GPS Performance for Various Applications

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Abstract: Until when the European Galileo system is ready for services as expected in 2010, the Global Positioning System (GPS) operated by the United States (US) Department of Defense (DoD) remains the only fully functional positioning system globally. Since the year 2000 when the GPS Selective Availability was turned off, GPS has become more accessible for civilian applications and contributed in many different fields requiring high accurate position and navigation solutions such as aviation, marine, civil, deformation control and geodetics to name a few. Moreover, driven by the demands for emergency call positioning, namely the E-911 mandate set by the United Stated Federal Communications Commission and the E-112 directive set by the European Commission, GNSS positioning technologies are now very popular for location-based services in the entertainment industry, transportation guides, wireless networking and communication and security, promising billions of dollars in revenue. Consequently, there is an ever-increasing demand for more available, more accurate and more reliable GPS positioning and navigation solutions that partly led to the development of modernized GPS and Galileo.

In order to provide readers with a review of GPS performance at the current stage, this paper briefly presents some positioning results and analysis using GPS indoor and DGPS Real-time Kinematic (RTK) for accuracy levels of ranging from a hundred metres to centimetres. Some user-oriented GPS positioning technologies and algorithms, namely High Sensitivity GPS (HSGPS), Receiver Autonomous Integrity Monitoring (RAIM) and Multiple Reference Station GPS (MRS GPS) are briefly presented and discussed with demonstrated results.
Keywords: GPS indoor, GPS network RTK, Performance

1. Introduction

Responding to the free-to-access existence of its satellite signals on the globe and to a dynamic development of hundreds of its different receiver types on the market, the nowadays first choice solution to locate and navigate objects on Earth would very possibly be using the Global Positioning System (GPS) operated by the United States (US) Department of Defense. Holding a USD 200 receiver as small as a mobile phone and letting it track GPS signals under a clear view of the sky, one could almost immediately obtain, with an accuracy of better than tens of metres at least, his or her current positions. More expensive geodetic receivers costing approximately USD 10,000 each along with a careful data analysis scheme could help to determine millimetre-level movements of the ground or manmade constructions. In all applications, the pure positioning coordinates of objects are transformed into more informative knowledge of their locations in spatial relation with surroundings on the earth surface. Positioning accuracy and reliability then become critical during the final process of decision-making.

In the era of merging different sciences and technologies, GPS technology is being involved into an expanding range of applications, from military, aviation, marine, and geodetics to emergency services (e.g. US E-911; European E-112), personal digital assistants and urban vehicular navigation. The former usually requires millimetre- to centimetre-accurate positioning services which are well achievable by DGPS users assuming undisturbed atmosphere and relatively short inter-receiver distance. The later is usually referred to as location-based services (LBSs), which resulted in a market of USD 0.5 billions in 2003 and promise USD 28 billions in 2008 [11] although still being received as “push” services by providers and challenged to gain its maturity and a truly acceptance of users [2]. Moreover, the fascinating plan of modernizing GPS and developing the European Galileo system keeps more civilian users coming to satellite positioning and navigation technology with a hope for an ever easier accessibility to global navigation satellite system (GNSS) civil signals and better positioning solutions.

This paper endeavors to provide users seeking the opportunity to use GPS for their applications a brief overview of GPS stand-alone performance at the current stage. The key notes are available for two important and independent sections: (i) GPS indoor and (ii) centimetre-level DGPS with multiple reference station approaches. GPS indoor requirements and challenges are firstly discussed. Some positioning results obtained in two representative indoor environments, namely inside a residential garage and inside a large sport facility, are shown as examples with discussions focused on the key issue of poor performance due to signal attenuation. In the following section, the attention is drawn into the achievement of GPS positioning at centimetre-level of accuracy. At this level of accuracy requirement, spatial correlation of errors and the ability to correctly resolve integer ambiguities play very important roles, especially under active ionospheric conditions and/or the inter-antenna distance is long. Multiple reference station (MRS) DGPS technique provides convincing theory to better model spatial correlated errors and significantly improve the positioning solutions compared to the traditional single reference station (SRS) DGPS. Interesting conclusions are founded from various evaluating studies worth discussions for the real benefit of the expensive MRS GPS system.

2. GPS Indoor Positioning and its Challenges

Indoor positioning was initiated by the United Stated Federal Communications Commission decision to locate emergency E-911 callers with an accuracy requirement of 50 m (67%) for handset-based solutions [11] and has become a vital component for the potential profit-generating location-based services. Giving the existing space-based infrastructure and global signal coverage, GPS obviously is a potential solution for LSB positioning and navigating problem [2]. However, due to the already extremely weak line-of-sight (LOS) signals, GPS indoor positioning faces the challenge of tracking signals under attenuated signal environments such as urban canyons, forested areas and indoors. The challenge becomes critical, moreover, when the demand for LBSs increases significantly under such environments. This has partly led to the development of high sensitivity GPS (HSGPS) receivers to improve ability to acquire and track weak GPS signals. This is done by maximizing the coherent integration interval of 20 ms and minimizing residual frequency errors by reducing thermal noise and using a stable oscillator. In general, high sensitivity methods can be implemented in either aided (AGPS) or unaided modes. In aided mode, high sensitivity receivers rely on assistance data including time, approximate position, satellite ephemerides, and possibly code differential GPS corrections. Massive parallel correlation is necessary to facilitate the complex task of searching for the weaker GPS signals while using long coherent integration periods and further non-coherent accumulation [15]. In unaided mode, the high sensitivity receiver lacks the ability of the aided receiver to acquire weak signals if it has no a-priori knowledge. However, if the receiver is initialized with the same assistance data, by acquiring and tracking four or more GPS satellites with strong signals, it has the same functional capability as an assisted GPS receiver so long as it can maintain timing, approximate position, and satellite ephemeris. HSGPS yielded promising results encouraging R&D efforts to improve indoor GPS performance further more to hopefully making the wish often expressed “10 m in 10 s anywhere at any time” [11] become a reality.

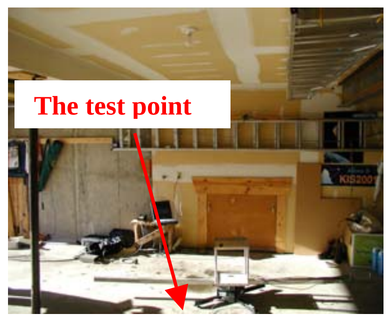
HSGPS measurements are, nevertheless, corrupted by a high noise level and multipath causing measurement faults ranging in magnitude up to kilometres in some cases, and thus requiring special measurement processing in order to obtain a reliable solution. There exist issues with all major positioning performance parameters, specifically availability, accuracy, continuity and reliability, when using GPS indoor. First of all, the availability performance is limited by a small number of observable satellites and their poor geometry. This results in a lack of redundancy and, consequently, reduces the effectiveness of RAIM. The reliability performance therefore degrades. In some cases, a trade off between excluding bad measurements and keeping vital observations to maintain the good geometry is required. In this case, adding a height constraint with the use of MEMS barometers or/and a clock constraint, assuming the latter is sufficiently accurate, helps to reduce the required number of observable satellites while still allowing RAIM algorithms to be executed. The accuracy performance of indoor GPS is severely affected by poor geometry and various fault measurement sources such as high noise and echo-only or high multipath signals, which are unfortunately spatial-uncorrelated errors and cannot be reduced by DGPS. However, DGPS still reduces the spatial-correlated error components such as atmospheric errors, clock errors and orbital error helping to improve the positioning solution accuracy in comparison with the equivalent case of using a single receiver. Some other assisting techniques such as pseudolites, cellular network or IMU yield also some improvements. In addition, special measurement processing techniques such as batch processing, using a twin antenna averaging system and RAIM methods, as shown in the following examples, also help to a certain extent. The continuity performance of GPS indoor suffers the rapid change in satellite geometry as signals come in and out and the fast decorrelation of multipath. These results in large jumps in epoch-by-epoch least-squares solutions and causes difficulties for filter approaches. Similarly to the case of accuracy, aiding from other sensors helps to improve the performance [11].

Followings are representative positioning results obtained with GPS stand-alone for two indoor environments, namely inside a residential garage and inside a recreational facility using HSGPS XTrac-LP™ evaluation kits provided by SiRF

Technologies Inc. and NovAtel 600 antennas. In these tests, the receivers was first initialized for about 20 minutes through line-of-sight tracking and then brought into the degraded signal environment. The differential positioning mode was used in both cases to significantly reduce orbit and atmospheric errors. The reference station was set up approximately 5 km and 1 km, respectively, from the test sites with clear lines of sight to the satellites. Testing points were surveyed to obtain their reference coordinates with accuracy of better than few centimetres.

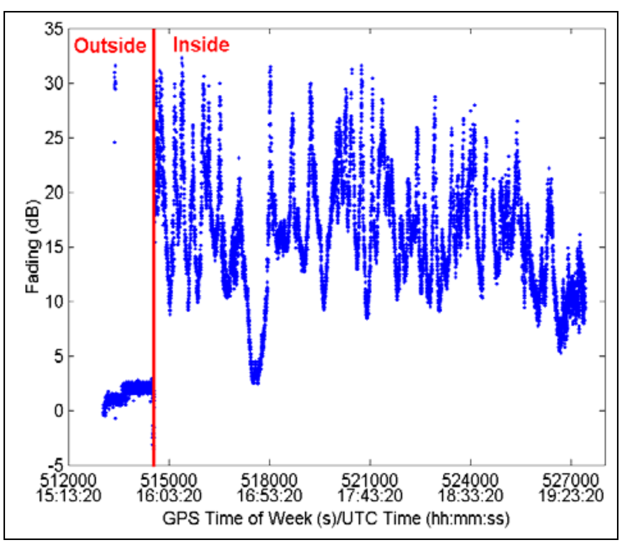
Positioning results inside a residential garage

This test was carried out inside a residential garage as shown in Figure 1 over a time period of 12 hours in June 2003. The garage wooden door was closed during the test. Signal attenuation, shown in Figure 2a for PRN 25 ranges from 13 to 25 dB. Least-squares positioning results with reliability testing are shown in Figure 2b, where the red statistics values represent the horizontal error information for all available epoch-by-epoch solutions and the green values denote the information for all available 20-second batch solutions. Unreliable solutions concluded by RAIM are marked by red stars and red dots. The epoch-by-epoch approach obtains an 2D RMS accuracy of 15 m while the batch approach yields 3 m more accurate, and certainly more reliable. The obtained improvement by batch processing shows the rapid temporal decorrelation of multipath. In both cases, however, reliability testing sometimes failed to exclude some erroneous measurements, due to either lack of redundancy or existence of multiple erroneous measurements, causing still large maximum errors of approximately 330 m and 74 m, respectively for epoch-by-epoch and batch solutions. This test case is described in more detail in [10].

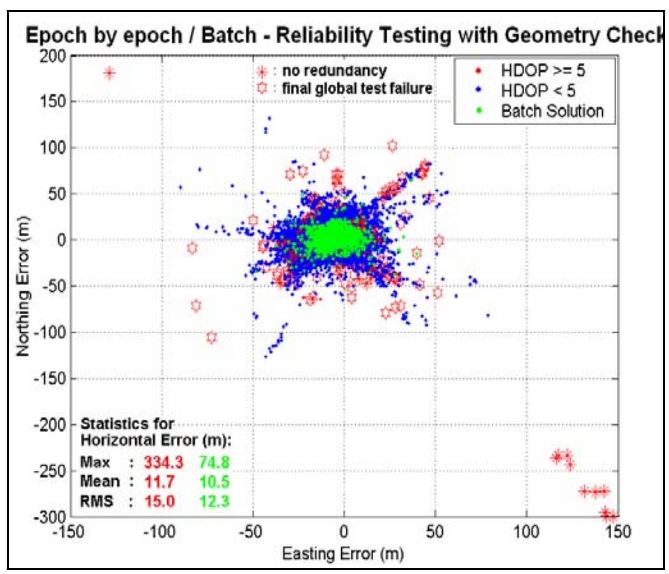


Test point looking from outside

Figure 1: Tracking condition inside a residential garage



(a)



(b)

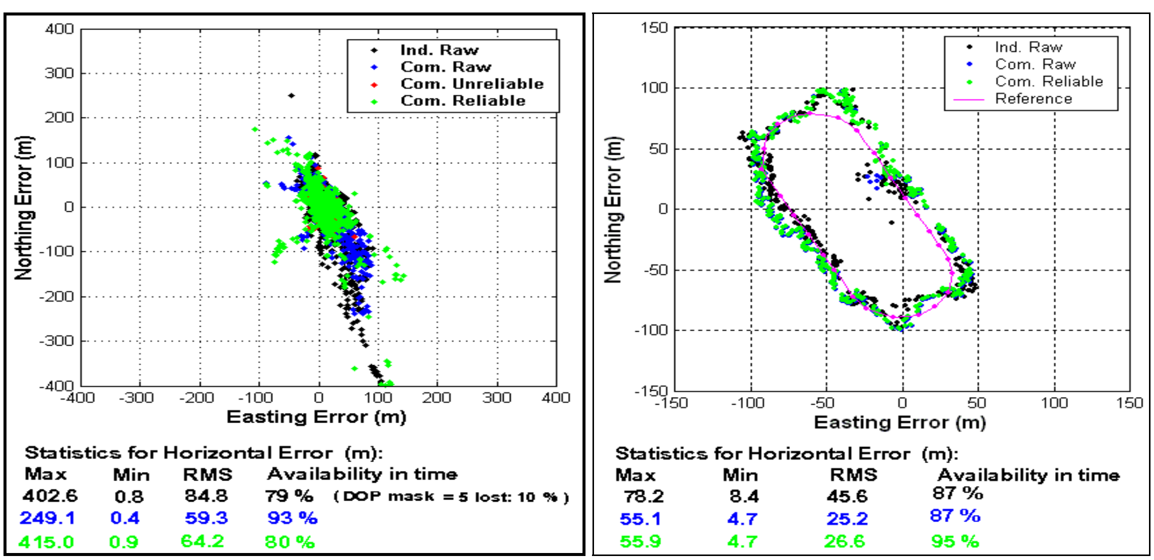
Figure 2: (a) Signal fading for PRN25 inside the garage; (b) Positioning results inside the garage

Positioning results inside a recreation facility

The Calgary Olympic Oval recreational facility, shown in Figure 3a was built for the 1988 Olympic Winter Games and includes a 400 m speed skating track bordered by a running track used for testing. The Oval is 25 m high at its centre, surrounded by concrete walls and a row of windows near the roof at a height of approximately 20 m. The equipment set up for static and kinematic tests, using three identical antennas placing 0.5 m apart on a straight line, are shown in Figure 3b & c. The C/No values for the satellites available during the test ranged between 18 and 27 dB-Hz, compared to the nominal C/N0 level for a LOS signal is 44 dB-Hz. The analysis focused on assessing spatial multipath decorrelation and the impact of antenna diversity being placed shortly apart on position estimation under such conditions. It was found in the static case that the fading difference between antennas reaches up to 5 dB; the pseudorange errors at each antenna reach nearly 200 m and the range error difference experiencing by the antennas reaches as large as 70 m in some cases. A difference of location of only 0.5 m between the two antennas leads to differences of up to 400 m for some epochs in positioning results using individual antennas demonstrating a rapid spatial multipath decorrelation indoors. Similar diversity was also observed in the kinematic case. The results of static test and one kinematic test run are shown in Figure 4a & b, respectively, together with position performance statistics. In these figures, the black color is used to present the results obtained using one individual antenna while the green color denotes the results obtained using twin antenna system algorithm, which uses all measurements obtained at the two antennas in one least-square estimation in addition to the inter-antenna distance constraint. In both static and kinematic tests, using twin antenna system yields improvement of approximately 20 m. Two important aspects of these results are that (1) antenna diversity can effectively average out some multipath effects in such an environment and (2) position accuracy and signal attenuation are only partly correlated, the impact of the indoor geometry and signal reflectivity also playing important roles. Full detail analysis can be obtained from [3].

(a) (b) (c)

Figure 3: (a) Tracking condition inside the Calgary Olympic Oval; (b) Static test setup; (c) Kinematic test



(a) (b)

Figure 4: Inside Calgary Olympic Oval - (a) Static test results using 0.5 m-apart twin antennas; (b) Kinematic test results using 1 m-apart twin antennas

3. DGPS Accurate Positioning: Multiple Reference Station versus Single Reference Station

In contrast with the GPS indoor applications, GPS accurate positioning referred herein requires solution accuracy of centimetres. Although leaving all the challenges of signal attenuations, indoor geometry and reflectivity, high noise and multipath on sides, GPS accurate positioning approaches struggle with different issues such as effects of atmospheric errors and integer ambiguity resolution using carrier phase measurements and DGPS techniques. Applications in important businesses like military, aviation, marine or geodetics demand a never-ending endeavor to improve the accurate positioning capability. Traditional single reference station (SRS) DGPS using precise but ambiguous carrier phase measurements is successful in providing decimetre to centimetre-level accuracy for static and kinematic positioning under normal atmospheric conditions where the inter-antenna distance is relatively short, namely below ten to twenty kilometres. However, under highly localized atmospheric activity, and/or with a longer inter-antenna distance, the residual differential error increases and the accuracy degrades. Carrier phase integer ambiguity resolution may be impossible. This has partly led to the development of multiple reference station (MRS) differential approaches, also referred as network RTK by some documents, which attempt to model the spatial correlated errors over a regional network and interpolate the corrections to rover positions [9]. Compared to the SRS approach which uses only one reference station, the MRS uses many reference stations ideally placed around the rover. Using highly accurate coordinates of the reference stations and assumed resolved ambiguities, the inter-reference-station differential misclosures are estimated and can be, then, spatially interpolated among the network region as corrections. This is done using different algorithms such as a linear combination [6], a low order surface-fitting function [16] or a least-squares adjustment technique [14], to name a few. Alves (2004) developed a tightly-couple approach to estimate the rover positions solely in a one network filter but omitting the correction generating process [1].

Extensive studies have been carried out to evaluate the effectiveness of MRS approaches over the traditional SRS approach and to make the call for vastly expensive investment in terms of network hardware, software and data management becoming convincing. The improvement offered by MRS approaches is indeed relative to the SRS approach on various scales, ranging from unfavorable to significant depending on many parameters. The degree of efficiency of the MRS LSQC approach depends mainly on the ability to estimate the ionospheric error and resolve the ambiguities with respect to the network scales. The largest improvement obtained by various reporters under medium ionospheric conditions with the use of L1 observations was approximately 40-60% (e.g. [14], [5], [1] and [4]). This is due to the MRS LSQC approach's ability to model the spatially correlated errors concurrent with the resolution of network ambiguities. When atmospheric conditions are quiet, the SRS approach performs very well on its own and the gain resulting from the MRS approach is insignificant (e.g [4]). High levels of ionospheric activities have a severe impact on both the SRS the MRS approach's means of fixing ambiguities and estimating the ionospheric error. Under these conditions, the MRS LSQC approach yields improvements between (approximately) 0% and 20% using L1 observations (e.g [4], [12]). This relatively low level of improvement is disappointing and is caused by a low spatial correlation of ionospheric effects and also low data quality with cycle slips occurrence under a highly disturbed ionosphere. The advantage produced by the MRS LSQC approaches is also reduced when using ionospheric-free observables under all atmospheric conditions. The MRS LSQC approach however generally provides better performance in convergence, in terms of both faster convergence and more accurate converging position solutions under most of the conditions studied. The accuracy again is however relatively limited.

The following table shows results obtained from an study on evaluating the performance of a least-squares collocation MRS approach developed at the University of Calgary using a medium scale network located in Alberta, Canada, with baseline lengths of 30 to 70 km under various ionospheric conditions. This case study is fully described in [4].

Table 1: Performance evaluation of Multiple Reference Station GPS RTK for the Alberta GPS network

Ionospheric conditions (average local K value) *Note the local K index ranges from 0-9 representing quite to active ionospheric activity scale*	Positioning accuracy improvement (percentage in 3D RMS)	
	Single frequency L1 mode	Dual frequency IF mode
Quiet (2)	0	0
Normal (3)	44	0
Medium (5)	70	70
High (7)	10-20	0-5

4. Conclusions

The past 10 years have seen the growing development and deployment of GPS technology and its applications in many difference fields. The current limitations of this technology are still severe, however, for indoors to catch up with the addictive user demand for accuracy. In the next few years, GPS users are eagerly waiting for the new coming GNSS signals, such as the 3rd GPS frequency and GALILEO. This obviously offers a significant benefit to users in term of greater signal availability. The use of combined GPS and Galileo will have a major impact on indoor positioning reliability [8] as well as on improving the accurate approach performance when using more frequency combined signals (e.g. [7], [13]).

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