Assessment of total body kinematics using GPS

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Assessment of Total Body Kinematics Using GPS

BY

S. Jolene L. Lepp

A Thesis/Practicum submitted to the Faculty of Graduate Studies of The University of Manitoba in partial fulfillment of the requirements of the degree of

MASTER OF SCIENCE

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Definitions

Accuracy

The degree of conformance between the estimated or measured position, time, and/or velocity of a GPS receiver and its true time, position, and/or velocity as compared with a constant standard. Radionavigation system accuracy is usually presented as a statistical measure of system error and is characterized as follows:

- **Predictable** - The accuracy of a radio navigation system's position solution with respect to the charted solution. Both the position solution and the chart must be based upon the same geodetic datum.
- **Repeatable** - The accuracy with which a user can return to a position whose coordinates have been measured at a previous time with the same navigation system.
- **Relative** - The accuracy with which a user can measure position relative to that of another user of the same navigation system (British Columbia Standards, 1997).

Differential GPS (DGPS)

A technique used to improve positioning or navigation accuracy by determining the positioning error at a known location and subsequently incorporating a corrective factor (by real-time transmission of corrections or by post-processing) into the position calculations of another receiver operating in the same area and simultaneously tracking the same satellites (British Columbia Standards, 1997).

Dynamic (Kinematic) Positioning

Dynamic or kinematic positioning refers to applications in which the position of a non-stationary object (vehicle, ship, aircraft) is determined (British Columbia Standards, 1997).

Ephemeris

A list of accurate positions or locations of a celestial object (i.e. GPS satellite) as a function of time. Available as "broadcast ephemeris" or as post-processed "precise ephemeris". GPS ephemerides can be used for:

- receiver position determination
- planning
- receiver aiding
- satellite selection

(British Columbia Standards, 1997).

Precision

Precision can be defined as a measure of the tendency of a set of sampled positions to cluster about a point determined by the set, although the exact, known position is unnecessary. This can also include *inter-receiver precision* and *inter-sampling precision* because the exact known earth-based position is not required. Precision is strongly related to relative accuracy. In fact, very good precision is a necessary condition for very good accuracy, and vice versa but very good precision does not necessarily indicate very good accuracy.

Pseudorange

A distance measurement, based on the correlation of a satellite-transmitted code and the local receiver's reference code, that has not been corrected for errors in synchronization between the transmitter's clock and the receiver's clock. It is the difference between the receiver's internally generated signal and the acquired satellite signal that is multiplied by the speed of light, which is the pseudoranges measurement (British Columbia Standards, 1997).

Real-Time GPS

The method by which Differential GPS (DGPS) corrections are transmitted from a GPS Reference Station to a field receiver while data logging in the field (i.e. in "real-time") which

enables the positions to be corrected on-site and in real time (British Columbia Standards, 1997).

Satellite Configuration/Geometry

The geometry of the satellite constellation at a specific time, relative to a specific geographic, earth-based position (i.e. user/receiver position) (British Columbia Standards, 1997).

Selective Availability (SA)

A United States Department of Defense program controls the accuracy of pseudorange measurements, which degrades the signal available to non-qualified receivers by dithering the time and ephemerides data provided in the navigation message (British Columbia Standards, 1997).

Static Positioning

Location determination accomplished with a stationary receiver. This allows the use of various averaging or differential techniques (British Columbia Standards, 1997).

Abstract

Purpose: Recent removal of the intentional positional errors by the United States Department of Defense for the global positioning system (GPS) provides new opportunities to measure unrestrained human motion in the outdoor environment. Further, there have been no investigations into the use of GPS for assessment of slow speed human movement. This study was designed to establish the relative accuracy and feasibility of using GPS for the assessment of human kinematics.

Subjects: A single female subject performed all tests (age =23 years, body mass = 55kg, height = 165cm) because the physiological characteristics of the individual do not have an effect on the GPS receiver measurement capabilities.

Methods: The GPS positional data was collected at ≈ 1 Hz on subjects performing various outdoor ambulatory tasks using three GPS receiver systems (Trimble GeoExplorer II, Garmin III, and a Garmin Vista). These tasks were specifically designed for assessment of the relative accuracy of GPS. The first task was a concentric circle test (CCT) (1, 2, 3, 4, 5, 10 m radii circles). The second task consisted of locomoting about a surveyed track, measuring the lane line distances. These two tasks were used to evaluate relative accuracy of selective availability off GPS and differentially corrected GPS. The third task consisted of an outdoor 3.5 km walk/run with a GPS receiver, which enabled a real-life field assessment of the relative accuracy of the GPS systems.

Analysis: The data collected from all three tests performed by all of the GPS receivers was post-processed and the total distance traveled was numerically derived. The CCT, track test and 3.5 km distance measurements were compared to the known distance measurements to determine the percent error in measurement. The CCT individual circle circumferences measured (1-5 m & 10 m radii circles) were compared between each circle circumference in their measurement percent error levels with each individual GPS receiver using an independent t-test. The GPS receivers were compared between each other in their measurement percent error levels with all of the circle circumferences measured using a paired t-test. The CCT 10 m radii circle data was down-sampled from a 1 second sampling rate to an 8 second sampling rate. The down-sampled data was used to calculate the distance measured by the GPS receiver and was then compared to the known circle circumference to

derive the percent error. The variable down-sampled distance measurement percent errors were compared using an independent t-test. This was performed using each of the GPS receivers, individually. The track test individual lane lines were compared in their measurement percent error within each receiver using an independent t-test. The track lane line measurement percent errors were then compared between GPS using a paired t-test. The occupation time and the Dilution of Precision (DOP) levels noted with the track lane line 1, the CCT 5 m and 10 m radii circles were noted. The DOP levels were compared between each test using an independent t-test. The 3.5 km field test measurement percent error levels were compared using a paired t-test between each of the GPS receivers.

Results and Conclusion: The CCT provided a known measurement both in circle circumference as well as circle radii, which the GPS positional data could be compared against. The circular pattern provides an ability to assess GPS in a more 'real world' setting since the orientation of the individual and GPS are constantly changing (rather than moving in a straight line). The curvilinear path (circular trajectory) also enables assessment of sampling rate, which is not as readily assessed when using straight line motion. Analysis of the CCT demonstrated that a minimum distance of 12.57 m could be measured with an accuracy of less than 5 % error using the Garmin III and the Trimble GeoExplorer II (differentially and non-differentially corrected) GPS receivers. There were marginal differences noted in the measurement percent error levels between the SA-off and differentially corrected Trimble GeoExplorer II.

The Garmin III and the Trimble GeoExplorer II (differentially and non-differentially corrected) all provided an accurate assessment of the CCT with a sampling rate of 1 second (1 Hz), although the Trimble GeoExlporer II demonstrated good relative accuracy with a 2 second sampling rate.

The track test distance measurements exhibited an increase in percent error with an increase in distance, although with the greatest distance of 440 m the percent error noted was less than 2.3 %. This was demonstrated by the Garmin III and GeoExplorer II (differentially and non differentially corrected. The GV had significant levels ($P<0.05$) of overestimation in the track test distance measurements due to the step-like measurement characteristics of the receiver.

The DOP levels analyzed in the track lane 1, CCT 5 m and 10 m radii circles were non-significant between the tests performed. Although, it was illustrated that the DOP

level and respective satellite configuration are critical to observe in order to ensure that the relative accuracy of the measurement will not be significantly affected. The satellite configurations change over variable time periods and a minimum occupation time of ≥ 45 seconds was observed to have non-significant changes in DOP levels when compared to longer sampling periods of greater than 20 minutes.

The 3.5 km field test provided an understanding of the GPS sampling capabilities with a 'real life' kinematic test in an outdoor environment, which demonstrated similar dynamic relative accuracy levels in comparison to the CCT and track test. Tests such as this have the potential to be combined with physiological measures to provide an understanding of the concurrent physiological response to unencumbered movement.

Overall, the accuracy, size and data logging capacity of GPS equipment with SA-off accuracy, opens new opportunities for application in both research and practical, human kinematic assessment in a non-controlled environment.

Introduction

Our present understanding of kinematics is based upon studies that have quantified various parameters of human movement in a controlled, laboratory setting. Some methods such as video motion analysis have been employed to study human motion in certain controlled outdoor settings (Lugne *et.al.,* 1999), but studies such as this are limited in their ability to continuously, objectively quantify human movement in an unencumbered manner in a free-living, outdoor environment.

Recent technological advances within the field of GPS have provided the measurement capabilities (size, sampling rate, data logging, static accuracy) that will enable assessment of unrestrained human movement in an outdoor environment. The GPS receivers have progressed, with the most current light weight hand held receiver (Garmin Vista) being 11.2 cm x 5.1 cm x 3.0 cm in dimension and a mere 170 g in mass (including 2 AA batteries), which provides position, time and velocity information on a second-by-second basis. GPS is evolving into a common tool, which has been included in car navigation systems, watches, cellular phones, and even handheld computers. Aside from the technological developments in GPS equipment, the most significant advancement within the field is the removal of selective availability (SA), which is the intentionally induced signal error imposed by the United States Department of Defense (DoD). As of May 2, 2000, this error was turned off, which has dramatically improved the accuracy of consumer GPS data (http://www.ngs.noaa.gov/FGCS/info/sans_SA/docs/statement.html). Further, recent availability of real-time, satellite based differential correction of GPS through a wide area augmentation system developed for aircraft navigation provides increased potential for GPS applications in human motion research. The static positional accuracy has been extensively studied to date (Schreenan *et. al.*, 1996; Milbert, 2001, http://www.ngs.noaa.gov/FGCS/info/sans_SA/docs/p-error.htm). There have been no studies examining the dynamic positional accuracy of GPS systems related to human motion research.

A diversity of applications within the military, commercial and recreational sectors have arisen due to the accuracy and utility of GPS. Exploration of this technology within the field of human kinematics has occurred recently. A small number of studies have

applied GPS for assessment of human movement, which have reported the averaged velocity and derived acceleration capabilities using large, heavy and special carrier phase GPS systems. Schutz and co-workers (Schutz *et. al.,* 1997, 2000, Terrier *et. al.,* 2000a, 2000b, 2001), and more recently Larsson and Larsen (2001), are the primary groups who have studied the use of GPS for assessment of human movement. They have documented the average velocity sampling capabilities of GPS, a differentially corrected form of GPS, and a high accuracy form of GPS, called carrier phase GPS. Schutz *et. al.,* (1997, 2000) have begun to establish a foundation for velocity and acceleration assessment capabilities using non-portable GPS, but have not analyzed the sampling characteristics (sampling rate, satellite configuration, etc.) of GPS. The sampling rate capabilities of a GPS will directly impact upon the velocity assessment, which has not been examined and has the potential to create a large degree of error, especially with slow speed movements such as human gait patterns. The other area, which has not been thoroughly examined, is the portable SA off GPS systems for assessment of human movement. It is the SA-off form of GPS that has the potential capabilities to enable human motion analysis.

Advancements in the field of GPS technology (size, mass, sampling rate, etc.) have enhanced the potential for kinematic assessment. However, analysis of the sampling characteristics is required in order to deem this tool useful for human movement analysis purposes. To date, the relative accuracy of GPS for the assessment of human movement has not been explored due to the absence of a test, which is able to quantify the sampling characteristic of GPS. Not only has the relative accuracy been undetermined, but also the effect of the removal of SA on relative positional accuracy of GPS has not been quantified to date. An understanding of the velocity and derived acceleration measurement characteristics has been determined in previous studies performed by Schutz *et. al.* (1997, 2000). Both the continuous low speed precision sampling capabilities and the minimum distance traveled required for a human movement assessment, which is affected by the relative accuracy of GPS has not been studied previously. These are critical sampling characteristics that are essential to analyze in order to establish the limitations and utility of GPS as a tool for kinematic assessment.

The focus of this study is to determine the relative accuracy levels of SA-off GPS in order to evaluate the utility of GPS for total body kinematic assessment in the outdoor environment. Tests to demonstrate and validate the continuous dynamic relative accuracy

capabilities of GPS (SA-off) will be developed in order to lay the foundation for the purposes of this study. These tests will be used to assess the measurement capabilities of various GPS systems during low speed locomotion. As well, the minimum sampling rate, which effects the accuracy of the minimum velocity and distance traveled by an individual, as well as the impact of satellite configuration on relative accuracy is necessary to quantify in order to define the sampling parameters required for an accurate description of movement. Finally, the GPS systems will be evaluated in 3.5 km field test and compared to the controlled tests.

Review of Literature

There have been many methods, which have attempted to quantify human movement, both objectively [pedometers (Kemper & Verschuur, 1977, Bassett *et. al.,* 1996), accelerometers (Hretbeck & Monotoye, 1992, Westerterp, 1999), video motion analysis systems (Selfe, 1998, Everaert *et. al.*, 1999), etc.] and subjectively [questionnaires (Washburn & Montoye, 1989), observations (Bailey *et. al.,* 1995), diaries (Klesges *et. al.,* 1990, Patterson, 2000]. There is a paucity of studies on objective documentation of human movement in the outdoor environment.

A review is provided below that examines GPS technology, the current utilization of GPS, and the present state of knowledge within the field of human GPS research. An understanding of GPS, as well as other motion analysis systems will create the basis for the present state of knowledge and provide a greater understanding of the current technological and research limitations.

Global Position Technology

GPS is a "space based, all weather, jam resistant, continuous operation radio navigation system" (US Army Space Reference Text, 1993). Essentially, GPS consists of a receiver, which communicates with a group of satellites in orbit around the earth in order to determine an earth-based position. This system provides military, commercial and civilian users with global, three-dimensional, earth referenced position/location, as well as precise time and velocity with an accuracy that has been unsurpassed by any other method to date. GPS can be broken into three primary components; space segment, control segment, and user segment. The NAVSTAR GPS was designed for, controlled and is operated by the United States of America DoD. It is important to note that there is a similar system designed and controlled by the Commonwealth of Independent States called GLONASS (Global Navigational Satellite System). The NAVSTAR GPS system will be discussed in detail due to its' system characteristics, utility and advancement in technology. So hereinafter the term GPS will refer to the NAVSTAR GPS system not the GLONASS system.

Space Segment

GPS is comprised of a constellation of 31 geosynchronous satellites, which are utilized to determine a receivers' position on earth. This constellation of satellites orbit the earth at an approximate altitude of 23,980 kilometers, spaced 60 degrees apart, inclined at 55° referenced to the equator in 6 orbital planes. These orbital specifications enable complete coverage of the earth's surface. The first satellite vehicle (SV) was launched in 1978. Operational status was declared on December 8, 1993 when 24 GPS satellites were operating in their assigned orbits, available for navigation use and providing adequate positioning levels. The U.S. Air Force Space Command formally declared the standards for Full Operational Capability were complete as of April 27, 1995. These requirements demand 24 operational satellites functioning in their assigned orbits with successful testing completed for operational military functionality (ftp://tycho.usno.navy.mil/pub/gps/gpsb2.txt). With full operational status of the system, a receiver can log at least 4 satellites from any location on earth at any time, due to the fact that an average of 6 satellites are in view at any given time period. Therefore, if a satellite fails to provide data, there are other satellites that can provide adequate coverage of an area. The signal that is generated by the GPS satellite and recorded by the receiver will be discussed in detail in a later section.

Control Segment

The U.S. Air Force Space Command operates the "control segment" component of GPS. The primary function of the GPS master control station and the network of monitoring stations is to log all SV orbital patterns, status, and clock data. The data is analyzed once it has been transmitted to a control centre and the clock and ephemeris data corrections are then transmitted to low orbiting satellites and incorporated into the navigation message logged by each receiver. This information is then relayed to each individual receiver (roving receiver or fixed base station receiver) on earth that logs the satellite's signal. This method ensures that the system remains functioning at optimal accuracy (US Army Space Reference Text, 1993).

User Segment

At its conception, GPS was initially created for the sole use of the military, although the utility of GPS quickly became realized for multiple civilian applications. With the development of this technology, there have been numerous applications explored within the civilian, commercial and recreational user segments. Due to the two primary divisions in the user group (military and civilian), the DoD created two GPS services; Standard Positioning Service (SPS) for the civilian user group and Precise Positioning Service (PPS) for the military user group. The DoD previously induced intentional errors into the civilian signal (SPS) in order to prevent enemy military utilization. However, the SPS still provided relatively accurate GPS data. The PPS is available only to authorized users from the DoD, of which the primary users are the U.S. military service, Coast Guard and select agencies. The PPS provides the more accurate position, velocity and timing data than SPS that is continuous on a worldwide basis. Therefore, the information transmitted on the PPS is encrypted of which only authorized military users have a key that decodes the signal provided by the PPS (US Army Space Reference Text, 1993).

Position Fix

The process through which a single point position solution (x,y,z referenced to an earth based coordinate system) is achieved is termed trilateration (a form of triangulation), which corresponds to the point of intersection of four (or preferably more) satellite pseudo-range measurements. The analogy of a position solution can be made to an individual standing in the middle of a room with strings attached to four unique but known points in the room. The measured length and angle of each string would vary, but the strings would intersect at one point; the place where the person was standing. With GPS, a single three-dimensional position with accurate time is determined through the intersection of <u>at least</u> four satellite range measurements (which is the distance from the receiver to the satellite). While the receiver logs the signal from each satellite, the receiver will internally generate a matching signal for each satellite sampled, which is used as a reference to determine the travel time of the satellite signal to the receiver. The receiver will slide its' internally generated signal against the logged satellites' signal until the signals match (termed correlation). The difference in the satellite and receiver signal, which is the signal's travel time, is then multiplied by the velocity of the signal transmission, which is the speed of light

to derive the distance from the receiver to the satellite (termed a pseudo-range measurement). In order for an accurate measurement to be obtained, each of the satellites' and the receiver clocks should be perfectly synchronized, but in reality there is a clock offset, which induces an error in the satellite range measurements, hence the term pseudo-range measurement. In fact, a pseudo-random clock offset error (termed dither) was introduced by the DoD to intentionally reduce the accuracy of the SPS service, termed SA (now defunct). This error can be computed and corrected for, which requires a fourth satellite to determine the clock offset, for each sampling period. Each of the individual pseudo-range measurements that are derived for the satellites sampled will intersect at a point. It is their intersection through trilateration, using both the satellite angle (termed azimuth) and pseudo-range measurements in a trilateration calculation, that enables a single point, three-dimension position solution.

Time to First Fix is the time interval required for a GPS to determine a position solution. There are two methods of Time to First Fix; warm start and cold start. The warm start method determines a position/location through using pre-programmed satellite information. The receiver uses this information to estimate the orbital pattern, timing, and location of each sampled satellite. An exact position is determined through measuring the frequency of each individual satellite radio signals' Doppler shift, which occurs because of the relative satellite/receiver motion. Through measurement of the Doppler shift in individual satellite frequencies, an initial position fix can be calculated in a relatively short period of time. Without the pre-programmed satellite information, the receiver must seek each satellite frequency on the radio band. Each signal that the receiver is able to log onto has to be identified using the PRN (pseudo-random noise) code. A position solution will not be determined until each satellite PRN code has been identified. This cold start method of determining a position solution is more tedious and requires a longer time period for a position solution to be calculated than the warm start technique. This is due to the fact that each satellite signal must be acquired, tracked, pseudo-range measurements extracted and the navigation message decoded in order to determine the position using the cold start method (US Army Space Reference Text, 1993).

GPS Signal

Each satellite transmits a characteristic signal, termed the PRN code that includes encoded information of the SV clock, ephemeris data, approximate orbital data set (termed almanac), an ionospheric model, and Universal Time Coordinate corrections. Each individual satellite transmits two microwave carrier signals; L1 frequency (1575.42 MHz) and L2 frequency (1227.60 MHz). The two L-band frequencies are generated from the fundamental satellite clock frequency of 10.23 MHz. In order to provide an instantaneous position, these two carrier frequencies are modulated by pseudorandom, binary codes (data bits consisting of 0 and 1); the Coarse Acquisition (C/A) code (modulates L1) and the P (precise) code (modulates L1 and L2). The P and C/A code, as well as the navigation data will be discussed in detail in the following paragraphs (US Amy Space Reference Test, 1993).

C/A Code

The C/A code is modulated onto the GPS L1 signal and is satellite specific. This code is a sequence of 1023 chips, which is the time required to transmit a single "0" or "1" in a binary pulse, that repeat every millisecond; therefore the modulation occurs at a rate of 1.023 MHz. This is also expressed as 1.023 Mbps, which is the rate each chip is modulated onto the carrier frequency, termed the chip rate. Due to the C/A code chipping rate, each chip length (due to the speed of light) is equal to 300 m, of which the total code is transmitted over a distance of 300 km. The C/A code can be likened to a series of rulers that extend from the satellite to the receiver. Each ruler is equivalent to one complete code length of 300 km, with each ruler's graduations equal to 300 m increments (analogous with the chip length). The C/A code "rulers" appear to be random, although its generation method is known, hence the term pseudorandom. This code is also known as the "civilian code" due to its' good acquisition properties (Leick, 1995).

P Code

The P code creates the PPS, which is exclusively used by the U.S. and allied military. The P code is a very long binary code, which only repeats every week versus every millisecond, as in the C/A code. The P code is transmitted at 10.23 MHz (chipping rate), therefore the chip length, or the length of one data bit, is approximately 30 m. The analogy of a ruler can also be used to describe the P code, although the length of this ruler is one

week, with the graduation marks approximately 30 m in length (chip length). Therefore, position solutions that are derived using the P code have greater accuracy; smaller chip length results in greater code resolution. It is because of this higher resolution or accuracy, that DoD encrypts the P code into what is termed the Y code. Receivers require an authorized cryptographic key that enables the receiver to decode the information. This P(Y) code has also been used for ionospheric delay correction (which is a time delay induced into the satellite signals by ionospheric particles as they through the ionosphere) that enhances the accuracy of the final position solution. Overall, the P code enables more accurate position solutions, however this service in not available to civilian users (Leick, 1995).

Navigation Data

The L1 carrier is modulated by the navigation data message, in addition to the C/A and P (Y) codes. The navigation message is transmitted at a 50 Hz frequency. The information transmitted includes data bits describing individual satellite specific clock offsets and corrections, GPS satellite orbits, and various system parameters, which are termed the broadcast ephemeredes. The approximate satellite constellation information is contained within an almanac, which provides a set of orbit parameters that allows calculation of approximate GPS satellite positions and velocities. The almanac is used by receivers to determine satellite visibility, as well as an aid during acquisition of GPS satellite signals. The error that is noted through using the broadcast ephemeredes can be corrected for by using precise ephemeredes post mission, which provide the exact satellite orbital pattern available via the Internet, therefore reducing the error (US Army Space Reference Text, 1993).

Geodetic Models

Geodesy is the study of the earth's variations in surface and the respective changes in gravity. The basis of GPS coordinates requires an understanding of geodesy and how the coordinate systems are derived from these collected geodetic datums. The selected geodetic datum is a mathematical model, which is defined by an ellipsoid in relation to a geoid model that provides the foundation for a position solution to be referenced to an actual earth-based location. The ellipsoid and geoid models will be discussed in further detail.

Gravity influences the entire earth surface, but does not act at a consistent –9.8 m/s^2 over the entire surface. Therefore, a plum line will not always fall perpendicular to the earth's surface and this is dependent upon the earth's uneven geographical mass distribution. For example, large masses such as mountains will cause a plum line to fall towards the landmass due to the change in the gravitational field. This change in the gravitational field is important to note because horizontal and vertical measurements used to measure the earth's surface and create a reference system are distorted due to uneven mass distribution. Therefore, a geoid was created in order to correct for the effect of variable gravitational field values due to the uneven mass distribution of the earth's surface. A geoid is technically defined as the "equipotential surface that coincides with the mean sea level and may be imagined to extend through the continents" (British Columbia Standards, 1997). This surface model is perpendicular to the force of gravity over the entirety of the surface (creating an equal gravity value), which is based upon the earth's gravity field and the outward, centrifugal force of the earth's rotation. Due to this unequal distribution of mass and therefore unequal distribution of gravity, the geoid is not perfectly spherical, but elevated over continents and depressed over oceans. It is important that the geoid be measured due to the earth's distorted distribution of mass. It is the geoid that provides the basis for various geodetic datums. The most current geoid is the Earth Geodetic Model 1996 (Dana, 1999).

The shape of the earth's surface is uneven; therefore a model was developed to "smooth" the shape of the earth, termed an ellipsoid. GPS uses the ellipsoid to determine height, although elevation in respect to mean sea level requires a referenced geoid. The use of a geoid model in combination with the GPS enables measurement of orthometric heights (H) (i.e. heights above the geoid along the plumb line). This is accomplished by subtracting a geoid height (N) from a GPS-observed ellipsoidal height (h): $H = h - N$ (Dana, 1999).

A three dimensional GPS coordinate position is based upon the right-hand Cartesian coordinate system with its origin located at the center of the Earth. A standardized datum, the World Geodetic System-1984, which is centered on a reference ellipsoid, has the "Z" axis aligned with the Earth's spin axis, the "X" axis through the intersection of the Prime Meridian and the Equator and the "Y" axis is rotated 90 degrees East of the "X" axis about the "Z" axis. This creates a global reference frame that is earth fixed and includes a model of the earth's surface. GPS, both Navstar and Glonass, measurements provide a three

dimensional position based on a spherical geodetic coordinate system. There are various geodetic datums, which have been locally based, but did not provide a global reference (Dana, 1999). The DoD recognized this complication and created a world system, which reference various local datums, to provide a reference system for global navigation. A consistent set of parameters describing the size and shape of the Earth, the positions of a network of points with respect to the earth's centre of mass, transformations from major geodetic datums, and the potential of the Earth (gravitational fields or geoid model (EGM 96)) are included within the World Geodetic System (WGS). This system is upgraded at intervals as new data and data reduction techniques emerge. The GPS NAVSTAR system utilizes the latest WGS-84 reference datum. It is these datums (WGS-84 and EGM-96) on the relief and gravitational changes of the earth that enable a three-dimensional location on earth to be referenced to a two-dimensional map projection. Each x, y, z coordinate derived through GPS measurement can be referenced within a coordinate system (e.g. UTM, Latitude and Longitude, etc.) based upon the WGS-84 datum. The vertical position is referenced to mean sea level (MSL) using the EGM96 Global geoid coordinate system (Dana, 1999). The use of a consistent global model of the geoid and an ellipsoid are integral in order to determine an accurate earth-referenced position for GPS.

Universal Transverse Mercator Coordinate System

The UTM coordinate system has been adopted throughout the world due to it's utility. In 1947 the U.S. Army adopted the UTM projection and grid system that was used for designating rectangular coordinates on large-scale military maps. UTM is currently used by the United States and NATO armed forces (Dana, 1998). UTM coordinate system provides the advantage of a constant distance relationship anywhere on earth. Latitude and longitude coordinate system does not provide a constant distance traveled measurement with any given earth-based position, due to its three dimensional characteristics (spherical trigonometry is required), which cause the latitude and longitude lines to converge, therefore disproportionate distances occur at the Equator and Prime Meridian respectively. The UTM coordinate system is based on a two dimensional square grid, much like the Cartesian coordinate system. The square grid design permits this coordinate numbering system to be tied directly to a metric distance measuring system, which values increase from left to right and bottom to top.

The UTM system divides the earth into 60 zones, each 6 degrees of longitude wide. Each individual zone creates a reference point for UTM grid co-ordinates within the zone. UTM zones are numbered 1 through 60 proceeding eastward starting at the International Date Line (longitude 180°). Zone 1 extends from 180° W to 174° W and is centred on 177° W. UTM horizontal zones extend from 80° S to 84° N latitude. Horizontal bands span 8 degrees of latitude, dividing each zone. These bands are lettered, south to north, beginning at 80° S with the letter C and ending with the letter X at 84° N (I and O are skipped to avoid confusion with the numbers one and zero) (Dana, 1999).

Within each zone, a smaller square grid is vertically aligned parallel to the middle of the zone, termed the central meridian. The UTM position can be described using the term easting to define the distance measured in meters east of central meridian, and "northing" to express the distance measured in meters north of the equator. A 500 km false easting (for positions west of the International Date Line) and 10, 000 km false northing (for positions south of the equator) was created to allow positive co-ordinates (Dana, 1999).

GPS Signal Errors

The factors that affect the accuracy of the GPS signal are SA, ephemeris and clock offset, multipath (reflections of transmitted signals of surfaces), receiver noise delays (signal to noise ratio is a measure of the signal strength), atmospheric delays (both ionosphere and troposphere), GPS signal noise, receiver oscillations, and poor DOP (dilution of precision) levels. Each SV broadcasts an individualized timing signal and orbital path (ephemeris data) on a continuous basis. The signals are relatively weak and are unable to penetrate buildings or metal. Meteorological conditions have little effect on the signal, although dense vegetation or canopy can block or weaken satellite signals dependent upon the density of the canopy. Numerous geodetic studies have documented the magnitude of errors measured in a static position (Dana, 1997; Leick, 1995; Geodetic Survey Division, 1996; Heroux, and Kouba, 1995). These previously noted error sources degrade accuracy levels at varying degrees (ionosphere~30m, troposphere~30m, measurement noise~10 m, ephemeris data 1-5 m, satellite clock drift~1.5 m, multipath~1 m and SA~70 m) (Wormley, 2001, http://www.ngs.noaa.gov/FGCS/info/sans_SA/docs/p-error.htm). Previously, the greatest source of error was due to SA, which was intentionally induced by the DoD.

Selective availability

Without post-processed or real-time differential correction, all civilian GPS receivers were subject to degradation of positional accuracy under the imposed SA. The accuracy of non-corrected GPS was degraded so that 95 % of horizontal positions were within 100 m (150 m vertical accuracy) of truth. The above accuracy estimations assume the receiver is tracking 4 SV, a Positional Dilution of Precision (PDOP) of <6, signal to noise ratio (SNR) >4, reasonable ionospheric conditions, multipath signals or obstructions of the sky by building or heavy tree canopy that may degrade precision by interfering with signal reception. As of 24:00 hours on May 1, 2000 the DoD discontinued the intentional civilian GPS signal degradation or SA. The accuracy of GPS changed from 95% of points falling within a 45 m radius with SA-on to 95 % of points falling within a 6.3 m radius with SA-off. (Milbert, 2001). Others have reported on the static positional accuracy and it is generally accepted that SA-off GPS will show less than 7 m deviation from truth in 95 % of cases (Milbert, 2001). Due to this recent event, there are currently no studies that identify the

improvement in dynamic positional accuracy or dynamic relative accuracy with SA discontinued. Accuracy and precision will be discussed in further detail.

Multipath

The path of a GPS satellite signal is not without obstacles, which cause the reflection of the signals to occur to the receiver. These reflected signals are then tracked like non-reflected signals and processed by the GPS receiver to determine a range measurement. The path of these reflected signals increases from the true path, which results in error of the satellite receiver distance due to an increase in travel time of the reflected satellite signal. This introduces ambiguity into the computation of the positional solution, which determines an inaccurate position solution. Buildings are the most common cause of multipath error.

Satellite Clock Drift

The difference between the SV and GPS time represents the clock error or drift. Individual satellites have 4 atomic clocks on board (2 cesium and 2 rubidium) in order to maintain accurate time. Accuracy of these clocks is maintained through transmission of the atomic clock status to the control centre, where the clock corrections are transmitted to the required satellites in order to maintain the clock accuracy specifications (Leick, 1995).

Ephemeris Error

GPS satellite orbits were specifically selected for their stability, coverage, and longevity. A high degree of satellite orbit precision is possible, although there are slight variations in the orbital paths due to the unequal gravitational pull of the earth (termed Kalperian motion) and other large masses in space (third body effects), atmospheric drag (minimal due to the height of the orbits), and the effect of radiation pressure caused by light photons from the sun (termed the albedo effect). Most of these sources of error in the satellite orbits can be modelled and thus corrected for. Radiation pressure is the most difficult to model, therefore causing the greatest degree of orbital error. Even though prediction models are available, corrections for orbital changes occur in the same manner as clock corrections, with the calculated errors being transmitted to the satellites for incorporation into the navigation message. For accurate positional solutions, even the different types of GPS satellites are important to consider since

the exact location of the radiating antenna must be known for accurate range measurement calculations. GPS satellites broadcast orbital data to the GPS receiver every 12.5 minutes. A number of earth-based tracking stations continuously evaluates the orbits of all the GPS satellites and provides precise orbital data for post-processing of GPS data.

Measurement Noise

The two main types of measurement noise are due to the receiver and GPS signal. The signal to noise ratio is the term used to describe this measurement of overall signal strength. The signal noise is generated from sources such as the ionospheric scintillations and various galactic sources (e.g. solar flares). The noise created by the receiver is dependent upon internal design characteristics of the receiver. Both sources of measurement noise can create a two to three nanosecond timing error into the GPS signal. Although, this may sound negligible, a two to three nanosecond timing error magnitude can result in errors up to 10 m in poorly designed GPS receiver equipment (British Columbia Standards, 1997).

Tropospheric Delays

The varying density of water vapour in the atmosphere causes a delay in the satellite signal as they pass through the troposphere, which is 8 to 13 km above mean sea level. Modelling for these weather-based troposhperic signal delays is difficult due to the high local variation, although the error induced by this effect is lower than that from the ionosphere.

Ionospheric Delays

Ionosphere is a portion of the atmosphere, which is comprised of charged particles. There are fluctuations in the density and size of different portions of the ionosphere that are caused by sunlight changes, earth magnetic field changes, solar radiation, etc. The error introduced by the ionosphere, due to the charge of particles comprising the ionosphere, results in variability in the signal transmission time used to determine range measurements. This error can have a relatively large effect on the GPS positional computations. Since SA has been removed, the ionospheric delay is one of the most important errors to consider in accuracy and reliability of GPS measurements. Receivers, which use the PPS, are able to account for ionospheric delays using the two carrier frequencies (L1 and L2) to estimate the delay, therefore providing a more accurate position solution. The SPS receivers are able to correct for most of

this error through the use of an ionospheric model that is less accurate than actually measuring the error through the carrier frequencies.

Satellite Configuration and Dilution of Precision

The quality of the satellite configuration or position of individual satellites will influence the accuracy of the position solution determined. The analogy of an individual standing in a room connected to four different points via strings can be used to understand the effect of satellite geometry. If the four points in a room are all in a row, the string measurements will have small variances in their distance and angle to the receiver. Alternately, if you had four points that were distributed throughout a room, the vectors and string measurements would have greater variability in their angle and distance, therefore determination of an x,y,z, position would be more accurate. The configuration of satellites will affect the resultant position solution in the same manner; the greater the distribution of satellites, the greater the variability in the range and vector measurements. The quality of the satellite configuration is indicated through a DOP level. An optimal orientation of satellites relative to the GPS receiver is one where the range measurements are provided from well-distributed SVs, which provides a low DOP level. Each individual satellite ephemeris data is known; therefore an optimal configuration of satellites can be calculated pre-sampling time period in order to optimize the satellite geometry utilized to determine a position fix. Although it is important to remember that the satellites are always in motion relative to the receiver, therefore the quality of the satellite configuration is constantly changing. To note the effects of changing satellite configurations, the satellites that provide the position solution and the quality of the satellite constellation configuration can be logged for the sampling time period. The lower the DOP value, the better the satellite configuration; therefore lower potential error level or higher accuracy of the derived position.

There are various types of DOP level measurements that account for different characteristics of the satellite configuration and its' effect on accuracy. The geometric dilution of precision is an indication of the effect of pseudorange errors on a complete position and time solution. Dilution of precision can be divided into a three-dimensional expression of 1) positional or spherical, 2) two-dimensional horizontal, or 3) one-dimensional vertical or time dilution of precision, which provide an estimate of satellite

geometry or configuration. Each of these expressions of satellite configuration provides an indication of the quality of data collected.

GPS Signal Error Summary

The primary sources of positional errors can and have been largely overcome by: 1) the removal of the DoD timing errors through ground based control software; 2) the use of stationary, GPS base stations which can be used to determine the clock or timing errors for each satellite and are used to derive accurate range measurements resulting in substantially improved positional computations (DGPS: Post-processed); and 3) using the high frequency carrier signals which carry the digital timing code to compute more precise range measurements (carrier phase correction or Real-Time Kinematics). There is a paucity of information on the effect and removal of SA and other sources of error on dynamic relative accuracy. This is largely due the lack of development and validation of a test to determine the dynamic positional accuracy.

Satellite Visibility

Field of View (FOV) obstructions or blockage of satellite signals to a receiver can also induce positional errors that are difficult to quantify. FOV obstructions can be created by improper placement of the antenna, tree canopy, buildings, a person's body, etc. Due to the variability of FOV obstructions, which is dependent upon the sampling location and techniques, these errors are inconsistent and therefore difficult to quantify. It is critical to minimize FOV obstruction error sources if possible because they can create a significant source of error. Loss of a single satellite signal can reduce the satellite configuration from 4 critical satellites to only 3 or could reduce the one good satellite signal or one satellite with a good position from the configuration, all of which would result in drastic measurement errors.

In certain types of GPS receivers, range measurements can be stored from each SV used to determine individual position solutions. It is possible to model the effects of SV signal obstructions on positional errors by simply removing a selected SV range

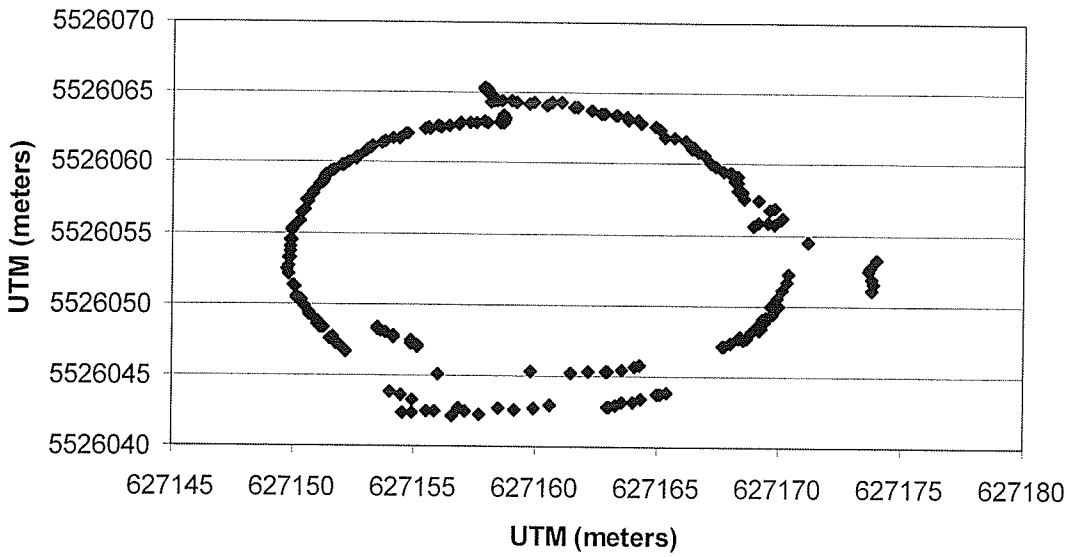


Figure 1 The effect of satellite geometry changes (number & position of satellites used for a positional solution) on positional accuracy is clearly shown for a person walking in a marked circular path (10 m radius). Step-like changes in position off of the known circular path can be observed with a shift in satellite configuration. The resultant shift in satellite configuration caused a change in the DOP level (a reflection of satellite geometry) consistent with the positional shifts (Human Performance Lab data, 2002).

measurement from the positional computation. This would represent a change in DOP level. This type of error can be observed while recording positional data under a varying tree canopy, where a large tree obscures the signal of one SV. This often results in an abrupt change in DOP that may be observed in a "step" change in position (figure 1). This effect can be minimized by computing positions using over-determined solutions (i.e. tracking greater than 4 SVs). Often more than 8 SVs are available at one sampling epoch (referring to time period) for positional solutions, and by computing positions using ALL of the range measurements, therefore the effect of one satellite on positional errors is minimized. The penalty for this approach is that satellites near the horizon are also used in the positional computation, hence the possibility of more ionospheric error and multipath, due to the greater density of the ionosphere near the horizon delaying the satellite time signal and

greater FOV obstructions. Studies have not been performed to assess the benefits of this over-determined approach.

Statistical Expression of GPS Accuracy

The accuracy and precision of a system can be expressed in a diversity of statistical terms. These terms have been primarily used to describe the accuracy of static positional data. There are various indicators such as root-mean-square (RMS), 2 distance root-mean-square (2dRMS)), standard deviation, ellipse error (circle error probable (CEP), spherical error probable (SEP)), and sigma, which all reflect the distribution of points about the mean value, or the random error of a data set in a variety of ways. CEP describes the horizontal distribution of data points of which 50 % lie within a specified circle radius. For example, a CEP value of 50m implies that 50 % of all data points collected will fall within a 50 m radius of the true position (noted as CEP R50). This can also be specified to 95 % of all positions are within a set radius of the known position (e.g. CEP R95). It is important to note that the specification of a CEP of 50 % or 95 % does not indicate the distribution of the remaining 5 % or 50 % of positions; therefore thorough data interpretation is critical. The same is applied to the SEP although this is a three dimensional expression of the data distribution that is analogous to CEP. The SEP is statistically expressed similarly to CEP in that if 50 % or 95 % of the data is within a specified spherical radius from the mean position it is expressed as SEP R50 and SEP R95 respectively.

The standard deviation is primarily a two-dimensional measure about a true position, which is expressed as a Sigma value. In relation to GPS, standard deviation is the dispersion of a set of data points about a mean value. A critical point to understand is that the standard deviation radius represents the distribution of positions during the sampling epoch, but does not represent the accuracy of the average position. The sigma value functions as a measure of the quality of the standard deviation. This value can be calculated using one variable for a distribution of positions. For example, the sigma value is calculated through determining the standard deviation of the northing positions with respect to the mean position for a data set. There are various measures or levels of quality of sigma values; 1 sigma signifies that 68.3 % of all positions are within 1 sigma value of the mean position, 2 sigma is representative of 95.4 % of positions are within two times the sigma value, 3 sigma represents 99.7 % of the measured positions are within 3 sigma values of the average position. Sigma 2D and 3D

represent the quality of the standard deviation in two and three dimensions with the similar sigma levels. The RMS is a linear expression, root mean square of radial errors from a true position. The 2dRMS is determined through multiplying the horizontal dilution of precision (satellite geometry measurement) by the standard deviation of the measured pseudoranges using covariance analysis. The only complication of this measure is that the probability of each of the measures is not constant due to the changing the horizontal dilution of precision with each measure. The 2dRMS values ensure that 98 % of all positions sampled are within a specified radius from the mean position. The percent levels with RMS and 2dRMS reflect the confidence that the set percentage of points are within the defined radius from the mean position. A greater confidence level in the positional data creates greater uncertainty of positional accuracy, due to an increase in the radius in which the points fall.

It is critical to understand the statistical expression of accuracy of GPS data in order to provide accurate data interpretation and appropriate statistical expression.

Accuracy and Precision

Accuracy and precision are two qualifiers used commonly when discussing the error of any measurement tool such as GPS. It is critical that one does not misuse or equate the two terms. *Accuracy*, in relation to GPS, can be defined as "the degree of closeness or conformance between the estimated or measured position, time, and/or velocity of a GPS receiver and its true time, position, and/or velocity as compared with a constant standard" (British Columbia Standards, 1997). Accuracy can be qualified as a statistical measure of system error and requires relative, reliable, and predictable characteristics. *Precision*, in respect to GPS, can be defined as a measure of the tendency of a set of sampled positions to cluster about a point determined by the set, but yet not necessarily at a known, pre-measured or specified point (British Columbia Standards, 1997). *Relative accuracy*, in relation to GPS, can be described by a receiver measuring two separate positions and its ability to determine the actual distance between the two points. Therefore, relative accuracy does not imply that each of the two points measured is accurate to the true known positions, but that the distance measurement between the two points is accurate (British Columbia Standards, 1997).

The analogy of a dartboard can be used to clarify the difference between the terms accuracy and precision. If one were to throw darts at a dartboard and all of the darts clustered at the centre of the board about the "bull's eye", your throws would be accurate because all of your darts were clustered at the exact centre of the board. If you were to throw more darts and they were to cluster at one point left of the "bull's eye", then you could say that you were precise, but since you were unable to cluster your darts about the centre of the board, you would have low accuracy. Therefore, the precision of a measurement instrument does not imply that the measurements are accurate, although accuracy implies that the instrument is precise. If there were two clusters of points on a 'bull's eye' board and each cluster of darts thrown had to be a specified distance apart, each cluster could or could not be on the bull's eye, but the distance in relation to each cluster would be accurate. Therefore, relative accuracy would indicate that the clustering of the points would imply that they were precise, but not necessarily accurate, although the cluster of points would have to be an accurate distance relative to each other.

For the purpose of kinematic assessment and understanding human movement with respect to position, velocity and acceleration, an exact earth referenced position is not necessarily required. Although the dynamic relative accuracy of sampled positions is integral in order to observe an accurate kinematic description of movement.

There is also an important distinction to be made between R*elative Accuracy* and *Kinematic Relative Accuracy*. Relative accuracy, as discussed previously, is the ability of a receiver to determine a position statically, relative to another point. For example, if a GPS receiver samples at one specified location and then samples at another specified location, relative accuracy is the ability of the receiver to accurately determine the distance between the waypoints. Continuous sampling is not required. Kinematic relative accuracy involves the receiver sampling while in motion, which requires continuous data logging. A key point is that when continuous sampling is required, the sampling rate of the GPS receiver will affect the relative accuracy, dependant upon the speed of the motion. For example, if a GPS receiver only sampled a position every 5 seconds and one were to walk in a straight line at a 1 m/s pace, the distance traveled over the sampling interval would be 5 m. The positions sampled at a 5 second sampling rate interval would be relatively accurate due to the straight path and constant walking velocity. If a soccer player were sampled at 5 second intervals while rapidly changing direction and velocity, the relative positioning measured from one

sample to the next would likely be inaccurate. Due to the relatively low sampling rate in comparison to the movement frequency, the data sampled would not be an accurate description of the movement. Therefore, the total distance and velocity measured between the two positions sampled would be inaccurate, both absolutely and relatively because the frequency of the movement and the velocity are non-constant and the sampling rate is less adequate for the movement frequency. Shannon's sampling theorem specifies that in order to provide an accurate measurement of a signal the sampling rate should be equally spaced and a minimum of twice the maximum frequency of the signal, which is termed the Nyquist sampling rate (http://www.euphoria.org/home/help/nyquist.html). In order for an accurate description of the movement pattern to be sampled, the Nyquist sampling rate should be the minimum sampling rate employed. Shannon's sampling theorem applies to the measurement of human movement. Therefore, the Nyquist sampling rate is a critical variable in kinematic relative accuracy that is required in order to determine if GPS can provide an adequate description of the motion.

Methods of Error Correction

Differential GPS

Differential GPS (DGPS) is a technique that enables correction of positional errors through the co-operation of two receivers, one that is stationary (termed base) and another that is roving (termed rover). Both the base and the rover receiver make simultaneous measurements. The base station receiver samples all the satellites within its FOV, which assimilates measurements into a solid local reference. The data collected at the base station is used to determine ephemeris and timing errors for each individual satellite, which can be applied for post-process correction. DGPS requires that both the base and rover receivers record similar individual satellite signals within the same FOV during the identical epoch (time interval) in order for correction of positional errors. Essentially, DGPS corrects positional errors at an unknown location (rover receiver data) with measured errors at a known position (base station receiver data). Reduction of error common to both the base and rover receiver (atmospheric effects, ephemeris, and satellite/receiver clock error), termed common-mode error, is possible with the use of DGPS. Error due to multipath or

receiver noise is not corrected through DGPS techniques because exposure of "ground" errors is individual to both base and rover receivers. The common-mode errors are more easily corrected when the receivers (base and rover) are close in relative distance (<100 km). Using DGPS, the absolute positional errors are typically reduced to 0.7 to 3.0 m horizontal error for dynamic, positioning measurements (Leick, 1995); however systematic evaluation in continuous human motion tracking has not been performed.

Post-Processed Differential GPS Correction

Instantaneous accurate positioning is not always necessary or possible for certain applications. Therefore, the method of post-process DGPS corrects for the inaccuracies after the data has been collected. The advantage of this correction method is that a real-time radio link is not required for data collection. For this method, both roving and base station receivers log the satellite pseudorange data, although the base station collects positional data at a known position during the same time period the rover receiver is collecting data in the field. The data collected by the base station is then merged after the sampling period has occurred. Once the errors are measured for the sampling epoch, the differences are applied to the roving receiver data, which derives the corrected position. The disadvantage of this method is the accuracy of the roving receiver's position is unknown until the data is corrected.

Remote base station

The second method of post-processed DGPS involves the use of pseudorange data that has been collected at a fixed reference base station that is controlled by various interest groups. The advantage of utilizing GPS reference station files is the convenience of Internet access that enables post-processed differential correction without the cost of a second base receiver. (e.g. http://www.trimble.com/trs). The data set for each sampling epoch can be downloaded for differential correction. This enables DGPS without the requirement or expense of a base station receiver.

Real-time DGPS Correction

The second method of post-processed DGPS can be applied in real-time by broadcasting the timing and ephemeris corrections from the base station to the rover using

one-way radio (AM or FM) communication. Real-time and post-processed DGPS differ in present versus post sampling accuracy, respectively; real-time DGPS tells you where you are and post-processing DGPS tells you where you have been. The accuracy realized with post-processed techniques is provided at the instantaneous moment through real-time DGPS, but only if the real-time data link with the base station or with a real-time DGPS data source is maintained. Therefore, there is an industry standard for real-time data links (RTCM (Radio Technical Commission Marine) SC-104) to ensure quality of the real-time precision. The disadvantage to this system is that a data link must be maintained, although the major advantage is that an extra receiver is not required.

A.M. beacon: Real-time corrections can be transmitted by radio link. The U. S. Coast Guard maintains a network of differential monitors and transmits DGPS corrections over radio beacons covering much of the U. S. coastline. DGPS corrections are often transmitted in a standard format specified by the RTCM.

F.M. radio station side band: Real-time DGPS corrections can be transmitted in a side band of F.M. radio.

Satellite – Wide Area Augmentation System (WAAS) was developed by the FAA (Federal Aviation Association) to enhance the accuracy of the current GPS system for greater aviation utility. WAAS utilizes a group of surveyed base stations, a master control station and two geosynchronous satellites. These base stations collect data on clock timing and ephemeris errors for each individual satellite within its FOV. Once the base station data has been differenced with the known position, the errors are calculated and transmitted to two INMARSAT III geostationary communication satellites. The two geostationary satellites then transmit the correction data, received from the master control station, to any WAAS enabled receiver. This use of communications satellites (INMARSAT III) have been employed to broadcast the correction data to suitably equipped GPS receivers, which provide the same real-time telemetry of position to a remote observer as other real-time techniques (United States Satellite Navigation Program Status, 1999).

Real-time Internet: This method of DGPS enables the use of the Internet for real-time DGPS data correction. The procedure involved in delivering real-time DGPS over the Internet requires that a base station collects, edits, and compresses the raw GPS data at a remote site. Once the pseudorange data is collected, it is then transmitted over the Internet to the processing station. The data is then compiled and studied for error enabling precise determination of orbits and timing.

Dual Frequency DGPS

Dual Frequency DGPS varies from regular DGPS in that the differential corrections are derived through using the carrier frequencies, which as discussed previously, have a greater resolution than the C/A and P(Y) codes. The L1 and L2 carrier frequencies, due to their higher level of accuracy, are differenced to each other in order to provide a higher level of positional accuracy. Through this method, errors in the ionosphere, troposphere, ephemeris and clock errors are corrected for due to the differences noted in the L1 and L2 carrier frequencies. Positioning and corrections using both the L1 and L2 carrier frequencies enable faster and higher positional accuracies than using only one code, although this correction method is only available to authorized military users due to the use of the L1 and L2 carrier frequencies.

Carrier Phase Correction

Differential GPS utilizing the carrier phase correction technique involves differencing the frequency that modulates the satellite PRN code. This enables a more precise satellite pseudorange measurement due to the precision or finer resolution of the carrier frequency. Carrier Phase correction also involves a base and rover receiver, which must be within 30 km of each other to enable accurate ionospheric correction.

The GPS satellite signals have a characteristic PRN code, which has a bit rate of 1 MHz, that is modulated by two carrier frequencies, L1 (1575.42 MHz) and L2 (1227.65 MHz). When a satellite performs a pseudorange measurement, it measures the time duration of the satellite PRN code from its initial transmission to the receiver signal acquisition. With carrier phase (which is a binary signal), the signal data chips seem very similar, although there are minor variances. The analogy of a ruler can be made to describe how a position can be determined

using the carrier phase. Imagine one ruler, which measures from the receiver, and one that measures from the satellite. The receiver will line up the rulers to determine its' distance from the satellite. If the ruler only measures to the centimetre level, or the signal transmits at a lower rate like pseudo-random code (1.023 MHz), then the accuracy or resolution of the measurement will be limited to the centimetre level. If the ruler also has millimetre gradations, or the signal transmitted has a sub-frequency which oscillates at a higher rate like carrier phase, then the receiver can determine the satellite pseudorange to the centimetre level (or use the PRN code), then use the millimetre gradations with a finer resolution to determine distance to the millimetre level with ease due to the narrowing of centimetre levels. Resolving the carrier phase ambiguity, which is the ambiguity noted due to the similarity of the carrier phase, requires determination of the code phase position to enable analysis of the fine binary carrier phase. This means that a position solution determined using the code phase is required to decrease the ambiguity of the similar carrier phase. The carrier phase that is sampled over the code phase position can then be analysed to determine a finer or more accurate position solution.

Current Applications

GPS technology has revolutionized a diversity of fields such as precision agriculture (Buick, 1997; Webster & Cardina, 1997), military operations (McCarthy & Munkacsy, 1997; Demczuk, 1998), fleet tracking (Lobo, 1998), geographical surveying (Segall & Davis, 1997), mining (Peck & Hendricks, 1997), navigation, including marine, land and aviation (Rowlands *et. al.*, 1997) and numerous other neoteric fields. The advent of this technology has also created a new commercial sector with the development of many corporations that utilize this technology as a primary source of revenue generation. A select number of companies have developed GPS technology to provide tracking or monitoring of any type of mobile asset, which allows their clients to monitor and manage their personal possessions or property (Sierra Wireless Inc., Richmond, BC; www.sierrawireless.com). This service is quite costly due to the duplication of satellite transmissions for monitoring purposes.

Aside from the commercial aspects, the development of GPS technology to externally monitor an object has facilitated wildlife management studies (Lutcavage, 1997; Rempel & Rodgers, 1997; Sisak, 1998) that have generated tracking or kinematic data of various animal behaviors such as migration, mating patterns, etc. While the utility of GPS to track the movement of various creatures has been studied, the application of GPS to study human motion has not been extensively explored. The only method used presently for human tracking is utilized within the judicial system to track the movement of convicts (SMART technology, Pro Tech Monitoring Inc, Palm Harbour, Fla.; www.ptm.com).

Human GPS Research

The application of GPS technology to human movement studies has primarily focused on assessing the accuracy of GPS for velocity assessment of human movement. There are a few recent studies that discuss the use of GPS for this purpose (Demczuk 1998; Perrin *et. al.,* 2000; Schutz & Chambaz, 1997; Schutz, & Herren, 2000; Terrier *et. al.*, 2000a, 2000b, 2001; Larsson & Larsen, 2001)

There is a primary group of researchers, most notably Schutz and colleagues (1997, 2000) that have examined the accuracy of GPS derived human velocity. The objective of the initial study performed by Schutz and Chambaz (1997) was to "utilize GPS to determine the exact location of individuals on earth." The study design evaluated the capabilities of

GPS and chronometry to assess various velocities of walking, running and cycling in comparison to the average velocity derived from chronometry assessment.

The initial study used a single subject (25 year old male, mass: 75 kg, height: 180 cm, percent body fat: 12 %) that was selected to perform all of the study trials on an athletic track. All trials were performed using a portable metronome in order to time the cadence to enable walking, running or cycling at near constant velocities. The GPS instrumentation that was used in this study was a consumer grade GPS 45 (Garmin, Lenexa, KS 66125, USA). There were nineteen velocities of walking and twenty two velocities of running assessed ranging from 2 – 20 km/h and 35 cycling velocities ranging ~40 km/h. The instantaneous velocities derived by the GPS receiver were averaged over a 1-minute time period. The GPS averaged velocities were then compared to the average velocity determined through the time measured by chronometry over a measured distance.

The results of the study found that there was a high correlation ($r=0.99$, $P<0.001$) between the known velocity and calculated velocity over a range of velocities up to 40 km/h. Schutz and Chambaz (1997) utilized the higher bike velocities derived from the bike tachometer for comparison to GPS derived velocities, which confirmed the linearity of response noted in the walking and running velocities. Variability noted in the walking, running and cycling assessments were 1.1 km/h, 0.7 km/h, and 0.8 km/h respectively. It is interesting to note that Schutz and Chambaz did not put these error levels into perspective. At a slow walking velocity, for example 4 km/h, an error level of 1.1 km/hr equates to a 27.5 % error level. This is quite large and would not provide an accurate description of human kinematics.

Schutz and Chambaz (1997) noted the advantages and disadvantages of using such an instrument for velocity assessment. They commented on the intentional signal degradation by the United States DoD and that the results obtained would improve without this degradation, although this source of error could be corrected for through differential GPS techniques.

Schutz and Herren (2000) performed a second study on GPS that focused on the use of DGPS for assessment of human locomotion. In their study, the walking and running trials were performed by a single subject (age: 24, mass: 70 kg, height: 187 cm, described as in good fitness). The rational for using an individual subject is that the physical and physiological characteristics of the individual would not influence the accuracy of GPS data collected. The

study protocol required the subject to perform 12 walking trials of 100 m and 15 running trials of 200 m in distance (measured by a calibrated topometric tape) performed at varying velocities ranging from 2.9 km/h ~ 25.2 km/h. The instrumentation that the subject wore was a Garmin 12XL (Garmin International, Olathe, KS) with the antenna attached to a cap. The GPS receiver was coupled to a DGPS receiver (RXMAR 1, Aztec SA, Strasbourg, France), which was placed on the subject in a bag about the subject's waist. The study was performed by recording the corrected GPS data onto a laptop, which was carried by the subject in a backpack during the walking assessment and then transferred to a car, which travelled beside the subject for the running assessment. The GPS recorded position and velocity at a frequency of 0.5 Hz (1 sample every 2 seconds)

Three methods were used in the second study to assess velocity: 1) Doppler derived velocity, 2) DGPS derived velocity at 6 second intervals, and 3) DGPS derived velocity averaged over the total distance. Each velocity assessment technique and varying velocity

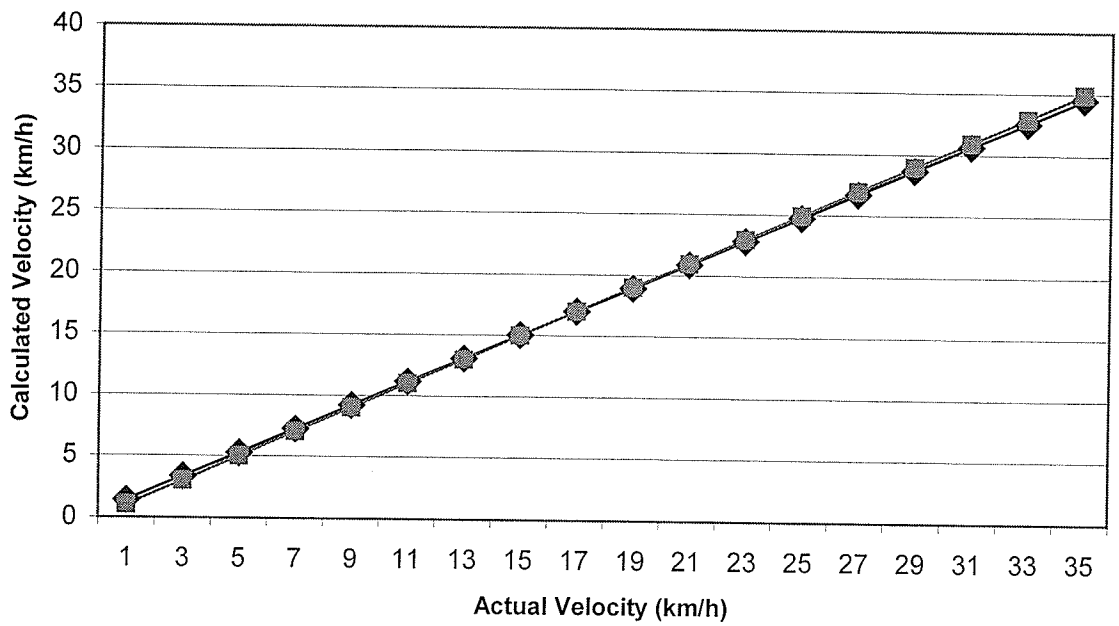


Figure 2 A comparison of GPS versus calculated velocity assessment from study 1 (squares) and 2 (diamonds) performed by Schutz, *et. al.* (1997, 2000). The equation for the slope of the line in study 1 is 0.974*(X)+0.42 and for study 2 is 0.9973*(X)+0.036. Note that there is no visible difference in the slope of the lines and therefore no difference between GPS and DGPS velocity assessment capabilities.

was averaged over the total sampling distance to compare to the "actual" chronometry derived velocity. The results demonstrated that the velocity derived from the DGPS 6

second displacement/time data was the most accurate assessment of velocity, when compared to the chronometry derived velocity data. The variability in utilizing this method of velocity assessment was 0.08 km/h for walking and 0.11 km/h for running. Schutz and Herren (2000) noted that there was an excellent correlation (r^2=0.9997) for the relationship between the velocity measured through chronometry and the velocity data derived from DGPS 6 second displacement (figure 2). The variability noted within the running trials was 0.6 km/h for 6s displacement derived velocity versus 0.3 km/h to the Doppler derived velocity.

The investigators concluded that DGPS demonstrates the velocity assessment accuracies required for assessment of human movement velocity and that it compares favorably to the chronometer's error magnitude (0.3 s - DGPS and 0.2 -0.3 s – Chronometry). Schutz and Herren (2000) also compared their results from the previous non-differential GPS study and concluded that their results had "substantially greater" accuracies with DGPS. They also claimed that the "accuracy of speed assessment by differential GPS is clearly high enough for any practical utilization in sport physiology and medicine." (Schutz & Herren, 2000). It was noted that the ability of DGPS to assess velocity on a curvilinear path would be decreased, such that it would underestimate the velocity.

The authors identified the utility of GPS technology for both research and practical applications due to its' ability to objectively assess velocity independent of a constrained laboratory environment. They noted that this portable measurement technique enables an unencumbered assessment of walking for extended periods of time and distance. The concurrent physiological response to walking, running, and cycling in both outdoor track studies were not measured, although they noted that GPS measurements could be used to determine energy expenditure. Schutz and Herren (2000) noted that GPS combined with other measurement devices such as heart rate monitors (HRM) and tri-axial accelerometers would facilitate further kinematic and physiological analysis of movement. Schutz and Herren felt that the practical aspects and utility of GPS still required further investigation to assess and demonstrate its' application within rehabilitation, sport and medical settings.

Both studies performed by Schutz *et. al.*(1997, 2000) focused specifically on demonstrating the use of GPS for assessment of human movement velocity. The initial study averaged velocity over a 1 minute interval and when analyzed demonstrated a correlation value of R^2=0.99 from a linear regression equation of speed $_{GPS}$ (y) = 0.42 + 0.974 speed $_{chrono}$. The second study using DGPS examined the instantaneous Doppler derived velocity, 6 second averaged, and 1 minute averaged velocities. They noted that the greatest accuracy in comparison to chronometry was the 6 second averaged velocity data, which noted an R^2=0.9997 correlation value from a linear regression equation of speed $_{GPS}$ (y) = 0.997x + 0.036 speed $_{chrono}$. Each of the studies, in comparison, produced similar correlation values, which also demonstrated overlapping lines of regression (Figure 2). Although, these studies produced similar R-values and highly correlated with chronometry, the initial study performed noted that the "present relative accuracy was inadequate for assessment of low walking speed." (Schutz & Chambaz, 1997). Upon examination of the linear equations from both studies, the variance between the different velocity sampling rates (1 minute vs. 6 second averaged velocity) can be noted when comparing the absolute percent error, derived through differencing the measured and known velocities, of the 1 minute

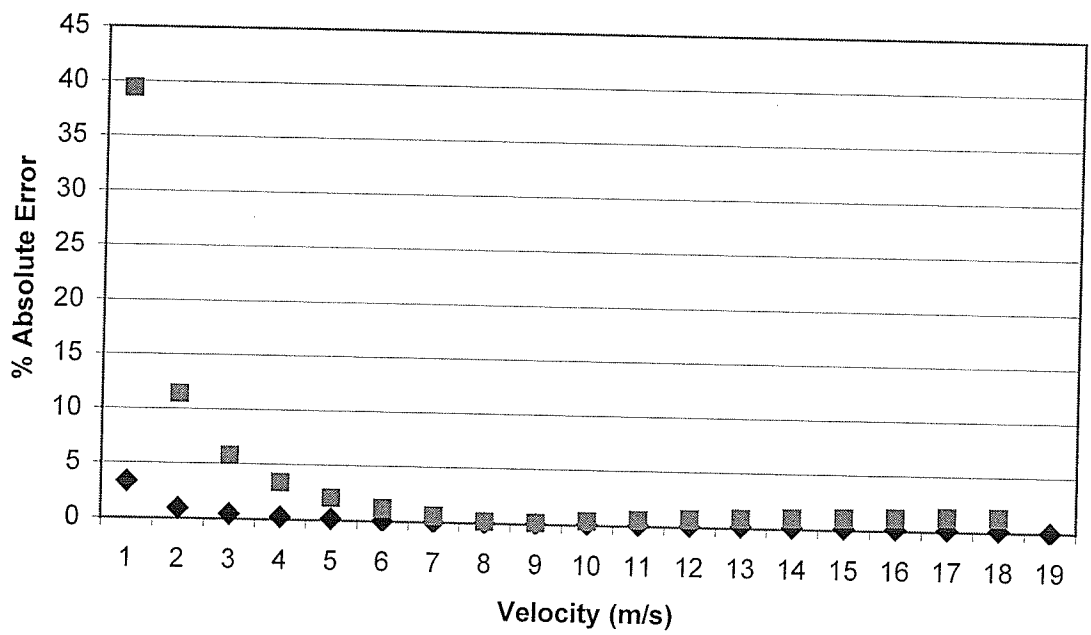


Figure 3 This figure represents the comparison of the absolute percent error between the velocity assessment capabilities of the two studies performed by Schutz (1997, 2000). These data were derived from the linear regression equations provided in each study (study 1: 1 minute average velocity represented by the squares; study 2: 6 second average velocity represented by the diamonds).

(study 1) and 6 second (study 2) averaged velocity data. Figure 3 demonstrates in study one and two that the absolute percent error is greatest at low walking velocities and this error attenuates with an increase in velocity. Although the 1 minute averaged velocity has a greater percent error value, the absolute percent errors noted with the 6 second average velocity data at low walking velocities (1 to 3 m/s illustrated 3 to 1 % absolute error respectively), are relatively great enough to have an effect on the accuracy of velocity assessed.

Comparing velocity measurements over different sampling time periods (study 1 compared 1 minute averaged velocity to the averaged total distance velocity; study 2 compared instantaneous velocity to 6 second and total distance averaged velocity data) is not appropriate. The second issue is that averaging velocities will always minimize error because it will smooth the random fluctuations, therefore the true error levels in velocity assessment were undetectable. The problem with the work by Schutz and colleagues is that they did not have an independent *instantaneous* velocity measure (such as Doppler radar or Lidar) to compare with the GPS derived velocity measurements over similar time periods.

Physiological measures and GPS were first applied in combination by Demczuk (1998), when first generation GPS equipment was employed with HRM and a portable ergospirometry system to measure energy expenditure of soldiers in a battle simulation. Their ability to measure the physiological response to the battlefield simulation was limited by the sampling time period of the portable metabolic analyzer (10 minute intervals per individual) and the sampling rate of the HRM (60 second average heart rate), which was logged from all study subjects. One officer wore the GPS during the battle simulation; therefore the movement patterns described by the GPS unit were generalized to the group. This is a useful indicator of the physical demands of the battlefield simulation, but the movement pattern is specific to the individual and therefore an estimate of energy expenditure can be made to this individual only. Although, a pattern of movement for the entire battlefield simulation was logged, on analysis of the GPS data, the study noted marginal GPS accuracy levels. Demczuk recommended that future studies acquire continuous, concurrent physiological data in combination with more accurate position data for each individual over the entire simulation time period.

More recently, two studies (Terrier *et. al.* 2001 and Larsson & Larsen, 2001) have combined physiological measures with GPS movement measurements. The most recent

study performed by Schutz and coworkers (Terrier *et. al.* 2001) was primarily a descriptive study to determine if GPS data could be utilized to assess the external mechanical work performed in outdoor walking. Five subjects walked on an athletic track for 5 minutes at five variable, imposed stride frequencies. The subjects wore a backpack, which contained a differential GPS (with carrier phase analysis) that sampled at 5 Hz, along with a portable indirect calorimeter that recorded breath-by-breath energy expenditure. The difficulty with utilizing this GPS equipment is that it is cumbersome to wear (involves wearing a backpack containing 4.8 kg of equipment), as well as they noted difficulty with antenna placement and movement, which added an extra oscillation that was indistinguishable from trunk vertical displacement. The physiological (energy expenditure) and GPS movement data was interpolated and analyzed for the last 2 minutes of steady state exercise for each stride frequency. A description of the interpolation method was not discussed and this is critical to know to ensure that the data was interpolated appropriately and that the derived waveform reflects the original waveform pattern.

Although this study was to progress their GPS tracking research to combine physiological measures in order to provide a measurement of mechanical work, their ability to provide a true measurement of the kinematic and concurrent physiological response to human movement is limited. Terrier, *et. al.* did note that a full validation of the utility of GPS to measure mechanical power of walking is required once a more ergonomically designed GPS receiver has been developed. The equipment utilized hindered the study and to date, a detailed assessment of the sampling characteristics of GPS have not been analyzed to determine their effect on the relative accuracy of GPS.

Larsson & Larsen (2001) also performed a field test to determine if DGPS could be combined with physiological measures. In their field test, a GPS 12CX (Garmin International, Inc., Olathe, KS) and a RXMAR 2 differential unit (Aztec SA, Strasbourg, France) were used to obtain positional data at a 5 second sampling rate and the velocity (using Doppler shift) was sampled at 2 second intervals. A MetaMax II (CORTEX Biophysik GmbH, Leipzig, Germany) portable metabolic gas analyzer and a portable HRM (Polar Electro, Kempele, Finland) were utilized to measure physiological data at 10 second sampling interval. The 10 male orienteers performed a 4.3 km orienteering course wearing the GPS and physiological measurement equipment. The oxygen uptake, carbon dioxide excretion, and HR were measured every 10 seconds over the entire 4.3 km course.

Their validation method of DGPS position, displacement and velocity (numerically derived and Doppler) was performed on two fixed positions and measured every 2 seconds on a 115 m straight asphalt road at 10 different walking and running velocities. The two fixed positions were determined through the National Land Survey of Sweden angle. The 115m asphalt road measurements for distance were differenced against a measuring tape measurement and the velocity measurements were derived from the distance measurement and time measured by chronometry for all 10 velocities performed.

The validation method of the GPS unit is inadequate in order to assess the utility of GPS to provide an accurate description of human movement. The two fixed position measurements will only assess the static positional accuracy of the GPS unit. This has been studied extensively in the literature and does not assess the dynamic positional accuracy of GPS. The 115 m straight road test provided an idea of the measurement capabilities of GPS, although it did not assess the sampling capabilities of GPS in curvilinear paths. The primary focus of the 115 m straight road test was to assess the velocity measurement capabilities, although these were assessed against the average velocity through chronometry and distance measurements that can be considered a downward comparison. The DGPS position and Doppler velocity was measured every 2 and every 5 seconds, respectively. Over a relatively small and straight distance, the measurement performed might be very accurate when compared to a calibrated measurement. They also performed distance measurements over specific sections of the 4.3 km course. The results noted had a relatively large range; 115 m measurements between 110 m-120 m and 247 m course distance measurements between 242-250 m.

The physiological data was measured at 10 second intervals, which was then related to the DGPS data that was collected at 2 second intervals over the 4.3 km course. The method that the variable sampling rate data was interpolated for analysis and observation in the study was not discussed. The ability of this data to provide an adequate description of the human movement in relation to the physiological responses is questionable.

Throughout the testing period, a loss of satellite and differential correction signals was noted. This affected their positional and velocity measurement accuracy, which was estimated and noted in their study. The duration of the satellite/differential signal loss and the effect of the change in satellite configuration were not quantified in order to determine the overall effect.

Satellite configuration, sampling rate, and FOV obstructions were all variables that were noted in their study, which affected the accuracy of the position and velocity measurements. The analysis of the effect of these variables on the dynamic relative accuracy of GPS has not been performed in this study or any other human movement studies that have been performed to date.

In order to assess human movement capacity during gait it would be necessary to be able to discern walking distances (total distances traveled) over a broad range from a only a few meters (less than 10) in a rehabilitation setting to multiple kilometers in sporting applications.

Human GPS Research Considerations

A new era for GPS has developed through the advancement of technology (receiver capabilities) and satellite signals (SA-off). Developments within this field have provided a new level of accuracy, both absolute and relative, that can be easily obtained and potentially applied within the field of human movement assessment. There are characteristics of GPS that are critical to define in order to delineate the utility of this tool for assessment of human movement that have been previously unanswered.

As previously noted, the static accuracy of GPS, both SA-on and SA-off, have been documented extensively to date (Strachan, 2000; Schreenan *et. al.* 1996), although this does not allow the assumption that GPS is capable of human movement assessment. It is the accuracy of the positions relative to each other, not the exact earth-based position of the GPS measurement that is critical to quantify in order to determine the suitability of GPS for assessment of total body kinematics.

The sampling rate will effect how well a movement is described and therefore is a key parameter to consider when analyzing GPS measurement for human movement assessment. The Nyquist sampling theorem specifies that the sampling rate should be two times the movement frequency (http://www.euphoria.org/home/help/nyquist.html). If the sampling rate is set too low the GPS unit will provide a less detailed description of the movement performed, especially if the individual is walking at low velocities, in a curvilinear or cutting, angular path. The positional data, as well as the instantaneous or numerically derived velocity data, will be inaccurate in all three instances due to the attenuation of the true path traveled, or the true velocity of the movement. GPS has the capabilities to

accurately assess higher velocities of human movement, as demonstrated by Shultz *et. al.* (2000), but lower velocity movement assessment capabilities of GPS have not been examined , which is primarily affected by an adequate sampling rate. Since the degree of absolute accuracy of the GPS determined position is relatively constant over speeds, when an individual is walking at a low velocity this will result in a higher relative inaccuracy (percent error), which will diminish with an increase in movement velocity. It is critical to note that in Schultz's velocity graph a broad range of velocities were measured. GPS is less accurate at lower velocities, therefore when a broad range of velocities was assessed the accuracy levels or inaccuracy at lower velocities was attenuated over the spectrum of velocities analyzed. This is also true in measuring shorter distances, in that the measurement error is constant and will have a greater effect on shorter distances than longer distances traveled. Therefore the accuracy of GPS at lower velocities and shorter total distances traveled is unknown and is primarily affected by the sampling rate of the GPS receiver. To date, studies have been performed to assess the broad picture of GPS kinematic capabilities leaving the need for studies that perform specific or systematic evaluations in order to determine the capabilities of GPS for human movement assessment.

Velocity can be determined through two methods, one is numerically derived from positional data and the other is through Doppler shifts. To date the GPS units used in human movement studies that provide Doppler velocity measurements have been large and cumbersome. This does not provide a true picture of the normal human movement pattern of an individual because they will change their kinematics due to the restrictions in movement. Over the past few years smaller, lighter units, which an individual can wear that allows full freedom of movement have been produced. These smaller and lighter systems log positional data, which can be used to numerically derive the velocity. Since these units enable the most unencumbered picture of human movement, they will be assessed in our study in order to determine their kinematic assessment capabilities.

As well, the configuration of satellites and their effect on accuracy and precision is measured by DOP level. The effects of a change in satellite configuration, as well as optimal satellite configurations have not been delineated. Schutz *et. al.*(1997, 2000) and Terrier *et. al.* (2000a, 2000b & 2001) did not report the sampling DOP level (including loss of satellites or FOV obstructions), which would effect the positional precision or relative accuracy of GPS measurements, including velocity assessment capabilities. The study

recently performed by Larsson and Larsen (2001) did report a loss of satellite signals due to obstructions in the FOV or satellite shifts during the sampling period. They reported a loss of adequate signal that occurred 1.6 times during a single field test, which was calculated as a 23.4 m data gap. They determined that the velocity could be averaged over this distance, although the study subjects' position or velocity over this period cannot be determined. Larsson and Larsen (2001) only noted that a loss of satellite signal occurred and there was no discussion in regards to DOP level changes which occur through loss of SV signals or satellite geometry changes and its' effect on accuracy. Therefore, the significance of DOP level needs to be determined in order to set adequate sampling criteria for human movement measurements.

Obstructions in the FOV can also affect the precision of position, which occur due to any obstruction in the satellite signal to the receiver and can be caused by buildings, tree canopy, or improper placement of the GPS unit or antenna. This parameter is inconsistent and therefore its effect cannot be quantified. Although, the error that is created due to obstructions in the FOV can be minimized through antenna or receiver placement and sampling environment.

Presently, studies have not critically examined the relative accuracy of GPS after the DoD turned off the intentional signal degradation. Further, the dynamic positional relative accuracy of GPS in human motion analysis, which is affected by the sampling rate and satellite configuration, has not been explored systematically to date. This is due to the lack of a technique that enables the quantification and analysis of the GPS dynamic positional accuracy. It is the sampling characteristics of GPS that dictate its relative accuracy, which impact upon its ability to assess low velocity human kinematics and total distances traveled. In order to assess human movement capacity during gait, it would be necessary to be able to discern walking distances (total distances traveled) over a broad range from a only a few meters (less than 10 m) in a rehabilitation setting to multiple kilometers in sporting applications (e.g. marathons). It is this ability of GPS to discern various walking distances that is an important component in the characterization of the capabilities of GPS to delineate very low velocity movements such as an elderly person walking (~0.8 m/s). GPS technology was designed to provide its users with detailed positional information. It is the total, detailed description of movement, including position, time, and velocity, that will

enable researchers, clinicians, and sports enthusiasts to have a greater understanding of various pathological and non-pathological human movements.

Movement Analysis

There are various methods that have been employed to quantify human movement. Some of the sensing technologies that have been utilized to track human movement include inside-in tracking systems (gloves and suits), electromagnetic position, acoustic position, mechanical position, electrostatic position and orientation tracker, in which all are limited to a laboratory setting methods of objective movement data collection (Harris & Wertsch, 1994; Yack, 1984; Mulder, 1994). Video motion analysis is one of the more commonly used techniques for assessment of movement patterns (Everaert *et. al.,* 1999; Lunge *et. al.,* 1999). This system employs markers that are attached to the subject at various body articulations. Temporal and kinematic analyses are achieved through correlating the derived data with a human reference model. There are some complications with the results derived because human skin is not rigidly linked to the skeleton, therefore the markers move relative to the joint articulations and create inaccurate measurements. The other complications noted with this method and others are the constraints of a laboratory setting for testing human movement. Most of the methods involve wire telemetry devices or large equipment that do not permit unencumbered movement outside of a laboratory environment. To date, there is no validated system that enables continuous, objective assessment of unconstrained human movement in an outdoors setting.

Recently developed portable tri-axial accelerometers have enabled the study of energy expenditure. The tri-axial accelerometer derives its estimate of energy expenditure from a proprietary equation that is based upon the measurement of change in acceleration. Changes in acceleration can be measured during physical activity and allow quantification of movement patterns by means of a tri-axial accelerometer. Energy expenditure has traditionally been used as a gauge for assessment of activity levels (Jakicic, 1999), but has never provided a detailed description of activity patterns. This technology has recently been utilized within the Human Performance Laboratory to study the pattern of activity over various time periods, through sampling acceleration packaged as a function of time. The doubly labeled water technique is considered the optimal measurement for determination of total energy expenditure, but this gross measurement does not provide a detailed description

of the pattern in which energy was expended (Schutz & Deurenberg, 1996). Therefore, a detailed description of movement cannot be understood through this method of energy expenditure determination. Although measurement of energy expenditure, both gross measures through doubly labeled water and more descriptive measurements through tri-axial accelerometry have been realized, a detailed description of the kinematic parameters of human movement are not provided through these methods.

The most recent publication of Terrier *et. al.* (2000b) used a GPS and a tri-axial accelerometer (raw acceleration profiles were used) to study various biomechanical parameters of gait. Velocity and acceleration were sampled at 5 Hz using a large, expensive and cumbersome GPS system (Leica System 500, Leica Intl.). A total of 8 subjects were studied while performing four different specified gait frequencies of walking and an individualized running velocity. A tri-axial accelerometer (Physilog, BioAGM, Lausanne, Switzerland) was used to record acceleration profiles at a sampling rate of 1 Hz and was positioned at the individuals' low back. The accelerations recorded by the accelerometers and GPS had a very high correlation (r^2= 0.9998) for each step of the subjects. Although, the ability to measure each individual step was not clearly determined by Terrier *et. al.*. The tri-axial accelerometer measurement of vertical trunk movement was the only method used for measuring the individual steps performed. The measurement of the vertical trunk lift by the tri-axial accelerometer is not specific enough to ensure that each vertical movement not by the tri-axial accelerometer was an actual step performed. Therefore, they did not have a specific method that ensured the measurement of each individual step performed. Terrier *et. al.* stated that they were able to note the intra-individual step variation in velocity and vertical displacement using GPS data, although this is questionable due to the measurement used (tri-axial accelerometry) to compare the GPS kinematic data. Through their testing methodologies and results, Terrier *et. al.*(2000a, 2000b) concluded that the GPS in comparison with tri-axial accelerometry was useful in providing accurate biomechanical gait parameters. Although, the questionable ability of the tri-axial accelerometer to measure individual steps may have altered the actual movement pattern and therefore would artificially enhance the correlation value of the GPS step measurement. The measurement of human movement acceleration profiles can provide insight into the kinematics of human movement, but due to the methodologies used, the conclusion in regards to the utility of GPS for measurement of biomechanical gait parameters is questionable. As well, the GPS

equipment employed in this study does not enable an unencumbered, continuous assessment of human movement in an outdoor environment due to the limitations of portability of the GPS unit.

Summary

The recent removal of SA by the United States DoD has dramatically improved the absolute positional accuracies of GPS. Various differential correction techniques have also augmented the positional accuracy of GPS. Understanding the technological requirements of each type of correction method, along with the improvement in positional accuracy, both absolute and relative positional accuracy, is key to determine the most appropriate method for kinematic assessment. With these technological developments, the potential to quantify human movement is possible through the development of these GPS sampling requirements. Currently, literature exists describing and demonstrating the *static* absolute positional accuracies of GPS (Geodetic Survey Division, Geomatics Canada, 1996; Heroux & Villeneuve, 1996). To date, there is no method to assess and validate the *dynamic* relative positional errors, or relative accuracy. Development of a methodology to observe the characteristics of continuous GPS kinematic tracking will facilitate an understanding of the utility and limitations of this tool.

Only recently has GPS been applied to the field of kinematics for assessment of human velocity and acceleration. The studies performed to date (Demczuk, 1998; Schutz & Chambaz, 1997; Schutz & Herren, 2000; Terrier *et. al.,* 2000a, 2000b & 2001; Larsson & Larsen, 2001) have primarily studied the averaged, not instantaneous, velocity and derived acceleration assessment capabilities of GPS. Aside from the research performed by the groups previously noted, continuous kinematic GPS tracking has not been explored extensively for human movement assessment. The present knowledge of the relative accuracy of GPS has been limited primarily due to the lack of a methodology enabling quantification of the dynamic relative accuracy GPS. The quantification of the dynamic relative accuracy of GPS requires assessment of the sampling characteristics of GPS (sampling rate, satellite configuration, etc.) in order to determine its suitability for human movement assessment. The assessment of GPS velocity measurement accuracy is the focus of the studies performed on human movement. Although higher velocity movement assessment capabilities of GPS have been deemed adequate, the studies performed to date

have not closely examined the sampling characteristics of GPS to determine low velocity movement. Determination of the effect of the sampling rate is most critical because this will influence both the accuracy of the positional data, as well as the derived velocity data.

There is a lack of data demonstrating its utility and relative accuracy for continuous motion analysis. A method of testing the relative dynamic positional accuracy capabilities of GPS for continuous human motion analysis, encompassing assessment of the sampling rate and satellite configuration effect on accuracy, has not been developed or validated for this purpose. The recent advents within the field of GPS provide the technological pre-requisites for quantification of human movement in uncontrolled environments, which are to be evaluated in order to deem GPS adequate for assessment of total body kinematics.

Purpose

The purpose of this research project was to assess the relative accuracy of GPS (SA-off and DGPS) to provide an objective, continuous kinematic description of unrestrained human movement in the outdoor environment. The continuously logged positional data enabled the computation of total distance traveled and velocity from numerical differentiation. This study will provide the foundation for future clinical and applied research studies.

Objectives

Objective 1: Develop a test that enables assessment of relative accuracy of SA-Off GPS and DGPS during dynamic conditions.

Objective 2 - Use the Concentric Circle Test (CCT) and Track Test to evaluate relative accuracy of GPS.

A – *Assess the distance measurement capabilities of different GPS systems.*

B – *Assess the impact of satellite geometry and configuration on relative accuracy.*

C – *Assess the impact of sampling rate on relative accuracy.*

Objective 3 – *Examine the relative accuracy of the GPS systems in a 3.5km field test for comparison to the CCT and track test.*

Clinical Relevance

Through demonstration of the utility of GPS technology with concurrent physiological measurement for assessment of human kinematics, researchers, clinicians, coaches and athletes can explore practical applications. Determination of the sampling rate, which will effect the minimum gait velocity accurately sampled, as well as the appropriate sampling requirements (e.g. satellite configurations, sampling time period) for an accurate kinematic description is integral for clinical and research application. Once this is determined, assessment of human kinematics with concurrent physiological measures can be

examined for its ability to provide greater insight into the total body response to exercise, training or competitive situations in an uncontrolled or natural environment. Currently, measurements of the physiological effects of human movement are largely confined to laboratory settings and therefore, an understanding of the physiological responses to movement performed in an outdoor environment are not well understood in normal, disease, and injury states. The added potential of acquiring a greater understanding of the physiological response to environmental factors such as inclination, windage, humidity, etc. may be possible through an accurate, reliable description of human movement.

Coupling kinematic assessment of movement with the physiological response will provide new insight into various ambulatory conditions (PVD, Parkinson's, MS) and human performance (athletic training and competition). Exploration, using both GPS and physiological measurements within practical and research environments will prove useful for researchers, clinicians and coaches.

GPS Limitations

With the recent technological advances within the field of GPS, there are a few inherent and technological characteristics that prevent the utility of this tool for further human kinematic assessment. Studies are needed to define the limits of the application of this technology to limit the application to the abilities of the GPS systems. For instance, can GPS derived kinematics be used to assess walking ability in humans.

The GPS signal is unable to penetrate buildings or thick canopy, therefore restricting its use to the outdoor environment. Aside from the inherent signal limitations, the primary restriction of GPS technology to date is the sampling rate. For higher velocity and high acceleration sports (such as sports requiring changes in direction) a compromised positional profile would be obtained using a sampling rate of 1 Hz. Current and future technological developments would enable a higher sampling rate and therefore provide an improved kinematic description of high velocity/ acceleration sports.

Methodology

The methodology will include sections that will address the subject selection, instrumentation and the test protocols that were used in order to achieve the outlined objectives. The subject criterion for each of the various tests performed in the study will be discussed. The GPS equipment, including the receiver/monitor specifications and sampling settings that were used to collect the data will be delineated in the instrumentation section. The test protocols for each of the CCT, track test and the 3.5 km field test will be outlined.

Subject

The physiological characteristics of the individual will not influence the GPS receiver sampling characteristics for relative accuracy tests. The subject that was used for this study to perform all GPS tests was a 23-year-old female who is 165 centimeters tall and has a body mass of 55 kilograms. This individual is healthy, defined as not having any type of medical problems within the last 12-month period that required medical attention. There is no known history of neuromuscular disease, arthritic conditions or previous major medical conditions (Appendix A). Informed consent was obtained for the study subject and this individual met the inclusion and exclusion criteria. (Appendix B, C & D)

Instrumentation

Global Positioning Systems

Small, handheld GPS receivers (Trimble GeoExplorer II (TGII), Trimble, Sunnyvale, CA, v. 2.11 firmware/ Garmin GPS III Plus (GIII), Garmin International Inc., Olathe, KS/ Garmin Vista (GV), Garmin International Inc., Olathe, KS) were attached to the subject. The TGII had a size of 15.6 cm L x 5.1 cm W x 1.23 cm D and a mass 0.64 kg. The GIII has dimensions of 12.7 cm L x 5.9 cm W x 4.1 cm D with a mass 0.26 kg. The GV dimensions were 11.2 cm L x 5.1 cm W x 3.0 cm D and mass of 0.15 kg. All of these GPS instruments employ a single frequency (L1 = 1575.42 MHz) receiver that uses broadcast ephemerides (satellite orbital coefficients) to compute positional solutions using the code

phase technique (cf. www.trimble.com). The positional data that was collected by these three units is expressed in meters using the UTM coordinate system. The UTM coordinates in each of the GPS receivers were referenced to the World Geodetic System, 1984 (WGS-84) and altitude was expressed with respect to mean sea level (MSL) using the EGM96 Global geoid.

Each of the GPS receivers used in this study have different setup options and data reduction processes that will be discussed in the following paragraphs.

1. TGII System Setup

For the TGII GPS, a small, remote antenna (65 mm diameter x 20 mm high) was used and securely attached to the head of the test subject using a baseball cap. By placing the antenna on the vertex of the head, an unobstructed view of the sky was obtained which increases the number of satellites used for positional solutions when compared to GPS receiver placement on other parts of the body (i.e. handheld). Increasing the number of satellites usually improves the accuracy of the positional solution by providing an over-determined solution and better geometry (decreased DOP). The TGII GPS receiver was configured in three-dimensional, over-determined mode, which allows a minimum of 5 and a maximum of 6 satellites to be sampled simultaneously. The positional sampling rate was set to "ALL" which provides a variable sampling rate ranging from 0.56 Hz to 2.0 Hz, with an average of 0.73 Hz from the bench test data. We used an elevation mask of 10 degrees (to minimize satellite data arising from multipath (reflections off of objects) or ionospheric delayed data (greater delay of the satellite signal through the horizon)), which would increase the DOP level or decrease the accuracy of the positions logged. The DOP levels and the respective satellite configurations were recorded for each trial.

TGII Data Downloading

The data that was collected by the TGII was downloaded into a PC utilizing a serial interface. The data was differentially corrected using the Pathfinder Office v. 2.11 software (Trimble, Sunnyvale, CA) for post-processing. The TGII GPS was differentially corrected through utilization of base station data downloaded from the nearest base station in Clay County, Minnesota. The data from both the CCT and track test was grouped and segregated into separate files according to the time intervals set between each concentric circle from 1-5

and 10 m in the CCT and from lane line 1-5 of the track test. Both the differentially corrected and non-corrected CCT and track test data was analyzed.

Each individual TGII file from the CCT, track test and 3.5 km run, both differentially and non-differentially corrected, was then converted from the GPS .ssf format into a text based format (.asc format) using the SSFTOASC program (Trimble Pathfinder Offcie v. 2.11, Sunnyvale, CA). The UTM co-ordinates, time stamp, and the instantaneous velocity (m/s) were transferred into the spreadsheet program (Excel, Microsoft Office 2000 Professional, Microsoft Corporation, United States). The DOP values and occupation time for each trial were observed through the Pathfinder Office v. 2.11 software (Trimble, Sunnyvale, CA) and manually recorded into a spreadsheet (Excel, Microsoft Office 2000 Professional, Microsoft Corporation, United States).

2. GIII System Setup

The GIII unit was handheld by the subject throughout the sampling time periods. The receiver observed up to 12 satellites within its FOV, which were used to determine a position solution. The GIII receiver configuration was set to sample positional and velocity data at 1 Hz. This receiver cannot log DOP level and satellite configuration.

GIII Data Downloading

The GIII receiver data was downloaded via a serial interface into a PC, which contains the Waypoint software (http://www.tapr.org/~kh2z/Waypoint/) that enables data to be transferred from the GIII unit. Appendix E contains a raw unprocessed file of GIII data imported from the software program. The UTM coordinates and time stamp data were sampled by the GIII and transferred to a computer. The data was saved into a .csv data format from the Waypoint software program, which separates the individual fields by a comma, that is compatible with importation to the spreadsheet program (Excel, Microsoft Office 2000 Professional, Microsoft Corporation, United States). When the data was opened in the spreadsheet program it is in one column that can be separated into individual columns based upon the comma field separations. Each of the circles (1-5, 10 m radii) of the CCT, the track lane lines 1-5 and the 3.5 km courses were visually inspected. The CCT (1-5 m and 10 m radii circles) and track lane lines 1-5 were segregated according to their individual circles and track lane lines.

3. GV System Setup

The GV receiver was also held in the subject's hand throughout the duration of each of the tests performed. The antenna is internal on this GPS unit therefore, the GV was hand held to ensure that the receiver was able to obtain an adequate number of satellite signals and to minimize FOV obstructions. The GV was set to sample data at a 1 Hz sampling rate. The GV determined a position through sampling up to 12 satellites that were used to determine a position solution. This GPS unit cannot log DOP levels and satellite configurations.

GV Data Downloading

Data collected by the GV including the UTM coordinates and time stamps was downloaded via serial interface into a PC. The software program G7TOWIN (http://www.gpsinformation.org/ronh/) was used to retrieve the sampled data from the GV receiver. Similar to the GIII data reduction process, data was saved as a .csv data format from the G7TOWIN software program, which provides a comma delimited file that allows data importation into a spreadsheet program (Excel, Microsoft Office 2000 Professional, Microsoft Corporation, United States).

Post-processing GPS data

The positional data was processed in order to determine the total distance traveled for each of the individual tests performed by all three GPS receivers and the differentially corrected method. The GPS data was expressed in UTM coordinates that are basically X and Y positions. Table 1 provides an example of the GPS positional data that was obtained in UTM coordinates. The distance that was calculated for each test and trial performed was determined using the following horizontal distance equation:

Table 1 The UTM positional data and the distance measurement between the two UTM positions.

	UTM 1	UTM 2		Distance (m)
X1	625830.583	5525762.967	**Y1**	1.209
X2	625830.748	5525764.165	**Y2**	

Distance = square root $((X_2-X_1)^2 + (Y_2-Y_1)^2))$

UTM coordinates are described in X, Y terms in this equation. Using the data from table 1 the X positions are found in the UTM 1 column with X1= 625830.583 and X2= 625830.748. The Y positions are in the UTM 2 column with Y1= 5525762.967 and Y2= 5525764.165. The full equation to determine the distance using this data would read:

Distance = square root $((625830.748 - 625830.583)^2 + (5525764.165 - 5525762.967)^2)$.

This calculation would equate to a 1.209 distance traveled in meters. Appendix F demonstrates a 10 m circle radii circle sampled by the GIII receiver, which has been fully post-processed to determine the average, minimum, and maximum UTM positions for each X and Y position. The minimum and maximum positions for each X, Y coordinate were differenced to determine the diameter between the two positions. The distance between each individual position was determined using the above stated equation and then summed to derive the total circumferential distance traveled. The GPS circumference measurement was then compared to the known circumference $((10 \text{ m radius} * \pi)^2 = 62.83$ m circumference) to determine the percent error of the GPS measurement.

Test Protocols

Objective 1 & 2- GPS Relative Accuracy Tests

Concentric Circle Test

Shreenan and coworkers (1996) sampled a known radius circle with various GPS receivers in order to illustrate and define differences in receiver characteristics as an internal report for the Government of Canada. We have adopted the idea of a circle measurement, but for the purpose of examining the dynamic or kinematic relative accuracy for the proposed study. A circle test enables a more realistic assessment of GPS sampling capabilities because there is a constant change in receiver orientation, which would occur in daily walking patterns and various sports. Assessments of GPS capabilities where a straight path has been used to quantify the sampling characteristics have not provided a thorough

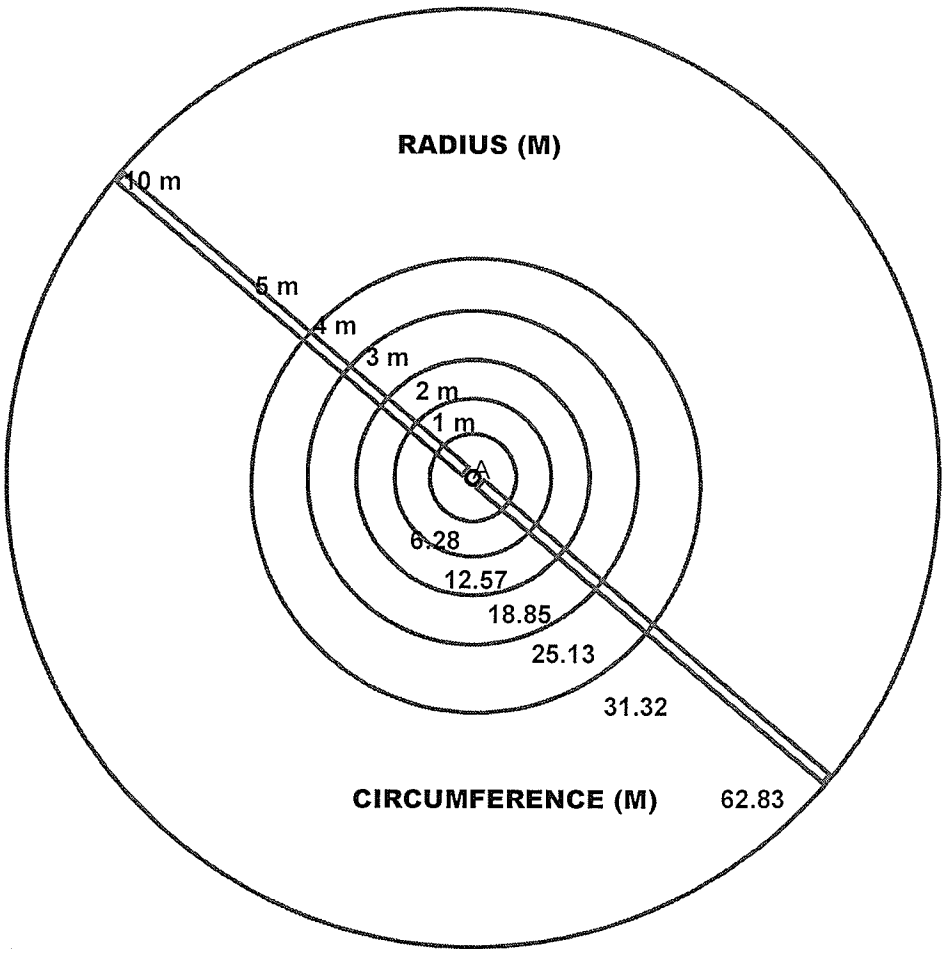


Figure 4 CCT – Concentric circles of 1 m radii increments from 1-5 m and 10 m. The circumference for each circle is also shown.

assessment because errors can be attenuated through a straight path and the ability of the receiver to accurately describe a curvilinear path is not understood. Therefore, when a movement test is performed in an outdoor environment, such as the Larsson and Larsen study, the errors due to moving in curvilinear paths is unknown. In our modification of the circle test, we employed concentric circles of different radii to illustrate dynamic positional accuracy of GPS. This test, termed the concentric circle test, is where a subject walks a circular path of known diameters with a progressive increase in circle radii from 1 to 10 m using all three GPS receivers to sample data simultaneously. This to provided both a visual and an objective assessment of dynamic positional precision of GPS. The fixed radii provided a known circumference of the total distance traveled per circular excursion. A chain marked and calibrated at 1 m increments was affixed to a solid immovable point located at the centre of the circle. The individual walked about the circle centroid in 1 m radii increments up to 5 m and then in a 10 m radius circle about a fixed point. The study subject performed each of the circles at a slow, constant walking pace ranging between 0.75 to 0.85 m/s (derived from TGII data). Each of the trials was performed in the same location. Errors were then computed between the known circular path and the path determined by GPS at each circle circumference increment and for each position. Further, the actual distance traveled about each was computed from GPS data and compared to the known circle circumferences. Finally the effects of sampling rate, satellite configuration and other factors influencing GPS error were investigated using this data.

For the CCT, the subject positioned the "fanny" pack containing a GPS on the anterior aspect of their hip at the level of the anterior superior iliac spine. The GPS units (GV, GIII, & TGII) were attached to an external antenna, which were positioned on top of a hat that was worn by the study subject.

Track Test

The study subject, utilizing all 3 of the GPS units simultaneously (GV, GIII, & TGII), performed a track test. The track used for the 1999 Pan Am Games inline speed skating event located at the Grant Park Collegiate was used for the study. The

Table 2 The average track lane line measurements performed in triplicate by the calibrated wheel measurement.

	AVG	SD
Lane 1	402.1	0.21
Lane 2	409.84	0.34
Lane 3	421.47	5.42
Lane 4	429.27	4.99
Lane 5	440.79	0.13

subject walked around the track following each of the 5 lines, starting with the inner most lane line and progressing outward to the next consecutive lane line up to lane line 5. The GPS units sampled positional data at 1 Hz (GIII and GV receivers) or approximately 1 Hz (TGII receiver) sampling rate. The study subject was required to walk at a self-determined walking pace following the track lane lines from 1-5. Instantaneous GPS velocity measurements were used to establish a constant walking pace, which were maintained for each lap performed. A survey grade wheel measurement (Digiroller Plus, Calculated Industries, 4-foot wheel 99.9 % accuracy) was used to measure the individual track lane lines from 1-5 (table 2). Once each of the track lane lines had been measured in triplicate, the average of the measurements for each lane line provided the known circumference for the track lane lines measured. This method of measurement enabled comparison between the GPS's distance measurement capabilities. An assessment of GPS sampling capabilities (including low velocity movement and minimum distance traveled) were determined through noting the difference measured between each of the lane lines using GPS and the calibrated wheel measurements.

Objective 3 - 3.5 Kilometre Field Test

This exercise was performed at a known 3.5 km path measured through survey grade wheel measurements performed in triplicate. The Assiniboine Park in Winnipeg, Manitoba was selected as the location because it is reflective of an average outdoor environment with tree canopy and other FOV obstructions that can be expected. The study subject performed the 3.5 km course with all three GPS receivers sampling data simultaneously at or approximately at a 1 Hz sampling rate over the entire duration of the course. The subject initiated the 3.5 km field test at a self-determined walking velocity. The walking velocity was increased to a self-determined slow running velocity for a section of the course with a small distance of the 3.5 km course performed at a faster running velocity. This data provided an understanding of the kinematic data that can be collected during a field test.

Data Analysis

CCT and Track Test *(Objective 1 and 2)*

Dynamic Relative Accuracy: The CCT and track test data (from a surveyed track) was used to assess the dynamic relative accuracy of the GPS systems.

The CCT positional data, once in a spreadsheet, was analyzed through numerically deriving the total distance traveled from the positional GPS data. The total circumferential distance traveled was calculated through deriving the distance between each point and summing the distance between each point. Note that the distance equation was explained in the post-processing data section. Once the total distance, as measured by the GPS, had been calculated, it was compared to the known circle circumference. The percent error of each individual trial and the average for each circle circumference measured was calculated. This was performed for each circle circumference measured by each of the three receivers and the TGII differentially corrected data.

The statistical analysis for the CCT and track test was similar. An independent t-test was used to determine significant differences between GPS receiver measurements of each circle circumference and track test lane lines measured (CCT - GIII, TGII, TGII DGPS / track test analysis – GV, GIII, TGII, TGII DGPS). The statistically significant differences in circle circumference percent error between all of the circumferences measured (circle radii 1-5 m and 10 m) by each individual GPS receiver and method was analyzed using a paired t-test. The percentage error for the 1 m radius circle was compared to all other radii circles.

Sampling Rate: The effect of sampling rate and its ability to determine position was analyzed through a post-processed method of varying the sampling rate by "dropping" positional data. The data was down sampled by decreasing the effective sampling rate by 1 sample per second (1 Hz) to 1 sample per every 8 seconds (0.125 Hz). This level of down sampling was chosen because previous research performed by Schutz and colleagues and Larsson and Larsen has sampled velocity data at 6 second and 2 second periods, respectively. The CCT 10 m radii circle data was used in order to analyze the effect of down sampling. The 10 m radii circle data, sampled at 1 second intervals with the GV and GIII and approximately 1 second intervals with the TGII, was used in which only the data points at the set sampling rate were kept in the data file. Therefore, the extra data points outside of the set sampling rate were discarded. The total circle circumference or distance traveled was numerically derived using the altered GPS positional data for each sampling rate. Once the total distance traveled had been determined for each circle circumference, it was differenced to the known circle circumference. The percent error in distance measurement by the GPS was then calculated. Once the percent error for each sampling rate for the GIII, TGII and TGII

DGPS had been determined, paired t-tests were used to detect significant differences in percent error between the different sampling rates for each individual GPS method. Down sampling the data helped to demonstrate the effect of variable sampling rates on distance measurements. This also enabled the establishment of a minimum sampling rate, which dictated the minimum velocity and distance traveled that was required to provide an adequate measure of human movement at walking speeds.

Satellite Configuration: Variable satellite configurations will affect the accuracy of position data obtained by GPS measurement. The degradation of positional accuracy due to satellite configuration is estimated in terms of the DOP level. Determination of the maximum level of degradation or the poorest satellite configuration that will still provide an adequate measurement of human movement needs to be defined. This thesis research will not undertake a systematic evaluation of DOP levels through satellite geometry changes, but will illustrate the relative impact of satellite configuration on dynamic positional accuracy.

The effect of satellite configuration was determined through using the Pathfinder Office v. 2.11 software (Trimble, Sunnyvale, CA) to note the satellites that had been utilized to determine a position solution, as well as the respective DOP level. The CCT data from the 5 m and 10 m radius circles, as well as lane 1 of the track test was used to determine changes in DOP level over the sampling time period. The average DOP levels (PDOP, HDOP, VDOP, & TDOP) for each trial of the 5 m and 10 m radii circle and lane line 1 of track test will be recorded. A paired t-test was used to determine the statistical significance between the PDOP, HDOP, VDOP and TDOP levels for each of the receivers and also for each of the 5 m and 10 m radii circles and the track lane 1 DOP levels. This ultimately contributed to the creation of a GPS criterion for data sampling for assessment of total body kinematics.

Occupation Time: The occupation time will effect the satellite configuration that is in the receivers FOV due to the variable orbital patterns of the satellites. The occupation time will affect the frequency of change in the number and configuration of satellites. Therefore with a longer sampling period or occupation time, it is more likely that changes in the DOP level due to the satellite configuration will occur, where some satellites will move out of the FOV and new satellites will enter the FOV. It is important to understand the effect of changes in

the satellite configurations in respect to the occupation time. Therefore, we examined the occupation times for the CCT, track test and the 3.5 km course. The occupation times were noted in relation to the DOP levels for the 5 m and 10 m CCT and the first lane line measurement of the track test. Statistical analysis of the significant DOP levels in each of the 5 m and 10 m CCT and the track lane 1 measurements, which each had variable occupation times, were contrasted. This provided an understanding of the occupation time required for a realistic human movement assessment and the effects of changes in DOP level over this time duration.

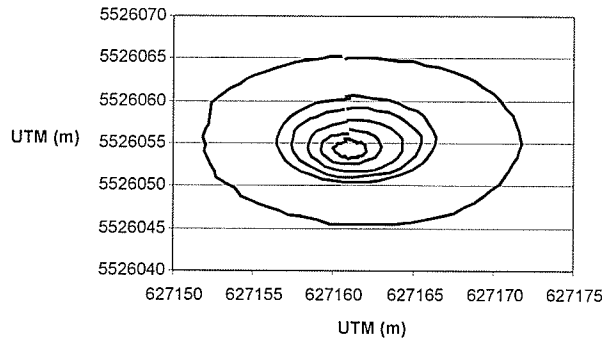
Results

CCT

The CCT was performed at 1-5 m and 10 m circle radii increments at a slow walking average velocity of 0.84 m/s (averaged TGII data) for all circle radii and trials performed. Figure 5 illustrates the results from the GPS systems used to perform the concentric circles. The corresponding results are illustrated graphically for the TGII DGPS (Figure 5A), TGII that was non-differentially corrected (Figure 5B) and the two Garmin GPS units, the GIII (Figure 5C) and the GV (Figure 5D). Note how clearly each of the circles are delineated for the CCT for the TGII DGPS (figure 5A), the TGII (figure 5B), and the GIII (figure 5C). Each circle is concentric and non-overlapping, and each trajectory is clearly that of a circle for these GPS systems. There are negligible differences that can be noted upon visual inspection between the CCT graphs performed by the TGII non-differentially corrected (Figure 5B) and TGII DGPS (Figure 5A). The CCT figure 5B and 5C were performed using the TGII and the GIII units, respectively, without differential correction. The concentric circle pattern is still illustrated well in both graphs, although the TGII GPS unit (Figure 5B) better illustrates the definition and the pattern of the individual circles. The last figure, which was performed by the GV receiver (Figure 5D), does not depict a circular shape, but rather block like features. The individual circle radii from 1-5 m are indistinguishable, but the 10m radii circle can be observed, although it does not depict a circular pattern.

Tables 3, 4 and 5 numerically demonstrate the capabilities of GPS systems when evaluated using the CCT. The GV measurements were not assessed due to a failure to pass visual inspection of data quality. Note how the total distance measured for each individual trial of circles by the 3 different GPS measurements (GIII, TGII & TGII DGPS) has relatively similar variability with the standard deviation of the GIII ranging from 0.7 m -2.27 m, the TGII ranging from 0.59 m -2.60 m and the TGII DGPS ranging from 0.74 m -2.51 m for all measurements performed. Table 6 demonstrates the circle circumference average measurements of all trials performed, segregated into individual GPS measurement types (GIII, TGII differentially and non-differentially corrected), as well as the known circle circumference for each circle radii. All three measurements analysed demonstrated relatively similar distance measurements for each of the circle circumferences measured.

A



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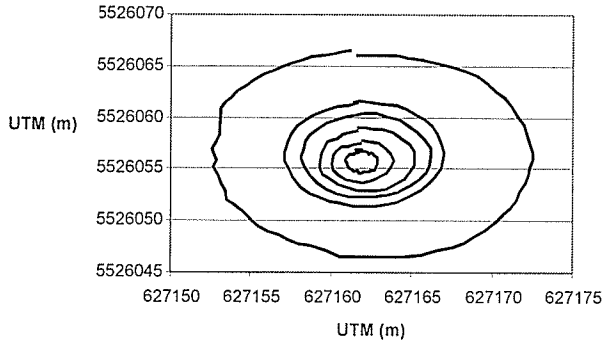

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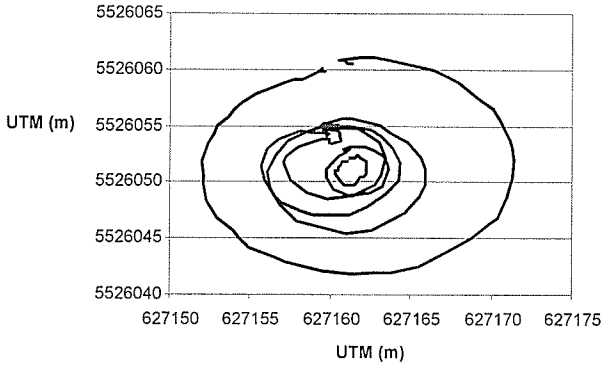

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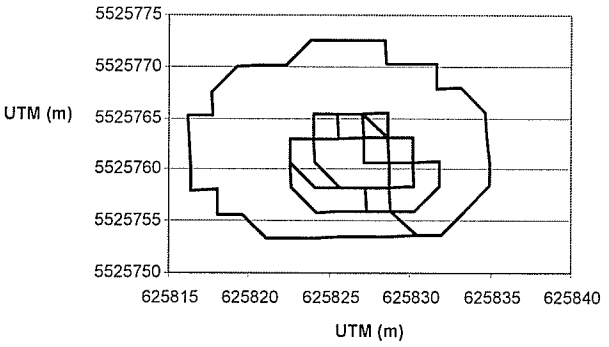

Figure 5 GPS positional data for the CCT for the TGII DGPS, TGII, GIII, and GV GPS units, graph A, B, C, and D respectively.

Table 3 The individual and averaged circumference measurements for each trial performed by the GIII.

Circle Radii (m)	1	2	3	4	5	10
Trial						
1	12.89	12.86	18.15	27.07	36.56	68.77
2	5.77	15.02	21.77	26.87	33.50	65.48
3	6.78	13.79	20.54	26.10	33.77	67.37
4	6.52	14.78	20.58	29.21	32.55	65.17
5	8.42	13.99	19.30	27.73	30.87	66.20
6	7.18	13.90	21.36	28.44	30.42	64.91
7	6.28	13.11	20.39	26.21	33.63	65.25
8	5.56	13.78	19.75	24.93	31.99	65.30
9	6.05	14.27	19.83	24.47	31.90	62.38
10	7.36	13.53	21.81	27.72	32.06	60.84
11	7.19	12.45	18.97	26.45	35.91	61.55
12		12.09	18.29	26.45	34.52	66.49
Average	6.75	12.74	18.75	25.05	30.98	60.75
SD	2.27	0.70	1.09	1.55	1.84	1.76

Figure 6 graphically illustrates the percent error noted when each of the GPS units' average distance measurements for the individual circle circumferences (1-5 m and 10 m circle radii) was compared to the known circle circumferences for each of the radii performed (1-5m and 10m). The largest percent error in distance measurement was noted with the smallest distance travelled (6.28 m) in all three of the GPS receivers (GIII- 6.92 %, TGII- 15.13 %, TGII DGPS- 16.27 %). With an increase in distance travelled there is a reduction in the measurement percent error for all of the GPS units. It can be noted that at the 2 m radii circle

Table 4 The individual and averaged circle circumference measurements for each trial performed by the TGII.

Circle Radii (m)	1	2	3	4	5	10
Trial						
1	8.61	13.11	18.59	26.18	32.31	63.39
2	6.65	14.67	25.98	25.86	32.09	64.44
3	6.66	13.46	19.33	25.93	32.26	68.87
4	7.00	11.95	18.77	26.26	32.87	64.00
5	6.98	12.55	19.10	25.27	31.17	63.68
6	9.10	12.77	19.24	25.17	30.17	70.08
7	8.57	11.17	18.55	25.53	31.42	63.93
8	5.68	12.78	18.95	24.51	30.21	66.74
9	7.76	11.97	18.88	25.36	31.76	62.82
10	8.23	12.22	18.52	24.92	30.70	62.85
11	6.18	12.74	21.59	26.11	32.20	71.34
Average	7.40	12.67	19.77	25.56	31.56	65.65
SD	1.20	1.03	2.51	0.59	1.00	2.60

Table 5 The individual and averaged circle circumference measurements for each trial performed by the TGII DGPS.

Circle Radii (m)	1	2	3	4	5	10
Trials						
1	8.62	13.11	18.58	25.76	32.25	63.39
2	7.21	14.62	25.99	25.85	32.11	64.41
3	6.66	13.46	19.33	25.94	32.26	68.85
4	6.95	11.96	18.78	26.24	31.96	63.55
5	6.99	12.54	19.09	25.28	31.18	63.70
6	9.07	12.77	19.26	25.15	30.89	60.99
7	8.11	11.28	18.55	25.48	31.43	63.95
8	5.68	12.79	18.96	23.57	30.24	66.71
9	7.79	11.97	18.90	25.38	31.75	62.85
10	8.23	12.22	18.52	24.92	30.70	62.85
11	7.23	12.62	21.57	25.93	32.22	52.89
Average	7.50	12.67	19.78	25.41	31.54	63.10
SD	1.11	0.99	2.51	0.83	0.74	2.37

(12.57m circumference), both the TGII (differentially corrected and non-differentially corrected) and the GIII were able to determine the total distance travelled with a relative accuracy (measured in percent error) of 1.34 % (GIII), 0.83 % (TGII) and 0.81 % (TGII DGPS). There is greater percent error with a 1 m circle radii circumference measurement for all three GPS receivers than was noted at the 2 m radii measurement percent error. This decreases with each CCT measured with the last 10 m radii circle percent error for the GIII equating to 3.43 %, the TGII at 2.6% and the TGII DGPS at 2.37 % error.

The GPS receivers that performed the CCT were analyzed through comparison of the percent error noted with each circle circumference measured between the GIII, TGII and TGII DGPS receivers. For example, the GIII 1 m radii circle percent error was compared to the TGII 1m radii circle percent error. There was no significant differences between the receivers in the percent error noted at the 1m circle radii circumference measurements. Both the TGII and TGII DGPS were found to demonstrate a significantly

Table 6 CCT average circumference measurements for all three GPS receivers and the known circle circumference.

Circle Circumference	TGII	TGII DGPS	GIII
6.281m (1m radius)	7.40	7.50	6.75
12.57m (2m radius)	12.67	12.67	12.74
18.85m (3m radius)	19.77	19.78	18.75
25.13m (4m radius)	25.56	25.41	25.05
31.42m (5m radius)	31.56	31.54	30.98
62.82m (10m radius)	65.65	63.10	60.75

lower percent error in measurement of the 2 m radii circle circumference with Ps of 0.009 and 0.008, respectively from the GIII 2m circle radii measurement (12.57 circle circumference). On observation of figure 6, there were marginal differences in measurement percent error between the differentially and non-differentially corrected TGII measurements. Although, the TGII differed from the TGII DGPS in its' measurement capabilities with a significantly higher measurement percent error in the 10 m radii circle (P =0.05).

The GIII, TGII and TGII DGPS receivers were analysed independently in the percent error calculated with each individual CCT radii performed. For example, a comparison of the percent error was performed between the 1m radii circle and the 2 m radii circle, 1m radii circle and the 3 m radii circle, etc. of a single receiver. The GIII demonstrated no statistically significant percent error differences between the 1m radii circle measurement and the 2 m, 3 m, 4 m, 5 m, and 10 m radii circle measurements. Table 7 lists the statistically significant differences in the TGII and TGII DGPS independent percent error measurements between the 1 m and 2 m, 3 m, 4 m, 5 m, and 10 m radii circle measurement percent error. The critical point to note is that there is a significant decrease in the percent error noted from the 1m radii circle measurement to the 2 m radii circle measurement with the TGII (P = 0.0047) and the TGII DGPS (P = 0.0009)

Table 7 Statistical comparison of the circle circumference percent errors calculated from the TGII and TGII DGPS compared to the 1m radii circle circumference.

Circle Radii (m)	TGII	TGII DGPS
10m/1m	0.0202	0.0008
5m/1m	0.0024	0.0003
4m/1m	0.0045	0.0005
3m/1m	0.0302	0.0099
2m/1m	0.0047	0.0009

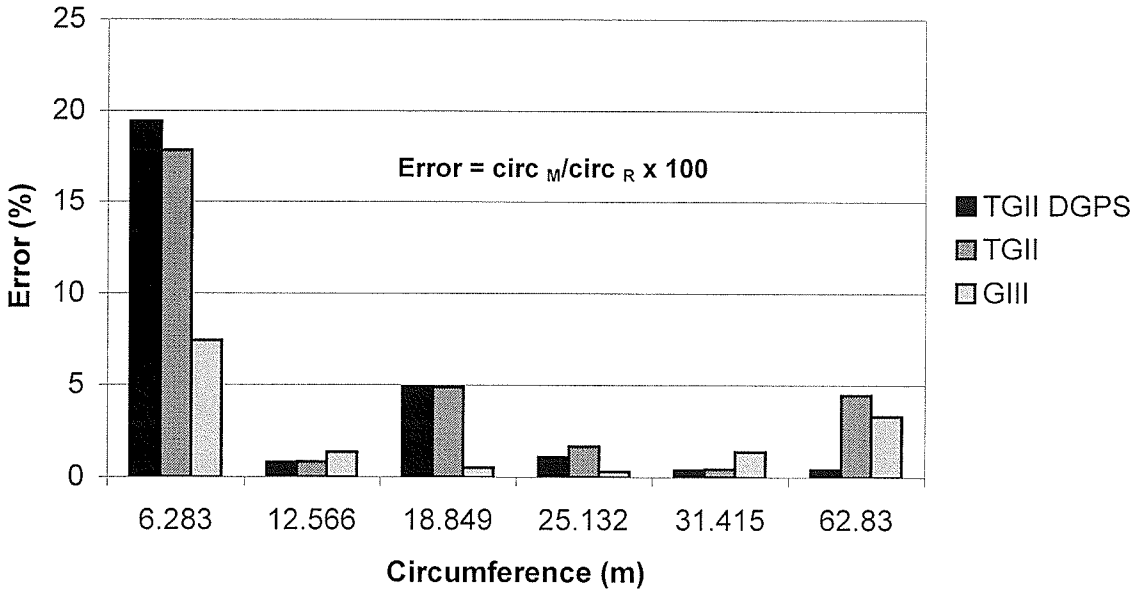

Figure 6 This figure demonstrates the absolute percent error noted between the TGII DGPS, TGII, and the GIII. Note that the greatest percent error is with the smallest circumference travelled (6.28 m) and that the absolute percent error drops with a greater distance travelled >12.57 m, especially with the TGII.

Sampling Rate

The sampling rate of a GPS unit is an important consideration in obtaining accurate data with respect to human motion. A sampling rate that is too low will underestimate the displacement. A sampling rate that is too high will be impractical (technologically constrained or expensive). The GIII and GV sampled data at a rate of 1 Hz (1 sample per second) and the TGII (differentially and non-differentially corrected) sampled data at an "ALL" setting, which provides an average sampling rate of 0.73 Hz that can range from to 0.56 Hz to 2.0 Hz. In order to determine the effect of a diminished sampling rate, the data collected for the 10m radii circle was analyzed by removing the 1 second or approximate 1 second sampled data points to achieve sampling intervals from 2 seconds up to 8 seconds. Figure 7 illustrates the effect of a diminishing sampling rate (2, 4, 6 and 8 second sampled GPS data) on the relative accuracy of GPS measurements. Note how the 10m radii circle

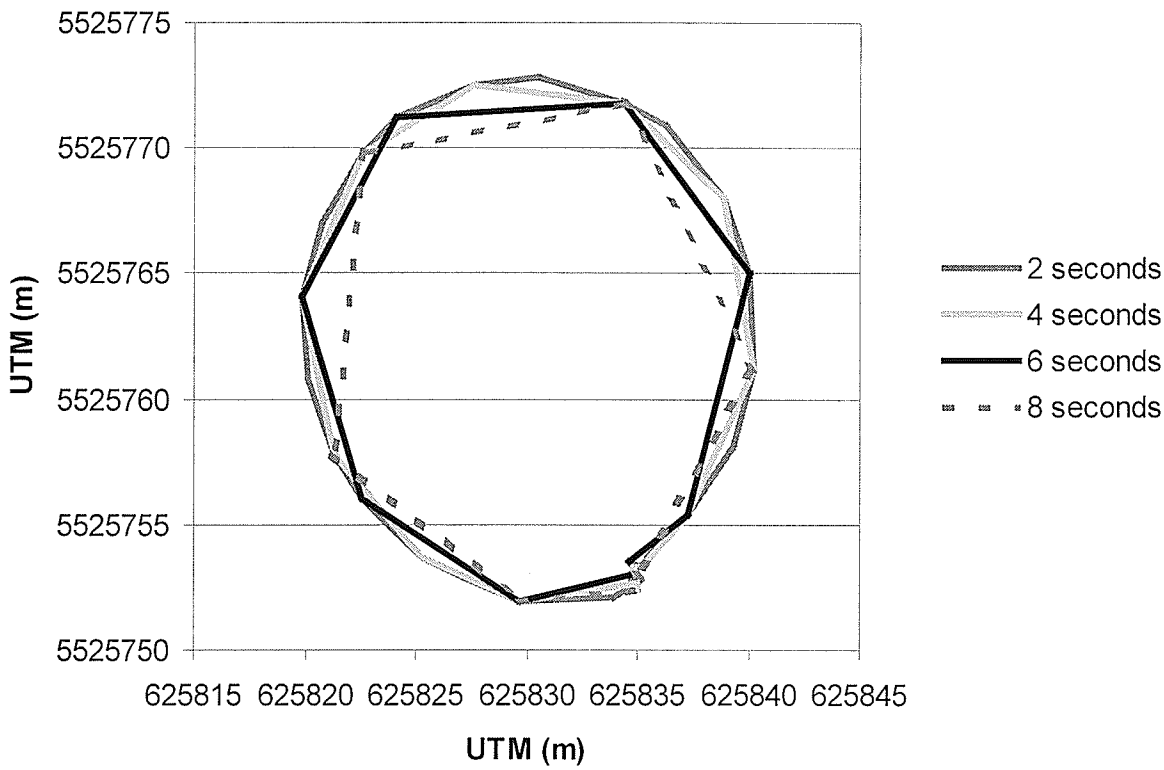

Figure 7 Sampling rate degradation from 1 second ~ 8 seconds and its' respective effect on the measurement of a 10 m radii circle.

becomes more angular as the sampling rate is diminished. These arc like angulations negatively impact on the accurate portrayal of the actual circular motion. Figure 8 demonstrates the error involved with down sampling from a rate of 1 second to 8 seconds per sample. This error was calculated by dividing the known circumference from the GPS measured circumference and was expressed as a percent of the known circumference for each sampling rate. The 10 m radii circle measurement percent error at a 1 second sampling rate was –4.36% for the GIII receiver, -4.28% for the TGII receiver and –2.23 % for the TGII DGPS receiver. The measurement percent error ranged up to 16.53 % for the GIII receiver, -18.25 % for the TGII receiver and –17.59 % for the TGII DGPS receiver at an 8 second sampling rate. As noted in figure 8, the measurement percent error ranges from underestimating to over estimating the total distance measured by all three of the GPS receivers.

The effect of sampling rate on error was assessed by comparing the percent error for each sampling rate within each receiver. The GIII noted a significantly higher percent error with the 2 second sampled data ($P = 0.015$) when the 1 second and 2 second sampled data was compared. The GIII demonstrated statistically significant increases in percent error when the 1 second sampled data was compared with each progressive down sampled data set (P – 3s= 0.0029, 4s= 0.0002, 5s= 0.0037, 6s= 0.0002, 7s= 0.0001, 8s= 0.0007). There was no significant difference between the 1 second and 2 second sampled data for the TGII and TGII DGPS receivers. There was a significant increase in the percent error noted with a sampling rate of 3 seconds per sample with the TGII ($P = 0.01$) and TGII DGPS ($P = 0.022$). The TGII measurement percent error of the 10 m radii circle when sampled at 1 second was also significantly lower than the 4 second ($P = 0.002$), 5 second ($P = 0.00005$), 6 second ($P = 0.0001$), 7 second ($P = 0.00007$), and 8 second ($P = 0.000005$) sampled data. The TGII DGPS also demonstrated that the 1 second sampled data had a significantly lower measurement percent error when compared to the 4 second ($P= 0.0087$), 5 second ($P= 0.0007$), 6 second ($P= 0.00002$), 7 second ($P= 0.000009$) and 8 second ($P= 0.000001$) sampled data.

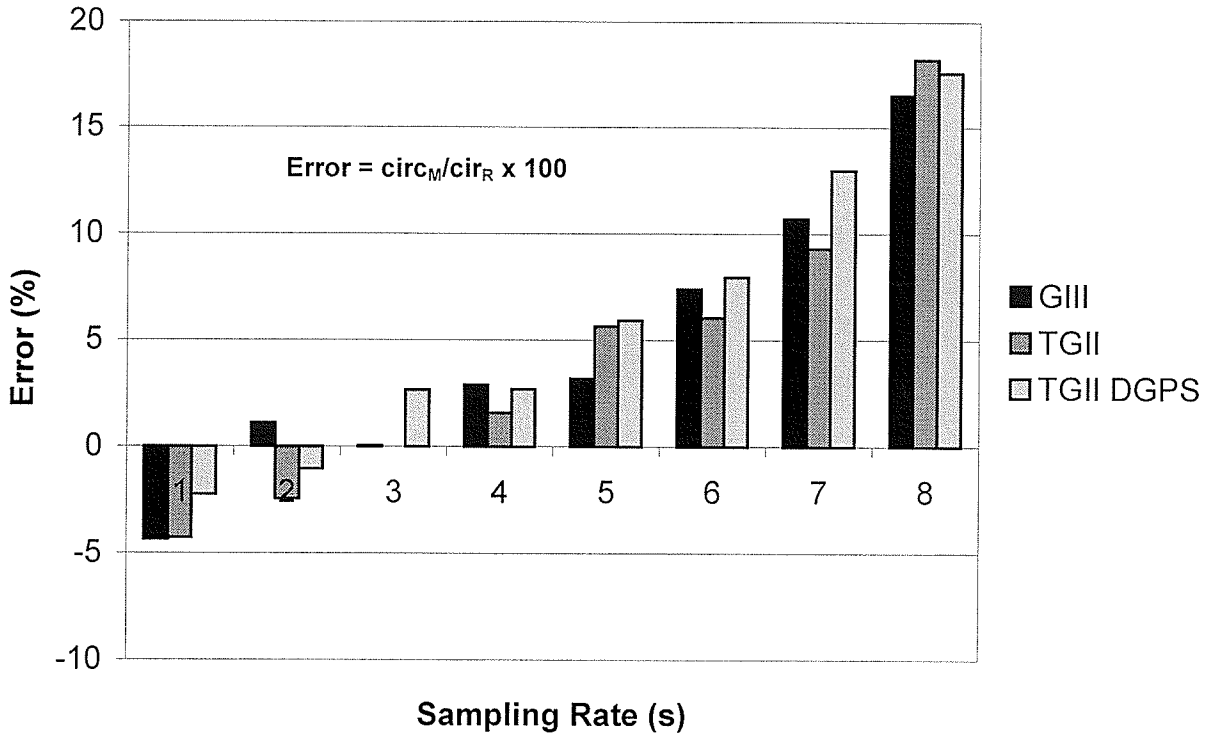

Figure 8 The error noted with a decrease in sampling rate on a 10 m radii circle is illustrated with the GIII, TGII and TGII DGPS GPS units.

Track Test

The track test was performed on a 400 m track using the first 5 lanes. All three GPS systems were used to perform the measurements (GV, GIII, TGII and TGII DGPS). Each track lane line was walked at an average pace of 1.82 m/s for all trials performed. The individual measurements of the 5 lanes measured by the GPS units are graphically displayed (Figure 10, 11, 12 & 13 respectively). Note that the definition between the lane lines is visibly distinguishable even though there is only a one-meter spacing between each of the individual lane perimeters. Each of the lane lines measured also reconnects to the start point of the individual lane line measured with all of the GPS receiver measurements.

Figure 10 illustrates the full, track test measurement performed by the GV. Each lane line measured is segregated and demonstrates an oval shape, although note how each lane line is not a perfectly straight line of the path, but depicts a path that has small oscillations or zig zags. Upon enlarging a section of the GV track test (figure 9), the lane line that was measured appears as a 'drunken sailor' effect where the path measured is a weaving or jagged line. Although, the GV track measurement illustrates a jagged movement path, each lane line is visually independent (figure 10) and was manually separated in order to determine the GV's total distance measured.

Through graphical observation, there appears to be minor differences between the track plots of the GIII, TGII non-differentially and differentially corrected GPS measurements (Figure 11, 12 & 13 respectively). These graphs derived from each GPS system demonstrated the pattern of movement and were able to illustrate the individual track lane lines.

Table 8 The average calibrated wheel measurements of the track lanes 1-5.

Lane Line	AVG	SD
1	402.1	0.21
2	409.84	0.34
3	421.47	5.42
4	429.27	4.99
5	440.79	0.13

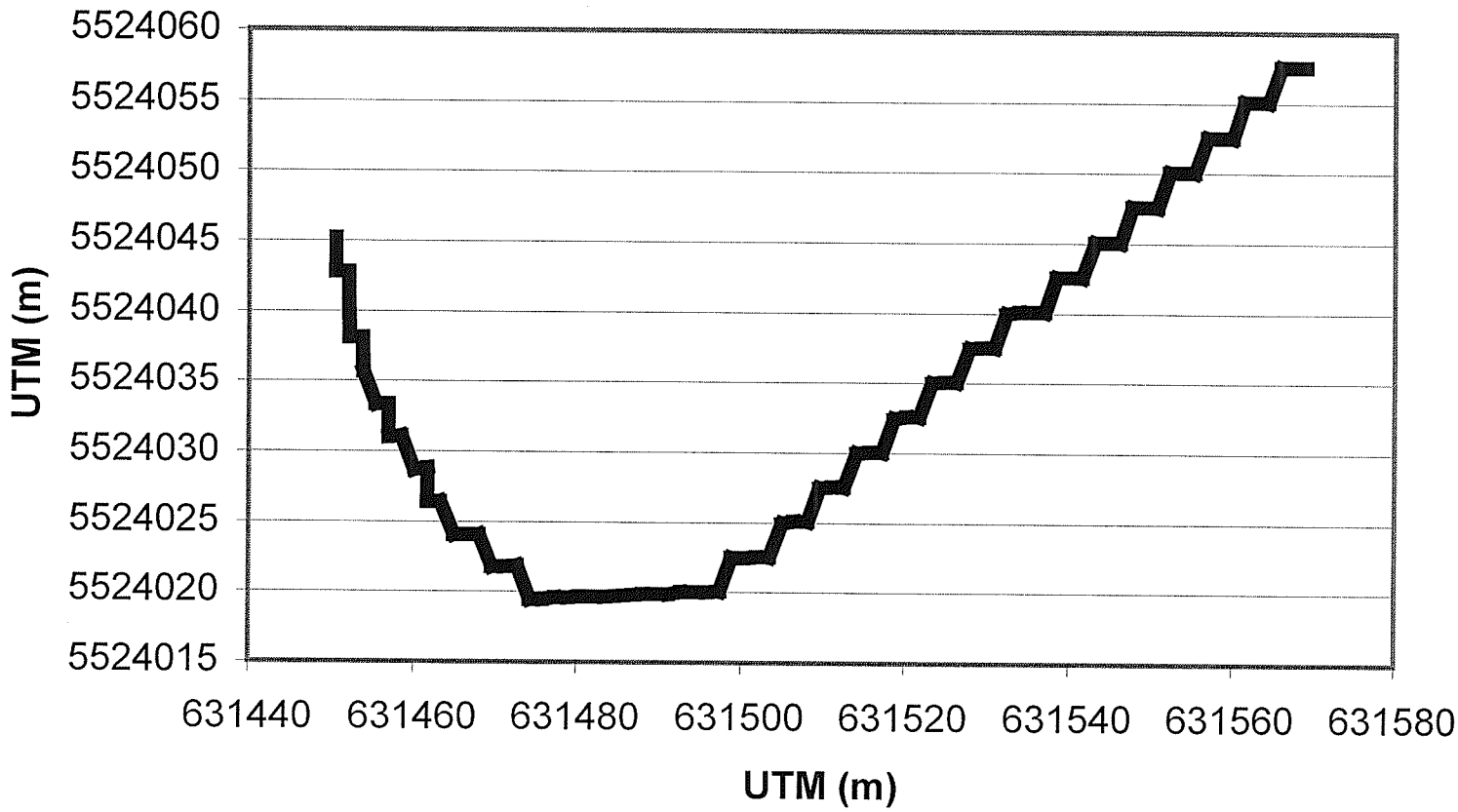

Figure 9 An enlarged section of the track lane illustrating the jagged appearance of the data measured by the GV GPS receiver.

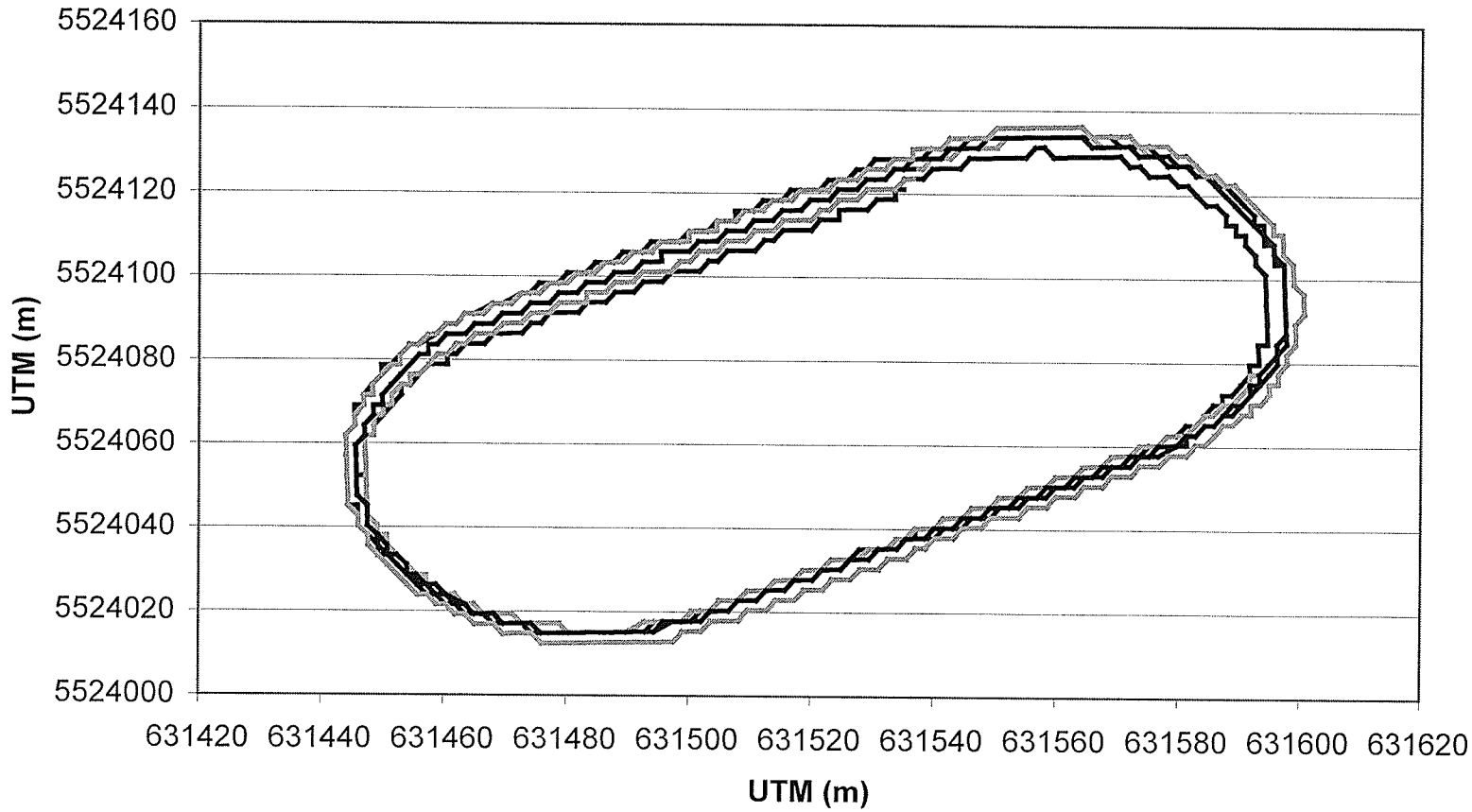

Figure 10 Track test lanes 1-5 as measured by the GV. Note the jagged appearance of the line travelled as measured by the GV.

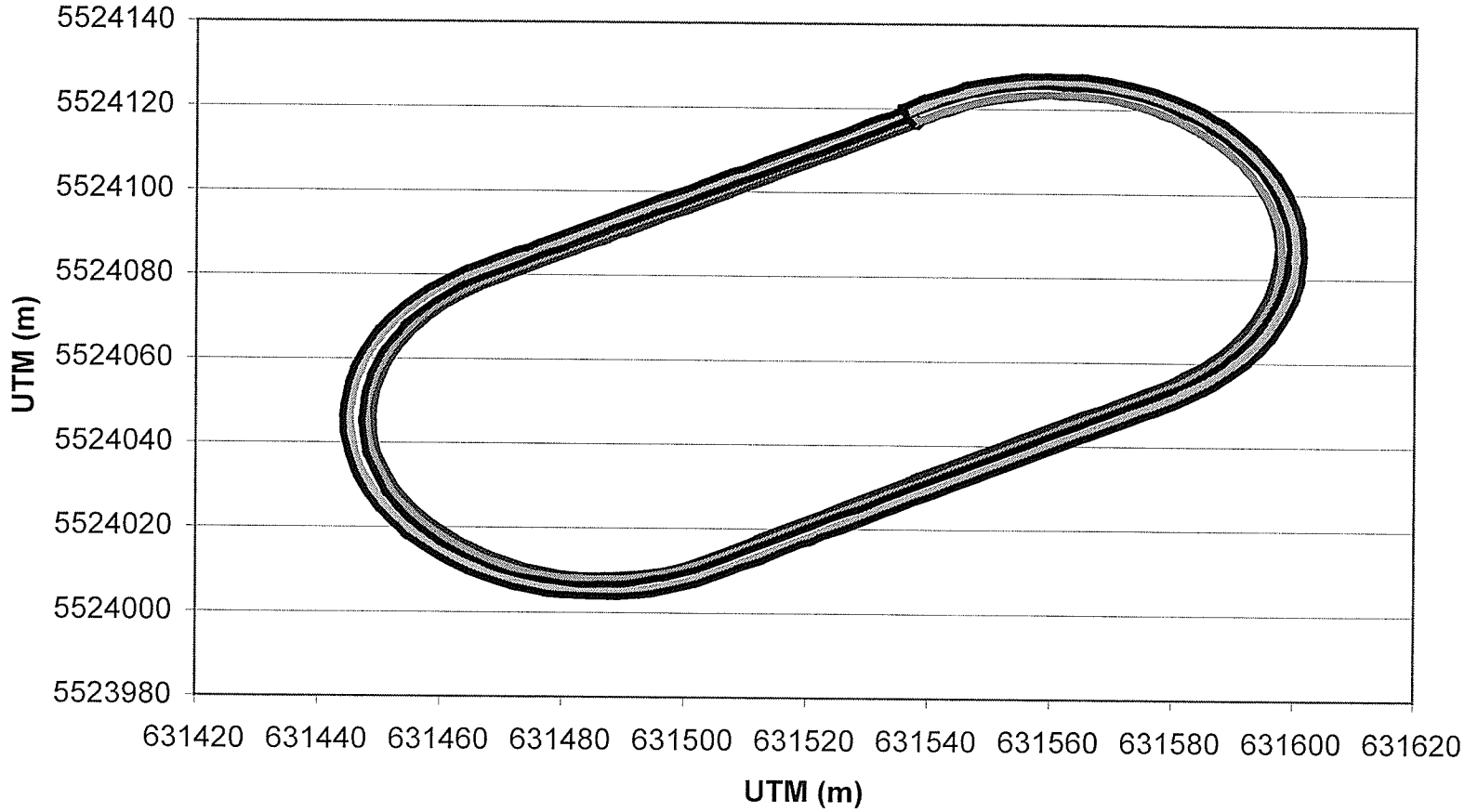

Figure 11 The GIII GPS receiver measurement of the track lane lines from the inner most lane line 1 to the outer most lane line 5.

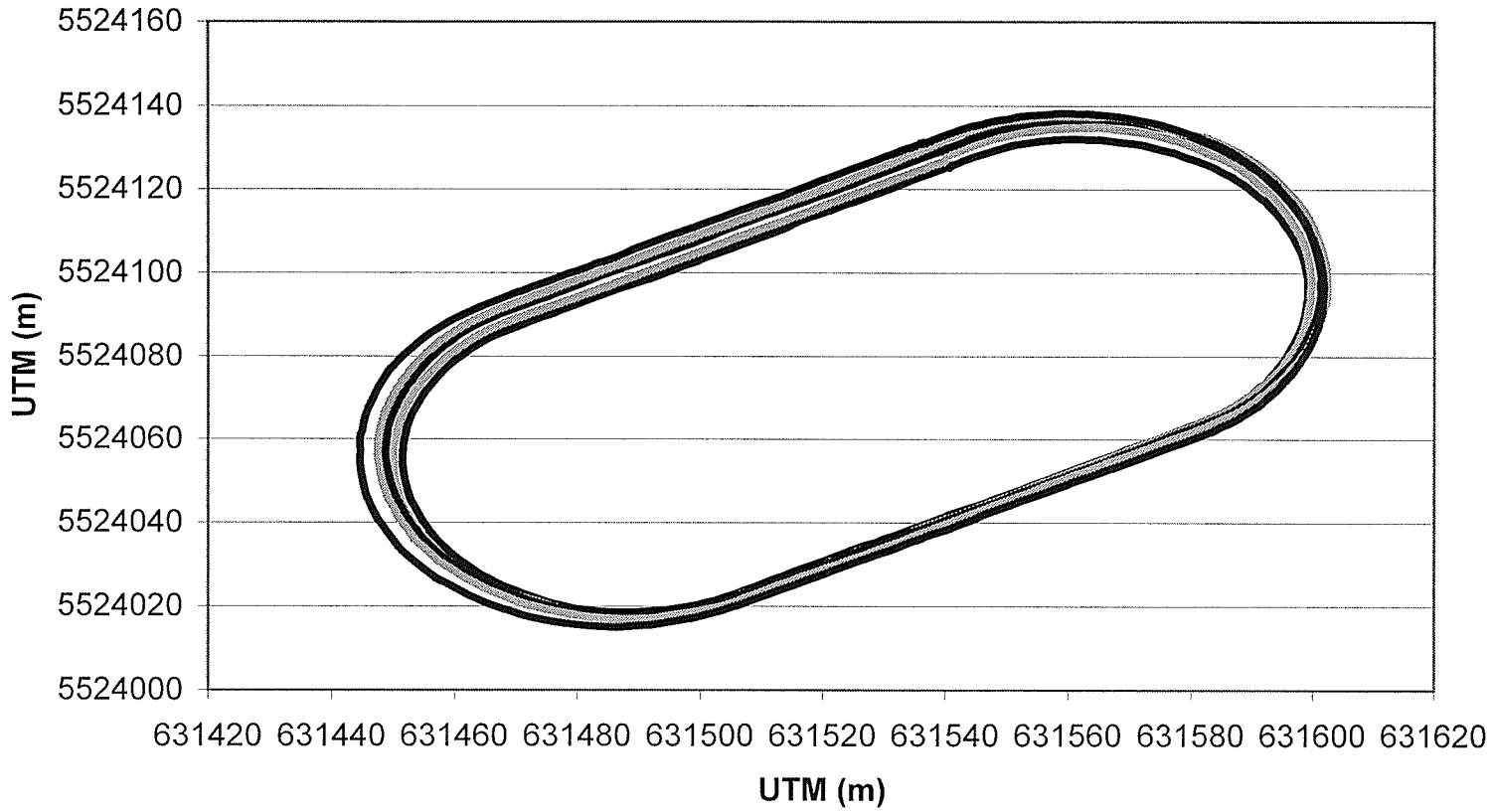

Figure 12 The track test as measured by the TGII GPS receiver from lane line1 (the inner most lane line) to lane line 5 (the outer most lane line). Note how the individual lane lines are distinguishable.

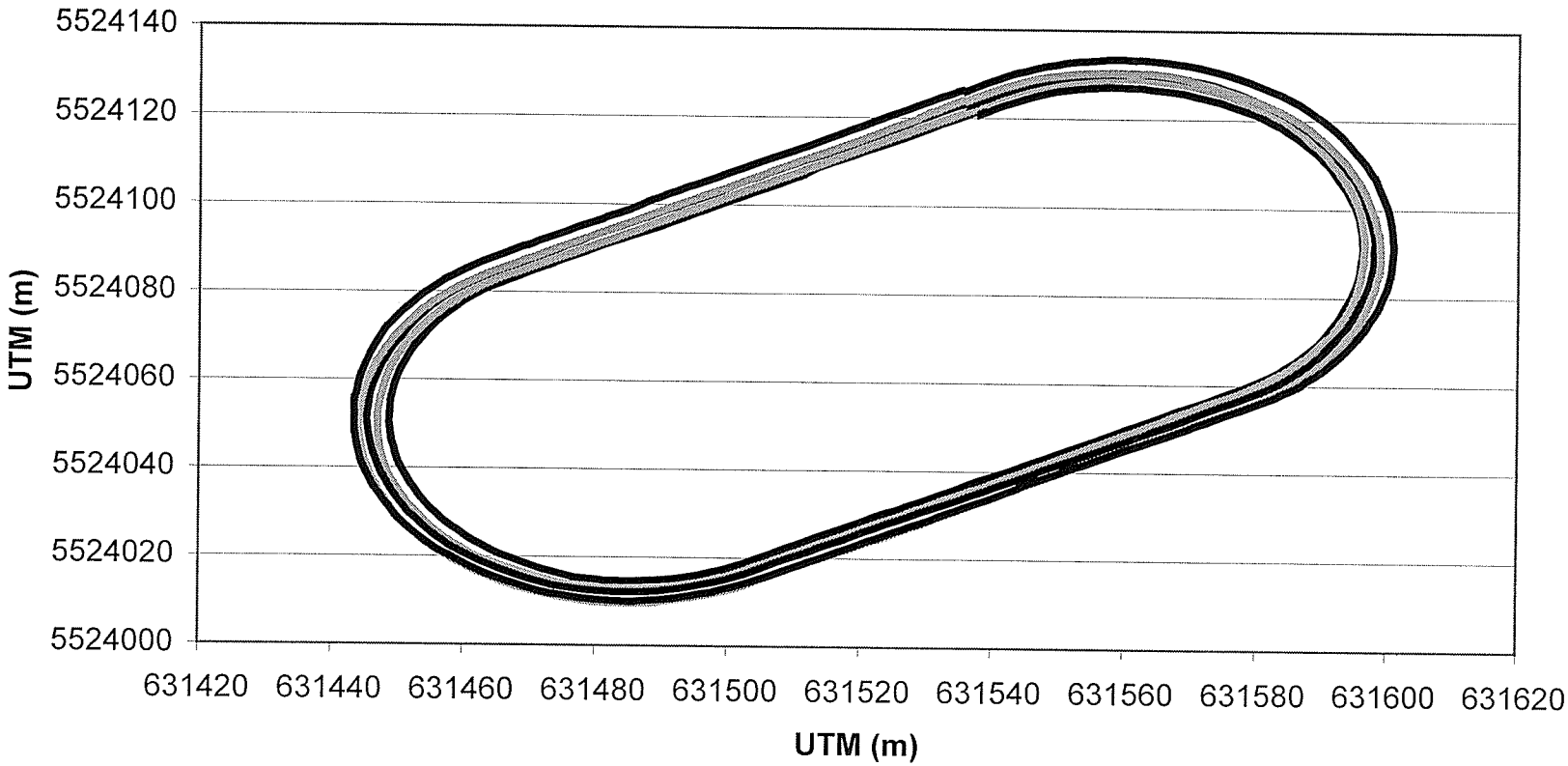

Figure 13 GPS positional data for the track test using the TGII DGPS. (Lane 1 – inner, Lane 5 outer).

In order to analyze the track test, the course was measured with a calibrated wheel (Digiroller Plus, Calculated Industries). Table 8 notes the average and standard deviations for each track lane line measurement. This created the standard measurement for each track lane line that was compared to each of the GPS receiver track measurements. Table 9 is a summary of each individual trial measurement of the track performed using a GV receiver. Table 10 outlines the GIII measurements of the track lane lines. The individual track lane line measurement standard deviations vary from 1.40 (lane 5) to 4.44 (lane 4) and are considerably lower than the variances noted in the GV track measurements (SD- 3.38 – 64.42 m). The track measurement trials performed using the TGII GPS, which was non-differentially and differentially corrected, are outlined in tables 11 and 12 respectively. The TGII non-differentially corrected measurements are relatively consistent with the standard deviations ranging from 0.67 m (lane 4) to 2.53 m (lane 1). The TGII differentially corrected data also demonstrated consistency in the individual trial measurements performed with the standard deviations varying from 0.83 m (lane 3 & 4) to 1.78 m (lane 5). The standard deviations noted in both the TGII differentially and non-differentially corrected measurements are much lower than the GIII and GV GPS receivers, although the TGII DGPS measurements have the lowest standard deviations of all the GPS measurements performed.

Table 9 Individual and average track lane 1-5 measurements performed by the GV.

GV	1	2	3	4	5
1	453.22	451.94	465.48	470.36	485.59
2	452.78	453.63	464.60	464.32	479.81
3	448.42	454.34	465.48	470.36	486.19
4	440.53	455.61	467.51	478.09	478.93
5	453.95	464.53	458.04	472.52	478.79
6	455.14	462.08	461.82	464.00	479.35
7	448.25	451.01	461.25	664.16	475.71
8	441.30	449.26	458.18	471.29	479.51
9	450.94	450.64	460.63	482.77	
Average	449.39	454.79	462.55	493.10	480.48
SD	5.35	5.25	3.38	64.42	3.57

Table 10 The track test individual and averaged measurements with the standard deviations for each lane line performed by the GIII.

GIII	1	2	3	4	5
1	399.26	405.73	417.62	421.72	429.72
2	402.94	406.62	417.09	433.06	431.93
3	402.90	409.09	423.98	424.49	428.56
4	400.63	406.14	415.18	424.30	431.58
5	402.55	406.66	412.51	423.47	430.29
6	405.35	408.47	418.12	426.19	431.31
7	397.63	404.41	414.37	422.63	429.75
8	398.15	405.28	415.21	421.49	429.34
9	394.81	409.38	410.65	413.40	429.51
10	404.87	407.39	416.59	423.93	431.57
11	399.59	408.89	419.19	424.23	433.57
12	401.80	406.70	417.69	426.00	430.92
AVG	400.87	407.06	416.52	423.74	430.67
SD	3.12	1.60	3.40	4.44	1.40

The average of the entire set of lane line measurements and individual trials performed by all of the GPS units and the calibrated wheel measurements are summarized in table 13. Note the consistency of the distance measurements for all the lane lines between the GIII and the TGII, both differentially and non-differentially corrected measurements. There is a large difference in the GV track lane distance measurements (Table 9) compared with each of the calibrated wheel lane measurements and the other GPS unit measurements. The lane length increase noted in the GV is likely due to the fact that the GV pins the GPS positions to values with fixed intervals resulting in a 'staggering walk' effect when the person was actually walking in a straight line.

Table 11 Individual and average track lane 1-5 measurements performed by the TGII.

TGII	1	2	3	4	5
1	400.63	409.05	416.46	423.06	431.23
2	401.98	410.07	428.81	432.60	439.90
3	403.89	410.78	417.93	423.84	433.73
4	400.69	407.96	416.61	422.83	430.69
5	409.35	408.36	416.35	422.94	430.81
6	399.34	407.45	414.98	423.44	430.88
7	392.76	408.72	415.78	422.83	430.78
8	400.86	408.17	416.00	422.55	435.18
9	399.28	406.91	414.05	424.08	430.84
10	399.28	408.39	414.64	422.87	430.49
11	398.95	407.90	414.12	423.04	431.19
12	400.51	408.44	415.44	422.81	432.14
13	399.45	407.02	415.07	421.78	430.03
Average	398.80	407.87	415.01	422.93	431.44
SD	2.53	0.68	0.72	0.67	1.62

Figure 14 demonstrates the percent error of the track lane lines 1-5 performed by the GV, GIII, TGII and TGII DGPS. The average of the individual GPS unit measurements for each lane line was divided by the lane line 1-5 distances obtained from calibrated wheel measurements performed in triplicate. This was then converted into the percent error for each lane line performed by each individual GPS receiver. On observation of figure 11, 12, and 13, there are visually negligible differences in the measurement of the track from lanes 1-5 between the TGII (differentially corrected and non-differentially corrected) and the GIII data. Measurements of lane line 1 of the track performed by the GIII and the TGII (differentially and non- differentially corrected) demonstrated very low percent errors (GIII=0.30 %, TGII=0.82 %, TGII DGPS=0.68 %). The error increased with each of the lane measurements, with the highest percent error noted in the lane 5 measurements with the GIII, TGII and TGII DGPS. Although, all three GPS receivers noted the greatest percent error with the lane line 5 measurement, they still demonstrated low percent error with the GIII at 2.29 %, TGII at 2.12 % and the TGII DGPS at 2.01 % error.

The measurement percent error of the GV, noted in figure 14, is markedly larger in magnitude, ranging from 9.01 % ~14.87 %, in comparison to the other three GPS measurements. This percent error in measurement equates to an average distance measurement error of 47.37 m with each lane line 1-5. While the GV systematically overestimated the total distance traveled, the other three GPS measurements systematically

underestimated the total distance traveled and varied on average, ranging from -4.92 m to -5.48 m. It is important to note in figure 14 that the TGII (differentially and non-differentially corrected) and GIII units' percent error values were negative, but are expressed in absolute terms for comparison with the GV measurement percent error.

Upon statistical analysis, there were two primary areas that were analyzed. The receivers were contrasted in their ability to determine the total distance traveled with each lane line and then the individual receivers were compared in their ability to determine the total distance traveled with each lane line. When the receivers were contrasted, it was interesting to note that the GIII had a significantly higher measurement percent error of lane line 2 in comparison to the TGII (P = 0.015) as well as the TGII DGPS (P = 0.018). With further analysis, the GIII demonstrated significantly higher percent error values in its measurement of lane line 5 in comparison to the TGII (P = 0.054) and the TGII DGPS (P = 0.023). The TGII and the TGII DGPS did not vary significantly in their percent error measurements with all of the track lane lines measured. Although, the large magnitude noted in the track lane line measurements of the GV proved to be statistically significantly higher when compared to the GIII, TGII and TGII DGPS measurement percent error with a P less than 0.01 for all receiver comparisons.

Table 12 Individual and average track lane 1-5 measurements performed by the TGII differentially corrected.

TGII DGPS	1	2	3	4	5
1	400.60	409.54	416.38	423.23	432.40
2	402.02	408.46	425.86	426.63	439.14
3	402.89	409.14	417.20	423.08	433.10
4	401.21	407.55	416.32	422.49	430.88
5	409.09	408.21	416.37	422.99	430.44
6	399.08	407.57	415.17	423.38	431.18
7	397.55	409.42	415.80	423.13	431.02
8	400.82	408.36	416.70	422.54	435.25
9	399.25	406.87	413.98	424.08	433.40
10	399.25	408.07	414.97	423.08	430.63
11	400.40	408.73	415.19	422.85	431.79
12	399.29	407.02	415.09	421.40	430.31
Average	399.38	408.00	415.27	422.92	431.94
SD	1.05	0.92	0.83	0.83	1.78

The individual GPS receivers' lane line percent errors were compared in order to determine statistical significance. For example the GV lane line 1 percent error was compared to lane line 2 percent error using an independent t-test. This analysis was performed for all the lane line percent errors calculated by the GV receiver. Then the GIII, TGII and TGII DGPS were all individually analyzed through the same process. The GV found no significant difference in the percent error between lane line 1 and 2, although there was a significant decrease in the percent error between lane line 1 and 3 (P = 0.0006). The

Table 13 The average distance measurements performed by the GV, GIII, TGII and TGII DGPS for each individual track lane line. The known lane line distance measured by the calibrated wheel measurements are also noted along with the lane line.

Track Laps	GV	GIII	TGII	TGII DGPS
1 (402.1 m)	449.39	400.87	398.80	399.38
2 (409.84 m)	454.79	407.06	407.87	408.00
3 (421.47 m)	462.55	416.52	415.01	415.27
4 (429.27 m)	493.10	423.74	422.93	422.92
5 (440.79 m)	480.48	430.67	431.44	431.94

GIII receiver also noted no significant difference in the measurement percent error between lane line 1 and 2, but did note a significantly higher percent error between lane line 1 and 3 (P = 0.0059). The GIII also noted significantly higher percent error levels when lane line 5 was compared to lane line 1,2, 3 and 4 with and P greater than 0.01. The TGII was the only receiver to note a significant decrease in the percent error noted between lane line 1 and 2 (P = 0.039). Although when lane line 5 was compared to lane line 1, 2, 3 and 4, lane line 4 was the only percent error value that did not demonstrate a significant change in the measurement percent error (P = 0.01). Unlike the TGII, the TGII DGPS only noted a significant increase in percent error when lane line 1 and 3 were compared (P = 0.00005). As well as with the GIII, the TGII DGPS noted significant decreases in percent error when lane line 5 was compared to lane line 1, 2, 3 and 4 with a P of greater than 0.01.

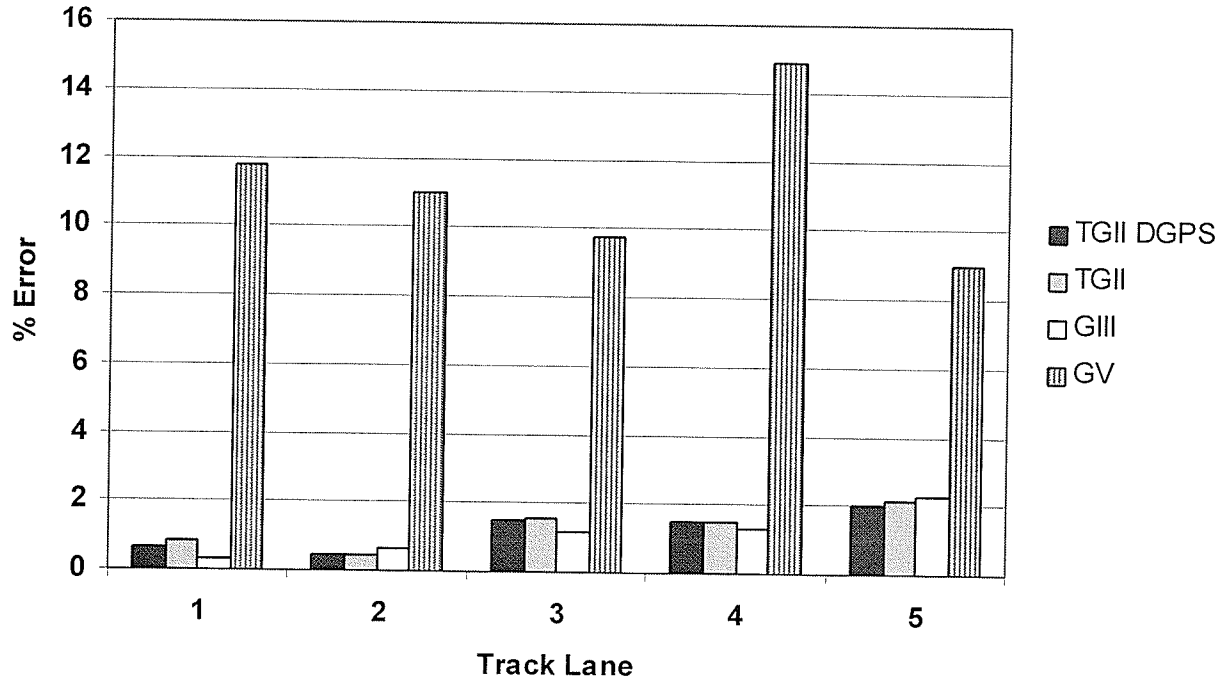

Figure 14 The measurement errors for each lane line measured by the GV, GII, TGII and TGII DGPS for the track tests.

Satellite Configuration

Over a GPS sampling time period, the satellites that a receiver utilizes to determine a position solution may change depending on FOV obstructions and individual satellite ephemeredes (i.e. rising and setting of the satellites in the sky). The DOP level is an indication of the quality of satellite configuration and therefore the satellite configuration

Table 14 The satellite configurations for a single 10 m radii circle are illustrated with the individual satellite ID # with the total number of satellites logged. Note the effect of the various satellite configurations on the PDOP level for the TGII.

Satellite ID #					Satellite #	PDOP
5	10	16	24	30	6	2.2
5	**10**		**24**	**30**	**5**	**3.3**
5	10	16	24	30	6	2.2
5	**10**		**24**	**30**	**5**	**3.3**
5	10	16	24	30	6	2.3
5	10	16	24	30	6	2.3
5	**10**		**24**	**30**	**5**	**3.4**
5	10	16	24	30	6	2.3
5	10	16	24	30	6	2.3
5	**10**		**24**	**30**	**5**	**3.4**
5	**10**		**24**	**30**	**5**	**3.4**
5	10	16	24	30	6	2.3
5	10	16	24	30	6	2.3
5	**10**		**24**	**30**	**5**	**3.4**
5	**10**		**24**	**30**	**5**	**3.4**
5	10	16	24	30	6	2.3
5	10	16	24	30	6	2.3
5	**10**	**16**	**24**		**5**	**2.8**
5	**10**	**16**	**24**		**5**	**2.8**
5	10	16	24	30	6	2.3
5	10	16	24	30	6	2.3
					Average	2.72
					Minimum	2.2
					Maximum	3.4

does have an effect on the relative accuracy of GPS measurements. Initial shifts in DOP can be observed during a kinematic or dynamic acquisition of satellites, which can cause substantive shifts in DOP level. Table 14 outlines the positional dilution of precision (PDOP) changes, along with the satellite configuration (denoted by the satellite ID #) and total number of satellites sampled for a single 10 m radii circle as measured by the TGII.

Note the bolded DOP changes and the respective influence of the satellite configuration on the DOP levels. With all 6 satellites within the receivers' FOV, the PDOP level is at 2.2 - 2.3. Note how the PDOP level is altered; with a loss of satellite number 16 the PDOP level will increase to 3.3 - 3.4 and with a loss of satellite number 30 the PDOP level will increase to 2.8. Each of the bolded PDOP level changes in table 14 are marked on the 10m radii circle graph in figure 15. Note the effect of PDOP level changes exemplified in figure 15, which are influenced by the satellite configuration during the 3 minute 39 second sampling time period. This trial was selected specifically for the purpose of illustrating the impact of DOP shifts.

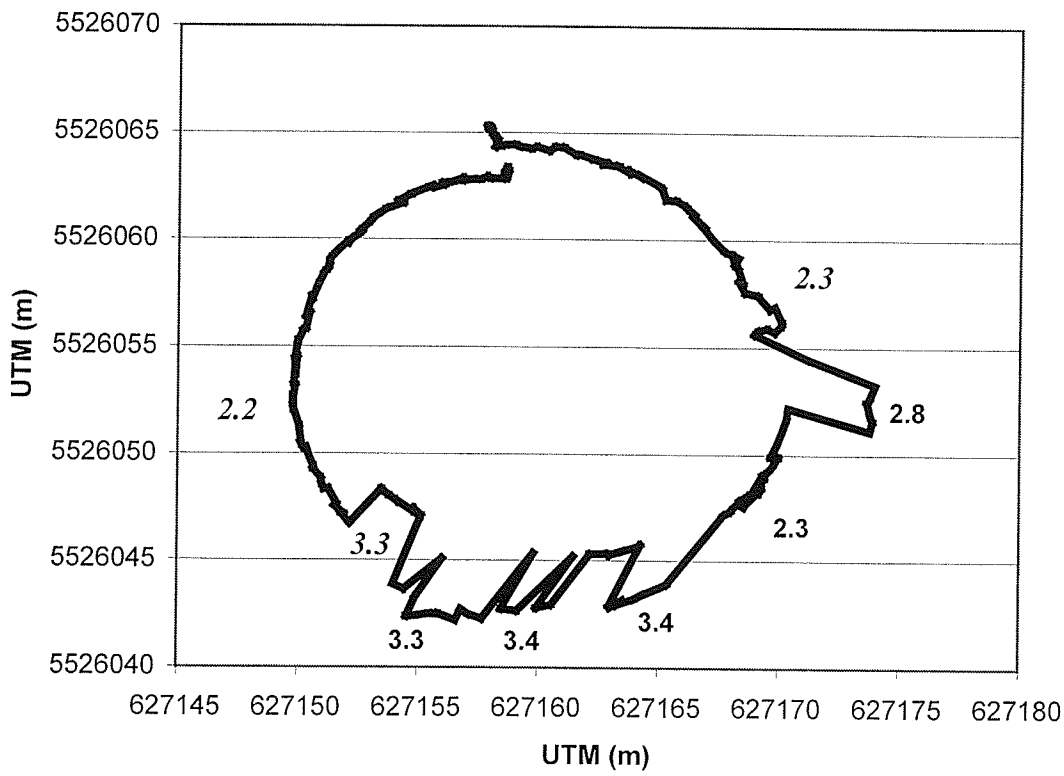

Figure 15 The changes in PDOP level and its' effect on the position solutions derived during a 10 m radii CCT as measured by the TGII GPS receiver.

GPS Occupation Time

The occupation time of a trial will influence the total number of satellites that are logged due to the respective satellite ephemerides (orbital paths), which may change the satellite configuration and therefore the relative accuracy of a measurement performed.

The CCT (table 15), track test (table 16) and 3.5 km field test (table 17) demonstrated varying sampling periods. Table 18 provides a summary of the average, minimum, maximum and standard deviations of the occupation times for the CCT, track and 3.5 km field tests. The track and 3.5 km field tests had similar sampling time periods (22:28 ± 0:43 and 21:46 ± 1:23 minutes respectively), with the CCT having the lowest occupation time overall (7:30 ± 1:07 minutes). All the tests performed had low standard deviations in the sampling time periods.

The respective positional, horizontal, vertical and time DOP levels are graphically illustrated in figure 16 for the CCT (5 m and 10 m radii circles) and the track test. The track test consistently has the greatest DOP values.

Table 15 CCT occupation time summary.

Trials	Time (min:seconds)
1	8:05
2	8:47
3	6:38
4	8:23
5	8:53
6	6:43
7	6:41
8	7:40
9	5:41
Average	7:30
Minimum	5:41
Maximum	8:53

Table 16 Track test occupation time summary.

Trials	Time (min:seconds)
1	21:55
2	22:31
3	22:45
4	23:49
5	22:15
6	22:48
7	21:19
8	22:23
Average	22:28
Minimum	21:19
Maximum	23:49

Table 17 3.5 km walk/run occupation time summary.

Trials	Time (min:seconds)
1	22:54
2	23:58
3	23:28
4	23:56
5	21:15
6	21:43
7	20:53
8	22:34
9	19:43
10	21:30
11	21:27
12	20:46
13	20:22
14	21:16
15	20:48
16	21:46
17	19:43
18	23:58
Average	21:46
Minimum	19:43
Maximum	23:58

Table 18 The average, minimum, maximum and standard deviation for the occupation time of the CCT, track and 3.5 km walk/run are outlined.

	CCT	Track	3.5 Km
Average	7:30	22:28	21:46
Minimum	5:41	21:19	19:43
Maximum	8:53	23:49	23:58
SD	1:07	0:43	1:23

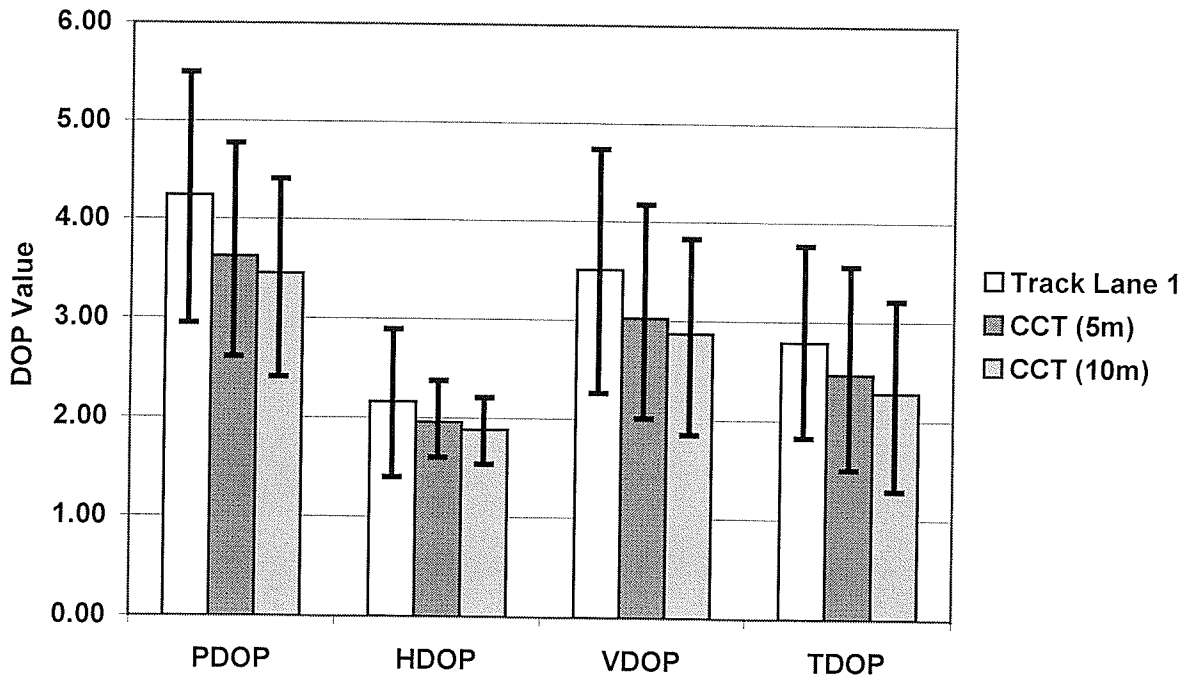

Figure 16 The DOP levels and the respective standard deviations in DOP levels are illustrated for the track, the CCT at 5m and at 10m.

Figure 16 illustrates the positional, horizontal, vertical and time DOP level changes observed with the track lane 1, CCT 5 m radii circle, and CCT 10 m radii circle with the respective standard deviations. Table 19 summarises the average occupation time and the standard deviation in time of each test performed that are specifically illustrated in figure 16. Note that the track test performed on lane 1 has the longest duration (4:46 minutes), the greatest standard deviation (±0:23) and the greatest DOP levels. The 10m radii CCT had the second longest occupation time at 1:25 minutes with a standard deviation of 0:14 minutes, but the 10m radii CCT demonstrated the lowest DOP levels out of the three tests performed. Contrarily, the 5 m radii CCT had the lowest occupation time and standard deviation (0:45 minutes, ±0:06 minutes), although the 5 m radii CCT demonstrated the second highest DOP levels. However, the variances between the DOP levels of each of the track lane 1, CCT 10 m circle

Table 19 Summary of the average occupation time and standard deviations of the time duration with the trials performed for each test.

	TIME	Standard Deviation
TRACK	4:46	0:23
CCT05	0:45	0:06
CCT10	1:25	0:14

radii and the CCT 5 m circle radii performed are negligible and proved to be statistically non-significant ($P > 0.05$).

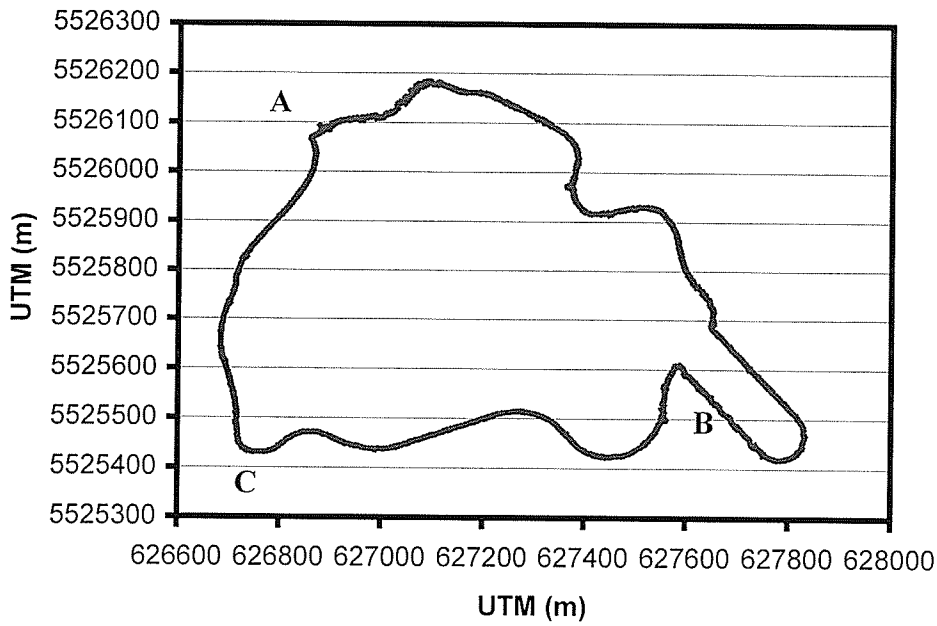

Figure 17 The 3.5 km run as visually displayed by the TGII GPS measured positions. **A** represents the start point where a walking pace was initiated. **C** represents the point where the individual increased their velocity to a running pace and **B** denotes the section where the individual sprinted or dramatically increased the running velocity.

3.5 km Field Test

The 3.5 km field test was performed on a fixed, calibrated course. Figure 17 illustrates the 3.5 km course that the subject performed. The course was started at point A at a low walking velocity (average derived velocity of 1.7 m/s) with an increase in velocity to a self-determined run at point C (average velocity of 3.4 m/s). The subject then sprinted (average 4.0 m/s) at point B for a segment of the course. Table 20 is a summary of the 3.5 km course measurements of each individual trial performed, with the average, minimum and maximum distances determined by the various GPS units. Note the variances in the averages of the 3.5 km course measurements between each of the GV, GIII and TGII receivers. The GIII and the TGII average measurements of the 3.5 km course are 3583.00 m and 3678.07 m respectively. The average measurement error difference from the 3.5 km course is 83 m for the GIII measurements and 178.07m for the TGII measurements. The GV average measurement of the 3.5 km course was 3733.09 m, which is a difference of 233.09 m from the calibrated 3.5 km measurement.

Table 20 The average, minimum and maximum distances measured by the GIII, GV and TGII of the 3.5 km test.

Trials	GIII	GV	TGII
1	3558.94	3740.10	3572.29
2	3561.48	3710.29	3674.89
3	3555.28	3748.86	3644.55
4	3580.18		3643.31
5	3587.56		3726.08
6	3552.45		3648.57
7	3583.72		3708.95
8	3577.40		3601.50
9	3553.17		3685.65
10	3551.93		
11	3644.77		
12	3609.74		
13	3568.39		
14	3596.99		
15	3662.97		
Average	3583.00	3733.09	3678.07
Minimum	3551.93	3710.29	3572.29
Maximum	3662.97	3748.86	3708.95

Figure 18 graphically depicts the percent error noted between the GPS unit measurements. Note how the GV has the greatest percent error (6.7 %), followed by the GIII (2.4 %) and TGII (5.05 %) GPS units. Although, when the GPS receiver measurement errors are graphically displayed (figure 18), the differences noted between the GPS units seem relatively marginal, but when analyzed each of the GPS receivers were found to have significantly greater measurement error from the calibrated 3.5 km course measurement ($P > 0.01$).

Figure 19 illustrates two overlapping measurements of the 3.5 km course performed by the GV (light gray) and GIII (black). It is interesting to note that on observation of figure 19, there are marginal differences between the two measurements outlined. Upon measurement of the 3.5 km course illustrated, the GV measured the course to be 3740.10 m and the GIII measured the course to be 3558.54 m. This equates to a difference of 181.56 m between the GIII and the GV. Overall the GV demonstrated a 6.86 % and the GIII demonstrated a 1.67 % measurement error in comparison to the known 3.5km distance. The GV's measurements of the 3.5 km course were significantly different from both the GIII ($P = 0.00000086$) and TGII ($P = 0.014$) 3.5 km course measurements.

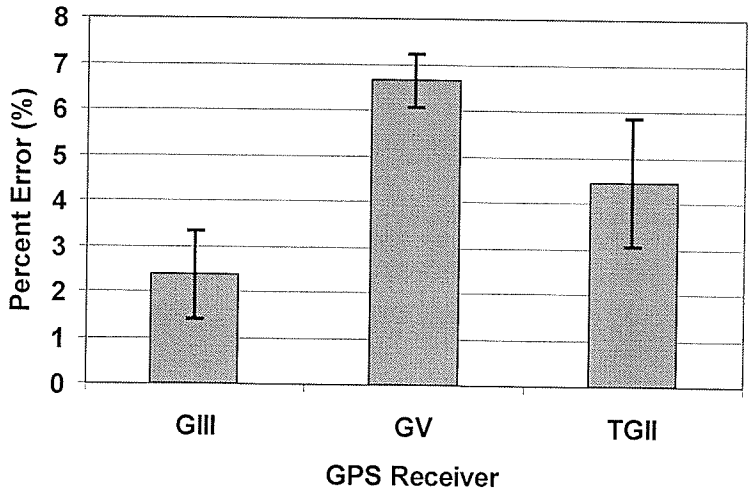

Figure 18 Percent error and standard deviations calculated from the distance measurements of the 3.5 km course performed by the GIII, GV and TGII.

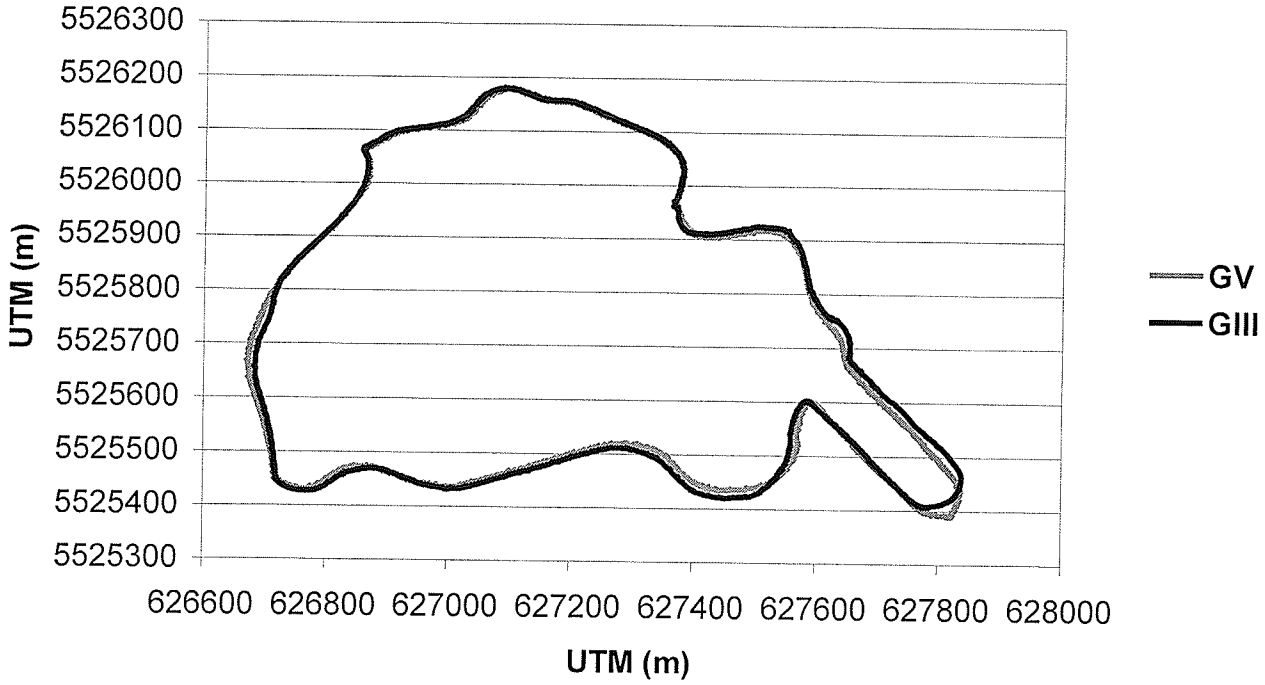

Figure 19 This illustrates the 3.5 km run as measured by the GV and GIII plus. Note that there is marginal difference on observation between the two tracks, although the measurement by the GIII i 3558.941 m and the GV is 3740.103 m.

Summary of Results

1. Distance assessment over 12 m can be achieved with less than 5 % accuracy for most GPS systems.

2. The GIII provides an adequate description of human movement at a sampling rate of 1 second and the TGII and TGII DGPS at a 2 second or lower sampling rate.

3. The track test demonstrated that distances of 440.79 m (lane line 5) could be measured with a relative accuracy of less than 2.3 % error with the GIII, TGII and TGII DGPS receivers.

4. The GV demonstrated significant percent error levels with all measurements in comparison to the GIII, TGII and TGII DGPS measurements. Therefore, the GV GPS receiver does not provide an adequate description of the movement performed due to the receiver sampling characteristics ('staggering walk' effect) and its' effect on the movement measured (distance overestimation).

5. The DOP levels noted over the testing occupation times required to perform the track lane 1 test and CCT 5 m and 10 m radii circles are reflective of kinematic testing time periods. On analysis of the DOP levels noted with each of these tests performed, there were no significant differences ($P > 0.05$) between each of the tests' DOP levels with a minimum testing time period of 45 seconds.

6. The 3.5 km field test provided a functional outdoor kinematic test that enabled comparison to the CCT and the track test. The 3.5 km distance measurement percent error levels noted with the GIII and TGII receivers' were comparable to the CCT and track test percent error levels.

7. When the 3.5 km field test GPS receiver measurements were compared, it was noted that the GV, due to its' 'staggering walk' effect, had a 6.7 % error for the 3.5 km

walk/run, field test. This error level was significantly, different from the GIII and TGII error levels.

8. The GIII demonstrates adequate levels of relative accuracy for assessment of human movement, although the TGII provides a higher level of relative accuracy. There are negligible differences between the accuracy of the TGII and TGII DGPS. Therefore, the SA-off GPS is adequate for assessment of human movement.

Discussion

Preamble

The assessment of velocity and acceleration data derived from GPS by Schutz and colleagues (1997, 2000 & 2001) has not fully examined the capabilities of GPS for movement assessment, especially those related to gait. Previous GPS assessments performed by Terrier, *et. al.* (2000) and Schutz, *et. al.* (1997,2000 & 2001) have attempted to determine the velocity measurement capabilities of GPS. Although they have concluded that GPS does provide an accurate measurement of human movement velocity, the spectrum of velocities analysed was broad, which would necessarily attenuate the overall error levels. These error levels would not represent the errors expected for assessment of walking at normal speeds. Gait is an obvious and important area for application of GPS measurement capabilities. As such, our understanding of the ability of GPS to provide low velocity assessment of movement is not well known. Further, there are other key factors important in the file of movement analysis that have not been well elucidated in their influence on GPS positional data (e.g. sampling rate, satellite configuration & occupation time). An initial characterization of these factors is important in order to have an improved understanding of the assessment capabilities of GPS for human movement studies.

Larsson and Larsen (2001) described a GPS speed and distance validation, which was performed on a straight 115 m path. Their "gold standard" was a tape measurement of the distance and the speed assessment was performed using the measured distance and a chronometer. The velocity data was sampled at 2 second intervals and the distance assessment was determined through the static positional difference between two individual points sampled at the beginning and end of the 115 m path. There was no continuous movement assessment of the GPS sampling capabilities and the sampling characteristics of GPS on curvilinear movement paths were not analysed. The CCT test, developed for this study, provided a benchmark test to understand the dynamic relative accuracy sampling capabilities of GPS receivers for human movement assessment.

All of the studies performed by Schutz, *et. al.* (1997, 2000 & 2001) and Terrier, *et. al.* (2000a & 2000b) occurred while the U.S. DoD still enforced SA. The only study that has been performed since selective availability has been discontinued was by Larsson and Larsen (2001). The downfall of all of these studies is that the validation of GPS for assessment of

human movement has not been comprehensive. This is due to the fact that they have not realised the effect that curvilinear paths can have on movement assessment and that their primary focus has been on velocity assessment. Through these studies the relative positional accuracy of GPS has not been fully addressed, which affects the assessment of velocity. To date, there has been no comprehensive assessment of SA-off GPS relative accuracy.

The present study was performed after SA was discontinued; therefore ensuring the most accurate satellite signals were employed for a comprehensive assessment of GPS for the study of human kinematics.

The primary application of GPS is to determine an exact earth based position. The study of human kinematics does not require that an exact known position on earth is determined, but that determination of a position relative to another is accurate (dynamic relative accuracy). The GPS receivers' logging characteristics, including the sampling rate and satellite configuration impact upon the dynamic relative accuracy of GPS. The CCT, track and 3.5 km field tests have provided an ability to analyze the application of GPS for the study of human movement, especially for the assessment of walking gait. Once the capabilities of GPS have been determined, the logging of an individuals' movement on a time-stamped position by position basis provides a wealth of kinematic information. This creates the basis for greater insight into not only the movement pattern, but also establishes an ability to examine the total body physiological response to movement when coupled with physiological sensors.

Objective 1: *Develop a test that enables assessment of relative accuracy of SA-Off GPS and DGPS during dynamic conditions.*

The concentric circle test described in this thesis was derived from the work of Shreenan and coworkers (1996). They originally developed a single concentric circle to provide a benchmark test for comparison of logging capabilities of various GPS receivers. The concept for the CCT was modified from the single circle to multiple increasing concentric circles. The variation of increasing the circle radii circumference measurements from 1-5 m and 10 m enabled both visual confirmation and statistical assessment of GPS relative accuracy. The CCT provided a known measurement both in circle circumference as well as circle radii, which the GPS position samples could be compared against. In addition, the circular pattern provides an ability to assess GPS in a more 'real world' setting since the

orientation of the individual and GPS are constantly changing (rather than moving in a straight line). Further, the use of a curvilinear path (circular trajectory) also permitted the assessment of sampling rate, which is not as readily assessed when using straight-line motion. The CCT also allowed for incremental assessment of relative accuracy with an increasing distance travelled from 6.28 m to 62.8 m. This also coincidentally provided a means to assess the impact of occupation time on GPS relative accuracy. Occupation time influences the degree to which a change in satellite geometry can occur – short occupation times can have relatively stable geometries, whereas longer occupation times will result in changes in satellite geometry due to the transit time of the satellites. The CCT (figure 5) is a test that can be applied to any GPS receiver that has been developed and this test provides an ability to analyse the positional, dynamic relative accuracy of an individual GPS unit in order to determine it's utility for assessment of human movement. Further, this is a good learning and familiarization test for those who use GPS for positional data logging.

Objective 2A - *Use the CCT and Track Test to evaluate relative accuracy of GPS by assessing the distance measurement capabilities of different GPS systems.*

CCT: The CCT enables a graphical representation of the dynamic relative accuracy of the GPS receiver and system. Figure 5 provides an illustration of the 4 types of GPS measurements. The placement of the consecutive circles with the first two measurements by the TGII, both differentially and non-differentially corrected (figure 5A and 5B respectively,) visually demonstrates the high level of relative accuracy through the clearly defined incremental circular trajectories. The GIII measurement of the CCT demonstrates how the concentric circles individually increase in size, although some of the circles overlap where there is a 1 m or greater distance between the circle radii (figure 5C). This provides a graphical demonstration of the degradation in relative accuracy in comparison to that of the TGII system. Although, the GIII measurement of the CCT is visually not as clear as the TGII measurements, it still provides an adequate description of the concentric circle pattern of movement travelled. The results from the GV GPS receiver are shown in Figure 5D. The individual circle radii measured by the GV, especially for the 1-5m radii circles are indistinguishable and do not represent a series of concentric circles. The GV tends to create

a step-like appearance of the circular pattern that was sampled. The algorithms used for computation within the GV receiver cause this step-like appearance. This unit likely uses integer mathematics for calculating each of the position solutions, contrary to the other units that utilize non-integer mathematical calculations. Therefore, the integer calculations restrict position solutions to fixed values (which appear as steps). As such for small distances travelled, especially in a curvilinear path, the positional data sampled is not an accurate reflection of the movement pattern measured. For example, if you were to sample data on a defined line and then sample data on a parallel line greater than one meter from the first line, the GV might show two lines clearly. Although, if the GPS unit were to sample data between the two lines, as the unit weaved closer to each of the lines, the data points would be confined by the integer computations to points on the two parallel paths but not in between. This would result in positional data that represents a path like that of a 'drunken sailor', staggering between two parallel lines. Therefore, instead of showing a wave like pattern of movement, a step like or jagged pattern of sharp angle changes in movement direction would be illustrated, hence the term 'drunken sailor effect' or 'staggering walk' effect. It is interesting to note that on a straight path, the sampling characteristics of the GV could go relatively undetected, but with a circular pattern test the sampling characteristics that affected the relative accuracy were clearly illustrated.

As expected, the greatest percent error in total distance travelled was noted with the smallest distance travelled (6.28 m) or the 1m radii circle. This was consistent for the three main GPS systems (GIII, TGII and TGII DGPS). A substantial decrease in percent error was then noted once again in all three receivers with an increase in distance travelled to the 2 m radii circle (12.58 m circumference). However, only the TGII and TGII DGPS demonstrated a statistically significant decrease in the percent error. One can conclude that the TGII and TGII DGPS provide relative accuracy levels that are acceptable (less than 5 % error) when the distances travelled exceed 12.58 m. The GIII demonstrated no significant differences in comparison of measurement percent errors for any radius of the CCT. This may have arisen from the relatively low percentage error observed for the 1 m radius circle for the GIII. The GIII uses a different method of positional computation than the TGII GPS units where all satellites in the field of view are used (normally between 6 and 8, but up to 12) to provide an over-determined positional solution. The TGII units can only use up to six satellites and then only use those satellites over a fixed angle from the horizon and those

satellites with good or better signal to noise ratios. The substantially lower GIII error may be a result of this computational difference. However, when the distances increase the TGII GPS units have statistically better error values which likely results from the improved receiver quality (low noise) of this system. Caution must be taken when interpreting the GIII measurement capabilities; the user must understand what the impact of the relative error will be for the specific application. The conclusion that a minimum distance travelled of 6.28 m (1 m radii circle) will provide an adequate relative accuracy level when performed by the GIII receiver could be made based upon a relative accuracy requirement under 7.5 %.

On observation of the individual CCT performed by the GIII, TGII and TGII DGPS (figure 5A, 6B & 6C) there is a recognisable circular pattern demonstrated with each of the measurements. Each of the CCT derived demonstrated graphical relative accuracy through their ability to reconnect to the start position, even though the absolute accuracy or position may have been displaced from the true position on earth. When the GPS measurements were individually analysed, the TGII and TGII DGPS were the only measurements that demonstrated significantly lower percent error levels at the 2 m radii circle. Therefore, a reasonable recommendation for distance measurements is that the minimum distance travelled be greater than 12.57 m is required in order to ensure that an accurate description (less than 5 % error) of the movement has been sampled. All of the GPS system results are consistent in showing that users can employ GPS for distance measurements over relatively small distances, and that the derived kinematics from the positional data (velocity and acceleration) will likely be acceptable given the appropriate mathematical derivation. The quality of the derived kinematics is wholly dependent upon the quality of the positional data identical to that observed in video motion analysis.

Track Test: The track test was performed in order to provide further assessment of the dynamic relative accuracy of GPS with incremental distances travelled over a longer baseline, as well as to detect any obvious impact of occupation times on satellite geometry and hence positional error. This test allowed for a broader understanding of the sampling characteristics of GPS for extended distances and sampling periods. Comparing the known track lane length to that derived from the GPS enabled assessment of relative positional accuracy. Graphically, all of the 4 GPS systems demonstrated a consistent pattern from the inner most lane 1 to the outer most lane 5. The measurements of the track lanes performed by the GIII, TGII and

TGII DGPS had similar measurement values, all of which underestimated the total distance measured. Although, it is important to note that this underestimation of the total distances equated to very low error levels for the GIII, TGII, and TGII DGPS. However, the GV measurement of the track lanes significantly overestimated the total distances. This effect was due to the 'drunken sailor' effect noted previously, where the computational method within the GPS resulted in an artificial increase in distance travelled as the positions 'stepped' between the integer based solutions (see below for further discussion).

The track test data error values illustrated in figure 14 demonstrated an increase in percent error with an increase in distance travelled with each lane line measured. This is in contrast to the percent error decrease noted in the CCT (figure 6) with an increase in distance travelled with each circle circumference measured. Although, it may seem as though there is conflicting data, the track test data actually had lower percent errors. At the greatest distance travelled in track lane line 5 for the track test demonstrated greater percent error (GIII- 2.29 %, TGII- 2.12 %, TGII DGPS 2.00 %) than the greatest distance travelled in the CCT, which is the 10m radii circle (GIII-3.43 %, TGII- 4.29 %, TGII DGPS- 0.43 %). The only exception was the TGII DGPS measurement in the 10 m radii circle in the CCT demonstrated a lower percent error than the percent error noted for lane line 5 of the track test. Overall the average percent errors for the track test were all less than the average percent error for the CCT for the GIII, TGII and TGII DGPS receivers. (Track test: GIII-1.14 %, TGII- 1.28 %, TGII DGPS 1.21 %; CCT: GIII-2.32 %, TGII- 4.5 %, TGII DGPS, 3.95 %). Overall, the track walk data demonstrates that with a greater distance travelled, the distance measurement percent error is smaller in relationship to lower distances travelled of less than 62.82 m.

The lane with the longest distance (lane 5 = 440.79 m) had an average maximum error of 2.30 % (GIII), 2.12 % (TGII) and 2.01 % (TGII DGPS) in comparison to the survey wheel measurement. The influence of this error in most measurement applications would be deemed to be acceptable, if not negligible. However, the percent error of the lane line 5 measurement by the GIII, TGII and TGII DGPS proved to have a statistically significant higher percent error from lane lines 3, 2 and 1. The lane line 1 measurement had a significantly lower percent error level when compared to lane line 2 with the TGII measurement. It is interesting to note that the GIII and the TGII DGPS measurement percent errors were not significantly different between lane line 1 and 2, but were significantly lower in lane line 1 than lane 3. Due to the fact that the TGII receiver data, once differentially corrected, indicated a significantly lower percent

error when lane line 1 was compared to lane line 3, differential correction of the data may slightly improve the accuracy of measurements performed.

Although when the GPS receiver data for the TGII and TGII DGPS was analysed and there were no significant differences between the measurements performed with all lane lines. The GIII also demonstrated a significantly lower percent error than both the TGII and TGII DGPS. Contrarily, the GVs' measurement of lane 1-5 demonstrates a significantly larger percent error in comparison to the other measurements, ranging from 9.0 to 14.9% error. Although, it is important to note that this error is incremental and not exponential with each of the lane lines measured. The lane length increase noted in the GV is likely due to the fact that the GV pins the GPS positions to values with fixed intervals resulting in a 'staggering walk' or 'drunken sailor' effect when the person was actually walking in a straight line. Therefore, this consistent error is caused by the oscillations created by the positional computation of the GV, which will artificially increase the total distance measured. As noted in figure 14, the GV consistently demonstrated a significant overestimation of each of the lanes in comparison to the other GPS measurements. Although, the relative accuracy of the GV track test measurement might graphically be acceptable, the analysis of the data in comparison to the known distance measurements demonstrates that the GV will systematically significantly overestimate the total distance travelled. Therefore, the GV will only provide a relatively modest level of accuracy for distances over 400 m in comparison to the GIII, TGII and TGII DGPS.

The track test provided an increased distance and sampling time over which to analyse the sampling characteristics of GPS receivers in comparison to the CCT. It also provided both a straight and curvilinear component to the distance measurement assessment, which caused a change in receiver orientation to the satellite constellation. Through the track test, an increased understanding of the GPS receiver sampling characteristics, which affects the dynamic positional accuracy, was enabled by the analysis of the GPS distance measurement capabilities.

Objective 2 B- *Use the Concentric Circle Test (CCT) and track test to evaluate the relative accuracy of GPS by assessing the impact of satellite geometry and configuration on relative accuracy.*

Previous studies employing GPS for human movement studies have failed to address the system characteristics that affect the relative accuracy of GPS, one of which is the satellite

configuration. Analysis of various satellite configurations and their effect on DOP level (measurement of satellite configuration) is critical to understand in order to ensure adequate GPS data collection conditions. Each of the GPS receivers observed a minimum of 4 satellites and a maximum of 6 satellites. The configuration, including both the satellite positions and number of satellites within the FOV will affect the DOP level. Therefore, with a greater number and better configuration of visible satellites, a lower DOP level will be observed which will influence the relative accuracy of the GPS data sampled.

Table 14 and figure 15 illustrate data on how various satellites and their respective ephemeris (rising and setting in the FOV) and or FOV obstructions will affect the positional accuracy due to the variances in the overall satellite configuration. Figure 15 demonstrates the changes in the position solutions with the respective changes in the PDOP level for a 10 m radii circle. With observation of the circle, there are quite a few drastic changes in the circumference sampled and this affected the overall total distance measured. Changes in PDOP values occur relatively smoothly, except when new satellites come into view, and then quick changes tend to occur which is illustrated in figure 15. An accurate demonstration of the movement pattern around the 10m radii circle is not illustrated in figure 15; therefore it is critical to ensure that there are an adequate number of satellites and that no major changes in the satellite geometry occur over the sampling time period.

Unfortunately, a set PDOP level criterion for sampling cannot be established. The DOP level is normally dependant upon the receiver because the TGII and the GIII demonstrate different DOP levels for a given satellite configuration (GIII= <2.0 good, TGII <4.5 good). It is also critical to note that a relatively good DOP level does not always indicate a good satellite configuration. The satellite geometry for any given sampling epoch can fall into numerous patterns. Although these various geometry alterations, such as in-line satellites, horizon satellites and FOV obstructions can change the geometry or configuration, they may present a good DOP level, but upon analysis of data derive poor relative accuracy in the measurements sampled. This is due to the fact that one or two satellites may be in a good FOV for the receiver and therefore have a strong signal. This will attenuate the poor DOP levels created by other satellites in less than optimal FOV positions. Therefore, the total configuration of the satellites within the FOV, as well as a good DOP level is critical in order to obtain an accurate measurement.

Occupation Time

Each satellite has an individual orbital pattern or ephemeris, which will change the configuration of the satellites within a receivers' FOV over a given sampling time period. The occupation time of a GPS data collection trial will affect the positional accuracy due to these changes in the satellite geometry over the sampling epoch. The occupation time of the CCT and track tests reflect the average testing time period that allows for a shift in the satellite configuration to occur which will affect the DOP levels. GPS human kinematic studies to date have not reported the sampling duration and have not assessed the impact of occupation time on the data sampled.

The track test provided a more thorough examination of the shift in satellite configurations and its effect on the dynamic relative accuracy than the CCT, due to the greater occupation time required to perform the test. The track tests were performed during various time throughout the day in order to prevent a biased understanding of the effect of the DOP level on the relative accuracy of the data collected. Further analysis of the PDOP levels occurred with the lane 1 measurement of the track, the 5m radii of the CCT and the 10m radii of the CCT, which demonstrated similar DOP levels despite variable occupation times. It seems as though with an increase in occupation time, there is an increase in the DOP level observed, but it is critical to note that this degradation in DOP level does not create a significant level of inaccuracy ($P > 0.01$). The DOP levels were the greatest with the track test, which had the greatest occupation time, although the DOP levels were still within an acceptable level for accurate assessment of human movement. The CCT had an occupation time of 0:45 (SD ±0:06) and still had an adequate DOP level in order to provide an accurate description of the movement pattern. Both the CCT and track tests provided a realistic reflection of the GPS dynamic relative accuracy levels over a short testing time period, which is adequate for human kinematic testing requirements.

Objective 2C - *Use the Concentric Circle Test (CCT) to evaluate the relative accuracy through assessing the impact of sampling rate.*

The sampling rate is one of the primary components in determining the kinematic assessment capabilities of GPS. In analysing the GPS data with a single trial, degrading the sampling rate at 1 second intervals, the effect of variable sampling rates was noted. Figure 7

graphically illustrated the change in the circle sampled with degradation of the sampling rate. As the sampling rate was decreased from a 1 second sampling rate to an 8 second sampling rate at a 1 second down sampling rate, it can be noted that the circle begins to lose its shape and increases in angularity. Therefore, the total distance travelled will be underestimated, with an increase in the magnitude of underestimation up to the 8 second sampling rate data. This is critical because the total distance measured by a GPS unit is affected by the sampling rate capabilities. If the sampling rate affects the total distance measured, it will also affect the measurement of the velocity due to deriving the velocity data from the distance/time measurements.

Figure 8 illustrated that the percent error of the CCT progressively increased with each level of down sampled data. Upon analysis, the GIII demonstrated a significantly lower percent error at the 1 second sampling rate than the 2 second sampling rate. The TGII and TGII DGPS noted significantly lower percent error levels in the 2 second sampled data when compared to the 3 second down sampled data. Schutz *et. al.* (2000) performed velocity assessment in their second study at 6 second average intervals. If the displacement data analysed in the present study has a significantly lower percent error at a sampling rate greater than 1 second with the GIII and 2 seconds for the TGII and TGII DGPS, then the velocity assessment performed by Schutz *et. al.* could possibly have a greater margin of error than if the instantaneous or 1 second data was utilised for velocity assessment. They were unable to detect this level of error in their velocity assessments due to the fact that their gold standard for comparison was chronometry measurements over a set distance. It is most likely that the chronometry measurements over the set distance were not an appropriate velocity measurement for comparison of the 6 second averaged GPS velocity data. Due to this down comparison, it is possible that they were unable to detect significant levels of velocity measurement error.

Through the analysis of the effect of the sampling rate on the total distance measured by the GPS, it has been possible to critique the minimum sampling rate required in order to obtain an accurate assessment of the movement performed. Therefore, the sampling rate is one of the most critical sampling characteristics of GPS that will directly impact upon the relative accuracy of position solutions and indirectly upon the velocity assessment and measurement capabilities of a GPS receiver. Through the CCT data analysis, the 1 second sampling rate for

the GIII and ~ 2 second sampling rate for the TGII and TGII DGPS has been found to provide a good and relatively accurate description of the distance traveled.

Objective 3 *- Examine the relative accuracy of the GPS systems in a 3.5 km field test for comparison to the CCT and track test.*

The 3.5 km course was calibrated in order to difference the total known distance to the distance measurement performed by the GPS receivers. On observation of the 3.5 km course, there is good, graphical relative accuracy due to the course start and end points reconnecting, as well as a good outline with minor deviations caused by satellite configuration shifts, FOV obstructions, etc.

As was noted with the GV measurement of the track lane lines, there are also small oscillations in the 3.5 km path measured, although it is critical to note that these are relatively undetectable unless sections of the course are magnified. It is the accumulation of these small oscillations over the entirety of the course that inflates the measurement of the total distance travelled. Although, the GV still demonstrates good relative accuracy in that the start and endpoints of the course still re-connect. It is also critical to note that the total distance measured is not accurate and therefore the derived velocity would not reflect an accurate description of the movement performed. The extent of the GV's measurement error of the 3.5km test is relatively low (~ 6.5 % error) in comparison to the shorter track test measurement (~22.5 %). It is probable that the error due to the measurement oscillations will attenuate with an increasing magnitude of distance travelled, although further testing of the magnitude of error in relation to the total distance travelled performed by the GV is required.

The 3.5 km course provided a kinematic test that allowed distance measurement comparisons to the CCT and track tests. The percent errors noted with the 3.5 km course (GIII-2.37 % & TGII- 4.46 %) are comparable to the error levels noted with the CCT (GIII-2.32 % & TGII- 4.5 %) and slightly higher than the track test (GIII- 1.14 % & TGII- 1.29 %). The GV demonstrated considerably higher percent error levels with the track test (11.27 %) than the 3.5 km course (6.5 %) due to the attenuation of the 'drunken sailor' effect over the distance travelled. Overall, the GIII and TGII have relatively comparable dynamic relative accuracy levels in the 3.5 km course, CCT and track test distance measurements. The 3.5 km field test illustrated that adequate levels of dynamic relative accuracy are achievable in unencumbered kinematic field tests using GPS.

Conclusions

The use of GPS for a variety of applications is well established, although its utility for assessment of human movement patterns is an area, which has only begun to provide assessment capabilities in an unrestrained, outdoor environment. The foundation that is required in order to fully comprehend the sampling characteristics and capabilities of GPS has not been adequately addressed in the literature to date. This research project data demonstrates the measurement capabilities of GPS that are required to enable a detailed record of unrestrained, outdoor activity that is technologically unsurpassed to date.

The CCT and track test enabled analysis of the dynamic relative accuracy sampling characteristics of GPS for assessment of human movement. The minimum distance that can be travelled with an accurate description of the movement is 12.57 m with an error level of less than 5 % using the GIII, TGII and TGII DGPS. The GV overestimated the total distance travelled with each of the tests performed; therefore this GPS receiver does not encompass adequate sampling characteristics. The GIII and the TGII (differentially and non-differentially corrected) encompassed adequate sampling capabilities that provide an accurate description of a human movement pattern. The GPS sampling criteria include a minimum sampling rate of 1 second, an occupation time of ≥ 45 seconds and a reasonable satellite configuration (receiver, time and location dependent). It is also important to note that since the removal of SA, accuracy with non-differentially corrected positional data has improved almost to the level of DGPS positional data with non-significant differences in their dynamic relative accuracy levels. Final analysis of the data from the concentric circle test demonstrated that present GIII and TGII GPS units encompass the required sampling characteristics that provide good dynamic relative accuracy for assessment of human movement.

The 3.5 km field test provided an understanding of the GPS sampling capabilities with a 'real life' kinematic test in an outdoor environment, which enabled comparison to the CCT and track test. The 3.5 km field test demonstrated comparable relative accuracy levels to that of the CCT and the track test. Tests such as this have the potential to be combined with physiological measures to provide an understanding of the concurrent physiological response to unencumbered movement.

Overall, the accuracy, size and data logging capacity of GPS equipment with SA-off accuracy, opens new opportunities for application in both research and practical, human

kinematic assessment in a non-controlled environment. The ability to quantify and demonstrate the dynamic relative accuracy of GPS is integral in order to deem this technology adequate for assessment of human kinematics. GPS measurement of movement can provide the sampling characteristics that are essential for kinematic assessment in an unrestrained, non-laboratory environment.

Future Research

GPS provides an unsurpassed and new ability to measure human kinematics in the field. We have assessed the dynamic relative accuracy and determined the minimum sampling requirements, including sampling rate and DOP level (satellite configuration), for an accurate positional description of the movement performed, which is integral for clinical and research applications. GPS kinematic data has the potential to be easily combined with other physiological, time-stamped data such as heart rate, VO_2 and three-dimensional acceleration. An appropriate data interpolation method needs to be established for synchronization of physiological and kinematic data sets. Currently, measurements of the physiological effects of human movement are confined to laboratory settings and therefore an understanding of environmentally induced physiological responses is not well understood. Coupling kinematic assessment of movement with the physiological response will provide a greater understanding of various ambulatory conditions (PVD, Parkinson's, MS) and human performance (athletic training and competition).

The future of this technology is through the demonstration and application within rehabilitation and athletic environments. Through the use of this kinematic tool, exploration of both pathological and non-pathological kinematics, using concurrent GPS and physiological measurements, has extensive potential within research and practical environments in order to provide researchers, clinicians, coaches and athletes with a greater understanding and documentation of human kinematics in an uncontrolled or natural environment.

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Appendix A: Screening Assessment

"Total body kinematics and physiological responses of unrestricted subjects in the outdoor environment using GPS."

---

13. 1Name _____

2. Date _____

3. Sex M F (Please circle one)

3. Date of Birth _____

4. Height _____

5. Weight_____

6. What leg would you kick a ball with? R or L

13. Any restriction in movement in your lower extremity?_____

13. Are you currently taking any medications?_____

14. Have you ever-used performance enhancing drugs? If yes, please specify types of drugs used, dosage of drugs consumed and period of time spent using each drug?

_____

15. Have you had any traumatic injury to your lower extremity including injury to the ligaments, injury to the cartilage, dislocations or previous surgery? Yes/No If

so,which area/joint and what side?

(R/L)_____

16. Do you have any cardiovascular problems (eg. dizziness, high blood pressure, pain in the chest, heart or lung problems) or other medical conditions that may affect your ability to participate in this study?_____

17. Do you have osteoarthritis, rheumatoid arthritis or have you ever been given the diagnosis of chondramalacia patella?_____

18. Have you been diagnosed with having a neurological or musculoskeletal condition?

_____

19. Are you currently pregnant or breastfeeding? _____

Exercise history:

1. Do you exercise regularly? _____

20. What type of activities do you participate in? _____

_____

21. How long are your workouts? _____

22. How frequently do you exercise? _____

23. Have you been exercising for less than three months? _____

Appendix B: Paraphrase for Experimental Group

"Total body kinematics and physiological responses of unrestricted subjects in the outdoor environment using GPS."

Paraphrase and Informed Consent Form

University of Manitoba 2000

Contact: Dr. Dean Kriellaars

787-2289

PARAPHRASE

Our understanding of human movement in an uncontrolled, non-laboratory setting is limited due to the lack of technology that allows measurement. Recent advances in technology have created the ability to perform assessment and measurement of movement in an outdoor environment. This will enable continuous recording of movement in an outdoor environment for extended periods of time. The aim of this study is to provide more information about human movement patterns and the concurrent physiological response to activity in an uncontrolled, free-living environment.

STUDY PURPOSE:

The purpose of this research project is to assess the capabilities of global positioning systems (GPS) and tri-axial accelerometers to measure human movement. The secondary aim is to apply both technologies to study normal human movement patterns with simultaneous measurement of the body response to movement in a free-living, uncontrolled environment.

PROCEDURE:

As a subject in this study you will be required to complete a general questionnaire and a Par-Q assessment to ensure suitability for participation within the research study. You will then be familiarized with the small and portable special equipment consisting of a GPS, tri-axial accelerometer, HRM, and VO_2 metabolic system, which you will wear for the duration of the study period. This equipment will measure your activity level and your body response as you perform the movement tasks.

You will be asked to perform any of the following tasks:

- Walk around a 400-m track following the white marked lines defining the running lanes. With each lap you will move to the next line to your left and walk at the same speed as you walked in the previous lap. A constant, pre-determined walking pace will be maintained for the each lap through observing your speed displayed by a device.

- A walk or run will be performed at various speeds about a 400-meter track. Starting with a set speed, you will follow the marked, white line around the track keeping a steady pace with the displayed speed of the GPS. With each lap around the track, you will increase your speed by a pre-determined amount.

- In an open field, you will be required to perform various activities involving walking or running a distance of equal to or less than 10 kilometers.

RISKS

The associated risk factors of exercise in individuals defined as healthy within this study are primarily activity-dependent. Musculoskeletal injury, myocardial infarction, sudden death, and exacerbation of pre-existing disease or injury states are all risks factors of exercising, although are minimal due to the subject selection inclusion criteria and the intensity of the exercise to be performed. There are no known risks associated with the use of any of the devices for assessment of human motion.

CONFIDENTIALITY

Your name will not be attached or identified in any published report of the results obtained from this study. All references to your participation in this study will be made through a coded entry. All information collected from this study will be stored on a secure computer file, which is located in a locked room at all times.

If you have any questions or do not understand any aspect of this form, please contact,

Dr. Dean Kriellaars
School of Medical Rehabilitation
University of Manitoba
Voice: 787-2289

Appendix C: Informed Consent Form

"Total body kinematics and physiological responses of unrestricted subjects in the outdoor environment using GPS."

Paraphrase and Informed Consent Form

University of Manitoba 2000

Contact: Dr. Dean Kriellaars

787 - 2289

Consent Form

I have read the paraphrase and understand the nature of the study including the potential benefits and risks. I have satisfied any questions that I may have had with respect to this study. I agree to participate in this study and abide by the procedural requirements.

I understand that I am voluntarily participating in this study and that I may withdraw from this study at any time without prejudice. Through signing this document I understand that I am not waiving my legal rights as a research participant and if I have any further questions, that I may contact the research ethics board at (204) 789-3389.

I am satisfied that my name will only be used on this consent form which will be stored in a filing cabinet and room that is secure at all times. Any future references to myself or my participation in this study will be referenced to a study participant code.

Subject: (Printed)_____

Date:_____

(Signed) _____

Witness: (Printed) _____ Date:

_____

(Signed) _____

Investigator: (Printed) _____ Date:

_____

(Signed) _____

Appendix D: Physical Activity Readiness Questionnaire

PAR-Q

For most people physical activity should not pose any problem or hazard. PAR-Q has been designed to identify the small number of adults for whom physical activity might be inappropriate or those who should have medical advice concerning the type of activity most suitable for them.

Common sense is your best guide in answering these few questions. Please read the questions carefully and check the yes or no opposite the question if it applies to you.

YES NO

1. Yes__ No__ Has your doctor ever said you have heart trouble?
2. Yes__ No__ Do you frequently have pains in your heart and chest?
3. Yes__ No__ Do you often feel faint or have spells of severe dizziness?
4. Yes__ No__ Has a doctor ever said your blood pressure was too high?
5. Yes__ No__ Has your doctor ever told you that you have a bone or joint problem such as arthritis that has been aggravated by exercise, or might be made worse with exercise?
6. Yes__ No__ Is there a good physical reason not mentioned here why you should not follow an activity program even if you wanted to?
7. Yes__ No__ Are you over age 65 and not accustomed to vigorous exercise?

Bottom of Form 1

If you answered YES to one or more questions...

If you have not recently done so, consult with your personal physician by telephone or in person before increasing your physical activity and/or taking a fitness test.

If you answered NO to all questions...

If you answered PAR-Q accurately, you have reasonable assurance of your present suitability for an exercise test.

Appendix E: GIII Raw CCT Data File

Datum	WGS84	WGS84	UTM	UTM		Date	Time
TP	UTM	14U	625828	5525766		09/04/2001	16:53:32
TP	UTM	14U	625828	5525766		09/04/2001	16:53:33
TP	UTM	14U	625828	5525766		09/04/2001	16:53:34
TP	UTM	14U	625828.1	5525765		09/04/2001	16:53:36
TP	UTM	14U	625828	5525766		09/04/2001	16:53:37
TP	UTM	14U	625828.1	5525765		09/04/2001	16:53:38
TP	UTM	14U	625828.1	5525765		09/04/2001	16:53:40
TP	UTM	14U	625828.1	5525765		09/04/2001	16:53:42
TP	UTM	14U	625828.1	5525765		09/04/2001	16:53:43
TP	UTM	14U	625828	5525767		09/04/2001	16:53:45
TP	UTM	14U	625828	5525768		09/04/2001	16:53:46
TP	UTM	14U	625827.8	5525769		09/04/2001	16:53:48
TP	UTM	14U	625827.8	5525769		09/04/2001	16:53:49
TP	UTM	14U	625827.6	5525769		09/04/2001	16:53:51
TP	UTM	14U	625827.4	5525769		09/04/2001	16:53:52
TP	UTM	14U	625827.6	5525769		09/04/2001	16:53:54
TP	UTM	14U	625827.6	5525769		09/04/2001	16:53:56
TP	UTM	14U	625827.8	5525770		09/04/2001	16:53:58
TP	UTM	14U	625827.8	5525770		09/04/2001	16:54:00
TP	UTM	14U	625827.4	5525770		09/04/2001	16:54:02
TP	UTM	14U	625827.2	5525770		09/04/2001	16:54:04
TP	UTM	14U	625827	5525770		09/04/2001	16:54:05
TP	UTM	14U	625826.9	5525769		09/04/2001	16:54:06
TP	UTM	14U	625826.7	5525769		09/04/2001	16:54:08
TP	UTM	14U	625826.9	5525769		09/04/2001	16:54:09
TP	UTM	14U	625827.1	5525768		09/04/2001	16:54:11
TP	UTM	14U	625826.9	5525768		09/04/2001	16:54:12
TP	UTM	14U	625827.1	5525767		09/04/2001	16:54:14
TP	UTM	14U	625827.1	5525767		09/04/2001	16:54:15
TP	UTM	14U	625827.5	5525766		09/04/2001	16:54:17
TP	UTM	14U	625827.7	5525765		09/04/2001	16:54:18
TP	UTM	14U	625828.3	5525765		09/04/2001	16:54:20
TP	UTM	14U	625829.1	5525764		09/04/2001	16:54:21
TP	UTM	14U	625829.3	5525764		09/04/2001	16:54:23
TP	UTM	14U	625828.5	5525764		09/04/2001	16:54:25

Appendix F: GIII Post-Processed Data

10m Radius Circle

Diameter	20.2533	19.734		**Known Circumference**	62.83
	625839.1	5525773		**GPS Circumference**	62.38
Minimum	625818.8	5525754		**% Error**	-0.72
Average	625828.7	5525763			
			Distance		
	625829.2	5525754	0.19		
	625829.4	5525754	0.19		
	625829.6	5525754	1.54		
	625831.2	5525754	1.19		
	625832.3	5525754	2.48		
	625834.6	5525755	2.11		
	625836.3	5525756	2.60		
	625837.8	5525758	2.30		
	625838.7	5525760	1.21		
	625838.9	5525762	1.21		
	625839.1	5525763	2.75		
	625838.4	5525765	1.25		
	625838	5525767	2.78		
	625836.7	5525769	1.32		
	625835.7	5525770	2.63		
	625833.7	5525772	1.30		
	625832.5	5525772	2.39		
	625830.2	5525773	2.39		
	625827.9	5525773	2.12		
	625825.8	5525773	1.19		
	625824.6	5525773	2.02		
	625822.7	5525772	0.97		
	625821.9	5525772	2.36		
	625820.4	5525770	2.39		
	625819.3	5525768	1.25		
	625819	5525767	1.21		
	625818.8	5525765	2.59		
	625818.8	5525763	1.25		
	625819.3	5525762	2.85		