind during the winter. Although the survey poles report an elevation drop on the order of meters, the elevation changes are more likely on the order of 0.1–0.5 m for the two survey positions.

6.5 Annual velocity model for Trapridge Glacier

A least-squares method was used to fit two linear functions to the post-processed data of Figure 6.6. The results of this fitting are shown in Figure 6.7. The two blue lines in Figure 6.7 are interpolations between the least-squares derived estimate for the first six months of the year, and the data from July 2003. The two lines correspond to upper and lower limits for the velocity during the last 6 months of the year.

The velocity for the first half of the year is found to be 17.6 m a$^{-1}$. To determine how sensitive this velocity estimate was the first and last data points in this period, the least squares estimate was performed removing the first three data points, and again removing the last three data points. It was found with
these points removed varied with $\pm 1.1 \text{ m a}^{-1}$.

The velocity for the January–July 2003 is estimated by an upper and lower bound to the velocity during this period. The lower bound is taken to be $0.0 \text{ m a}^{-1}$, and the upper bound is found to be $6.9 \text{ m a}^{-1}$. The occurrence of a spring/summer velocity mode and a winter mode has been observed on other glaciers (Willis et al. (2003), Hubbard et al. (1998)).
7. Conclusions

The Global Positioning System has revolutionized scientific surveying. Using GPS receivers, it is now possible to autonomously track movement of natural phenomenon of interest to scientists such as glaciers, landslides, and volcanos and obtain high accuracy movement records which span several years. However, high accuracy GPS equipment can cost over $20,000 USD per installation site, and require sophisticated processing software. With the possibility of damaging or losing equipment when placed in difficult environments, many scientists choose not to use year-round GPS receivers.

An inexpensive GPS receiver system, built using off-the-shelf components, has been designed and built at the University of British Columbia. To fit within constraints of cost, power, and environment, low accuracy L1 frequency GPS receivers were selected. Although these GPS receivers yield accuracies much less than expensive, survey grade GPS receivers, they still have the potential to obtain useful movement information. Two GPS device prototypes were deployed on the Trapridge Glacier research site in the Yukon Territory in July 2002; and re-visited in July 2003. Both prototypes were in working operation, having survived the harsh arctic winter.

<table>
<thead>
<tr>
<th>ID</th>
<th>East(m)</th>
<th>North(m)</th>
<th>Elev.(m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GPS Surveying</td>
<td>12.1</td>
<td>2.90</td>
<td>-5.05</td>
</tr>
<tr>
<td>Optical Surveying</td>
<td>11.95</td>
<td>2.00</td>
<td>-2.45</td>
</tr>
</tbody>
</table>

Table 7.1: Net movement of Trapridge Glacier from July 2002 to July 2003 using GPS and optical surveying methods.

The data collected by the GPS prototypes spans 6 months, and has been post-processed using IGS Final orbital products. Although the geographic positions determined by the GPS prototypes have an estimate noise of ±5.0 meters,
averaging was used to estimate the net annual movement of Trapridge Glacier. The result obtained through least squares is in agreement with the amount of net movement obtained through traditional optical surveying, and is summarized in Table 7.1.

A linear two-velocity model was determined from the post-processed GPS results using a least-squares method. This velocity model suggests that Trapridge Glacier experiences summer/spring velocities of $17.6 \text{ m a}^{-1}$, and winter/fall velocities of between $0.0–6.9 \text{ m a}^{-1}$. Studies of Trapridge Glacier have shown that it has experienced net annual movement on the order of $30 \text{ m a}^{-1}$ (Kavanaugh, 2000). Results of this study suggest that Trapridge Glacier is experiencing annual movement rates of approximately $12 \text{ m a}^{-1}$.

This study demonstrates the feasibility for low-cost GPS receivers to track glacier motion in a harsh arctic setting. This system, which can easily be fabricated by scientists, has demonstrated the potential for low-cost GPS receivers of this nature to obtain useful scientific information.
8. Recommendations for Further Work

The results presented in this thesis demonstrate the ability of low cost GPS systems to operate in harsh glaciated environments. Experience gained through operating the devices in the field from both the 2002 and 2003 field seasons should be incorporated into future devices. Experience from the 2003 field season illuminated several shortcomings of the current design. The following sections are possible improvements which can be made to both the design of the GPS system hardware, and to the survey design and data processing.

8.1 GPS survey improvements and recommendations

The 2002 GPS devices analyzed in this these each measured two minutes of GPS data per day. This short observation length did not yield adequate data for post-processing and limited the post-processing to C/A code derived pseudo-ranges, and it is unlikely that the increase to five minutes observation lengths in the 2003 models will improve this result. Significant improvements in accuracy may be obtained by using differential processing techniques on the L1 carrier phase. Differential post-processing require much longer observation periods in order to track changes in the carrier phase. Hoffman-Wellenhoff et al. (1995) recommend, that at a minimum, 20 minutes of observation be used for differential processing, plus additional time for large receiver/base station separation distances. The observation length for the GPS prototypes should be determined through field testing, as it will depend on both the GPS receiver/antenna, and the processing software involved. The additional power and memory requirements needed to accommodate the longer observation period need to be addressed to ensure that
it is realizable within the constraints of the system.

Differential processing will also require a stationary base station. This base station should be located on the lateral moraine of Trapridge Glacier, such that it is visible from the LN survey site to allow its location to be accurately surveyed. Multiple base stations should be deployed to guard against the possibility of a base station failing. Additional base stations could also be incorporated into the differential post-processing, such as done in Janssen et al. (2002).

Currently, the GPS receivers power on at 3 pm each day. Although it may be possible to determine a wake-up time each day to ensure that an optimal satellite constellation geometry is obtained, it is not recommended to do so. Changes to the wake-up time could cause all receivers on the glacier lose their time synchronization, or cause the device to wake-up at times when it is colder and darker.

### 8.1.1 Processing software

Complex software packages are required to post-process GPS data. Several professional processing packages are available, but at a cost of several thousand dollars. Two free processing packages available are GAMIT/GLOBK\(^1\) and GIPSY-OASIS\(^2\). The GAMIT/GLOBAK software was tested on the 2002 data, but I was unable to get the software to work. Further investigation needs to be done to explore the potential of these software packages to post-process the GPS data. The U.S. Positioning Rhino Post Processing software used to post-process the 2002 data, and is available for around $300 USD. In addition to the post-processing software, various pieces of software were needed to convert the data into the

\(^{1}\)GAMIT: http://www-gpsg.mit.edu/~simon/gtgk/

\(^{2}\)GIPSY-OASIS: http://gipsy.jpl.nasa.gov/
8.2 Hardware improvements and recommendations

Various shortcomings in the design and layout of the electronic components surfaced when the GPS devices were deployed and operated in the field.

8.2.1 Memory storage and transfer

The Garmin GPS 15L receivers currently output approximately 0.3 kilobytes-per-second. With this data rate, collecting twenty minutes of data per day for an entire year would require approximately 1.3 gigabytes of storage, although some of the data output by the GPS can be neglected to reduce this memory requirement. The current GPS device uses 8 megabyte flash memory, which is clearly not enough to handle the large amount of data. To further reduce the storage requirement it may be possible to reduce the sampling frequency. The 2002 GPS prototypes used a sample frequency of 0.2 Hz (1 observation every 5 seconds) which allowed them to maximize their 4-megabyte flash memory. The effects of reducing the sample frequency may create difficulties when preforming the differential post-processing, and should be investigated further.

Obtaining the GPS data is currently handled by connecting the GPS to a personal computer via the serial port. Raw binary information is sent over the serial connection at a speed of 9600 kbps (kilo-bits per second). At this rate, an 8 megabyte memory card would take just under 2 hours to transfer. Furthermore, there is no error checking on the communication so there is a large possibility for transfer data errors or missing data. This method of transferring data also

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3 The Receiver Independent Exchange Format (RINEX) is a format for storing the GPS observations for processing.
requires using a laptop on the glacier surface, which limits the weather conditions and mobility of the operator in gathering the data.

A new memory storage system needs to be developed. To transfer this large amount of data to a computer, it is necessary to use a specialized card reader. To be compatible with these card readers, the data must be stored in using either the FAT–16, or FAT–32 filesystems\(^4\). Compact flash or Multimedia (MMC) cards with sizes of 128 or 256 megabytes should be selected for the new memory system. This will allow cards to be swapped from the GPS devices and transferred at a later time.

### 8.2.2 PCB design and component selection

Thru-hole components should be selected over surface mount components when they are available. This will make it easier to replace components in the field, and will remove dependency on specialized soldering equipment and expertise required to solder surface mount components. However, some parts, such as the Texas Instruments microcontroller are not available in thru-hole packaging. Two options for the microcontroller are to design and build a header board, or purchase one from a vendor\(^5\).

Header pins can be incorporated into the circuit board for a very small cost. These pins will allow multimeters and other testing equipment to be easily attached to the various components on the circuit board, as the current design makes this nearly impossible because of the small component size. Experience has shown that in some instances, the probe of the multimeter can connect two pins together, causing a short circuit, and results in damage to the device. Header

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\(^4\)File Allocation Table (FAT) formats are format for storing data developed by Microsoft.\(^5\)MSP430 header boards are available from Olimex, [http://www.olimex.com](http://www.olimex.com)
pins will also enable new features to be added and tested to the devices without re-designing the circuit board.

Incorporating protection diodes into the design of the power supply will prevent the board from sustaining damaged in the event that the battery is attached with the wrong polarity. It was also found that the current voltage regulators did not provide adequate protection from voltage spikes caused by static-electric discharge when operator comes in contact with the device. The operator should ensure adequate grounding when working on the device, and a proper grounding system should be purchased for future development.

8.2.3 PCB layout and mounting

The current PCB layout positions the GPS receiver on the underside of the circuit board. This creates a serious difficulty when attaching the GPS antenna, and required that the back-plate be removed when attaching the antenna. Future designs must ensure that the layout allows convenient access when attaching the antenna, battery connectors, or memory card when the device is inside the Hoffman enclosure with the battery.

The GPS device is mounted with machine screws to a steel back-plate within the Hoffman enclosure, and is elevated using plastic stand-offs. To remove the device, it is first required to remove the back-plate to access the mounting screws. This process can take considerable time and can lead to damage of the device. Also, in the event that the GPS receiver itself was in-operable, the entire GPS device had to be removed by the same procedure. Future designs should allow for quick removal of the GPS receiver and the GPS board which will allow for quicker maintenance and troubleshooting, and will reduce the risk of
accidental damage to the device when removing it from the Hoffman enclosure.

8.2.4 Measurement of battery voltage and temperature

The MSP430 chipset contains several analogue–to–digital (A/D) converters which can be used to measure the voltage of the 12 V battery. Software logic could then be implemented to prevent the system from running should the battery voltage fall below a certain point. Data loggers on Trapridge Glacier are currently programmed to stop execution should the battery voltage drop below 11.8 V. A suitable level of voltage cutoff should be determined for the GPS devices based on the energy requirements of the solar regulator, and the amount of current the GPS device will consume when operating. Protection diodes and surge protection will need to be incorporated to prevent damaging the microcontroller in the event of incorrect battery polarity or static shock. The MSP430 also has the ability to measure temperature using the A/D converter, by incorporation of a thermistor circuit. This temperature could be monitored, and could suspend operation of the device should the temperature drop below the operating specifications of the components.

8.3 Software improvements and recommendations

The compiler used for development thus far has been IAR Systems Embedded Workbench. A limited–use compiler was provided with the MSP430 development kits purchased from Texas Instruments, and was limited in the size of executables it could generated. To overcome this limit, a 30-day demo of the full version of IAR Embedded Workbench was used to finish development of the software. This 30-day limit almost proved disastrous when development of the software needed
to be complete at the Trapridge Glacier field site. However, a free compiler for the Texas Instruments MSP430 product line, MSPGCC\textsuperscript{6} has been under development. This compiler has advanced to the point that is is now a viable alternative to IAR Systems Embedded Workbench. Future development should be done with the MSPGCC compiler.

Currently the GPS devices do not store a record of when they power-up. A log file should be kept which tracks the date, time, battery voltage, temperature and the GPS satellite tracking status each time the device powers on. There are several periods during 2002-2003 in which no GPS data was collected by the devices (Figure 6.4). Currently no account can be made for why the device failed to collect data during these periods.

\textsuperscript{6}MSPGCC is an open source port of the GCC compiler, \url{http://mspgcc.sourceforge.net/}
A. Visible Satellites at Trapridge Glacier

To understand the distribution of visible GPS satellites above Trapridge Glacier, several skyplots have been generated. The following skyplots show where GPS satellites will be visible in the sky, and show traces of their movement.

A.1 Trapridge Glacier

Figures A.1 and A.2 show skyplots over Trapridge Glacier on July 16, 2003. Figure A.1 shows the satellite constellation for a two hour period centered around the observations made by the GPS prototypes on that day at 22:00. An elevation cutoff mask of $10^\circ$ is used, so satellites below this mask are not plotted. The satellites in the northern portion of the sky have low elevations, and are likely to not be used in the positioning solutions. At the time of observation, the GPS prototypes would have had 8 visible satellites; enough for a positional fix. However, satellites 4, 7, 11, 30 are low in the sky at this point in time, and may bring additional errors into the resulting position.

Figure A.2 shows an 11 hour skyplot for Trapridge Glacier on July 16, 2003. It is clear to see that there is a large empty hole in the northern portion of the plot where no satellites will ever be visible due to the geometry of the satellites orbits. The very nature of the satellite orbit geometry favors East–West coordinates over the North–South coordinates as the satellite geometry provides more constraints on the East–West coordinates.
A.2 North pole and Equator

For comparison, skyplots for the north pole, and the equator are displayed in Figures A.4 and A.3. No satellites are visible above 45° at the north pole, while at the equator, all portions of the sky are covered by GPS satellites.
Figure A.1: Satellite coverage at Trapridge Glacier for July 16, 2003 for 2 hours during the time the GPS data observations were collected.
Figure A.2: Satellite coverage at Trapridge Glacier for July 16, 2003 for 11 hours. This shows the general spatial extent that Trapridge Glacier will obtain from the GPS satellite geometry.
Equator
Lat: 0.0000 Lon: 0.0000 Ell Ht: 1.0 (m)
GPS Time: Start 2003/07/16 12:00:00 Stop 2003/07/16 23:00:00

Figure A.3: Satellite coverage at the Equator.
North_Pole
Lat: 90.0000  Lon: 0.0000  Ell Ht: 1.0 (m)
GPS Time: Start 2003/07/16 12:00:00 Stop 2003/07/16 23:00:00

Figure A.4: Satellite coverage over the north pole.
B. Linearized GPS Solution

Determination of the unknown geographic coordinates of the receiver from the observations made by the receivers antenna requires solving a non-linear system of equations. Recall from chapter 4 the mathematical model of the pseudo-range measured for each satellite by the GPS receiver:

\[ P = \rho + c\delta t + T_{trop} + T_{ion} + T_{rel} + \epsilon \]  

(B.1)

Where \( P \) is the pseudo-range, \( \rho \) is the exact geometric distance, \( c \) is the speed of light in a vacuum, \( \delta t \) is the unknown clock bias, \( T_{trop} \) is the signal path delay due to troposphere, \( T_{ion} \) is the signal path delay due to the ionosphere, \( T_{rel} \) is the signal delay due to relativistic errors due to the high satellite velocity and \( \epsilon \) is an estimate of the noise. By neglecting the tropospheric, ionospheric, and receiver errors equation B.1 becomes

\[ P = \rho + c\delta t \]  

(B.2)

The geometric distance between the jth satellite and the receiver is given by

\[ \rho_j = \sqrt{(X^j - X)^2 + (Y^j - Y)^2 + (Z^j - Z)^2} \]  

(B.3)

All that remains is to solve the equation for the the unknown receiver coordinates, \((X, Y, Z)\). A Taylor series expansion is used to expand Equation B.2 about estimates of the geographic coordinates of the receiver, \((X_0, Y_0, Z_0)\), and the higher order terms are dropped. Perturbations \((\Delta X, \Delta Y, \Delta Z)\) in Equation B.4 are solved at each iteration, until they become negligible in size.
\[ P^i_k \approx P_0 + \frac{\partial P^i_k}{\partial X_0} \Delta X + \frac{\partial P^i_k}{\partial Y_0} \Delta Y + \frac{\partial P^i_k}{\partial Z_0} \Delta Z + c\delta t_0 \] (B.4)

Where \( P_0 \) is the pseudo-range estimated from the approximate receiver coordinates. Substituting the derivative of Equation B.2 and simplifying results in a linear equation of the perturbations.

\[ P^i_k \approx P_0 + \frac{(X_0 - X^j) \Delta X + (Y_0 - Y^j) \Delta Y + (Z_0 - Z^j) \Delta Z}{\sqrt{(X_0 - X^j)^2 + (Y_0 - Y^j)^2 + (Z_0 - Z^j)^2}} + c\delta t_0 \] (B.5)

Letting \( \rho_0 \) be the geometric distance from the estimated receiver position to the satellite, and defining \( \Delta P^i_k \) as

\[ \Delta P^i_k = P^i_k - P_0 \] (B.6)

results in the system of linear equations which are solved

\[ \Delta P^i_k = \frac{(X_0 - X^j)}{\rho_0} \Delta X + \frac{(Y_0 - Y^j)}{\rho_0} \Delta X + \frac{(Z_0 - Z^j)}{\rho_0} \Delta X + c\delta t_0 \] (B.7)

Assuming that 4 satellites are being tracked, the system has four unknowns: the 3 receiver coordinates, and the clock bias. The resulting matrix is

\[
\begin{pmatrix}
\Delta P_1 \\
\Delta P_2 \\
\Delta P_3 \\
\Delta P_4
\end{pmatrix} = 
\begin{pmatrix}
\frac{(X_0 - X^1)}{\rho_1} & \frac{(Y_0 - Y^1)}{\rho_1} & \frac{(Z_0 - Z^1)}{\rho_1} & 1 \\
\frac{(X_0 - X^2)}{\rho_2} & \frac{(Y_0 - Y^2)}{\rho_2} & \frac{(Z_0 - Z^2)}{\rho_2} & 1 \\
\frac{(X_0 - X^3)}{\rho_3} & \frac{(Y_0 - Y^3)}{\rho_3} & \frac{(Z_0 - Z^3)}{\rho_3} & 1 \\
\frac{(X_0 - X^4)}{\rho_4} & \frac{(Y_0 - Y^4)}{\rho_4} & \frac{(Z_0 - Z^4)}{\rho_4} & 1
\end{pmatrix} 
\begin{pmatrix}
\Delta X \\
\Delta X \\
\Delta X \\
c\delta t
\end{pmatrix}
\] (B.8)

Which is a matrix system of equations \( A\tilde{x} = \tilde{b} \). This system can be solved using a least squares, or generalized inverse operator:

The new estimate of the receiver position is updated after each iteration,
\[ (X_n, Y_n, Z_n) = (X_{n-1}, Y_{n-1}, Z_{n-1}) + (\Delta X, \Delta Y, \Delta Z) \quad (B.9) \]

The process is iterated until convergence, when

\[ \|(\Delta X, \Delta Y, \Delta Z, \delta t)\| \approx 0 \quad (B.10) \]

### B.1 ECEF coordinate system

The coordinate system used for this solution is the Earth Centered Earth Fixed (ECEF) coordinate system. The ECEF coordinate system places the center of mass of the earth’s reference ellipsoid at \((0, 0, 0)\). A coordinate transformation can be applied to convert the \((X, Y, Z)\) ECEF coordinates obtained in the solution to WGS-84 Latitude/Longitude, or UTM coordinates.
C. Trapridge Coordinate Transformation

Surveying has taken place on Trapridge Glacier for more than three decades. To place the positions surveyed at Trapridge Glacier to a map system, the latitude and longitude of the Trapridge Glacier survey site were determined by Sam Collins. This was accomplished by determining the longitude and latitude of the survey location by monitoring the Sun and the Moon, and was likely based on the NAD–27 mapping datum, which is standard for government maps of Canada. With the advent of GPS, Trapridge Glacier can now be accurately tied to the commonly used map datum, WGS–84. A transformation can now be applied to convert the historic Trapridge survey data to the WGS–84 datum. Once in this established map datum, further transformations can be applied to convert Trapridge survey coordinates to any mapping system.

C.1 Method

Several locations exist on or near Trapridge in which both the GPS determined coordinates, and the relative Trapridge coordinates are known. Trapridge coordinates exist in a pseudo-UTM form of Easting, Northing, and Elevation.

In 2003 a Garmin eTrex Vista handheld GPS receiver was used to obtain WGS–84 coordinates of several points around Trapridge Glacier, Figure C.1 shows the comparison of the GPS points to the Trapridge points. Clearly, there is a simple shift to translate one set of coordinates to the other.
C.2 Results

By taking the average Easting, Northing and Elevation difference between the WGS–84 coordinates and the Trapridge UTM coordinates, a transformation can be defined that will place traditional Trapridge survey coordinates into the WGS–84 datum. From this point, further coordinate transformations can take place to place results of the Trapridge Glacier survey in any mapping system. Table C.3 shows the difference between Trapridge coordinates, and GPS derived WGS–84 coordinates. The last row displaying the average difference, and provides the transformation Equation C.1.

\[
(x, y, z)_{WGS84} = (x, y, z)_{TRAP} + (96.091 \text{ m}, -154.721 \text{ m}, -11.460 \text{ m}) \quad (C.1)
\]

Where \((x, y, z)_{TRAP}\) are the Easting, Northing, and Elevation in Trapridge pseudo-UTM coordinates, and \((x, y, z)_{WGS84}\) are the Easting, Northing, and Elevation in WGS–84.

\[\]
### Table C.1: Trapridge pseudo–UTM coordinates obtained through traditional survey techniques.

<table>
<thead>
<tr>
<th>ID</th>
<th>Easting(m)</th>
<th>Northing(m)</th>
<th>Elevation(m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>02GPS02</td>
<td>535618.885</td>
<td>6787741.735</td>
<td>2373.100</td>
</tr>
<tr>
<td>02GPS03</td>
<td>535762.038</td>
<td>6787776.420</td>
<td>2355.000</td>
</tr>
<tr>
<td>LN</td>
<td>536216.223</td>
<td>6788600.271</td>
<td>2347.380</td>
</tr>
<tr>
<td>TN</td>
<td>534874.626</td>
<td>6788135.605</td>
<td>2543.952</td>
</tr>
<tr>
<td>HK</td>
<td>538361.800</td>
<td>6787497.165</td>
<td>2358.289</td>
</tr>
</tbody>
</table>

### Table C.2: Trapridge WGS–84 Coordinates obtained through GPS measurements in 2003.

<table>
<thead>
<tr>
<th>ID</th>
<th>Easting(m)</th>
<th>Northing(m)</th>
<th>Elevation(m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>02GPS02</td>
<td>535533.945</td>
<td>6787891.345</td>
<td>2388.700</td>
</tr>
<tr>
<td>02GPS03</td>
<td>535673.233</td>
<td>6787926.177</td>
<td>2371.000</td>
</tr>
<tr>
<td>LN</td>
<td>536104.000</td>
<td>6788760.000</td>
<td>2355.000</td>
</tr>
<tr>
<td>TN</td>
<td>534791.940</td>
<td>6788289.281</td>
<td>2554.000</td>
</tr>
<tr>
<td>HK</td>
<td>538250.000</td>
<td>6787658.000</td>
<td>2367.000</td>
</tr>
</tbody>
</table>

### Table C.3: Difference between GPS WGS–84 coordinates and Trapridge coordinates, and average difference.

<table>
<thead>
<tr>
<th>ID</th>
<th>Easting(m)</th>
<th>Northing(m)</th>
<th>Elevation(m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>02GPS02</td>
<td>84.940</td>
<td>-149.610</td>
<td>-14.900</td>
</tr>
<tr>
<td>02GPS03</td>
<td>88.805</td>
<td>-149.757</td>
<td>-16.000</td>
</tr>
<tr>
<td>LN</td>
<td>112.223</td>
<td>-159.729</td>
<td>-7.620</td>
</tr>
<tr>
<td>TN</td>
<td>82.686</td>
<td>-153.676</td>
<td>-10.050</td>
</tr>
<tr>
<td>HK</td>
<td>111.800</td>
<td>-160.835</td>
<td>-8.710</td>
</tr>
<tr>
<td>AVG</td>
<td>96.091</td>
<td>-154.721</td>
<td>-11.460</td>
</tr>
</tbody>
</table>

### C.3 Applicability of Results

The above results use only a simple average to determine a transformation between WGS–84 and Trapridge–UTM coordinates. Details such as the curvature of the earth, and rotations between the two coordinate systems have not been taken into account. Due to the relative low accuracy of the GPS derived positions of ∼9 meters horizontal, and ∼18 meters vertical, a more general coordinate transformation would yield little new information. However, the transformation derived above is applicable only for the immediate region of Trapridge glacier.
and should not be applied for distances of more than a few kilometers away from the glacier.
D. GPS Printed Circuit Board

In 2003, a printed circuit board was designed to seat the electrical components comprising the GPS prototype. Figure D.2 show the layout for the PCB, which which was fabricated by Enigma Corp, located in Burnaby. Figure D.1 is the schematic showing showing the logical relationship between the various components.

D.1 Part List

<table>
<thead>
<tr>
<th>Part</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>IC1</td>
<td>MSP430F149 Texas Instruments Microcontroller</td>
</tr>
<tr>
<td>IC2 - IC3</td>
<td>3.3V Voltage Regulators</td>
</tr>
<tr>
<td>IC4</td>
<td>RS232 Transmitter, MAX3222</td>
</tr>
<tr>
<td>Q4</td>
<td>32,768 Hz Quartz Oscillator</td>
</tr>
<tr>
<td>R2</td>
<td>175 kΩ resistor</td>
</tr>
<tr>
<td>R3</td>
<td>47 kΩ resistor</td>
</tr>
<tr>
<td>R4</td>
<td>560 Ω resistor</td>
</tr>
<tr>
<td>C1</td>
<td>10 nF capacitor</td>
</tr>
<tr>
<td>C2-C14</td>
<td>100 nF capacitor</td>
</tr>
</tbody>
</table>

*Table D.1: Electrical component list for the 2003 GPS prototype.*

<table>
<thead>
<tr>
<th>Part</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Battery</td>
<td>Sonnenschein 6.5 Amp-hour lead acid battery</td>
</tr>
<tr>
<td>Solar Regulator</td>
<td>Morningstar Sunsaver-6 solar regulator</td>
</tr>
<tr>
<td>Solar Panel</td>
<td>15 Watt</td>
</tr>
<tr>
<td>GPS Receiver</td>
<td>Garmin GPS 15L</td>
</tr>
<tr>
<td>GPS Antenna</td>
<td>Tri-M Systems Might Mouse II</td>
</tr>
<tr>
<td>Memory</td>
<td>Atmel 8 megabyte flash memory, MMC form factor</td>
</tr>
</tbody>
</table>

*Table D.2: Other components for the 2003 GPS prototype.*
Figure D.1: Schematic for the 2003 GPS prototypes.
Figure D.2: Printed circuit board design for the 2003 GPS prototypes.
References


