An Investigation of GPS Accuracy and the Potential for Auto-Correction

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Abstract: A Global Positioning System (GPS) receiver passively receives signals from satellites orbiting the earth. Using signals from at least four of these satellites enables the receiver to calculate it present position to within 10 meters. With the cancellation of selective availability of GPS in May 2000, the main cause of inaccuracy in GPS is the incorrect compensation for the Ionospheric effects on signals travelling from the GPS satellites. Differential GPS (DGPS) is one method that addresses this inaccuracy by providing roving GPS receivers with more accurate correctional information. Traditionally, DGPS requires expensive reference stations and a dedicated radio link to the receiver to transfer this correctional data. This mini-dissertation will focus on a low cost approach to providing DGPS in a local environment. A simple statistical model of GPS positioning error will be developed and applied to data obtained by measurements in order to verify its accuracy. Once verified, this model will be used to generate more accurate correctional information, which is then transmitted to a roving unit. The benefits of this form of DGPS will be examined by comparing accuracy of positional data obtained from a GPS receiver that uses the correctional data provided by DGPS to one that does not.

Keywords: GPS DGPS WAAS LAAS EGNOS

1 Introduction

The Global Positioning System (GPS) is a navigation system developed and controlled by the American Department Of Defence. It allows roving units determine their position using radio signals which are being constantly transmitted by a constellation of satellites travelling in fixed orbits above the earth. A roving unit calculates it distance from a satellite by analysing the length of time it took for a signal transmitted from that satellite to arrive. Calculating this distance from at least four satellites allows the unit determine it position in 3D-space, i.e. its latitude, longitude and elevation.

There are a number of factors that affect the accuracy of the GPS system but up until May 2000 [1],[2] the main one was the intentional interference with the information being broadcast by the service. Termed Selective Availability (SA), its purpose was to deny foreign powers access to remote targeting mechanisms using GPS and to prohibit unapproved military usage.

SA operated by dithering satellite signal transmission times and thus reducing a receiver's ability to accurately calculate its position. This dithering of signal transmission times produced range errors of up to 70 meters. [1] This signal degradation affected all unequipped GPS receivers, in a given area, in a similar manner. The loss of accuracy caused by SA leads civilian and commercial bodies to develop a correction system called Differential GPS (DGPS).

The principle of DGPS is that the error factor introduced by SA can be determined by comparing the positional information at a *"known"* location to that calculated using the GPS system. To achieve this, reference stations, which determined the correction factor, were constructed at precisely mapped locations and then broadcast the correction factor via a radio link. GPS receiver units, equipped with the appropriate radio receivers, could then use this correction factor to augment their own positional calculations. With the widespread availability of DGPS technology, SA became redundant and was eventually deactivated in May 2000. SA was to be totally discontinued by 2006. [1]

Although its initial function was to counteract the affects of SA, DGPS provides significant correction for other error sources inherent in the GPS system and is still widely used in a post-SA era. Propagation delay of satellite signals as they pass through the layers of the earth's atmosphere is now the main contributor to error in the accuracy of the GPS system. As this error contribution is the same for all receivers in the same locality, its affects can be counteracted using the same differential techniques as those used for SA.

The focus of this mini-dissertation is to examine the operations of the GPS system, the problems associated with it and some of the techniques used to address these problems. Through experiment, using multiple low-cost GPS receivers, it is hoped to demonstrate that there is potential for a low-cost auto-correction system for GPS data using differential techniques.

2 Components of the GPS System

The GPS System is comprised of three segments, namely the space, control and user segments. The space segment consists of constellation of 24 satellites (plus some spares), each with its own fixed orbit approximately 26550Km [3] above the earth. These satellites are constantly broadcasting signals that are used by ground based roving receivers to determine their position.

Six ground based stations make up the control segment of the GPS system and their function is to constantly monitor the quality of the data being broadcast by the satellites in the constellation. Five of these stations are unmanned and are based at Hawaii and Kwajalein in the Pacific Ocean; Diego Garcia in the Indian Ocean; Ascension Island in the Atlantic Ocean and Cape Canaveral, Florida. [4] All five stations track the navigation signals being transmitted by the GPS satellites and send this information to a Master Control Station based at Schriever Air Force Base in Colorado. There this information is analysed and any adjustments needed to correct the navigational information are determined. These adjustments are then sent back to the satellites.

The third element of the GPS system, the User Segment, consists of GPS receivers which can be hand-held or vehicle mounted units. These receivers detect, decode and process GPS signal information. These signals are passively received by the unit and contain the transmission time of the signal and a satellite identification number. This allows a roving unit calculate its distance from that satellite based on the time it took for the signal to travel from the satellite, as each receiver has its own internal clock. With at least 24 satellites in operation at any time and using 3-D trilateration techniques and the signals from at least 4; a roving unit can determine its latitude, longitude and elevation. The system includes a mechanism for synchronising the receiver clocks, the satellite clocks, and the ground based station clocks, making GPS units a good source for accurate time.

3 GPS Services

While the original intention of GPS was to provide the American Department of Defence and its allies with an accurate global positioning mechanism; a civilian and commercial role for this technology was also recognised. This led to the development of two GPS services; the Precise Positioning Service (PPS) for military use and the Standard Positioning Service (SPS) for civilian and commercial applications.

This two tiered development of the GPS system lead to two different types of data being modulated by transmissions from the GPS satellites, P-Codes and S-Codes. P-Codes are transmitted at a much higher rate than S-Codes and allow the calculation of more precise positional information that can only be decoded by authorised users. The S-Codes, often termed C/A-Codes (Course Acquisition or Clear Acquisition), are transmitted at a lower rate and can be used by civilian GPS receivers to determine their position [3].

4 How GPS Operates

The GPS constellation comprises of 24 satellites which are placed asymmetrically in six orbit planes which are inclined at 55^0 relative to the equatorial plane. The satellites are approximately 262550 Km above the centre of the earth and have an orbital period of 12 hours [3].

Each satellite continuously broadcasts discrete sequences of data on two signals, L_1 and L_2, on two separate frequencies f_{L1} (1575.42 MHz) and f_{L2} (1277.60MHz) [3]. The L_1 signal is used to transmit the C/A codes used by civilian GPS receivers when determining their position. P-Codes are transmitted at a much faster rate (chipping rate) over the two signals and can be encrypted. If encrypted, these codes can only be decrypted by users authorised by the U.S. Department of Defence.

Each satellite in the GPS constellation is constantly transmitting radio signals, which contain two types of information, Almanac and Ephemeris. Almanac data contains course orbital parameters for all satellites in the GPS constellation. Almanac data is not very precise and is considered valid for long periods of time. When a roving unit is initially turned on, it *"looks"* for visible satellites based on the Almanac data and the current time. With this information in hand, appropriate satellites can be searched for and *"locked-on"* to. Ephemeris data, which contains very precise information, provides data such as the transmission time of the signal, the satellite identification number and the satellite's orbit data. Using this information a roving unit can estimate the signal's travelling time and consequentially the unit-to-satellite range. This range estimation is termed the pseudorange and is subject to errors, which are inherent in the GPS system. By estimating the pseudorange to at least four satellites, a unit can determine its position as being at the intersection of four spheres, which have the four satellites at their centres.

5 Accuracy of the GPS System

The structure of the GPS satellite constellation and the data transmission mechanisms it employs make it prone to a range of inherent errors. These errors are classified as either Dilution of Precision (DOP) or User Equivalent Range Error (UERE). Whereas DOP is associated with the relative geometry of the satellites within the GPS constellation that are being used to calculate pseudoranges, UERE is considered the sum of the contributions from each error source associated with an individual satellite.

5.1 Dilution of Precision (DOP)

When determining its position, a unit uses the pseudoranges it calculates to at least four satellites; its location being at the intersection of the *"Spheres"* with the satellites being used at the centres. Ideally these spheres would intersect at one point meaning that there is only one possible position where the receiver can be located. In reality, however, this intersection forms an area, any point in which the receiver can be located. The precision is said to be *"diluted"* as this area grows large hence the term Dilution of Precision (DOP).

DOP Error is associated with the geometric distribution of the satellites being used by the roving unit to determine its position. If the visible satellites are close in the sky, the geometry is said to be *"bad"* and the DOP value is high; if far apart, the geometry is said to be *"good"* and the DOP value is low. Therefore a lower DOP value, represents a greater accuracy due to the wider angular separation between the satellites used to determine position. DOP is expressed as a number and is comprised of the separate measurements Horizontal DOP (HDOP), Vertical DOP (VDOP), Mean or Positional DOP (PDOP) and Time DOP (TDOP). These values are calculated from the positions of the usable satellites in the constellation.

5.2 User Equivalent Range Error (UERE)

The UERE is considered the sum of the contributions from each of the error sources associated with an individual satellite. These error sources are

- Signal Propagation Delay through the Atmosphere
- Disturbances to Satellite Orbit
- Multipath Interference
- Clocking and Receiver Errors

5.2.1 Signal Propagation Delay through the Atmosphere

As discussed earlier, Signal Propagation Delay is caused by the satellite signals being refracted as they pass through the ionosphere and troposphere layers of the earth's atmosphere. This increases the length of time taken by signals to travel to earth and results in incorrect distance estimations from the receiver to the satellite. Since the deactivation of SA, this error source is the largest contributor to GPS error and can be in the order of 10 meters [2]

5.2.2 Disturbances to Satellite Orbit

Although satellites are positioned in precise fixed orbits, slight shifts in orbits are possible due to the gravitational forces of the sun and moon. This orbit data is monitored by the ground segment of the GPS system and correctional information is sent to the satellites on a regular basis. The resultant error is therefore low and normally not greater than a couple of meters.

5.2.3 Multipath Interference

Multipath interference is caused by satellite signals being reflected by obstacles they meet on their path to the receiver. The error normally occurs in mountainous areas or areas with high buildings. Signals reflected off high buildings take longer to reach a GPS receiver than direct signals and result in error in distance to satellite estimation and thus in the positional calculation. Multipath is more commonly considered to be the reflections due to surfaces surrounding the receiver's antenna and can cause range error of the order of 15-20 meters [5] but in extreme cases it can be of the order of 100s meters. Methods have been developed to counteract some of the effects of multipath interference using specialised antenna, ground planes and analysing the phase of the GPS signals and the angles at which they are received. These methods, however, are beyond the capabilities of most low-cost civilian GPS receivers and the scope of this mini-dissertation.

5.2.4 Clocking and Receiver Error

Despite the synchronization of the receiver clock with the satellite time during the position determination, the remaining inaccuracy of the time still leads to an error of about 2 meters [25] in the position determination. Rounding and calculation errors of the receiver sum up approximately to 1 meter [25].

Table 1: Effects of rounding error

P1			Distance From
Latitude	Longitude		Mean P1
52.3262140000	-7.2026920000		0.7543696898
52.3262140000	-7.2026920000		0.7543696898
52.3262140000	-7.2026920000		0.7543696898
52.3262140000	-7.2026930000		0.6853550666
52.3262140000	-7.2026930000		0.6853550666
52.3262140000	-7.2026930000		0.6853550666

Table 1 depicts a subset of sample data collected during experiment trials which were carried out whilst researching this paper. [Appendix B] As can be seen from this data, the rounding of the seventh decimal place can produce error in the order of 10 centimetres using the Haversine formula to calculate the distance from these points to the mean of the data sample. GPS receiver units that report with less precision or that uses a different distance calculation formula than the units used for these experiments may produce rounding error far in excess of this.

5.2.5 Summary of GPS Error

Errors inherent in the GPS system are categorised as DOP and UERE. DOP is caused by the relative geometry of the satellites being used to determine position. A *"Good"* geometry is where the satellites are spread so that measurements to each satellite are in different directions whereas a *"Bad"* geometry is when all these measurements are taken in the same basic direction. This is because the intersection point of the *"Spheres"* being used to determine position can lie in a much wider area. UERE is the sum of all the contributing error factors associated with one particular satellite. This includes atmospheric, multipath, satellite orbit perturbations, receiver and clocking errors. UERE affects receivers in the same *"locality"* in a similar manner as they are processing data from the same set of satellites.

Because DOP is due to satellite geometry, which is beyond the control of civilian authorities, and is independent of pseudorange determination, all the efforts that look to improving civilian GPS services are focused on methods that reduce the effects of UERE.

6 GPS Correction Systems

The increase in demanded for more accurate positional information, especially from the aviation and engineering industries, has lead to the development of a variety of systems to augment the data being supplied by the GPS system. These systems can be classified as either Space Based Augmentation Systems (SBAS) or Ground Based Augmentation Systems (GBAS). The difference in these systems is the method in which augmentation is delivered to the end user. Whereas SBAS use satellite to broadcast correctional data over very large areas, GBAS uses ground based reference stations to broadcast information to enabled receivers in the same general area via dedicated radio links.

As mentioned, since the cancellation of SA, the current main source of error in the GPS system is due to effects of signal delay as they pass through the layers of the earth's atmosphere. Techniques used to determine the error due to this factor include Differential and Dual-Frequency. Differential techniques calculate the error factor by comparing the position determined using data supplied by the GPS satellites to that of it precisely mapped location. Dual-Frequency techniques are only an option for authorised users as they need access to both signals, L_1 and L_2, which are broadcast simultaneously by the GPS satellites. These signals, which are broadcast on different frequencies, are affected differently as they travel through the layers of the atmosphere. This causes the signals to arrive at different times at the receiving unit. If the unit has the appropriate access and processing equipment, it can determine the atmospheric effects on the signals as a function of the difference in arrival times.

Technologies using different combinations of these delivery systems and techniques have been developed by both civilian and governmental authorities to provide the intended end user with more accurate positional data. Examples of these solutions are:

- Differential GPS – GBAS using Differential Techniques
- Wide Area Augmentation system – SBAS using Dual Frequencies Techniques
- Local Area Augmentation System – GBAS using Differential Techniques
- EGNOS – SBAS using Dual Frequencies Techniques

6.1 Differential GPS (DGPS)

Differential GPS is a GBAS system that was developed to counteract the affects of Selective Availability (SA) which was enabled until May 2000. SA introduced an intentional error into GPS data by altering the time stamp of the GPS signal and thus preventing accurate position determination.

DGPS uses precisely located reference stations to monitor the data being transmitted by the visible elements of the GPS constellation. From this data, the station determines the inherent error and broadcasts correctional information over a dedicated radio link, which is picked up by receivers in the area.

Differential methods use the *"difference"* between *"known"* and *"unknown"* values to calculate a correction factor. All GPS receivers within a given area, even the one in the DGPS reference station, are subject to the same error due to SA degraded signals. The DGPS reference station can determine a correction factor by comparing the positional information it determines using GPS signals to its known location. This correction factor is then broadcast by the reference station and used by receivers with the appropriate hardware to augment their own positional calculations.

Although DGPS was originally intended to correct the SA degraded positional information, it also eliminated some of the other error associated with the GPS system. The error caused by the Ionosphere which, since the deactivation of SA, is the largest contributor to GPS error. This can also be eliminated using DGPS technology. Because of this, DGPS is still widely used as GPS augmentation system.

The main draw back of the DGPS system is the broadcast media used to transmit its correctional information. To take advantage of this technology, GPS receivers must be capable of receiving radio signals from the reference station. Coupling this with the need for a dedicated radio link has reduced this augmentation method's popularity as an overall solution to the inherent problems of the GPS system.

6.2 Wide Area Augmentation System (WAAS)

The Wide Area Augmentation System (WAAS) was developed by the Federal Aviation Authority (FAA) to augment the data transmitted by the GPS system as an aid to navigation in American airspace.

The system uses a nationwide network of ground stations to monitor the health of all GPS satellites and flag situations that threaten flight safety. As with DGPS, these ground stations can determine a correction factor for the GPS data and broadcast this factor to enabled receivers. Unlike DGPS, these broadcasts are sent via communication satellites which now act as extra satellites in the GPS constellation. This correctional information is broadcast using spread-spectrum ranging signals [3] which WAAS enabled receivers then add to the ranging signals from the GPS constellation to improve on its position determination.

Although developed by a Federal Authority, the WAAS is not allowed to use the more precise positional signals available to the military, the reason being that aircraft from other jurisdictions need to avail of this facility whilst flying in American airspace. The ground stations, however, have access to the two signals L_1 and L_2 which are broadcast by the satellites. These two signals, being broadcast simultaneously, allow the base station compensate for atmospheric effects using dual frequency techniques. WAAS correction is capable of reducing the pseudorange measurement error to approximately 1 or 2 meters. [3]

6.3 Local Area Augmentation System (LAAS)

To compliment the precision approach services provided by the WAAS, the FAA has developed a ground based augmentation system termed the Local Area Augmentation System (LAAS). While WAAS is a space based system that provides DGPS services over a very large geographical area, LAAS provides these services at a *"local"* level. Whereas dual-frequency techniques are employed by WAAS to compensate for error caused by atmospheric affects; LAAS uses a differential technique of a single correction for each satellite that accounts for all measured common errors between a local reference station and the end user.

LAAS broadcast its correctional data via a very high frequency (VHF) line-of-sight radio link. [6] The local area nature of LAAS means it can provide more accurate information than WAAS in the immediate area of the reference station. This means that less time is needed to notify users of system failures and hazardous conditions. The accuracy of the information provided by a LAAS is degraded as the distance from the Ground Segment is increased. Typical coverage is 30 nautical miles (NMI) which is adequate for a specific airport or airports with a close proximity. [6]

6.4 European Geostationary Navigation Overlay System (EGNOS)

The European Geostationary Navigation Overlay Service (EGNOS) is being developed by the European Space Agency (ESA) to provide error correction to geopositioning signals. The service relies on dedicated equipment installed on three geostationary satellites and a network of ground based reference stations. EGNOS obtains corrected location information using 34 ranging and integrity monitoring stations (RIMSs). [7] Each RIMS measures its distance to each geostationary satellite. Comparing this known distance to the distance they calculate enables each RIMS determine the correction required to counter act the affects of atmosphere. The RIMSs relay their data to four master control centres over a dedicated communications network that in turn determine the overall inaccuracies caused by atmospheric affects and incorporate deviation data into a signal. This data is uplinked to the three EGNOS satellites which then transmit it to EGNOS enabled receivers. The resultant accuracy of EGNOS enabled receivers is boosted to 1-2 meters as compared to the typical 15-20 meter accuracy achievable using normal GPS units. [7]

Initially EGNOS error corrects signals for both the American GPS system and the Russian Global Positioning System (GLONASS). The reluctance, however, of both operators to guarantee an uninterrupted service has spurred the European authorities into the development of its own independent global satellite navigation system called Galileo. Galileo will employ a constellation of 30 low-earth-orbiting satellites together with a network of ground based reference stations. The Galileo project is meant to challenge the current dominance of GPS. It will be the only global positioning system under civilian control. Galileo is scheduled to be operational by 2013 [8] and when it is, EGNOS will combine signals from Europe’s own constellation of global positioning satellites with those of GPS and GLONASS. With this infrastructure in place, Europe will no longer be reliant on GPS or GLONASS to provide accurate positional information.

EGNOS is primarily targeted at aviation and marine navigation. In addition to correction, its also provides information about the general status and usability of GPS data. A disadvantage of EGNOS is the relatively low elevation of its satellites which means their signals are easily obstructed by buildings and other obstacles at higher latitudes. The improvement in accuracy provided by EGNOS can not be utilised if EGNOS signals cannot be received. To remedy this situation, the ESA has being involved in a project which will deliver the benefits of EGNOS to regions that cannot receive full strength, uninterrupted EGNOS signals. The Terrestrial Regional Augmentation Network (TRAN) project was setup in 2001. *"Its goal is to develop and demonstrate applications in which the EGNOS data are made available to the user via terrestrial networks to fill the geostationary coverage gaps due to urban environment and high latitudes."* [9] The TRAN (Aviation Project) concluded in 2003 and one of the conclusions drawn from its research was *"The availability of EGNOS corrections is strongly increased in high latitude where the GEO visibility is easily lost due to obstacles or low signal."* [10]

6.5 Summary

GPS is a satellite navigation system which was developed by the American Department of Defence. It comprises three segments; space, ground and user. The space segment consists of 24 satellites, each with a fixed orbit, which continually broadcast signals which can be used to determine position. The ground segments consists of a network of base stations which continually monitor the quality of the information being transmitted by the satellites and send correction information via a Master Station when errors are detected. The user segment of the system is receivers which can take the form of hand held or vehicle mounted units. These receivers determine their current location by determining their distance from at least 4 satellites.

Until May 2000, the main cause of error in the GPS system was the deliberate interference with the data being transmitted from the satellites by the American Department of Defence. This interference, termed Selective Availability, was introduced to deter the remote targeting of American facilities by hostile nations or terrorists. The facility was deactivated by a Presidential Order and was completely eliminated by May 2006.

The GPS system also suffers from other inherent errors that fall into two categories; Dilution of Precision (DOP) and User Equivalent Range Errors (UERE). Whilst DOP is attributed to the geometry of the satellites being used to determine position, UERE is caused by a number of factors that contribute error when a receiver estimates its distance from a satellite namely atmospheric and multipath affects, perturbations in a satellites orbit and clocking and receiver errors. The combined contribution of UERE is of the order of +/- 10-15 meters.

The rise in demand for accurate positional information by the aviation and other industries lead to the development of systems that augment the information provided by GPS. This augmentation provides mechanisms for more precise positional calculation and is incorporated into many aviation and engineering applications. Since the cancellation of SA, UERE factors are the main contributor to GPS error. The main augmentation mechanisms in use today employ differential techniques to minimise the effect of UERE.

7 Research Question

When Selective Availability (S/A) was active, a differential global positioning system (DGPS) was introduced to improve the accuracy of positioning systems. When S/A was cancelled in May 2000, the accuracy of civilian GPS receivers improved significantly (in the order of +/- 10-15m) reducing the need for DGPS in many applications.

> *With demand increasing for even more accurate positional information, like a golf advisor system, does local, low cost DGPS still have a roll to play in position determination?*

Traditionally the error in GPS is analysed using complex statistical information on pseudoranges and the GPS satellite constellation. This approach can be too complicated when all we need is the statistical distribution describing the radius of error of the GPS data. The scope and time limitations of this mini-dissertation do not allow for the development of the DGPS but should suffice for the analysis of the error distribution.

As already shown, the error due to atmospheric conditions (Ionospheric and Tropospheric) constitutes the largest error source when determining position using GPS. If two roving units are in the same locality, say, within 200m of each other, they should be subject to not only the same error caused by atmospheric conditions but also to the same error from all error sources due to the fact that from the satellite's view they are basically in the same location. If this is the case then the error in the positional data can be calculated by fixing one unit at a known location. If the error correction calculated can be broadcast to the second unit, the unit should be able to use the error correction to improve its positional data.

The validity of this assertion was tested in 2006 using lost-cost GPS receivers [2]. Their experiment set out an approach to implementing low-cost DGPS using standard, widely available GPS equipment. Their objective was to determine whether a low-cost DGPS system would provide improved positional data within a local environment.

Rather than using complex statistical analysis techniques normally associated with DGPS, they opted for a simple algorithm which calculated a pseudorange correction (PRC) by comparing the precise location of a DGPS receiver station (RS) to that it calculated using ephemeris data. This PRC was then transmitted to a roving unit or wireless network. The roving unit itself comprised two identical GPS receivers which used a common antenna. Both receivers were capable of receiving DPGS augmentation data but this facility was only used by one on them. Three relevant findings are taken from this experiment

- “The accuracy of low-cost code range DGPS was significantly higher than the accuracy of the plain GPS”
- “In DGPS measurements, short periods of significant error (glitch) have been detected, but the average value of error was consistently low, regardless of the time of day”

- “When a rover was placed next to the RS, the average value of DGPS measurements was very close to the estimated position of the RS used in the algorithm. If the estimated position of the RS is changed, the average value of the DGPS measurements will change by an equal amount in the same direction”

The significance of the first result is self evident in that this experiment advocates the use of even low-cost DGPS as a method of improving the positional accuracy of GPS. Result 2 highlights the fact that although the system is not always perfect, it produced a low average error value regardless of the time of day. The “glitch” experienced could be eliminated using filtering or may be due to some independent processes running on the control logic. Examining result 3, it can be inferred that this form of low-cost DGPS provides a re-locatable solution to positional needs. The fact that when the RS was moved, the DGPS measurements changed by an amount equal to the change in the RS’ location. This would indicate that the functionality of the RS is independent of its location although it still needs to be aware of its reference position.

The results of this experiment would seem to indicate that there is a correlation between the errors experienced by separate GPS receivers within the same locality. For the purposes of this dissertation, an experiment will be designed and implemented in an effort to verify that this is the case.

8 Experiment

This dissertation involves the development of one set of repeatable experiments. The objective of these experiments is to test whether there is a correlation between the errors experienced by GPS receivers in the same locality. Identical GPS data logging units, positioned at different points in the same general area, will be used to record the data being transmitted by GPS satellites (known as “ephemeris data”) visible at that time in that area. The data recorded by each unit is then analysed to determine if there are fluctuations in the positional data determined by the units, the magnitude and direction of these fluctuations and whether this magnitude and direction is similar for all devices at the same instance in time. The analysis of the data collected by this experiment will be limited to latitude and longitude. Other experiments can be designed where altitude analysis is required.

8.1 Special Resource Requirements

This experiment will require the use of three identical GPS data logging units and a PC or laptop running standard and open source software tools to analyse the data.

8.1.1 Hardware Requirements

The data logging unit chosen for this experiment is the HOLUX M-241 wireless GPS data logger [15]. This unit was chosen because it is a compact, low cost and widely available device. A standard AA battery allows the unit operate for a full 24 hours, which is well within the scope of our requirements. The unit comes equipped with a USB interface which can be used to transfer the logged data to a PC for analysis.

Although version 1.11 of the firmware for this device allowed data be logged at 200 millisecond intervals, the current firmware version (1.12) only allows data be logged at one second intervals. This logging rate is sufficient for this experiment as the timestamp for the data is being supplied by the satellite signals and thus the readings are taken by all devices at the same instance in time and are subject to the same error factors at that instance in time.

The HOLUX M-241 device can log a variety of data relating to it current position and the satellites that are currently available to it. For the purpose of this experiment, the unit will be used to log

- GPS date and time (milliseconds)
- GPS fix type (SPS-Standard Position System, dGPS-Differential GPS – the latter will not be enabled, see explanation below)
- Latitude and longitude (decimal degrees)
- Number of satellites visible and being used
- The satellite ID numbers

The date and time supplied by the satellite signals will be used to timestamp the recoding. Timing data is fundamental to the way that GPS position is calculated; the main measurement is the time delay between transmission and reception of a signal from a satellite to the receiving device. Therefore, the GPS devices automatically set their local time to be in sync with the satellites, so this means that we can safely assume that all timestamps are synchronised. As the units will be configured to record at one second intervals, the positional data determined at the same second will be subject to the same general environmental error factors. The GPS fix type field will tell the type of GPS data being recorded at that instance. This data can be either SPS (Standard Positional Service) or dGPS which would indicate that data is being used from some differential service to augmentation the positional calculations. Although the units will be configured not to use any SBAS, recording this field will verify that this is the case and if by chance some readings are augmented, they can be eliminated from the analysis. The units will also be set to record the number of satellites visible, the number being used to determine position and their ID number. This information may be useful if any unexpected data is recorded. Knowing the satellites being used may help to explain the unexpected readings.

It is important to note that configuration settings may be lost when the unit is powered off so when doing a log with special settings, the settings should be checked before commencing and the units should be left powered on until all data has been collected.

8.1.2 Software Requirements

There are three software systems required for this experiment namely

- BT747
- MICROSOFT EXCEL 2007
- Java Open Street Maps (JOSM)

The BT747 package is a GPS data logger management package that is open source and free to download. [26] The software integrates with a variety of logging devices and the current version, V1.68.28, is used to interface with the HOLUX M-241 device. This application is suitable to configure the details logged by the device and the desired logging interval. Once collected, the raw data can be uploaded to a PC using the same software where it can then be converted into range of other formats such as GPX, CSV, KML, HTML KMZ and NMEA, allowing it to be processed by a broad range of other software systems.

Different sets of track data gathered by GPS data loggers can be compared using Java Open Street Maps (JOSM). The version used while preparing this paper is V1981. This system is free to download [22] and take GPX files as inputs. Using these input files, it can produce a plot of multiple tracks for analysis and comparison. These GPX input files can be generated by the BT747 package using the raw data uploaded from the loggers used to record the experimental data. Although the data collected represents locations rather than tracks, the system will provide a visual representation of the data and any spikes in any of the data sets should be immediately noticeable. The main analysis of the data collected in this experiment will be performed using the standard spreadsheet package Microsoft Excel 2007. The data uploaded from the logging devices can be converted into CSV format that can then be examined in Excel. A set of functions, as described in the analysis section, will be devised and inserted as column functions to perform the specified analysis.

8.2 Experimental Design

For this experiment, three identical GPS data loggers labelled H-B1, H-B2 and H-B3 are used. The units are positioned in a line, at points P1, P2 and P3 at 100 meters intervals (approx) thus providing data over 200 meters in total. The data logged will be time stamped by the satellite signals and recorded at one-second intervals [2] to give 3600 readings over a period of one hour.

The experiment will be conducted in a large, level green field from which there is a clear un-obstructed view of the sky in all directions. The distance between reference points is measured using a standard wheel measure [23], similar to that used on road works or construction sites. The accuracy of the measuring device is not important as slight humps and hollows in the surface of the experimental area will distort this measurement value. This experiment does not depend on an exact distance between reference points; it is designed to determine if there is a relationship between the fluctuations in different GPS readings taken in the same general area at the same instance in time. Reference points are marked with stakes made with standard 50mm X 25mm (2in x 1in) timber latte. These stakes are cut in lengths of 60 cm; a 10 cm point allows 50 cm to stand proud upon which the data logging unit is placed. Again these measurements are not critical as altitude is not being analysed in this experiment. On a practical note, small holders made from water dispenser cups that are altered to ensure they do not interfere with the unit's antenna are tacked to the top of the stakes to keep the data logging devices upright and prevent them being knocked over by the wind.

An example of the application for the findings of this experiment would be a golf advisor system. Golf, in general, is played in daylight hours and an average game would last in the order of four hours. Using this application as an example, data will be collected during daylight hours over an 8 hour period at times between 8am and 6pm. The reading used for analysis will be allowed to "settle" for at least 15 minutes to allow units an opportunity to select the most appropriate satellites. This will provide us with 4 sets of 3600 data readings for the specified time period. This should be an adequate amount of data for analysis, but if any anomalies are found, analysis can be applied to the entire data set.

It is hoped, if time allows, that this experiment can be repeated for the different atmospheric conditions in which a game of golf would be played i.e. clear, cloudy, light rain and for this reason the climatic conditions are noted as well as local barometric details at the time of data collection. [24].

8.3 Data Analysis

The objective of this experiment is to determine whether the error associated with GPS affects roving receivers in the same general area, in the same manner at the same time. To do this, data is collected over the same time periods by multiple data logging devices positioned at 100 meter intervals. This data is then analysed to determine if the magnitude and direction of error is similar for each device at the same instance in time.

To check the magnitude of error at each instance, the distance between each coordinate set for each reading in the sample set will be calculated using the Haversine formula [Appendix A]. These distance calculations are then graphed over time providing a visual representation of the distance between each reference point at any interval in time. If the magnitude of error is similar at each point at the same time then all results should follow the same trend when plotted on a graph. If the results are found to follow the same trend then the values can be inputted to a more specialised statistical software package to yield more formal analysis of the data.

To analyse the direction of the error, the latitude and longitude of each reading from each data set is graphed over time. The graphs for each reference point should also follow the same trend if the direction of the error is similar at the same instance of time.

The final analysis of the data will be to determine the radius of error at each of the test points P2 and P3 based on the mean reference point P1, which is calculated as the mean of all P1 readings. The distance between the mean of P2 and the mean of P3 is also calculated using the Haversine formula. The data required for this analysis is the residue of the calculation of the distance between the mean point P1 and the actual reading for the points P2 and P3 at each interval less the relative distances between mean of P1 and the means of the test points, P2 and P3. When plotted as histograms, these residues should be normally distributed with values clustered around zero.

9 Results Of Experiments

The results of the experiments, as discussed here, are a comparison of findings at P1 and P2. P1 is the assumed reference point from which measurements are taken and the results at P3 are used to confirm to the finding at P2.

From visual inspection of the graphs of the latitudes and longitudes at each point over the time interval, it can be seen that there is no obvious relationship between the values at any instance in time. There seems to be a continuous rather than erratic trend to each of the graphs but this may only be indicative of a drift in position calculations based on moving satellites.

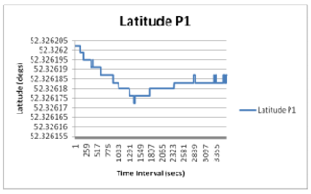

Fig 1: Change in Latitude P1

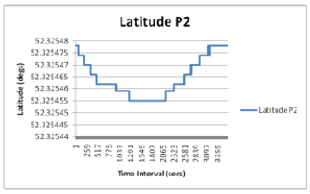

Fig 2: Change in Latitude P2

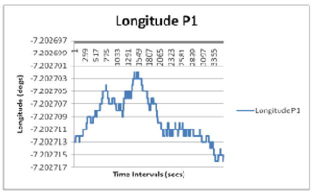

Fig 3: Change in Longitude P1

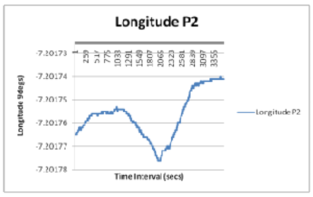

Fig 4: Change in Longitude P2

Analysing the results from the distance calculations from P1 to P2 at each instance shows that this distance does fluctuate over the specified time period. From closer examination of these values, however, it can be seen that these fluctuations do not exceed 2 meters.

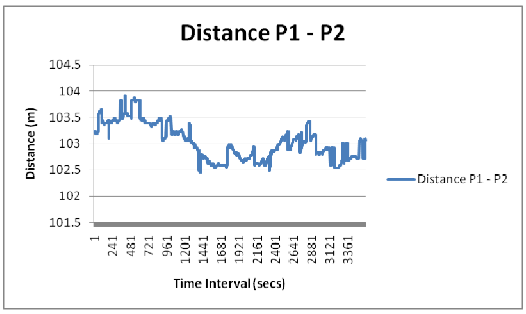

Fig 5: Distance P1 - P2

To determine a radius of error of these distance calculations, the distances from an assumed reference point (mean P1) to the calculated position of the test point P2 is determined at each instance in time. The distance between the reference point and the assumed location of the test point (mean P2), is subtracted from the distances calculated at each interval, the residue being the radius of error in the calculated position of P2 and its assumed position.

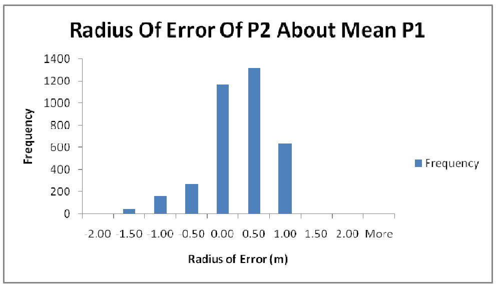

Fig 6: Radius of Error

Table 2: Descriptive Statistics

Mean	0.004947
Standard Error	0.008041
Median	0.040278
Mode	-0.4829
Standard Deviation	0.482455
Sample Variance	0.232763
Kurtosis	0.598525
Skewness	-0.7142
Range	2.376103
Minimum	-1.52427
Maximum	0.85183
Sum	17.80979
Count	3600

Plotting the resulting values produces a frequency histogram as shown in Fig. 6. Using the Data Analysis Add-On module for Excel 2007, the descriptive statistics for this histogram are produced with a 95% confidence level at the mean are shown in Table 2. For the purposes of this paper, the Skewness and Kurtosis values are of most interest.

When Skewness values are between +1 and -1 this indicates substantially skewed distribution. [11] Kurtosis is a measure of the peakness or flatness of the distribution curve. A Kurtosis value outside the range of +3 to -3 indicates that the distribution does not conform to the rules governing Normal Distribution. [11]

The values of these statistical components as calculated for this histogram would indicate that the radius of error values calculated for P2 are governed by the laws of normal distribution.

10 Discussion & Further Work

The results of the experiment clearly indicate that there is no correlation between the latitude and longitudes at same instance in time at the different points. A unit determines its position based on the satellites visible to it at that time. Satellites, especially ones at low elevations, visible to one unit may not be visible to another. The signal strength from some visible satellites may be greater at one location than another, even if they are in close proximity, resulting in calculations that can drift in the direction of the stronger signal or the extra satellites. Another factor to be considered is any bias the algorithm being used would have in relation to the order in which satellites are selected. Coupling these with the continuous independent calculation of distances to rapidly moving satellites, the clocking inaccuracies and rounding errors, it would be surprising if the position calculations for a single point followed any pattern not to mention follow a similar pattern to those calculated for other positions. The screen shot below, taken from JOSM, shows the plot of the data gathered at P1 over period of one of the experiments. This image clearly shows the erratic nature of position determination by a GPS receiver even when it is stationery.

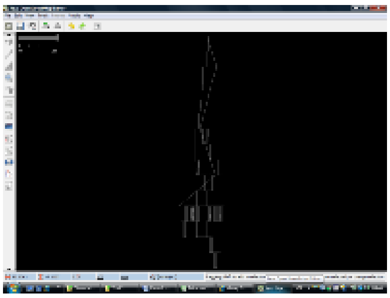

Fig 7: JOSM Plot

The results of the distance analysis are more positive. The fact that residue values calculated at test point P2 around the reference point (mean P1) are normally distributed with a 95% confidence level indicates that applying the augmentation, calculated at a known reference point, to the positional data calculated at some other point, in the same general area, should improve the accuracy of the positional calculation at the unknown point to within +/- 1-2 meters. [12]

Some approaches to DGPS using consumer grade units to calculate a correction distance factor which is then broadcast for other units to use as position augmentation.

This approach has been criticised for not being reliable. With earlier chipsets, the number of receiver channels and correlation banks available were quite limited. This meant that, even though receivers may be in close proximity, they may obtain positional information from different sets of available satellites. Applying distance augmentation based on error calculated from data from a different set of satellites may actually compound error rather than improve on it. Even though more modern chipsets have increased capacity and can process data from a larger number of GPS satellites, there is still no guarantee that they will calculate their augmentation factor based on the same satellites being used by other receivers in the area. Another problem with this approach is the post-processing nature of the augmentation. The error correction factor will always lag behind the current data available and thus may also result in compounded error.

Purpose built, more expensive DGPS stations are sited and have the capacity to allow them receive data from all visible satellites in an area. This allows them calculate correction factors for each satellite individually which they can then relay to consumer grade receivers in the area. These individual corrections are then applied by the receiver to the respective data being obtained from the satellites being used.

This approach may have merit, even using consumer grade GPS receivers. The HOLUX-M241 units, as used in the experiments set out in this paper, are capable of processing information from 32 satellites.[15] Since there will be only 12 GPS satellites covering a hemisphere at any one time, this is adequate capacity to process data from them all. These units can be connected to an external processing system, such as a laptop or PC, via Bluetooth or USB link. Processing this satellite information in real time, models of the time delay caused by atmospheric conditions can be built up for each of the satellite. These models can then be use to predict the timing error at the next interval and correction information can be broadcast, its arrival at the receiver to coincide with the arrival of the GPS signal it is intended to correct. This approach is similar to that taken by Matosevic *et al* [] in their paper on comparing the accuracy of GPS and Low-Cost DGPS. Ideally the reference unit being used to collect satellite data would be positioned so that all available satellites would be visible to it at all times. If this is not possible, as might be the case in valleys, there may still be merit in correcting the data for the ones that can be seen, as this may constitute a significant portion of the satellites visible in the area. The value of this correction would have to be quantified through localised experiment.

11 Conclusion

The Global Position System (GPS) was developed by the American Department of Defence to provide it with an accurate global positioning mechanism. The recognition of the role that this technology could also play in both civilian and commercial applications led to the two tiered development of the services it could provide.

The infrastructure of GPS and the technologies used to transport its information has rendered it prone to a range of inherent error. Several systems, including Differential GPS (DGPS) and Wide Area Augmentation Service (WAAS), have been developed to augment the positional data provided by the service. To benefit from these augmentation services, a user needs to be located within a coverage area and be equipped with a GPS receiver which is capable of receiving augmentation data.

The lack of availability of these services in European areas has lead the European Space Agency (ESA) to develop it own augmentation service. The European Geostationary Navigation Overlay System (EGNOS) was designed to augment the data provided by both the American GPS and its Russian equivalent, GLONASS.

The services of EGNOS are primarily directed at aviation and marine navigation. The low orbits of EGNOS satellites make it difficult for users at high latitude to receive correctional information from the system. This fact is borne out by the ESA involvement in Terrestrial Regional Augmentation Network (TRAN) projects. These projects were set up to investigate technologies that would bring the benefits of EGNOS correction to areas in which EGNOS satellite signals could not be received.

The focus of this paper is to determine if there is potential to provide the type of correction provided by these expensive systems using low-cost equipment. It has been shown that modern, widely available, consumer grade equipment is capable of determining augmentation data for the GPS system with accuracies comparable to that of the more expensive options. Combining the findings of the experiments set out in this paper with other research carried out on signal transport mechanisms could be an option for bringing the benefits of augmented GPS data to areas not currently serviced by existing augmentation systems.

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Appendix A: Distance formula selection.

The analysis of data collected using experiments described in this paper is highly dependant on the formula used to calculate the distance between two points of latitude and longitude. While researching this paper, four formulae were found that would perform this calculation to different degrees of accuracy namely

- Spherical Law of Cosines[18][19]
- Haversine Formula [19]
- Vincenty's Formula [13][20]
- Pythagoreans Theorem [21]

To aid with formula selection, a simple experiment was devised using two HOLUX-M241 data logging units. Each unit was placed on a raised platform, 2 meters apart in an area with a clear view of the sky in all directions. Data, as depicted in the main experiment, was gathered over a period of 40 minutes and a 30 minute sample was extracted for analysis. The analysis involved calculating the mean latitude and longitude position for each point and calculating the distance between these two mean points using each formula. For calculations the WSG-84 value for semi-major axis, 6378137 meters, is used. [14][17] Table 3 contains a summary of these calculations.

Table 3 – Distance Formulae calculations

	Latitude	Longitude
Max P1	52.3257640000	-7.2007770000
Min P1	52.3257410000	-7.2007900000
Mean P1	52.3257551728	-7.2007836067
Max P2	52.3257790000	-7.2007610000
Min P2	52.3257680000	-7.2007790000
Mean P2	52.3257740528	-7.2007692128
		Distance (m)
Spherical Law Of Cosines	(Calculated)	2.3183149669
Haversine Formula	(Calculated)	2.3183149669
Vincenty's Formula	(Web Function)	2.3190000000
Pythagoreans Theorem	(Calculated)	2.3186614712

As can be seen from this table, all formulae produce similar distance results from the calculated mean points. For the rest of the experiments the Haversine Formula is used to calculate distance for two reasons

- It is a derivation of Vincenty's formula
- The ease of incorporating it as a column function in Excel

Appendix B: Observing the nature of GPS data

A simple experiment to determine the order of GPS error in the locality is carried out using a single HOLUX-M241 GPS data logger. GPS data readings are recorded at a precisely mapped location in the locality. Details of a precisely mapped location are obtained from a local civil engineering company. The location is a quiet village street in Ireland which is subject to some vehicular and pedestrian traffic but is quiet in the main. The data provided for the reference point is, 258135.222 eastings 165928.193 northings which is in the Ordinance Survey Ireland (OSI) coordinate system format. Using a coordinate system converter [16] these reference coordinates translate to latitude 52.2922253451 N and longitude -7.14906705603 W in the WGS-84 coordinate system as used by the GPS system.

The configuration settings for the data logger are the same as those used in the main experiment

- UTC date and time (milliseconds)
- Latitude
- Longitude
- Elevation

- SBAS is un-ticked (disable augmentation)
- Number of satellites being used
- Satellite ID's
- Record at 1 second intervals

When collecting data, the GPS data logging device is positioned on top of a meter long, 100mm water pipe. As the accuracy of this experiment is not critical, the pipe, which acts as a pedestal, is lined up visually with the reference point at its centre. This configuration raises the data collection unit above low-lying obstructions to GPS signals such as footpaths and boundary walls.

Data is collected over a period of 40 minutes and a 20 minute sample set of it (20mins * 60 readings/min = 1200 readings) is used for analysis. The initial 10 minutes of readings are ignored to allow for the device to select the satellites it is going to use.

The simple data analysis is performed in Microsoft Excel 2007 and involves computing the mean latitude and longitude from the sample dataset. The distance from this mean point was to the precisely mapped reference point is then calculated using the Haversine formula. This distance was found to be 34.9 meters. Fig. 7 provides a visual representation of the data collected for this experiment. The staggered nature of a track generated using GPS track data can clearly be seen. Although the majority of the plotted points are located in the same general area, the "tail" on the track may have being by multipath interference from reflections of passing traffic or by tracking being started before the unit was positioned.

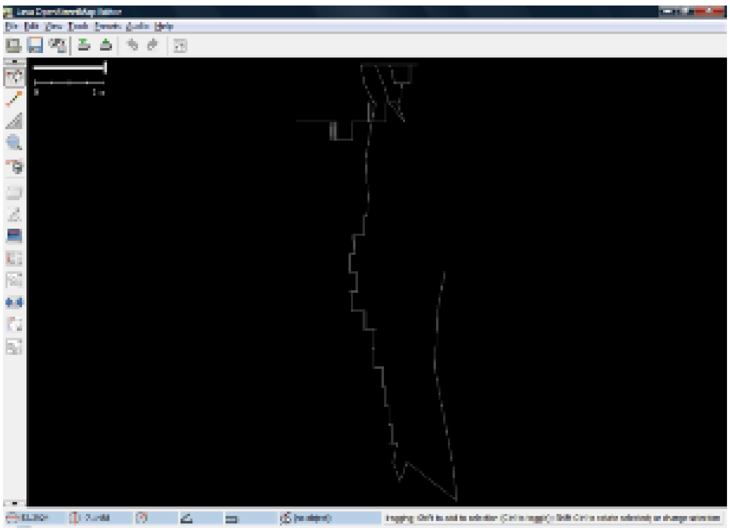

Fig. 7: JOSM Plot at Reference Point