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Positional accuracy of the Wide Area Augmentation System

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Positional Accuracy of the Wide Area Augmentation System

BY

Lisa L. Arnold

Bachelor of Science
Information Technology

THESIS

Submitted in Partial Fulfillment of the
Requirements for the Degree of
Master of Science

Geography

The University of New Mexico
Albuquerque, New Mexico

August, 2009

DEDICATION

For my husband Brian Arnold, thank you for the undying support and love. I could not have achieved this goal without you.

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Finally, thank you to my friends and family that have supported me along the way. Your support and encouragement has been invaluable.

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ABSTRACT OF THESIS

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Lisa L. Arnold

B.S., Information Technology, University of Phoenix, 2003
M.S., Geography, University of New Mexico, 2009

ABSTRACT

Global Positioning System devices are increasingly being used for data collection in many fields. Consumer-grade GPS units without differential correction have a published horizontal accuracy of approximately 10 to 15 meters (average error). An attractive option for differential correction for these GPS units is the Wide Area Augmentation System (WAAS). Most consumer-grade GPS units on the market are WAAS capable. According to the FAA, the WAAS broadcast message provides integrity information about the GPS signal as well as accuracy improvements which are reported to improve accuracy to 3 to 5 meters. However, limited empirical evidence has been published on the accuracy of WAAS-enabled GPS compared to autonomous GPS. Results are presented of an empirical study comparing the horizontal and vertical accuracy of WAAS corrected GPS and autonomous GPS under ideal conditions using consumer-grade receivers. Data were collected for thirty minute time spans over accurately surveyed control points. Metrics of median, 68^{th} and 95^{th} percentile, RMSE and average positional error in x, y and z were computed and statistically tested with a hypothesis test. There was no statistical difference found between WAAS and autonomous position fixes when using two different consumer-grade units. A statistical difference was evident in a third unit type tested. Analysis of data collected for a twenty

seven hour time span indicates that while WAAS is altering the estimated position of a point compared to autonomous position estimate, WAAS augmentation actually appears to increase the positional error.

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1. Introduction

1.1 Background

The Global Positioning System (GPS) is a satellite navigation system developed by the United States Department of Defense (DOD) in the early 1970's. The system provides continuous, instantaneous positioning and timing information under any weather conditions, anywhere in the world. GPS, originally put in place as a military navigation system, became fully functional in 1994 (Shoval and Isaacson 2006). In order to restrict the high accuracy positioning capability of GPS, the DOD deliberately degraded the satellite signal available to civilians, in a policy known as Selective Availability (SA). Following extensive studies, the DOD terminated SA in May, 2000. This termination greatly improved the accuracy of the GPS signal available to civilians and resulted in widespread growth of GPS applications for individuals and commercial interests (El-Rabbany 2002; Shoval and Isaacson 2006).

GPS works as a one-way broadcasting system where the satellites transmit signals that can be picked up by a receiver (GPS unit). Any number of receivers can pick up the GPS signals. GPS positioning accuracy varies greatly and is impacted by satellite and receiver clock inaccuracy, ephemeris error, signal delay due to atmospheric refraction, reflection of signal known as multi-path errors, receiver noise, and satellite geometry relative to the receiver (El-Rabbany 2002; Trimble 2004).

Several technologies have sought to correct the inaccuracies of GPS readings due to the above factors. Differential correction is the method employed to remove GPS error. Real time differential GPS (dGPS) is based on error correction signals for individual satellites, broadcast from ground-based radio beacons or geostationary satellites (Witte and Wilson 2004). Postprocessing is differential correction measures taken after data are collected, based on error correction information logged by reference station receivers (Trimble 2004). This thesis will look at the real time differential correction method known as the Wide Area Augmentation System (WAAS). WAAS was created by the Federal Aviation Administration (FAA). It is available only in the continental United States and has been active since August, 2000 (Trimble 2004). Nearly all GPS receivers created within the past five years can receive the WAAS correction signal.

1.2 Problem Statement

GPS is increasingly being used for data collection and resulting data analysis in many fields. GPS is employed in environmental studies, biological and biomechanical studies, social sciences, meteorology, military applications, archaeology, navigation, mapping, surveying and more (Trimble 2004; Witte and Wilson 2004; Dauwalter, Fisher, and Belt 2006; Shoval and Isaacson 2006). An attractive option for differential correction for these GPS applications is WAAS. WAAS provides real time correction free of charge, and does not require extra hardware or software to use the correction signal.

Many different consumer grade GPS units are available. It is expected that consumer grade units are comparable and consumers can expect different brands of units to perform similarly. This study will specifically evaluate three different GPS units, the Garmin 60cx, the Timble Juno ST, and the DeLorme Earthmate PN-20.

The WAAS broadcast message improves GPS signal accuracy both horizontally and vertically to approximately 7m according to analyses by the FAA (FAA.org). However, few independent evaluations of WAAS have been published which evaluate the performance of WAAS and its positional accuracy relative to autonomous data (Trimble 2004; Bolstad et al. 2005). Because WAAS is widely used as a real time differential correction method, it is necessary to independently test its performance in the field.

1.3 Objectives

The goal of this thesis is to evaluate the performance of WAAS and its positional accuracy relative to autonomous GPS as implemented in consumer grade units.

The following objectives and hypothesis are established to meet the goal of this thesis:

1) Compare horizontal and vertical positional accuracy of WAAS corrected GPS and autonomous GPS to surveyed control points under ideal conditions. This research hypothesizes autonomous GPS data gathered under ideal conditions is statistically different than WAAS corrected GPS data gathered under ideal conditions.
2) Determine the variability in the performance of WAAS between different receivers. It is hypothesized the benefits of WAAS correction are greater on a lower end recreational receiver compared to a higher end recreational receiver. Higher end receivers have more advanced signal processing algorithms and better hardware, which improve the

accuracy of autonomous GPS, and decrease the amount of correction WAAS can provide.

3) Determine if WAAS correction benefits are the same for data collected at different times of the day. It is hypothesized that correction benefits differ with the time of day data are collected.

Hypotheses two and three relate to a general hypothesis that as the accuracy of autonomous GPS increases, the marginal improvement potentially provided by WAAS decreases.

2. Literature Review

2.1 GPS Theory

2.1.1 Overview

GPS consists of three basics segments: the space segment, the control segment, and the user segment. The space segment is a constellation of 24 operational satellites, dispersed in six planes, with four satellites in each plane, inclined with respect to the equator by 55 degrees (Figure 1) (Spilker and Parkinson 1996). Several additional satellites are typically included in the constellation as well, with the current total being 32, however the nominal number is 24 (William Stone, New Mexico Geodetic Advisor, National Geodetic Survey, May 11 2009, pers. communication).

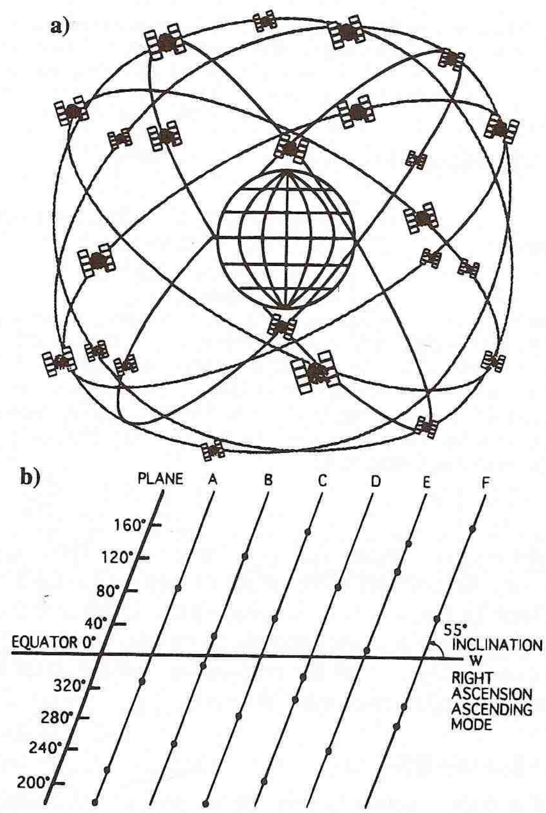


Figure 1: GPS Constellation

This constellation geometry is designed to ensure that four to ten satellites are visible anywhere in the world, at any given time. GPS satellite orbits are nearly circular and are approximately 20,200 km above Earth's surface with an orbital period of ~11 hours, 58 minutes (12 sidereal hours) (El-Rabbany 2006). The primary function of the GPS satellites is to transmit precisely timed signals containing navigation data, satellite time, and satellite position (Spilker and Parkinson 1996).

The control segment is a network of monitoring stations, and ground antennas located worldwide (Figure 2) (El-Rabbany 2006). The network consists of twelve satellite monitoring stations and four ground antenna upload stations operated by the Air Force and the National Geospatial Intelligence Agency. The Master Control Station (MCS) is located in Colorado Springs, Colorado at Schriever Air Force Base (El-Rabbany, 2006). Control sites were selected to provide significant longitudinal separation between each site and allow for each satellite in the GPS constellation to be tracked by two monitoring stations.

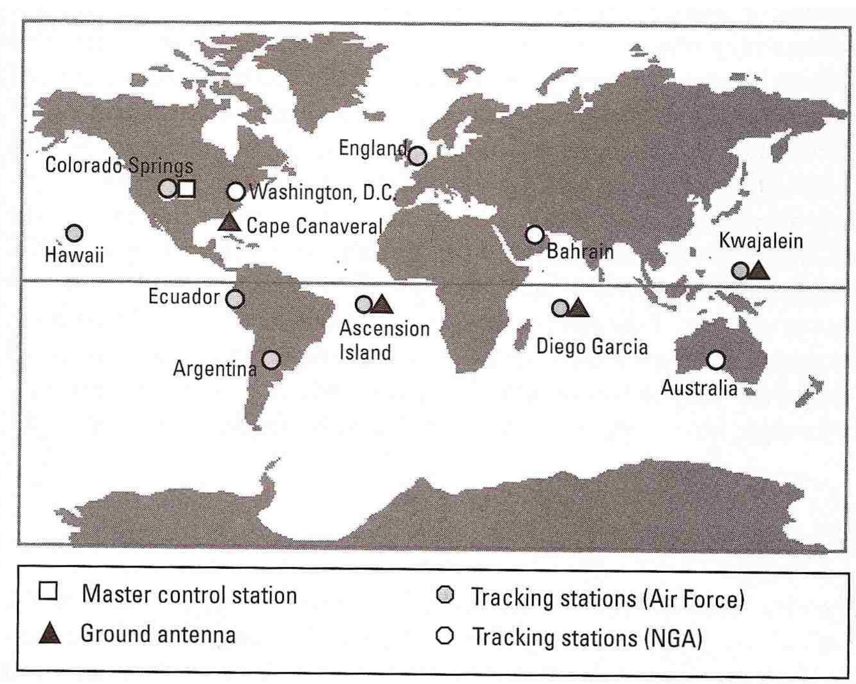


Figure 2: GPS Control Sites

GPS control sites track satellite position as well as local meteorological conditions. All gathered data are sent to the MCS for processing. Wide area differential correction data are then uploaded to the satellites. Predicted satellite navigation data is the result of processing the collected data. The navigation data provide information on satellite position as a function of time, the satellite clock parameters, atmospheric data, and the satellite almanac (El-Rabbany, 2006). The MCS also monitors the integrity of all satellites in the constellation and transmits satellite health condition as part of the navigation data.

The user segment consists of all military and civilian users of GPS. The GPS signal can be received by a wide range of receiver types, and is used to determine user positions anywhere on Earth. While receivers require an investment, the GPS signal is free to all users (El-Rabbany 2006). Low end recreational receivers are readily available for around $100 with survey grade GPS equipment potentially exceeding $25,000 (Wing, Eklund and Kellogg 2005). GPS navigation systems are frequently an option in new vehicles, as well as available as after market add-ons. GPS receivers are also appearing now in portable devices such as cell phones, PDA's, and digital cameras (Frenzel 2007).

The relationship of the three GPS segments is shown below in Figure 3 (El-Rabbany 2006).

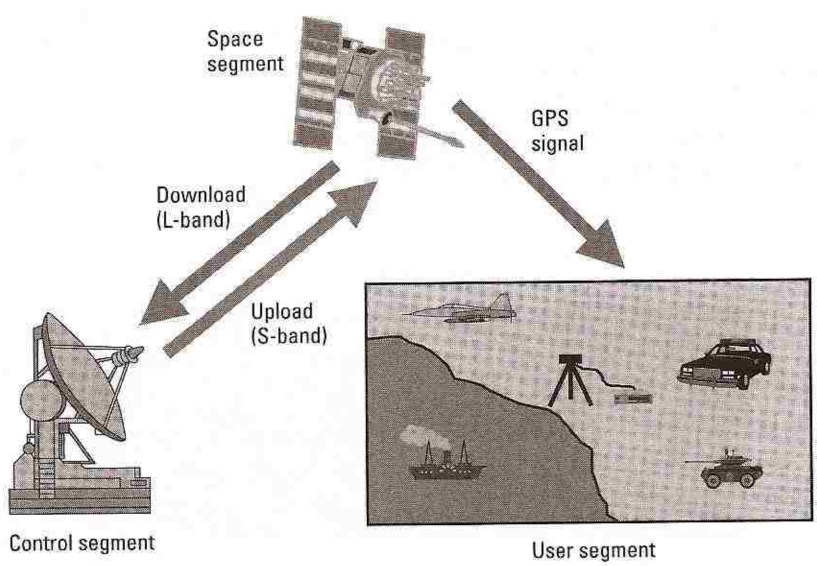


Figure 3: GPS Segments

2.1.2 Signal Structure

The GPS ranging signal is a microwave radio signal composed of two carrier frequencies modulated by two codes, and a navigation message. The two carrier frequencies are known as L1 and L2. These carrier frequencies are generated simultaneously, which enables a user receiving both L1 and L2 to calibrate directly for ionospheric delay (Parkinson 1996). L1 is generated at 1,575.42 MHz, L2 is generated at 1,227.60 MHz. The two modulation codes are the coarse acquisition code (C/A-code) which is modulated onto the L1 frequency, and the precision code (P-code) which is modulated onto both the L1 and L2 frequency. The C/A-code is principally for civilian users and is not encrypted. The P-code is principally for military use and is encrypted to prevent civilian use. The P-code is slightly more precise due to its higher broadcast speed of 10.23 MHz compared to the L1 broadcast speed of 1.023 MHz (Parkinson 1996). Some newer satellites transmit two additional codes, the L2 civil moderate (L2 CM) and the L2 civil-long (L2 CL). The addition of these codes allows civilian users the benefit of a code modulated onto both the L1 and L2 carrier frequency allowing for direct correction of the ionospheric delay.

2.1.3 Positioning

A single GPS receiver can be used to determine a user's point position instantaneously. On the simplest level, if the distance from the receiver to three GPS satellites is known, as well as the satellites locations, position can be determined through trilateration. However, determining position with only three satellites does not account for clock error, which can be significant because low-cost receivers have only moderate accuracy clocks. Therefore, an accurate point position determination requires that four satellites be visible. Each GPS satellite continuously transmits a signal of two carriers, two codes, and a navigation message. The GPS receiver picks up this signal and processes it. This processing produces the pseudorange, which is the measure of distance between the GPS receiver's antenna phase center, and the satellites antenna. Pseudorange distance is calculated based on the difference between the time signal of the satellite clock and the time of the receiver, coupled with the speed of light (Spilker and Parkinson 1996). The receiver also processes the navigation message to produce the coordinates of the satellite. Pseudorange accuracy is impacted by satellite and receiver clock synchronization errors. Satellite clock errors can be accounted for by applying the satellite clock correction information contained in the navigation message. Receiver clock error is an unknown. Thus, there are four unknowns in determining point position of the user, the X, Y and Z coordinate components of the receiver, and the receiver clock error (Figure 4) (El-Rabbany 2006).

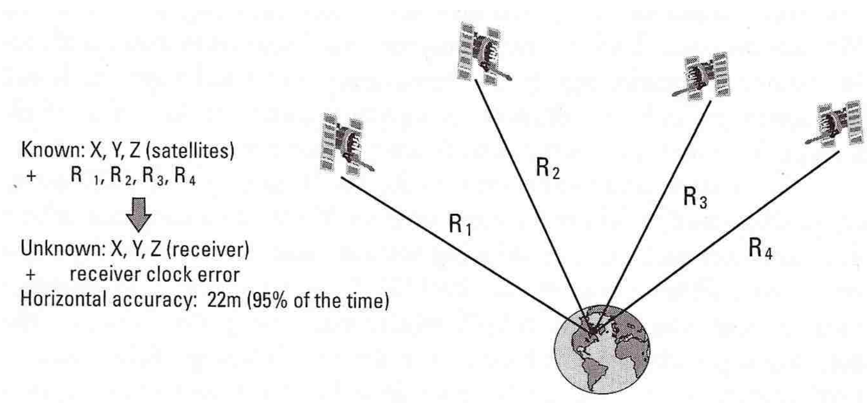


Figure 4: GPS Point Positioning

2.1.4 Velocity Determination

Some GPS receivers determine velocity based on the Doppler effect. The Doppler effect is a representation of the difference in frequency of an acoustic or radiation signal received at the receiver, and the frequency at the source. The receiver would be the GPS unit, the source would be the GPS satellite. The Doppler effect, or frequency shift, is a result of the relative velocity between the source of the signal and the receiver. The received GPS signal will be Doppler shifted as a result of the relative motion between the GPS satellites and the receiver. The relationship can then be established which relates the amount of Doppler shift, the satellite velocity, and the receiver velocity. Because the GPS satellites are at an altitude of 20,200 km, the relative motion between the source and the receiver is minimal. This results in a minimal Doppler shift and a Doppler based receiver velocity which may not be accurate enough for some applications (El-Rabbany 2006).

2.2 GPS Error Sources

Although GPS is very accurate, accuracy can be impacted by significant errors. Errors stem from the satellite, the receiver, or signal propagation errors (El-Rabbany 2006). The total typical error for a GPS receiver is 10m. Error sources and approximations are listed in the table below, and detailed in the following sections (Table 1) (Parkinson 1996)

GPS Error Sources

Error Source	Estimated Range Error (m)
Ephemeris data	1 – 2
Satellite clock	~ 1
Ionosphere	5 – 10
Troposphere	~ 1
Receiver noise	~ 1
Multipath	1 – 2
Total	~ 10

Table 1: GPS error table

2.2.1 Ephemeris Errors

Satellite position is a function of time, as predicted by previous GPS observations at monitoring stations. The position of each satellite is included in the broadcast navigation message. The operational control center uses overlapping 4-hour data spans to predict satellite orbital elements every hour. Modeling all forces acting on GPS satellites is not perfect, which results in satellite positional errors known as ephemeris errors (El-Rabanny 2006). The effect of ephemeris range error, or positional estimate by a receiver is in the order of 1.6m.

Ephemeris error from a particular satellite is the same for all users worldwide, however the effect of the error is different as users see the same satellite from different angles. Differencing the error between two receivers cannot totally remove ephemeris error. Differencing the error can have some benefit if the two receivers have a short baseline (have a short separation), since the ephemeris error of each receiver will be nearly identical (El-Rabbany 2006).

2.2.2 Clock Error

GPS satellites are equipped with onboard atomic clocks. Older models carry two cesium and two rubidium clocks, while newer models carry just three rubidium clocks. One of the onboard atomic clocks is designated to provide the frequency and timing requirements for generating the GPS signals the other clocks are backups. While the atomic clocks are highly accurate, they are not perfect and do generate some error (El-Rabbany 2006). The clock stability is approximately 1 part in 10^{13} over one day (Parkinson, 1996). This equates to 8.64 - 17.28 nanoseconds (ns) of satellite clock error per day. The range error resulting from the clock error is 2.59m to 5.18m, with 1 ns of error equating to a range error of approximately 30cm (El-Rabbany 2006). The MCS continually monitors satellite clock performance and the offset between the satellite clock and GPS time is transmitted as part of the navigation message. Satellite clock error can be differenced between two receivers, nearly removing the error. The clock correction contained in the navigation message can be applied; however this still leaves a residual of a 7 ns error, which corresponds to a range error of 2.1m (El-Rabbany 2006).

GPS receivers use inexpensive crystal clocks, which are significantly less accurate than atomic clocks. Receiver clock error is much greater than satellite clock error, but it can be removed by differencing the error between satellites (El-Rabbany 2006). It is possible to add an external atomic clock to a GPS receiver, but this is prohibited in most cases by cost.

2.2.3 Multipath Error

Multipath errors occur when the GPS signal reaches the receiver via multiple paths attributed to signal reflection and diffraction (Figure 5) (El-Rabbany 2006). Multipath errors distort the signal modulation and decrease accuracy (Braasch 1996). Both the carrier-phase and the pseudorange are affected by multipath errors. The pseudorange is affected to a greater extent and can theoretically produce errors of several tens of meters for the C/A-code measurements.

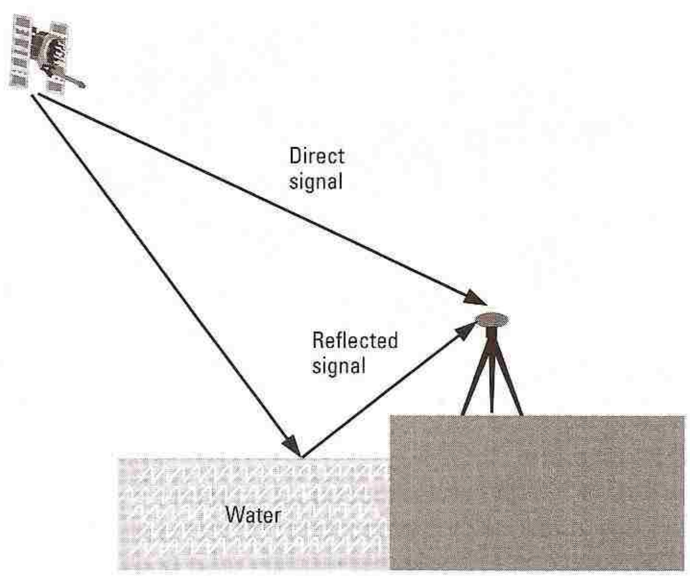


Figure 5: Multipath Effects

The easiest way to avoid multipath error is to choose an observation site with no reflecting objects near the receiver antenna. There is not presently a solid general multipath error model due to the changing nature of the satellite-reflector-antenna geometry. However, advances in signal processing and receiver technology can greatly reduce multipath error. It is also possible to use a special antenna called a choke-ring antenna that attenuates the reflected signal to help reduce the effect of multipath errors (El-Rabbany 2006).

2.2.4 Receiver Noise

Receiver noise is a result of the receiver's electronics. The receiver and antenna combined should have a minimum noise level. Most receivers will perform a self test when the unit is turned on, to evaluate the receiver noise. More precise units may require the user to perform an evaluation for receiver noise. These evaluations are done with either a zero baseline test or a short baseline test (El-Rabbany 2006). Receiver noise can equate to approximately .5m in range error (Parkinson 1996).

2.2.5 Atmospheric Refraction

The GPS signal travels at the speed of light in a vacuum. As the signal travels through the atmospheric layers of the ionosphere and troposphere the speed deviates from the vacuum speed of light (Parkinson 1996).

The ionosphere is the uppermost part of the Earth's atmosphere extending from approximately 50km above the Earth's surface, to at least 1,000km or more (the upper limit is not clearly defined). The interaction of X-ray radiation from the Sun and gas molecules and atoms results in gas ionization, producing free negatively charged electrons and positively charged atoms and molecules. Gas ionization makes the ionosphere a dispersive medium, which results in bending and altering the speed of the GPS signal (Klobuchar 1996). While the bending of the signal causes minimal error, the change in speed can cause significant error. This effect is referred to as the “ionospheric delay.” Ionospheric delay is proportional to the total electron content (the number of free electrons along the GPS signal path). The total electron count varies with the time of day (max density in the early afternoon, minimum density at or after midnight local time), the time of year (electron density is higher in winter than in summer), and the 11-year solar cycle (density reaches a max every 11 years corresponding to solar flare activities). Ionospheric delay error is in the order of 5m to 15m; in extreme cases error can exceed 150m (Klobuchar 1996; El-Rabbany 2006).

Ionospheric delay can be accounted for a number of different ways. The error can be differenced between two receivers with short separation. If a user can receive both the C/A-code (civilly accessible code) and the P-code, the ionospheric error can be determined by combining the P-code pseudorange measurement on both L1 and L2. To open this option to all users, the GPS modernization program is adding a C/A-code on L2. This will mean that users with dual frequency receivers can combine the L1 and L2 carrier-phase measurements to produce what is referred to as the ionosphere-free linear combination, with error of only a few centimeters. Post processing using ionosphere information provided by organizations such as the National Oceanic and Atmospheric Administration (NOAA) and International GNSS Service (IGS) can also be used to account for ionospheric delay (El-Rabbany 2006).

The troposphere also causes a deviation of the GPS signal from the vacuum speed of light. In the troposphere the signal is affected by variations in temperature, pressure and humidity. The troposphere is electrically neutral and extends up to about 50km above the Earth's surface (Parkinson 1996). The troposphere affects GPS carriers and codes in the same manner, resulting in the measured satellite-to-receiver range being longer than the actual measured geometric range. Tropospheric delay cannot be accounted for by combining L1 and L2 observables. A GPS signal from a satellite at lower elevations has to travel longer through the troposphere than a signal from a satellite at higher elevations. As a result, the tropospheric delay is greater for signals coming from an elevation angle of 15 degrees with an error of approximately 9.3m, than for a signal coming from the zenith, where the error is approximately 2.3m (El-Rabbany 2006).

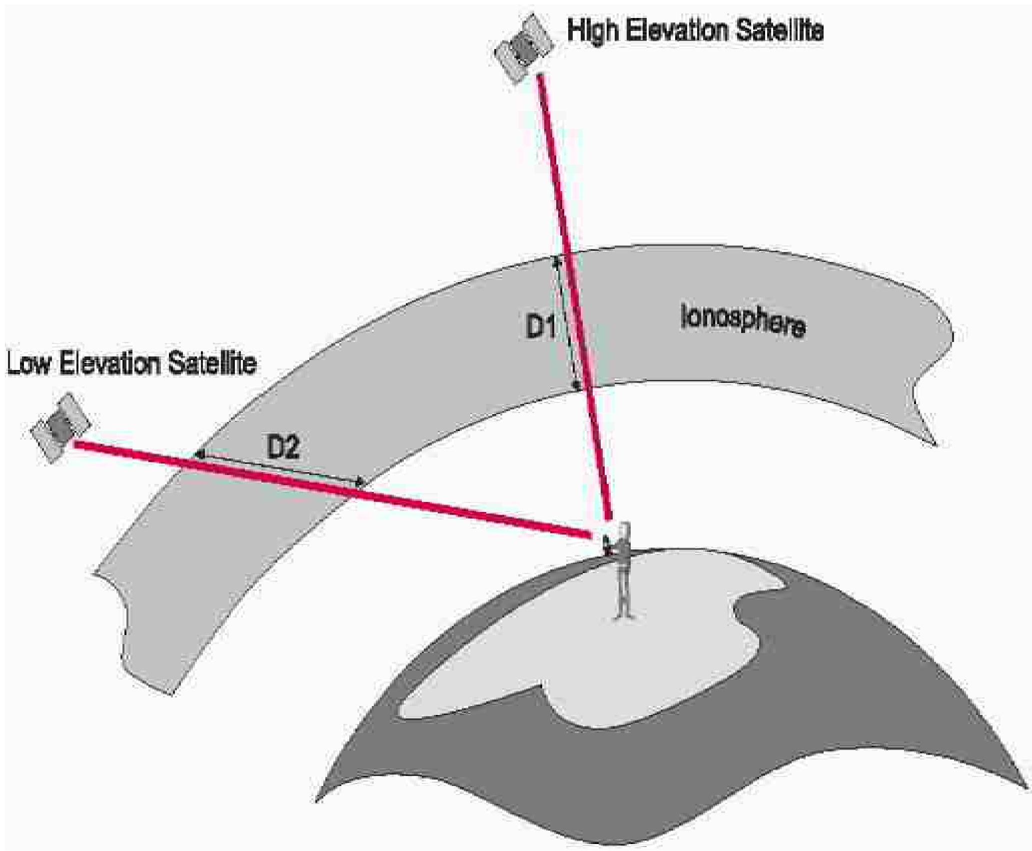


Figure 6: Troposphere Travel Distance

The troposphere has a wet and dry component that affects the propagation delay of the GPS signal very differently. The dry component is predictable and is easily modeled. The wet component depends on the amount of water vapor present which is highly variable and difficult to model (Spilker 1996). Tropospheric error models often make predictions based on surface conditions, however this weakly correlates to the actual wet component in the troposphere. Fortunately the dry component which can be modeled and predicted to account for error equates to 90% of the tropospheric delay (El-Rabbany 2006).

2.2.6 Satellite Geometry

Satellite geometry refers to the geometric location of the visible satellites, from the perspective of the receiver. A wide spread in the visible satellite geometry equates to better positioning accuracy of GPS. If all visible satellites are clumped together, GPS positioning accuracy will be less. The positional area of uncertainty is decreased when satellites are spread out, as shown in Figure 7.

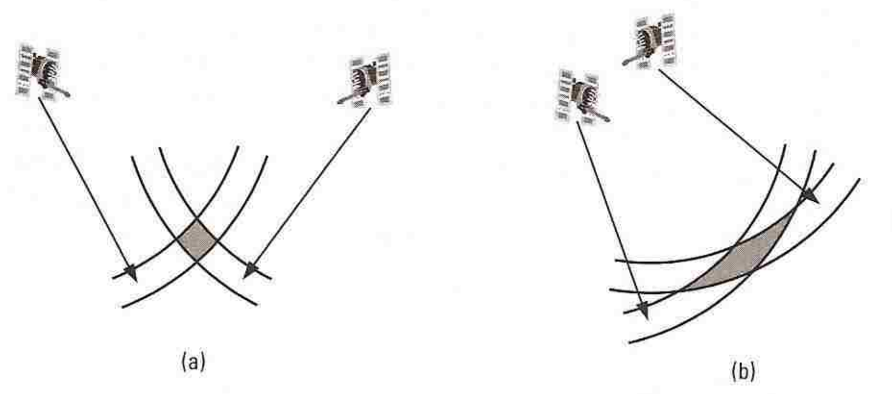


Figure 7: a) Good satellite geometry; b) bad satellite geometry.

The effect of satellite geometry is measured in a dimensionless unit called the dilution of precision (DOP). A lower DOP value indicates stronger satellite geometry. DOP is calculated based on satellite and receiver coordinates. Different forms of DOP measurement are used depending on the application. Position dilution of precision (PDOP) is used to evaluate the impact of satellite geometry on three-dimensional positioning - latitude, longitude and height. PDOP is broken into two components, horizontal dilution of precision (HDOP) and vertical dilution of precision (VDOP). VDOP will always be larger than HDOP because the GPS receiver can track only those satellites above the horizon, thus resulting in the GPS height solution being less accurate than the horizontal position solution. DOP can also be represented in time dilution of precision (TDOP) and geometric dilution of precision (GDOP). GDOP is representation of PDOP and TDOP combined. High-precision GPS positioning requires a PDOP value of five or less. This is typically achievable and often PDOP values are around two (El-Rabbany 2006).

2.3 Differential Correction

Differential correction is a technique that uses information from a stationary receiver at a known location to enhance the quality of location data used by GPS receivers (Chivers 2003; Bolstad et al. 2005). Differential correction can be applied in real-time in the field, or through postprocessing after data is collected. Regardless of which technique is applied, all differential GPS (dGPS) methods apply the same underlying concept. dGPS requires the use of a base station, which is a GPS receiver at a precisely known location. The base station compares its known location to its location as calculated based on GPS satellite signal. This calculated difference in location is then applied to the roving GPS receiver as differential correction on the premise that any two receivers relatively near each other will experience similar errors (Chivers 2003). The source of correction for dGPS is always a base reference station, but the medium to transmit the correction varies. Corrections can be accessed via radios, beacons, satellites or the internet (Trimble 2004). A few dGPS systems are detailed in the following sections, the table below shows an over view of the most common differential correction methods (Table 2).

Of the errors that effect GPS, dGPS primarily corrects for errors due to ionospheric and tropospheric refraction. Ephemeris error and satellite clock error is also slightly improved with dGPS. dGPS cannot however correct for error from receiver noise, multipath or signal refraction, or high DOP values due to poor satellite geometry.

Method	Typical Accuracy	Coverage	Cost & Equipment	How It Works
WADGPS	1-3m	Large areas (e.g. North America) which are covered by geostationary satellite footprint and where ground reference stations are located.	Freely available in many parts of the world. Signal can be received by a consumer grade receiver which is WADGPS capable.	Utilizes a network of ground reference/monitoring stations, ground uplink stations, and geostationary satellites. Reference stations gather GPS information which is sent to master station which computes a correction message. Ground uplink stations upload this to geostationary satellites, which broadcast the message to GPS receivers. If receiver isn't in line of site of geostationary satellite correction message cannot be received. This method offers real time correction but can be affected by data latency in corrections
Radio Beacons	<1m – 3m	Within the area of a beacon station. Beacon coverage depends on	Signal is typically free, but users must have a beacon receiver which	A real time differential correction message is created by a ground reference station gathering GPS data, the correction message is then transmitted via ground based radio beacons. Users receive the corrected message with a GPS receiver

		transmitter power output, atmospheric noise, and receiver sensitivity. Beacon range can be on the order of ~400 km (tfhrc.gov).	interfaces with a differential-ready GPS receiver	equipped with a beacon receiver. This dGPS method does not require line of site.
Multisite RTK	10-15cm	15 to 20 km from ground reference station.	This service is not freely available. It requires multiple high end receivers with special software built in.	A network of reference stations is used to create GPS measurements for a virtual reference station which is located near the receiver. The virtual reference station measurements are transmitted to the receiver, which then uses normal, single reference station RTK positioning.
Postprocessing	<1m	Wherever a permanent GPS	There are free networks world wide	Postprocessing software is used to calculate the error in each GPS measurement as logged by a ground reference station. Error

		reference station network has been established. Networks can cover large areas (e.g. North America).	which provide correction messages, however user requires postprocessing software as well as a receiver which is postprocessing capable.	correction messages are downloaded from the internet for the time period data was collected. This method requires user proficiency in postprocessing software. There are no issues of signal obstruction or limited coverage as reference stations are built to avoid these. There is no latency in data corrections. Users have options in editing and cleaning collected data.

Table 2: Differential Correction Method

2.3.1 Real-time dGPS

Real-time dGPS computes the error value as the GPS signal is received and transmits the correction to the roving receiver over a radio or other link medium. The correction message contains error values for all satellites visible to the reference station, the receiver applies only the correction for the satellites it is using (Trimble 2004).

Marine radio beacons are one example of a real-time dGPS method. Marine beacons are often installed around waterways and at lighthouses to aid in maritime safety. Marine beacons calculate dGPS corrections, and broadcast the correction in a special format known as RTCM (Radio Technical Commission for Maritime Services). The maritime dGPS system is free to all users; however, users must be equipped with a beacon receiver that interfaces with a differential-ready GPS receiver (El-Rabbany 2006). Providers of a maritime dGPS system (typically a country's coast guard) publish the expected coverage of the beacon system. A beacon based augmentation system provides positional accuracy of better than one meter, at the beacon station. This accuracy degrades over distance. Some maritime dGPS systems are expanding to include beacons inland, thus providing beacon dGPS for land navigation (El-Rabbany 2006).

Another type of real-time dGPS is ground based augmentation systems (GBAS). The GBAS being implemented in the U.S. is known as the Local Area Augmentation System (LAAS) which is an entity of the FAA. LAAS is a differential correction method which focuses service around an airport area to provide information for precision approaches, departure procedures and terminal area operations. LAAS serves only a 20-30 mile radius from the LAAS ground facility which is located on airport grounds.

Accuracy of LAAS is less than 1m both vertically and horizontally. LAAS is still in the research and development phase and is seeking to gain approval as an aviation tool in the near future. Organizations or government groups in Australia, Brazil, Germany and Spain are also working to establish GBAS in their countries. The FAA is working with these countries to share technical knowledge with the goal of establishing international GBAS implementation and interoperability (faa.gov).

The LAAS network consists of a ground equipment component and an avionics equipment component. The ground segment includes four reference GPS receivers, a LAAS ground facility station which receives data from the reference stations and generates the correction message, and a data broadcast transmitter to transmit the correction message to LAAS equipment in airplanes. The coverage area of LAAS is designed to support an aircraft's transition from en route airspace where WAAS is being used, to terminal area airspace where higher accuracy correction is provided by LAAS (faa.gov).

Another example of real-time dGPS is wide-area differential GPS (WADGPS). WADGPS is a method which employs a network of widely spread reference stations, one or more master control stations, uplink stations, and communication satellites. There are four main government operated WADGPS systems in place which are satellite based augmentation systems (SBAS). SBASs compute the dGPS corrections based on data collected from the network of reference stations, forward this to a master station for processing, upload the correction to geostationary satellites, and rebroadcast the correction to receivers. Geostationary satellites appear to be motionless in the sky because they orbit equal to the Earth's rotational period. SBAS systems require that the receiver be capable of receiving and decoding the dGPS correction. Examples of systems that utilize a form of SBAS are OmniSTAR, a commercial service, and WAAS, a free service (El-Rabbany 2006). Several other SBAS systems are detailed in a further section of this paper.

A disadvantage of real-time dGPS is that the real-time corrections suffer from data latency. Corrections used are actually based on the broadcast corrections from a few seconds before hand. However, a great advantage is that only the data necessary is collected and the correction is provided on the spot by built in software (Trimble 2004; El-Rabbany 2006).

2.3.2 Postprocessed dGPS

Postprocessed dGPS uses software in the lab to process data collected from reference stations, and applies the corrections to the gathered GPS data. Postprocessing is typically more accurate than real-time dGPS because there is more flexibility in editing and cleaning the collected GPS data. Additionally, postprocessing has no data latency, nor does it suffer from problems of limited coverage area or signal obstruction (El-Rabbany 2006). Postprocessing uses more sophisticated algorithms and can utilize multiple base observations from before and after data was collected (Trimble 2004).

Many organizations around the world have established highly precise, permanent GPS reference stations that are used for postprocessing applications. A freely available, world wide system is the IGS network. Correction data can be downloaded from the IGS website. There are also regional data services such as the Continuously Operating Reference Station (CORS) network in the U.S. operated by the National Geodetic Survey (NGS), a part of NOAA. NGS also operates the Online Positioning User Service (OPUS), in which end users can submit their GPS data files where they will be postprocessed using NGS computers and software (ngs.noaa.gov/OPUS/). All WAAS reference stations are also part of the CORS network.

2.4 WAAS

This thesis looks specifically at the U.S. based differential correction system known as WAAS. WAAS is a SBAS and was designed to augment and enhance GPS accuracy and reliability for use as a navigation aid for civilian aviation (Bolstad et al. 2005). The WAAS system reached full operational status in July of 2003 (FAA 2008). The FAA manages WAAS and publishes quarterly performance analysis reports. The FAA reports that WAAS will provide 7m accuracy - a 3m improvement on the 10m accuracy which is usually specified for most recreational receivers gathering data autonomously. However, FAA testing shows that WAAS accuracy is typically better than 7m accuracy, with tests from the first quarter of 2008 indicating “the 95% horizontal and vertical accuracy at all evaluated sites are less than 2 meters for both WAAS operational service levels” (FAA 2008).

2.4.1 WAAS History

WAAS was originally developed by the FAA in partnership with the U.S. Department of Transportation (DoT). The FAA first issued a request for proposals to build the WAAS network in 1994. The initial program was scheduled for six years and an estimated $400-500 million (Phillips 1994). It was hoped that the system would reach initial operational capability in 1997. In August, 1995 the FAA awarded a $475 million contract to Wilcox Electric, teamed with Hughes Aircraft and TRW. This contract called for development and placement of approximately 35 ground stations to be located at air traffic control sites across the U.S. Wilcox Electric failed to meet the FAA's expectations for WAAS development, and the contract was terminated and quickly awarded to Hughes Aircraft in 1996 (Nordwall 1996). In 1998 Raytheon purchased Hughes Aircraft's Defense Electronics business, thus taking over the WAAS contract from the FAA. Testing and building of the WAAS network continued and after several delays it was finally certified for aviation use in July 2003 and reached full operational service.

The WAAS network continues to expand. In 2006-07 thirteen new reference stations were added. In 2006 a third master control station was added, and in 2007 the two geostationary satellites were upgraded. The current operational service area is shown below (Figure 8). LPV, localizer precision with vertical guidance, is an FAA term which is an operational service level with a horizontal alert limit of 40 m and a vertical alert limit of 35 meters. LNAV is a representation of lateral navigation area, and VNAV is a representation of vertical navigation area.

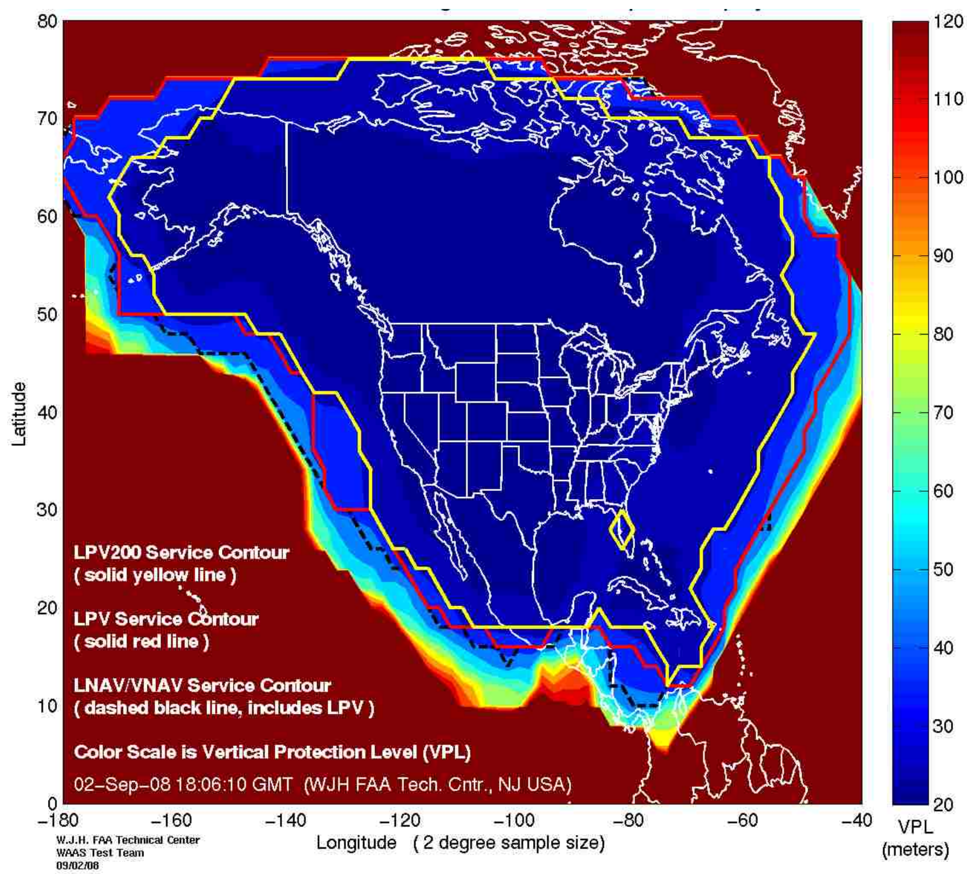


Figure 8: WAAS Service Area

2.4.2 WAAS Network

The WAAS network is composed of 38 WAAS reference stations (WRS) located across the continental United States, Alaska, Puerto Rico, Hawaii, Canada and Mexico, three master control stations, two geostationary Earth orbit (GEO) satellites, and four ground uplink stations (GUS) (Figure 9) (Eldridge 2008).

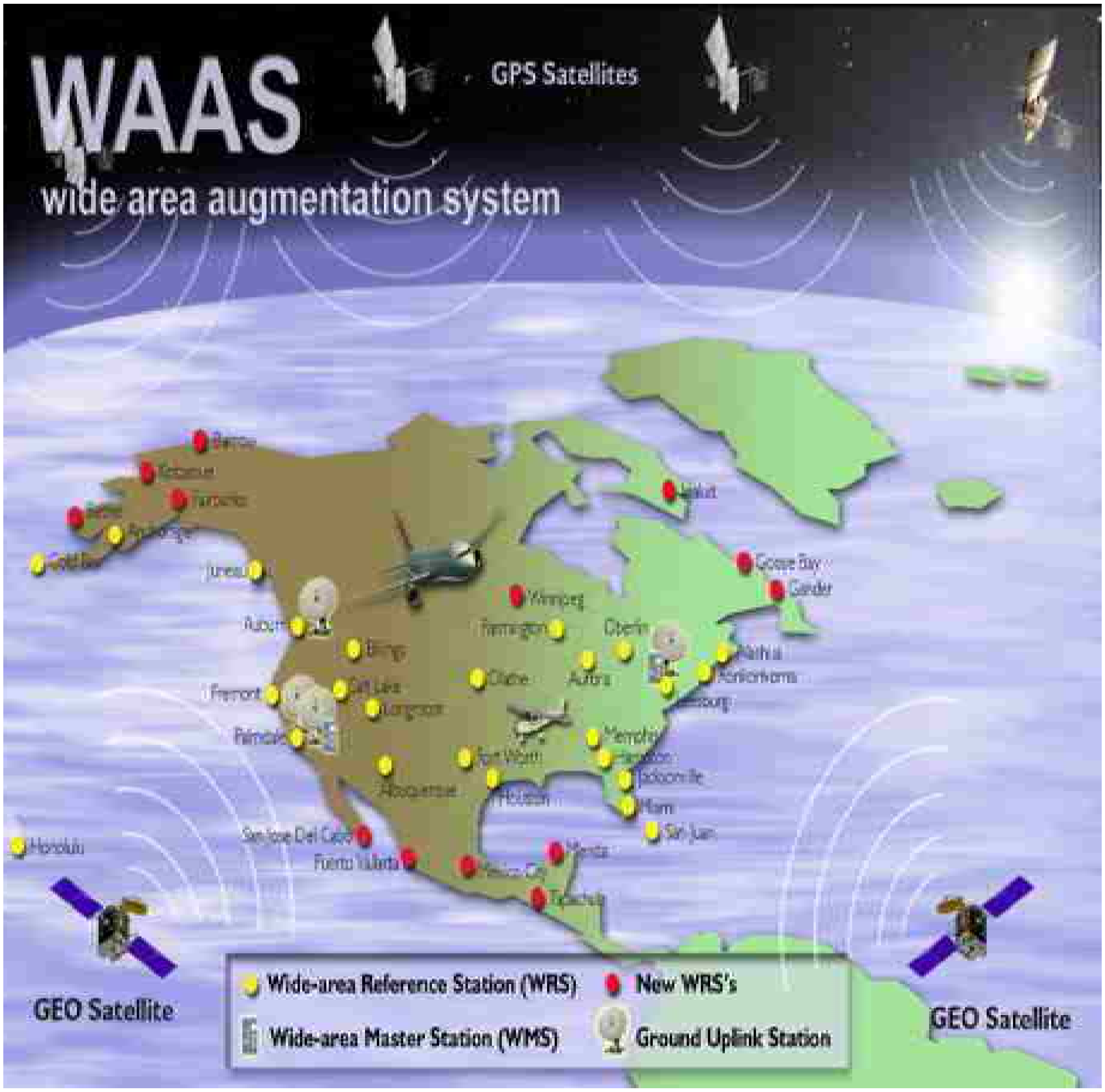


Figure 9: WAAS Network

The WRS's are widely spread and collect data from all visible GPS satellites as well as the WAAS GEO satellites. Each WRS is equipped with a high quality clock and multiple GPS receivers (Kee 1996). The collected data are then sent to the master control stations. The master control stations process this data to determine satellite integrity, differential corrections, residual errors, and ionospheric delay (Enge and Van Dierendonck 1996). The correction information is uploaded to the two GEO satellites, which then transmit the correction at the GPS L1 frequency. The GEO satellites also broadcast an L5 signal which currently is only used by GUS to calculate ionospheric delay (Schempp 2008). The correction message consists of two components, the location independent parameters of ephemeris and clock error, and area specific ionospheric errors transmitted in a latitude-longitude grid (Trimble 2004; El-Rabbany 2006; Schempp 2008). Because the correction message is transmitted on the GPS L1 frequency, it can be received by all WAAS enabled receivers at no cost, with no extra hardware or software needed.

2.4.2.1 WAAS Reference Stations

In 2006-07, thirteen new WRS were added to the WAAS network. Stations were added in Alaska, Mexico and Canada greatly increasing performance in North America. Additionally, all WRS were upgraded to use a new GPS receiver which provides detailed information about GPS signal quality to be used in an improved signal-quality monitoring algorithm (Schempps 2008).

The third WAAS master control station was added to the network in June 2006. The addition of this station ensures that the WAAS network will always have at least two operational master control stations even when one is down for maintenance or upgrades (Schempp 2008).

2.4.2.2 GEO Satellites

In July 2007 the WAAS legacy GEO satellites were replaced with upgraded satellites which provide superior ranging capabilities. One of the GEO satellites is located at 133°W, it is identified by the pseudorandom noise code (PRN) 135. This is the Galaxy 15 PANAMSAT and is operated by Intelsat. The second GEO satellite is located at 107.3°W, PRN 138. It is the Anik F1R satellite operated by Telesat. These new GEO satellites ensure dual GEO coverage for all WAAS users (Schempp 2008). Figure 10 shows the footprint of the two GEO satellites (FAA 2008). The GEO satellites are located 36,000km above the Earth's equator.

The GEO satellites broadcast a signal at the earth whose footprint is defined by the curvature of the Earth. The signal cannot bend around the Earth and the footprint is circular on the surface of the Earth. Once projected the footprint appears oval in shape. While the GEO satellite signal covers such a large area, the service area as shown in Figure 8 is only the area where reference and master stations are in place to work with the GEO satellites.

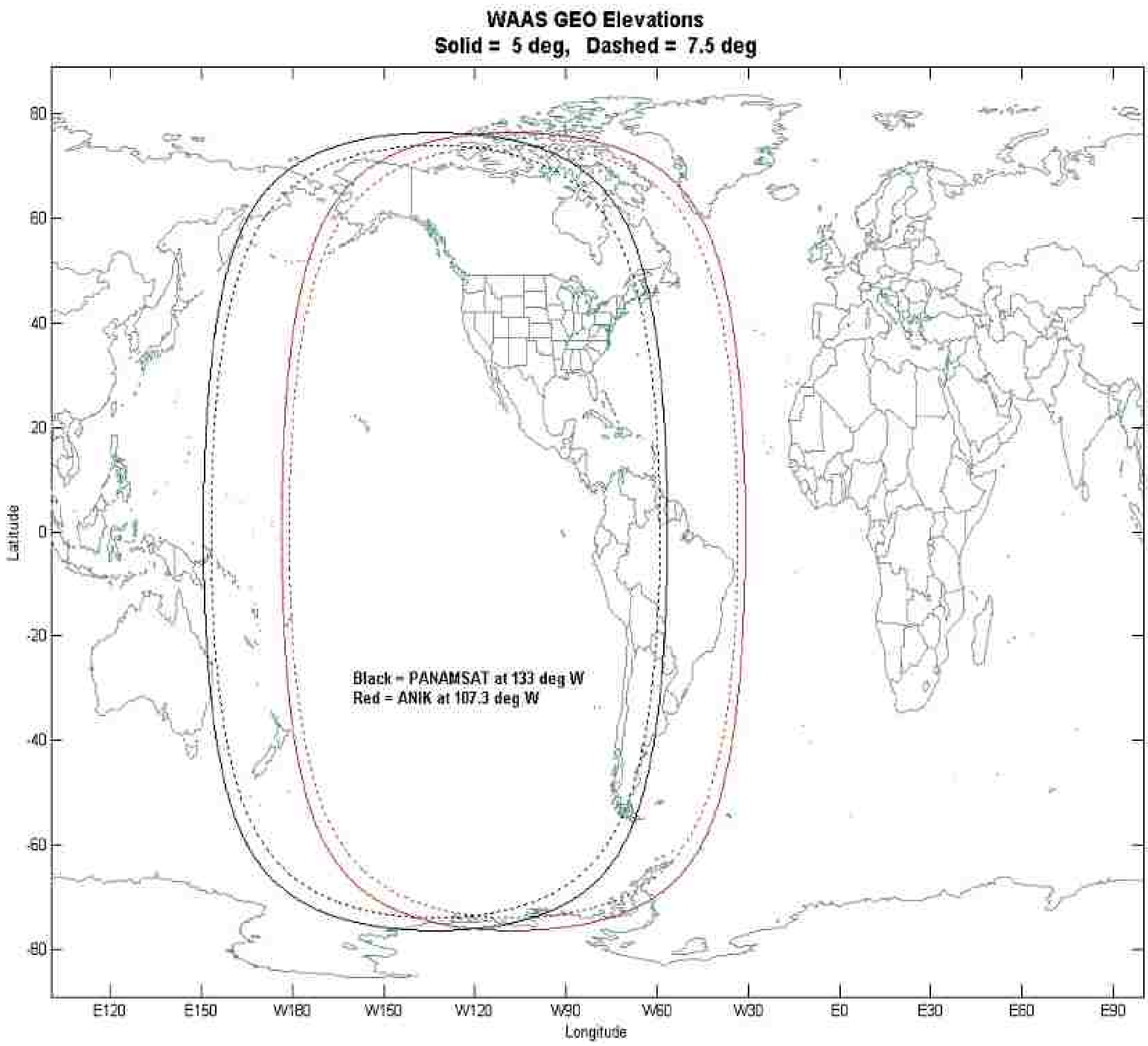


Figure 10: WAAS GEO Footprint

2.4.3 WAAS Architecture

WAAS is a SBAS based on the WADGPS model, and is specifically a state-space-domain WADGPS (El-Rabbany 2006). Instead of providing a scalar range error correction for each satellite as is done in dGPS, WADGPS calculates a vector of error corrections. WADGPS is nearly constant in the monitored region, and degrades smoothly on the perimeter. Computation of the error correction vector is the key component of WADGPS. The correction accounts for three-dimensional ephemeris clock error and clock bias for each visible GPS satellite, plus ionospheric delay (Kee 1996).

Communication between WAAS components is handled by a terrestrial communication network (TCN) (Figure 11). Redundancy is built into the network to increase system reliability. Each WRS is equipped with three reference equipment units, data is used from two of the units while the third is a backup. The TCN is divided into two separate networks, each of which utilizes a high reliability T1 backbone. Each master control station is equipped with two correction processors and two safety processors. If an error is detected in the safety processors another correction and validation device automatically takes over. Each GUS receives a message from each master control station. Should the GUS fail to receive a message from a master control station, a different master control station is used in its place. A pair of GUS sites is assigned to each GEO satellite, should one of the GUS sites fail the other automatically takes over. Most users in North America have dual GEO satellite coverage. Should one of the GEO satellites fail, the users' receiver will automatically switch to the other satellite.

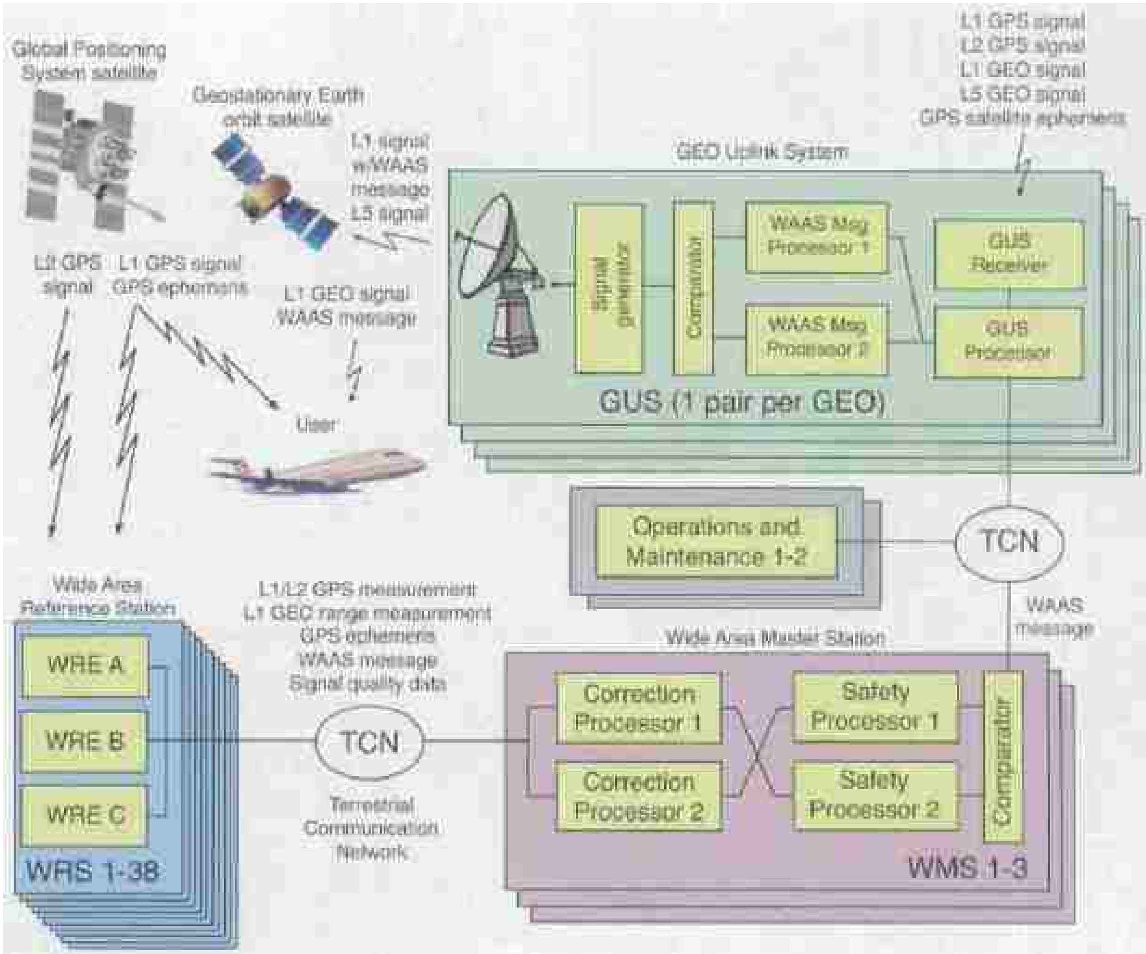


Figure 11: WAAS Architecture

2.4.4 Other SBAS networks

The U.S. is not the only country with a SBAS in place. Japan, Europe, India and China have, or are implementing similar augmentation systems.

In 2007 Japan's augmentation system known as the Multifunction Satellite-based Augmentation System (MSAS) became operational. MSAS was developed by the Japanese Civil Aviation Bureau. The system is similar to the U.S.'s WAAS and is compatible with WAAS and Europe's SBAS, EGNOS. MSAS covers the area around

Japan, the GEO satellite footprint is shown in figure 12. The system follows the typical SBAS architecture utilizing four ground monitoring stations, two master control stations, two uplink stations, and two GEO satellites located at 140°E and 145°E. Although the Japanese Civil Aviation Bureau does not publish test results as the FAA does for WAAS, MSAS is reported to be on the same accuracy level as WAAS (Gakstatter 2008).

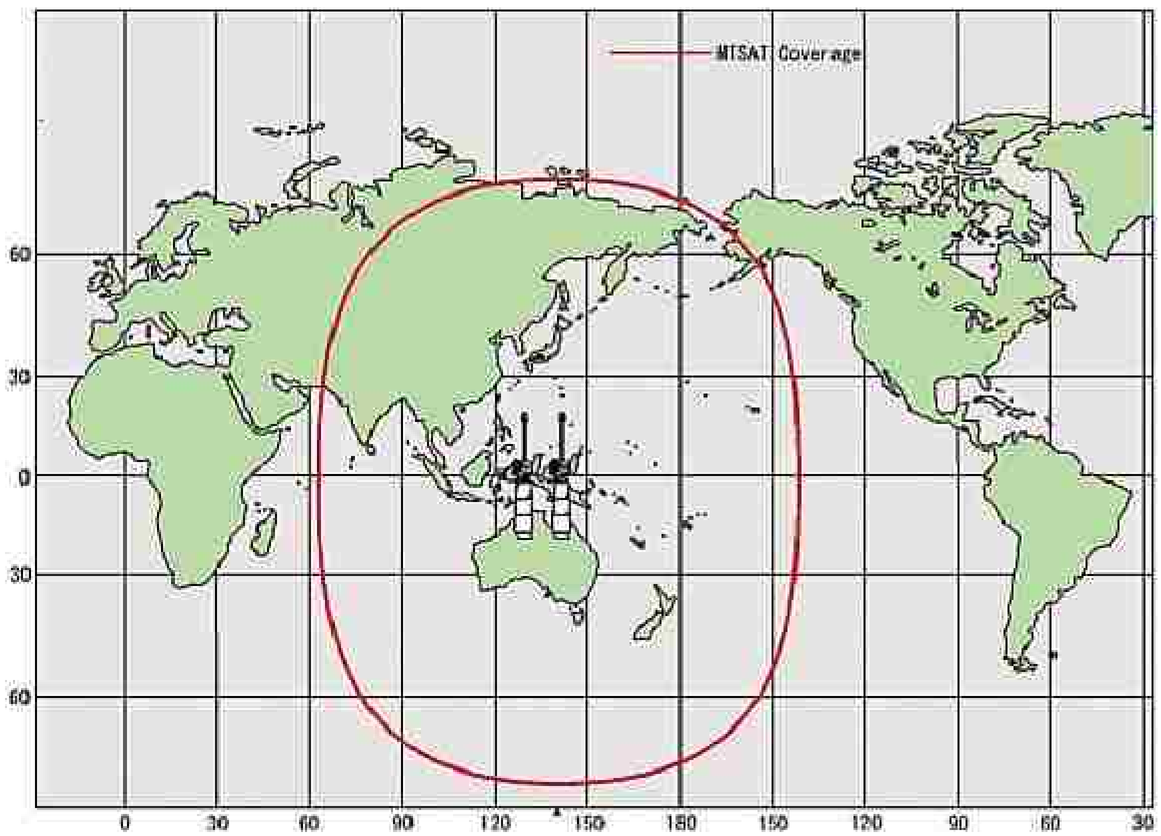


Figure 12: MSAS GEO Footprint

Europe's SBAS is the European Geostationary Navigation Overlay Service (EGNOS). The infrastructure for EGNOS is in place, but the system has not yet been certified for complete operation. EGNOS is being developed by the European Commission (ESA) and EUROCONTROL (European Organization for the Safety of Air

Navigation). Certification of EGNOS is complex as the plan is to have it certified globally rather than country by country. Current plans have EGNOS being fully certified in 2009. It has been planned that EGNOS would be run by the concessionaire for Galileo (Europe's equivalent of the U.S.'s GPS), however, Galileo's future is uncertain as funding issues build (Wilson 2008).

Technically EGNOS is the same as WAAS. Any WAAS enabled receiver can receive the EGNOS signal. EGNOS is also compatible with MSAS. The EGNOS network consists of 34 ranging and integrity monitoring stations, equivalent to WAAS reference stations, four master control centers, six uplink stations and three GEO satellites. The GEO satellites are located at 15.5°W, 21.5°E and 64.5°E. EGNOS is striving for an accuracy standard of 1m. A notable difference between EGNOS and WAAS is that EGNOS has been designed from the start as a system intended for applications other than just aviation. The system is designed to provide service area coverage to the whole of Europe, the GEO footprint is shown below (Wilson 2008) (Figure 13).

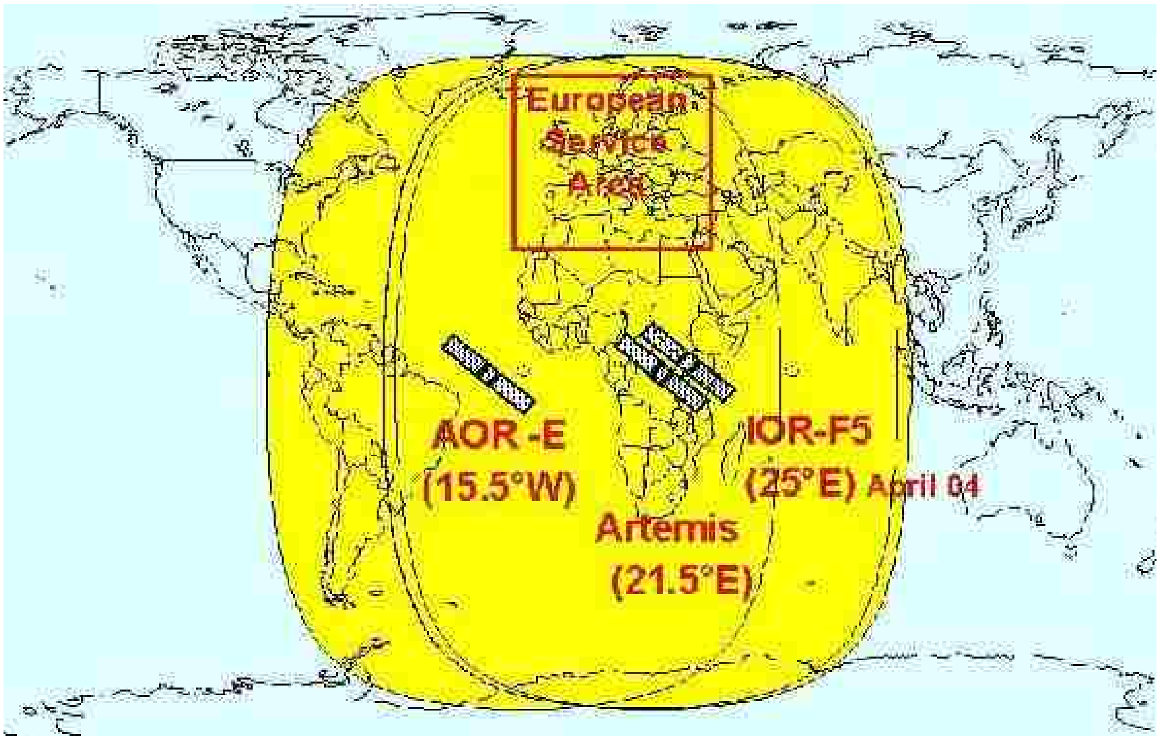


Figure 13: EGNOS GEO Footprint

The Geo-Aided GPS Augmented Navigation system (GAGAN) is currently under development in India, with plans to be operational by 2012-14. GAGAN is a joint partnership between Airports Authority of India and the Indian Space Research Organization and is modeled after the U.S.'s WAAS. India is motivated to have their own SBAS in place to provide navigational services to its quickly growing aircraft activity. GAGAN will cover an area from Africa to Australia, complimenting the coverage of WAAS, EGNOS and MSAS. GAGAN will utilize the same architectural model as WAAS, implementing eight reference stations, one master control station, one uplink station, and one GEO satellite. GAGAN aims to provide at least 7.6 meter accuracy, however early tests of the system are providing near meter accuracy both vertically and horizontally (Matthews 2007). The proposed GEO footprint for GAGAN is shown in figure 14 (Kibe 2006).

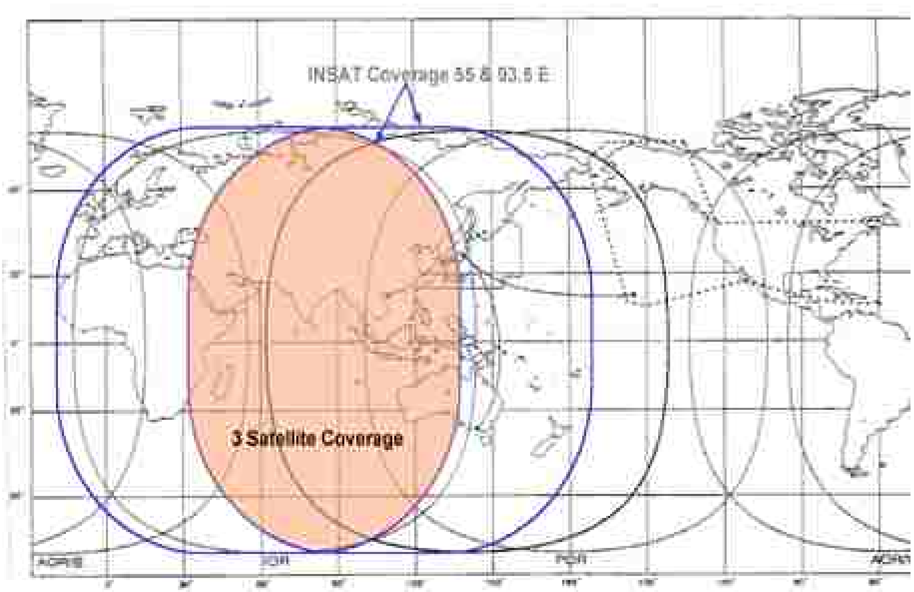


Figure 14: GAGAN GEO Footprint

China is implementing an SBAS known as the Satellite Navigation Augmentation System (SNAS) (Wilson 2008). Information on SNAS is incomplete, although it has been documented that 11 reference stations have been installed around Beijing. Further growth of the system is expected as a Canadian company has received a contract to supply GPS receivers for SNAS (Grewal, Weill and Andrews 2007).

Canada has also implemented a WADGPS, however it is not intended for commercial aviation. Canada's system is known as the Canada-wide differential GPS (CDGPS). This is not the equivalent of the U.S.'s WAAS system (El-Rabbany 2006). However, the U.S.'s WAAS system is expanding into Canada with the intention to cover the entire country. In some documentation this is referred to as Canadian WAAS (CWAAS).

A general service area map of the SBASs across the globe is shown in figure 14.

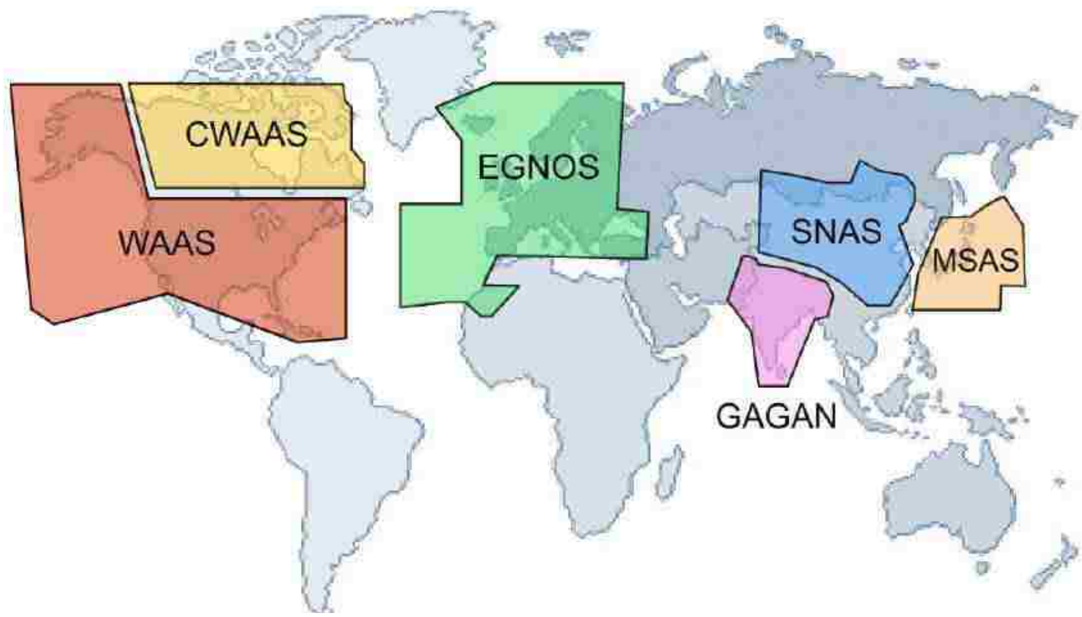


Figure 15: World SBAS Service Areas

2.4.5 Ideal WAAS Conditions

In order to get the most out of the WAAS correction message, several factors should be considered. Strong satellite geometry, a low PDOP value, is required as WAAS cannot overcome weak satellite geometry. Mission planning software can be used to predict GPS satellite location based on user location and ensure data are collected at a time of strong satellite geometry (El-Rabbany 2006). Mission planning software, or the GPS receiver it self can be used to set an elevation mask. An elevation mask is set to exclude GPS satellites that are below a certain elevation point. An elevation mask is typically set to 10 or 15 degrees (El-Rabbanny 2006). WAAS cannot correct for multipath errors, thus a location with little or no multipath effect should be chosen for data collection. Another consideration is the effect of averaging numerous points collected at one position to get a result closer to the coordinates of the known point. When only a few points are gathered to estimate a point location, more large errors and variability in error exists than when many points are gathered to estimate a point location (Bolstad et al. 2005).

2.5 Performance

2.5.1 Performance Metrics

While very few studies have evaluated the accuracy of WAAS, some studies have been conducted to evaluate the accuracy of autonomous GPS. Horizontal and vertical accuracy is a key metric to evaluate.

2.5.1.1 Availability

In order to utilize the WAAS signal, the GPS signal must first be available. In theory, GPS and WAAS signals are always available; in practice, GPS and WAAS signals can be equally affected by obstructions. The availability of the signals can be affected by line of sight problems. Line of sight between the receiver and either the GPS or WAAS satellite can be obstructed for example by tall buildings, mountains, or thick tree canopies. Additionally GPS and WAAS signals are generally not available indoors. A study conducted by Bolstad et al. (2005) evaluated availability of the WAAS signal. It was found that in the open the WAAS signal was available 98% of the time. Under a forest canopy the WAAS signal was available 23-33% of the time while stationary in the forest, and only 7-22% while moving in the forest (Bolstad et al. 2005).

2.5.1.2 Accuracy

Accuracy is determined by collecting fixes over a known point, and comparing the collected points to the known point location. A known point can be determined by using NGS high accuracy control points (Bolstad et al. 2005).

Accuracy is commonly expressed as the average of the points collected compared to the true location point. One study conducted by Wing, Eklund and Kellogg (2005) simply stated the "process of averaging should, statistically, result in coordinates that are more accurate than that collected by a single measurement, or by fewer than 25 measurements." Another study conducted by Bolstad et al (2005) tested the effect of number of fixes on average accuracy by performing regression on the average error versus the number of fixes. Significance of the regression slope was determined based on a reduced sum of squares f-test and significance varied by receiver type, but over all it was indicated that the spread of error would be less when more points are collected and averaged.

Accuracy is also commonly expressed at the 68th and 95th percentile, one standard deviation and two standard deviations from the mean respectively. For example, a data point at the 68th percentile would indicate that 68% of the data is better than that specification. A third measure of accuracy in this category is Circular Error Probable (CEP), which is a representation of the 50th percentile, or the median. CEP indicates half of the data points fall within a circle of this radius centered on the true location, and half lie outside of this circle (Gilbert 2003). While the median can be determined for both horizontal and vertical accuracy, CEP is only a representation of horizontal accuracy.

Computing the root mean square error (RMSE) is a way of measuring the average magnitude of the error. RMSE is calculated by finding the distance between the known location point and the collected data points, squaring these distances, then taking the square root of the mean of the squared distances (Devlin, McDonell and Ward 2007). Since errors are squared before they are averaged, RMSE gives a relatively high weight to large errors.

2.5.1.3 Time to First Fix

Time to first fix (TTFF) is a metric which specifies the time it takes a GPS unit to acquire satellite signals and navigation data, and calculate the receiver's position based on this information. TTFF is categorized into cold start, warm start, and hot start. A cold start is start of a receiver fresh from the factory. This means the unit has no almanac information and must search for all possible satellites and download the almanac which is rebroadcast every 12.5 minutes. A typical cold TTFF estimate is 15 minutes.

A warm TTFF is what is considered a normal start of the receiver. A warm start relies on the unit having an almanac downloaded within the past few weeks and an estimate of the current time and position. A warm start TTFF is typically in the range of 2.5 to 5 minutes.

A hot fix occurs when the receiver already has time, position, and satellite ephemeris data, but has lost satellite acquisition for example due to line of sight issues.

Since the unit already has most data required for a position fix, as soon as satellites are acquired again position can be determined quickly, typically in 2 to 10 seconds. A hot fix may also be referred to as Time to Subsequent Fix (TTSF) (NAVSTAR 1996).

2.5.2 Accuracy of Autonomous GPS

One study compared the accuracy of six different consumer grade GPS units. The results showed autonomous GPS provides approximately 5m accuracy in open sky settings, 7m accuracy in young forest conditions, and 10m accuracy under closed canopies (Wing, Eklund and Kellogg 2005). Another study conducted similar testing and concluded that there was little difference in accuracy among different receiver types when used in open areas. In an open area environment errors among different receivers ranged from .88m – 2.2m. There was however significant difference amongst receiver types when using GPS below a forest canopy where errors between receivers ranged greatly from 2.5m – 7.1m. This study also compared data that was corrected via postprocessing, WAAS and autonomous and concluded that in a higher end unit the difference between these three methods was minimal and therefore differences in lower end units were caused by other outside influences and not the type of correction used (Bolstad et al. 2005).

2.5.2 Accuracy Determination

A study conducted by Wing, Eklund, and Kellogg set out to “test the accuracy and reliability of consumer-grade GPS receivers in a variety of landscape settings” (2005). To test accuracy the researchers established known points to use as benchmarks. Known points were determined with the use of a digital total station and were placed purposely in a low multipath location, or in a location with known satellite view or multipath problems. Mission planning software was used to schedule collection times around particularly strong satellite geometry (low PDOP). In order to maintain consistency during collection, wooden staffs were built to hold each GPS receiver 1.2m above the surface. To realize the benefits of averaging, twenty five observations were taken at each known location, approximately four seconds apart. Positional error was determined based on the straight line distance between the averaged coordinate and the known coordinate. Standard deviation was calculated as an estimate of GPS reliability. Maximum PDOP values were also recorded during testing by a separate mapping grade receiver. Results were presented in a table showing the average error and max PDOP for each course and repetition (Wing, Eklund, and Kellogg 2005).

The second reviewed study set out to compare accuracy among a range of GPS receivers when collecting data in the open and below the U.S. northern forest canopies. The study also compared recreational receivers using WAAS, to high end receivers in autonomous, WAAS, real-time differential and post-processed modes. Data were collected at three known locations specifically in an open area with an ideal collection environment, and three known locations in a closed canopy area. While mission planning software wasn’t used, a threshold value for PDOP was established, 6 for open areas and 14 for closed canopy areas. Known points were determined directly from NGS first or second order control points, or carrier-phase, differentially corrected points calculated based on the NGS points. Testing consisted of standing over a known point with the receiver, obtaining position fixes until a specified number was met, noting the average position location, and downloading the data if it was meant for postprocessing. Receivers were held 1.2m – 1.8m above the surface. This study aimed to evaluate the effect of number of fixes on average accuracy and found that the spread of error would be less when more points are collected and averaged. An analysis of variance (ANOVA), Tukey's tests and linear regression were used to identify significant factors and differences in the Euclidean error distances. Period of day, number of fixes, and receiver type were used as explanatory factors in the ANOVA. F-tests were used to determine factor significance and the Tukey test to determine differences among levels for each factor (Bolstad et al. 2005).

2.5.3 Statistical Power Analysis

Statistical power analysis is a method used to determine if the conclusion from a traditional statistical hypothesis test are representative of the real population, or if the conclusion is in a range that could be produced from random sampling error. Statistical power analysis can be used to determine necessary sample size, level of power of a proposed of completed study, estimates of size of effect, and appropriate criteria for statistical significance. Statistical power analysis is most significant when three conditions are met: the study is highly sensitive, meaning there is a large sample size (N); the effect size is large, meaning the treatment is significant, in this case if WAAS were largely different than autonomous the effect size would be large; and lastly the criteria for statistical significance are lenient, for example it is easier to reject a null hypothesis at the .05 alpha level than at the .001 alpha level. A desirable power level for a study is .80 (Murphy, Myors and Wolach, 2009).

3. Methodology

3.1 Field Experiment

3.1.1 Control Point Determination

In order to evaluate positional accuracy, collected data must be compared to a known point. The location of known points is determined with a system of higher accuracy than the handheld receivers being used in this test. The known point is the "true" location of the point in question, also referred to as the control point. Control points were selected from National Geodetic Survey (NGS) and Albuquerque Geodetic Reference System (AGRS). NGS points used were "high-accuracy" GPS control points. AGRS control points used were 1^{st} order horizontal, and 2^{nd} order vertical accuracy. These data are obtained from the NGS datasheet retrieval page (ngs.noaa.gov) and the City of Albuquerque web page (cabq.gov/gis/survey.html) respectively. A total of ten control point locations were selected in the study area of Albuquerque, NM, within relative proximity (13 miles) of the WRS located in the northeast part of the city at approximately 35°10'19 N, 106°33'59 W (Figure 16). Control points referred to in this research as Sinclair and Lee were established using a survey grade GPS receiver. Control point Sinclair was established in a location convenient for data to be collected for an extended time. The GPS receiver used was the Ashtech Z-Xtreme with the Geodetic IV, Rev. A antenna. Data were collected with the Ashtech receiver for eight hours and processed using NGS's On-line Positioning User Service (OPUS). For each control point used in the study, information is documented on horizontal and vertical order, and horizontal and vertical coordinates. Details on each control point used are listed in Appendix 1.

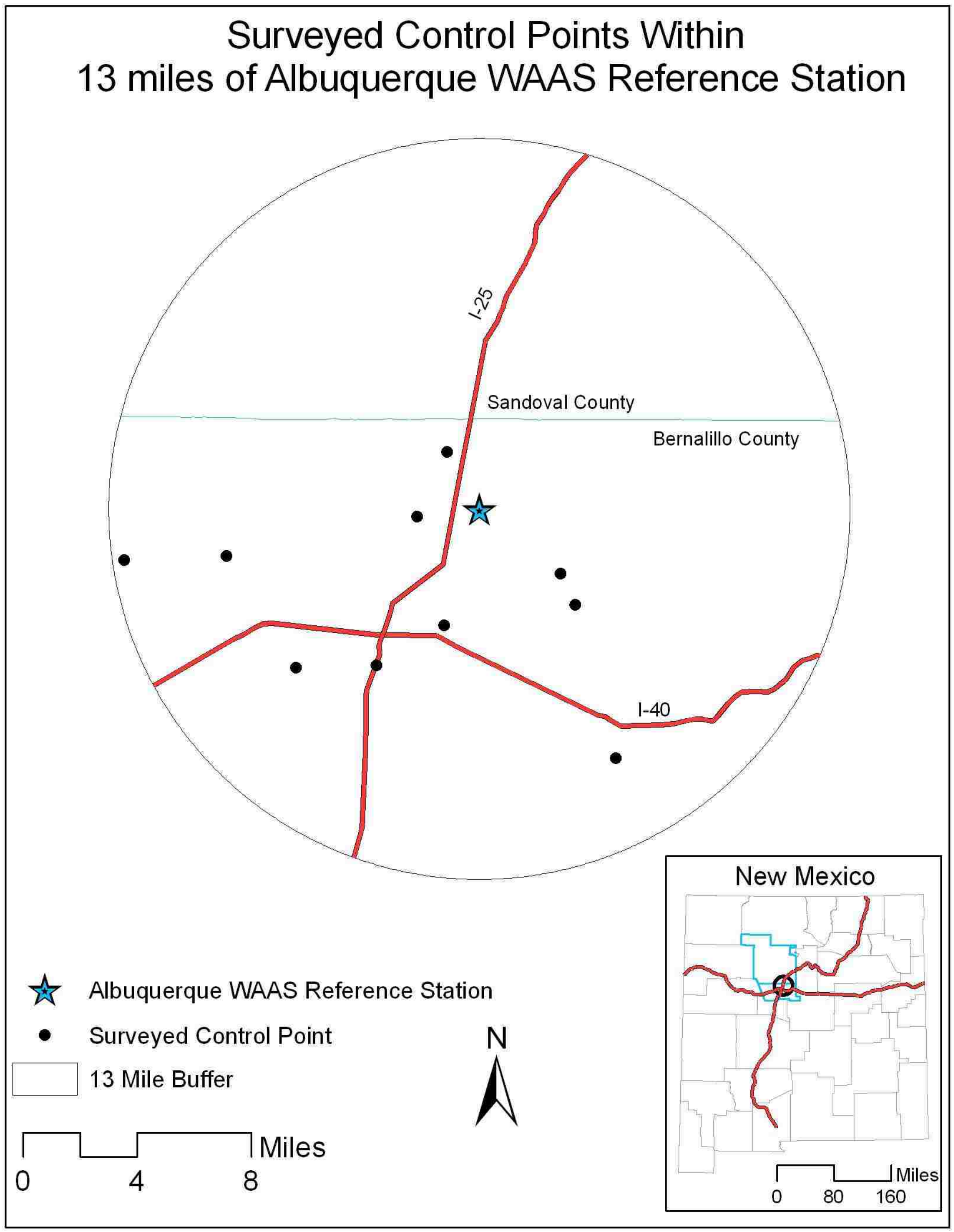


Figure 16: Surveyed Control Points

3.1.2 Data Logging

The first objective of this thesis is to compare horizontal and vertical accuracy of WAAS corrected GPS and autonomous GPS under ideal conditions. Ideal conditions for this test were such that the control point is in an open area with minimal obstructions, within thirteen miles of the WRS. Data were initially collected at 11:00am daily, and then moved to anytime between 10:00am and 3:00pm after data on diurnal patterns were collected and analyzed.

Three different types of consumer grade units were used in data collection Garmin 60cx, DeLorme Earthmate PN20, and Trimble Juno ST (Table 3). Technical specifications for each unit are listed in Appendix 5. As can be seen in Appendix 5, the Garmin and DeLorme units have external antennas, whereas the Trimble unit's antenna is embedded in the ring of the unit.

GPS Hardware Details

Model	Chip set	High Sensitivity	Channels	Published autonomous accuracy 95%	Published WAAS accuracy 95%
Garmin	SiRFstar III	x	12	< 10 m	< 5 m
Trimble	SiRFstar III	x	12	not published	2-5 m
DeLorme	STMicroelectronics SiGE RF front-end	x	12	< 15 m	< 3 m

Table 3: GPS Hardware Details

Data collection was first tried by capturing the GPS NMEA string, which is the raw GPS data unaltered by the unit for presentation. It was found that there was no significant difference between the NMEA string and the data presented by the different receiver types in track or point files. Thus to simplify logistics of data collection, the NMEA string was not gathered for data analysis.

Data were collected at each of the ten control points for thirty minute intervals, on two unique visits, resulting in a sample of twenty data collection sets for each type of unit. Control point Lee was inaccessible for the second visit using the DeLorme and Trimble units, and control point NGS Reeves2 was substituted for this instance. Data were collected during the months of January to April, 2009. Details on data collection dates and times are available in Appendix 2. The units were set to record a fix every second, thus resulting in 1800 data points collected at each control point.

For the purpose of comparing autonomous GPS with WAAS corrected GPS, two identical receivers were mounted side by side on a tripod which was placed directly over the control point (Figure 17). The height from the control point to the antenna was measured, and accounted for when calculating observed height. Receivers were positioned such that the antennas of each unit were as close over the control point as possible, within approximately fifteen cm. One receiver was operating in autonomous mode, the other in WAAS mode.

Figure 17: Data Collection Field Setup

The last objective is to determine if WAAS correction benefits are the same for data collected at different times of the day. In order to meet this objective data were collected at a control point for a continuous twenty seven hours. This test was conducted using only the pair of Garmin 60cx units. The track record was set to record one point every ten seconds. This test was conducted on two separate occasions, first on January 12, 2009 and second on February 2, 2009. The same control point was used on each occasion.

3.1.3 Data Processing

After data were collected, data points from the GPS receivers were downloaded to a computer. For the Garmin units this was done using either DNR Garmin software or MxGPS. Data from the DeLorme units were transferred to the computer using DeLorme's TopoUSA 7.0 software. Data were transferred from the Trimble units using Trimble's GPS Pathfinder Office software. For all unit types, data were set to transfer in geographic coordinate system WGS 1984 to avoid any automatic datum transformations. WGS is the native reference system used in GPS.

A shapefile was created for each set of points and loaded in ESRI ArcMap 9.2. Thus for one control point there would be a shapefile for the control point location, the WAAS track for thirty minutes, and the autonomous track for thirty minutes. Point data were projected from the GPS default of WGS 84 to NAD 83 New Mexico State Plane Central Zone using the ESRI transformation NAD_1983_to_WGS_1984_5. Details on this seven parameter geographic datum transformation are as follows: code: 1515, method: Coordinate Frame, dX: -0.991, dY: 1.9072, dZ: 0.5129, rX: -0.02579, rY: -0.00965, rZ: -0.01166, ds: 0.

Only GPS data was projected, since control point coordinates were already in New Mexico State Plane Central Zone on the respective data sheets. An example of the resulting shapefiles is shown in Figure 18.

. To ensure equal comparison of elevation information, it was noted whether a given unit recorded orthometric or ellipsoid height and this information was used accordingly when computing vertical error. The Garmin and DeLorme units recorded orthometric height. In investigating the cause behind large discrepancies in height, it was found that the Garmin and DeLorme units use a very coarse geoid model, resulting in unreliable elevation estimates. The geoid model is what is used to convert from ellipsoid height, which is inherent to the GPS signal, to orthometric height, which the Garmin and DeLorme units report. The Timble units could be set to record either orthometric or ellipsoid height. The units were set to record ellipsoid height to avoid possible problems caused by the geoid model.

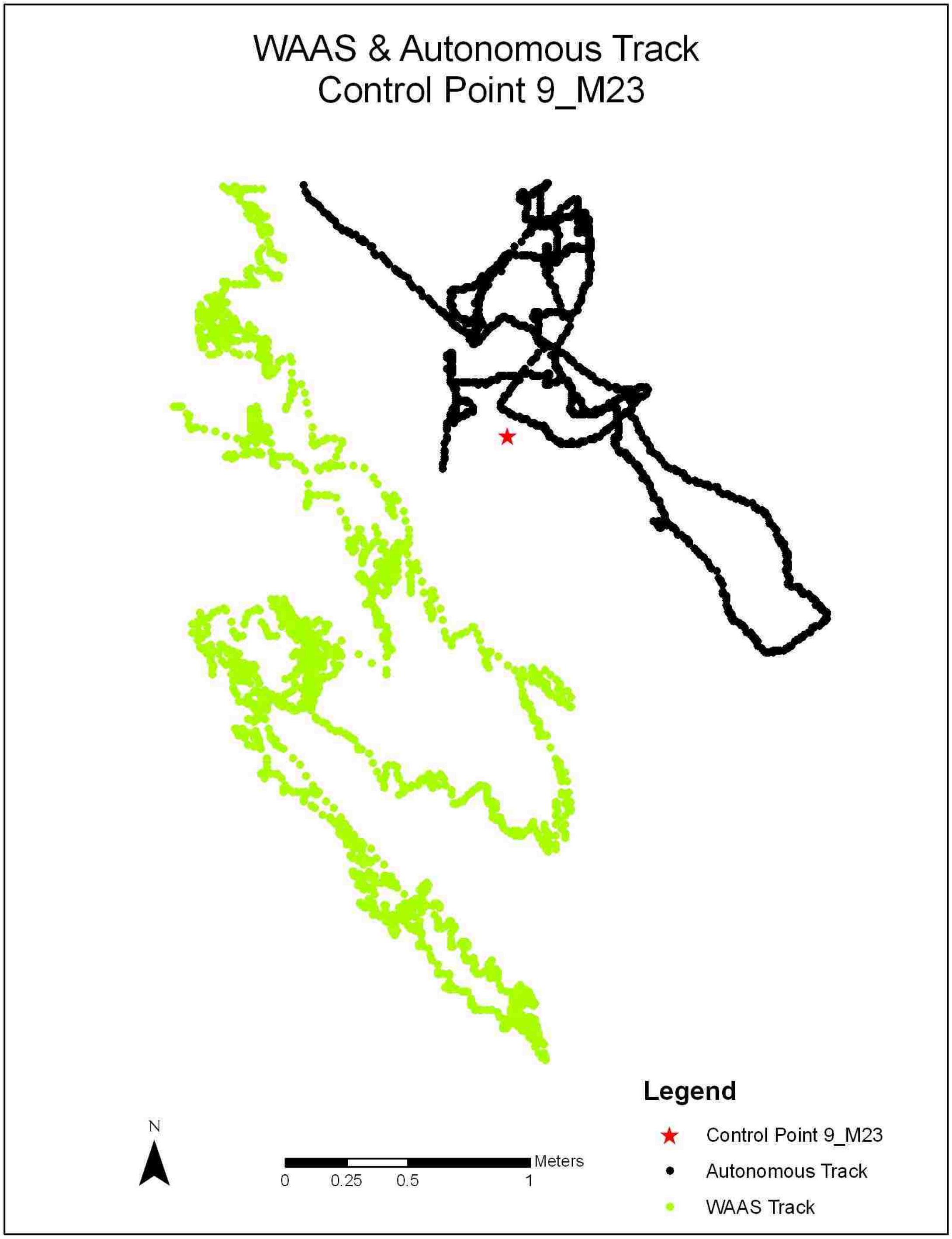


Figure 18: WAAS and Autonomous Track Data

From the coordinates of each point in the thirty minute span, the median, 68th percentile, 95th percentile, and RMSE is determined for horizontal (x,y) and vertical (z) dimensions. Additionally, the error in averaged x, y, xy and z is computed. The average x, y and z error for each position fix is determined using the mean formula: $\bar{x} = \frac{1}{n}\sum x_i$. The 68th and 95th percentile determines the k-th percentile of values in a range of *n* values. The formula used for RMSE is shown below, where e_i is the error in each unique GPS position fix.

$$RMSE = \sqrt{\frac{e_1^2 + e_2^2 + \ldots + e_n^2}{n}}$$

These metrics were recorded for every data collection session and cataloged. The metrics for all control points are available in Appendix 3.

3.2 Testing

3.2.1 Testing Average Position for Bias

For each set of data collected, the average location error in x, y and z was tested against zero in a one sample hypothesis test to determine if bias is present. For instance, after being tested for normality, the twenty values of average x error in autonomous GPS using Garmin units were tested against zero, then the twenty values of average x error in WAAS were tested against zero. The test was repeated for each metric, and for each unit type. It is expected that these metrics will be near zero. A test of bias shows if the metric is statistically different from zero. Testing is conducted at the .05 α level. The null and alternative hypothesis are as follows.

H_0: $\mu_1 = 0$

H_A: $\mu_1 \neq 0$

For example:

H_O: The mean of the average x error for WAAS GPS data is equal to zero.

H_A: The mean of the average x error for WAAS GPS data is not equal to zero.

3.2.2 Test of Means

For each set of data collected at a given control point, the median, 68th percentile, 95th percentile, and RMSE was calculated and compared to determine if WAAS and autonomous GPS data are statistically different. To test these data, a two sample t-test, a hypothesis test of means was conducted. A table for each metric being tested was created showing the error for WAAS and autonomous for each dataset. This sample was then tested for normality using an Anderson-Darling test in the statistical software package, Minitab. Assuming the data were normal, a two sample t test is conducted to test the following hypothesis at the .05 α level:

H_0: $\mu_1 = \mu_2$

H_A: $\mu_1 \neq \mu_2$

For example:

H_O: The population mean of the horizontal RMSE for WAAS GPS data and the population mean of the horizontal RMSE for autonomous GPS data are equal.

H_A: The population mean of the horizontal RMSE for WAAS GPS data and the population mean of the horizontal RMSE for autonomous GPS data are not equal.

3.2.3 Error Variability in Different Receivers

The second objective is to determine variability in WAAS correction between different receivers. All units were tested under similar conditions and the data were processed in the same manner. Thus, this objective is fulfilled by comparing the results of the hypothesis tests for each type of unit. A non-parametric Mann-Whitney hypothesis test was conducted testing the autonomous median values of each unit type against each other.

3.2.4 Error Variability versus Time of Data Collection

Data were collected for a period of twenty seven hours to determine if WAAS correction varied with time of day. Charts were created in Excel showing the rolling three hour x and y average error value for WAAS and autonomous. Charts provide a clear visual representation of how the positional error changes over time.

3.2.5 Statistical Power Analysis

Further data processing was completed using statistical power analysis following the method presented by Murphy, Myors and Wolach (2009) in their book *Statistical Power Analysis, a Simple and General Model for Traditional and Modern Hypothesis Tests*. Statistical power analysis was completed using the *One Stop F Calculator* which accompanies the author's book.

4. Results and Discussion

4.1 Horizontal and Vertical Positional Accuracy

Scatter plot diagrams of each individual data collection session suggest that there is no statistically significant difference between the WAAS population and the autonomous population when using the Garmin or Trimble units in ideal conditions (Figure 19). This suggestion is not supported when assessing data collection sessions using the DeLorme units (Figure 20). It is further noted that wandering in the position fixes collected over a thirty minute time span as expected is not seen in the DeLorme data. Rather, the DeLorme scatter plots present data that is often in a straight line. The data points also appear to follow an obvious grid. These two factors suggest that the DeLorme units could be averaging and truncating positional information. While the Garmin and Trimble data also appears to be grided, the grid pattern is only evident at a large scale. This suggests that the Garmin and Trimble data are also truncated, but not to the extent that the DeLorme data are. Scatter plots for all tests are shown in Appendix 4.

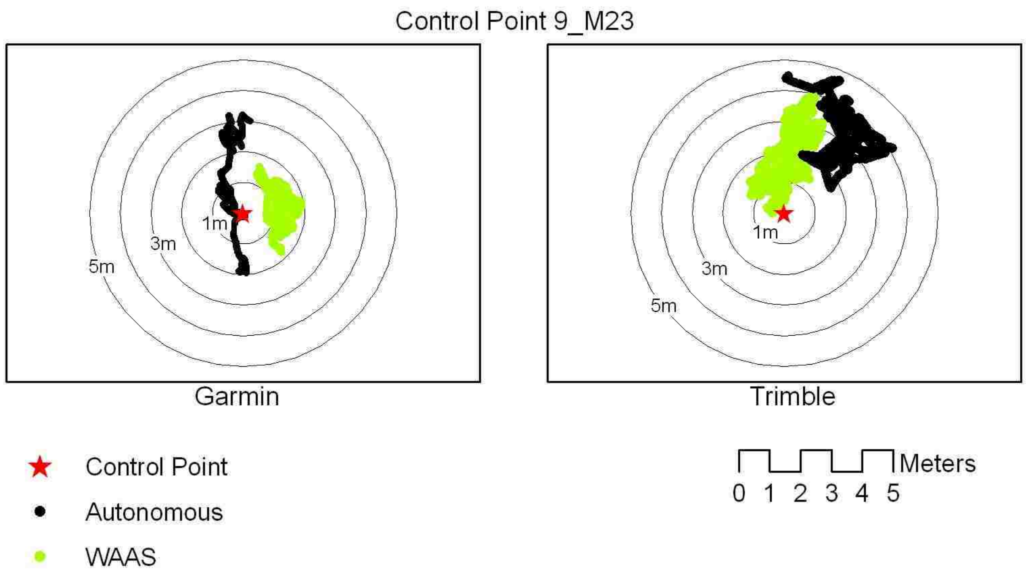


Figure 19: Control Point Scatter Plot Example – Garmin and Trimble

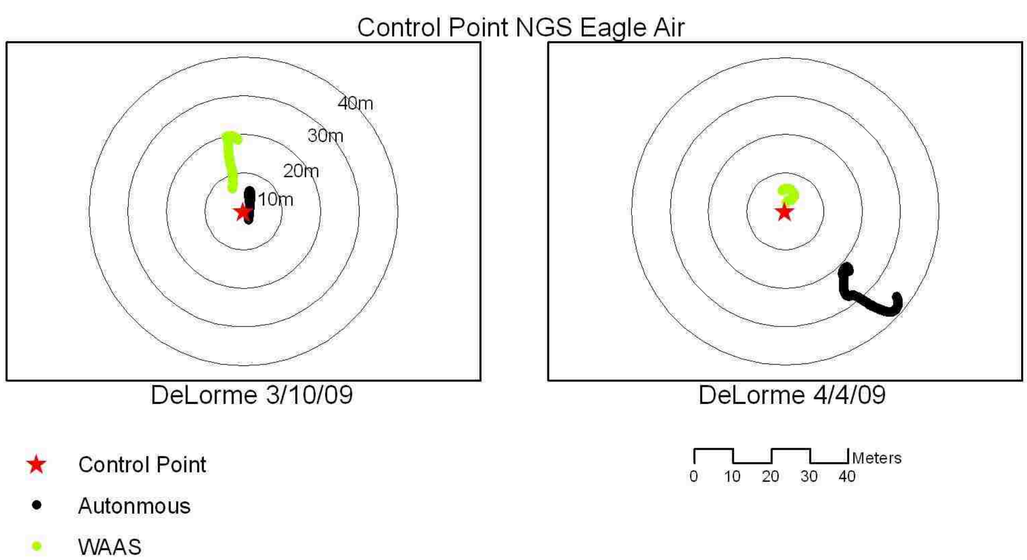


Figure 20: Control Point Scatter Plot Example - DeLorme

Average x, y, and z metrics were first tested against zero in a one sample t-test. It is expected that the error of these metrics will be near zero. These data are represented in Figure 21, which shows box plots of the average x, y and z metrics for each unit type.

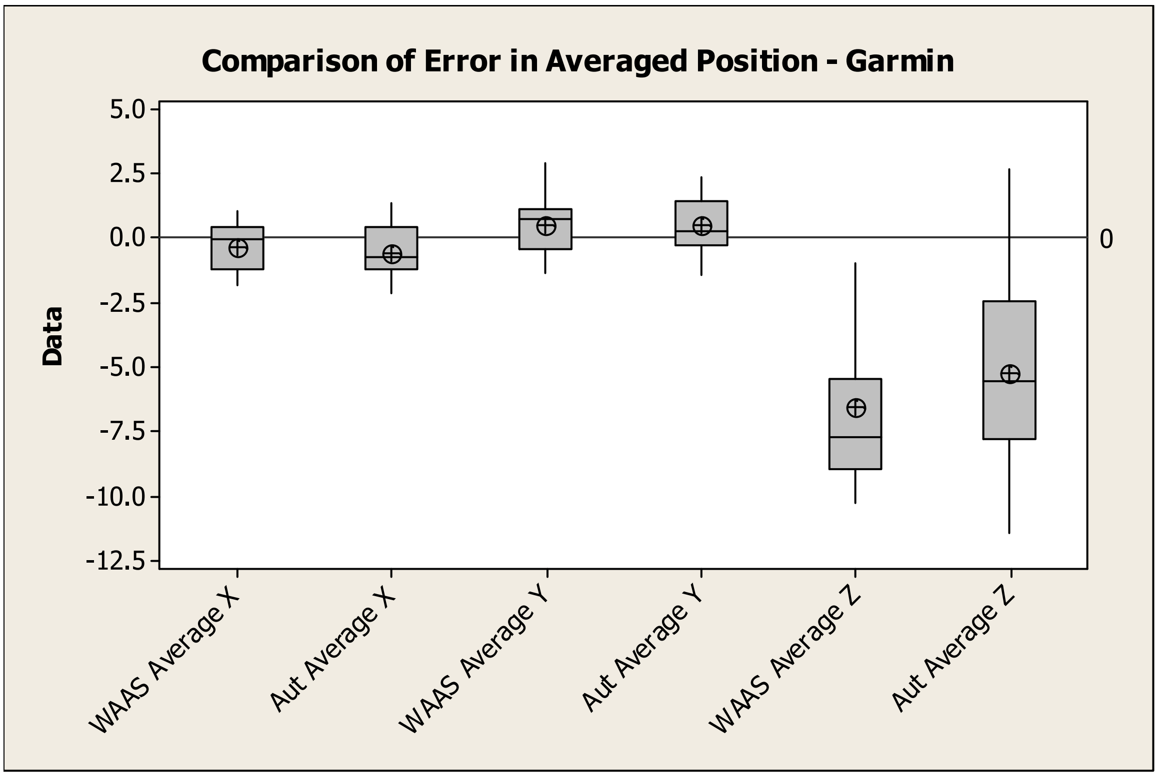
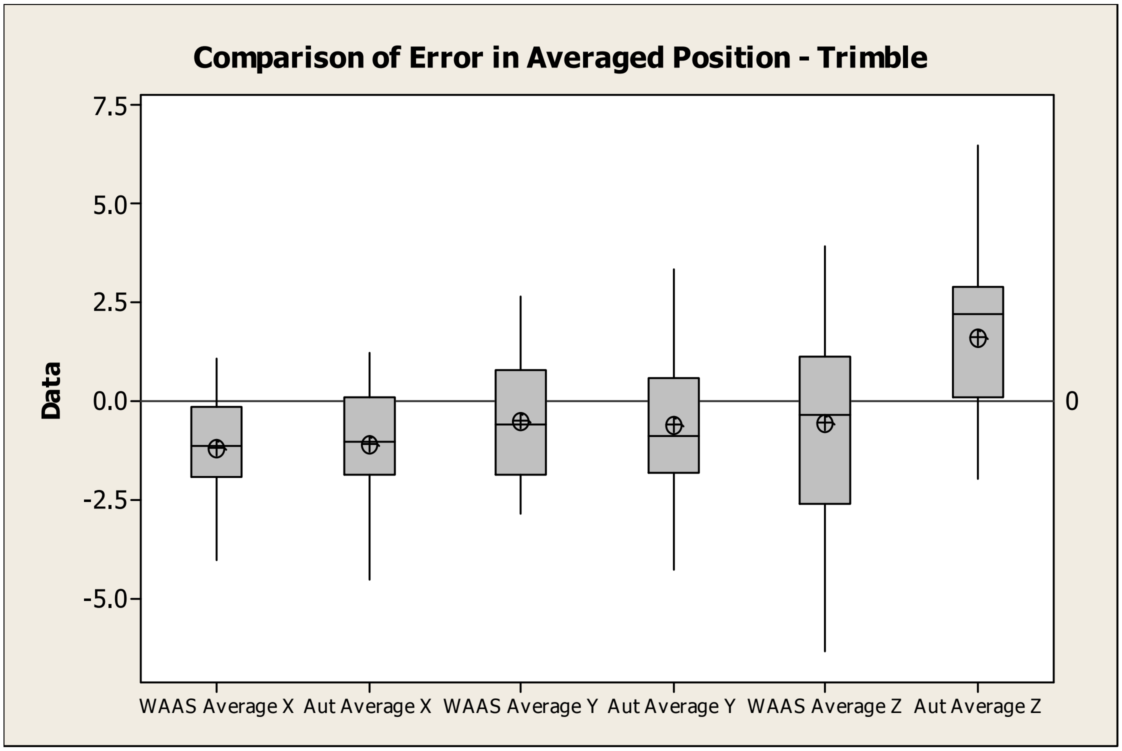


Figure 21: Comparison of Error in Averaged Position



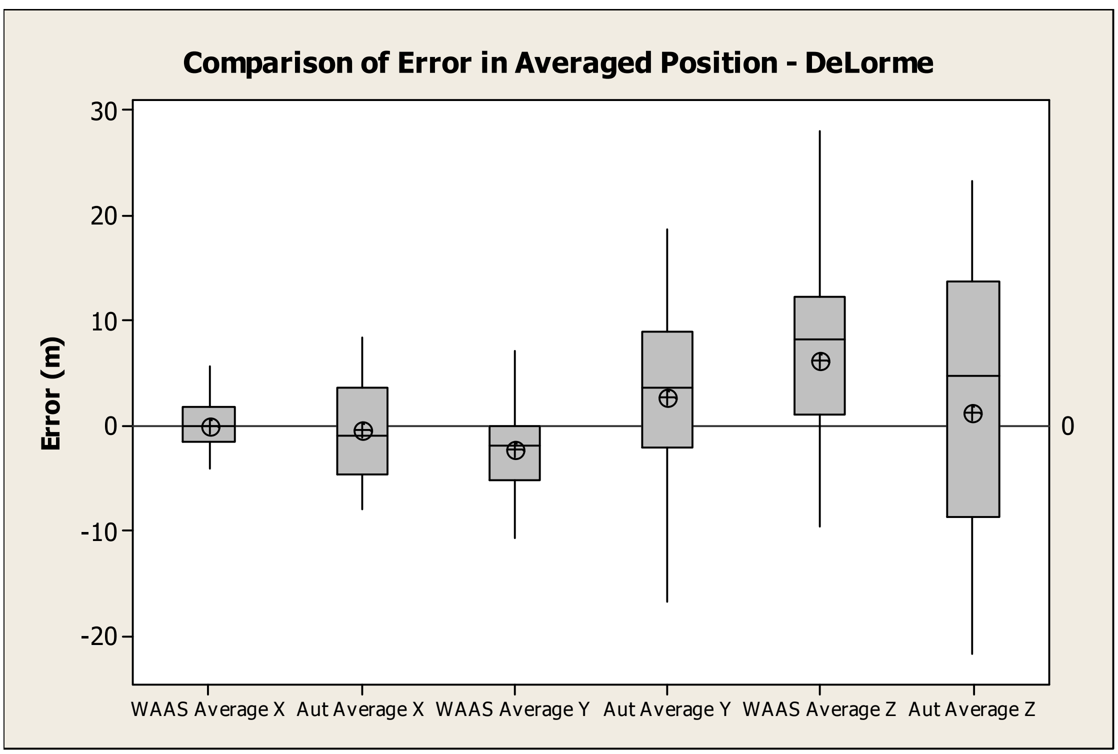


Figure 21: Comparison of Error in Averaged Position

The diagrams above are supported by the results of the one sample hypothesis test against zero. A p-value greater than .05 suggests that the mean of the given average metric is not statistically different than zero; conversely a p-value less than .05 suggests that the given metric is statistically different than zero (Table 4).

One Sample t-test Against Zero

	Garmin	Trimble	DeLorme
		p-value	
WAAS Average X	0.096	0.000	0.922
Aut Average X	0.016	0.009	0.767
WAAS Average Y	0.087	0.169	0.030
Autonomous Average Y	0.073	0.252	0.183
WAAS Average Z	0.000	0.466	0.022
Aut Average Z	0.000	0.003	0.764

Sample size n=20

A p-value >.05 suggests that the given metric is not statistically different from zero

Table 4: One Sample t-test Results

For metrics that are statistically different than zero - Garmin autonomous x, Garmin z both WAAS and autonomous, Trimble x both WAAS and autonomous, and Trimble autonomous z, it can be seen that the range of error is close to zero for x and y metrics. A striking difference can be seen in the Garmin units regarding average z error. Whether with WAAS or without, the estimate of height was considerably different from zero. This is due to the coarse geoid model used in the Garmin units.

Of note in the Trimble units is the evidence that while the y average error is not statistically different than zero, the x average values are, for both WAAS and autonomous. In evaluating average z error, autonomous elevation error estimates are closer to zero which would be expected, whereas WAAS elevation estimates are not near zero. This opposes the idea that WAAS improves positional accuracy.

Of note in the DeLorme units is the wide range of error in positional accuracy. Average x and y error in the Trimble and Garmin units is typically five meters or less, whereas the DeLorme units are closer to ten meters or less. Large error variability in average z error was shown in the DeLorme units for both autonomous and WAAS.

After the test for bias was completed, the test of means between all WAAS and autonomous metrics was completed. Using the resulting metrics from data processing, hypothesis tests were conducted for each metric, for each different unit. Absolute values of x, y and z average positional error were used because directional error was not being tested. The results of this testing show that based on the collected sample, there is no statistically significant difference in horizontal or vertical metrics between the autonomous GPS population and the WAAS corrected GPS population when using the Garmin or Trimble units (Table 5). This result rejects the common belief and published manufacturer specifications that WAAS positional estimates are better than autonomous positional estimates.

Hypothesis Test Results

	Garmin	Trimble	DeLorme
	p-value		
Horizontal Median	0.505	0.262	0.021
Horizontal 68th	0.375	0.500	0.013
Horizontal 95th	0.569	0.470	0.007
Horizontal RMSE	0.499	0.372	0.011
Average XY	0.811	0.245	0.016
Average X	0.302	0.705	0.028
Average Y	0.645	0.201	0.034
Average Z	0.293	0.819	0.261

Sample size n=20
A p-value > .05 suggests there is no statistically significant difference between the two populations

Table 5: Hypothesis Test Results

When using the DeLorme units there is a statistically significant difference between WAAS and autonomous locations when looking at horizontal metrics (Figure 22). Thus, this result supports the common belief and published manufacturer specifications that a WAAS positional estimate is better than an autonomous positional estimate. However a statistically significant difference was not found in the average vertical position.

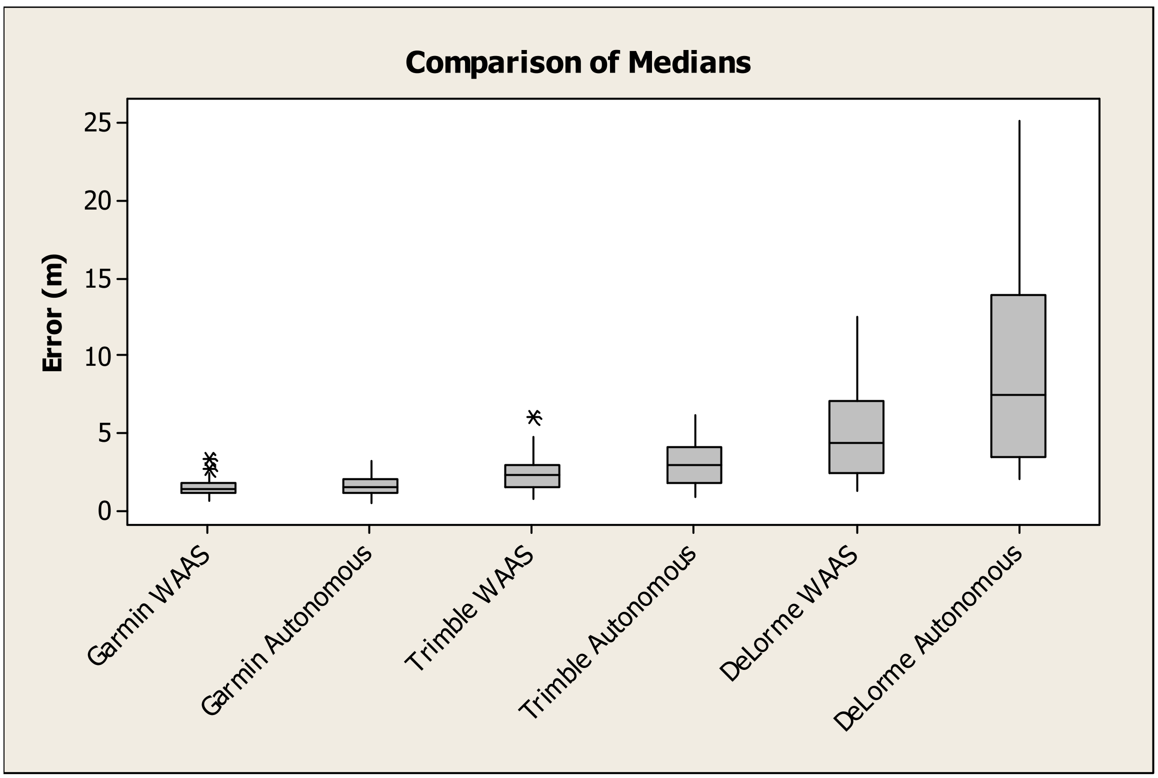


Figure 22: Comparison of Median Value

A lower-tailed one-sided, two sample statistical test was completed for the DeLorme metrics which showed a statistically significant difference between the WAAS population and the autonomous population. Resulting p-values suggest that for all horizontal metrics using the DeLorme units, the average positional error is less when using WAAS than autonomous. As shown previously, there is no statistically significant difference in the average z error between WAAS and autonomous. This result could be tied to the unreliable height reported by the DeLorme units which use a very coarse geoid model. P-values are presented in Table 6.

DeLorme One Sided Hypothesis Tests

	p-value
Horizontal Median	0.01
Horizontal 68th	0.007
Horizontal 95th	0.004
Horizontal RMSE	0.005
Average XY	0.008
Average X	0.014
Average Y	0.017
Average Z	0.13

Sample size n=20

A p-value <.05 suggests that the WAAS metric is significantly less than the autonomous metric.

Table 6: DeLorme One Sided Hypothesis Test Result

Diagrams of WAAS median versus autonomous median and WAAS RMSE versus autonomous RMSE were created to gain a better understanding of the effect of WAAS (Figure 23). The diagrams show that no relationship is evident between WAAS and autonomous data. If there were no affect at all from WAAS, all points in the graphs in Figure 23 would lie along a straight line. As can be seen, many points do not lie close to a straight line. The data presented in the diagrams highlight the cases where WAAS has a large effect. If WAAS were making a large impact, it would be expected to see many points of the case where the autonomous error was very high, and the WAAS error was very low. While there are a few cases of this scenario, there are also a few cases of the exact opposite, points where the WAAS error is very high and the autonomous error is very low. It can be seen in the graphs representing the DeLorme units, there are more cases where the autonomous error was very high, and the WAAS error was very low.

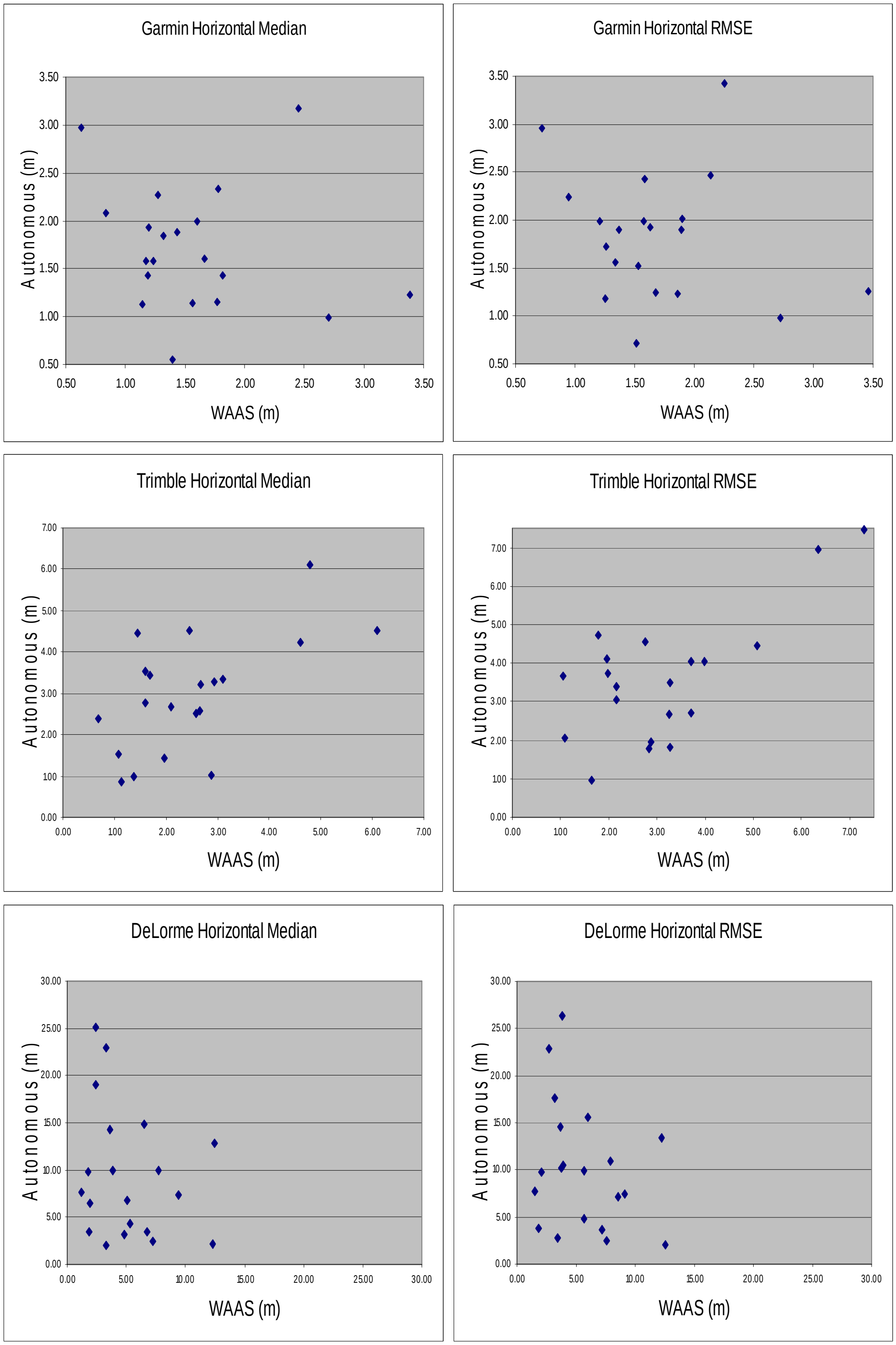


Figure 23: Median and RMSE Scatter Plots

Hypothesis tests were conducted testing the autonomous median values of each unit type against each other to determine if the autonomous position fixes of the units were the same or different. The hypothesis test results showed significant difference between all receiver types. The test between Garmin and Trimble was significant at $p = 0.0031$, indicating that the Garmin unit was more accurate than the Trimble unit; the test between Garmin and DeLorme was significant at $p = 0.000$, indicating that the Garmin unit was more accurate than the DeLorme unit; and the test between Trimble and DeLorme was significant at $p = 0.0006$, indicating that the Trimble unit was more accurate than the DeLorme unit. Thus, Garmin was the most accurate unit tested. In assessing the average median of each unit type, Garmin was the most accurate with an autonomous average median from the twenty tests of 1.7m. The Trimble unit was the next most accurate with an autonomous average median of 3.0m, followed by the DeLorme unit with an autonomous average median of 9.4m.

4.2 Statistical Power

Statistical power analysis was used to get a representation of the probability that the study has lead to the correct conclusion. In this study, an effect size of zero was tested and the resulting power level is a representation of the ability to be able to reject the null hypothesis which states that based on the sample collected, there is no statistically significant difference between accuracy metrics of the WAAS population and accuracy metrics of the autonomous population.

Statistical power analysis is largely based on the t-statistic resulting from the completed t-tests. If there were no difference in the two populations for the given metric, the t-statistic would be near zero. Therefore, if the observed difference in the two populations is statistically zero, and the t-statistic is near zero, a very large sample size would be needed to prove the null hypothesis with a high level of power.

For example, the test between WAAS RMSE and autonomous RMSE using the Garmin units results in a t-statistic of -0.68. From this, the F-statistic of .462 is computed, $t^2(df_{err})=F(1, df_{err})$. The resulting computed power is .098 meaning the power to reject the null hypothesis is very low. This supports the conclusions of the preceding t-tests, where the null is rarely rejected. If for example the sample size was increased to 100 and the t-statistic remained the same, the resulting power is still only .1, with the sample size increased to 1,000 the resulting power is only .101. Conversely, if a sample size of only 10 was used, and the t-statistic remained the same the resulting power would be .09, nearly the same as using a sample of size twenty. This shows that with a t-statistic, and thus an F-statistic, so near zero, an unrealistically large sample size would be needed to achieve a high power level. Alternatively, if the t-statistic were not near zero, the power of the study would quickly increase. For example if the resulting f-statistic were 1, with the same sample size of forty, the power increases to .155. However, since it is expected that the t-statistic will be near zero, it is reasonable to see a resulting statistical power of .098.

In cases where the t-statistic is not near zero, such as is the case with the DeLorme units, the power of the study is much greater. Because there is a statistically significant difference between the WAAS population and the Garmin population using the DeLorme units, the effect size is greater, which results in a greater power level. The resulting statistical power for each t-test completed in this study is shown below, along with the corresponding F ratio (Table 7).

Power Levels for Completed Study

		F ratio	Power Level
Garmin 60cx	Horizontal Median	.449	.097
	Horizontal 68th	.810	.135
	Horizontal 95th	.325	.084
	Horizontal RMSE	.462	.098
	Average XY	.058	.056
	Average Z	1.14	.171
Trimble Juno ST	Horizontal Median	1.30	.188
	Horizontal 68th	.462	.098
	Horizontal 95th	.533	.106
	Horizontal RMSE	.810	.135
	Average XY	1.39	.198
	Average Z	.053	.055
DeLorme Earthmate PN20	Horizontal Median	6.05	.699
	Horizontal 68th	7.02	.739
	Horizontal 95th	8.58	.828
	Horizontal RMSE	7.45	.766
	Average XY	6.60	.710
	Average Z	1.32	.033
Sample size n=20			

Table 7: Statistical Power Levels for Completed Study

In order to determine what benefit was gained from using a sample of size twenty versus a sample of size ten, power levels for RMSE were computed for each unit based on the group of first ten samples, and the group of second ten samples (Table 8). The resulting power level for the Garmin and Trimble units, for both sets of ten samples as well as the overall set of twenty samples, are similar and the change is not significant. This is a reflection of the fact that the t-statistic in all cases remains near zero. While there is significant change in the f-ratio between the first ten samples and the second ten samples using the Trimble unit, the resulting power levels have the same interpretation – there is very low ability to reject the null hypothesis.

The resulting power level for the DeLorme units does increase significantly, .367 and .415 for the respective sets of ten, up to .766 for the over all sample of twenty. This is a reflection of the fact that there was more statistical difference between the WAAS and autonomous population as more samples were collected.

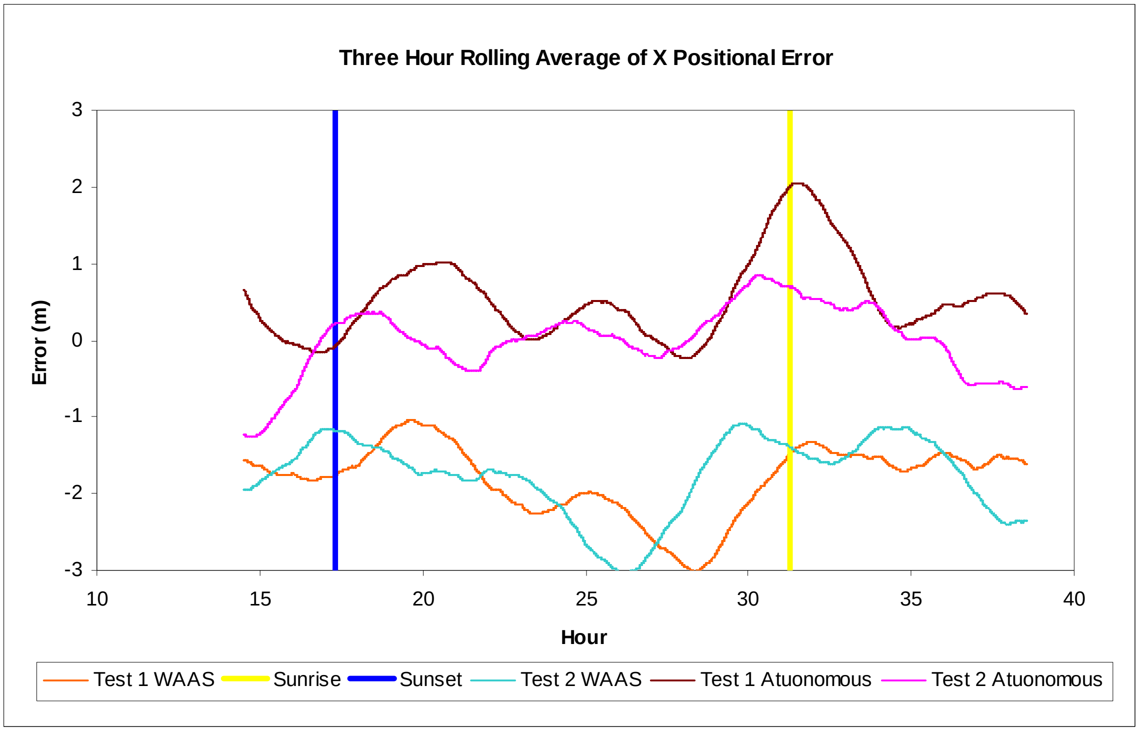
Resulting Power Level Based on RMSE for Groups of Ten Samples

	F Ratio	Power Level
First Ten Samples		
Garmin	0.084	0.057
Trimble	0.006	0.050
DeLorme	3.500	0.367
Second Ten Samples		
Garmin	0.384	0.083
Trimble	3.090	0.330
DeLorme	4.040	0.415

Table 8: Statistical Power Level for Sample Groups of Ten

4.3 Error Variability versus Time of Data Collection

Data were collected on two separate occasions over a twenty seven hour time span, at the same control point to asses how WAAS correction varied with time of day. The first set of data, referred to as “Test 1” in the following charts, was collected January 12, 2009. The second set of data, referred to as “Test 2” in the following charts, was collected February 2, 2009 (Figure 24). The most striking results can be seen in the rolling three hour average of x positional error. There is evident difference between the WAAS and autonomous error in the x direction. However, the WAAS augmentation actually appears to increase positional error. Additionally, the largest amount of correction applied by WAAS occurs around the same time of day in each of the tests. This largest amount of correction is also in the direction of increasing positional error. The WAAS signal does not appear to significantly change the average y positional error. This pattern seems to repeat itself as the results from the two separate tests are very similar. However, data would need to be collected over a longer time span, for example a month, to make any true conclusions about error variability versus the time of data collection.



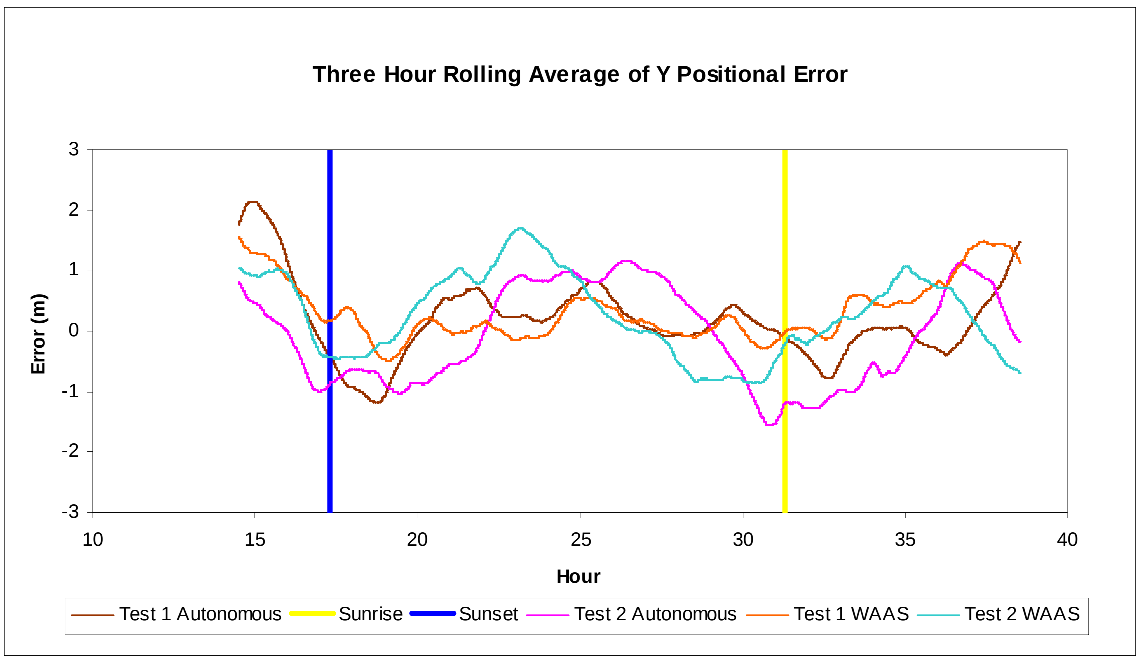


Figure 24: Three Hour Rolling Average of Positional Error

5. Conclusions

This study set out to determine if there was a statistically significant difference between WAAS and autonomous position fixes, if the difference varied with unit type, and how WAAS correction varied with time of day.

Data were first evaluated to determine if bias was present. This study found that in general, there is no bias in horizontal positional error using the Garmin units. There is some slight bias in the average x positional error for the Trimble units. The Garmin units provided biased estimated heights that were consistently higher than the actual surveyed height. The DeLorme units only showed bias in the average z WAAS positional error, and the average y WAAS positional error. However, the bias was not very large.

In the absence of bias, the primary test of means to determine if there is a statistically significant difference between WAAS and autonomous was completed. Based on the sample collected, this study found that while the range of error appears to be lower for WAAS position fixes than autonomous position fixes, there is no statistically significant difference between the horizontal and vertical positional accuracy of WAAS corrected GPS and autonomous GPS when using the Garmin receiver or the Trimble receiver. This conclusion supports the conclusion reach by Bolstad et al. in that they found no statistical difference between post-processed differential, WAAS differential and uncorrected fixes when using GIS grade Trimble units (Bolstad et al. 2005). This study provides evidence that this conclusion also holds true when using some consumer grade units. In testing the DeLorme receiver, this study found there is a statistically significant difference between the horizontal positional accuracy of WAAS corrected

GPS and the horizontal positional accuracy of autonomous GPS. The difference is such that WAAS provides a more accurate horizontal position estimate compared to autonomous GPS. However, no statistically significant difference was found in the vertical positional accuracy between WAAS and autonomous when using the DeLorme receivers.

A statistical test was also completed to determine if the autonomous accuracy was statistically the same amongst receiver types. The hypothesis test results showed significant difference between all receiver types. The Garmin units were the most accurate (1.7m) followed next by Trimble (3.0m) and last by DeLorme (9.4m). This conclusion supports the results of the study conducted by Wing, Eklund and Kellog (2005). In that study it was reported that in comparing six different units, there was a wide range of error, but the majority of the units had average error less than 4m. However, the Wing study based error on only twenty five position fixes recorded over approximately a minute and a half. This study recorded 1800 position fixes over a thirty minute time span. Averaging the error from a larger number of position fixes reduces the noise in the data and thus makes the results more reliable.

Statistical power analysis was used to get a representation of the probability that the study has lead to the correct conclusion. It was concluded that the sample size selected for this study was appropriate based on the completed power analysis. There is a very low chance of rejecting the null hypothesis that there is no statistically significant difference between the WAAS and autonomous position fixes when using the Garmin or Trimble units. For the DeLorme units where the null hypothesis is rejected, and there is a statistically significant difference between the two populations, power levels for all horizontal metrics are very near the desirable level of .80 suggesting that there is a high probability this study has reached the correct conclusion.

Finally, data collected over a twenty seven hour time span were analyzed to determine how WAAS varies with time of day. Based on data collected on two occasions over a twenty seven hour time span, some diurnal pattern can be seen in the WAAS autonomous error. Based on these results it is clear that the WAAS correction message is altering the estimated position of a point compared to autonomous position estimate, but only in the x direction. However, the WAAS augmentation actually appears to increase the positional error. More data would need to be gathered to make a statistically supported conclusion about the diurnal patterns and variances in WAAS corrected GPS versus autonomous GPS.

5.1 Limitations and Recommendations

The results of this study lead to several other unanswered questions. First, only three different types of receivers were used in this study. The Garmin and Trimble units which have the same chipset showed that WAAS was not statistically different from autonomous GPS. It should be investigated if this same conclusion is reached when testing with other brands of units that also use the same chipset. The DeLorme unit has a different chipset than the Garmin and Trimble units. A different brand of receiver which runs on the same chipset as DeLorme should be tested to see if the same conclusion is reached. Overall, more unit types should be tested, both ones with the same type of chipset as one already tested, as well as other chipsets.

Data should be gathered in varying locations within the WAAS coverage area. Testing at a wide variety of geographically separated locations would provide information on how positional accuracy varies for both the autonomous and WAAS population. Of particular interest would be to test at more northern latitudes where the WAAS satellites are lower on the horizon. Also of interest would be to test near the edge of the WAAS coverage area and compare these results with data collected well within the coverage area.

This study collected data near a WAAS reference station. The effect of distance from a WAAS reference station should be evaluated using a unit that does show a statistically significant difference between the WAAS population and the autonomous population.

More data should be gathered over an extended time period to enable a detailed evaluation of diurnal patterns in positional accuracy. A suggested design is to have mounted GPS units in a semi-permanent location (e.g. the roof of a building). Data could be streamed directly into a computer for collection, thus enabling data collection to occur twenty four hours a day for a month or more.

Another component that should be evaluated for accuracy both autonomously and with WAAS is velocity. This would require a method for determining velocity at a higher magnitude of accuracy than is reported by the hand held units being tested. Additionally, all units used in testing would need the capability to record and report a velocity reading.

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7. Appendices

Appendix 1

Control point details

*AGRS refers to Albuquerque Geodetic Reference System control points. NGS refers to National Geodetic Survey control points. Points Sinclair and Lee do not have a NGS PID as these control points were established by the researcher for the purposes of this study and were not registered with the NGS. However, a survey grade GPS borrowed from the NGS was used to establish these control points with Opus. The GPS receiver used was an Ashtec Z-Xtreme with a Geodetic IV, Rev. A. antenna. All heights and NAD 83 NM State Plane Central coordinates are listed in meters.

Name	**AGRS 77_120_2**
Horizontal	Order 1, Class 1
Vertical	Order 2, Class 1
NAD 83 NM State Plane Central	
Easting (meters)	475781.935
Northing (meters)	459045.055
Elevation (NAVD 88) (orthometric) (meters)	1762.389
Ellipsoid height (meters)	1741.94

Name	**AGRS 9_M23**
Horizontal	Order 1, Class 1
Vertical	Order 2, Class 1
NAD 83 NM State Plane Central	
Easting (meters)	478894.755
Northing (meters)	448612.481
Elevation (NAVD 88) (orthometric) (meters)	1826.261
Ellipsoid height (meters)	1805.983

Name	**AGRS 1_G22**
Horizontal	Order 1, Class 1
Vertical	Order 2, Class 1
NAD 83 NM State Plane Central	
Easting (meters)	476609.035
Northing (meters)	457290.854
Elevation (NAVD 88) (orthometric) (meters)	1753.555
Ellipsoid height (meters)	1733.191

Name	**NGS Eagleair**
NGS PID	FO1669
GPS Site	
NAD 83 NM State Plane Central	
Easting (meters)	451135.415
Northing (meters)	459803.612
Elevation (NAVD 88) (orthometric) (meters)	1767.990
Ellipsoid height (meters)	1746.586

Name	**NGS Reeves2**
NGS PID	FO1739
GPS Site	
NAD 83 NM State Plane Central	
Easting (meters)	467658.170
Northing (meters)	462251.378
Elevation (NAVD 88) (orthometric) (meters)	1547.167
Ellipsoid height (meters)	1526.075

Name	**AGRS 9_J15**
Horizontal	Order 1, Class 1
Vertical	Order 2, Class 1
NAD 83 NM State Plane Central	
Easting (meters)	465390.885
Northing (meters)	453854.755
Elevation (NAVD 88) (orthometric) (meters)	1552.363
Ellipsoid height (meters)	1531.059

Name	**AGRS 20_E10**
Horizontal	Order 1, Class 1
Vertical	Order 2, Class 1
NAD 83 NM State Plane Central	
Easting (meters)	456934.844
Northing (meters)	460025.466
Elevation (NAVD 88) (orthometric) (meters)	1619.893
Ellipsoid height (meters)	1598.426

Name	**Lee**
Opus GPS Site	
NAD 83 NM State Plane Central	
Easting (meters)	469215.571
Northing (meters)	456101.965
Elevation (NAVD 88) (orthometric) (meters)	1591.299
Ellipsoid height (meters)	1570.286

Name	**AGRS 14_J12**
Horizontal	Order 1, Class 1
Vertical	Order 2, Class 1
NAD 83 NM State Plane Central	
Easting (meters)	460847.862
Northing (meters)	453710.112
Elevation (NAVD 88) (orthometric) (meters)	1513.473
Ellipsoid height (meters)	1492.008

Name	**AGRS CC_EG_11_12_11N_3E**
Horizontal	Order 1, Class 1
Vertical	Order 2, Class 1
NAD 83 NM State Plane Central	
Easting (meters)	469366.192
Northing (meters)	465907.245
Elevation (NAVD 88) (orthometric) (meters)	1565.317
Ellipsoid height (meters)	1544.337

Name	**Sinclair**
Opus GPS Site	
UTM Zone 13N NAD83 (meters)	
Easting (meters)	494921.764
Northing (meters)	456761.170
Elevation (NAVD 88) (orthometric) (meters)	2097.412
Ellipsoid height (meters)	2077.931

Appendix 2

Data Collection Log

Garmin Data Collection

Control Point	Date	Time (MST)
AGRS 77_120_2	1/16/2009	11:00 - 11:30 a.m.
AGRS 9_M23	1/17/2009	11:00 - 11:30 a.m.
AGRS 1_G22	1/18/2009	11:00 - 11:30 a.m.
NGS Eagle Air	1/19/2009	11:00 - 11:30 a.m.
NGS Reeves2	1/20/2009	11:00 - 11:30 a.m.
AGRS 9_J15	1/21/2009	11:00 - 11:30 a.m.
AGRS 20_E_10	1/22/2009	11:00 - 11:30 a.m.
NGS Lee	1/23/2009	11:00 - 11:30 a.m.
AGRS 14_J12	1/24/2009	11:00 - 11:30 a.m.
AGRS 77_120_2	1/27/2009	11:00 - 11:30 a.m.
AGRS 9_J15	1/28/2009	11:00 - 11:30 a.m.
AGRS CC_EG_11_12_11N_3E	1/29/2009	11:00 - 11:30 a.m.
NGS Reeves2	1/30/2009	11:00 - 11:30 a.m.
AGRS 9_M23	1/31/2009	11:00 - 11:30 a.m.
NGS Lee	2/1/2009	10:54 - 11:26 a.m.
AGRS 1_G22	2/19/2009	10:31 - 11:01 a.m.
AGRS 14_J12	2/19/2009	11:44 - 12:14 a.m.
NGS Eagle Air	2/20/2009	10:47 - 11:17 a.m.
AGRS 20_E_10	2/20/2009	12:04 - 12:34 p.m.
AGRS CC_EG_11_12_11N_3E	2/20/2009	1:41 - 2:11 p.m.

Trimble Data Collection

Control Point	Date	Time (MST)
AGRS 77_120_2	3/2/2009	1:07 - 1:37 p.m.
AGRS 9_J15	3/4/2009	12:44 - 1:14 p.m.
NGS Eagle Air	3/10/2009	11:00 - 11:30 a.m.
AGRS 20_E_10	3/10/2009	1:23 - 1:53 p.m.
AGRS 14_J12	3/10/2009	2:43 - 3:13 p.m.
NGS Lee	3/14/2009	11:19 - 11:49 a.m.
AGRS CC_EG_11_12_11N_3E	3/17/2009	10:36 - 11:06 a.m.
NGS Reeves 2	3/17/2009	11:35 – 12:05 a.m.
AGRS 9_M23	3/18/2009	12:39 - 1:09 p.m.
AGRS 1_G22	3/18/2009	1:48 - 2:18 p.m.
NGS Eagle Air	4/4/2009	11:05 - 11:35 a.m.
AGRS 20_E_10	4/5/2009	11:30 - 12:00 a.m.
AGRS CC_EG_11_12_11N_3E	4/5/2009	1:26 - 1:56 p.m.
AGRS 9_J15	4/6/2009	10:12 - 10:42 a.m.
AGRS 14_J12	4/6/2009	12:16 - 12:46 p.m.
NGS Reeves 2	4/6/2009	2:16 - 2:46 p.m.
AGRS 9_M23	4/7/2009	10:26 - 10:56 a.m.
AGRS 77_120_2	4/7/2009	1:43 - 2:13 p.m.
NGS Reeves 2	4/10/2009	11:01 - 11:31 a.m.
AGRS 1_G22	4/10/2009	1:53 - 2:23 p.m.

DeLorme Data Collection

Control Point	Date	Time (MST)
AGRS 9_M23	2/23/2009	1:55 - 2:25 p.m.
AGRS 77_120_2	2/24/2009	2:40 - 3:10 p.m.
AGRS 1_G22	2/25/2009	11:40 - 12:10 a.m.
AGRS CC_EG_11_12_11N_3E	2/26/2009	1:32 - 2:02 p.m.
NGS Reeves2	2/27/2009	11:43 - 12:13 a.m.
NGS Lee	2/28/2009	11:00 - 11:30 a.m.
AGRS 9_J15	3/4/2009	1:18 - 1:48 p.m.
NGS Eagle Air	3/10/2009	11:36 - 12:06 a.m.
AGRS 20_E_10	3/10/2009	12:50 - 1:20 p.m.
AGRS 14_J12	3/10/2009	3:15 - 3:45 p.m.
NGS Eagle Air	4/4/2009	11:40 - 12:10 a.m.
AGRS 20_E_10	4/5/2009	12:04 - 12:34 p.m.
AGRS CC_EG_11_12_11N_3E	4/5/2009	1:58 - 2:28 p.m.
AGRS 9_J15	4/6/2009	10:46 - 11:16 a.m.
AGRS 14_J12	4/6/2009	12:49 - 1:19 p.m.
NGS Reeves2	4/6/2009	2:48 - 3:18 p.m.
AGRS 9_M23	4/7/2009	10:59 - 11:29 a.m.
AGRS 1_G22	4/7/2009	12:53 - 1:23 p.m.
AGRS 77_120_2	4/7/2009	2:15 - 2:45 p.m.
NGS Reeves2	4/10/2009	11:33 - 12:03 a.m.

Appendix 3

Control Point Metrics

Garmin Data – Horizontal (meters)				
Test	WAAS Horizontal Median	Aut. Horizontal Median	WAAS Horizontal 95th	Aut. Horizontal 95th
1	1.20	1.93	1.62	2.99
2	1.32	1.84	1.73	2.97
3	1.78	2.33	3.41	4.28
4	1.14	1.13	2.29	1.71
5	1.19	1.43	2.64	2.14
6	1.43	1.88	2.47	2.44
7	1.24	1.58	2.05	1.93
8	1.60	2.00	2.46	2.87
9	1.17	1.58	1.85	2.77
10	3.38	1.23	4.21	1.57
11	2.70	0.99	3.52	1.23
12	1.40	0.55	2.36	1.30
13	1.66	1.60	2.93	2.90
14	1.77	1.15	2.56	1.61
15	1.56	1.14	2.41	2.02
16	0.83	2.09	1.35	3.24
17	0.63	2.98	1.13	3.94
18	1.82	1.43	2.92	3.34
19	2.45	3.18	3.09	4.78
20	1.27	2.27	2.92	3.07
	WAAS Horizontal 68th	Aut. Horizontal 68th	WAAS Horizontal RMSE	Aut. Horizontal RMSE
1	1.30	2.40	1.21	1.99
2	1.48	2.32	1.37	1.90
3	2.54	2.79	2.14	2.47
4	1.32	1.22	1.26	1.18
5	1.50	1.62	1.53	1.52
6	1.85	2.03	1.63	1.93
7	1.42	1.70	1.34	1.55
8	1.79	2.17	1.57	1.98
9	1.33	1.89	1.26	1.72
10	3.58	1.42	3.46	1.26
11	2.95	1.08	2.72	0.98
12	1.56	0.76	1.52	0.72
13	2.07	2.07	1.89	1.90
14	1.98	1.32	1.86	1.23
15	1.69	1.36	1.68	1.24
16	1.12	2.38	0.95	2.24
17	0.81	3.12	0.72	2.96
18	2.11	2.42	1.90	2.01
19	2.64	4.04	2.25	3.43
20	1.55	2.61	1.59	2.43

Garmin Data – Vertical (meters)				
	WAAS Vertical Median	Aut. Vertical Median	WAAS Vertical 68th	Aut. Vertical 68th
1	7.31	8.27	7.79	9.23
2	6.90	9.78	7.38	11.71
3	7.98	7.50	9.42	9.42
4	10.15	5.83	10.63	7.27
5	5.77	4.33	7.22	5.77
6	7.31	8.76	7.79	10.20
7	7.09	3.72	8.05	3.72
8	8.29	1.56	9.25	2.04
9	8.59	6.67	10.03	7.63
10	8.80	11.20	8.80	12.16
11	8.79	4.46	9.75	5.42
12	8.85	5.00	9.33	5.48
13	5.53	6.97	6.49	7.45
14	1.05	1.36	1.53	1.36
15	7.72	8.20	8.20	8.68
16	9.68	9.20	10.64	9.68
17	1.83	1.35	2.79	1.53
18	7.81	5.41	9.25	6.37
19	1.85	2.00	2.81	2.96
20	1.13	2.72	1.61	3.20
	WAAS Vertical 95th	Aut. Vertical 95th	WAAS Vertical RMSE	Aut. Vertical RMSE
1	8.75	10.68	7.38	8.11
2	8.82	13.15	7.12	10.47
3	12.79	12.31	8.70	8.42
4	13.52	9.19	10.22	6.18
5	8.18	9.62	5.85	5.55
6	9.72	16.45	7.45	10.28
7	9.49	7.09	7.09	4.12
8	10.21	3.00	8.35	1.69
9	13.88	9.55	9.61	6.67
10	10.72	13.12	8.64	11.52
11	11.19	6.87	9.24	4.96
12	11.25	7.40	8.60	5.47
13	9.38	7.94	6.04	6.72
14	2.01	2.32	1.30	1.38
15	10.13	10.61	8.02	8.07
16	11.60	10.64	9.89	9.02
17	4.24	2.97	2.45	1.59
18	11.18	8.29	7.97	5.74
19	4.25	4.40	2.33	2.51
20	2.57	3.20	1.36	2.73

Garmin Data – Averages (meters)				
	WAAS Average X	Aut. Average X	WAAS Average Y	Aut. Average Y
1	0.75	-0.60	0.51	-1.46
2	-1.24	0.33	-0.10	-1.21
3	-1.37	0.57	1.26	-0.26
4	-0.07	-0.89	-0.64	0.11
5	0.40	-0.91	1.06	0.04
6	0.33	1.30	-1.21	0.16
7	0.33	-1.26	0.86	-0.30
8	0.47	0.51	1.12	1.44
9	-0.88	-0.60	-0.12	1.40
10	-1.82	0.80	2.90	0.90
11	-1.27	-0.40	2.22	-0.61
12	0.60	-0.27	1.03	-0.29
13	-0.09	0.43	1.62	1.71
14	-1.62	-0.93	-0.48	-0.52
15	-1.01	-0.91	-1.23	0.40
16	0.26	-1.59	-0.32	1.46
17	-0.45	-2.19	0.24	1.84
18	1.01	-1.12	0.90	1.23
19	-1.70	-2.17	1.12	2.37
20	0.18	-1.88	-1.39	0.62
	WAAS Average XY	Aut. Average XY	WAAS Average Z	Aut. Average Z
1	0.91	1.58	-7.33	-7.74
2	1.24	1.26	-6.98	-10.29
3	1.87	0.62	-8.32	-7.87
4	0.65	0.90	-9.94	-5.72
5	1.14	0.91	-5.40	-4.87
6	1.26	1.31	-10.29	-9.81
7	0.92	1.30	-6.74	-3.48
8	1.21	1.52	-8.17	-0.77
9	0.88	1.53	-9.34	-6.34
10	3.43	1.20	-8.59	-11.46
11	2.55	0.73	-9.11	-4.68
12	1.19	0.39	-8.40	-5.37
13	1.63	1.76	-5.75	-6.60
14	1.69	1.07	-1.07	1.17
15	1.59	0.99	-7.91	-7.75
16	0.41	2.15	-9.84	-8.96
17	0.52	2.86	-1.95	0.86
18	1.35	1.66	-7.57	-5.48
19	2.03	3.22	1.38	-2.13
20	1.40	1.99	-0.99	2.66

Trimble Data – Horizontal (meters)				
	WAAS Horizontal Median	Aut. Horizontal Median	WAAS Horizontal 68th	Aut. Horizontal 68th
1	1.37	0.98	1.99	1.58
2	1.60	3.54	2.50	3.76
3	2.10	2.69	2.41	3.14
4	1.08	1.53	1.24	2.20
5	6.08	4.53	7.29	5.93
6	2.59	2.51	3.32	2.67
7	1.14	0.85	1.79	1.00
8	4.79	6.12	8.69	7.54
9	2.66	3.21	3.64	3.76
10	1.96	1.43	2.49	1.87
11	1.60	2.76	2.02	3.93
12	2.66	2.56	3.24	2.80
13	2.94	3.27	3.76	4.03
14	2.45	4.53	2.81	4.98
15	1.68	3.44	1.91	3.97
16	3.10	3.35	3.63	3.88
17	1.46	4.46	2.00	5.19
18	4.61	4.23	5.38	5.00
19	0.69	2.39	1.01	3.40
20	2.88	1.01	3.48	1.62
	WAAS Horizontal 95th	Aut. Horizontal 95th	WAAS Horizontal RMSE	Aut. Horizontal RMSE
1	6.48	4.74	2.88	1.95
2	3.62	4.10	2.17	3.38
3	3.13	4.44	2.16	3.04
4	1.52	3.93	1.10	2.07
5	9.75	13.60	6.36	6.95
6	5.87	4.55	3.25	2.66
7	2.83	1.55	1.64	0.96
8	12.72	13.34	7.30	7.47
9	5.56	5.27	3.28	3.49
10	5.38	3.02	2.83	1.78
11	3.21	7.66	1.96	4.10
12	7.88	3.71	3.71	2.72
13	7.25	6.94	3.99	4.03
14	4.66	6.81	2.75	4.57
15	3.51	6.30	1.99	3.74
16	6.56	7.53	3.71	4.06
17	2.93	6.71	1.79	4.71
18	8.69	6.82	5.08	4.44
19	2.22	7.61	1.05	3.65
20	5.04	3.71	3.28	1.81

Trimble Data – Vertical (meters)				
	WAAS Vertical Median	Aut. Vertical Median	WAAS Vertical 68th	Aut. Vertical 68th
1	4.78	2.55	6.53	3.10
2	1.08	2.37	1.60	2.87
3	2.53	6.40	3.09	8.15
4	0.81	0.95	1.19	1.32
5	8.93	1.45	12.71	2.05
6	1.98	1.76	2.83	2.47
7	0.90	3.29	1.67	3.85
8	4.85	3.87	9.91	6.09
9	2.08	5.25	2.76	7.41
10	1.21	1.71	1.93	2.41
11	2.20	3.59	3.29	4.27
12	4.91	1.98	6.26	3.11
13	2.96	3.77	4.28	4.84
14	1.72	2.88	2.22	3.51
15	2.57	2.78	3.13	3.29
16	2.75	1.68	3.61	2.30
17	1.98	2.83	2.62	3.55
18	2.06	1.39	3.37	2.29
19	2.53	2.86	3.02	3.71
20	3.31	3.09	3.88	4.40
	WAAS Vertical 95th	Aut. Vertical 95th	WAAS Vertical RMSE	Aut. Vertical RMSE
1	13.18	4.62	6.88	2.70
2	3.70	4.03	1.78	2.66
3	6.09	12.45	3.21	7.38
4	2.34	2.10	1.24	1.19
5	20.19	4.63	11.77	2.21
6	5.90	7.74	3.01	3.25
7	2.84	4.71	1.46	3.21
8	18.09	18.18	9.50	8.34
9	5.78	13.00	2.90	6.84
10	3.74	3.86	1.92	2.18
11	4.52	7.84	2.74	4.38
12	24.09	7.47	9.22	3.17
13	6.93	10.11	3.87	5.11
14	7.65	6.71	2.97	3.64
15	6.02	7.25	3.22	3.67
16	5.23	4.73	3.11	2.30
17	5.94	4.53	2.76	3.08
18	13.49	4.57	5.31	2.25
19	4.72	5.80	2.68	3.41
20	9.90	8.06	4.63	4.30

Trimble Data – Averages (meters)				
	WAAS Average X	Aut. Average X	WAAS Average Y	Aut. Average Y
1	1.08	0.12	0.94	-0.02
2	-0.18	-1.93	-1.84	-2.63
3	-1.35	-1.48	-0.08	-0.08
4	-0.76	-1.22	0.35	-0.92
5	-3.64	-4.55	1.67	3.33
6	-1.29	1.24	-2.33	-1.67
7	-0.17	-0.63	-0.96	-0.12
8	-2.30	-5.06	1.68	0.59
9	-0.37	1.20	-2.57	-1.04
10	-0.99	-0.11	-2.05	-1.13
11	-1.45	-1.13	0.05	2.86
12	-2.60	-1.76	-0.21	-1.90
13	-1.85	-0.06	-1.06	2.68
14	-1.67	-1.32	-1.64	-4.14
15	-0.61	-2.42	1.15	0.52
16	-1.98	-1.96	2.66	2.49
17	0.05	0.65	-1.14	-4.30
18	-4.05	-1.00	-1.91	-3.96
19	-0.11	0.72	0.06	-1.61
20	-0.06	-0.99	-2.88	-0.89
	WAAS Average XY	Aut. Average XY	WAAS Average Z	Aut. Average Z
1	1.43	0.12	-5.49	2.11
2	1.84	3.26	-0.27	2.41
3	1.35	1.48	1.22	6.48
4	0.84	1.53	0.54	-0.02
5	4.01	5.64	7.23	-0.92
6	2.66	2.08	-2.34	-1.70
7	0.97	0.65	-0.46	2.93
8	2.85	5.09	0.73	3.99
9	2.60	1.59	-0.09	2.49
10	2.27	1.13	0.32	1.34
11	1.45	3.08	2.36	2.31
12	2.61	2.59	-6.37	2.37
13	2.13	2.68	-2.95	-1.94
14	2.34	4.35	-1.69	3.27
15	1.30	2.47	-2.73	1.44
16	3.31	3.17	-2.30	1.13
17	1.14	4.35	-1.67	2.68
18	4.47	4.09	-3.20	0.50
19	0.12	1.76	2.25	-1.98
20	2.88	1.33	3.94	3.61

DeLorme Data – Horizontal (meters)				
	WAAS Horizontal Median	Aut. Horizontal Median	WAAS Horizontal 68th	Aut. Horizontal 68th
1	9.42	7.30	9.92	7.86
2	1.79	9.84	2.44	10.43
3	6.73	3.40	7.64	4.02
4	2.40	19.09	3.51	19.48
5	12.48	12.84	14.23	15.17
6	4.85	3.13	5.59	4.18
7	1.83	3.48	1.88	4.14
8	3.88	9.95	4.01	11.58
9	7.76	9.99	8.22	12.13
10	5.28	4.31	5.42	7.01
11	5.04	6.72	6.58	7.91
12	6.51	14.88	6.82	19.18
13	3.64	14.21	4.13	16.12
14	3.31	22.98	4.16	26.48
15	3.34	2.02	3.92	2.18
16	1.21	7.62	1.37	8.34
17	7.23	2.38	8.60	2.57
18	1.94	6.46	3.17	8.20
19	12.34	2.14	12.80	2.35
20	2.40	25.07	2.51	27.15
	WAAS Horizontal 95th	Aut. Horizontal 95th	WAAS Horizontal RMSE	Aut. Horizontal RMSE
1	10.39	8.97	9.15	7.35
2	3.32	12.54	2.06	9.79
3	8.55	5.24	7.16	3.62
4	5.36	19.81	3.23	17.60
5	16.11	17.22	12.23	13.41
6	10.70	10.23	5.64	4.82
7	2.43	4.93	1.87	3.83
8	4.17	12.39	3.88	10.44
9	8.76	15.25	7.94	10.87
10	7.12	23.25	5.66	9.84
11	17.39	9.80	8.57	7.18
12	7.06	22.49	5.99	15.58
13	4.35	17.64	3.65	14.50
14	5.78	37.88	3.85	26.36
15	4.21	5.49	3.43	2.80
16	2.62	9.55	1.49	7.78
17	11.14	2.98	7.60	2.50
18	7.78	21.57	3.73	10.27
19	13.43	2.54	12.58	2.04
20	4.16	28.91	2.76	22.88

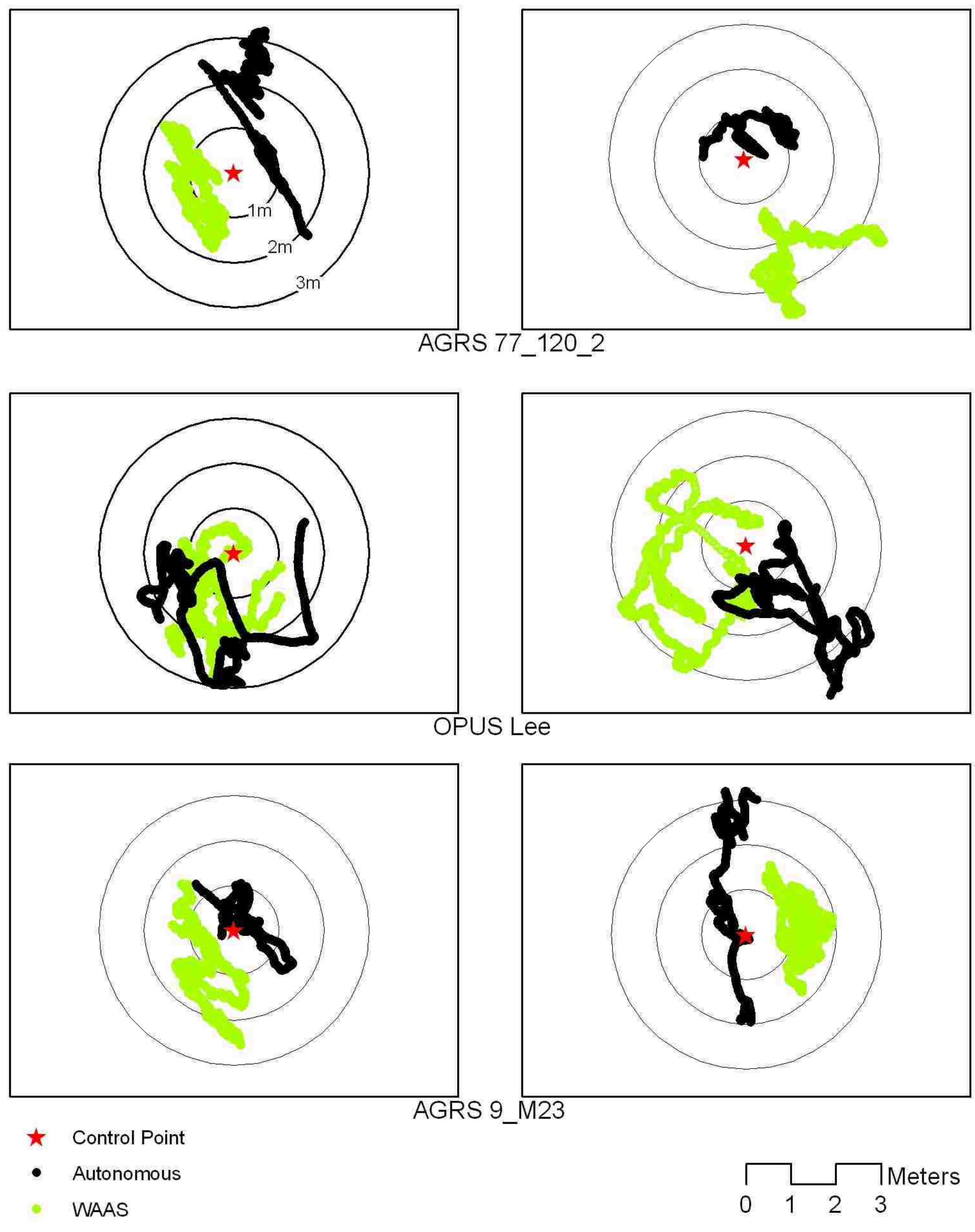
DeLorme Data – Vertical (meters)				
	WAAS Vertical Median	Aut. Vertical Median	WAAS Vertical 68th	Aut. Vertical 68th
1	12.13	23.36	12.78	23.69
2	12.74	11.02	13.04	13.90
3	2.66	3.43	2.76	3.91
4	2.41	17.04	3.84	19.29
5	14.76	14.41	17.36	17.01
6	7.06	1.79	7.27	4.05
7	8.17	14.73	8.81	15.46
8	0.63	11.07	0.86	11.42
9	2.18	22.37	2.61	24.50
10	4.98	2.17	11.05	2.47
11	0.56	21.53	0.86	23.44
12	7.69	4.68	8.35	5.01
13	5.30	8.85	8.35	10.70
14	20.41	26.05	21.36	31.80
15	12.56	6.46	15.82	7.51
16	8.97	10.08	9.77	12.08
17	28.51	12.84	30.51	13.07
18	2.64	8.22	7.90	13.37
19	29.71	11.48	33.03	14.25
20	7.99	68.70	11.24	79.57
	WAAS Vertical 95th	Aut. Vertical 95th	WAAS Vertical RMSE	Aut. Vertical RMSE
1	13.27	23.79	11.01	23.27
2	13.91	23.17	12.86	13.88
3	5.98	5.30	3.25	3.70
4	5.65	23.80	3.30	18.71
5	20.73	19.86	14.52	14.60
6	16.88	24.05	8.72	9.21
7	12.13	16.14	8.57	13.34
8	2.97	11.81	1.38	10.39
9	11.41	25.93	4.31	21.94
10	17.23	24.81	9.34	9.47
11	11.70	24.30	4.19	19.97
12	15.76	18.79	9.10	7.40
13	29.46	43.18	12.61	17.10
14	30.69	34.09	22.12	26.09
15	32.11	8.43	16.51	6.42
16	10.28	15.35	8.82	10.25
17	37.92	14.02	28.54	12.92
18	26.42	54.14	11.52	22.42
19	34.72	19.47	27.93	11.91
20	23.78	86.93	12.20	65.33

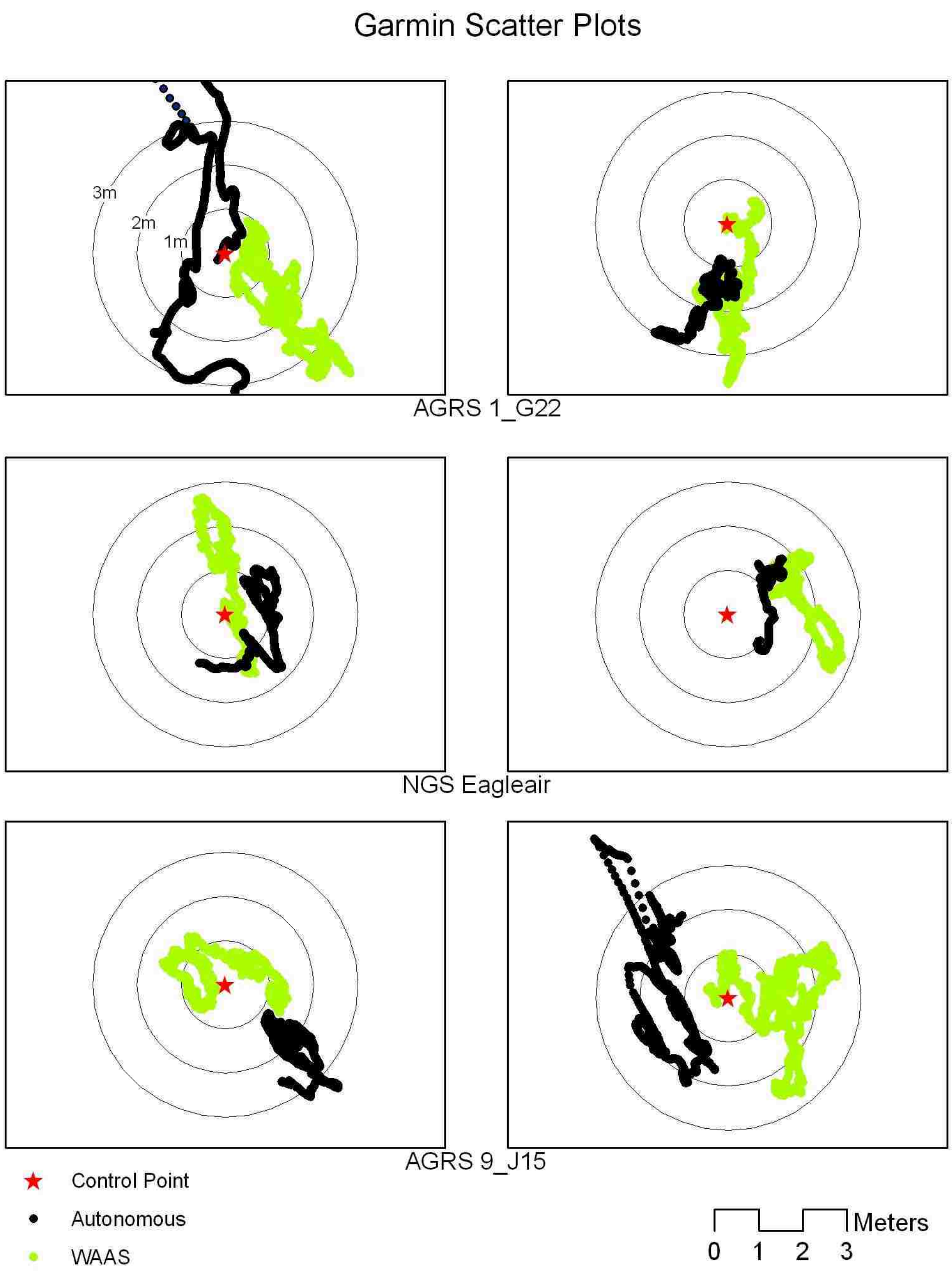
DeLorme Data – Averages (meters)				
	WAAS Average X	Aut. Average X	WAAS Average Y	Aut. Average Y
1	5.17	-1.77	-7.42	-6.62
2	-1.07	8.38	-1.18	4.76
3	-0.34	2.60	7.07	-1.99
4	-1.56	3.21	-1.15	-16.85
5	-10.40	-3.31	-5.23	12.62
6	0.96	3.74	-4.90	-1.81
7	-1.71	-1.19	0.34	-2.31
8	3.56	-5.67	-1.47	8.38
9	-0.05	4.58	-7.84	9.08
10	3.06	3.76	-4.65	5.14
11	-1.17	-4.50	6.50	5.18
12	1.04	-0.93	-5.57	11.72
13	-2.52	-7.89	-1.49	-11.66
14	-1.45	-17.78	-3.36	18.68
15	1.93	1.41	-1.14	-1.98
16	-0.24	-4.73	1.07	5.06
17	-4.07	1.89	-4.40	1.54
18	1.51	-7.20	1.58	2.40
19	5.66	-1.55	-10.68	-0.41
20	0.17	17.40	-2.36	11.88
	WAAS Average XY	Aut. Average XY	WAAS Average Z	Aut. Average Z
1	9.04	6.85	-9.53	23.26
2	1.59	9.63	12.84	-12.92
3	7.08	3.28	3.06	3.53
4	1.94	17.15	-1.84	18.52
5	11.64	13.05	13.36	13.99
6	4.99	4.15	7.91	-4.32
7	1.75	2.60	8.35	12.61
8	3.86	10.12	0.73	10.18
9	7.84	10.17	0.35	-21.70
10	5.57	6.37	6.44	-3.33
11	6.61	6.86	1.70	19.35
12	5.66	11.76	8.52	1.54
13	2.93	14.08	9.56	-3.27
14	3.66	25.79	21.79	22.29
15	2.24	2.43	14.76	5.87
16	1.10	6.93	8.72	7.51
17	5.99	2.43	28.02	12.91
18	2.19	7.59	5.88	-10.12
19	12.09	1.60	-26.31	-10.33
20	2.37	21.06	10.72	-59.64

Appendix 4

Scatter Plots

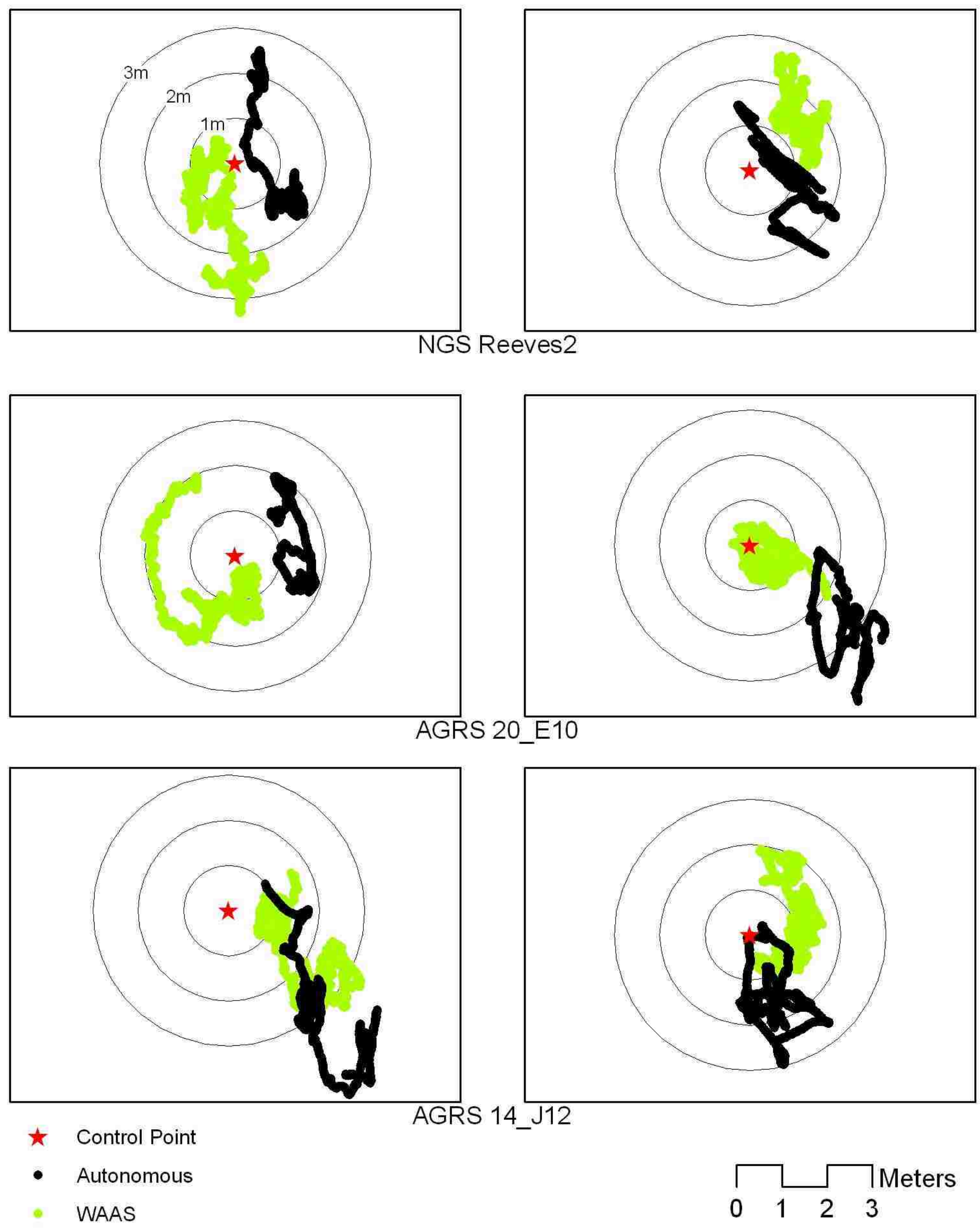
Garmin Scatter Plots



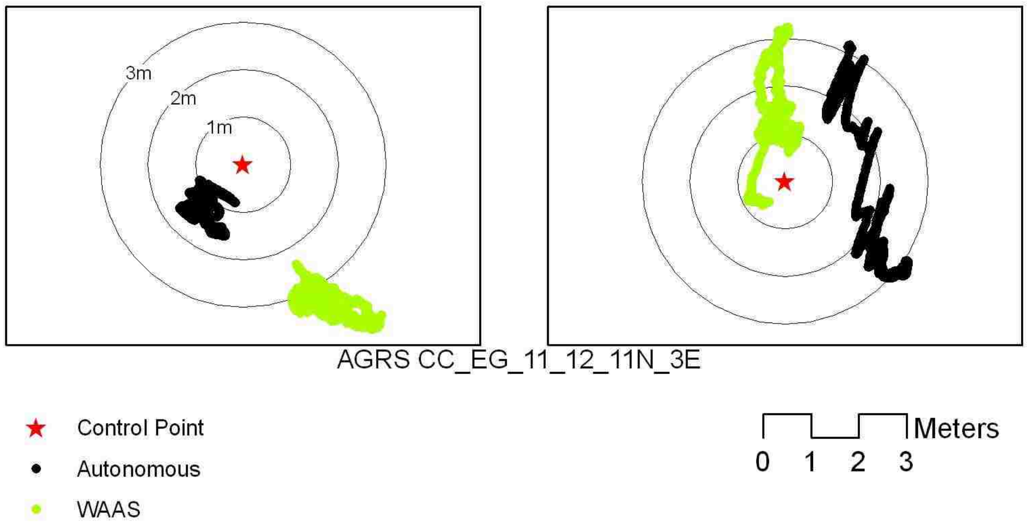


Garmin Scatter Plots
3m
2m
1m
AGRS 1_G22
NGS Eagleair
AGRS 9_J15
Control Point
Autonomous
WAAS
Meters
0 1 2 3

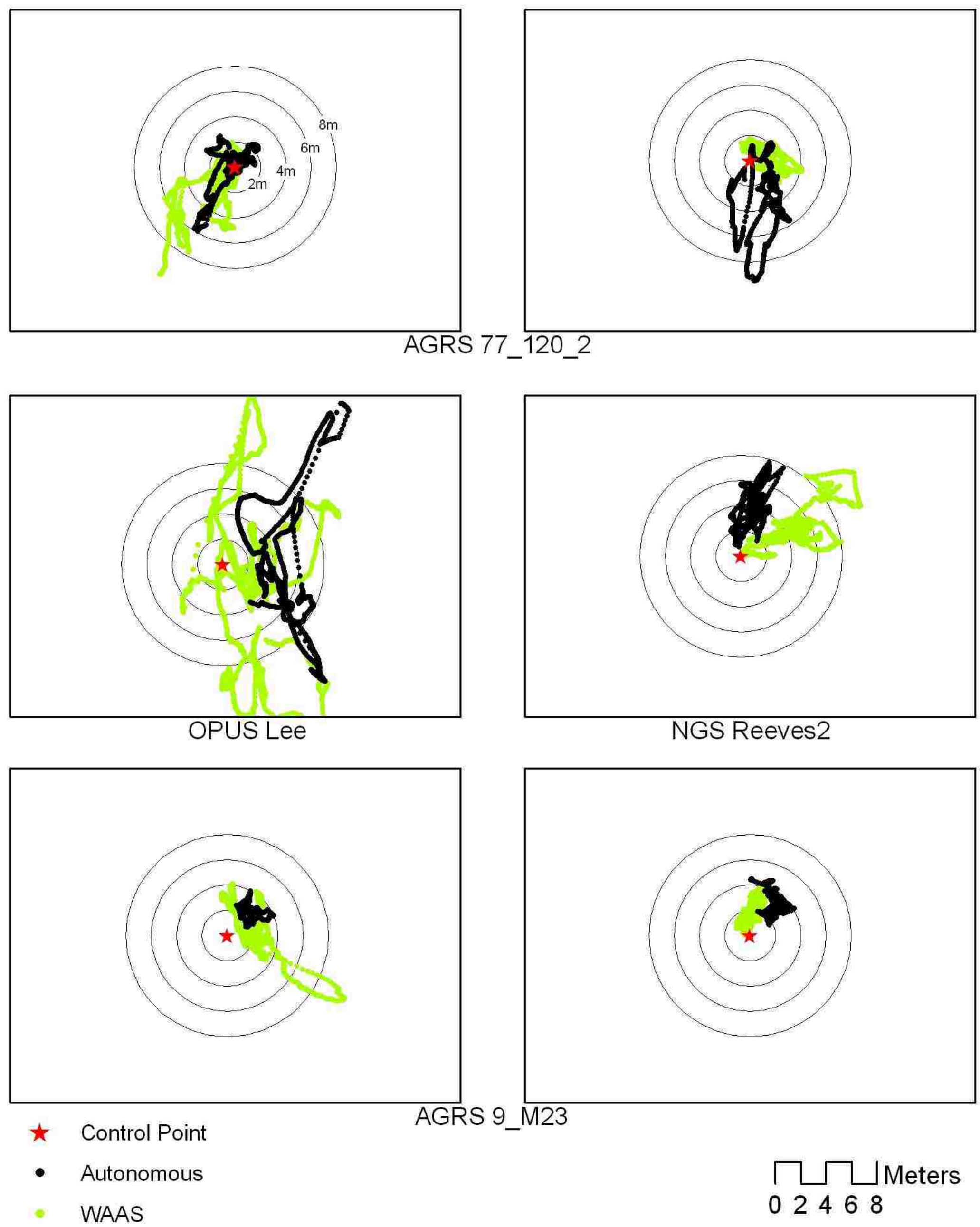
Garmin Scatter Plots



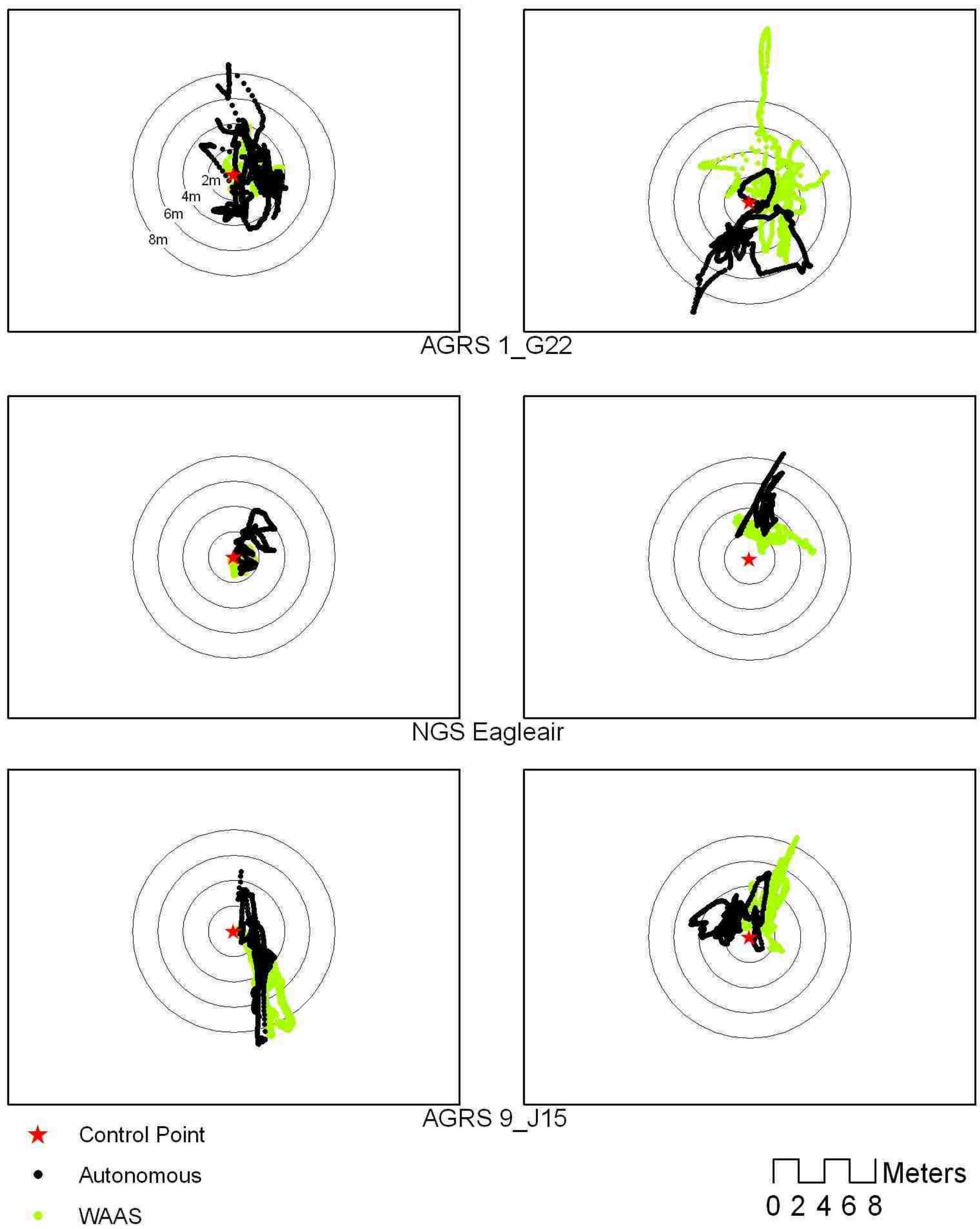
Garmin Scatter Plots

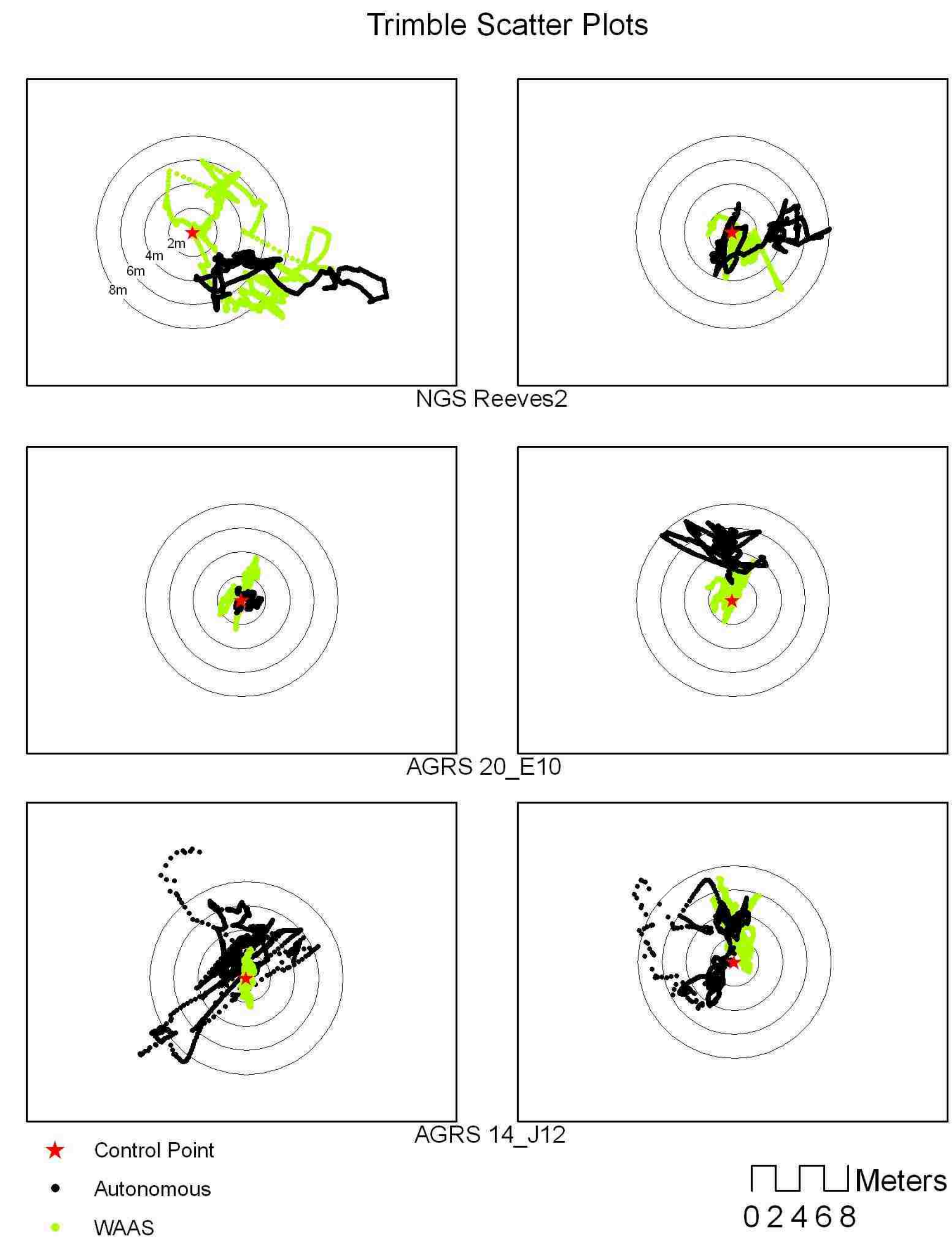


Trimble Scatter Plots

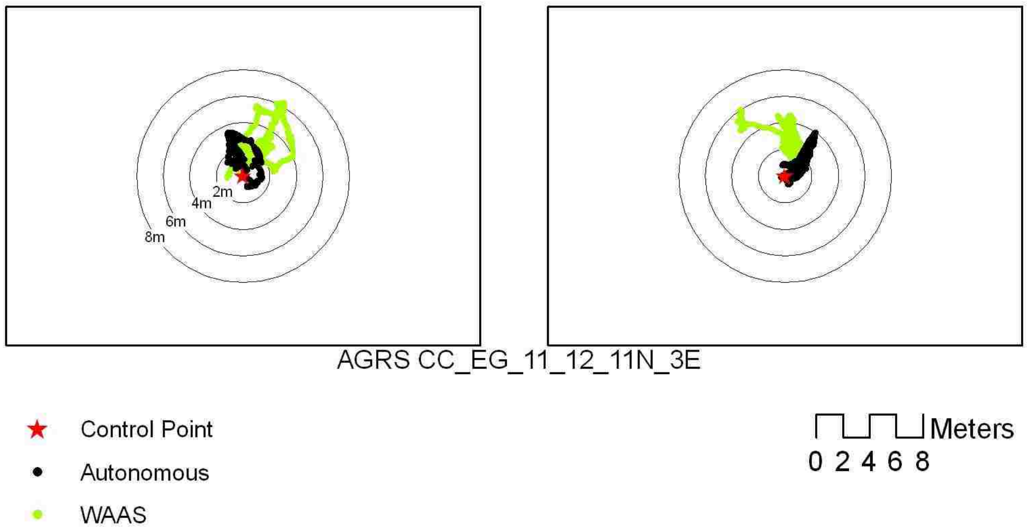


Trimble Scatter Plots

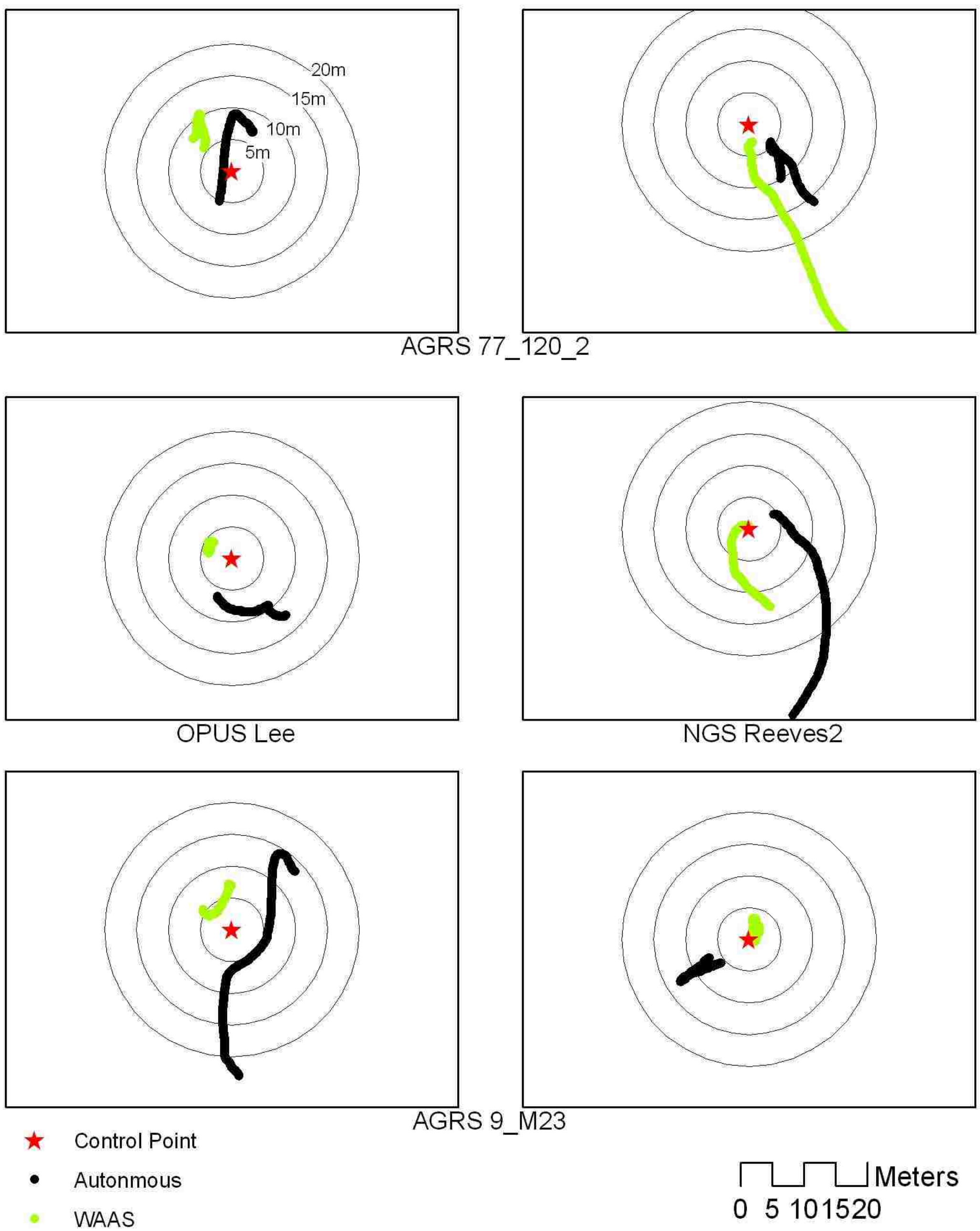



Trimble Scatter Plots
2m
4m
6m
8m
NGS Reeves2
AGRS 20_E10
AGRS 14_J12
Control Point
Autonomous
WAAS
Meters
0 2 4 6 8

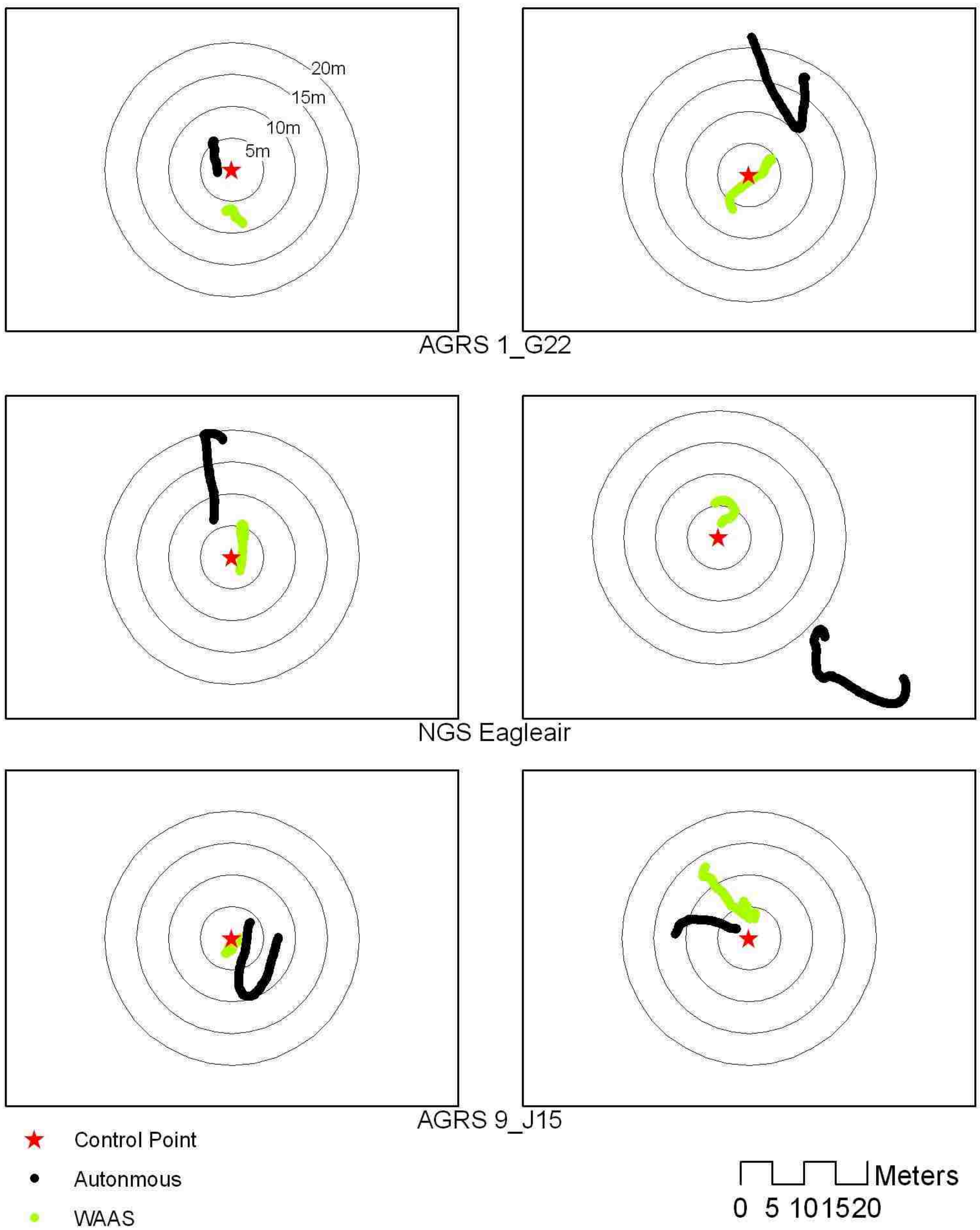
Trimble Scatter Plots



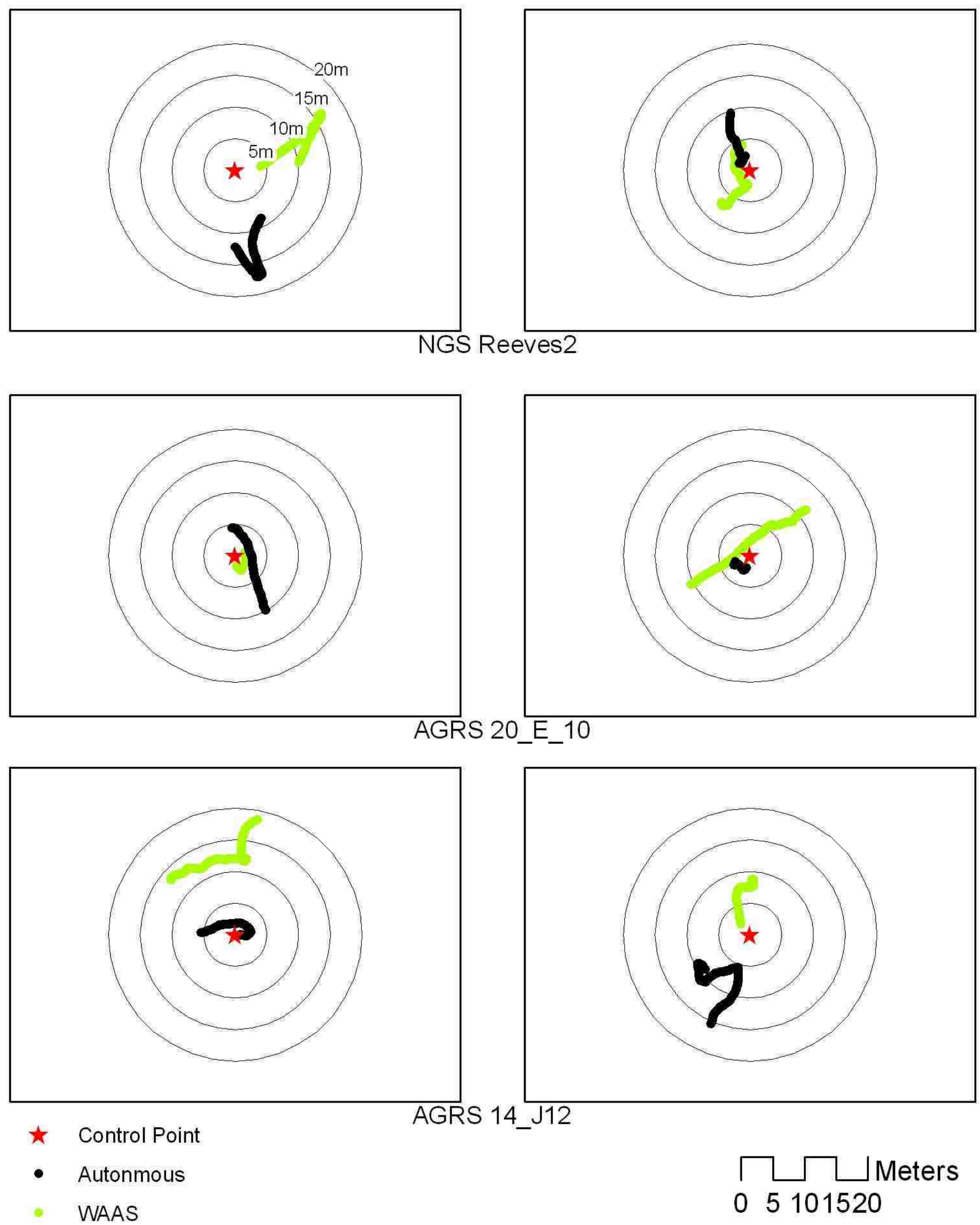
DeLorme Scatter Plots



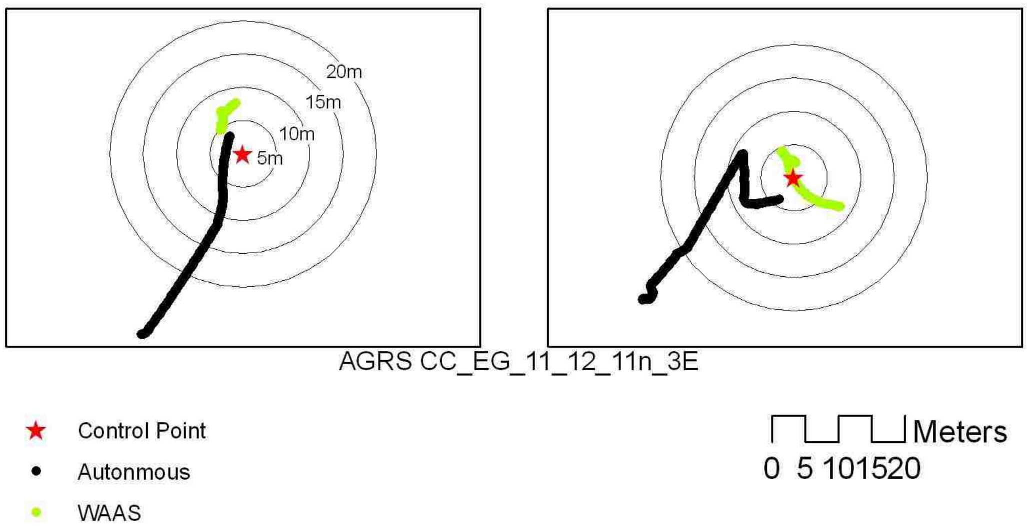
DeLorme Scatter Plots



DeLorme Scatter Plots



DeLorme Scatter Plots



Appendix 5

GPS Hardware Data Sheets

GARMIN

GPSMAP® 60Cx and 60CSx

Add a dash of color to your outdoor adventures

On the road, on the trail, or on the water, the Garmin GPSMAP® 60 series is your ideal guide to the great outdoors. Both the 60Cx and 60CSx versions are rugged, waterproof, full-color navigators that feature a built-in autorouting basemap and include a 64 MB microSD card for storage of optional MapSource® topo, marine or city street map detail. High-sensitivity GPS receivers assure improved reception in tree cover or canyons. And both units feature auto-save of track data to help guide you back to any point along your route. In addition, the "sensor version" 60CSx includes an electronic compass and barometric altimeter – making it the trailblazing tool of choice for hikers and climbers.

GARMIN

GPSMAP® 60Cx and 60CSx

Navigation features

Waypoints/Icons:	1000 with name and graphic symbol, 10 nearest (automatic), 10 proximity
Routes:	50 reversible routes with up to 250 points each, plus MOB and TracBack® modes
Tracks:	10K point automatic track log; 20 saved tracks 500 points each let you retrace your path in both directions
Trip computer:	Current speed, average speed, resettable max. speed, trip timer and trip distance
Alarms:	Anchor drag, approach and arrival, off-course, proximity waypoint, shallow water and deep water
Tables:	Built-in celestial tables for best times to fish and hunt, sun and moon rise, set and location
Map datums:	More than 100 plus user datum
Position format:	Lat/Lon, UTM/UPS, Maidenhead, MGRS, Loran TDs and other grids, including user UTM grid only

GPS performance

Receiver:	12 channel SiRFstar III™ high-sensitivity GPS receiver (WAAS-enabled) continuously tracks and uses up to 12 satellites to compute and update your position
Acquisition times*:	
Warm:	<1 sec
Cold:	<38 sec
AutoLocate®:	<45 sec
Update rate:	1/second, continuous
GPS accuracy:	
Position:	<10 meters, typical
Velocity:	.05 meter/sec steady state
DGPS (WAAS) accuracy:	
Position:	<5 meters, typical
Velocity:	.05 meter/sec steady state
Protocol messages:	NMEA 0183 output protocol
Antenna:	Built-in quad helix receiving antenna, with external antenna connection (MCX)

Moving map features

Basemap:	Detailed routable basemap with cities, highways, interstates, exit info, rivers, lakes; preloaded with worldwide cities
Uploadable maps:	Accepts downloaded or plug-in microSD map detail from a variety of optional MapSource media (64 MB microSD card included)

Electronic compass feature:
(GPSMAP 60CSx only)

Accuracy:	±2 degrees with proper calibration (typical); ±5 degrees extreme northern and southern latitudes
Altimeter feature:	(GPSMAP 60CSx only)
Resolution:	1 foot
Range:	-2,000 to 30,000 feet
Elevation computer:	Current elevation, resettable minimum and maximum elevation, ascent/descent rate, total ascent/descent, average and maximum ascent/descent rate
Pressure:	Local pressure (mbar/inches HG)

Power

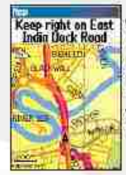
Source:	Two "AA" batteries (not included)
Battery life:	18 hours, typical; up to 30 with battery saving

Physical

Size:	2.4W x 6.1H x 1.3D inches (61mm x 155mm x 33mm)
Weight:	7.5 oz. (213 g) est.
Display:	1.5 x 2.2 inches (38.1mm x 56mm) 256-color transflective TFT (160 x 240 pixels) (160 x 240 pixels)
Case:	Waterproof to IPX-7 standards
Temp. range:	5°F to 158°F (-15°C to 70°C)

Accessories

Standard:	64 MB microSD data card Belt clip USB PC interface cable MapSource Trip & Waypoint Manager CD Users manual Quick reference guide Wrist strap
Optional:	Automotive Navigation Kit (includes City Navigator™) Automotive mount Marine mount Suction cup mount Carrying case 12-volt adapter cable Power/data cable Remote GPS antenna



With enhanced street map detail from optional MapSource software, you can look up destinations and view automatic point-to point routes.

The GPSMAP 60 series accepts downloaded map detail, including topo maps with elevation information.

The barometric altimeter feature on the GPSMAP 60CSx provides elevation profiles for climbers and hikers.

Garmin's "sensor version" GPSMAP 60CSx also features a large, easy-to-read electronic compass display.

GARMIN

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Olathe, Kansas 66062, U.S.A.
913/397.8200 fax 913/397.8282

Garmin (Europe) Ltd.
Unit 5, The Quadrangle
Abbey Park Industrial Estate
Romsey, SO51 9DL, U.K.
44/1794.519944 fax 44/1794.519222

Garmin Corporation
No. 68, Jangshu 2nd Rd.
Shijr, Taipei County, Taiwan
886/2.2642.9199 fax 886/2.2642.9099

www.garmin.com

Specifications are preliminary and subject to change without notice.

* Subject to accuracy degradation to 100m 2DRMS under the U.S. Department of Defense imposed Selective Availability Program.

** These units are also able to transfer waypoints, routes and tracks between the PC and GPS using MapSource.

DATASHEET

Juno ST handheld

KEY FEATURES

Priced to equip an entire workforce

Lightweight and compact

Productive field and office workflow

Windows Mobile 5.0 software familiarity and convenience

Bluetooth and WLAN connectivity

BEST VALUE GIS DATA COLLECTION SYSTEM

The Juno™ ST handheld is a highly productive yet affordable, non-rugged GPS receiver for field data collection and mobile GIS. The Juno ST handheld is Trimble's most compact, lightweight, fully-integrated field computer, providing 2 to 5 meter GPS positioning in real time or after postprocessing.

Easy to deploy

The Juno ST handheld is ideal for utility companies, government organizations, and agencies that are managing large deployments and tight budgets.

In applications such as forestry mapping and workforce automation, where accuracy may be less important, and high productivity is essential, the Juno ST handheld is ideal. Incorporating a high-sensitivity GPS receiver, it has been specifically designed to maximize yield of positions in hostile environments, such as under forest canopy and up against buildings.

If you need 2 to 5 meter accuracy in the field, you can use the integrated WAAS receiver for real-time corrections. Or you can collect data in the field and postprocess it back in the office to ensure positions are defined to the required accuracy level for your GIS, and to control the overall quality and consistency of your data.

Keeping you mobile

Weighing in at only 133 g (0.3 lb), the Juno ST handheld provides the ultimate in portability to keep your workforce mobile.

The Juno ST handheld is easily carried in a shirt pocket and you won't be weighed down by a large receiver. Every member of your workforce can be equipped at all times.

You never have to worry about running out of memory in the field with the Juno ST handheld's SD card capability. You can be sure that you always have ample storage for data and raster background maps.

Software for field and office productivity

As part of the Trimble family of GPS solutions, the Juno ST handheld is fully compatibile with the entire range of Trimble Mapping & GIS software.

Enabling robust, professional data collection and maintenance, you have a choice of TerraSync™ software or the Trimble® GPScorrect™ extension for ESRI ArcPad. You can also choose any off-the-shelf NMEA protocol GPS field software, or use the GPS Pathfinder® Tools Software Development Kit (SDK) to build an application that's customized to your needs.

Office processing and postprocessing capability is provided with GPS Pathfinder Office software and Trimble GPS Analyst™ extension for ESRI ArcGIS. Full software compatibility allows existing Trimble customers to continue to use the same streamlined workflows and DGPS infrastructure.

Industry standard software

Powered by industry standard Microsoft® Windows Mobile® version 5.0 software, you get all the benefits of an open platform for mobile devices. With Windows Mobile 5.0 software, all your data and applications reside in persistent storage, so they are secure even in the event of power loss.

The Windows Mobile 5.0 software also includes familiar Microsoft productivity tools such as Word Mobile, Excel Mobile, Internet Explorer Mobile, and Outlook® Mobile.

Stay connected

Integrated Bluetooth® and wireless LAN technology provide options for connecting to the Internet and your corporate network to access data and maps and to send and receive email and instant messages.

Use the built-in wireless LAN radio in conjunction with TrimPix™ technology to connect to a range of WiFi-capable Nikon digital cameras for automated capture of digital images. With TrimPix software you can take photos with a high resolution camera and send them wirelessly to your Juno ST handheld to be added as attributes to features in your GIS.

It doesn't get any bigger than this

Don't underestimate the Juno ST handheld based on its size—it may be diminutive in stature but it still provides all the heavy-hitting power of a fully-integrated GPS solution backed by Trimble's entire range of software and support.

Providing reliable, high-quality data collection capability, the Juno ST handheld is available at a price that will allow you to maximize your entire workforce's potential.

Trimble.

Juno ST handheld

STANDARD FEATURES

System

- Microsoft Windows Mobile version 5.0 software
- 300 MHz Samsung processor
- 64 MB RAM
- 128 MB non-volatile Flash data storage
- SD memory card slot
- Internally rechargeable and removeable Li-Ion battery
- Integrated Bluetooth wireless technology for connectivity to other devices
- Integrated 802.11b/g wireless LAN for local network connectivity

GPS

- Integrated high-sensitivity GPS/WAAS[1] receiver and antenna
- 2–5 meter accuracy after differential correction (real-time or postprocessed)
- NMEA and SiRF protocol support

Software

- GPS Controller for controlling NMEA output and in-field mission planning
- Microsoft ActiveSync®, Calculator, File Explorer, Internet Explorer, Pictures, Excel Mobile, Outlook Mobile (Inbox, Calendar, Contacts,Notes, Tasks), Word Mobile, Windows® Media Player
- Transcriber (handwriting recognition)
- TrimPix software for wireless camera support. Download from www.trimble.com/trimpix.asp

Accessories

- Power supply with international adapter kit
- Vehicle power adapter
- 1m mini USB cable
- Quick Start Guide
- Carry case
- Rechargeable Li-ion battery

OPTIONAL FEATURES

Software

- TerraSync software
- Trimble GPScorrect extension for ESRI ArcPad software
- GPS Pathfinder Tools Software Development Kit (SDK)
- GPS Pathfinder Office software
- Trimble GPS Analyst extension for ESRI ArcGIS software

Accessories

- Replacement Li-Ion battery
- External GPS antenna
- Stylus (pack of 2)

TECHNICAL SPECIFICATIONS

Physical

Size .... 10.9 cm × 6.0 cm × 1.9 cm (4.3 in × 2.4 in × 0.7 in)
Weight .... 0.133 kg (0.3 lb) with battery
Processor .... 300 MHz Samsung S3C2442 processor
Memory................64 MB RAM and 128 MB internal Flash disk
Power[2]
Low (no GPS or backlight)................................10 hours
Normal (with GPS and backlight[3]) ....6 hours
Battery......Removeable 1200 mAh lithium-ion, rechargeable in unit

Environmental

Temperature
Operating ....–10 °C to +50 °C (14 °F to 122 °F)
Storage..........................–20 °C to +70 °C (–4 °F to 158 °F)

Input/output

Communications. . Bluetooth[4], 802.11b/g wireless LAN, USB slave port[5]
Display......... 2.8" QVGA (Transmissive with micro reflective; TMR)
Touch panel, 240 × 320 pixel 65,536 colors, with backlight
Audio............Mono speaker, unidirectional microphone speaker
Record and playback utilities
Industry-standard 3.5 mm stereo earphone jack
Interface .... Touch screen, Soft Input Panel (SIP) virtual keyboard
handwriting recognition software, power status LED
Audio system events, warnings, and notifications

GPS

Channels .... 12 (L1 code only)
Integrated real-time......................................WAAS[1]
Update rate...1 Hz
Time to first fix.............................. 30 seconds (typical)
Protocols .... SiRF
NMEA-0183 v3.0 (GGA, VTG, GLL, GSA, ZDA, GSV, RMC)

Accuracy (HRMS)[6] after differential correction

Code Postprocessed .... 2–5 m
Real-time (WAAS[1]) .... 2–5 m

1 WAAS (Wide Area Augmentation System) available in North America only.
2 Using Bluetooth wireless technology or wireless LAN connectivity will consume additional battery power.
3 Backlight setting at default level of medium brightness.
4 Bluetooth and wireless LAN type approvals are country specific. Juno ST handhelds have Bluetooth and wireless LAN approval in the U.S. and EU. For other countries please consult your local Reseller.
5 Fully compatible with USB v2.0 computers.
6 Horizontal Root Mean Squared accuracy. Requires data to be collected using horizontal mounting, minimum of 4 satellites, PDOP mask at 99, SNR mask at 12 dBHz, elevation mask at 5 degrees, and reasonable multipath conditions. Ionospheric conditions, multipath signals or obstruction of the sky by buildings or heavy tree canopy may degrade precision by interfering with signal reception. Accuracy varies with proximity to base station by +1 ppm for postprocessing and real-time.

Specifications subject to change without notice.

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Earthmate® GPS PN-20 – Technical Specifications

Display

- Bright color transflective TFT screen for clarity in any light conditions
- 2.2" diameter
- 220 x 176 pixels

Physical

- Waterproof to IPX7 standard,
- Impact-resistant rubberized housing
- Device dimensions: 2.43" W x 5.25" H x 1.5" D
- Weight: 5.12 ounces

Performance

- WAAS-enabled, 12 parallel channel GPS receiver continuously tracks and uses up to 12 satellites to compute and update your position
- High-sensitivity NMEA-compliant 12-channel GPS receiver with low-power baseband and RF chipset
- STMicroelectronics chip technology with SiGE front-end and DeLorme firmware for faster acquisition times and outstanding signal retention
- Proprietary Kalman filter for enhanced GPS accuracy

Acquisition Times

- Warm: Approximately 15 seconds
- Cold: Approximately 60 seconds
- Update rate: 1/second, continuous

GPS accuracy

- Position: < 15 meters, 95% typical
- Velocity: 0.05 meter/sec steady state

WAAS accuracy

- Position: < 3 meters, 95% typical

Memory and Storage

- 75 MB available internal flash memory for user-uploaded maps
- SD card slot for up to 2 GB additional map storage (1GB SD card and Reader included)
- Holds up to 10 tracks (10,000 points per track), 1,000 user-defined waypoints, and 50 routes

Power

- Retail package includes 2 AA batteries

Topo USA® System Requirements

Operating Systems

- Microsoft Windows Vista® Home/Basic/Home Premium/Ultimate/Business with 512 MB RAM
- U.S. Version Microsoft Windows XP or 2000 (Service Pack 3 and higher): 128 MB RAM (256 MB recommended)
- Microsoft Windows 98/ME is not supported with this release

Internet Browser

- Microsoft Internet Explorer 5.01 or later

Hardware

- Intel® Pentium III 900 MHz or higher processor (1.8 GHz recommended)
- 1 GB of available hard-disk space
- DVD-ROM Drive
- 3D-capable video card with 32 MB VRAM (64 MB VRAM recommended)

Earthmate® PN-20

DELORME

Rock-Solid Design, Exceptional Value

Our original handheld GPS - versatile, reliable, with Topo USA DVD mapping software included

- High-sensitivity 12-channel STMicroelectronics chipset for fast, reliable signal acquisition
- DeLorme ConstantLock™ for exceptional signal retention in even the most challenging GPS environments
- 75 MB of onboard Flash memory
- Supports SDHC high-capacity SD cards
- 1 GB SD card and reader included
- Holds 1,000 user-defined waypoints, 50 routes, and 10 tracks
- Rugged, impact-resistant rubberized housing
- Waterproof to IPX7 standard
- Onboard basemap of major highways and thoroughfares for the entire world
- 65K-color daylight-readable TFT screen for clarity in any light conditions
- WAAS-enabled for accuracy within 3 meters
- Topo USA DVD software with complete U.S topo and street maps included - no extra purchase required. Also displays USGS 7.5-min quads, aerial imagery, and NOAA nautical charts via online download from DeLorme

PN-Series Comparison Chart ➤