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Performance Evaluation of EGNOS in Challenging Environments

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Abstract

Space-based augmentation systems (SBAS), such as EGNOS, are largely used to complement GPS for accurate and reliable positioning, which is required by rapidly growing location-based services (LBS). However, it is challenging to use EGNOS in the environments including urban areas and marginal area of the monitoring networks, where many LBS are delivered. Through the experiments in the challenging observation conditions, this study first evaluates the performance of EGNOS in these environments. Challenges consist in two aspects: EGNOS signals may be interrupted by blockages; EGNOS messages are not produced at all for marginal geographical areas due to the lack of raw satellite measurements. In order to use EGNOS for enhanced positioning performance in these environments, this paper then discusses several potential solutions. It is concluded that the two autonomous approaches, i.e. using aged corrections and mixing corrected and uncorrected satellites, can improve the positioning accuracy with a stand-alone receiver, and a full EGNOS positioning performance can be achieved in urban areas via a terrestrial access to EGNOS data, for example, the Internet connection with a smartphone. This paper discusses the effectiveness and usability of these approaches.

Keywords: EGNOS; European GNSS Evolutions Programme; EGNOS in high-latitude areas; EGNOS in urban; EGNOS network time;

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1. Introduction

Global Positioning System (GPS) has been most widely used in various positioning, navigation and timing (PNT) applications due to its ease of use, low cost and satisfactory accuracy. However, the accuracy of the GPS Standard Positioning Service (SPS) may be inadequate for certain applications, e.g. mapping, geomatics engineering and precise navigation (DoD, 2008). More importantly, GPS alone cannot provide integrity information concerning the reliability and accuracy of the system itself. In order to complement GPS and future other GNSS (Global Navigation Satellite System) constellations, space-base augmentation systems (SBAS) have been developed in different regions of the globe, such as WAAS (Wide Area Augmentation System) in North America, EGNOS (European Geostationary Navigation Overlay Service) in Europe and MSAS (Multi-functional Satellite Augmentation System) in Japan. All of these SBAS systems are interoperable and adhere to the Minimum Operational Performance Standards (MOPS) that are published by RTCA, Inc. The MOPS standards define the minimum performance, functions and features for SBAS-enabled GPS positioning.

EGNOS monitors GPS signals in space through a ground network of ranging and integrity monitoring stations (RIMS), and provide European users with differential corrections and integrity data to enhance positioning reliability and accuracy. EGNOS Open Service (OS) and Safety of Life (SoL) service have been officially declared available since October 2009 and March 2011, respectively (ESSP, 2011). EGNOS has been a major asset of European transport, maritime and civil aviation sections to improve the capacity, safety and efficiency of transport infrastructure and traffic control. As a time standard, EGNOS provides a reliable and accurate clock reference for computer and telecommunication networks. A number of location-based services (LBS) require EGNOS service for accurate and reliable positioning, and hence European Commission recently provided a set of ready-for-use EGNOS toolkits, which can be easily integrated with a smartphone, to promote the market adoption of EGNOS.

Although EGNOS has been used in many applications, its performance is degraded in challenging observation conditions. In this paper, the challenging environments include urban areas and marginal region of the RIMS network. An increasing number of applications require accurate and reliable positioning in these environments (Kuusniemi et al., 2012). For example, numerous LBS take place in urban areas where EGNOS signals are blocked frequently by surrounding structures. Human activities in the high-latitude region have been increasing in recent years, such as scientific research, resource exploitation, airlines over the arctic, etc, and they also require EGNOS service for accurate and reliable positioning. The high-latitude region is located at the edge of the RIMS network, and includes a few Member States of European Civil Aviation Conference (ECAC) organization. These member states should have been covered by EGNOS signals with a full capability according to the official statement (CNES & ESA, 2009). However, in fact, some of satellites visible for users in the marginal region are not monitored by the RIMS network, and therefore their correction and integrity data are not generated. As a result, the availability and performance of EGNOS services are limited in these environments.

In order to promote EGNOS service in the challenging environments, many studies have been conducted in the past years. As part of the European GNSS Evolution Programme (EGEP), multiple projects were funded by the European Commission (EC) and European Space Agency (ESA) to overcome the challenges of EGNOS in these environments (Wang et al., 2003; ESA, 2010; Durba, Armengou & Tossaint, 2009). This study was a part of the ESA-funded project EGURE (Use of EGNOS in Urban Environments), and it investigated issues of using EGNOS in urban areas and the high-latitude region through the field experiments, and analysed several potential solutions for an enhanced EGNOS positioning performance in the challenging conditions.

2. Overview of the EGNOS Signals

EGNOS is the European satellite-based augmentation system, and it currently complements the US GPS by providing differential corrections and integrity information over Europe. EGNOS consists of a space segment of three Geostationary (GEO) satellites, and a ground system that includes a RIMS network and data processing facilities. EGNOS is a safety critical system, and the RIMS network and data processing facilities assess current GPS performance and generate three types of differential corrections that are defined by the MOPS:

- Fast correction. This type of corrections aims to correct rapidly changing errors such as GPS satellite clock errors;
- Long-term correction. This type of corrections compensates slow changing components in atmospheric errors and satellite clock and ephemeris errors;
- Ionospheric correction. Ionospheric correction data correct vertical ionospheric delays relative to the L1 signal. They are broadcast in the forms of a wide-area ionosphere delay grid model.

In addition to differential corrections, EGNOS system also monitors and broadcasts the integrity of GPS and EGNOS geostationary satellite signals. With the integrity information, user-end receivers can determine which satellites are usable for the positioning calculation, and determine the reliability of calculated position estimate.

These correction and integrity data are broadcast via multiple channels. As a primary channel, EGNOS data are modulated into an L1-band radio frequency (RF) signal that has a same frequency as L1 signals transmitted by GPS satellites and the modulated signal is broadcast by three geostationary satellites. This design reduces the complexity of RF front-end and the cost of user receivers to make GPS receivers compatible with EGNOS. The three geostationary satellites are located respectively at three geostationary orbits with different longitudes as listed in Table 1. Given the longitude of 24.5 degree, the elevations of the three geostationary satellites are shown in Figure 1 when a user's latitude varies from 0 to 90 degrees on the earth's surface. At the high-latitude region, where the latitude is higher than 60 degrees, the elevations of the three geostationary satellites are lower than 20 degrees. Therefore, EGNOS signals are blocked more easily in these areas.

Table 1: Locations of EGNOS Geostationary Satellites

Satellite	PRN	Location (Longitude)
INMARSAT AOR-E	120	15.5˚ W
ARTEMIS	124	21.5˚ E
INMARSAT IOR-W	126	25˚ E

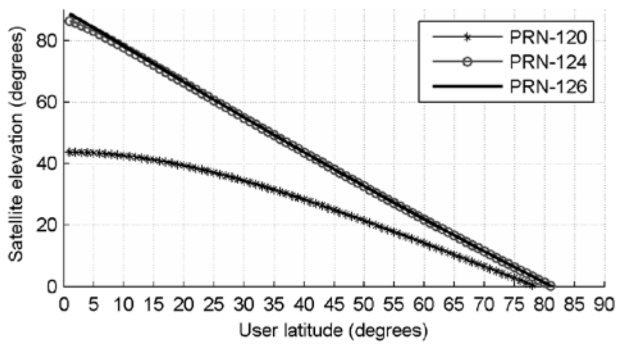

Figure 1: The elevations of three EGNOS geostationary satellites observed at a latitude ranging from north 0 to 90 degrees, given the longitude of 24.5 degree.

In addition, EGNOS system also provides data dissemination services via Internet, such as SISNeT (Mathur, et al., 2006), EGNOS Message Server (EMS) (Toran-Marti, et al., 2004) and Commercial Data Distribution Service (CDDS) (GSA, 2001). With the provision of EGNOS corrections and integrity data, major benefits include the improvement in GPS positioning accuracy and the awareness of GPS system integrity. In terms of accuracy, 95% radius error of horizontal positions is reduced typically from 2.6m to 1.3m for a static receiver in open sky conditions (Sheridan et al., 2010; Kuusniemi et al., 2011). For integrity, EGNOS provides near real-time information on satellite status and correction quality to ensure that any faulty satellites can be quickly removed from the positioning calculation. Therefore, the most of modern GPS receivers are capable of EGNOS functionality.

3. Performance of EGNOS in the Challenging Environments

This section analyses the challenges of using EGNOS through the field experiments conducted in the harsh conditions.

3.1 Availability of EGNOS corrections in the high-latitude region

In the high-latitude region, the availability of EGNOS data may be reduced due to two factors:

1) Corrections and integrity data are not produced for some satellites due to the lack of raw satellite measurements. In the edge of the RIMS network, some of satellites visible for users probably are not monitored by the RIMS network. As a result, EGNOS signals broadcast by the geostationary satellites do not contain the data regarding these satellites.

2) The reception of EGNOS signals may be intermitted due to blockages by surrounding objects. The geostationary satellites have quite low elevations in the high-latitude region, and blockages are more frequent than that in low- or middle-latitude regions.

A set of 24-hour static experiment was conducted in this study to investigate the availability of EGNOS in high-latitude region. The data were collected in an open-sky condition at the roof of the office building of Finnish Geodetic Institute (FGI) (*N60.16º, E24.55º*), where it is at the edge of RIMS network. A repeat period of GPS constellation is approximately 24 hours.

With the 24-hour data, the number of satellites, which are not usable for positioning due to the lack of EGNOS data, was counted epoch by epoch, and the epoch amounts of the different reduced satellite numbers were added up. Figure 2 showed the epoch percentages of the different reduced satellite numbers in the 24-hour dataset. The result showed that even in an open-sky condition of the high-latitude region, there are one or more satellites missing EGNOS data in 90% epochs of a constellation repeat period, and there are three or more satellites missing EGNOS data in one third epochs. As GPS constellation has worse geometry for the polar area than that in low- or middle-latitude areas (Parkinson & Spilker (Eds), 1996; Wang et al., 2006), a reduced number of usable satellites may cause further deteriorated positioning performance.

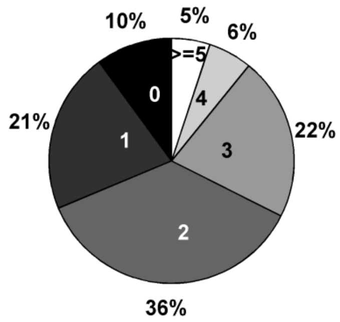

Figure 2: The different satellite numbers and corresponding percentages of reduced satellites due to the lack of their EGNOS data.

3.2 EGNOS positioning performance in the urban environments

As a regional augmentation system, the availability and performance of EGNOS services are dependent with geographical area, and most of past evaluations were conducted in open environments (ESSP, 2011). This subsection examines EGNOS-enabled positioning performance in the challenging conditions through the field experiments with a few commercial receivers.

The experiments were conducted at three typical scenarios of city ecosystem in Helsinki metropolitan area: urban commercial area of the city center, residential area and motorway. These scenarios are deep-blocked, middle-blocked and slight-blocked for EGNOS observation, respectively. Helsinki area has a typical urban environment and higher latitude than 60 degree where EGNOS geostationary satellites have very low elevations and are very frequent to be blocked. Helsinki is also at the edge of the RIMS network where some of satellites visible for users are not monitored by the RIMS network and have no EGNOS data available. Therefore, the experiment environments are very challenging for EGNOS service.

Two sets of experiments were carried out at two separated days, called Test 1 and Test 2. Three u-blox receivers were used: u-blox 5H, 5T and 6T. EGNOS function was enabled with the 5T and 6T receivers, and was disabled with the 5H receiver for the comparison. A NovAtel SPAN GPS/IMU geo-reference system was used as the truth trajectory, which was stated to have centimeter-level accuracy (NovAtel Inc., 2005). The antenna of the SPAN system was placed on the roof of the vehicle in the two tests, and the antenna places of these receivers were marked in Table 2. Each of the tests spanned about 40 minutes for every scenario, and roughly two and half hours for the whole process.

GPS positioning results were always obtainable through the experiments as GPS observation conditions were good enough. When EGNOS data are available and applied to positioning solutions, corresponding epochs are flagged with EGNOS solutions. Otherwise the solutions that do not use EGNOS data are flagged as GPS solutions (u-blox AG, 2009). Table 2 compared the percentage of EGNOS solutions in the different testing scenarios. The result of u-blox 5H was not included in Table 2 as EGNOS function was disabled with this receiver.

Table 2: The Availability (in percentages) of EGNOS Solutions in Different Testing Conditions, including Antenna Places and Testing Environments

	Test 1		**Test 2**	
Receiver	u-blox 6T	u-blox 5T	u-blox 6T	u-blox 5T
Antenna place	Dashboard	Roof	Roof	Roof
Urban area	0	23.2%	45.6%	58.7%
Residential area	1.4%	100%	100%	97.9%
Motorway	12.5%	100%	100%	100%

When the antennae were placed under the dashboard, it is difficult to get EGNOS solutions mainly due to signal attenuation of the dashboard. Furthermore, the sensitivity of EGNOS signal tracking is usually lower than that of GPS signal tracking in most of GPS/EGNOS receivers. For example, NAVSYNC CW20 receiver, unveiled at 2007 by Navsync Ltd., showed a 7dB lower SBAS tracking sensitivity than GPS signal tracking sensitivity. In addition, the MOPS also states that expected user received signal levels at different areas may have a variance of up to 4dB depending on user elevations (RTCA Inc., 2001). The results showed that at the high-latitude area, an antenna under dashboard almost could not successfully receive EGNOS messages even in an open-sky condition. When an antenna was placed on the roof, EGNOS solutions can be obtained for 50 percent epochs at the heavy-blocked urban area, and for almost all of epochs at the middle- and slight-blocked areas.

Table 3 compared EGNOS-enabled and -disabled positioning accuracy in the different observation conditions. All antennas of the three receivers were placed nearly on the roof of the vehicle and they have same observation conditions. It showed that EGNOS corrections did not improve positioning accuracy in the urban area, while it improved significantly positioning accuracy on the slight-blocked motorway. The horizontal positions have about 28% less RMS and R95 errors. In the middle-blocked residential area, the two EGNOS-enabled receivers had inconsistent results with each other. One of possible causes for the above observation is the multipath effect, which has greater impact on positioning accuracy in urban areas.

Table 3: Comparison on EGNOS-enable and-disable Positioning Accuracies Represented by the 95% Error Radius (R95) and Root Mean Square (RMS) Error in the Horizontal and Vertical Domains.

		Receiver model	**uBx-6T**	**uBx-5T**	**uBx-5H**
		EGNOS option	On	On	Off
Urban area	horizontal	R95	19.25	21.02	18.73
		RMS	8.33	8.63	7.74
	vertical	R95	13.25	15.48	15.82
		RMS	5.85	6.74	6.40
Residential area	horizontal	R95	5.55	4.64	5.56
		RMS	3.10	2.59	3.21
	vertical	R95	5.00	4.14	4.29
		RMS	2.65	2.23	2.62
Motorway	horizontal	R95	4.05	3.98	5.45
		RMS	2.50	2.43	3.51
	vertical	R95	3.25	2.79	4.57
		RMS	2.30	1.33	2.96

4. Potential Solutions and Corresponding Evaluations for Using EGNOS in the Challenging Environments

This section presents several potential solutions to enhance EGNOS performance in the challenging conditions.

4.1 Extended correction timeouts

In the MOPS standard, each type of EGNOS corrections is limited to use by their respective timeouts to ensure the validity of these corrections. For non-aviation applications, these timeout thresholds may be too stringent under certain conditions. This section explores the possibility of extending the timeouts, and evaluates positioning accuracy when aged corrections are used.

An extended timeout can be applied if its utilization does not cause a worse positioning accuracy. Maximum timeout values of these corrections are limited by respective physical facts. Fast and long-term corrections can only be used when their issue of data (IOD) matches with the IODC and IODE (IOD of satellite clock and ephemeris, respectively) of GPS navigation data. As GPS satellite clock and ephemeris data are regularly updated every two hours, the validity of fast and long-term corrections can be up to two hours until GPS navigation data are updated. The validity of ionospheric corrections depends on ionosphere condition. This study assumed that first 30 minutes of two-hour GPS navigation data period are taken to collect EGNOS messages, and these collected EGNOS corrections are then used in the following 1.5 hours. This assumption is actually a typical user scenario in harsh conditions. The effectiveness of aged EGNOS corrections is evaluated in this study through the comparison on positioning accuracy. Six cases were designed as follows to compare the effects of different types of aged EGNOS corrections on positioning accuracy:

a) *FL+old_I* case: Fast and long-term corrections are updated while aged ionosphere corrections are used in the period of 1.5 hours;
b) *I+old_FL* case: Ionosphere corrections are updated while aged fast and long-term corrections are used in the period of 1.5 hours;
c) *FI+old_L* case: Fast and ionosphere corrections are updated while aged long-term corrections are used in the period of 1.5 hours;
d) *old_FLI* case: Aged ionosphere, fast and long-term corrections are used in the period of 1.5 hours.
e) *FLI* case: Ionosphere, fast and long-term corrections are updated, and no aged corrections are used.
f) *GPS-only* case: Do not use any EGNOS corrections.

With the six cases as above, a same dataset was processed using *UNavi* software package to compare the positioning accuracies. The dataset was collected by a Fastrax iTrax03 receiver with an antenna located at the roof of the office building of FGI. The iTrax03 receiver was manufactured by Fastrax Ltd, and it can provide L1 C/A pseudorange measurements via the particular iTalk protocol (Fastrax, 2007). GNSS/SBAS positioning software package UNavi was developed by FGI, and it is capable of processing EGNOS in accordance with the MOPS standard (Do-229C) (RTCA Inc., 2001). In this study, positioning solution was calculated with Kalman filter. C/A pseudorange measurements were used and their noise levels were calculated with signal powers and elevations as follows (Liu, et al., 2008a):

$$\sigma^2_{noise} = 9 / \left[\sin^2(el) * 10^{(CN0/10-4)} \right] \qquad (1)$$

where σ^2_{noise} is the estimated variance of signal noises related to pesudorange measurements, el is the elevation of satellites, and $CN0$ is the carrier-to-noise ratio of satellites in unit of dBHz.

Based on the signal noise variance calculated by Eq. (1), the variances of measurement errors in the Kalman filtering were then evaluated by:

$$\sigma^2_{msr} = \sigma^2_{noise} + \sigma^2_{UDRE} + \sigma^2_{UIRE} \qquad (2)$$

where σ^2_{msr} is the measurement variance, σ^2_{UDRE} is the variance of a Normal distribution associated with the user differential range error for a satellite after application of fast corrections and long-term corrections, excluding atmospheric effects, and σ^2_{UIRE} is the variance of a Normal distribution associated with the residual ionospheric vertical error at an IGP (Ionospheric Grid Point) for an L1 signal.

The parameters $\sigma^2_{UDRE}, \sigma^2_{GIVE}$ can be calculated with the broadcast messages UDREI (User Differential Range Error Indicator) and GIVEI (Grid Ionospheric Vertical Error Indicator) that are defined by the MOPS, and the calculation methods can be found in (Do-229C) (RTCA Inc., 2001). All above processing cases used same configurations other than EGNOS corrections that were defined by the above six cases. Thus, different positioning results are caused by the different EGNOS corrections. Figure 3 showed horizontal position residuals related to the different cases when aged EGNOS corrections were used in the 1.5-hours period.

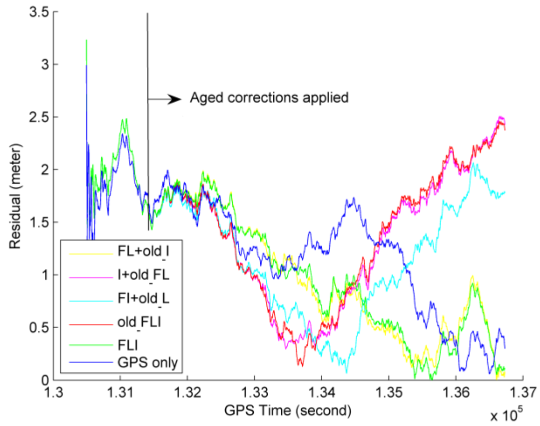

Figure 3: Horizontal positioning residuals of the six cases when different combinations of EGNOS corrections were used.

The following observations can be made from the above results:

1. Aged ionosphere corrections produced almost same positioning result as that of up-to-date ionosphere corrections as the ionosphere kept quite stable during the experiment period from UTC 12:00 to 14:00, according to the a-index values as shown in Figure 4. However, the ionosphere delay of GPS signals probably varies up to tens of meters in a period of 2 hours when geomagnetic activity is severe (Susan, 1998; Hernández, et al., 2007; Liu, et al., 2008b; Liu, et al., 2011). Therefore, the usability of aged ionosphere corrections depends on the level of geomagnetic activity that may be indicated by geomagnetic activity indices, such as K- and A- index.

2. Long-term corrections with an age of 1.5 hours may degrade positioning accuracy by approximately 1 meter under the given geometry, while fast corrections with the same age cause roughly 2 meters worse positioning accuracy. An aged fast correction has a larger error than long-term correction of a same age.

3. When geomagnetic activity is at a low level, e.g. an A-index value of no more than 27 in this paper, EGNOS corrections can be used with an extended timeout for non safety-critical applications. The extended timeout values are recommended as shown in Table 4. It should be pointed out that ionosphere condition should be checked to determine if aged ionospheric corrections can be used. When ionosphere condition keeps stable, the timeout can be extended up to 5400 seconds. Otherwise, the MOPS standard should be applied when the ionosphere varies significantly. This should be carefully considered especially for users in polar areas as ionosphere activities are more active in these areas (Meng et al., 2007; Liu, et al., 2009; Liu, et al., 2010).

4. Some of tracked satellites had no EGNOS corrections available during the experience period as they were not monitored by the RIMS network. Therefore, the numbers of usable satellites in EGNOS solutions are less than that in GPS-only case. Reduced satellite numbers cause worse geometry and positioning accuracy. This issue is further addressed in the following section.

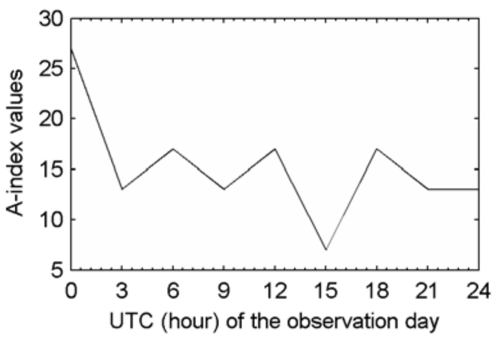

Figure 4: Three hourly a-index values in the observation day

Table 4: The MOPS Standard Timeouts and The Recommended Values of Extended Timeouts of EGNOS Corrections for Non Safety-critical Applications

Correction types	**Timeout (seconds)**	
	MOPS standard	Extended timeout
Fast corrections	18 - 180	1800
Long-term corrections	360	3600
Ionospheric corrections	600	600 - 5400

4.2 Positioning with mixed corrected and uncorrected measurements

EGNOS system uses a system time known as EGNOS Network Time (ENT). The ENT is continuously steered towards GPS System Time (GST) by EGNOS system and the relative consistency between the two time scales is maintained at the level of tens of nanoseconds that is equivalent to a few meters (CNES and ESA, 2009). Due to the gap of two time systems, EGNOS users are recommended not to mix uncorrected and corrected measurements for positioning (CNES and ESA, 2009). However, the number of usable satellites is reduced and the geometry and positioning accuracy is degraded significantly if uncorrected measurements are excluded from the positioning solution. A more intelligent approach is to mix uncorrected and corrected measurements for positioning. Thus, all of observed satellites can be used to form the best geometry.

In order to use uncorrected and corrected measurements together for positioning estimation, the gap between ENT and GST should be parameterized. The gap parameter may be estimated with two approaches:

- Calculate the GST-ENT offset using EGNOS message type 12 (MT12) and GPS navigation data.
- Estimate the offset as an additional unknown within the positioning solution.

For the first approach, EGNOS MT12 provides UTC parameters to calculate the offset between ENT and UTC (Δt_{EU}), while GPS navigation data provide UTC parameters to calculate the offset between GST and UTC (Δt_{GU}). The definition of UTC parameters and an applicable synchronization algorithm can be found in Sections 20.3.3.5.1.8 and 20.3.3.5.2.4 of GPS Interface Control Document (Arinc, 2000). The GST-ENT offset can be then calculated by:

$$\Delta t_{EG} = \Delta t_{EU} - \Delta t_{GU} \quad (3)$$

Although the GST-ENT offset is nominally calculated as above, its accuracy is restricted by the bias of different time systems. ENT is synchronized with UTC time issued by the Paris Observatory (UTC(OP)), while GPS time is referred to UTC time maintained by the U.S. Naval Observatory (UTC(USNO)). The inconsistency between UTC(OP) and UTC(USNO) may be up to 100 ns that is equivalent to 30 meters (Arinc, 2000; CNES and ESA, 2009). Therefore, the utilization of the GST-ENT offset will cause worse positioning accuracy as shown in Table 5.

In the second approach, an additional parameter of the GST-ENT offset is appended into the system model. For uncorrected and corrected measurements, measurement models are expressed respectively as follows (Parkinson & Spilker (Eds), 1996):

$$\rho^{j} - \mathrm{P}^{0j} = u_x^j dx + u_y^j dy + u_z^j dz + dt \tag{4}$$

$$\bar{\rho}^{j} - \mathrm{P}^{0j} = u_x^j dx + u_y^j dy + u_z^j dz + dt - dt_{\Delta} \tag{5}$$

where ρ^j is the pseudorange measurements of satellite *j*, $\bar{\rho}^j$ is the corrected pseudorange measurements by EGNOS corrections, P^{0j} is the geometry distance between receiver and satellite *j* given an initial receiver coordinate $\left(x^0, y^0, z^0\right)$, u_x^j, u_y^j and u_z^j are direction cosines between the initial receiver position and satellite *j*, the added parameter dt_{Δ} is the GST-ENT offset.

A random constant model is used to represent the random process of GST-ENT offset, and the dynamic model of this additional parameter is defined as follows (Brown and Hwang, 1997):

$$dt_{\Delta k} = dt_{\Delta k-1} + w_{k-1} \tag{6}$$

$$E\left\langle w_k, w_k^{\ T} \right\rangle = Q_k \tag{7}$$

where w_k is the random process noise of the GST-ENT offset, and Q_k is the variance of noises.

The process noise covariance of the GST-ENT offset was given as $(0.1\ \mathrm{ns})^2$ in this study.

With the offset parameter, the two time references are transformed each other as follows:

$$dT_{\mathrm{GPS}} = dT_{\mathrm{ENT}} + dt_{\Delta} \tag{8}$$

where dT_{GPS} and dT_{ENT} is the clock parameter referred in GPS system time and ENT, respectively; dt_{Δ} is the GST-ENT offset.

In a real observation process, three scenarios as below have to be handled adaptively to use all corrected and uncorrected satellites. The processing software automatically switches among the different scenarios.

Scenario 1: All observed GPS satellites have no EGNOS corrections.
Scenario 2: All observed GPS satellites have EGNOS corrections available.
Scenario 3: Part of observed GPS satellites have EGNOS corrections, whereas others have no.

For Scenario 1, the additional offset parameter is not observable in the system (Yang et al. 2007; Grewal and Andrews, 2008), and the measurement model Eq. (4) is used. Consequently, positioning solution in this scenario is referred in GST. For Scenario 2, the offset parameter dt_{Δ} could not be separated from the clock error dt in Eq. (5), and they are actually combined into one parameter. Thus, the measurement model Eq. (4) is also used, while positioning solution is referred in ENT. For Scenario 3, corrected and uncorrected measurements are mixed, and the measurement models Eq. (4) and (5) both are used, respectively. The offset parameter dt_{Δ} as well as position parameters is estimated, and the positioning solution is referred in GST. The *UNavi* software automatically switches among these scenarios to adapt to the real observation condition as shown in Figure 5.

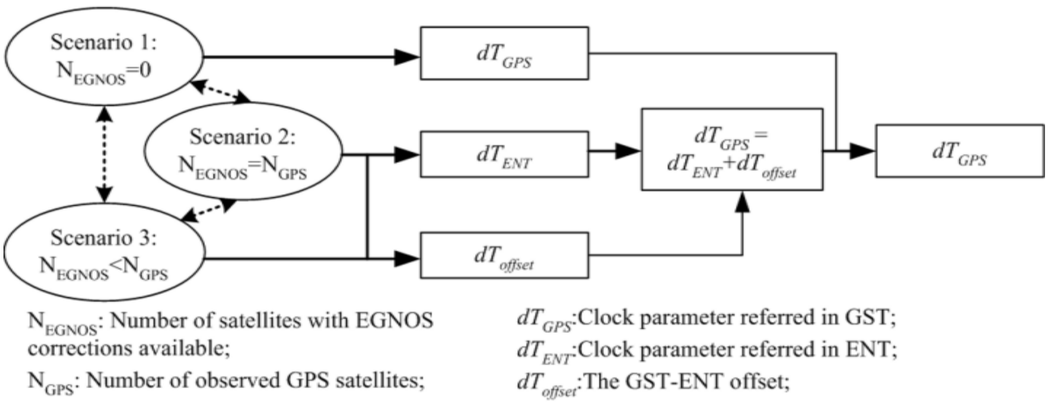

Figure 5: A positioning solution of mixing corrected and uncorrected measurements in different scenarios of EGNOS correction availability

For accuracy comparison, a 24-hour dataset was processed with different setting cases as follows:

MT12-Offset: All measurements were used. Corrected and uncorrected measurements were aligned using the GST-ENT offset calculated by MT12 and GPS navigation data.
EGNOS-M: Corrected and uncorrected measurements were mixed together to calculate position estimates. The GST-ENT offset was estimated as an additional parameter. The MOPS standard was used to calculate the availability of EGNOS corrections.
EGNOS-A: Only corrected measurements were used for position estimates. The MOPS standard was used to calculate the availability of EGNOS corrections.
EGNOS-A-ET: Only corrected measurements were used for position estimates. The extending timeouts recommended in Table 4 was used to calculate the availability of EGNOS corrections.
GPS-E: Used only satellites that have EGNOS corrections available according to the MOPS standard, while measurements were not corrected by EGNOS corrections in the position estimation.
GPS only: Used all GPS measurements while no EGNOS correction was used.

The dataset were collected with the antenna located at the roof of FGI, and it was processed by *UNavi* software package. Table 5 showed the root mean square (RMS) and 95% radius errors of different test cases. The case of MT12-Offset produced the worst positioning accuracy although it had the best geometry. EGNOS-M case produced the smallest positioning errors. These two cases had same satellite geometry as they both used all measurements. The worst positioning accuracy of MT12-Offset case was caused by the gap between different UTC standards mentioned above. Figure 6 showed the different results of GST-ENT offsets obtained respectively by the two approaches, and they had a bias of roughly 13.8 meters for this dataset. EGNOS-M case had a better positioning accuracy than EGNOS-A, EGNOS-A (Extended timeout) GPS-E and GPS-only cases as it used all measurements as well as EGNOS corrections. By contraries, in the cases of EGNOS-A, EGNOS-A (Extended timeout) and GPS-E, the numbers of usable satellites were reduced by the availability of EGNOS corrections, and they hence had worse geometry. GPS-E case had worse positioning accuracy than EGNOS-A and EGNOS-A (Extended timeout) cases as it did not use EGNOS corrections. The case of EGNOS-A (Extended timeout) had slightly better positioning accuracy than EGNOS-A case as the extended timeout enabled slightly more satellites to be used in positioning solution. This experiment was conducted in an open environment, and the missing of EGNOS corrections were mainly caused by the fact that corresponding satellites were not observed by the RIMS network. Therefore, only slightly more satellites can be included even with the extended timeouts.

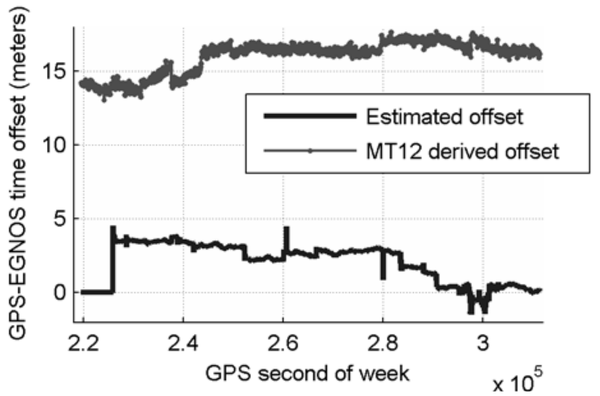

Figure 6: The GST-ENT offsets derived from MT12 and estimated in positioning solution.

It is concluded that positioning with mixed corrected and uncorrected measurements produces the best positioning accuracy when the GST-ENT offset was estimated as an additional parameter rather than using the value derived from MT12 and GPS navigation data.

Table 5: Comparison on Positioning Errors and Satellite Geometry Related to Different Test Cases.

Modes	**MT12-Offset**	**EGNOS-M**	**EGNOS-A**	**EGNOS-A-ET**	**GPS-E**	**GPS only**
Horizontal RMS	9.66	1.47	2.18	2.14	2.97	1.91
Vertical RMS	16.74	3.56	3.89	3.85	6.59	4.57
95% horizontal error	11.85	2.74	3.78	3.80	5.06	3.26
95% vertical error	22.03	7.92	7.50	7.43	12.18	8.37
95% PDOP	2.16	2.16	3.49	2.95	3.49	2.16

4.3 Terrestrial access services of EGNOS
Other than signals broadcast by the geostationary satellites, users can also access to EGNOS data via terrestrial services, e.g. SISNeT, EGNOS Message Server (EMS) and Commercial Data Distribution Service (CDDS). These services enable users with Internet

connections to obtain complete EGNOS data broadcast by the geostationary satellites, and avoid possible data missing due to signal blockage of objects in harsh environments. It should be pointed out that these services could not improve the situation of satellites that could not be observed by the RIMS network at the edge of the RIMS network.

In order to facilitate the market adoption of EGNOS in various LBS, a set of EGNOS toolkits, including EGNOS SDK (Software Development Kits), PEGASE tool and SIGNATURE tool, has been presented to application developers, and they can be used on a broad set of mobile platforms such as iPhone, Android, Blackberry and Windows Phone (GSA, 2011). The usage of these services and toolkits is not covered in this paper, and their user guides can be found in (Mathur, et al., 2006; Toran-Marti, 2004; GSA, 2011).

4.4 EGNOS correction prediction

When old corrections get expired and new EGNOS signals are blocked, an alternative method for correcting measurements is to predict corrections based on the old corrections. The previous studies showed that the utilization of predicted corrections for a period of 30 minutes can produce a better positioning accuracy than the GPS-only case (Ziebart, 2004; Jwo et al., 2004; Indriyatmoko et al., 2007). An autoregressive–moving-average (ARMA) model or a polynomial model can be utilized to predict EGNOS corrections. These methods require the continuous reception of corrections in a long period, e.g. 1 hour. However, this requirement can rarely be met in the challenging environments due to the signal blockages. As a result, the methods of prediction are limited to use in terms of usability and accuracy. This paper could not recommend these methods for adoption in the challenging environments.

5. Conclusion

EGNOS service is restricted to use in the challenging environments. In this paper, the experiments were conducted to examine EGNOS performance in urban areas and the high-latitude area. In these environments, two reasons have caused the degraded EGNOS performance. First, EGNOS signals are blocked by surrounding objects in urban areas, and blockages are much heavier in the high-latitude areas as the geostationary satellites have lower elevations. Second, corrections of some satellites are not generated as they are not monitored by the RIMS network.

Even in the challenging environments, advantages of EGNOS adoption have been recognized through the experiment results. Several potential solutions have been discussed further in this paper to overcome the restrictions. Two receiver autonomous methods have been analysed in details through the comparison of experiment results. Other than the signals in space, EGNOS data can also be obtained via terrestrial Internet connections. This approach provides a full access to EGNOS data and it is not impacted by blockages. The Internet-based method is effective and useful for various smartphone applications of mobile LBS as smartphones have become a most used mobile platform that have a capability to connect mobile Internet in a wide scale. Related SDK and toolkits have been provided by the service provider (GSA) to facility the development of smartphone applications.

For the high-latitude region, ionosphere delay and its modeling remain challenging. Efforts will be paid to investigate the relation between the degradation rate of ionospheric corrections and levels of solar activity. The modeling of ionospheric delay in the high-latitude region will also be studied to provide correction data for precise positioning.

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Biography

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