

## A Matlab Implementation of Differential GPS for Low-cost GPS Receivers

Q. Ali & S. Montenegro  
*University of Wuerzburg, Germany*

**ABSTRACT:** A number of public codes exist for GPS positioning and baseline determination in off-line mode. However, no software code exists for DGPS exploiting correction factors at base stations, without relying on double difference information. In order to accomplish it, a methodology is introduced in MATLAB environment for DGPS using C/A pseudoranges on single frequency L1 only to make it feasible for low-cost GPS receivers. Our base station is at accurately surveyed reference point. Pseudoranges and geometric ranges are compared at base station to compute the correction factors. These correction factors are then handed over to rover for all valid satellites observed during an epoch. The rover takes it into account for its own true position determination for corresponding epoch. In order to validate the proposed algorithm, our rover is also placed at a pre-determined location. The proposed code is an appropriate and simple to use tool for post-processing of GPS raw data for accurate position determination of a rover e.g. Unmanned Aerial Vehicle during post-mission analysis.

### 1 INTRODUCTION

The term Global Navigation Satellite System (GNSS) refers to satellite based global positioning system that is used to provide autonomous geo-spatial positioning [1]. The system allows tiny electronic receivers to determine their absolute position (longitude, latitude and altitude) anywhere on the globe. NAVSTAR Global Positioning System (GPS) is the first GNSS that was developed to provide precise location, based on data transmitted from a constellation of 30+ satellites [2]. Users can determine their coordinates by receiving range information (and other observables, if required) from at least four GPS satellites. A GPS receiver is used not only for position determination but also for other purposes like navigation, attitude determination and relative positioning of vehicles [3] etc. Other similar systems are Russian GLOBal NAVigation Satellite System (GLONASS), European Union Galileo and Chinese

Beidou [1]. The latter two are still in deployment phase. A GNSS can generally be used under all weather conditions [4].

GPS signal contains a pseudo-random code, broadcast ephemeris and almanac data [2]. The pseudo-random code identifies which satellite is transmitting. Ephemeris is description of the satellite orbits and clock correction parameters which vary over the time. This data is transmitted by each satellite and contains information like status of the satellite (healthy or unhealthy), current time/date, Ionospheric correction parameters, Keplerian orbital parameters and satellite clock corrections etc. Each satellite broadcasts only its own ephemeris data. This data is used to compute the coordinates of GPS satellites, which are subsequently used to determine the receiver coordinates. The ephemeris may be broadcast (projected ahead into time) or precise (post-fitted). The orbital positions sent in the navigation

message are based on the predicted position of the satellite, and are updated every two hours by the ground control [5]. As GPS satellites travel at a speed of approx. 4km/sec [6] so they travel almost 29,000 km between orbit updates. In order of ascending accuracy, the ultra-rapid orbits are available after approx. 6 hours, the rapid orbits are available after 13 hours and the final post-fit precise orbits are available after about 10 days on International GNSS Service (IGS) website [7]. The almanac data are a reduced-precision subset of the clock and ephemeris parameters; and are updated by the Control Station at least once every 6 days [8].

The GPS navigation solution determines the 3D coordinates and clock offset of a GPS receiver using the pseudorange measurements of at least four GPS satellites. The equations linking the pseudoranges and the receiver coordinates are nonlinear. Direct solution of these nonlinear equations is possible and different solutions have been described in the literature [9]. The widely used alternative is to linearize the pseudorange equations and to use the tool of linear algebra for position determination.

GPS observations include four fundamental quantities i.e. time, pseudorange, carrier phase and Doppler. Using these observables, a typical GPS receiver is able to determine the position and velocity. Further processing of data gives heading, attitude information and relative position. However these observables are corrupted by the biases and noises thereby leading to positioning inaccuracy. In order to remove these errors, Differential GPS (DGPS) technique was developed. It improves the accuracy of coordinates of a GPS receiver (usually a rover) applying some correction methodology. The technique is of utmost importance for many applications, like photogrammetry, requiring information of true coordinates of a camera carrying vehicle. To accurately geo-reference the data, it is important to know the exact position and attitude of the vehicle when a measurement or a picture was taken [10]. Depending on the requirements of a particular application, the position of the vehicle often needs to be known with a precision down to the decimeter-level or even centimeter-level. Such demands can be met for e.g. by applying the DGPS technique.

Differential GPS techniques are well documented and a number of codes exist for its realization in off-line mode. A well-known open source software is 'rtklib' developed in C language [11]. A remarkable contribution is the set of MATLAB codes developed by Kai Borre [12]. It is quite comprehensive suite to visualize a number of GPS working principles. This set of codes is tailored to the Receiver INdependent EXchange (RINEX) files provided with the suite. Another key development is 'goGPS Project' [13]. It is basically a software library designed to improve the positioning accuracy. Another contribution is by Wen Zheng who post processed GPS raw data from RINEX files with MATLAB codes for single point positioning [14] and base line estimation using dual frequency receiver [15]. Algorithms for position determination and relative positioning stated in 'GPS Theory and Practice' by B. Hofmann-Wellenhof [2], and Interface Control Document IS-GPS-200F [8] formed the basis for almost all of these codes. An open source

MATLAB code for single point positioning developed by Michael Gaeb [16] is well structured and same was extended to develop the present algorithm for DGPS. Although some public MATLAB codes are already available for positioning using RINEX files. However, DGPS implementation in offline mode *using correction factors* for determination of rover 'true' coordinates without using double differences is not seen in literature, as per the knowledge of author. Main contribution of this study is the development of a simple to use DGPS algorithm *using correction factors* computed at base station in post-processing mode exploiting Course Acquisition (C/A) code on single frequency (L1 signals) to make it practicable for low-cost GPS receivers.

Further description of the paper is organized as follows. In Section 2, we first provide a synopsis for GPS errors and then discuss different DGPS techniques to remove these errors. In Section 3, a brief introduction to RINEX format files is provided. Section 4 describes in details all aspects of software code for DGPS and mathematical model for correction factors. Simulation results of data processing with and without DGPS implementation are also shown. Finally, in Section 5 conclusions are provided and future work is proposed.

## 2 DIFFERENTIAL GPS TECHNIQUES

GPS measurements consist of biases and noises that affect the positioning accuracy. In order to improve the GPS positioning solution, it entails to know these errors and the methods to remove them. DGPS is a technique that improves the solution accuracy while removing these errors. It was developed to meet the needs of positioning and distance measuring applications that required higher accuracies than stand-alone Standard Positioning Service (SPS). DGPS can be considered as a calibration method where the calibration standard is established at the base station.

### 2.1 GPS Error Sources

Major sources of error that affect the accuracy of stand-alone GPS receiver include ephemeris errors, atmospheric errors (including Ionospheric and Tropospheric propagation delays), satellite and receiver clock errors, Dilution of Precision (DOP), receiver noise and multipath errors. Ephemeris errors are largely diminished by differential corrections. Ionospheric errors can be remedied either with dual frequency (L1/L2), or with proper mathematical modelling like *Klobuchar model*. Double difference information also caters for these errors. Troposphere affects the two frequencies equally, however their effects can be fixed by *Hopfield model*. When base station and rover are close enough, satellite signals pass through almost same atmospheric conditions, so ionosphere and troposphere errors are almost identical and can be effectively cancelled with DGPS technique. Satellite clock errors are due to asynchronization between satellite clock and receiver clock. These include Satellite Vehicle (SV) clock offset, clock drift and clock drift rate. It can be corrected using the polynomial coefficients  $a_{f0}$ ,  $a_{f1}$  and  $a_{f2}$

transmitted in navigation message. This error can be effectively compensated as per the algorithm defined in [8]. Receiver clock drift is usually treated as an extra parameter and corrected in the standard solution. Furthermore, it does not significantly add to differential errors.

How precisely a GPS receiver can measure the pseudorange and carrier phase largely depends on how much noise accompanies the signals in the receiver's tracking loops. This noise either comes from the receiver electronics itself or is picked up by the receiver's antenna [17]. Multipath error is site dependent and varies significantly as the site conditions change. This type of error cannot be modelled. Multipath and receiver noise errors cannot be corrected by DGPS and hence leads to residual errors in DGPS methods.

## 2.2 Correction Methodologies

Some of the correction methodologies include *Position Differential*, *Pseudo Range Differential*, *Carrier Phase Differential*, *Precise Point Positioning (PPP)* and *Satellite Based Augmentation System (SBAS)* etc., each technique having its own merits and demerits. Most widely used method is carrier phase *Double Difference* to achieve high accuracy (centimeter level), but the solution suffers from integer ambiguity and cycle slips. Whenever a cycle slip occurs, it must be corrected for, and the integer ambiguity must be re-calculated.

For our present study, we have implemented pseudorange correction method in offline mode. With this technique, a reference station is set up to track all satellites in view, ensuring that it will see at least the four satellites that the roving receiver is using to compute positions. This station with exactly known position measures the signal travel time to all visible GPS satellites and uses these values to calculate pseudoranges. These measured values will typically include errors. Since the real position of the reference station is known, the actual distance (nominal value) to each GPS satellite can be calculated. The difference between geometric and measured ranges can be calculated by a subtraction called as correction factor. These correction factors are different for all GPS satellites and are even different for same satellite at different epochs. Epoch is a moment when a measurement is taken by a GPS receiver. These correction factors are sent to rover receiver for all the epochs using suitable media, in case of real-time applications. Rover uses these factors to correct its pseudorange measurements which are subsequently used to determine its accurate position. The corrected pseudorange at the moving receiver is corrupted by only two errors i.e. multipath and receiver noise.

## 2.3 DGPS Implementation Modes

DGPS data processing may be realized in following two ways:

- *Real-Time Processing*; For navigation applications, pseudorange corrections are needed in real-time that can be transmitted to the user via a communication link in Radio Technical Commission for Maritime Service (RTCM) SC-104

standard format. This is the most common technique where a large number of users may be served in real-time. Although precision level of real time applications is comparatively low, however the technique is quite useful to confirm that a test is progressing properly and also because many applications require real time processing. However data latency issues are to be taken care of for such applications. SBAS systems like WAAS, EGNOS and MSAS are all real time DGPS applications.

- *Post Mission Processing*; For off line processing, GPS raw observations (pseudoranges, carrier phase, Doppler and Signal to Noise Ratio (SNR)) are stored by a rover receiver and then later processed in combination with raw observations of base station receiver stored for the same time period. Most of the low-cost GPS receivers are also able to provide the raw data. The advantage of the post-mission solution over the real-time one is being more accurate and reliable, because the user can detect data errors and analyse the residuals. Also for some applications, like photogrammetry, the cost and effort to maintain a real time data link may be unnecessary. On the other hand the main disadvantage of the post-mission solution is that the results are not available immediately.

## 2.4 DGPS Accuracy

Two levels of accuracy are achievable with DGPS, meter-level and centimetre level. Meter-level accuracy relies on C/A code data while centimeter-level relies on carrier phase data. Many applications of DGPS use C/A code pseudorange as the only observable, with achieved accuracies of 1 to 5 m in real-time [2]. DGPS not only increases the GPS positioning accuracy, but also enhances GPS integrity by compensating for anomalies in the satellite ranging signals and navigation data message. If intermediate level accuracy is required, the SBAS services may be exploited. A big advantage to use these services is that the signals are transmitted on L1 frequency and no decoder is required which make this service usable for low-cost receivers. Performance of EGNOS, the European SBAS, for *Open Service* in terms of accuracy is 3m lateral and 4m vertical, while its availability is 99% [18]. Typical applications of DGPS include determination of rover accurate coordinates, baseline, attitude and relative navigation.

## 3 RINEX FILES

Although receivers calculate positions in real time; in many cases it is suitable to store GPS observables for later use. RINEX is a standard format that allows the management of the observables generated by a receiver, as well as their off-line processing by a number of applications. It is a set of standard definitions to promote the free exchange of GNSS data and to facilitate the use of data from any GNSS receiver with any post processing software package. RINEX allows the user to post-process the received data in order to produce a more accurate solution, usually with other data unknown to the original

receiver such as better models of the atmospheric conditions at time of measurement. Rover data may be used in combination with other data stored at a base station. RINEX format is designed to evolve over time, adapting to new types of measurements and new satellite navigation systems. It enables storage of raw measurements for all GNSS along with data from SBAS simultaneously.

*RINEX Files Classification;* RINEX files are classified into six categories as depicted in Table 1. For this study, only first two types of files have been utilized. In fact, at least these two files are required to completely define the data in RINEX format. Each observation file and each meteorological data file contains the data from one site and one session. Each file type consists of a header section and a data section. The header section contains global information for the entire file and is placed at beginning of the file. The header section contains header labels in columns 61-80 for each line contained in the header section. These labels are mandatory and must appear exactly as specified in [19] and [20]. There is no limitation for maximum length of observation records.

We briefly describe the two types of files used for our study. RINEX *observation file* (data section) typically includes number/ type of observations, epoch time when the measurement was taken, number of visible satellites, visible satellites ID commonly referred as Pseudo-Random Noise (PRN) code, and numerical value of observables. For DGPS applications, we need to record observation file simultaneously at base station and at rover site. RINEX *navigation message file* contains the broadcast ephemeris data. This data is useful for a number of functions like computation of satellite clock error and satellites coordinates etc. If data from more than one receiver have to be exchanged, it would not be economical to include the identical satellite messages collected by the different receivers several times. Therefore the navigation message file from one receiver may be exchanged or a composite navigation message file may be created containing non-redundant information from several receivers in order to contain complete information in one file. For DGPS with short baseline (till 10 km), one navigation file collected either at base station or at rover may serve the purpose. Every GNSS has its own navigation message data.

Table 1. Classification of RINEX files

S No	File Category	Description
1	Observation data file	Contains measurement data like GPS time, pseudoranges, carrier phase, Doppler and SNR etc.
2	Navigation message file	Contains GPS broadcast ephemeris data and Ionospheric parameters
3	Meteorological data file	Contain meteorological data (ambient pressure, temperature and humidity etc.) for post processing with high accuracy
4	GLONASS navigation Message file	Contains GLONASS satellites ephemeris data
5	GEO navigation message file	For WASS/EGNOS geostationary satellites
6	Satellite and receiver clock data file	Contains clock data

*Conversion of GPS Binary Data to RINEX Format;* GPS binary data may be converted to RINEX format using suitable software like 'teqc' or 'rtklib'. Many proprietary formats (like .ubx files of u-blox GPS receivers) may be converted to RINEX format using such software. Care should, however, be exercised to ensure that proper settings have been made on the receiver to output both observation as well as navigation data. User can choose the RINEX version, as required, provided the software supports the chosen version.

#### 4 DGPS SOFTWARE AND SIMULATION RESULTS

DGPS data has been post processed using MathWorks MATLAB® that facilitates matrices handling/manipulation, as required for this study. DGPS simulations have been performed with observations collected at base station and a rover. Differential correction factors computed at base station have been exploited for determination of rover accurate coordinates.

Base station and rover coordinates have been calculated with iterative least square method using pseudoranges from at least four SVs. If more than four satellites are visible (as mostly is the case for airborne vehicles or for GPS receivers in open area), it is recommended not to utilize the data from the near-horizon satellites. As signals from these satellites travel comparatively longer distances through atmosphere, so are more prone to atmospheric effects. It is recommended to set the elevation mask to at least 10° to eliminate the most noisy data (but not more than 15° so that usable data is not lost). Spherical coordinates of SVs are therefore computed for determination of corresponding elevation angle. For our present study, we have set elevation mask to 10°. As total transmitted power from a satellite is less than 50 watts, so GPS signals are relatively weak. Comparison of SNR between satellites can show the source of the cleanest data. It is important to use only that data for computation that does not fall below acceptable SNR (commonly set as 20-30 dB). For our study, this threshold is set to 20 dB. Base station and rover do not see the same set of satellites for all the epochs. Most of the time, a new satellite appears (or disappears) at different epochs at base station and rover. So we make a further criterion of common satellites to improve the position accuracy at the rover side.

For our study, TRIMBLE NETR5 GPS receiver installed at the German State Survey SAte lliten POSitionierungs dienst (SAPOS), Stuttgart was treated as base station. Its GPS receiver antenna coordinates are exactly known. While data from Trimble NETR8 GPS receiver, positioned at Institute of Navigation, University of Stuttgart was treated as rover data. Its coordinates are also accurately known. With this arrangement, we can compare the rover coordinates (determined by using correction factors) with those already known accurately, thereby verifying the efficacy of developed algorithm. Rover coordinates have been computed with and without applying correction factors for comparison purpose.

A self-explanatory flow chart is shown in Figure 1.

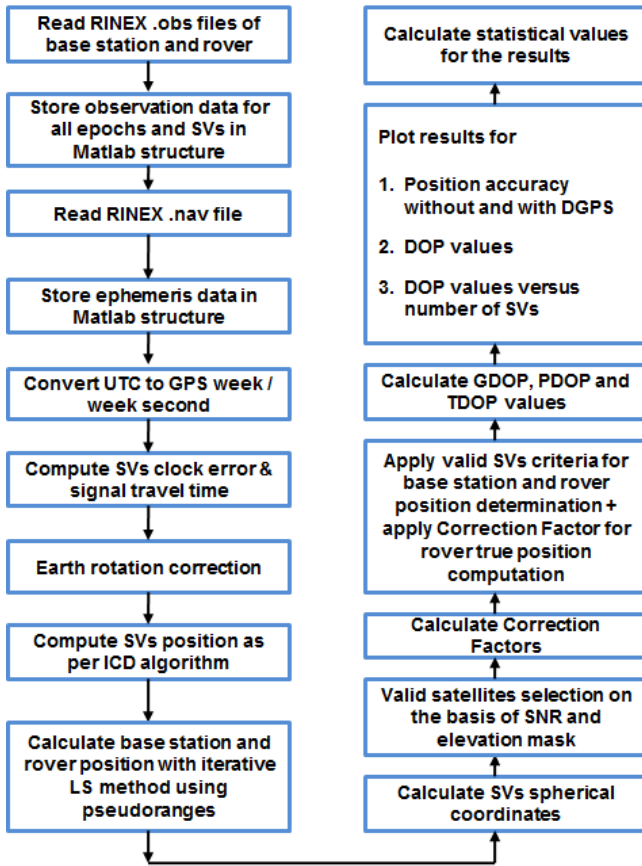


Figure 1. Flow chart for DGPS implementation

A MATLAB script using C/A pseudoranges on L1 frequency for positioning and velocity computation of GPS receiver was developed by Dipl.-Ing. Michael Gaeb [16]. This code was extended for DGPS implementation in our study. The original code is written while taking into consideration RINEX format 2.11 as input files containing GPS observables in the sequence C1, L1, D1, S1, where,

**C1:** C/A code pseudoranges on L1 frequency (m)

**L1:** Carrier phase on L1 frequency (cycle)

**D1:** Doppler on L1 frequency (Hz)

**S1:** Signal to noise ratio on L1 frequency (dBHz)

Main features of the code for DGPS implementation are as following:

- 1 RINEX observation files (recorded at base station and rover) and navigation message file (recorded at either location) can be used.
- 2 Correction factors are computed at base station and sent to rover for its accurate position determination.
- 3 No atmospheric model has been used. Atmospheric errors have been catered through correction factors.
- 4 The code provides solution for rover coordinates with and without DGPS for all the epochs.
- 5 Number of epochs for processing can be selected.
- 6 Total number of visible satellites and valid satellites can be viewed for all the epochs. Corresponding PRNs are also observable.
- 7 DOP values for Geometric Dilution Of Precision (GDOP), Position Dilution Of Precision (PDOP) and Time Dilution Of Precision (TDOP) have been

calculated at rover. Effect of number of visible valid satellites on PDOP values has been studied.

- 8 Code has been validated while placing a rover at known location. Coordinates determined with the code have been compared with the accurately known coordinates.
- 9 Statistical results are computed for minimum offset, maximum offset and mean positional error.
- 10 Results for position error in three axes Earth Centered Earth Fixed (ECEF) as well as radial difference have been plotted.

#### 4.1 Mathematical Model for Correction Factor (CF)

Before describing the computation of CF, we need to precisely define the notion of *pseudorange* and *geometric range*. Pseudorange is an indicative of travel time of satellite signals. It is a noisy estimate of range, hence named as pseudorange. Pseudorange  $\rho$  is defined as the distance from the receiver antenna to the satellite antenna including receiver and satellite clock offsets (and other biases such as atmospheric errors). Mathematically, it can be expressed as:

$$\rho = r + c.(dt_r - dt^s + dT) \quad (1)$$

where  $r$  is the geometric range between satellite and receiver,  $dt_r$  is the receiver clock offset,  $dt^s$  is the satellite clock offset,  $c$  is the speed of propagation and  $dT$  corresponds to other biases. Pseudo-range reflects the actual behaviour of the receiver and satellite clocks. It can be measured via code and/or carrier phase, and is stored in units of meters.

Geometric range is the 'true' distance between two points. If coordinates of satellite and receiver are known, geometric range ' $r$ ' between these two points can be obtained using the following formula:

$$r = \sqrt{(X^s - X_r)^2 + (Y^s - Y_r)^2 + (Z^s - Z_r)^2} \quad (2)$$

where  $(X^s, Y^s, Z^s)$  are satellite coordinates and  $(X_r, Y_r, Z_r)$  are receiver coordinates in ECEF coordinate system. The CF at base station for any satellite in view at epoch  $t$ , is computed as following [21]:

$$CF = r - \rho + (dt_r - dt^s + T) * c \quad (3)$$

where,

$r$  = Geometric range between satellite and base station receiver (determined as per eq. (2))

$\rho$  = Pseudorange (GPS observable measured by receiver)

$dt_r$  = Receiver clock offset (estimated through GPS navigation solution)

$dt^s$  = Satellite clock offset (part of ephemeris transmitted by GPS satellite)

$T$  = Tropospheric delay (not used in present algorithm)

$c$  = Speed of propagation (a constant)

These CFs are then handed over to rover for all valid satellites observed during each epoch. The rover takes it into account while adding it to its observed pseudorange for correction. Its position is then computed based on the corrected pseudoranges. Here, *no atmospheric model* has been used for computation of base station and rover receiver coordinates. As atmospheric conditions at base station

and rover site are almost identical for short base line, hence their effects are mutually cancelled out. In other words, atmospheric effects are included in correction factors. Corrected position at rover site is free from atmospheric effects.

## 4.2 Results

Correction factors computed at base station are handed over to rover to compute its own exact coordinates for respective epochs. For simulation purpose, the computation is repeated for 900 continuous epochs (15 minutes). For the sake of comparison, rover coordinates are determined with and without utilizing the correction factors. Results are plotted in Figure 2 and Figure 3. Here x-axis (zero vertical position) corresponds to true coordinates of rover. Mean positional error from true position without and with DGPS is 18.73m and 0.78m respectively. Significant improvement in position accuracy is observed.

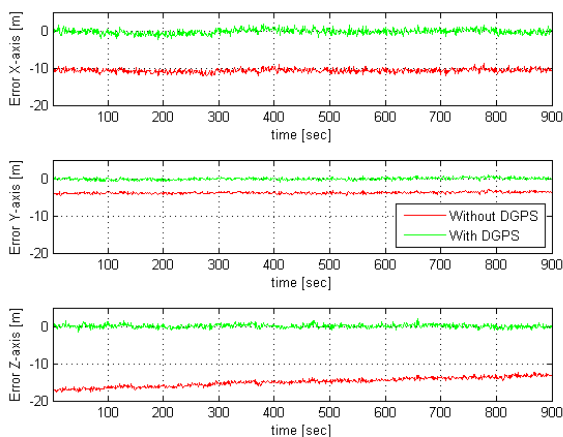


Figure 2. Position error with and without DGPS in three-axes

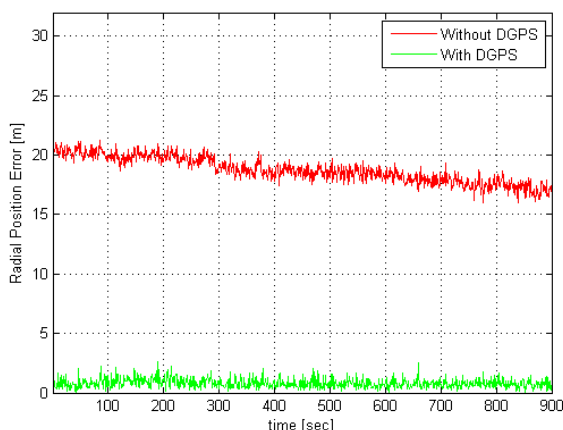


Figure 3. Radial position error with and without DGPS

To appreciate the results in 3D view, corresponding plot for one epoch is shown in Figure 4. It shows the relative positions of true coordinates, coordinates determined without DGPS and the coordinates determined with DGPS. Statistical results for the simulation are placed in Table 2.

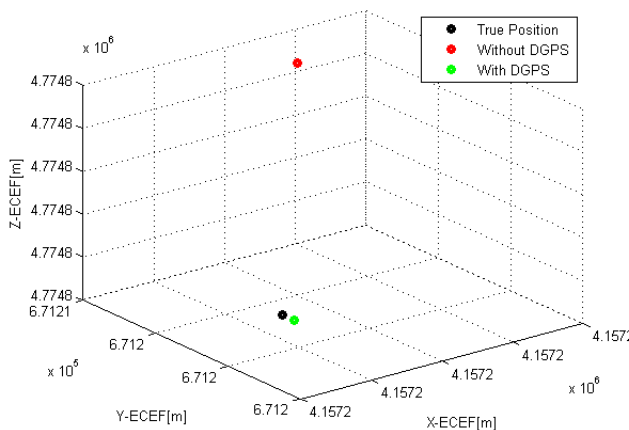


Figure 4. Relative position of rover for one epoch

Table 2. Statistical results

	X (cm)	Y (cm)	Z (cm)	Norm (cm)
Minimum Error	0.01	0.1	0.1	5.3
Maximum Error	214.4	93.4	193.0	258.9
Mean Error	55.1	23.4	36.6	77.8

We calculate GDOP, PDOP and TDOP values at rover for 900 epochs with an elevation mask of  $10^\circ$  with our code. The results are shown in Figure 5. In order to examine the effect of number of SVs on PDOP values, we compute PDOP values under two different elevation mask values, so that different numbers of SVs become visible. First, we set elevation mask to  $30^\circ$  and then to  $5^\circ$ . Corresponding plots are shown in Figure 6 and Figure 7 respectively. We notice that number of visible satellites increase with decrease in elevation mask, and correspondingly PDOP values decrease and hence the smaller the solution error. DOP values increase with increases in the elevation mask angle. DOP value multiplied by measurement error, some component of position error, or time error [22]. This means that when the DOP value doubles, the positional error increases by a factor of two. Because various DOPs are only functions of receiver and satellite coordinates, they may be predicted ahead of time for any given set of satellites in view from a specified location using a satellite almanac [23].

## 4.3 Reasons for Not Using Double Differences and Dual Frequency in Our Study

For GNSS real time and post mission applications, the receiver data from the base station may be combined with the data from the other receiver to form double-differenced observations, which is used for baseline vector determination. We have not used double differences for this study for the following reasons:

- 1 For double differences, we need to transmit the complete raw data from rover to base station that is voluminous information consuming larger bandwidth. After computing the double differences at base station, we get the baseline information. With this information, we can obtain the rover true information that can be transmitted to the rover. This strategy has two considerations;

first it requires more bandwidth and second it necessitates two way transmission of information.

- 2 Errors due to receiver noise and multipath are amplified up to a factor of two, in the worst case [24].
- 3 Notations also become cluttered in case of double difference.

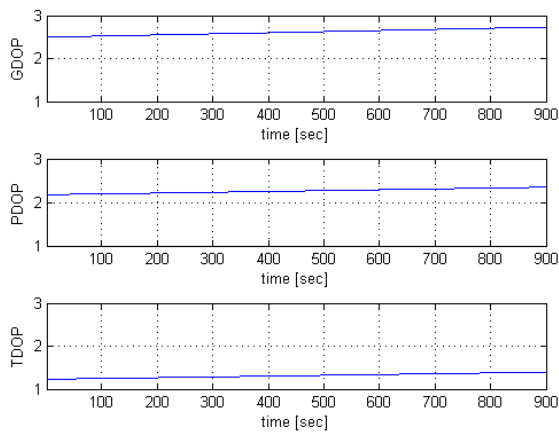


Figure 5. Dilution of Precision values at rover

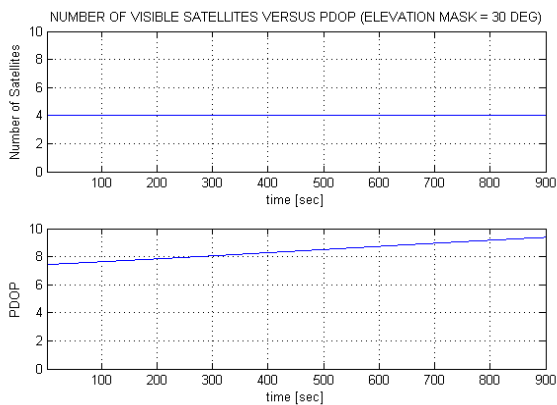


Figure 6. Visible satellites and PDOP for 30° elevation mask

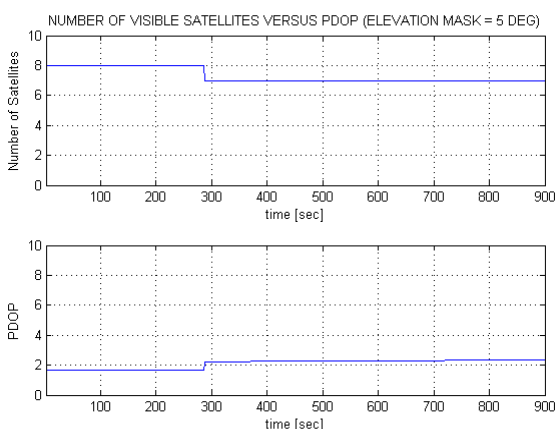


Figure 7. Visible satellites and PDOP for 5° elevation mask

It may be mentioned that double difference technique is suitable where rover true position information is required at base station, while DGPS technique with correction factors is appropriate in scenarios where rover true position information is required at the rover.

High end professional receivers exploit both L1 and L2 frequency while low cost GPS receivers rely on single frequency L1. Encrypted P(Y) code is transmitted on both L1 and L2, however access to P-code is provided in Precise Position Service (PPS) that is designed primarily for authorized users [25]. Without decryption keys, it is still possible to use a codeless technique to compare the P(Y) codes on L1 and L2 to gain much of the same error information. However, this technique is slow, so it is currently available only on specialized surveying equipment. Also it is lot more expensive to build, mostly because there is no high-volume consumer market for these chips [26]. This technique is appropriate for geodetic applications but not for navigation purposes. As ionospheric effects can be cancelled in a better fashion with dual frequency receivers, so their performance is better than single frequency receivers. However following considerations are made for use of dual frequency receivers on small platforms like MUAVs:

- 1 P-code on L2 frequency is encrypted and reserved for authorized users.
- 2 Dual frequency receivers are quite expensive, at least of the order of 40 than single frequency receivers.
- 3 Dual frequency receivers necessitate dual band antenna.
- 4 For real time DGPS applications using double differences, dual frequency raw data would require more bandwidth compared with single frequency raw data.

Most of the other codes deal with dual frequency receivers, while this code is meant for single frequency receiver (L1 only), that makes this study useful for DGPS implementation with low cost and tiny GPS receivers like u-blox and Skytraq etc. However feasibility of using L2 frequency for better performance may be explored while exploiting new L2C signals (free from encryption) being transmitted by GPS satellites block IIR-M.

#### 4.4 Technical Constraints

This software may be used in situations where true coordinates of rover are of interest for post-mission analysis e.g. geo-referencing for aerial photography. GPS binary (or proprietary format) data recorded at base station and rover may be later converted to RINEX format and used in conjunction with this code, provided the following conditions are met:

- 1 RINEX observation files are version 2.11.
- 2 GPS observables are in the sequence of "C1 L1 D1 S1" in RINEX observation files.
- 3 First epoch is identical for RINEX observation files generated from the data recorded at two sites.

For points (1) and (2), measures can be taken to conform to RINEX version and order of observables while converting GPS binary (or proprietary format) data to RINEX format. Open source software 'rtklib version 2.4.2' (April, 2013) allows to convert GPS binary data directly to RINEX version 2.11. Also RINEX files of other version (2.10/3.00 etc.) may be converted to desired format (RINEX 2.11) using this software [11]. So RINEX 2.11 is not really a limitation of the code. For point (3), appropriate changes may be made to RINEX observation files if first epoch is not

same in both the files. 'Start Time' and 'End Time' can also be selected using 'rtklib' to include only the time of interest in resultant RINEX files.

## 5 CONCLUSIONS

In this study, DGPS positioning for rover is accomplished in offline mode using RINEX files. Correction factors have been exploited instead of computing double differences. All computations have been performed in MATLAB using C/A code and L1 frequency only to make the code compatible with low-cost GPS receivers. Almost all error factors which are common to base station and rover (in case of short baseline) are cancelled out. The residual errors are due to multi-path reflections and receiver noise. It is an easy to use tool and is quite flexible for processing of RINEX files. The code can reliably be used to improve the accuracy of the rover position in DGPS mode for the scenarios where rover true coordinates are valuable like in case of aerial photography for accurate geo-referencing.

In order to enhance the usage of this code, some improvements are suggested; for e.g. the code may be modified to read and process Galileo GNSS data and its performance may be compared versus GPS. It is envisaged that easy availability of Galileo would play an important role in the development of many systems. Code may be extended to read other versions of RINEX too (e.g. version 2.10 and 3.00) and may be improved to read the RINEX files with diverse sequence of GPS observables. Carrier phase measurements may also be used to improve navigation solution. It is proposed to undertake a feasibility study for setting up an indigenous local reference station in the field using EGNOS + PPP services.

## ACKNOWLEDGEMENTS

Scholarship to Qasim Ali was provided by Higher Education Commission (HEC) Pakistan and administered by Deutscher Akademischer Austausch Dienst (DAAD) Germany. This publication was funded by the German Research Foundation (DFG) and the University of Wuerzburg in the funding programme Open Access Publishing.

## LIST OF CONSTANTS

$c = 2.99792458 \times 10^8$  m/sec (Speed of light)

$L1 = 1575.42$  MHz (GPS L band primary carrier frequency)

$L2 = 1227.60$  MHz (GPS L band secondary carrier frequency)

## REFERENCES

- [1] Hofmann-Wellenhof, Bernhard, Herbert Lichtenegger, and Elmar Wasle. *GNSS—global navigation satellite systems: GPS, GLONASS, Galileo, and more*. Springer, 2007.
- [2] B Hofmann, H Lichtenegger, and J Collins. *GPS theory and practice*. Springer Verlag. Wien, New York, 2001.
- [3] Kaplan, Elliott D., and Christopher J. Hegarty, eds. *Understanding GPS: principles and applications*. Artech house, 2005.
- [4] Rocken, Christian, Teresa Van Hove, and Randolph Ware. "Near real-time GPS sensing of atmospheric water vapor." *Geophysical research letters* 24.24 (1997): 3221-3224.
- [5] Langley, R. B., et al. "The GPS broadcast orbits: an accuracy analysis." 33rd COSPAR Scientific Assembly, Warsaw, Poland (2000).
- [6] Ashby, Neil. "Relativity in the global positioning system." *Living Rev. Relativity* 6.1 (2003).
- [7] NASA. International GNSS Service (IGS), 2014, <http://igsceb.jpl.nasa.gov/>.
- [8] US Air Force. *NAVSTAR GPS space segment/navigation user interfaces. Interface Specification IS-GPS-200F*, US Air Force.
- [9] Alfred Kleusberg. *Analytical GPS navigation solution*. IFP, page 247, 2003.
- [10] Leyssens, Jan. "GNSS positioning for UAV Applications." International Symposium Light Weight Unmanned Aerial Vehicle Systems and Subsystems, Oostende (Belgium), marzec. 2009.
- [11] T Takasu. *RTKLIB ver. 2.4.2 manual*.
- [12] Kai Borre. *The GPS Easy Suite—Matlab code for the GPS newcomer*. GPS Solutions, 7(1):47–51, 2003.
- [13] Eugenio Realini. *goGPS Project: Open source positioning software*, August 2009, <http://www.gogps-project.org/>.
- [14] Wen Zhang, Mounir Ghogho, and L. Enrique Aguado. *GPS single point positioning and velocity computation from RINEX files under Matlab environment*. In 13<sup>th</sup> IAIN World Congress, Stockholm, Sweden, October 27-30 2009.
- [15] Wen Zhang, Mounir Ghogho, and L Enrique Aguado. *GPS short-distance baseline estimation from RINEX files under Matlab environment*. In Proc. of the 13<sup>th</sup> IAIN World Congress and Exhibition, pages 1–10, 2009.
- [16] Michael Gaeb. *GNSS receiver*, 2012, <http://www.gnssreceiver.de/projects.php>.
- [17] Richard B Langley. *GPS receiver system noise*. *GPS world*, 8(6):40–45, 1997.
- [18] European Space Agency (ESA). *EGNOS*, February 2012, [http://www.navipedia.net/index.php/EGNOS\\_Performances](http://www.navipedia.net/index.php/EGNOS_Performances).
- [19] Werner Gurtner. *RINEX: The Receiver independent exchange format version 2.10*, 10th December, 2007.
- [20] W Gurtner and L Estey. *RINEX: The receiver independent exchange format version 2.11*. IGS Central Bureau, 2009.
- [21] Kai Borre. *Easy Suite II: Easy17 - Visualizing satellite orbits, Easy18 – Computing range and range rate corrections*. *Inside GNSS*, 5(4):50–51, 2010.
- [22] JM Zogg. *GPS compendium: Essentials of satellite navigation*, 2009.
- [23] Richard B Langley. *Dilution of precision*. *GPS world*, 10(5):52–59, 1999.
- [24] JG García, PI Mercader, and CH Muravchik. *Use of GPS carrier phase double differences*. *Latin American applied research*, 35(2):115–120, 2005.
- [25] Richard B Langley. *Why is the GPS signal so complex*. *GPS world*, 1(3):56–59, 1990.
- [26] Richard D Fontana, Wai Cheung, and Tom Stansell. *The modernized L2 civil signal*. *GPS world*, 12(9):28–35, 2001.