IMPROVED POSITIONING BY DISTANCE-BASED DIFFERENTIAL GPS

A THESIS SUBMITTED TO
THE GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES
OF
MIDDLE EAST TECHNICAL UNIVERSITY

BY

MATIN GHAZIANI

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR
THE DEGREE OF MASTER OF SCIENCE
IN
MECHANICAL ENGINEERING

SEPTEMBER 2013

Approval of the thesis:

IMPROVED POSITIONING BY DISTANCE-BASED DIFFERENTIAL GPS

submitted by **MATIN GHAZIANI** in partial fulfillment of the requirements for the degree of **Master of Science in Mechanical Engineering Department, Middle East Technical University** by,

Prof. Dr. Canan Özgen
Dean, Graduate School of **Natural and Applied Sciences**

Prof. Dr. Süha Oral
Head of Department, **Mechanical Engineering**

Assoc. Prof. Dr. İlhan Konukseven
Supervisor, **Mechanical Engineering Dept., METU**

Asst. Prof. Dr. Buğra Koku
Co-Supervisor, **Mechanical Engineering Dept., METU**

Examining Committee Members:

Prof. Dr. Tuna Balkan
Mechanical Engineering Dept., METU

Assoc. Prof. Dr. İlhan Konukseven
Mechanical Engineering Dept., METU

Asst. Prof. Dr. Buğra Koku
Mechanical Engineering Dept., METU

Asst. Prof. Dr. Kıvanç Azgın
Mechanical Engineering Dept., METU

Asst. Prof. Dr. Ali Emre Turgut
Mechatronics Engıneering Dept., THK

Date: 04.09.2013

I hereby declare that all information in this document has been obtained and presented in accordance with academic rules and ethical conduct. I also declare that, as required by these rules and conduct, I have fully cited and referenced all material and results that are not original to this work.

Name, Last name: MATIN GHAZIANI

Signature:

ABSTRACT

IMPROVED POSITIONING BY DISTANCE-BASED DIFFERENTIAL GPS

Matin Ghaziani
M.Sc., Department of Mechanical Engineering
Supervisor: Assoc. Prof. Dr. İlhan Konukseven
Co-Supervisor: Asst. Prof. Dr. Buğra Koku

September 2013, 83 pages

This study presents a new method of differential GPS which is based on distance between GPS receivers. To navigate a robot on unstructured area, different methods have been used. One of the important methods is using GPS. Using single GPS leads to inaccurate navigation of a robot. One way to overcome this problem is using Differential GPS which is based on using one or several based stations and rover receivers. These base stations depend on exact coordinate of its coordinates and without them; this method does not work correctly. To overcome this problem, a method which does not depend on exact position is needed. In this study distance-based differential GPS is proposed. In this method seven fixed GPS receivers and a rover receiver are used. By solving the distances between fixed points, the error of each GPS is found. By using the inverse distance weighting method, the error of rover receiver is found. In this method, exact positions of based points are not needed. This method can be implemented anywhere, therefore local navigation system can be achieved easily.

Keywords: Differential Global Positioning System, GPS receivers, rover receiver, fixed points, distance

ÖZ

MESAFE TABANLI DİFERANSİYEL GPS İLE GELİŞMİŞ KONUMLANDIRMA

Matin Ghaziani
Yüksek Lisans, Makine Mühendisliği Bölümü
Tez yöneticisi : Doç. Dr. E. İlhan Konukseven
Ortak tez yöneticisi : Yrd. Doç. Dr. A. Buğra Koku

Eylul 2013, 83 sayfa

Bu çalışma, GPS alıcıları arasındaki mesafelere dayanan yeni bir diferansiyel GPS methodu önermektedir. Bir robotun yapılandırılmamış alanlarda hareket edebilmesi için bir çok farklı yöntem mevcuttur. Bu yöntemler arasında GPS kullanımı önemli bir yere sahiptir. Ancak tek GPS kullanımı hatalı navigasyona sebep olmaktadır. Bu sorunu aşmak için kullanılan en yaygın yöntem birden çok istasyondan yapılan yayınlara dayanan diferansiyel GPS'tir. Bu istasyonların çalışma prensibi istasyonların gerçek koordinatına dayanmaktadır ve bu koordinatlar olmadan çalışamazlar. Bu gereksinimi ortadan kaldırmak için gerçek koordinatların bilinmesine ihtiyaç duymayan bir yönteme ihtiyaç vardır. Bu çalışmada mesafe tabanlı diferansiyel GPS yöntemi önerilmiştir. Bu yöntemde yedi adet sabit ve bir adet hareketli GPS alıcısı kullanılmıştır. Sabit noktalar arasındaki mesafelerin çözülmesi ile her GPS'in hatası hesaplanmaktadır. Daha sonra ters mesafe ağırlık metodu kullanılarak hareketli GPS'in hatası bulunmaktadır. Bu yöntemde sabit noktaların gerçek koordinatlarının bilinmesi gerekmemektedir. Bu sayede bu yöntem her bölgede uygulanabilmekte ve kolayca yerel navigasyon sistemi elde edilebilmektedir.

Anahtar Kelimeler: Diferansiyel Küresel Konumlama Sistemi, GPS alıcıları, Hareketli alıcı, sabit noktalar, mesafe

To my family

ACKNOWLEDGEMENTS

First of all, I would like to express my sincere appreciation to my supervisors Assoc. Prof. Dr. E. İlhan Konukseven and Asst. Prof. Dr. A. Buğra Koku for their invaluable guidance, advice, and criticism and especially their extreme support that made this study possible.

I would like to express my thanks to my dear friends and colleagues Reza Aghazadeh, Masoud Latifi-Navid, Akif Hacınecipoğlu and Kadri Buğra Özütemiz for their friendship and technical support throughout the thesis period. I would also like to thank my friends and collegues Armin Aghakarimi, Serkan Tarçın, Rasim Aşkın Dilan, Burak Şamil Özden, Yaser Mohammadi Nazarabad, Hasan Ölmez and Gökhan Bayar for all the good times we have spent.

I am grateful to my lovely family for their support, love and encouragement through all my life.

I also want to thank my lovely wife Ezgi Çağlar Ghaziani for her understanding and love which made life easier for me and made this work be completed.

Last, but not least, I thank the Scientific and Technological Research Council of Turkey (TUBITAK) for their financial support.

TABLE OF CONTENTS

LIST OF TABLES

TABLES

LIST OF FIGURES

FIGURES

LIST OF SYMBOLS

SYMBOLS

b	A polar radius
a	An equatorial radius
$\boldsymbol{\varepsilon}$	Error of GPS
h	Height above ellipsoid (altitude)
φ	Latitude
λ	Longitude
N	Radius of Curvature
d	The distance between the two points
e	The eccentricity of the ellipsoid
$L1$	The frequency which is carried the navigation message (1575.42 MHz)
L2	The frequency which is carried the P Code used for the PPS (1227.60 MHz)
R	The radius of the Earth in specified latitude
$\boldsymbol{X}$	X Axis in ECEF Coordinate
Y	Y Axis in ECEF Coordinate
Z	Z Axis in ECEF Coordinate

LIST OF ABBREVIATIONS

ABBREVIATIONS	
BMCS	Backup Master Control Station
DoD	Department of Defense
DGPS	Differential GPS
DOP	Dilution of Precision
EGNOS	European Geostationary Navigation Overlay Service
EGNOS	European Geostationary Navigation Overlay System
GDOP	Geometric of Dilution of Precision
GDGPS	Global Differential GPS
GGN	Global GPS Network
GLONASS	GLObal NAvigation Satellite System
GNSS	Global Navigation Satellite Systems
GPS	Global Positioning System
GBAS	Ground Based Augmentation Systems
HDOP	Horizontal of Dilution of Precision
IRNSS	India’s Regional Navigation Satellite System
IDW	Inverse Distance Weighted
QZSS	Japan’s Quasi-Zenith Satellite System
MCS	Master Control Station
PDOP	Position Dilution of Precision
PVT	Position, Velocity and Time
PPS	Precise Positioning Service
RTK	Real time kinematic

SBAS	Satellite Based Augmentation Systems
SBAS	Satellite Based Augmentation Systems
SA	Selective Availability
SPP	Single Point Positioning
SV	Space Vehicle (SV)
TEC	Total Electron Content
UTC	Universal Time Coordinates
VDOP	Vertical Dilution of Precision
WAAS	Wide Area Augmentation System
WAAS	Wide Area Augmentation Systems
WADGPS	Wide Area Differential GPS

CHAPTER 1

INTRODUCTION

In this chapter the definition of the problem, outlines of the objectives and scopes of this work are presented.

1.1 Background

1.1.1 The Global Navigation Satellite Systems

Global Navigation Satellite Systems (GNSS) include satellites that broadcast their location in space and several stations on the Earth with receivers to calculate the position of stations on the Earth. Different transportation systems such as: rail, road, mass transit and maritime use GNSS. Navigation plays an important role in telecommunications, precision agriculture, land surveying, scientific research and so on [1, 2, 3].

Nowadays GNSS contain two fully operational global systems, the United States' Global Positioning System (GPS) and the Russian Federation's GLObal NAvigation Satellite System (GLONASS), as well as the developing global and regional systems, namely Europe's European Satellite Navigation System (GALILEO) and China's COMPASS/BeiDou, India's Regional Navigation Satellite System (IRNSS) and Japan's Quasi-Zenith Satellite System (QZSS) [1, 2, 3].

1.1.2 GPS versus Differential GPS Techniques

Nowadays GNSS, particularly GPS, is used in many applications such as land, transportation, mapping, agriculture and telecommunications and so on. For many applications especially location-based services such as autonomous navigations, the accuracies of GPS are insufficient. These systems need to have high accuracy, thus the method to improve accuracy is needed. Several Differential GPS (DGPS) techniques are designed to improve the accuracy of the systems. DGPS is a method that needs to have one or several base stations on known positions and a rover receiver. The base stations provide correction for rover receiver. By using DGPS methods, the accuracy decreases from 1-3 meters to centimeter level [4].

To improve the accuracy from tens of meters to a few meters the existing GNSS systems are augmented, for example, Satellite Based Augmentation Systems (SBAS), such as USA's Wide Area Augmentation Systems (WAAS) European Geostationary Navigation Overlay System (EGNOS), and Ground Based Augmentation Systems (GBAS). To increase the accuracy to millimeter level, several DGPS method which are based on carrier phase are implemented. Real time kinematic (RTK) and Network RTK are two examples of carrier phase DGPS [4].

1.2 Scope and Limitations

As regards that GPS accuracy is insufficient for many applications, Various Differential GPS (DGPS) techniques have been designed to overcome this problem. A principle of DGPS method is using 1 reference station and 1 rover receiver. The correction data is generated by a base station, which is a high quality GPS receiver with a good antenna sited at an accurately known location. The correction data is derived from the satellites pseudorange data which is distances between satellites and GPS receivers, and the position of base station [5].

According to principle of DGPS methods, for using these techniques, reference coordinate of base station is needed. Without having the reference station's coordinate, DGPS method does not work correctly and cannot increase the accuracy of GPS.

To overcome this problem, a technique that is not dependent on the base station's coordinate is needed.

1.3 Objectives and Contributions

1.3.1 Research Objectives

This Master thesis studies the generation of network-based differential GPS corrections with an emphasis on technique that does not need for base station's coordinate to navigate robot in an unstructured area of METU campus (Figure 1). The goal of this research is to investigate and develop techniques to navigate robot by using GPS positioning method with centimeter level accuracy for a local network positioning.

The objectives of this research include:

- Implement local Differential GPS without using base station's coordinate.
- Correct rover receiver position by using Inverse Distance Weighted (IDW) method.
- Prove that this method can be implemented on robot.

The proposed method uses distance between base stations to correct their positions and by using Inverse Distance Weighted (IDW) method, rover receiver's position is corrected.

Figure 1 - Unstructured area of METU campus

Figure 2 - ATV

1.3.2 Contributions to Research

This proposed DGPS method is based on distances between several fixed receivers and a rover receiver. The current Differential GPS methods used one or several base stations whose exact coordinates are known. Without knowing the exact coordinates of base stations, they do not work correctly.

1.4 Organization of the Thesis

The contents of the remaining chapters are as follows:

Chapter 2 provides an overview of GPS and current positioning services and their accuracies. In this chapter the principles of GPS and DGPS positioning, including the review of fundamental GPS measurements, GPS errors, and existing algorithms of DGPS positioning and corrections are reviewed.

Chapter 3 explains the proposed methods of DGPS. In this chapter, the reasons for choosing this method are discussed and how to correct the position of rover receiver is explained.

Chapter 4 explains the hardware which is used in tests. In this chapter, parts used in hardware and why they are chosen are explained.

Chapter 5 explains all tests which are done to validate the proposed method. In this chapter, 4 tests which are done are explained. Test 1 discusses the potential problems that the proposed method will face with them. Test 2 explains about running the proposed method in small area and the results of it. Test 3 explains about running the proposed method in large area and the results of it. Test 4 explains the proposed method for rover receiver and shows the fact that the result of this method is good for purpose of this thesis.

Finally, chapter 6 presents the conclusions of the thesis and recommendations for future investigations.

CHAPTER 2

OVERVIEW OF GPS AND CURRENT POSITIONING SERVICES

In this chapter, reviews of GPS and current positioning services are presented. The sources of errors of GPS and the ways of determining the accuracy of GPS are explained. Then, the prevailing methods which are used to decrease these errors are introduced.

2.1 The U.S. Global Positioning System

The Global Positioning System (GPS) is a satellite-based navigation system which was started in 1973 by the U.S. Department of Defense (DoD). This system works in any climate and provides information related to 3D position, velocity and time of the GPS receiver anywhere on the Earth [6, 7].

2.1.1 GPS Segments

The GPS system has started to work as a full function system since 1995 and comprises three main segments, namely, space segment, control segment and user segment [8] (Figure 3).

Space Segment

This segment comprises the set of satellites and the signals which are broadcasted from them. The current space segment of GPS system includes 31 satellites which are placed about 20,200 kilometers above the Earth in six orbital planes with equal angular distance of 60 degrees. The orbital period of each satellite is half a sidereal day, so at least four satellites are visible anytime on the Earth’s surface [7, 8].

Using an atomic oscillator, each satellite continuously broadcasts signals. Two L-band frequencies (L1 at 1575.42 MHz and L2 at 1227.60 MHz), messages contacting navigation data such as broadcast orbits, clock corrections and status of the satellites, and the ranging codes frequencies are transmitted through these signals.

Control Segment

This segment comprises four main parts [4, 8, 7]:

1. Master Control Station (MCS) which is located at Colorado and collects the satellite data to correct them.
2. Backup Master Control Station (BMCS)
3. Five monitor stations which are located at Hawaii, Colorado Springs, Diego Garcia, Ascension Island, and Kwajalein. This part tracks the space vehicles (SVs) and measures signals from them, and then sends these data to the MCS.

4. Three ground control stations which are located at Ascension, Diego Garcia, and Kwajalein, are used to upload the results from MCS to the SVs.

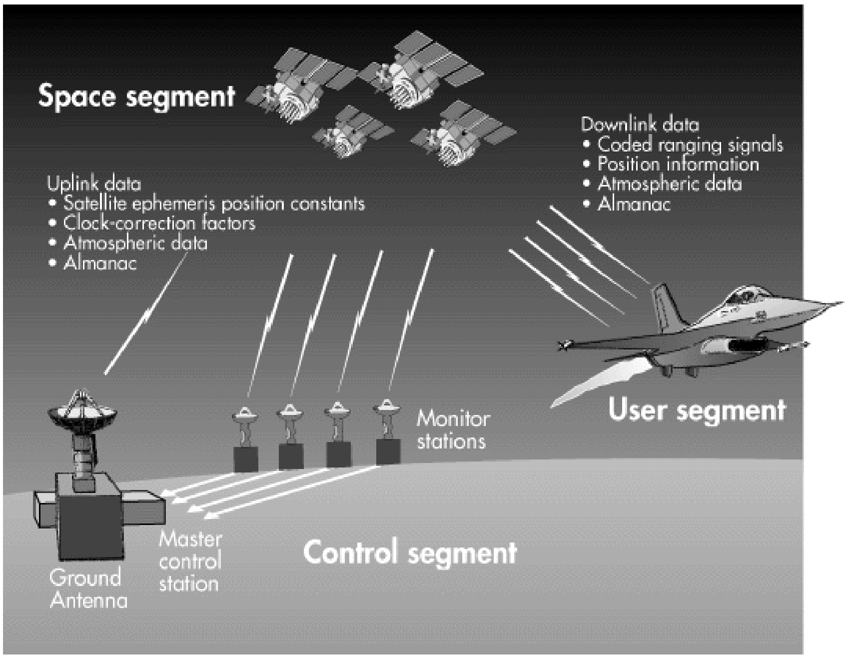

Figure 3 - Three segments of GPS: space segment, control segment and user segment [9]

User Segment

This segment comprises techniques and equipment such as GPS receivers to provide position, velocity and time (PVT) data for user. As mentioned above, at least four satellites are visible simultaneously that makes GPS receiver capable of computing four dimensions (three position dimensions, X, Y, Z, and one time dimension, t) [8].

2.1.2 GPS Errors Sources

There are number of errors that effect the position estimates derived from GPS measurements. These errors are divided into three different groups; [10, 11] (Figure 4):

1. Satellite errors: consist of satellite orbit and clock errors.
2. Receiver errors: consist of receiver clock errors.
3. Propagation errors: consist of tropospheric and ionospheric delay and multipath.

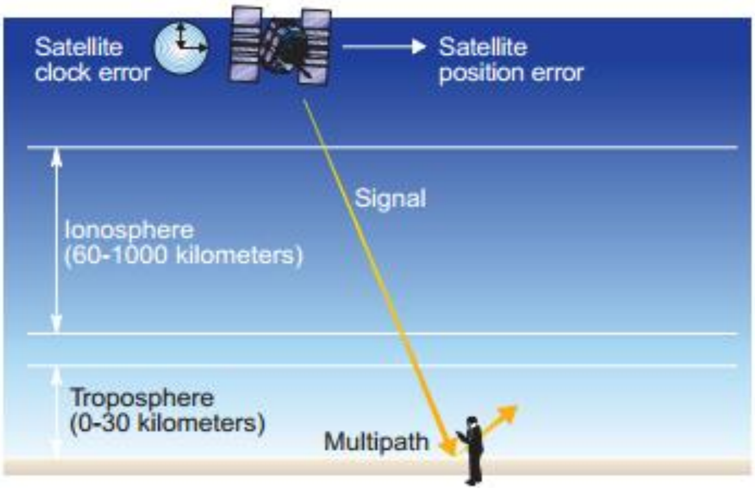

Figure 4 - GPS Errors Sources [12]

Satellite Orbit Errors

The semi-circular orbits of the GPS satellites are approximately 20,200 kilometers above the Earth's surface. The movement velocity of satellite at this altitude which is caused by the force of gravity is about four kilometers per second.

Particles of the Earth's atmosphere, solar radiation pressure and gravitational attraction are the three significant perturbations which influence the satellite orbit. The suspended particles of the atmosphere decrease the velocity of the satellite. The photons may change the path of satellite orbit by impacting on it. Finally, a kind of perturbation may be caused by gravitational effect which is generated by sun and moon [10, 13].

Satellite Clock Error

An atomic time scale which is referenced to Universal Time Coordinates (UTC) is used in the GPS satellite. The satellite clock error may be caused by the drifting in the oscillator of GPS satellite. However, the difference between the accuracy of the GPS satellite clock which is an expensive and accurate atomic clock and the accuracy of time of GPS receiver which uses inexpensive and less accurate oscillators can be another source of satellite clock error [10, 13].

Receiver Clock Error

As it is mentioned, the oscillator which is used in GPS device is inexpensive to be affordable for user. These kinds of oscillators may give data with errors [10, 13].

Tropospheric Delay

The troposphere is a layer of the Earth's atmosphere under an altitude of 50 kilometers through which the GPS signals travel from satellite to GPS receiver. By causing a delay on pseudorange and carrier phase measurements, the troposphere leads to errors between 2.5 and 30 meter. Pressure, temperature and humidity and the height of the GPS receiver impress the tropospheric delay [10, 13].

Ionospheric Delay

In the altitudes between 50-1000 kilometers is the main region of atmosphere called ionosphere where free thermal electrons exist. The Total Electron Content (TEC) defines the number of free electrons. The delay errors in L1 and L2 frequencies are different for the GPS signal traveling through the ionosphere. The pseudorange is lagged and the carrier phase is advanced while the magnitude of them is the same [10, 13].

Multipath

The multipath error occurs when the directly received signal is decreased by an indirectly received signal. The indirect signal reaches the receiver by reflecting from the various surrounding objects such as constructions [10, 13].

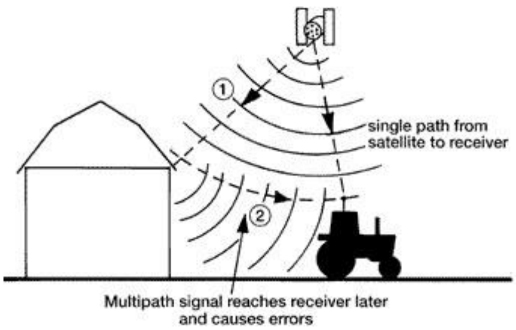

Figure 5 - multipath error [14]

It is difficult to eliminate these errors because of the characteristic of multipath. Therefore, differential positioning techniques such as DGPS are ineffective to remove errors of multipath.

2.1.3 Dilution of Precision (DOP)

The Dilution of Precision (DOP) shows the accuracy of the GPS computations. Mathematically, DOP is the ratio between the standard deviations of a computed parameter and the pseudorange. For instance, Vertical DOP (VDOP) is obtained by dividing the standard deviation of the pseudorange by the altitude of the GPS receiver. For parameters that include more than one variable such as Geometric DOP (GDOP) and Position DOP (PDOP), the root sum square of the standard deviation of the variables (x, y, z coordinates and time) is used [15, 8, 16].

Physically, DOP determines the geometric stability of the visible satellites' configuration and its effect on the GPS accuracy. The ideal configuration of visible satellites which is strong and possesses low value of DOP is formed when the angles between the satellites are large (Figure 6).

Table 1 describes the description for various DOP values. It should be mentioned that DOP values of less than 1 are possible.

Table 1 - Meaning PDOP value

DOP Value	Rating	Description
1	Ideal	This is the highest possible confidence level to be used for applications.
2-3	Excellent	At this confidence level, positional measurements are considered accurate enough to meet all but the most sensitive applications.
4-6	Good	Represents a level that marks the minimum appropriate for making business decisions, Positional measurements could be used to make reliable in-route navigation suggestions to the user.

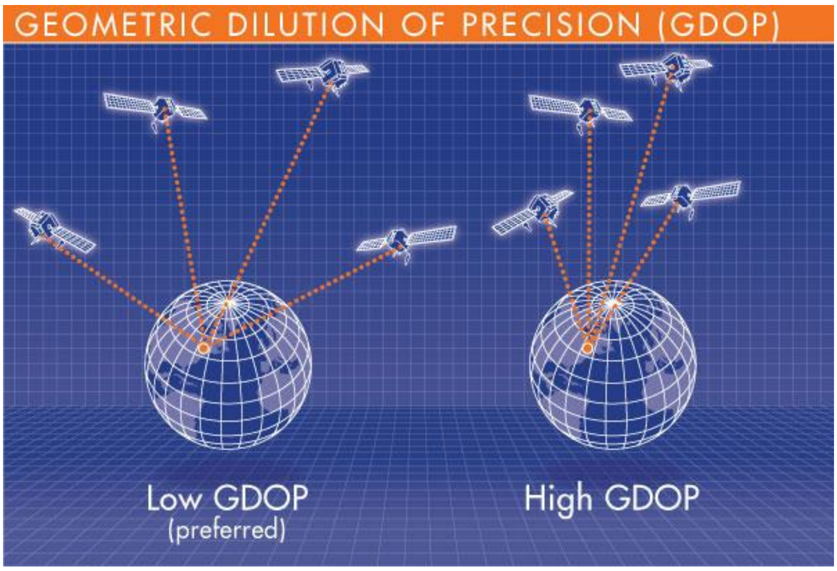

Figure 6 – Effect of Satellite Geometry on Dilution of Precision [17]

2.4 Current Positioning Services

In this part, current positioning services are described. First, standalone GPS positioning is described. Then the augmentations of GPS such as Satellite Based Augmentation Systems (SBAS), Ground Based Augmentation Systems (GBAS) are explained.

2.4.1 Single Point Positioning

Single Point Positioning (SPP), also known as Standalone Positioning, is the use of a single GPS receiver. SPP is divided in two services [18]:

1. Standard Positioning Service (SPS)
   SPS is purposed for civilian use. SPS transmits on only one frequency and uses only the coarse/acquisition (C/A) code which has a 1.023 MHz chip rate on L1 frequency. The L1 frequency contains a navigation data message that is available for peaceful civil uses [19].
2. Precise Positioning Service (PPS)
   PPS is purposed for military use. PPS transmits on both L1 and L2 frequencies; this means that military users can execute ionospheric correction, a technique that decreases radio destruction caused by the Earth's atmosphere. With this correction, PPS provides better accuracy than the basic SPS [20].

2.4.2 Global Differential GPS

The Global Differential GPS (GDGPS) System is a complete, extremely accurate, and highly robust real-time GPS monitoring and augmentation system which is used both L1 and L2 frequencies [21]. The GDGPS System is used to manipulate and control real-time GPS data streaming from a large global GPS tracking network, containing the NASA Global GPS Network (GGN) [22].

Differential corrections for GPS transmission ephemeris with unmatched accuracy and seamless global validity is created by the GDGPS System. Different GDGPS technology components and data products are used by almost all of the providers of premium global differential corrections [22].

2.4.3 Space Based Augmentation System

Satellite Based Augmentation System (SBAS), also known as Wide Area Differential GPS (WADGPS) system, is a network of ground reference stations which are located all over the inclusion area takes GPS measurements and sends them to the master station (Figure 7). The master station makes a model of DGPS corrections that are usual at any reference station. These corrections included satellite orbit and clock errors and parameters of ionospheric delay. Then, these corrections are uploaded to one or more geostationary satellites which are not part of the GNSS constellations. These satellites are controlled by civilian organizations. After that, these satellites transmit correction messages to the users just at L1 frequency [23, 24].

Three regional SBAS systems are currently available: The U.S. Wide Area Augmentation System (WAAS) which has become fully operated since 2003 [25], The European Geostationary Navigation Overlay Service (EGNOS) which has become fully operated since 2009 [26] and the Japanese MTSAT Satellite Augmentation System (MSAS) [27] which has become fully operated since 2005 (Figure 8).

SBAS can supply augmented positioning service at the meter-level accuracy to any users, regardless of user distance from reference station [28].

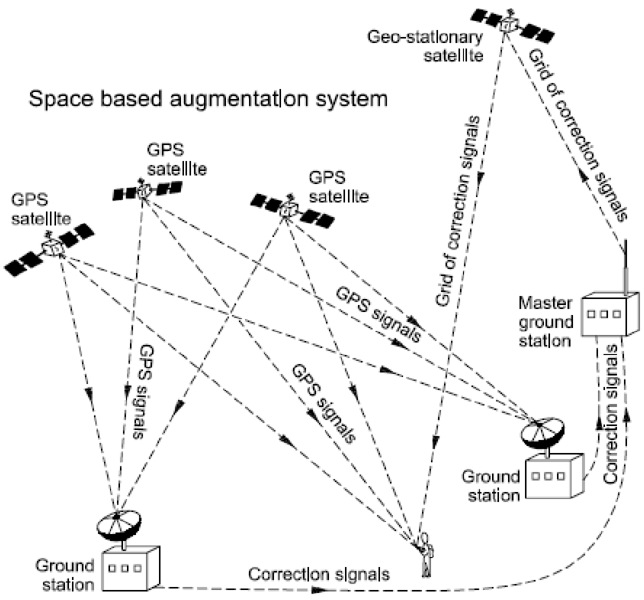

Figure 7 - Space Based Augmentation System [29]

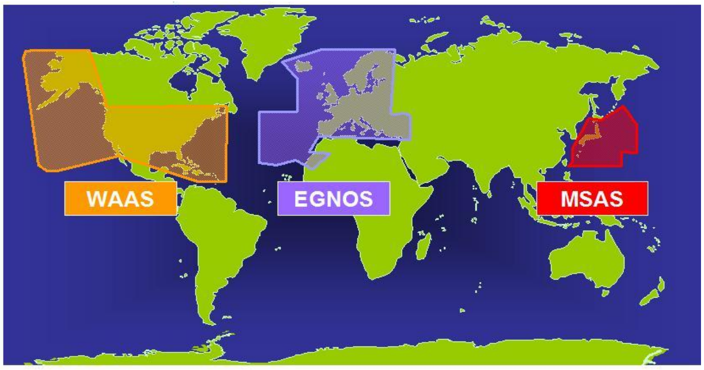

Figure 8 - The networks of the five SBAS systems [30]

2.4.4 Ground Based Augmentation System

The Ground Based Augmentation System (GBAS), also known as the Local Area Differential GPS (LADGPS) is a local civil navigation system which is used for better performance in landing phase. GBAS refers to real-time differential positioning by using only one base station, transmitting corrections to nearby users over distances up to a few hundred kilometers. Typical ranges for a GBAS base station are up to 150 km. For data transmission, UHF (Ultra High Frequency) or VHF (Very High Frequency) radio links are used [24](Figure 9).

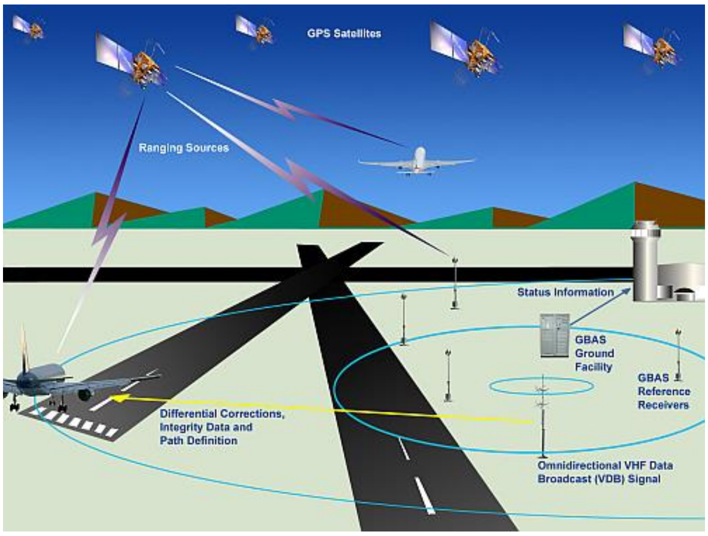

Figure 9 - Ground Based Augmentation System (GBAS) [31]

2.4.4.1 Local Area Augmentation System

The Local Area Augmentation System (LAAS) is an aircraft landing system based on real-time differential correction of the GPS signal by using a single base station located at the airport. This base station has several reference receivers which are located around the airport that independently estimate pseudorange and carrier phase of GPS and send them to a central location at the airport. These corrections are transmitted to users near the 45 km of the LAAS base station via a VHF radio data link by the base transmitter [32, 33, 34](Figure 10).

2.4.7 Carrier Phase Differential GPS

By using the code-based DGPS techniques, accuracies around 2-3 meters in static mode and 5-10 meters in dynamic mode can be achieved, but in order to get higher accuracies better than 0.1 meter to several centimeters or even millimeter level, Carrier Phase Differential GPS or CDGPS methods must be used. Both single and dual frequency receivers can provide centimeter level accuracies, but these receivers are not same. Dual frequency receivers are more expensive because they can remove the effects of clock and atmospheric errors.

Static surveying, Real-Time-Kinematic (RTK) and The Network RTK technique are different methods of Carrier Phase Differential GPS. Post-processed static carrier phase surveying can provide accuracy of 1-5 centimeters. Real-Time-Kinematic (RTK) method can prepare centimeter level accuracy in maximum 10 kilometers. To increase the accuracy of RTK and increase the baseline of system, the Network RTK technique is used. Network RTK requires minimum of five base stations with an inter-station spacing of up to 70 kilometers.

Figure 10 - Local Area Augmentation System (LAAS) [32]

Static Surveying

Post-processed GPS or static GPS surveying is a carrier-phase DGPS method which is based on using two or more base station receivers. These receivers simultaneously track a common set of satellites (at least four) for about 20 minutes to a few hours depending on the distance between the base stations and the rover receiver. The number of visible satellites, the satellite geometry and the atmospheric conditions affect the accuracy of the results. Whatever the distances between base stations and rover receiver are short; the precision of positioning will be higher [35] (Figure 11).

This method is the most accurate positioning technique. For this method, although both the single and dual frequency receivers can be used, but dual frequency receivers are preferred.

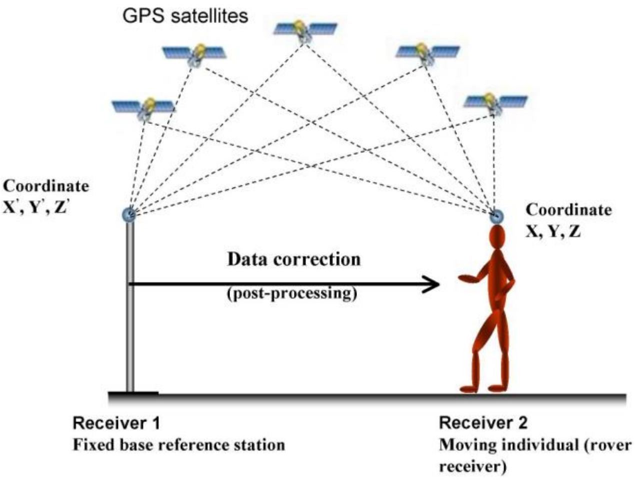

Figure 11 - Principle of Differential GPS [36]

Real-Time Kinematic

Real-Time Kinematic (RTK) is a specific configuration of Differential GPS that observes not only the signal code but also the signal carrier. The carrier wavelength is more than 100 times smaller than the signal code wavelength; therefore, RTK efficiency is about 100 times better than normal DGPS methods [37].

In this method, a single base station and a number of rover receivers are used. The base station broadcasts its raw measurements or observation corrections to a rover receiver and the rover receiver compares its own phase measurements with the data which is received from the base station. Different ways are available for broadcasting a correction signal from base station to rover receiver. The current way to get real-time transmission is to use a radio modem [38, 39].

The principal limitation of using the single base RTK is that the distance between base station and rover receiver cannot be more than 10 to 20 kilometers, because otherwise the system cannot be able to quickly and reliably resolve the carrier phase indefiniteness. Some errors such as orbit errors, and ionospheric and tropospheric refraction which are distance dependent errors, cause this limitation. To overcome this limitation, Network RTK which is multi-base technique instead of single base technique, is used [40, 41].

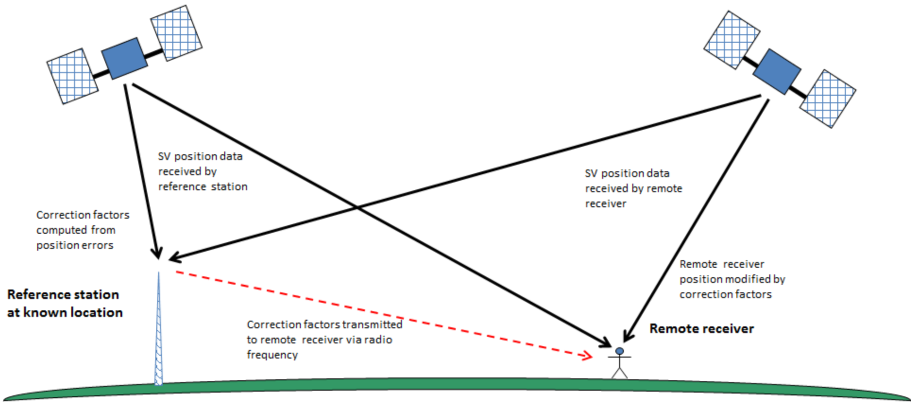

Figure 12 - Real-Time Kinematic (RTK)

Network RTK

In order to overcome limitation of RTK and provide a system to work in large area, many reference stations are used. This system is named Network RTK [4] (Figure 13).

By using the Network RTK system, the number of base stations that are needed to prepare a required accuracy of rover receiver is reduced, because by integrating several base stations in a network, the less number of base stations are needed to increase the accuracy of rover receiver. This method also decreases the number of base stations required to cover a large area [42].

For Network RTK positioning, the data processing includes three different steps:

In the first step, in each reference station, ambiguity resolution processing is done to fix the ambiguities of the network of reference stations.

In the second step, for the distance-dependent errors, correction model parameters which are also named area correction parameters are estimated. These errors can be modeled totally or case by case, for instance, Ionospheric and orbit errors must be modeled individually for each satellite, while tropospheric errors are estimated station by station. The uploading time depends on the type of error, for example, every 10 seconds the ionospheric corrections must be updated but uploading every 60 seconds is sufficient for orbit and tropospheric delay corrections.

In the third step, an optimum set of reference stations and the precise correction models are calculated. Then, based on these models and differences between reference base position and approximate rover receiver position, the reference station are virtually shifted to a “virtual” non-existing station, called Virtual Reference Station (VRS), which is located only a few meters from the rover receiver. This short baseline between rover receiver position and VRS helps to predict the correction [43] (Figure 14).

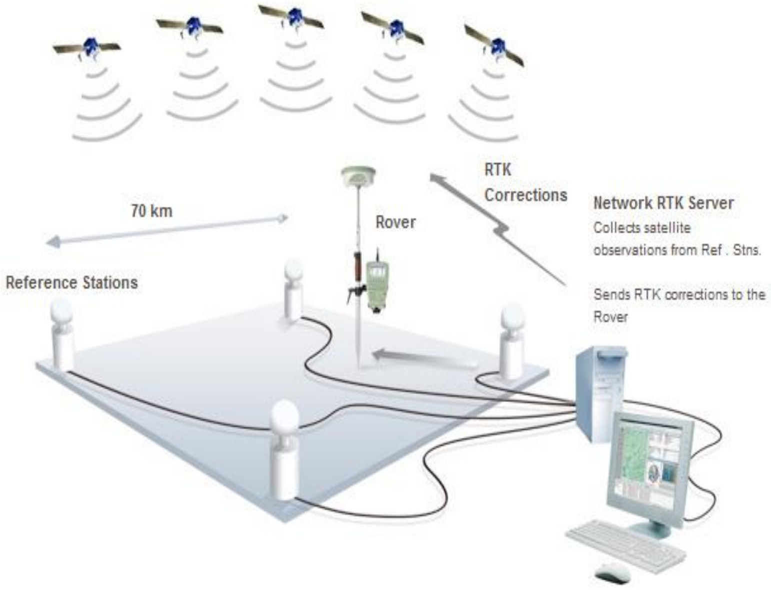

Figure 13 - Network RTK [44]

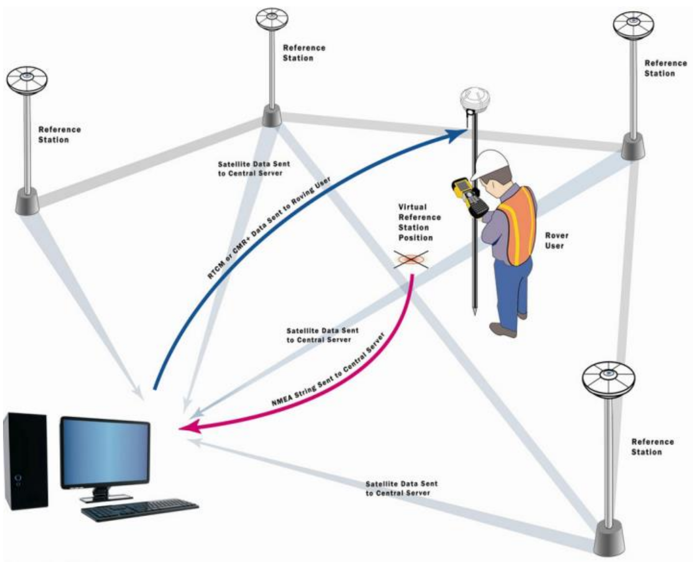

Figure 14 - Virtual Reference Station [45]

Up to now, different methods of current satellite based navigation systems are explained. Figure 15 summarizes all current GNSS positioning services and accuracies.

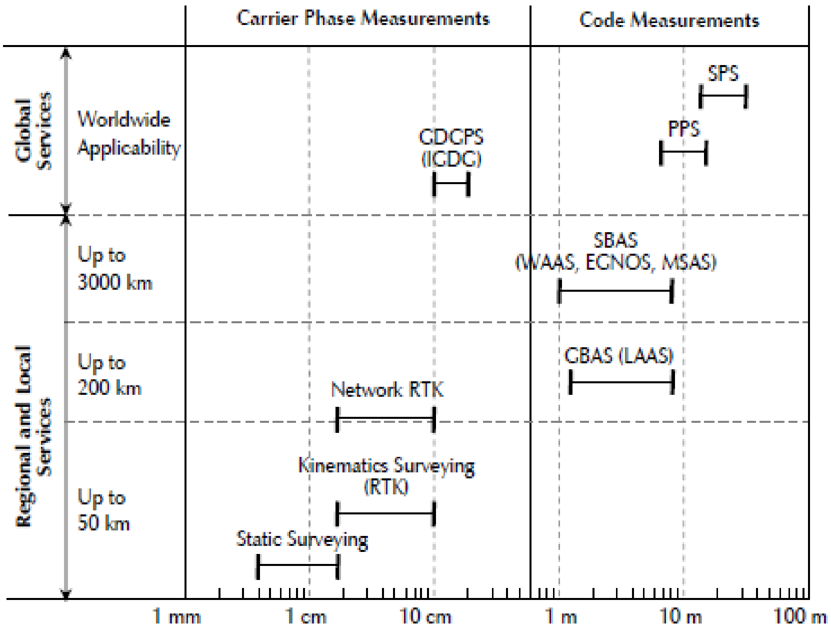

Figure 15 - Current GNSS positioning services and accuracies, using pseudo-range and/or carrier phase measurements, for global, or regional and local services.

CHAPTER 3

PROPOSED DIFFERENTIAL GPS METHOD

3.1 Introduction

According to chapter 2, the GPS has insufficient accuracy to navigate the autonomous robots; therefore, Differential GPS is used. Differential GPS has different methods to show the position of robot by accuracy from millimeter to 1 meter. All of those methods use reference station to find the error of GPS then they correct the rover receiver.

As regards that for using DGPS method, reference coordinates are needed and it is not easy to obtain the exact coordinate of a point to create a base station, therefore to use the DGPS technology, it is required to get corrections from centers which give these services. According to dispersion of DGPS centers in around the world, it is not possible to get these service anywhere on the world, therefore, a method which is avoided to be dependent to DGPS centers is needed.

3.2 Problem Definition

In this part the new method for DGPS is proposed which is independent from the reference point coordinate. In this method, by having some normal GPS receivers, errors of rover receiver are compensated.

As it is mentioned in chapter 2 (Figure 15) static GPS surveying gives the best result in positioning. In this method, all conditions such as satellite in view and DOP are the same. Therefore, the proposed method is based on the static GPS surveying to get better result.

According to Appendix C, each GPS receives some strings which have different data, such as: longitude, latitude, altitude, etc. Another important data received from satellite is Dilution of Precision (DOP). As mentioned in chapter 2, these data demonstrate accuracy of the GPS. In NMEA0183 protocol, these data are shown as Position of Dilution of Precision (PDOP), Horizontal of Dilution of Precision (HDOP) and Vertical of Dilution of Precision (VDOP) in $GPGSA string. This string also contains the information ID of satellites used in position fix. Another important data is $GPGGA string that contains information about time, longitude, latitude and altitude. According to this information, each GPS receiver can determine its position and the accuracy of that point.

According to appendix A to calculate distance between two points on the earth, coordinates of them are needed. In this way, by putting two GPS receivers on two points, the distance between them can be calculated. According to chapter 2, some errors effect GPS performance, therefore the position which GPS receiver shows has errors. Because of these errors, distance which is calculated is not correct. To find the exact distance between two points, the net positions of those points are needed. As it is mentioned, finding the net position is not easy; therefore, calculated distance is Inaccurate.

If distance between two points is known, then it is possible to find errors of GPS receivers which are located on those points.

As mention in appendix A, two methods are available to calculate distance between two points on the earth:

1. Great Circle Calculation
2. Pythagorean Theorem

Great Circle Calculation

According to appendix A the Great Circle Calculation is the shortest distance between two points on the surface of the Earth which is calculated in two ways:

1. Haversine Formula

$$d = 2 \times R \times arcsin\left(\sqrt{sin^2\left(\frac{\varphi_2 - \varphi_1}{2}\right) + \cos(\varphi_1)cos(\varphi_2)sin^2\left(\frac{\lambda_2 - \lambda_1}{2}\right)}\right) \tag{1}$$

2. Spherical Law of Cosines

$$d = \arccos\left(\sin(\varphi_1) \times \sin(\varphi_2) + \cos(\varphi_1) \times \cos(\varphi_2) \times \cos(\Delta\lambda)\right) \times R \tag{2}$$

where,

$$R = \frac{a \times (1 - e^2)}{\sqrt[3]{(1 - e^2 \times \sin^2 \varphi)}} \rightarrow \text{The radius of the Earth in specified latitude} \tag{3}$$

$$a = 6378137 \rightarrow \text{an equatorial radius} \tag{4}$$

$$b = a(1 - f) = 6356732.31424518 \rightarrow \text{a polar radius} \tag{5}$$

$$f = \frac{1}{298.257223563} \tag{6}$$

$$e = \sqrt{\frac{a^2 - b^2}{a^2}} \rightarrow \text{the eccentricity of the ellipsoid} \tag{7}$$

d is the distance between the two points,

φ_1, φ_2: Latitudes of point 1 and 2

λ_1, λ_2: Longitudes of point 1 and 2

As it is observed, in Great Circle Calculation only the effects of latitude and longitude are considered and the effect of altitude is not considered. In this way, it is not possible to calculate distance in 3D, accurately.

Pythagorean Theorem

In Pythagorean Theorem, 2D and 3D methods of calculation are used. For using the Pythagorean theorem in calculating distance on the Earth, GPS coordinates must be converted from longitude, latitude and altitude (LLA) coordinates to Earth-centered Earth-fixed (ECEF) coordinates. Conversion from LLA to ECEF is explained properly in the Appendix B. The brief expression of such conversion is shown below:

$$X = (N+h)\cos\varphi\cos\lambda \tag{8}$$

$$Y = (N+h)\cos\varphi\sin\lambda \tag{9}$$

$$Z = \left(\frac{b^2}{a^2}N + h\right)\sin\varphi \tag{10}$$

where,

φ : latitude
λ : longitude
h : height above ellipsoid (altitude)

N : Radius of Curvature, defined as $\Rightarrow \mathrm{N} = \dfrac{a}{\sqrt{1-e^2\sin^2\varphi}}$ (11)

By converting data to ECEF coordinates, distance between two points is calculated as:

$$d = \sqrt{(X_2 - X_1)^2 + (Y_2 - Y_1)^2 + (Z_2 - Z_1)^2} \tag{12}$$

As it is mentioned, position of each GPS has 3 errors in each dimension; error in longitude (ε_x), error in latitude (ε_y) and error in altitude (ε_z). Therefore, the net position of GPS receiver is:

$$\begin{pmatrix} X+\varepsilon_x \\ Y+\varepsilon_y \\ Z+\varepsilon_z \end{pmatrix} \tag{13}$$

In this way, distance calculation between 2 net points has 6 unknowns:

$$d_{12} = \sqrt{\left((X_2+\varepsilon_{x2}) - (X_1+\varepsilon_{x1})\right)^2 + \left((Y_2+\varepsilon_{y2}) - (Y_1+\varepsilon_{y1})\right)^2 + \left((Z_2+\varepsilon_{z2}) - (Z_1+\varepsilon_{z1})\right)^2} \tag{14}$$

If the value of distance between point 1 and 2(d_{12}) is known, this equation has many answers and the exact errors of GPS devices are not found. By increasing the number of GPS devices and constraining them in a known way, the number of equations is increased and a set of defined system of equations will be achieved, therefore the system can be solved. To define the system of equations, seven GPS devices are used. By calculating distances between these devices, a heptagon shape is achieved. In this way, each GPS device is mounted on one corner of the heptagon. The length of each side is calculated by:

$$d_{ij} = \sqrt{\left(\left(X_j + \varepsilon_{xi}\right) - \left(X_i + \varepsilon_{xi}\right)\right)^2 + \left(\left(Y_j + \varepsilon_{yj}\right) - \left(Y_i + \varepsilon_{yi}\right)\right)^2 + \left(\left(Z_j + \varepsilon_{zj}\right) - \left(Z_i + \varepsilon_{zi}\right)\right)^2} \tag{15}$$

where,

d_{ij} is distance between 2 known points i, j.

X_i, Y_i and Z_i are position of first point in ECEF coordinate which are read from GPS receiver.

X_j, Y_j and Z_j are position of second point in ECEF coordinate which are read from GPS receiver.

$\varepsilon_{xi}, \varepsilon_{yi}$ and ε_{zi} are errors of first point which are unknown .

$\varepsilon_{xj}, \varepsilon_{yj}$ and ε_{zj} are errors of second point which are unknown .

As it is mentioned before, the goal of this work is correcting the position of GPS receiver which is mounted on the robot; therefore, one rover receiver is used. In this way, seven fixed receivers and one rover receiver are utilized.

To correct the rover receiver's position, first of all, the defined system of equations which is obtained from seven fixed points must be solved.

Then, by using the errors obtained from fixed points, the rover receiver position will be corrected.

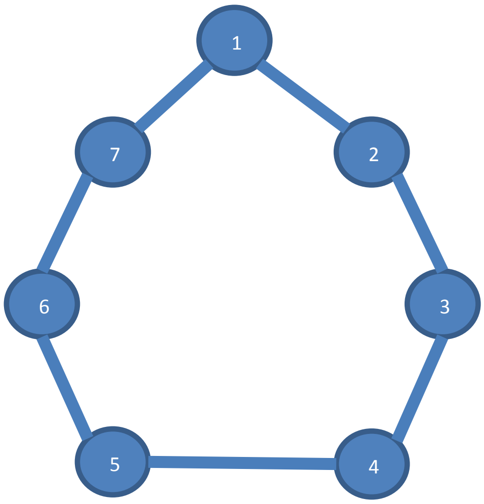

Figure 16 – Heptagon shape of GPS receivers set

3.2.1 Calculating Position of Fixed Receivers

As it is mentioned before, if the distance between two points is known, the equation (15) will have six unknowns. To find the error of each point, the system of equations with 21 unknowns and 21 equations are needed.

$$\begin{cases} d_{12} = \sqrt{\left((X_2+\varepsilon_{x2})-(X_1+\varepsilon_{x1})\right)^2+\left((Y_2+\varepsilon_{y2})-(Y_1+\varepsilon_{y1})\right)^2+\left((Z_2+\varepsilon_{z2})-(Z_1+\varepsilon_{z1})\right)^2} \\ d_{13} = \sqrt{\left((X_3+\varepsilon_{x3})-(X_1+\varepsilon_{x1})\right)^2+\left((Y_3+\varepsilon_{y3})-(Y_1+\varepsilon_{y1})\right)^2+\left((Z_3+\varepsilon_{z3})-(Z_1+\varepsilon_{z1})\right)^2} \\ . \\ . \\ d_{67} = \sqrt{\left((X_7+\varepsilon_{x7})-(X_6+\varepsilon_{x6})\right)^2+\left((Y_7+\varepsilon_{y7})-(Y_6+\varepsilon_{y6})\right)^2+\left((Z_7+\varepsilon_{z7})-(Z_6+\varepsilon_{z6})\right)^2} \end{cases} \tag{16}$$

In general, a defined system of equations can be solved when the unknowns match with the equations. Thus, to find solutions, the system in form below can be solved:

$$\begin{aligned} f_1(x_1, x_2, x_3, \ldots, x_n) &= 0 \\ f_2(x_1, x_2, x_3, \ldots, x_n) &= 0 \\ f_3(x_1, x_2, x_3, \ldots, x_n) &= 0 \\ . \\ . \\ . \\ f_n(x_1, x_2, x_3, \ldots, x_n) &= 0 \end{aligned} \tag{17}$$

In this way the system of equations is:

$$F = \begin{cases} \sqrt{\left(\left(X_2+\varepsilon_{x2}\right)-\left(X_1+\varepsilon_{x1}\right)\right)^2+\left(\left(Y_2+\varepsilon_{y2}\right)-\left(Y_1+\varepsilon_{y1}\right)\right)^2+\left(\left(Z_2+\varepsilon_{z2}\right)-\left(Z_1+\varepsilon_{z1}\right)\right)^2}-d_{12} \\ \sqrt{\left(\left(X_3+\varepsilon_{x3}\right)-\left(X_1+\varepsilon_{x1}\right)\right)^2+\left(\left(Y_3+\varepsilon_{y3}\right)-\left(Y_1+\varepsilon_{y1}\right)\right)^2+\left(\left(Z_3+\varepsilon_{z3}\right)-\left(Z_1+\varepsilon_{z1}\right)\right)^2}-d_{13} \\ . \\ . \\ \sqrt{\left(\left(X_7+\varepsilon_{x7}\right)-\left(X_6+\varepsilon_{x6}\right)\right)^2+\left(\left(Y_7+\varepsilon_{y7}\right)-\left(Y_6+\varepsilon_{y6}\right)\right)^2+\left(\left(Z_7+\varepsilon_{z7}\right)-\left(Z_6+\varepsilon_{z6}\right)\right)^2}-d_{67} \end{cases} \tag{18}$$

For solving the mentioned set of equations, Newton's algorithm can be used. In order to solve this nonlinear system of equations by Newton's method, the following instruction should be followed:

1. Generation of Jacobian matrix of the system of equations:

$$J\left(\varepsilon_{x1},...,\varepsilon_{x7},\varepsilon_{y1},...,\varepsilon_{y7},\varepsilon_{z1},...,\varepsilon_{z7}\right)= \begin{pmatrix} \frac{\partial}{\partial\varepsilon_x} f_1\left(\varepsilon_{xi},\varepsilon_{yi},\varepsilon_{zi}\right) & \frac{\partial}{\partial\varepsilon_y} f_1\left(\varepsilon_{xi},\varepsilon_{yi},\varepsilon_{zi}\right) & \frac{\partial}{\partial\varepsilon_z} f_1\left(\varepsilon_{xi},\varepsilon_{yi},\varepsilon_{zi}\right) \\ . & . & . \\ \frac{\partial}{\partial\varepsilon_x} f_7\left(\varepsilon_{xi},\varepsilon_{yi},\varepsilon_{zi}\right) & \frac{\partial}{\partial\varepsilon_y} f_7\left(\varepsilon_{xi},\varepsilon_{yi},\varepsilon_{zi}\right) & \frac{\partial}{\partial\varepsilon_z} f_7\left(\varepsilon_{xi},\varepsilon_{yi},\varepsilon_{zi}\right) \end{pmatrix} \tag{19}$$

2. Solving the equations as:

$$J\left(\varepsilon_{x1},...,\varepsilon_{x7},\varepsilon_{y1},...,\varepsilon_{y7},\varepsilon_{z1},...,\varepsilon_{z7}\right)\Delta\varepsilon = F\left(\varepsilon_{xi},\varepsilon_{yi},\varepsilon_{zi}\right) \quad \text{for}\,\Delta\varepsilon_i \tag{20}$$

3. Calculate $\varepsilon_{i+1} = \varepsilon_i + \Delta\varepsilon_i$
4. Repeat calculation steps 1 to 3 until $\left|\varepsilon_{i+1} - \varepsilon_i\right| < \xi$.
5. The root of ε_{i+1} is the result of the system of equations.

where, ξ is a lower bound on the change in the value of the objective function during the step. If $\left|\varepsilon_{i+1} - \varepsilon_i\right| < \xi$, the iterations end.

Solving this system of equations, errors of each GPS $\left(\varepsilon_{xi},\varepsilon_{yi},\varepsilon_{zi}\right)$ can be obtained. Then it becomes easy to calculate modified position of the receivers as:

$$\left\{\left(X+\varepsilon_x\right),\left(Y+\varepsilon_y\right),\left(Z+\varepsilon_z\right)\right\} \tag{21}$$

In MATLAB, this method is run with LSQNONLIN function which is shown in Listing 1.

```
function [X] = solve_ECEF_cartesian(X_point_1…7,Y_point_1…7,
Z_point_1…7, mean_X_point_1…7,mean_Y_point_1…7,
mean_Z_point_1…7,d_net_1…7, d_net_2…7,d_net_3…7,d_net_4…7,d_net_5…7,
,d_net_6…7);


    initial_ X_p1…7 = X_point_1…7 - mean_X_point_1…7;
    initial_ Y_p1…7 = Y_point_1…7 - mean_Y_point_1…7;
    initial_ Z_p1…7 = Z_point_1…7 - mean_Z_point_1…7;

    X_initial = [initial_ X_p1…7, initial_ Y_p1…7, initial_ Z_p1…7]
    options = optimset('Display','iter','TolFun',1e-60);
    X = lsqnonlin(@eqns, X_initial,[rang of accuracy of lat,long and alt in meter]

   function F = eqns(X)
    F =[...
       (((x_point_1+X(1))-(x_point_2+X(2))))^2 + (((y_point_1+X(8))-
(y_point_2+X(9))))^2                    + (((z_point_1+X(15)) - (z_point_2+X(16))))^2
- (d_net_12)^2;
.
.
.
     (((x_point_6+X(6))-(x_point_7+X(7))))^2 + (((y_point_6+X(13))-
(y_point_7+X(14))))^2 + (((z_point_6+X(20))-(z_point_7+X(21))))^2 - (d_net_67)^2]
  end
end
```

Listing 1 – Finding error of seven fixed points with LSQNONLIN function in MATLAB

3.2.2 Correcting Position of Rover Receiver

After finding the errors of fixed points, the position of rover receive can be corrected. Each fixed point can be used as a base station to correct the error of rover receiver. By using this strategy, seven corrected points of rover receiver positions which are located on the circle is achieved (Figure 17). To find the net position of rover receiver, it is possible to get mean value of all results. As mentioned in chapter 2, the geometry of GPS satellites affects the accuracy of GPS receivers. In this way, if two same GPS receivers are near to each other, the errors of them will be similar to each other. The result of this theorem is that the distance between rover receiver and fixed points, effect on accuracy of rover receiver. In this way, to increase the accuracy of net position of rover receiver, distance between rover receiver and fixed points must be considered. Therefore to correct rover receiver position, Inverse Distance Weighting (IDW) method is used.

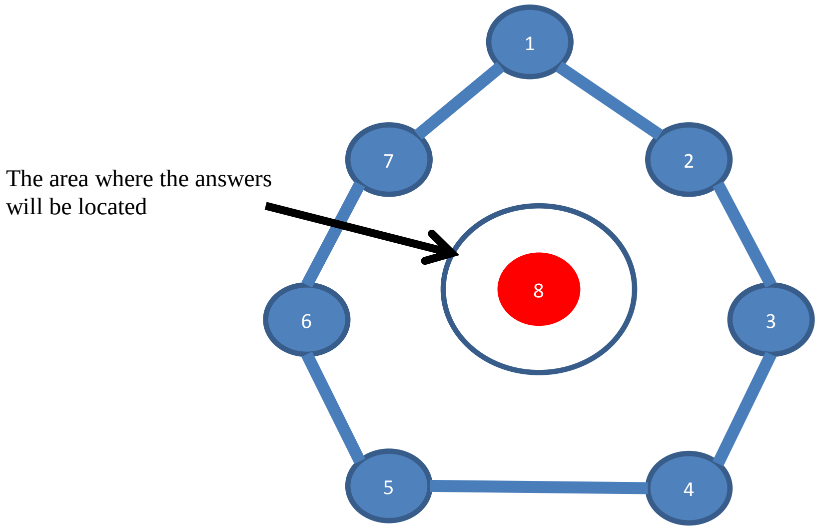

Figure 17 – The area where the corrected point of rover receiver will be located

Using this approach, the errors of fixed points are weighted and the position of rover device is revised with respect to these weighted errors. It means that if rover receiver is near the one of the fixed points, the error of that GPS device will have greater impact on positioning of rover device. Actually, it is similar to get mean of values of corrections of rover receiver position by fixed points individually if the rover receiver is located on the middle of the heptagonal, but as the distance between the rover receiver and fixed points changes, the effect of fixed points on rover receiver positioning will change.

The Inverse Distance Weighting Method

The Inverse Distance Weighting (IDW) interpolator within the Geographic Information Systems (GIS) operates on the assumption that entities in close proximity to one another are more alike than those farther away. IDW uses the values of surrounding measured locations to predict the value of unmeasured locations. The measured values closest to the prediction location will have a larger impact on the predicted value than those farther away. Thus, IDW interpolation weights measured values at locations closer to a prediction location more than those farther away [46].

The general formula of IDW is:

$$\hat{Z}(s_\circ) = \sum_{i=1}^{N} \lambda_i Z(s_i) \qquad (22)$$

where,

$\hat{Z}(s_\circ)$ is the value which is tried to predict for location $s_\circ$.

N is the number of points close to the location that will be used in the prediction.

λ_i are the weights defined to each point. These weights will decrease with increasing distance.

$Z(s_i)$ is the value of a point at the location s_i.

The formula to determine the weights is as follows:

$$\lambda_i = d_{i0}^{-p} \Big/ \sum_{i=1}^{N} d_{i0}^{-p} \qquad \sum_{i=1}^{N} \lambda_i = 1 \tag{23}$$

As the distance becomes larger, the weight is reduced by a factor of *p*. The power parameter (*p*) controls how the weighting factor decreases with distance from a measured location. Weights are proportional to the inverse distance raised to the power p. The greater the power, the less effect distant points have on the value for a predicted location. As a result, the predicted location's value nears the value of the closest point. The converse is also true.

where,

d_{i0} is the distance between the prediction location $s_{\circ}$ and each of the measured locations, s_i.

Solving Error of Rover Receiver:

As it is mentioned before, fixed points effect on rover receiver independently and to use the effect of all of them on rover receiver, IDW method is used. In this method, errors of fixed points are weights and distances between fixed points and rover receiver are the distances between weights of points.

Distances between fixed points are known but distances between fixed points and rover receiver are unknowns and in using the IDW method, those distances are needed. Therefore, although calculating distances between real position of rover receiver and corrected positions of fixed points does not give the net distances, but to calculate weights, these errors can be ignored. Therefore, to calculate d_{i0}, distances between real position of rover receiver and corrected positions of fixed points are used.

As it is mentioned before, each point has three errors $(\varepsilon_x, \varepsilon_y, \varepsilon_z)$, therefore to find weights in 3 dimension (X, Y, Z) using equations (22) and (23) and *p*=1 we have:

$$
\begin{cases}
\varepsilon_{x8} = \sum\limits_{i=1}^{7} \dfrac{d_{i8}^{-1}\varepsilon_{xi}}{\sum\limits_{i=1}^{7} d_{i8}^{-1}} \\
\varepsilon_{y8} = \sum\limits_{i=1}^{7} \dfrac{d_{i8}^{-1}\varepsilon_{yi}}{\sum\limits_{i=1}^{7} d_{i8}^{-1}} \\
\varepsilon_{z8} = \sum\limits_{i=1}^{7} \dfrac{d_{i8}^{-1}\varepsilon_{zi}}{\sum\limits_{i=1}^{7} d_{i8}^{-1}}
\end{cases}
\tag{24}
$$

where, d_{i8} denotes distances between corrected fixed points and real position of rover receiver.

$\left(\varepsilon_{xi}, \varepsilon_{yi}, \varepsilon_{zi}\right)$ are fixed point's errors.

$\left(\varepsilon_{x8}, \varepsilon_{y8}, \varepsilon_{z8}\right)$ are errors of rover receiver.

$$
\varepsilon_{rover} = \frac{\frac{\varepsilon_1}{d_1} + \frac{\varepsilon_2}{d_2} + \frac{\varepsilon_3}{d_3} + \frac{\varepsilon_4}{d_4} + \frac{\varepsilon_5}{d_5} + \frac{\varepsilon_6}{d_6} + \frac{\varepsilon_7}{d_7}}{\frac{1}{d_1} + \frac{1}{d_2} + \frac{1}{d_3} + \frac{1}{d_4} + \frac{1}{d_5} + \frac{1}{d_6} + \frac{1}{d_7}}
$$

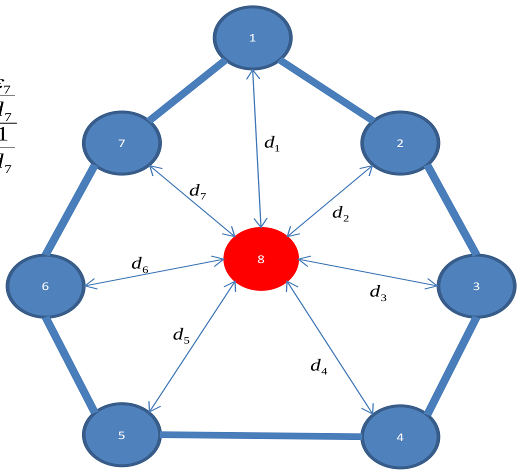

Figure 18 – The inverse distance weighted method for rover receiver

To find the modified rover receiver position $\left(X_{rover}, Y_{rover}, Z_{rover}\right)$, the position which is received from rover receiver $\left(X_8, Y_8, Z_8\right)$ is corrected by the error of rover receiver $\left(\varepsilon_{x8}, \varepsilon_{y8}, \varepsilon_{z8}\right)$ which is obtained from equation (24) (Figure 18):

$$\begin{pmatrix} X_{rover} \\ Y_{rover} \\ Z_{rover} \end{pmatrix} = \begin{pmatrix} X_8 + \varepsilon_{x8} \\ Y_8 + \varepsilon_{y8} \\ Z_8 + \varepsilon_{z8} \end{pmatrix} \tag{25}$$

After correcting the rover receiver position, distances between rover receiver and fixed points are calculated again. These results will show the corrected position of rover receiver.

These coordinates are in ECEF coordinates and according to Appendix B; these coordinates are converted to LLA coordinates.

Listing 2 shows how to implement the Inverse Distance Weighting to find error of rover receiver in MATLAB

```
function  [weighted_distance_rover] = moving_point (i_points,X_point_1…8,
Y_point_1…8,Z_point_1…8,mean_X_point_8,X);

error_x = [X(1) X(2) X(3) X(4) X(5) X(6) X(7)];
error_y = [X(8) X(9) X(10) X(11) X(12) X(13) X(14)];
error_z = [X(15) X(16) X(17) X(18) X(19) X(20) X(21)];

distance_from_point8 = [d_18 d_28 d_38 d_48 d_58 d_68 d_78];

ind = find(distance_from_point8<0.5);
if ~isempty(ind)
   error_x_weighted_mean = error_x(ind);
   error_y_weighted_mean = error_y(ind);
   error_z_weighted_mean = error_z(ind);
else

   error_x  =
sum(((1./distance_from_point8).*error_x)./((sum(1./distance_from_point8))));
   error_y_=
sum(((1./distance_from_point8).*error_y)./((sum(1./distance_from_point8))));
   error_z  =
sum(((1./distance_from_point8).*error_z)./((sum(1./distance_from_point8))));

end

weighted_rover_x = x_point_8 + error_x;
weighted_ rover_y = y_point_8 + error_y;
weighted_ rover_z = z_point_8 + error_z;
weighted_distance_rover = [weighted_ rover_x weighted_ rover_y weighted_ rover_z];
```

Listing 2 - Implementation of inverse distance weighted to find error of rover receiver

Listing 3 presents the main program which contains Listing 1 and Listing 2 and calculates distances between points and plots them.

```
for i_points = lowwer_point:upper_point

X_point_1…8 ← X in ECEF coordinate
Y_point_1…8 ← Y in ECEF coordinate
Z_point_1…8 ← Z in ECEF coordinate
mean_X_point_1…8 ← mean of 5 point before X_{i_points} in ECEF coordinate
mean_Y_point_1…8 ← mean of 5 point before Y_{i_points} in ECEF coordinate
mean_Z_point_1…8 ← mean of 5 point before Z_{i_points} in ECEF coordinate


[X] = solve_ECEF_cartesian();← finding the errors of fixed points
[Weighted_rover_receiver] = moving_point()← finding error of rover receiver with
using inverse distance weighted

[corrected distance between fixed points] = distance_fixed_points();← finding
distance between corrected fixed points and collect them in matrix

[corrected distance between fixed points and rover receiver] =
distance_from_point_8();← finding distance between corrected fixed points and
corrected rover receiver and collect them in matrix


Plot ← plot result in google map and scatter plot

end
```

Listing 3 – Main program

CHAPTER 4

HARDWARE

In this chapter the hardware which is used in tests is explained. In this chapter, parts used in hardware and why they are chosen are explained.

4.1 Design

As it is mentioned in Chapter 4, to run all tests, GPS receivers which can gather and save data are needed .To do that, a hardware which is shown in Figure 19 is designed. In this hardware, a 66-Channel GPS is used to receive signals from satellites. To save receiving data, raspberry pi is used. This GPS receiver must work for long hours; therefore an external battery is used. This system is put on the tripod to work better in test area shown in Figure 20.

Figure 19 – Hardware which is used in all tests

Figure 20 - Hardware which is used in all tests on the tripod

4.2 Hardware Components

4.2.1 GPS Receiver

All the GPS satellites broadcast on the same frequency. They are technically walking all over each other's signals. Each satellite broadcasts a different message every millisecond. The message is 1024 bits long, and is generated by a pseudo random number generator. After receiving all signals by the GPS receivers, the correlation process is started. In this process, the GPS receiver arrange signal in a specific way and if a signal matches with satellite's signal exactly, the correlation part has found one satellite. However, if it hasn't found a match, it has to shift its signal by one bit and try again, until it's gone through all 1023 bit periods and hasn't found a satellite. Then it moves on to trying to detect a different satellite at a different period [47].

In theory it can completely search a code in one second to find (or determine there's nothing) at a particular code. Because of the code shifting (there are currently 32 different PRN codes, one each for each satellite) it can therefore take upper than 30 seconds to search each satellite. Because of the speed of the satellite relative to ground speed, it requires searching about 40 different frequency shifts for a correlation process before it can give up on a particular PRN and timing. Therefore for one correlation process part, it takes at least 32 seconds to process all PRN. By increasing the number of correlation process part, the process time will be decreases. For example by using 12 correlators the process time takes less than a few seconds. Each correlator is called a "channel" for the sake of marketing. If you have a 12 channel receiver, you can use 4 of the strongest channels to provide your fix, a few channels to lock onto backup satellites so it can switch the calculations to them if needed, and several channels to keep searching for satellites the receiver should be able to see. In this way you never lose the full 3D fix [47].

There are 24 or so GPS satellites operating at any given time, which means that on one point on the earth only see 12 of them can be seen by GPS receiver.

Only one satellite per correlator can be searched, so the principle reason to increase correlators more than twelve is to improve the time to first fix, and the main reason to improve that is for power consumption. If your GPS chipset has to be powered all the time, it's a 100mW power drain all the time. If, however, it is only needed to turn on once per second for only 10mS each time, then the power consumption can be cut down to 1mW. This mean that the device can be operated for longer time on the same set of batteries while still maintaining a full real time fix on their location [47].

While only 4 satellites are needed to get a 3D fix, good receivers use more satellites in its position algorithm to get a more accurate fix. So only a 4 channel receiver is required, but a 12 channel receiver can get more accuracy.

Using the more correlators in GPS receivers caused as:

- Speeds up satellite acquisition
- Reduces power consumption
- Reduces likelihood of losing a 3D fix even in urban canyons
- Provide better sensitivity, allowing fixes in dense forests, and even in some tunnels
- Provides better positioning accuracy

After checking many GPS devices, 66-Channel LS20031 GPS Receiver Module is selected which is explained in Appendix D.

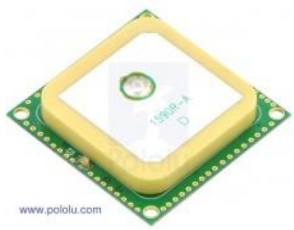

Figure 21 - 66-Channel LS20031 GPS receiver module

The Features of 66-Channel LS20031 GPS Receiver Module:

- MediaTek high sensitivity solution
- Support 66-channel GPS
- Fast TTFF at low signal level (Time to first fix)
- Support AGPS

- Up to 10 Hz update rate
- Capable of SBAS (WAAS, EGNOS, MSAS)
- Build-in micro battery to reserve system data for rapid satellite acquisition
- LED indicator for GPS fix or not fix

4.2.2 Raspberry Pi

After selecting a GPS device, the data received from GPS receiver can be saved. To do this a device capable of saving data is required. Different kind of computers and microcontrollers can do it. It is necessary that the device should be small and cheap to be affordable and work easily. Different kind of microcontrollers and computers are evaluated. After checking their costs and abilities, Raspberry Pi - Model B is selected which is explained in Appendix D.

The Features of Raspberry Pi - Model B are given below:

- Broadcom BCM2835 SoC
- 700 MHz ARM1176JZF-S core CPU
- Broadcom VideoCore IV GPU
- 512 MB RAM
- 2 x USB2.0 Ports
- Video Out via Composite (PAL and NTSC), HDMI or Raw LCD (DSI)
- Audio Out via 3.5mm Jack or Audio over HDMI
- Storage: SD/MMC/SDIO
- 10/100 Ethernet (RJ45)
- Low-Level Peripherals:
  - 8 x GPIO
  - UART
  - I2C bus
  - SPI bus with two chip selects
  - +3.3V
  - +5V
  - Ground
- Power Requirements: 5V at 700 mA via MicroUSB or GPIO Header
- Supports Debian GNU/Linux, Fedora, Arch Linux, RISC OS

A raspberry Pi has GPIO to connect it to sensors. To connect a GPS which is explained in Appendix D to raspberry Pi, a connection which is shown in Figure 23 is needed.

Figure 22 - Raspberry Pi

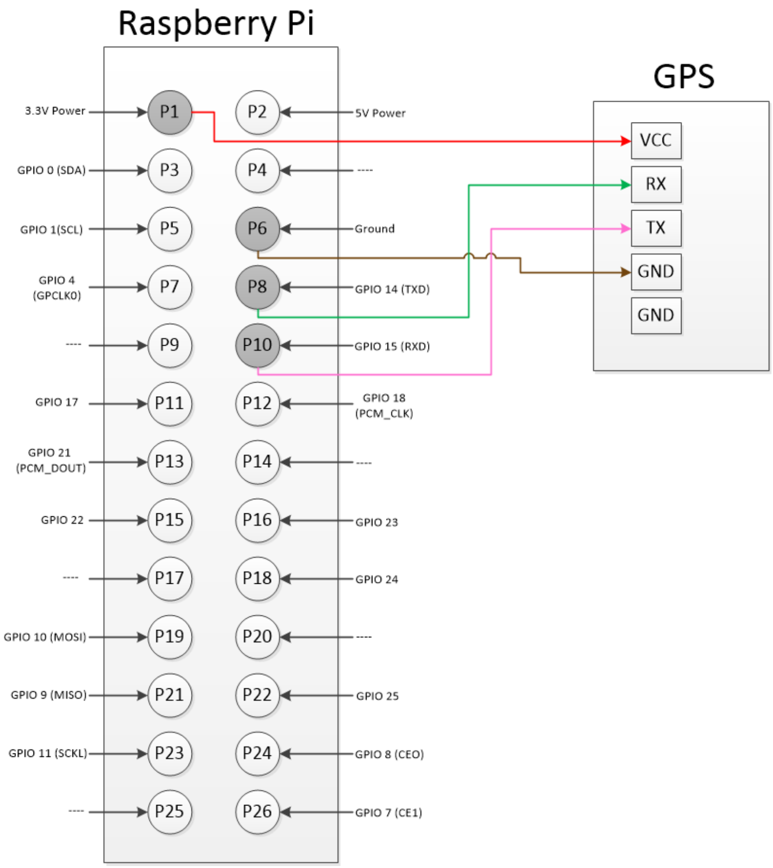

Figure 23 – Schematic of connection Raspberry Pi and GPS

4.2.3 Rechargeable External Battery

A system explained in Figure 23, needs an external battery to set up the system. To do that, S-link IP715 is chosen.

Figure 24 - Rechargeable External Battery

CHAPTER 5

TEST DESCRIPTION AND RESULT

5.1 Test Description

To validate the proposed method, different tests have been done. These tests are done in Devrim stadium of Middle East Technical University.

Figure 25 - Test area (Middle East Technical University)
$\left(\text{latitude}: 39^{\circ} 53^{'} 29.76^{''} N, \text{longitude}: 32^{\circ} 47^{'} 07.85^{''} E, \text{elevation}: 923m\right)$

Test 1 discusses the potential problems that the proposed method may face with them.

Test 2 explains running the proposed method in small area and its results.

Test 3 explains running the proposed method in large area and its results.

Test 4 explains the proposed method for rover receiver and shows that the results of this method are acceptable for the purpose of this work.

Potential Problem for Proposed Method:

Each GPS device has an accuracy range that is specified in the catalog. In good weather conditions, GPS receiver determines its position within a circle with a radius equal to the accuracy range (Figure 26).

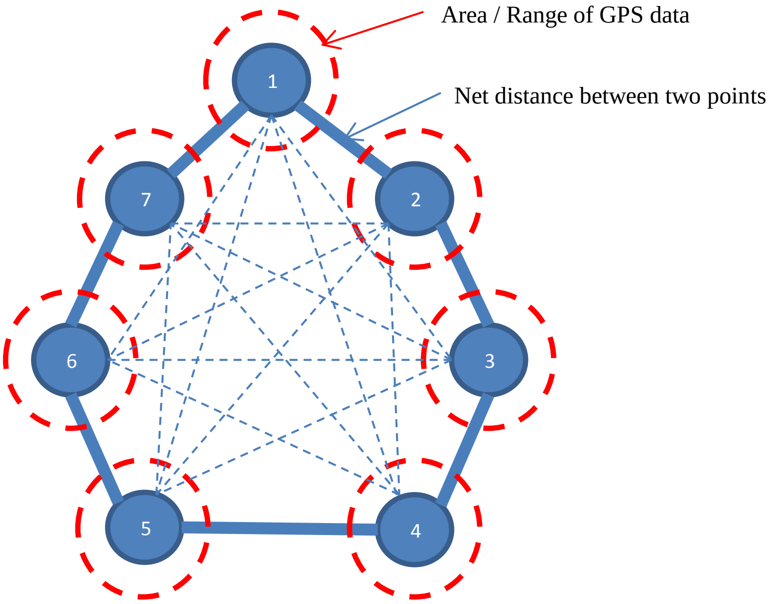

Figure 26 – The region of GPS errors and distances between them.

If all GPS receivers have the same errors i.e. all the errors move or rotate in the same direction, the proposed method will not work properly, because, although the method maintains the distances between receivers correctly, but if all errors of fixed points are equal, the corrected heptagonal will be parallel with real heptagonal (Figure 27).

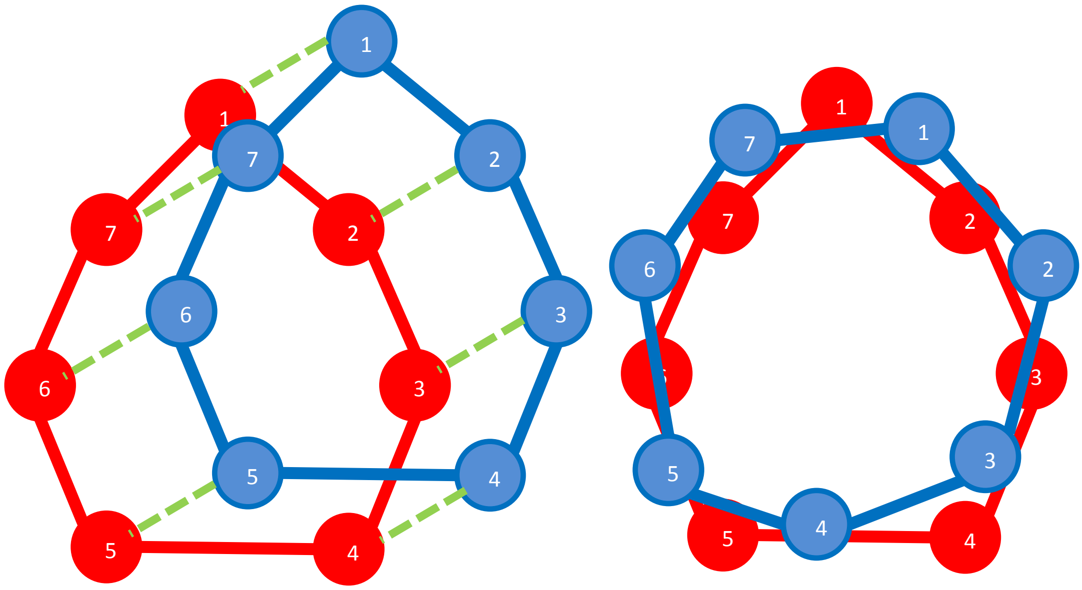

Figure 27 – Potential problems of proposed method

This problem will occur when all the conditions of GPS devices are similar to each other; for example, all of them receive data from the same satellite at the same time. Therefore, all tests are done in the same condition (data from the same satellite with the same PDOP in the same time).

5.1.1 Test 1

As it is mentioned before, if all errors of GPS devices are similar to each other, the proposed method will not work properly. Test 1 shows that each GPS device has unique errors. The result of plotting these errors shows that, the corrected heptagonal will not be parallel with real heptagonal.

In Figure 28 it is observed that each GPS receiver has its own errors and all errors do not move or rotate in the same direction which is shown and explained in Figure 27, therefore, net position of each coordinate can be achieved by proposed method. As explained in chapter 2, these errors have many reasons, but the most important source of error is multipath which is caused by the objects around the test area.

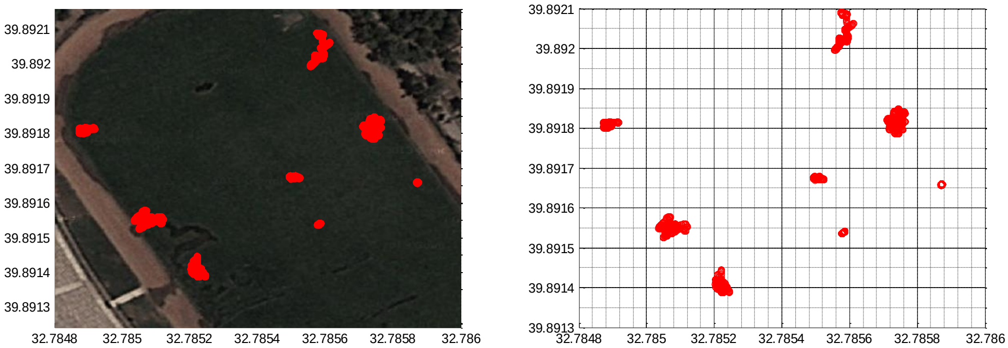

Figure 28 – Result of Test 1

5.1.2 Test 2

The second major case which must be checked in proposed method is distances between fixed points. As it is mentioned before, this method is based on distances between fixed points. Test 2 shows that this method does not work properly in small area and (Figure 29).

Figure 29 – Executing proposed method in small area

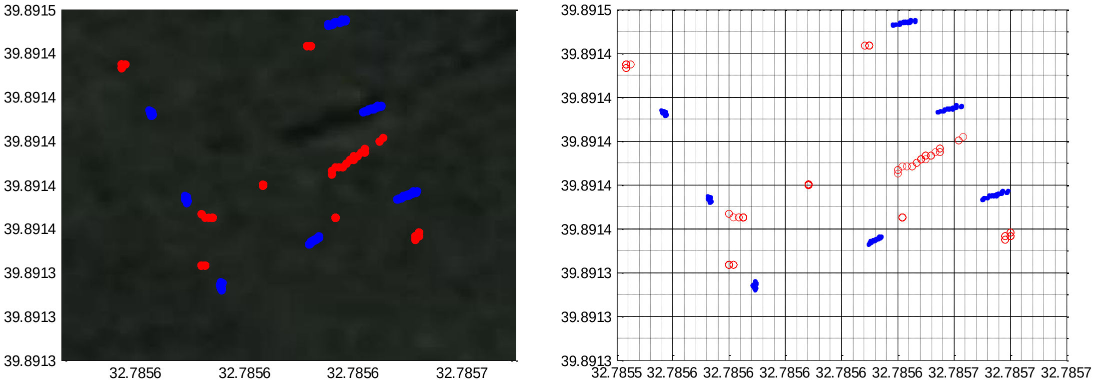

Figure 30 - Correction method for same satellite: (Left) plot in Google Maps. (Right) plot in MATLAB plot. Red points show the real data and blue points show corrected points.

To execute this test, GPS receivers are put in small area and before starting to calculate rover receiver position, the positions of fixed point are calculated.

Figure 30 demonstrates the correction of fixed points in small area. It shows that, in small area proposed method can calculate positions of fixed points.

Table 2 shows the ground truth of distance between fixed points, the result of calculating distances between real positions of fixed points and calculating distances between corrected positions of fixed points.

Figure 31 shows the errors of test 2. These errors are differences between calculating distances and ground truth which are mentioned in Table 2.

By investigating this figure, it can be concluded that the errors of correcting data are near zero which means that actual data are found.

Table 2 - Distance between fixed points in small area

Distance between Fixed Points (meter)					
distance	**Ground Truth**	**distance with real data**	**errors (m)**	**distance with corrected data**	**errors (m)**
Point 1-2	5.00	7.05	2.05	5.00	0.00
Point 1-3	10.00	12.03	2.03	10.00	0.00
Point 1-4	11.18	10.57	-0.61	11.18	0.00
Point 1-5	14.14	11.83	-2.31	14.14	0.00
Point 1-6	11.18	7.66	-3.52	11.18	0.00
Point 1-7	10.00	7.57	-2.43	10.00	0.00
Point 2-3	5.00	5.27	0.27	5.00	0.00
Point 2-4	7.10	4.72	-2.38	7.07	0.00
Point 2-5	11.18	10.85	-0.33	11.18	0.00
Point 2-6	10.00	8.69	-1.31	10.00	0.00
Point 2-7	11.18	12.60	1.42	11.18	0.00
Point 3-4	5.00	3.36	-1.64	5.00	0.00
Point 3-5	10.00	10.94	0.94	10.00	0.00
Point 3-6	11.18	10.75	-0.43	11.18	0.00
Point 3-7	14.14	16.48	2.34	14.14	0.00
Point 4-5	5.00	8.78	3.78	5.00	0.00
Point 4-6	7.10	9.03	1.93	7.07	0.00
Point 4-7	11.18	13.86	2.68	11.18	0.00
Point 5-6	5.00	4.97	-0.03	5.00	0.00
Point 5-7	10.00	10.75	0.75	10.00	0.00
Point 6-7	5.00	8.28	3.28	5.00	0.00

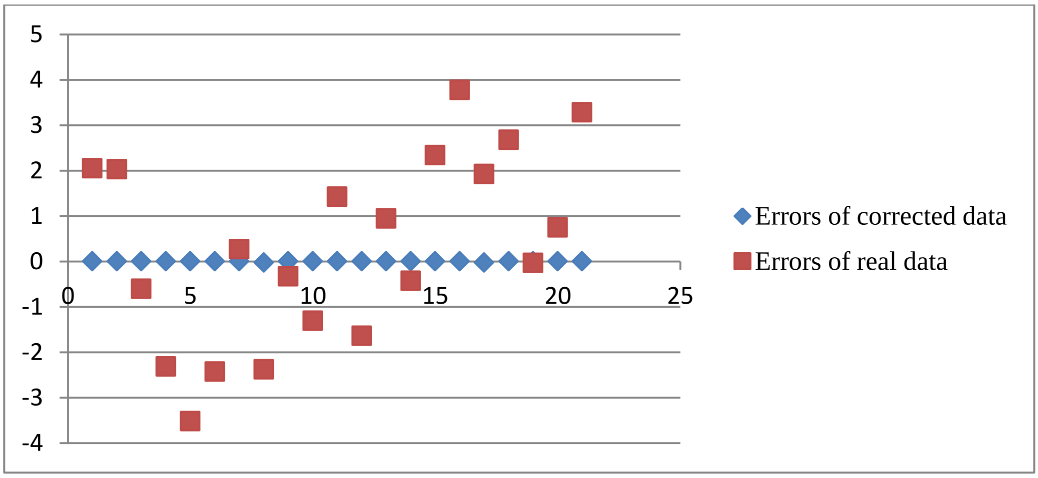

Figure 31 – Errors of corrected and real data of fixed points in small area

After correcting distances between fixed points, the position of rover receiver can be estimated. Figure 32 shows the result of correcting the position of rover receiver. As it can be seen, proposed method cannot correct the position of rover receiver, because, as it is mentioned before, to use IDW method distance between real position of rover receiver and corrected positions of fixed points are used and if the rover receiver is close to the one of the fixed points, the impact of that point is more than others. As it can be seen in Figure 32 the corrected position of rover receiver is plotted near the point that is closer to real data.

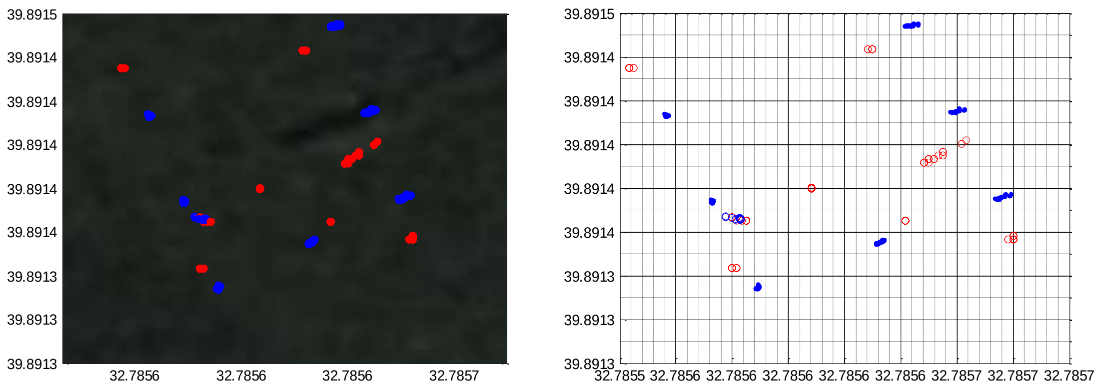

Figure 32 - Correction between fixed points and rover point in small area: (Left) plot in Google Maps. (Right) plot in MATLAB plot. Red points show the real data and blue points show corrected points.

Table 3 shows the results of the calculating distances between rover receiver and fixed points and the errors of them. According to this table and Figure 32 and Figure 33, it can be seen that in small area this method cannot work correctly.

Table 3 - Distance between fixed points and rover point in small area

Distance between Fixed Points and Rover Point (meter)					
distance	**Ground Truth**	**distance with real data**	**Errors**	**distance with corrected data**	**Errors**
Point 1-8	7.10	13.34	6.24	11.40	4.30
Point 2-8	5.00	9.53	4.53	9.06	4.06
Point 3-8	7.10	9.25	2.15	8.71	1.61
Point 4-8	5.00	6.33	1.33	4.94	-0.06
Point 5-8	7.10	10.52	3.42	3.60	-3.50
Point 6-8	5.00	12.23	7.23	0.98	-4.02
Point 7-8	7.10	13.97	6.87	5.55	-1.55

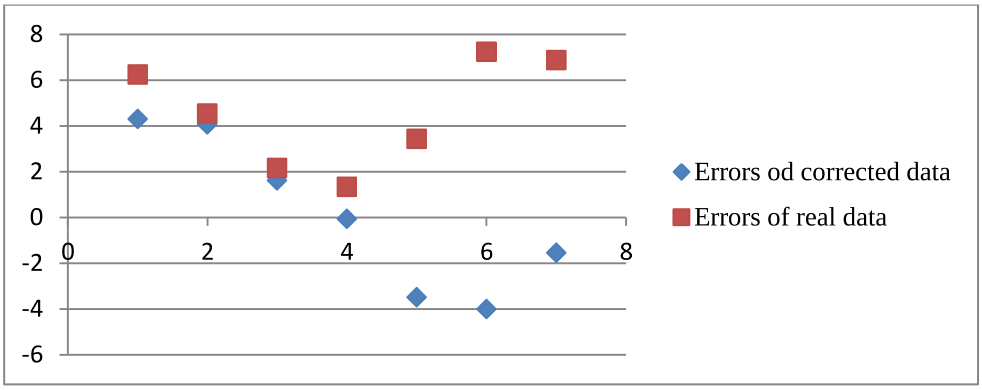

Figure 33 - Errors of corrected and real data of rover receiver in small area

5.1.3 Test 3

After showing that the proposed method does not work correctly in small area, this method is implemented in a large area. In order to implement the method in large area, GPS receivers are put in specific points in a large area and the distances between them are measured. Similar to the previous test, first, the positions of fixed points are corrected then the position of the rover receiver is corrected using IDW method.

1. Plot fixed points (real and corrected data)

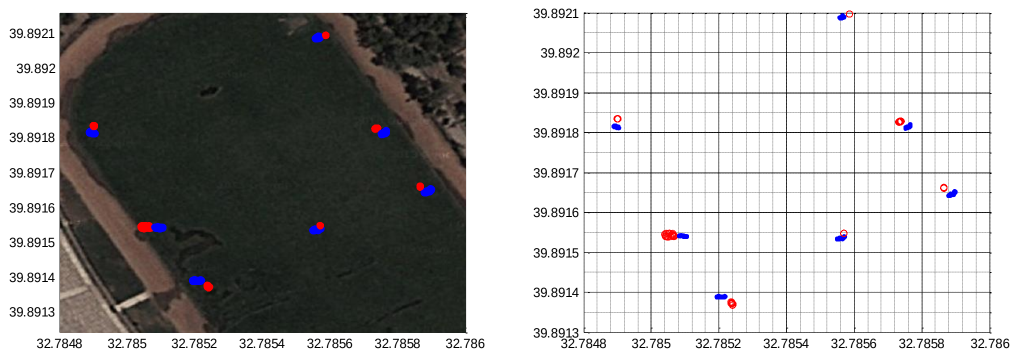

Figure 34 - Correction method: (Left) plot in Google Maps. (Right) plot in MATLAB plot. Red points show the real data and blue points show corrected points.

The result of this test is given in Table 4. Table 4, shows the ground truth of distances between fixed points, the result of calculating distance between real position of fixed points and calculating distances between corrected position of fixed points.

Table 4 - Distance between fixed points

Distance between Fixed Points (meter)					
distance	**Ground Truth**	**distance with real data**	**errors (m)**	**distance with corrected data**	**errors (m)**
Point 1-2	64.75	65.77	1.02	64.76	0.01
Point 1-3	73.81	71.59	-2.22	73.81	0.00
Point 1-4	86.91	84.65	-2.26	86.91	0.00
Point 1-5	64.68	65.47	0.79	64.69	0.01
Point 1-6	54.22	59.68	5.46	54.21	-0.01
Point 1-7	34.7	35.58	0.88	34.77	0.07
Point 2-3	34.72	32.68	-2.04	34.80	0.08
Point 2-4	56.60	54.58	-2.02	56.62	0.02
Point 2-5	61.66	61.09	-0.57	61.62	-0.04
Point 2-6	83.68	86.15	2.47	83.68	0.00
Point 2-7	73.11	76.13	3.02	73.09	-0.02
Point 3-4	21.80	22.42	0.62	21.87	0.07
Point 3-5	35.44	34.14	-1.30	35.48	0.04
Point 3-6	66.98	66.31	-0.67	67.00	0.02
Point 3-7	64.65	65.44	0.79	64.63	-0.02
Point 4-5	30.59	28.51	-2.08	30.68	0.09
Point 4-6	65.17	63.14	-2.03	65.14	-0.03
Point 4-7	68.97	69.52	0.55	69.03	0.06
Point 5-6	34.54	34.82	0.28	34.56	0.02
Point 5-7	39.97	42.93	2.96	39.93	-0.04
Point 6-7	19.53	24.70	5.17	19.61	0.08

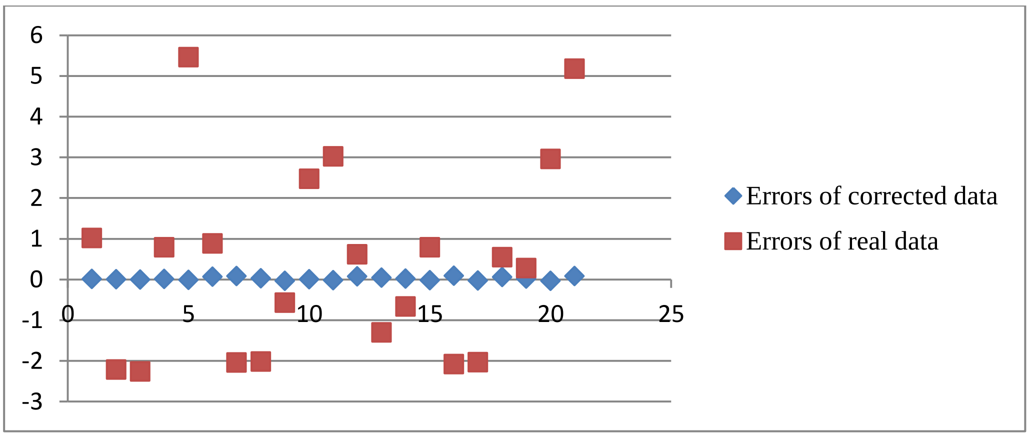

Figure 35 - Errors of corrected and real data of fixed points

Figure 35 shows the errors of test 3. These errors are differences between calculating distances and ground truth which is mentioned in

Table 4. By investigating this figure, it is concluded that the errors of correcting data are near zero which means that actual data are found.

2. Plot rover receiver (real and corrected data)

After correcting distance between fixed points, the position of rover receiver can be calculated.

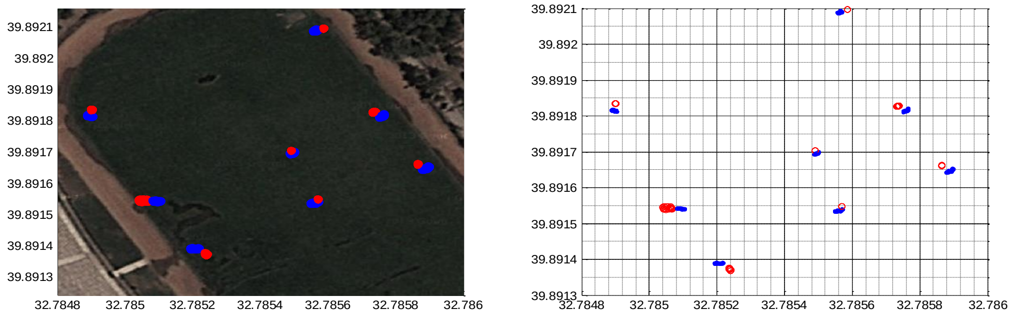

Figure 36 – Correction between Fixed Points and Rover Point: (Left) plot in Google Maps. (Right) plot in MATLAB plot. Red points show the real data and blue points show corrected points.

Figure 36 shows the results of correcting position of rover receiver. Rover receiver is put in specific position whose distances between it and fixed points as a ground truth are known. After correcting the position of rover receiver by using the IDW method, distance between corrected fixed points and rover receiver is calculated and compared with ground truth (Table 5).

These results show that unlike the test 2 which is done in small area, in large area, proposed method works correctly. The results obtained with different tests show that the maximum error is less than 1 meter and this result is acceptable for this work. Figure 37 shows the errors of rover receiver corrections. These errors are differences between calculating distances and ground truth which is given in Table 5.

Table 5 - Distance between fixed points and rover point

Distance between Fixed Points and Rover Point (meter)					
distance	**Ground Truth**	**distance with real data**	**Errors**	**distance with corrected data**	**Errors**
Point 1-8	51.59	52.47	0.88	51.56	-0.03
Point 2-8	44.30	44.49	0.19	44.21	-0.09
Point 3-8	27.22	29.09	1.87	27.87	0.65
Point 4-8	35.23	34.28	-0.95	35.73	0.50
Point 5-8	18.99	18.61	-0.38	18.88	-0.11
Point 6-8	41.56	43.06	1.50	41.05	-0.51
Point 7-8	37.37	39.57	2.20	37.01	-0.36

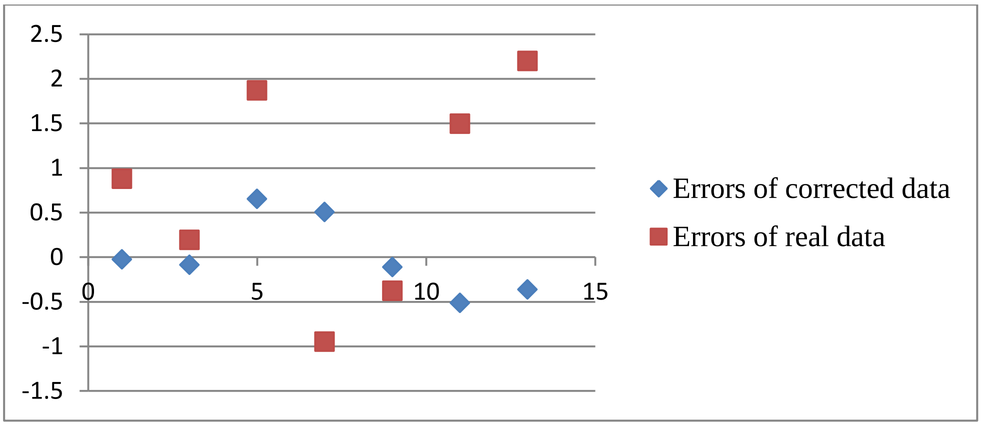

Figure 37 - Errors of corrected and real data of rover receiver

To implement the method in large area, it is indispensable to consider the multipath effect. As discussed in Chapter 2, the constructions and structures surrounding the GPS receivers may cause the signals to be reflected and hence they lead to multipath error. To investigate the influence of multipath on the results and validate the method to be used in arbitrary large areas, test 3 is repeated in an area without surrounding objects around, as shown in Figure 38. This area is located in TEKNOKENT in Middle East Technical University.

Figure 38 - Test area (TEKNOKENT in Middle East Technical University)
$\left(\text{latitude}: 39^{\circ}53'40.18'' N, \text{longitude}: 32^{\circ}46'27.07'' E, \text{elevation}: 897m\right)$

Similar to the previous test, first, the positions of fixed points are corrected then the position of the rover receiver is corrected using IDW method.

1. Plot fixed points (real and corrected data)

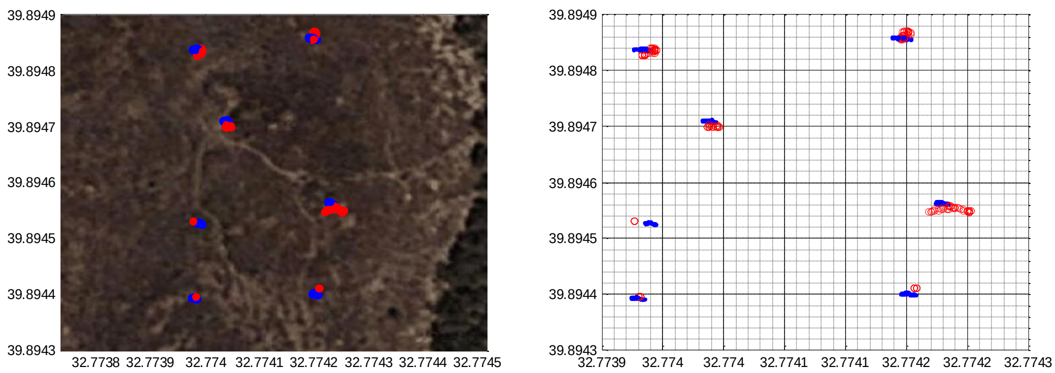

Figure 39 - Correction method: (Left) plot in Google Maps. (Right) plot in MATLAB plot. Red points show the real data and blue points show corrected points.

The result of this test is given in Table 6. Table 6, shows the ground truth of distances between fixed points, the result of calculating distance between real position of fixed points and calculating distances between corrected position of fixed points.

Table 6 - Distance between fixed points in an area without surrounding objects around

Distance between Fixed Points (meter)					
distance	**Ground Truth**	**distance with real data**	**errors (m)**	**distance with corrected data**	**errors (m)**
Point 1-2	19.05	19.87	0.82	19.05	0.00
Point 1-3	22.95	23.92	0.97	22.95	0.00
Point 1-4	37.06	34.9	-2.16	37.06	0.00
Point 1-5	52.00	50.24	-1.76	52.00	0.00
Point 1-6	50.75	50.74	-0.01	50.75	0.00
Point 1-7	18.18	15.45	-2.73	18.16	-0.02
Point 2-3	15.00	15.22	0.22	14.90	-0.10
Point 2-4	35.50	34.25	-1.25	35.53	0.03
Point 2-5	49.40	47.94	-1.46	49.39	-0.01
Point 2-6	54.96	55.81	0.85	54.96	0.00
Point 2-7	28.55	28.80	0.25	28.55	0.00
Point 3-4	20.85	19.63	-1.22	20.72	-0.13
Point 3-5	34.50	33.02	-1.48	34.52	0.02
Point 3-6	41.05	42.00	0.95	41.05	0.00
Point 3-7	20.90	23.64	2.74	20.97	0.07
Point 4-5	15.10	15.42	0.32	14.97	-0.13
Point 4-6	21.90	22.90	1.00	21.90	0.00
Point 4-7	23.2	24.49	1.29	23.15	-0.05
Point 5-6	19.23	19.54	0.31	19.22	-0.01
Point 5-7	37.10	38.99	1.89	37.11	0.01
Point 6-7	32.90	36.02	3.12	32.90	0.00

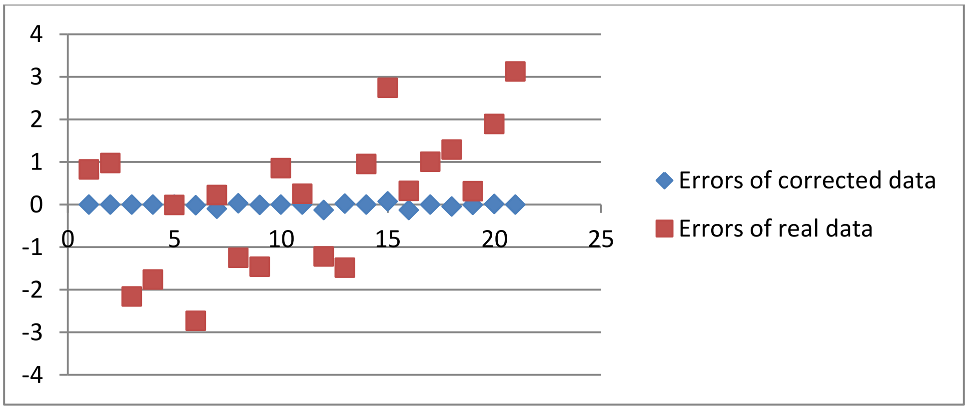

Figure 40 - Errors of corrected and real data of fixed points in an area without surrounding objects around

Figure 40 shows the errors of test 3. These errors are differences between calculating distances and ground truth which is mentioned in Table 6. By investigating this figure, it is concluded that the errors of correcting data are near zero which means that actual data are found.

2. Plot rover receiver (real and corrected data)

After correcting distance between fixed points, the position of rover receiver can be calculated.

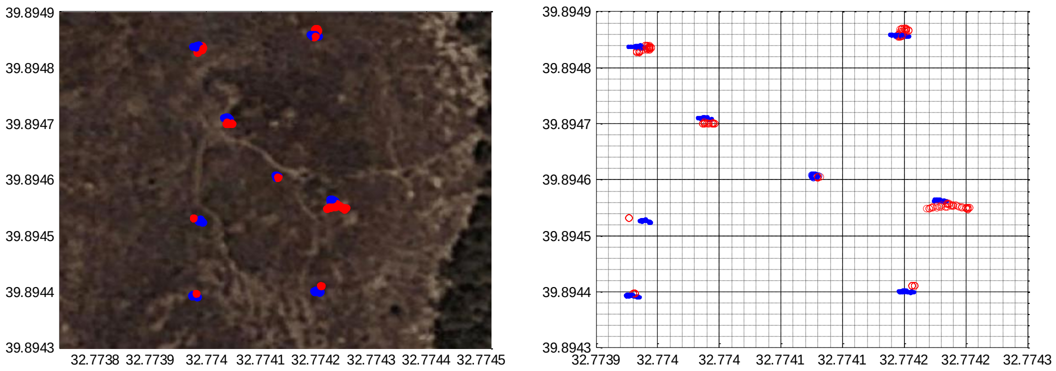

Figure 41 - Correction between Fixed Points and Rover Point: (Left) plot in Google Maps. (Right) plot in MATLAB plot. Red points show the real data and blue points show corrected points.

Figure 41 shows the results of correcting position of rover receiver. Rover receiver is put in specific position whose distances between it and fixed points as a ground truth are known. After correcting the position of rover receiver by using the IDW method, distance between corrected fixed points and rover receiver is calculated and compared with ground truth (Table 7).

Figure 42 shows the errors of rover receiver corrections. These errors are differences between calculating distances and ground truth which is given in Table 7.

Table 7 - Distance between fixed points and rover point in an area without surrounding objects around

Distance between Fixed Points and Rover Point (meter)					
distance	**Ground Truth**	**distance with real data**	**Errors**	**distance with corrected data**	**Errors**
Point 1-8	22.23	23.55	1.32	21.87	-0.36
Point 2-8	25.50	26.14	0.64	25.81	0.31
Point 3-8	13.90	15.33	1.43	14.49	0.59
Point 4-8	15.25	16.44	1.19	15.48	0.23
Point 5-8	30.00	28.58	-1.42	30.15	0.15
Point 6-8	30.16	30.93	0.77	30.05	-0.11
Point 7-8	8.90	8.43	-0.47	8.51	-0.39

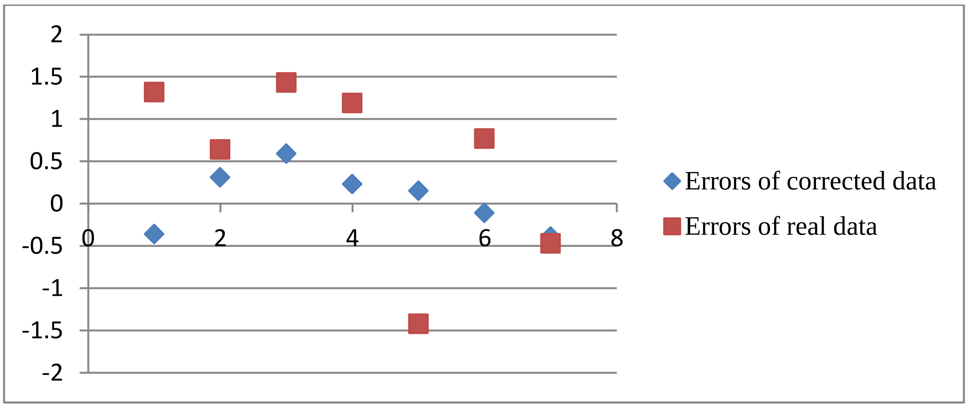

Figure 42 - Errors of corrected and real data of rover receiver in an area without surrounding objects around

Comparing the results of this test, which are given in Table 5 and Table 7 and Figure 37 and Figure 42, to the results of test 3 show that the effect of multipath on the proposed method is negligible and hence this method can be used in desired large areas.

5.1.4 Test 4

After proving the proposed method for rover receiver in large area, the rover receiver can be moved to correct the position of it at any time. In this test rover receiver is moved 10 meters in one direction (along point 5) and the position of rover is corrected in each step. In this test, movement of rover receiver is divided to 10 steps and 1 meter in each step. In each step, distances from the new position of rover receiver to all fixed points are calculated to compare results with ground truth (Figure 43).

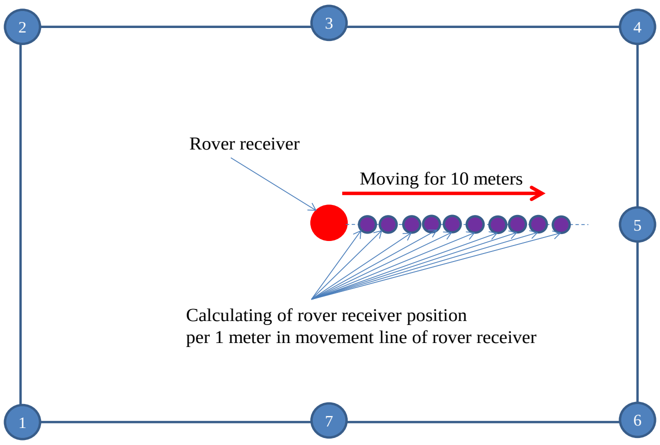

Figure 43 – Schematic of test 4

Figure 44 shows the real position of rover receiver and Figure 45 shows the position of rover receiver after correction.

Table 8 to Table 14 show the results of distances between fixed points and rover receiver in each step.

Figure 46 to Figure 52 show the errors of distances from fixed points to rover receiver in each step for real and corrected data.

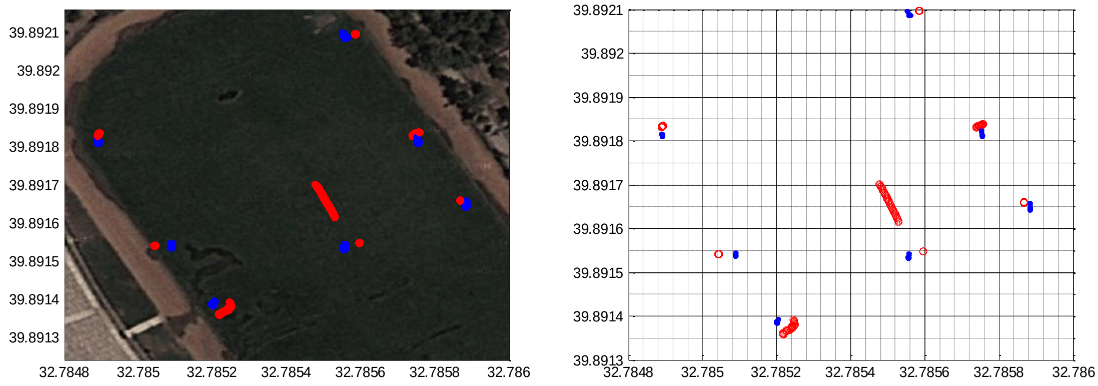

Figure 44 – Plotting rover receiver with real data: (Left) plot in Google Maps. (Right) plot in MATLAB plot. Red points show the real data and blue points show corrected points.

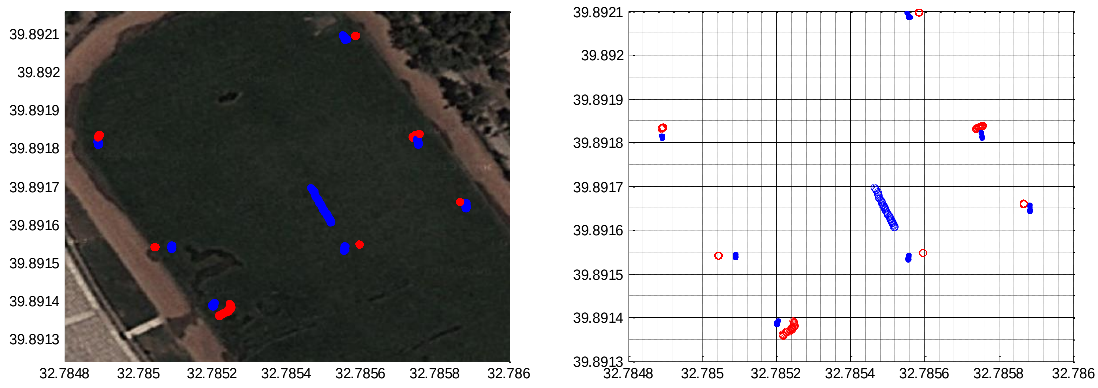

Figure 45 - Plotting rover receiver with corrected data: (Left) plot in Google Maps. (Right) plot in MATLAB plot. Red points show the real data and blue points show corrected points.

Table 8 – Distance between point 1 and rover receiver

Distance between point 1 & 8	Ground Truth	distance with real data	errors (m)	distance with corrected data	errors (m)
1	51.59	52.38	0.79	51.27	-0.32
2	52.30	52.91	0.61	52.05	-0.25
3	53.00	53.52	0.52	52.69	-0.31
4	54.00	54.34	0.34	53.42	-0.58
5	54.50	55.11	0.61	54.13	-0.37
6	55.20	55.96	0.76	54.98	-0.22
7	56.00	56.96	0.96	55.66	-0.34
8	56.50	57.77	1.27	56.39	-0.11
9	57.00	58.80	1.80	57.13	0.12
10	58.00	59.76	1.76	57.84	-0.16

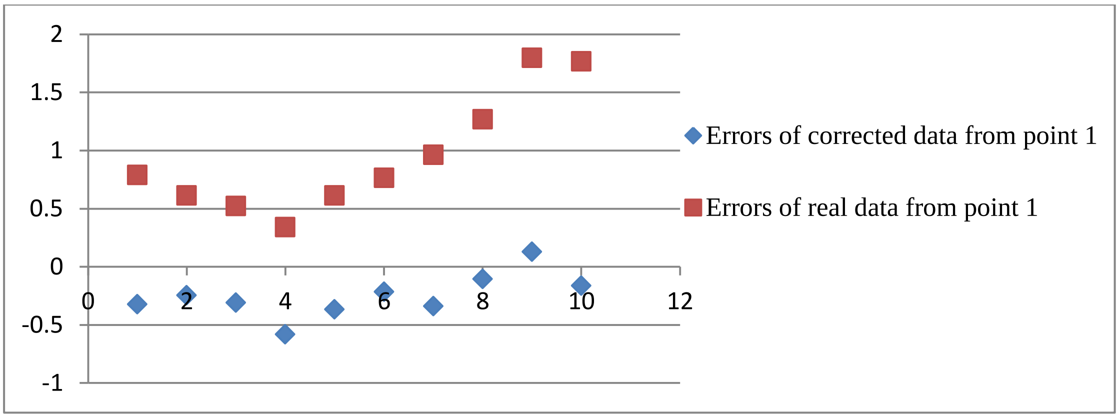

Figure 46 - Errors of corrected and real data of rover receiver from point 1

Table 9 - Distance between point 2 and rover receiver

Distance between point 2 & 8	Ground Truth	distance with real data	errors (m)	distance with corrected data	errors (m)
1	44.30	44.91	0.61	44.76	0.46
2	46.00	45.55	-0.45	45.55	-0.45
3	46.70	46.38	-0.32	46.32	-0.38
4	47.30	47.37	0.07	47.16	-0.14
5	48.30	48.40	0.10	48.13	-0.17
6	49.20	49.21	0.01	49.01	-0.19
7	50.00	50.42	0.42	49.83	-0.17
8	51.00	51.48	0.48	50.69	-0.31
9	51.80	52.72	0.92	51.50	-0.30
10	52.60	53.77	1.17	52.33	-0.27

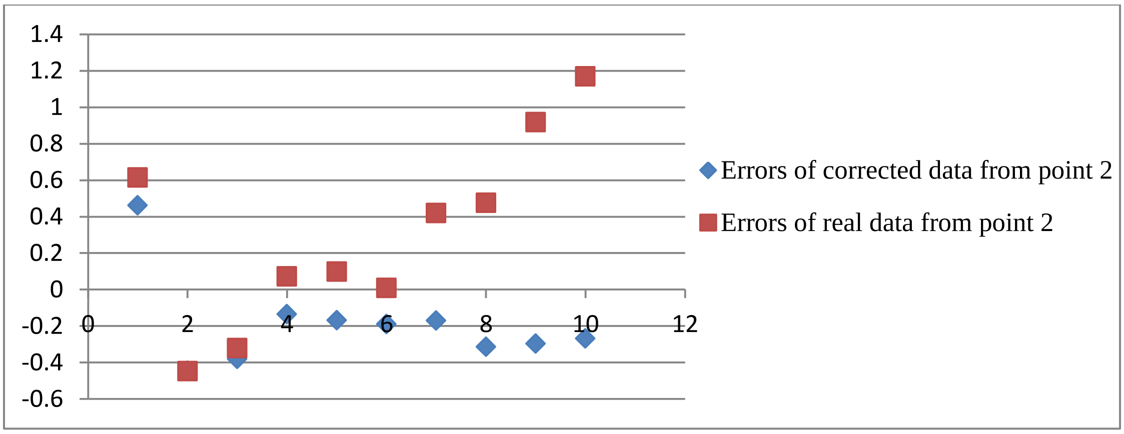

Figure 47 - Errors of corrected and real data of rover receiver from point 2

Table 10 - Distance between point 3 and rover receiver

Distance between point 3 & 8	Ground Truth	distance with real data	errors (m)	distance with corrected data	errors (m)
1	27.22	28.37	1.15	27.71	0.49
2	27.50	28.30	0.80	27.68	0.18
3	28.00	28.37	0.37	27.78	-0.22
4	28.30	28.36	0.06	27.91	-0.39
5	28.50	28.52	0.02	28.19	-0.31
6	28.70	28.61	-0.09	28.34	-0.36
7	28.90	28.78	-0.12	28.60	-0.30
8	29.10	28.98	-0.12	28.88	-0.22
9	29.20	29.51	0.31	29.15	-0.05
10	29.30	29.80	0.50	29.48	0.18

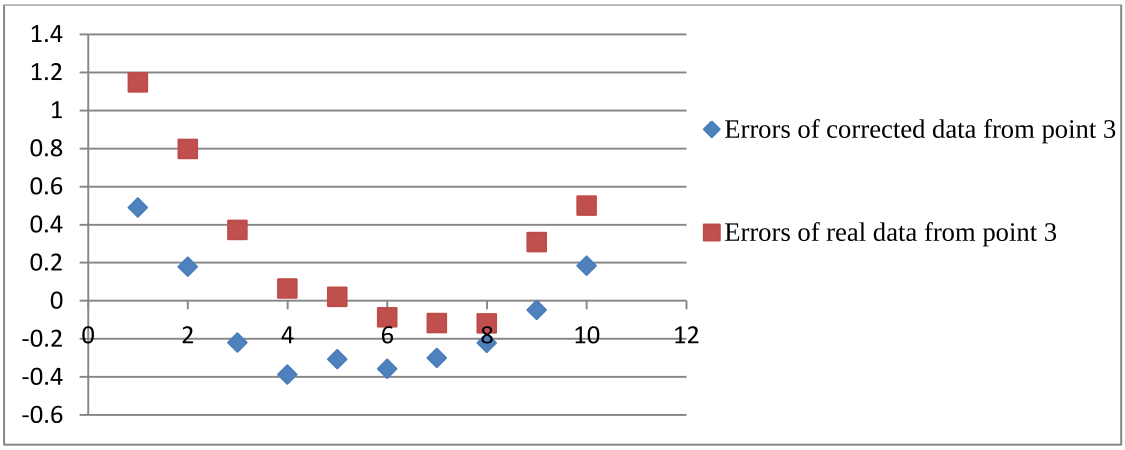

Figure 48 - Errors of corrected and real data of rover receiver from point 3

Table 11 - Distance between point 4 and rover receiver

Distance between point 4 & 8	Ground Truth	distance with real data	errors (m)	distance with corrected data	errors (m)
1	35.23	34.25	-0.98	35.62	0.39
2	35.00	33.74	-1.26	34.95	-0.05
3	34.70	33.24	-1.46	34.46	-0.24
4	34.00	32.59	-1.41	33.92	-0.08
5	33.60	32.12	-1.48	33.46	-0.14
6	33.00	31.55	-1.45	32.87	-0.13
7	32.60	31.03	-1.57	32.48	-0.12
8	32.20	30.66	-1.54	32.06	-0.14
9	31.80	30.25	-1.55	31.65	-0.15
10	31.50	29.88	-1.62	31.31	-0.19

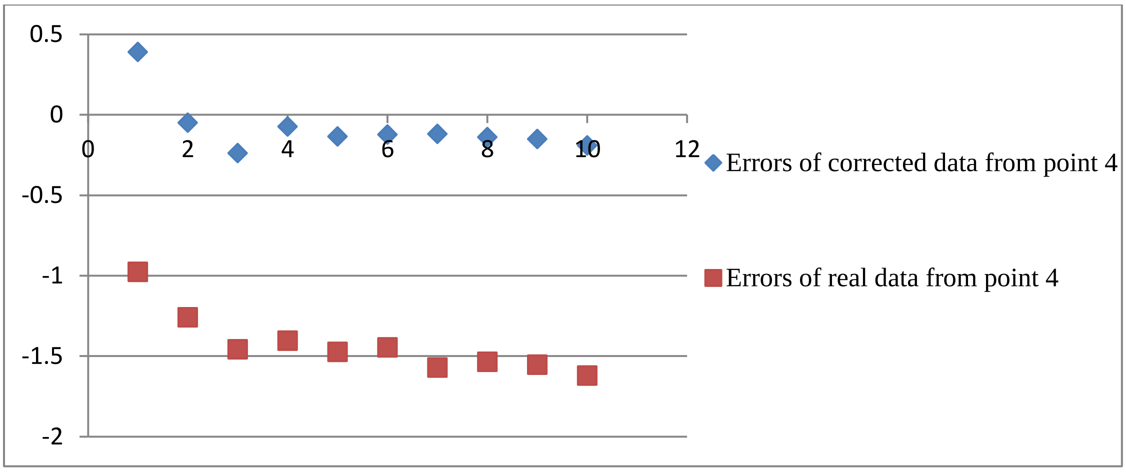

Figure 49 - Errors of corrected and real data of rover receiver from point 4

Table 12 - Distance between point 5 and rover receiver

Distance between point 5 & 8	Ground Truth	distance with real data	errors (m)	distance with corrected data	errors (m)
1	19.00	20.04	1.04	19.03	0.03
2	18.00	19.19	1.19	17.98	-0.02
3	17.00	18.18	1.18	17.07	0.07
4	16.00	16.94	0.94	16.06	0.06
5	15.00	15.78	0.78	14.97	-0.03
6	14.00	14.69	0.69	13.89	-0.11
7	13.00	13.31	0.31	12.96	-0.04
8	12.00	12.14	0.14	11.97	-0.03
9	11.00	10.76	-0.24	11.00	0.00
10	10.00	9.54	-0.46	10.08	0.08

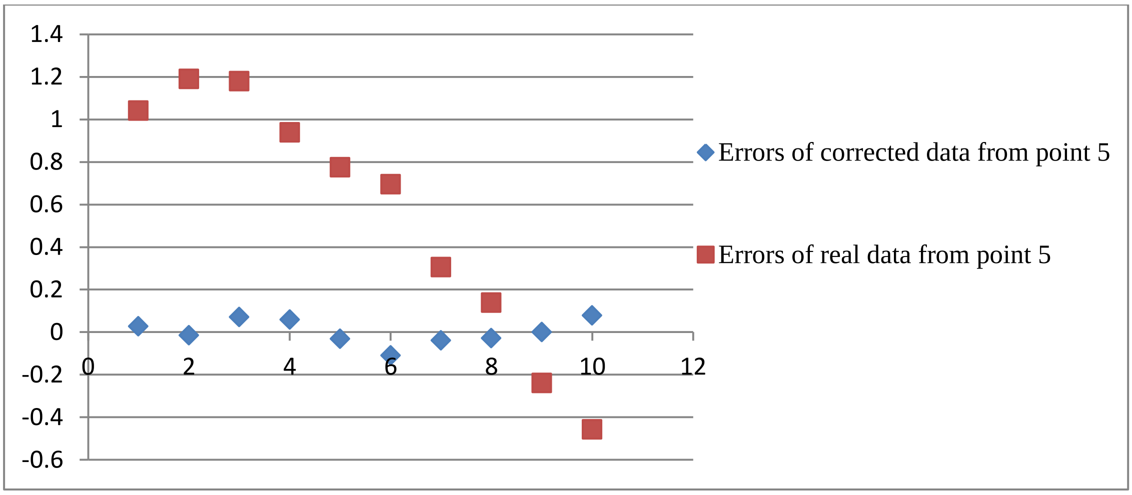

Figure 50 - Errors of corrected and real data of rover receiver from point 5

Table 13 - Distance between point 6 and rover receiver

Distance between point 6 & 8	Ground Truth	distance with real data	errors (m)	distance with corrected data	errors (m)
1	37.37	40.00	2.63	37.46	0.09
2	37.50	39.65	2.15	37.56	0.06
3	37.52	39.71	2.19	37.59	0.07
4	37.70	39.58	1.88	37.66	-0.04
5	38.00	39.18	1.18	37.66	-0.34
6	38.10	38.82	0.72	37.87	-0.23
7	38.20	38.50	0.30	37.98	-0.22
8	38.30	38.96	0.66	38.15	-0.15
9	38.40	39.46	1.06	38.35	-0.05
10	38.50	38.89	0.39	38.55	0.05

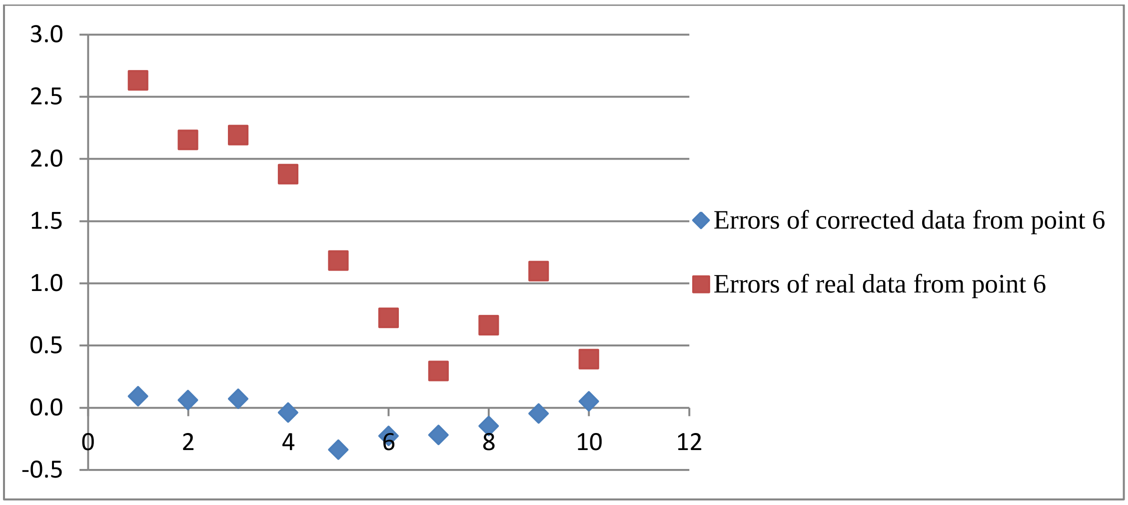

Figure 51 - Errors of corrected and real data of rover receiver from point 6

Table 14 - Distance between point 7 and rover receiver

Distance between point 7 & 8	Ground Truth	distance with real data	errors (m)	distance with corrected data	errors (m)
1	41.56	42.62	1.06	41.09	-0.47
2	40.20	42.29	2.09	40.67	0.47
3	40.00	42.04	2.04	40.23	0.23
4	39.50	41.80	2.30	39.79	0.29
5	39.30	41.64	2.34	39.24	-0.06
6	39.00	41.40	2.40	38.88	-0.12
7	38.60	41.39	2.79	38.50	-0.10
8	38.20	41.28	3.08	38.14	-0.06
9	38.00	41.27	3.27	37.85	-0.15
10	37.80	41.19	3.39	37.55	-0.25

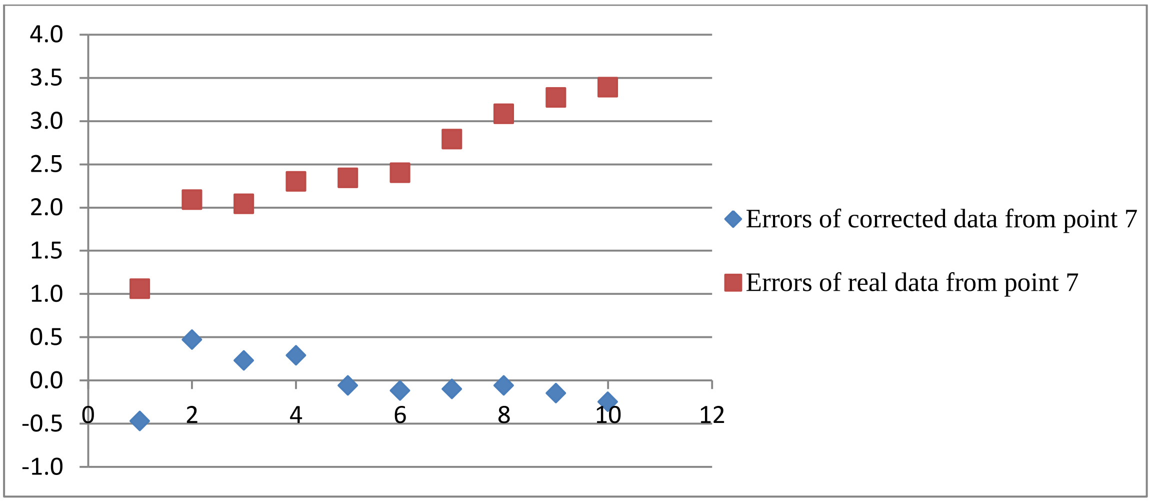

Figure 52 - Errors of corrected and real data of rover receiver from point 7

CHAPTER 6

CONCLUSION & FUTURE WORK

6.1 Conclusion

In this study a low cost local navigation system is proposed, in order to navigate robot in the METU unstructured area. To do that, a GPS receiver will be mounted on the robot and the goal is to obtain the position of the robot rather than the position of receiver on the map. The accuracy of the results in this study is shown to be acceptable (Figure 53).

As it is mentioned before, because of the errors of GPS devices, different methods such as DGPS are used. Differential GPS is required to the base stations that the exact positions of them are known. Without knowing the exact position of the base station, the DGPS method does not work correctly. To overcome this problem, proposed method is not dependent to base station coordinates and distance-based DGPS is proposed.

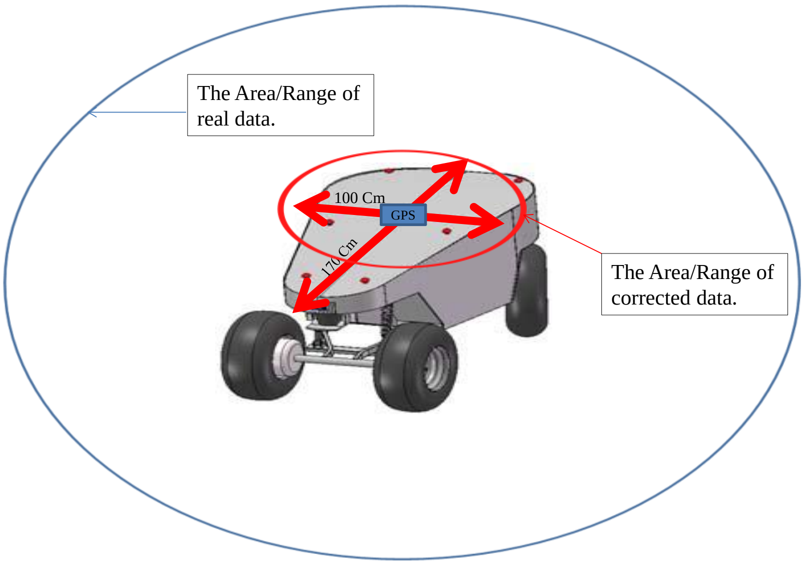

Figure 53 – Area/Range of data for GPS device which is mounted on the robot

This method depends on the distances between GPS receivers and by fixing these distances, the errors of each GPS receiver are found. By finding the errors of GPS receivers the rover receiver position will be corrected. The hardware which is used to validate this method is explained in chapter 4. After that, all tests that show accuracy of the method are explained in chapter 5. The results of these tests show that the maximum error is ± 55 centimeter which is enough as required accuracy in this study, because the resultant corrected point will be a point on the robot and it is good to navigate a robot on unstructured area. By using the normal GPS device, the accuracy will be around 3 meters which is not enough for navigating a robot in unstructured area (Figure 53).

6.2 Future Work

This study is based on static post-processing GPS method and the result of all tests shows that this method is applicable in real-time method. As the future works, the procedures used in this study can be implemented into a real-time navigation system.

The error considered in this method is the sum of the all errors of the GPS. Another future work can be separating the errors and discuss the impact of each error separately.

REFERENCES

[1] Global Navigation Satellite Systems, New York: United Nations, 2012.

[2] "Report of the Committee on the Peaceful Uses of Outer Space," United Nations Publications, New York, 2006.

[3] W. Lechner and S. Baumann, "Global navigation satellite systems," *Computers and Electronics in Agriculture,* vol. 25, no. 1-2, p. 67–85, January 2000.

[4] Y. Zheng, "Generation of Network-Based Differential Corrections for Regional GNSS Services," Queensland University of Technology, Australia, 2006.

[5] "What is Differential GPS?," [Online]. Available: http://www.effective-solutions.co.uk/dgps1.html. [Accessed 10 July 2013].

[6] B. W. Parkinson and J. J. Spilker, "Global Positioning System: Theory and Applications," *Progress in Astronautics and Aeronautics,* p. 793, 1996.

[7] B. Hofmann-Wellenhof, H. Lichtenegger and J. Collins, GPS Theory and Practice, New York: Springer, 2001.

[8] D. Munoz, F. Bouchereau, C. Vargas and R. Enriquez, "Position Location Techniques and Applications," in *Chapter 7 – Satellite-Based Location Systems*, Academic Press, 2009, p. 231–260.

[9] "What is GPS?," New Mexico Tech University, [Online]. Available: http://infohost.nmt.edu/~mreece/gps/whatisgps.html. [Accessed 23 July 2013].

[10] B. Sudha Neelima Thipparthi, "Improving Positioning Accuracy Using Carrier Smoothing Techniques in Inexpensive GPS Receivers," New Mexico State University, Las Cruces, New Mexico, 2004.

[11] R. Rizzi and A. Ortolani, Probabilistic Tomography of Atmospheric parameters from GNSS data, Bologna: University of Bologna, 2011.

[12] "Satellite Navigation," *Crosslink* , p. 14, Summer 2002.

[13] A. Aghakarimi, "Local Modeling of The Ionospheric Vertical Total Electron Content (VTEC) Using Particle Filter," The Degree of Master of Science in Geodetic and Geographic Information Technologies of Middle East Technical University, Ankara, September 2012.

[14] D. Pfost, W. Casady and K. Shannon, "Precision Agriculture: Global Positioning System (GPS)," University Extension, University of Missouri-System, 1998.

[15] M. F. Yuen, "Dilution of Precision (DOP) Calculation for Mission Planning Purposes," NAVAL Postgraduate School, Monterey, California, 2009.

[16] W. Huihui, Z. Xingqun and Z. Yanhua, "Geometric dilution of precision for GPS single-point positioning based on four satellites," *Systems Engineering and Electronics*, vol. 19, no. 5, p. 1058–1063, August 2008.

[17] J. Fischer, "Navigating with more than just GPS," electronic design, 17 May 2012. [Online]. Available: http://electronicdesign.com/automotive/navigating-more-just-gps. [Accessed 10 August 2013].

[18] C. Shi, S. Gu, Y. Lou and M. Ge, "An improved approach to model ionospheric delays for single-frequency Precise Point Positioning," *Advances in Space Research*, vol. 49, no. 12, p. 1698–1708, 15 June 2012.

[19] J. G. Grimes, "Global Positioning System Standard Positiong Service Performance Standard," U.S. Department of Defence, Washington, 2008.

[20] P. Misra and P. Enge, Global positioning system: signals, measurements, and performance, Ganga-Jamuna Press, 2006.

[21] "The Global Differential GPS System," NASA, [Online]. Available: http://www.gdgps.net/. [Accessed 15 July 2013].

[22] "Applications of the Global Differential GPS System," [Online]. Available: http://www.gdgps.net/applications/index.html. [Accessed 15 July 2013].

[23] Z. Huanga and H. Yuan, "Improving the ionospheric delay correction of satellite-based augmentation systems in equatorial regions," *Advances in Space Research*, vol. 39, no. 10, p. 1552–1558, 2007.

[24] A. Andrews, L. Weill, and M. Grewal, Global Positioning Systems, Inertial Navigation, and Integration, New Jersey: Wiley, 2007.

[25] W. J. Hughes, "Wide-Area Augmentation System performance analysis report," Federal Aviation Authority, Atlantic, 2008.

[26] esa, "What is EGONS?," 2 August 2013. [Online]. Available: http://www.esa.int/Our_Activities/Navigation/The_present_-_EGNOS/What_is_EGNOS. [Accessed 12 August 2013].

[27] A. Shimamura, "MSAS (MTSAT satellite-based augmentation system) project status," *Air & Space Europe,* vol. 1, no. 2, p. 63–67, March–April 1999.

[28] Y.-c. Chao, Y.-J. Tsai, W. Todd , K. Changdon , E. Per and P. Brad , "An Algorithm for Inter-frequency Bias Calibration and Application to WAAS Ionosphere Modelling," pp. 639-646, 12-15 September 1995.

[29] "Space-based augmentation systems," [Online]. Available: http://bivouac.com/img/gde/330_GPS.pdf. [Accessed 12 August 2013].

[30] D. S. Kibe, "Indian plan for Satellite-Based Navigation Systems for Civil Aviation," [Online]. Available: http://mycoordinates.org/indian-plan-for-satellite-based-navigation-systems-for-civil-aviation/. [Accessed 12 August 2013].

[31] T. L. Jones, "Ground Based Augmentation System," 21 September 2009. [Online]. Available: http://www.faa.gov/news/press_releases/news_story.cfm?newsId=10808. [Accessed 12 August 2013].

[32] S. University, "Local Area Augmentation System Laboratory at Stanford University," 18 October 2001. [Online]. Available: http://waas.stanford.edu/laas.html. [Accessed 12 August 2013].

[33] S. University, "Local Area Augmentation System (LAAS)," 2004. [Online]. Available: http://waas.stanford.edu/research/laas.htm. [Accessed 12 August 2013].

[34] R. Xue , J. Zhang and Y. Zhu , "Cascade Dual Frequency Smoothing for Local Area Augmentation System," *Chinese Journal of Aeronautics,* vol. 22, no. 1, p. 49–55, February 2009.

[35] W. Qiu, An Analysis of Some Critical Error Sources in Static GPS Surveying, Calgary: University of Calgary, December 1993.

[36] "Principle of Differential GPS," [Online]. Available: http://www.jneuroengrehab.com/content/2/1/28/figure/F2. [Accessed 23 July 2013].

[37] F. Koenig and D. Wong, "Real-time Kinematics Global Positioning System (GPS) Operation and Setup Method for the Synchronous Impulse Reconstruction (SIRE) Radar," Army Research Laboratory, Adelphi, 2010.

[38] N. C. Talbot, M. T. Allison and M. E. Nichols, "Centimeter accurate global positioning system receiver for on-the-fly real-time kinematic measurement and control". U.S. Patent 5,602,741, 11 February 1997.

[39] M. Perez-Ruiz, D. C. Slaughter, . C. Gliever and S. K. Upadhyaya, "Tractor-based Real-time Kinematic-Global Positioning System (RTK-GPS) guidance system for

geospatial mapping of row crop transplant," *Biosystems Engineering,* vol. 111, no. 1, pp. 64-71, January 2012.

[40] L. Haojun , C. Junping , W. Jiexian, H. Congwei and L. Zhiqiang , "Network based real-time precise point positioning," *Advances in Space Research,* vol. 46, no. 9, pp. 1218-1224, 1 November 2010.

[41] M. Berber and N. Arslan, "Network RTK: A case study in Florida," *Measurement,* vol. 46, no. 8, pp. 2798-2806, October 2013.

[42] "Application Note on Network RTK for the OEMV Receivers," NovAtel Customer Service, Calgary, 2013.

[43] Rizos, "Network RTK Research and Implementation - A Geodetic Perspective," *Journal of Global Positioning Systems,* vol. 1, no. 2, pp. 144-150, 2002.

[44] "Network RTK," SmartNet powered by Leica Geosystems, [Online]. Available: http://ukrtk.co.uk/SpiderWeb/SmartNet/2fNetworkRTK.html. [Accessed 12 July 2013].

[45] "Real-Time Network (RTN) Surveying," science for a changing world USGS, 30 Jul 2013. [Online]. Available: http://water.usgs.gov/osw/gps/real-time_network.html. [Accessed 12 August 2013].

[46] "Inverse Distance Weighting Methodology for Interpolating Surface Sediment Chemistry," The Washington State Department of Ecology, Northwest Regional Office, Bellevue, WA, October 2012.

[47] E. Engineering, "How many GPS channels make sense?," [Online]. Available: http://electronics.stackexchange.com/questions/11884/how-many-gps-channels-make-sense. [Accessed 7 July 2013].

[48] C. Robusto, "The cosine-haversine formula," *The American Mathematical Monthly,* vol. 64, no. 1, pp. 38-40, January 1957.

[49] "Spherical Law of Cosines,", [Online]. Available: http://www.math.unl.edu/~shartke2/teaching/2011m896/SphericalLawOfCosines.pdf. [Accessed 11 August 2013].

[50] "Pythagorean Theorem," Wolfram MathWorld, 25 September 2013. [Online]. Available: http://mathworld.wolfram.com/PythagoreanTheorem.html. [Accessed 10 August 2013].

[51] "Datum Transformations of GPS Positions," ublox, Zurikh, 5th July 1999.

[52] T. Soler, J. Han and N. Weston, "Alternative transformation from Cartesian to geodetic coordinates by least squares for GPS georeferencing applications," *Computers & Geosciences*, vol. 42, pp. 100-109, 13 August May 2012.

[53] K. Betke, "The NMEA 0183 Protocol," August 2001. [Online]. Available: http://www.tronico.fi/OH6NT/docs/NMEA0183.pdf. [Accessed 13 August 2013].

[54] Sparkfun, "66 Channel LS20031 GPS 5Hz Receiver," 2013. [Online]. Available: https://www.sparkfun.com/products/8975. [Accessed 12 August 2013].

[55] Sparkfun, "Description of Raspberry Pi - Model B," [Online]. Available: https://www.sparkfun.com/products/11546. [Accessed 10 August 2013].

APPENDIX A

CALCULATE DISTANCE BETWEEN TWO SET OF COORDINATE

There are two methods to calculate distance between two set of coordinate:

1. Great Circle Calculation
2. Pythagorean Theorem

Great Circle Calculation:

The great-circle distance is the shortest distance between two points on the surface of a sphere, measured along the surface of the sphere (as opposed to a straight line through the sphere's interior). The distance between two points in Euclidean space is the length of a straight line between them, but on the sphere there are no straight lines. In non-Euclidean geometry, straight lines are replaced with geodesics. Geodesics on the sphere are the great circles (circles on the sphere whose centers coincide with the center of the sphere).

Through any two points on a sphere which are not directly opposite each other, there is a unique great circle. The two points separate the great circle into two arcs. The length of the shorter arc is the great-circle distance between the points. A great circle endowed with such a distance is the Riemannian circle.

Between two points which are directly opposite each other, called antipodal points, there are infinitely many great circles, but all great circle arcs between antipodal points have the same length, i.e. half the circumference of the circle, or πr, where r is the radius of the sphere.

The Earth is nearly spherical (see Earth radius) so great-circle distance formulas give the distance between points on the surface of the Earth (as the crow flies) correct to within 0.5% or so.

Haversine Formula:

The haversine formula is an equation important in navigation, giving great circle distances between two points on a sphere from their longitudes and latitudes. It is a special case of a more general formula in spherical trigonometry, the law of haversines, relating the sides and angles of spherical triangles [48].

For any two points on a sphere, the haversine of the central angle between them is given by:

$$haversin\left(\frac{d}{r}\right) = haversin(\varphi_2 - \varphi_1) + \cos(\varphi_1)cos(\varphi_2)haversin(\lambda_2 - \lambda_1)$$

Where haversin is the haversine function:

$$haversin(\theta) = sin^2\left(\frac{\theta}{2}\right) = \frac{1 - cos(\theta)}{2}$$

- d is the distance between the two points (along a great circle of the sphere; see spherical distance),
- r is the radius of the sphere,
- φ_1, φ_2: latitude of point 1 and latitude of point 2
- λ_1, λ_2: longitude of point 1 and longitude of point 2

On the left side of the equals sign d/r is the central angle, assuming angles are measured in radians (note that φ and λ can be converted from degrees to radians by multiplying by $\pi/180$ as usual).

Solve for d by applying the inverse haversine (if available) or by using the arcsine (inverse sine) function:

$$\mathrm{d} = \mathrm{r} \times \mathrm{haversin}^{-1}(\mathrm{h}) = 2 \times \mathrm{r} \times \arcsin\left(\sqrt{\mathrm{h}}\right)$$

Where h is $\mathrm{haversin}(\mathrm{d}/\mathrm{r})$, or more explicitly:

$$\begin{aligned} \mathrm{d} &= 2 \times \mathrm{r} \times \arcsin\left(\sqrt{\mathrm{haversin}(\varphi_2 - \varphi_1) + \cos(\varphi_1)\cos(\varphi_2)\mathrm{haversin}(\lambda_2 - \lambda_1)}\right) \\ &= 2 \times \mathrm{r} \times \arcsin\left(\sqrt{\sin^2\left(\frac{\varphi_2 - \varphi_1}{2}\right) + \cos(\varphi_1)\cos(\varphi_2)\sin^2\left(\frac{\lambda_2 - \lambda_1}{2}\right)}\right) \end{aligned}$$

Spherical Law of Cosines

In fact, when Sinnott published the haversine formula, computational precision was limited. Nowadays, most modern computers & languages use floating-point numbers, which provide 15 significant figures of precision. With this precision, the simple spherical law of cosines formula $\left(\cos(c) = \cos(a)\cos(b) + \sin(a)\sin(b)\cos(C)\right)$ gives well-conditioned results down to distances as small as around 1 meter. (Note that the geodetic form of the law of cosines is rearranged from the canonical one so that the latitude can be used directly, rather than the colatitude) [49].

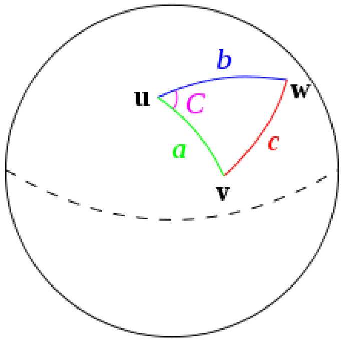

Figure 54 - Spherical triangle solved by the law of cosines [49].

This makes the simpler law of cosines a reasonable 1-line alternative to the haversine formula for many purposes.

$$d = a\cos\left(\sin(\varphi 1)\sin(\varphi 2) + \cos(\varphi 1)\cos(\varphi 2)\cos(\Delta\lambda)\right).r$$

Pythagorean Theorem:

2D Pythagorean Theorem

The distance between two points is the length of the path connecting them. The shortest path distance is a straight line. In a 2 dimensional plane, the distance between points (x_1, y_1) and (x_2, y_2) is given by the Pythagorean Theorem [50]:

$$d = \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2}$$

3D Pythagorean Theorem

The distance between two points is the length of the path connecting them. The shortest path distance is a straight line. In a 3 dimensional plane, the distance between points (x_1, y_1, z_1) and (x_2, y_2, z_2) is given by [50]:

$$d = \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2 + (z_2 - z_1)^2}$$

APPENDIX B

COORDINATE FRAMES

GPS Coordinate Frames

Coordinates representing positions on the earth can be given in two formats, Spherical or Cartesian. Spherical or Geodetic coordinates are three dimensional with the components of latitude (φ), longitude (λ) and height above ellipsoid (h). With two of the components being non-linear with angular units, computations are more complex for coordinate geometry problems. Alternatively, Cartesian coordinates are entirely linear and provide for an excellent platform for mathematics. The origin and orientation of the coordinate frame is dependant on the user's application and many well defined systems already exist. For global applications the system known as earth centered - earth fixed (ECEF) is preferred. Figure 3 illustrates the relationship between Spherical coordinates (φ, λ, h) and Cartesian ECEF coordinates (X, Y, Z) with respect to a reference ellipsoid [51, 52].

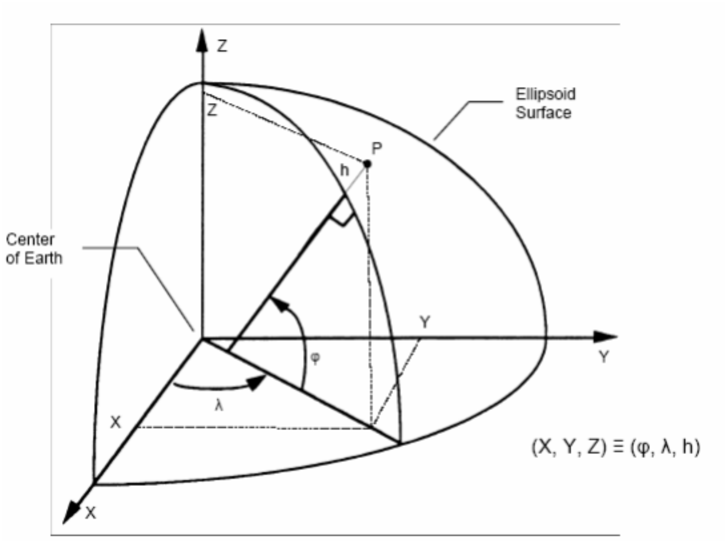

Figure 55 - Relationship between Cartesian and Spherical Coordinate Systems

LLA Coordinate System

The most commonly used coordinate system today is the latitude, longitude, and altitude (LLA) system. The origin of the system is at the mass center of the earth. The Prime Meridian and the Equator are the reference planes used to define latitude and longitude. The geodetic latitude (there are many other defined latitudes) of a point is the angle from the equatorial plane to the vertical direction of a line normal to the reference ellipsoid. The geodetic longitude of a point is the angle between a reference plane and a plane passing through the point, both planes being perpendicular to the equatorial plane. The geodetic altitude at a point is the distance from the reference ellipsoid to the point in a direction normal to the ellipsoid.

ECEF Coordinate System

Earth Centered, Earth Fixed (ECEF) Cartesian coordinates are also used to define three-dimensional positions. Earth centered, earth-fixed, X, Y, and Z, Cartesian coordinates (XYZ) define three-dimensional positions with respect to the center of mass of the reference ellipsoid and follow rotations of the earth. The origin of the system is at the mass center of the earth. The Z-axis is along the axis of rotation and points toward the North Pole. The X-axis is defined by the intersection of the plane define by the prime meridian and the equatorial plane. The Y-axis completes a right-handed orthogonal system by a plane 90° east of the X-axis and its intersection with the equator.

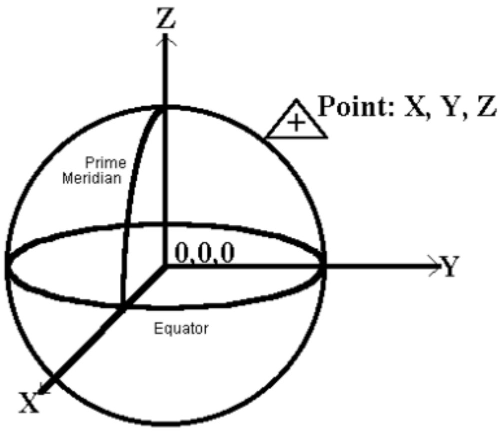

Figure 56 - ECEF Coordinate Reference Frame

The Global Positioning System (GPS) is based on the World Geodetic System of 1984 (WGS84) datum.WGS84 is a geocentric system, which provides an excellent mathematical representation in relation to the orbiting satellite constellation. Upon the introduction of satellite navigation, several national geodetic organizations immediately grasped the technology to update their datum with modernized geocentric ellipsoids and to reduce existing distortions.

A reference ellipsoid can be described by a series of parameters that define its shape and which include a semi-major axis (a), a semi-minor axis (b) and its first eccentricity (e) and its second eccentricity (e). Depending on the formulation used, ellipsoid flattening (f) may be required. This ellipsoid has its origin coincident with the ECEF origin. The X-axis pierces the Greenwich meridian (where longitude = 0 degrees) and the XY-plane make up the equatorial plane (latitude = 0 degrees). Altitude is described as the perpendicular distance above the ellipsoid.

WGS84 parameters:

$$a = 6378137$$
$$b = a(1 - f) = 6356732.31424518$$
$$f = \frac{1}{298.257223563}$$
$$e = \sqrt{\frac{a^2 - b^2}{a^2}}$$
$$e^{'} = \sqrt{\frac{a^2 - b^2}{b^2}}$$

Conversion between ECEF and Local Tangential Plane

GPS coordinate frame conversions are accomplished by various methods. Complete datum conversion is based on seven parameter transformations that include three translation parameters, three rotation parameters and a scale parameter. Simple three parameter conversions between latitude, longitude, and height in different datum can be accomplished by conversion through ECEF X, Y, Z Cartesian coordinates in one reference datum and three origin offsets that approximate differences in rotation, translation and scale.

LLA to ECEF

The conversion from LLA to ECEF is shown below.

$$X = (N + h)\cos\varphi\cos\lambda$$
$$Y = (N + h)\cos\varphi\sin\lambda$$
$$Z = \left(\frac{b^2}{a^2}N + h\right)\sin\varphi$$

Where,

$$\varphi = \text{latitude}$$
$$\lambda = \text{longitude}$$
$$h = \text{height above ellipsoid}$$
$$N = \text{Radius of Curvature, defined as:}$$
$$= \frac{a}{\sqrt{1 - e^2 \sin^2\varphi}}$$

ECEF to LLA

The conversion between XYZ and LLA is slightly more involved but can be achieved using one of the following methods:

By iteration for φ and h. There is quick convergence for $h \ll N$ starting at $h_\circ = 0$.

$$\lambda = \arctan\frac{Y}{X}$$

Start with $h_\circ = 0$

$$\varphi_0 = \arctan\frac{Z}{p\left(1-e^2\right)}$$

Iterate φ and h

$$N_i = \frac{a}{\sqrt{1-e^2\sin^2\varphi_i}}$$

$$h_{i+1} = \frac{p}{\cos\varphi_i} - N_i$$

$$\varphi_{i+1} = \arctan\frac{Z}{p\left(1-e^2\frac{N_i}{N_i+h_{i+1}}\right)}$$

Or by closed formula set.

$$\lambda = \arctan\frac{Y}{X}$$

$$\varphi = \arctan\frac{Z+e'^2 b\sin^3\theta}{p-e^2 a\cos^3\theta}$$

$$h = \frac{p}{\cos\varphi} - N$$

Where auxiliary values are:

$$p = \sqrt{X^2+Y^2}$$

$$\theta = \arctan\frac{Za}{pb}$$

APPENDIX C

NMEA 0183 PROTOCOL

What is the NMEA 0183 Standard?

The National Marine Electronics Association (NMEA) is a non-profit association of manufacturers, distributors, dealers, educational institutions, and others interested in peripheral marine electronics occupations. The NMEA 0183 standard defines an electrical interface and data protocol for communications between marine instrumentation. NMEA 0183 is a voluntary industry standard, first released in March of 1983. It has been updated from time to time [53].

General Sentence Format

All data is transmitted in the form of sentences. Only printable ASCII characters are allowed, plus CR (carriage return) and LF (line feed). Each sentence starts with a "$" sign and ends with <CR><LF>. There are three basic kinds of sentences: talker sentences, proprietary sentences and query sentences.

Talker Sentences: The general format for a talker sentence is:

$ttsss,d1,d2,....<CR><LF>

The first two letters following the „$" are the talker identifier. The next three characters (sss) are the sentence identifier, followed by a number of data fields separated by commas, followed by an optional checksum, and terminated by carriage return/line feed. The data fields are uniquely defined for each sentence type. An example talker sentence is:

$HCHDM,238,M<CR><LF>

Where "HC" specifies the talker as being a magnetic compass, the "HDM" specifies the magnetic heading message follows. The "238" is the heading value, and "M" designates the heading value as magnetic.

A sentence may contain up to 80 characters plus "$" and CR/LF. If data for a field is not available, the field is omitted, but the delimiting commas are still sent, with no space between them. The checksum field consists of a "*" and two hex digits representing the exclusive OR of all characters between, but not including, the "$" and "*".

Proprietary Sentences: The standard allows individual manufacturers to define proprietary sentence formats. These sentences start with "$P", then a 3 letter manufacturer ID, followed by whatever data the manufacturer wishes, following the general format of the standard sentences.

Query sentences: A query sentence is a means for a listener to request a particular sentence from a talker. The general format is: $ttllQ,sss,[CR][LF]

The first two characters of the address field are the talker identifier of the requester and the next two characters are the talker identifier of the device being queried (listener). The fifth character is always a "Q" defining the message as a query. The next field (sss) contains the three letter mnemonic of the sentence being requested. An example query sentence is:

$CCGPQ,GGA<CR><LF>

where the "CC" device (computer) is requesting from the "GP" device (a GPS unit) the "GGA" sentence.

The GPS will then transmit this sentence once per second until a different query is requested.

Sentence Identifiers and Formats

The GPS receiver which is used in this thesis receives 6 different sentences which explained in following:

GGA Global Positioning System Fix Data. Time, Position and fix related data for a GPS receiver

```
                                                    11
       1             2      3 4        5 6 7 8   9   10 |     12 13  14   15
       |             |      | |        | | | |   |    ||      |  |   |    |
$--GGA,hhmmss.ss,llll.ll,a,yyyyy.yy,a,x,xx,x.x,x.x,M,x.x,M,x.x,xxxx*hh
```

1) Time (UTC)
2) Latitude
3) N or S (North or South)
4) Longitude
5) E or W (East or West)
6) GPS Quality Indicator,
   6.1) 0 - fix not available,
   6.2) 1 - GPS fix,
   6.3) 2 - Differential GPS fix
7) Number of satellites in view, 00 - 12
8) Horizontal Dilution of precision
9) Antenna Altitude above/below mean-sea-level (geoid)
10) Units of antenna altitude, meters
11) Geoidal separation, the difference between the WGS-84 earth ellipsoid and mean-sea-level (geoid), "-" means mean-sea-level below ellipsoid
12) Units of geoidal separation, meters
13) Age of differential GPS data, time in seconds since last SC104 type 1 or 9 update, null field when DGPS is not used
14) Differential reference station ID, 0000-1023
15) Checksum

GLL Geographic Position – Latitude/Longitude

```
       1    2 3       4 5        6 7
       |    | |       | |        | |
$--GLL,llll.ll,a,yyyyy.yy,a,hhmmss.ss,A*hh
```

1) Latitude
2) N or S (North or South)
3) Longitude
4) E or W (East or West)
5) Time (UTC)
6) Status A - Data Valid, V - Data Invalid
7) Checksum

GSA GPS DOP and active satellites

```
       1 2 3                    14 15  16  17 18
       | | |                    |  |   |   |  |
$--GSA,a,a,x,x,x,x,x,x,x,x,x,x,x,x,x,x.x,x.x,x.x*hh
```

1) Selection mode
2) Mode
3) ID of 1st satellite used for fix
4) ID of 2nd satellite used for fix
5) ...
6) 14) ID of 12th satellite used for fix
7) PDOP in meters
8) HDOP in meters
9) VDOP in meters
10) Checksum

GSV Satellites in view

```
       1 2 3 4 5 6 7     n
       | | | | | | |     |
$--GSV,x,x,x,x,x,x,x,...*hh
```

1) total number of messages
2) message number
3) satellites in view
4) satellite number
5) elevation in degrees
6) azimuth in degrees to true
7) SNR in dB
8) more satellite infos like 4)-7)
9) n) Checksum

RMC Recommended Minimum Navigation Information

```
                                                              12
        1             2 3      4 5         6 7    8   9     10 11  |
        |             | |      | |         | |    |   |      |   | |
$--RMC,hhmmss.ss,A,llll.ll,a,yyyyy.yy,a,x.x,x.x,xxxx,x.x,a*hh
```

1) Time (UTC)
2) Status, V = Navigation receiver warning
3) Latitude
4) N or S
5) Longitude
6) E or W
7) Speed over ground, knots
8) Track made good, degrees true
9) Date, ddmmyy
10) Magnetic Variation, degrees
11) E or W
12) Checksum

VTG Track Made Good and Ground Speed

```
        1   2 3   4 5 6 7     8 9
        |   | |   | | | |     | |
$--VTG,x.x,T,x.x,M,x.x,N,x.x,K*hh
```

1) Track Degrees
2) T = True
3) Track Degrees
4) M = Magnetic
5) Speed Knots
6) N = Knots
7) Speed Kilometers per Hour
8) K = Kilometers per Hour
9) Checksum

APPENDIX D

HARDWARE

66 Channel LS20031 GPS Receiver Module

The LS20031 GPS receiver is a complete GPS smart antenna receiver that includes an embedded antenna and GPS receiver circuits. This low-cost unit outputs an astounding amount of position information 5 times a second. The receiver is based on the proven technology found in LOCOSYS 66 channel GPS SMD type receivers that use MediaTek chip solution [54].

Figure 57 - 66-Channel LS20031 GPS Receiver Module [54]

The GPS smart antenna will track up to 66 satellites at a time while providing fast time-to-first-fix, one-second navigation update and low power consumption. It can provide you with superior sensitivity and performance even in urban canyon and dense foliage environments. The capabilities meet the sensitivity requirements of car navigation as a well as other location-based applications.

Features:

- MediaTek high sensitivity solution
- Support 66-channel GPS
- Fast TTFF at low signal level (Time to first fix)
- Support AGPS
- Up to 10 Hz update rate
- Capable of SBAS (WAAS, EGNOS, MSAS)
- Build-in micro battery to reserve system data for rapid satellite acquisition
- LED indicator for GPS fix or not fix

Raspberry Pi

Figure 58 - Raspberry Pi - Model B [55]

The Raspberry Pi is a credit-card sized computer that plugs into your TV and a keyboard. It’s a capable little PC which can be used for many of the things that your desktop PC does, like spreadsheets, word-processing and games. It also plays high-definition video. We want to see it being used by kids all over the world to learn programming [55].

The Model B's two built-in USB ports provide enough connectivity for a mouse and keyboard, but if you want to add more you can use a USB hub. It is recommended that you use a powered hub so as not to overtax the on-board voltage regulator. Powering the Raspberry Pi is easy; just plug any USB power supply into the micro-USB port. There's no power button so the Pi will begin to boot as soon as power is applied, to turn it off simply remove power [55].

On top of all that, the low-level peripherals on the Pi make it great for hardware hacking. The 0.1" spaced GPIO header on the Pi gives you access to 8 GPIO, UART, I2C, SPI as well as 3.3 and 5V sources. Mating ribbon cables can be found in the related products below.

Dimensions: 85.60mm x 56mm x 21mm

Features:

- Broadcom BCM2835 SoC
- 700 MHz ARM1176JZF-S core CPU
- Broadcom VideoCore IV GPU
- 512 MB RAM
- 2 x USB2.0 Ports
- Video Out via Composite (PAL and NTSC), HDMI or Raw LCD (DSI)
- Audio Out via 3.5mm Jack or Audio over HDMI
- Storage: SD/MMC/SDIO
- 10/100 Ethernet (RJ45)
- Low-Level Peripherals:
  - 8 x GPIO
  - UART
  - I2C bus
  - SPI bus with two chip selects

    - +3.3V
    - +5V
    - Ground

- Power Requirements: 5V @ 700 mA via MicroUSB or GPIO Header
- Supports Debian GNU/Linux, Fedora, Arch Linux, RISC OS