ENGINEERING JOURNAL

Article

Performance Analysis of GPS Aided Geo Augmented Navigation (GAGAN) Over Sri Lanka

Thilantha Dammalage[1,a], **D. N. De Silva**[2,b], **and Chalermchon Satirapod**[3,c,*]

1 Department of Remote Sensing and GIS, Faculty of Geomatics, Sabaragamuwa University, Sri Lanka
2 Survey Department of Sri Lanka, Sri Lanka
3 Department of Survey Engineering, Faculty of Engineering, Chulalongkorn University, Thailand
E-mail: [a]thilantha@geo.sab.ac.lk, [b]nishshanka312@gmail.com, [c]chalermchon.s@chula.ac.th (Corresponding author)

Abstract. Satellite-Based Augmentation Systems (SBAS) are being developed worldwide due to their unique advantage of wide area coverage. GPS Aided Geo Augmented Navigation (GAGAN) is an Indian implementation of SBAS, with three (03) geo stationary satellites in space covering a huge area even beyond Indian Territory. This study focused on analyzing the improvement in position solution with GAGAN corrections over Sri Lanka. In order to test its performances, several dual and single frequency GNSS receivers were used in this experiment, one receiver was configured as SBAS receiver and other two were kept as GPS stand-alone receivers. Observations were carried out over seven (07) known control stations of six (6) different districts to investigate its coverage over Sri Lanka. At each of the tested stations the GAGAN active L1 receiver has always shown a significant accuracy improvement over L1 uncorrected observations. Further, five out of the seven (7) observation locations the calculated average 3D positional errors were lower than 1m. Almost 79% of observations (out of 24 hours of observations) have shown acceptable 3D positional accuracy, of less than 1m, for many spatial data collection applications. However, the local DGPS correction has shown higher reliability than GAGAN corrections with almost 85% of observations with less than 1m, 3D positional error.

Keywords: SBAS, GAGAN, performance analysis.

ENGINEERING JOURNAL Volume 21 Issue 5
Received 4 March 2017
Accepted 11 April 2017
Published 29 September 2017
Online at http://www.engj.org/
DOI:10.4186/ej.2017.21.5.305

DOI:10.4186/ej.2017.21.5.305

1. Introduction

Global Navigation Satellite System (GNSS) technology enables land, sea, airborne and space users to determine their three dimensional position, velocity and time, twenty-four hours a day, in all weather conditions, anywhere in the world [1, 2]. Nowadays GNSS is often discussed in the context of consumer applications such as car and personal navigation, and location-based services in general [3]. GNSS is based on several globally available satellite based positioning systems including the United States' GPS, Russia's GLONASS, China's Beidou, the expected European Union's Galileo, and the Regional systems such as Japan's Quasi Zenith Satellite System (QZSS) and Indian Navigation Satellite System (IRNSS), etc. It has been noticed that the use of satellite based positioning and its integrations in various applications are growing rapidly within Sri Lanka after its three decades of civil war. The country is now on a rapid infrastructure development and within next several years of which can obviously expect a higher growing demand for accurate and reliable satellite based positioning and navigation in various surveying and mapping applications, car navigation, aviation, maritime, and numerous geospatial and remote sensing applications in and around Sri Lanka. According to the average number of GNSS satellites expected to be visible across the globe by 2020 (http://www.multignss.asia/campaign.html), the future GNSS applications in Sri Lanka will benefit significantly through higher visibility of GNSS satellites. While the higher availability ensure the reliability of satellite based positioning and navigation and it encourages the use of GNSS in most of all possible applications. According to the EU market research on GNSS for the year 2015 (https://www.gsa.europa.eu/2015-gnss-market-report); the use of GNSS devises by 2020 would be almost same as the world population due to the significant improvement of location based services (LBS) with respect to the applications in Road Transportation, Aviation, Maritime, Rail, Agriculture, Surveying and, Timing & Synchronisation. According to the same report, more than 91% of the GNSS devises are used in LBS and vehicle navigation. Further, when compared to the same GNSS market report published in 2013, a significant improvement is observed in LBS within these two years. The use of LBS's has improved from 47% in 2013 to 53.2% by 2015. However, all of these LBS's and vehicle navigation systems are directly linked to a GNSS device with slandered positioning capabilities. Irrespective of the rapid development of positioning and navigation satellite systems and innovative applications with advanced hardware and software, the ultimate accuracy of positioning and navigation would still significantly be influenced by measurement errors [4]. For instance, impact of the atmospheric errors in GNSS measurements especially for an equatorial zone has been emphasised in Tsujii et al. (2012) [5] and Kitpracha et al., (2017) [6]. The most acceptable and reliable possibility to ensure the accuracy of the GNSS is to use one of the key benefit of differential GPS (DGPS) to reduce or eliminate many of the measurement errors as a group [1, 7]. Therefore, a significant motivation could be observed towards the use of real-time differential augmentation systems with local and wide area differential positioning capabilities to cater the present day complicated, accurate and reliable requirements of positioning and navigation.

However, the accuracy and reliability of the differential corrections broadcasted by the DGPS reference station depend on the tracking capability and the nature of its surrounding environment [8].In addition, for real-time applications, the validity of the corrections estimated and broadcasted by the DGPS reference station is restricted to specific local users [9, 10]. The larger separation of distances between the reference and the rover, errors estimated at the reference site become de-correlated with those errors affected at the rover location due to the spatial difference between the error sources [1, 11, 12]. These logistical, economic and technical limitations have primarily contributed to the evolution of multi-reference (or network) DGPS techniques. To provide nationwide multi-reference DGPS coverage, however, multitudes of differential base stations are required with all sorts of GNSS and communication equipment. This would obviously be overly expensive and uneconomical. Therefore, wide area differential GPS (WADGPS) techniques can be identified as a reasonable solution to overcome the limitations of multi-reference DGPS technique. The accuracy of WADGPS is independent of the geographical location of the user relative to the nearest reference station, though the validity of the correction still decreases with an increase in the age of the correction data [13]. The following subsections will briefly describe the concept of Wide Area Differential GPS (WADGPS), Satellite-Based Augmentation Systems (SBAS) and GPS Aided Geo Augmented Navigation (GAGAN).

1.1. Wide Area Differential GPS (WADGPS)

A typical WADGPS mathematical algorithm combines the various WADGPS corrections received from the different reference stations to produce locally-valid single set of DGPS corrections. The algorithm accounts for spatial decorrelation of GPS error sources at the different reference stations due to the large separation distances involved [14]. All the WADGPS algorithms used can be classified into three groups: measurement domain, position domain and state-space domain algorithms [15]. Measurement domain WADGPS algorithms provide DGPS network corrections computed as the weighted mean of the various DGPS base station corrections. A possible disadvantage of such algorithms, however, is the degradation of the correction accuracy with the distance from the network centroid [16]. Position domain WADGPS algorithms, on the other hand, provide DGPS position solutions computed as the weighted mean of the different DGPS position solutions resulting from using each of the available DGPS corrections independently. In other words, each of the incoming set of DGPS corrections are used separately to produce an independent position fix for the remote receiver. The resulting position fixes are then weighted and averaged to produce the final solution [14].

Finally, state-space domain WADGPS algorithms provide highly accurate baseline-independent corrections using a number of DGPS reference stations equipped with GPS receivers (usually of the dual frequency type) and complex software. The algorithm models the involved GPS error sources including satellite clocks and orbits, the ionosphere, the troposphere and the reference station clocks. The principle behind the various state-space models developed so far is to use the available multiple sets of WADGPS corrections to estimate the different error components involved, and thus be able to estimate local measurement errors. Therefore, the majority of state-space WADGPS reference networks employ dual-frequency GPS receivers for real-time dual-frequency ionospheric modeling [15]. Users typically receive their differential corrections in multiple components to be integrated within their equipment with the locally measured GPS data.

1.2. Satellite-Based Augmentation Systems (SBAS)

Satellite-Based Augmentation Systems (SBAS) are being developed worldwide due to their unique advantage of wide area coverage to use as wide area differential GPS (WADGPS) technique to improve the accuracy of GNSS observations over a large spatial region. Most of the available SBAS used state-space domain WADGPS algorithms [15]. The US Wide Area Augmentation System (WAAS), European Geostationary Navigation Overlay system (EGNOS) and the Japanese Multi-functional Satellite Augmentation System (MSAS) are good examples. In the case of WAAS and EGNOS, the users receive their corrections in the RTCA DO-229 format, which provides satellite clock corrections, satellite orbital corrections and ionospheric corrections all in separate components [17]. Initial test results of Asia-Pacific GNSS Test Bed were reported in Pringvanich and Satirapod (2007) [18] and Pringvanich and Satirapod (2009) [19].The system architecture of the Test Bed is illustrated in Fig. 1. Flight trial result from the Asia-Pacific Test Bed demonstrates the benefits of SBAS messages in increasing Approach with Vertical guidance (APV) availability by lowering the horizontal protection levels (HPL) and vertical protection levels (VPL), while maintaining an appropriate level of integrity. It was recommended that further investigations are needed to ensure the system integrity performance.

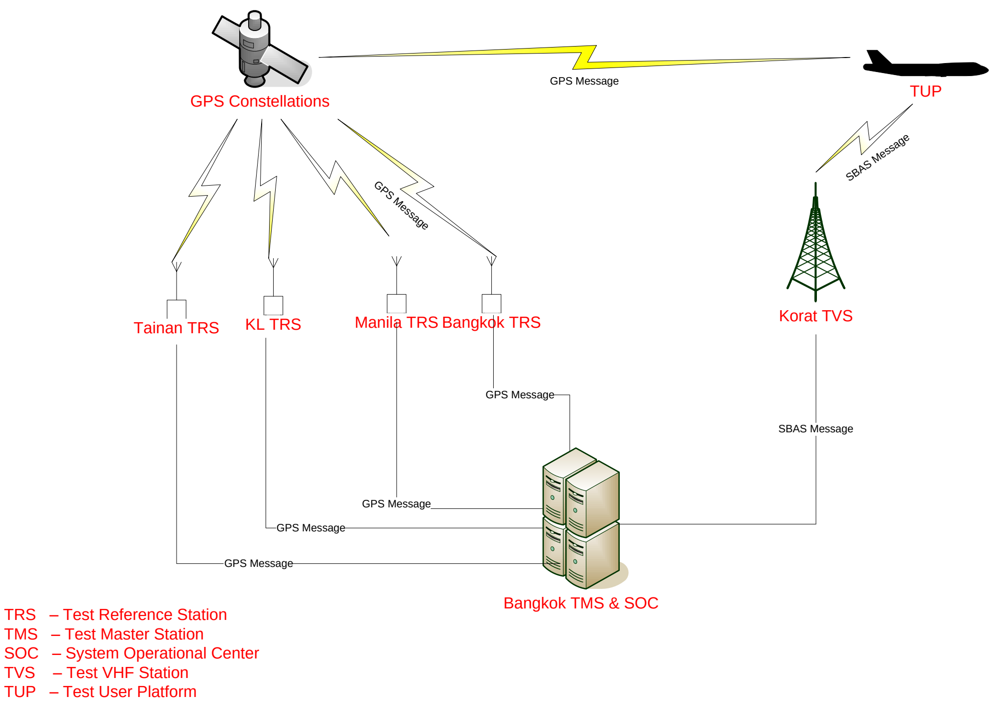

Fig. 1. System Architecture of the Asia-Pacific GNSS Test Bed and Test Configuration [18].

1.3. GPS Aided Geo Augmented Navigation (GAGAN)

GPS Aided Geo Augmented Navigation (GAGAN) is an Indian implementation of SBAS, developed jointly by Airports Authority of India (AAI) and Indian Space Research Organization (ISRO) [20, 21]. The Directorate General of Civil Aviation (DGCA) in India certified GAGAN's full operation potential by December, 2013 with three (03) geo stationary satellites in space covering a huge area beyond Indian Territory, extending from Africa to Australia [21]. In the GAGAN system, location-specific ionosphere induced signal propagation delay is mapped onto multiple grid points of 5° by 5° latitudes and longitudes as shown in Fig. 2. Each grid point is called an ionospheric grid point (IGP). Ionospheric delay is estimated for each of these IGPs by utilizing the observations of precisely surveyed network of 15 ground reference stations called Indian Reference Stations (INRES) established throughout India [20].

According to the GAGAN system architecture illustrated in Fig. 3, Indian Master Control Centers (INMCC) located at Bangalore receives the data collected by all the reference stations and uses these data to calculate the differential corrections and the ionospheric delay estimates for each of the observed GNSS Satellites and the IGPs respectively [20]. The compiled corrections for each monitored GNSS satellite are then uplinked to geostationary satellites GSAT-8 and GSAT-10 as SBAS messages and which then broadcast the same messages on the same GNSS frequency, but with different data rate and PRN code allowing SBAS compatible receivers to identify these satellites and receive, decode and process the correction data. GSAT-8 and GSAT-10 transmit the data with PRN codes 127 and 128, respectively, and will appear on some SBAS-compatible GNSS receivers as satellites 40 and 41. A third satellite, GSAT-15 will serve as an "in-orbit spare", to be switched on if either GSAT-8 or GSTA-10 fails. [22].

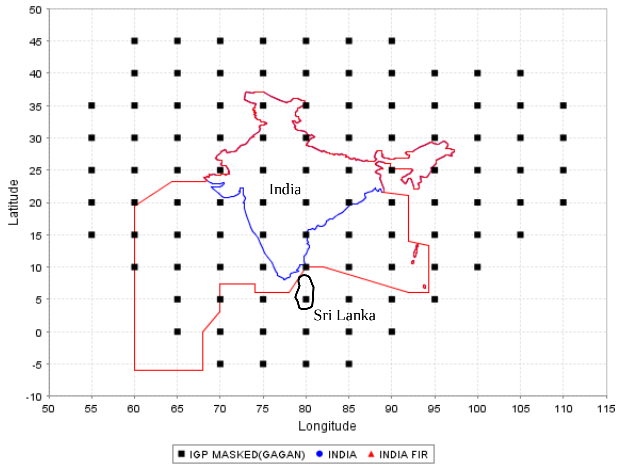

Fig. 2. Ionospheric Grid Points (IGP).

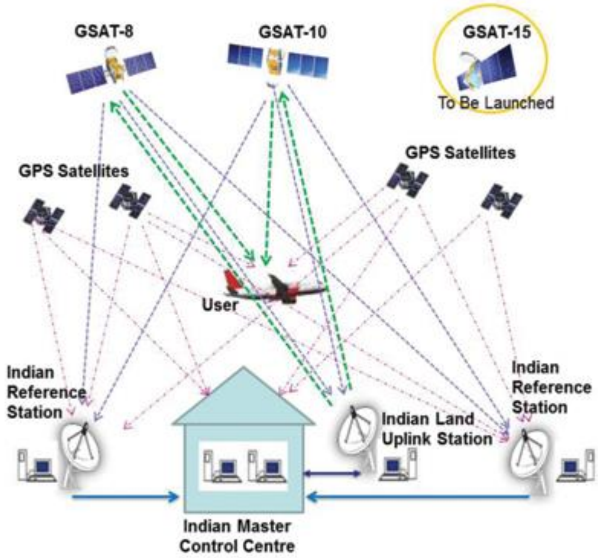

Fig. 3. GAGAN system architecture [23].

With the availability of GAGAN signal-in-space (SIS), this study will therefore focus mainly on analyzing the improvement in position solution with GAGAN corrections over Sri Lanka.

2. Performance Analysis

There are many GPS users in Sri Lanka in different fields such as surveying, geodesy, GIS professionals, security agencies, intelligent transportation, maritime, highways, railways, telecom industry, personal users with location based applications and etc. For any of these professional works; accurate, reliable, continuously available and cost effective correction services are essential. However, due to the limited availability of free DGPS services and cost of utilizing personal DGPS; most of the GPS/GNSS users in Sri Lanka, except professional land surveyors, work with L1 or L1/L2 GPS or GNSS receivers as standalone observations without any real-time or post-processing differential corrections. However, GAGAN is a satellite based augmentation service (SBAS), freely available over Indian region including Sri Lanka, and is operated to diminish ionospheric, satellite clock and ephemeris errors from the GPS/GNSS satellites to improve the accuracy of positioning and navigation. Unfortunately, SBAS technology is a new experience for GPS/GNSS users in Sri Lanka and yet not many of them even know about the availability of GAGAN over Sri Lanka. However, GAGAN service is freely available since early 2014; hence, the general standalone GPS/GNSS users in Sri Lanka can get the benefit of real-time positional accuracy enhancement with the utilization of SBAS capable GPS/GNSS receiver.

Therefore, the primary objective of this study is focused on testing the availability of GAGAN satellite based augmentation service over Sri Lanka. In addition, majority of GIS professionals use L1 GPS/GNSS receivers to collect point, line, and polygon spatial feature for various decision making GIS and remote sensing applications. Hence, this study also focused on assessing the GAGAN service capability to improve the accuracy of point, line, and polygon feature collection over Sri Lanka. Further, the investigation is extended to validate the performance and continues operational accuracy of GAGAN service, at any time of a day, compared to the general standalone L1, L1/L2 and local DGPS observations.

2.1 Study Area and Instruments Used

In this initial experiment, only seven GPS observation locations were selected in six districts of three provinces in Sri Lanka. The control stations of national geodetic network were selected for the observations. 24-hour observations are conducted at a temporally established known station. Garmin Etrex 10 –GPS L1 Receiver, SXBLUE-IIB receiver with GPS L1 + GAGAN + SBAS capability, PENTAX GPS+ GLONASS L1/L2 receiver and Kolida Total Station with 2" angle and 2mm distance accuracy were used for the observations and testing. In order to test the performances of GAGAN service the single frequency SXBLUE-IIB receiver is configured as a SBAS receiver and others were kept as GPS stand-alone receivers.

2.2 Analysis Method

In order to analyse the performance of GAGAN active receiver in point feature collection, 10 minutes of observations in static mode is performed at all the 7 known points and compare the achievable accuracy with respect to L1 and L1/L2 standalone observations. The same observations are used to check the availability of GAGAN satellite based augmentation service over Sri Lanka. For the study of linear and area feature observation accuracies, three sample line and area features collected with GAGAN active receiver are compared with Total Station measurements of the same. Moreover, observations were carried out for 24 hours at a temporally established known station to validate the availability of GAGAN corrections throughout a day.

3. Results And Analysis

Table 1 shows the average values of 3D positional error for 10 minutes of observations at the selected 7 known points at six districts of three provinces in Sri Lanka. The accuracy is analyzed by comparing the average 3D positional error, observed at each point, with L1, L1/L2 and GAGAN active L1 receivers. Accordingly, the GAGAN active L1 receiver has always shown a significant accuracy improvement over L1 uncorrected observations. This indicates that GAGAN corrections are available and easily tracked through PRN 128 (GSAT-10) over the tested districts. Further, except at two locations all the other stations it has shown improved accuracy even over L1/L2 uncorrected observations. Five, out of the 7 observation locations, the calculated average 3D positional errors are lower than 1m.

Three line features were observed with a combination of different number of points and compared the distance difference between the total station observed distance and the distance calculated with GAGAN receiver observed points. A curved line is collected along the center of a road, of about 30m width, to avoid disturbances from the roadside structures and a line from the edge of the same road. Further, a short straight line on an open-sky-view playground is also collected for analysis. As shown in Table 2, the distance difference is well within centimeter level and most significantly the accuracy is not influenced by the number of points included for each line. The resulted accuracies listed in Table 1 and 2 are accurate and reliable enough to perform various real-time surveying and mapping applications, car navigation, aviation, maritime, and numerous geospatial and remote sensing applications with single frequency receivers.

Table 1. 3D positional accuracy and Standard Deviation comparison at deferent locations over Sri Lanka.

Observation location	Date of July 2016 & Starting Time	L1 receiver		L1/L2 receiver		GAGAN active L1 receiver		Highest accuracy with GAGAN
		A3D	*SD*	*A3D*	*SD*	*A3D*	*SD*	
Narammala	12th , 13:41	4.6	3.1	1.7	0.5	1.6	0.6	YES
Athugala	12th , 18:23	3.4	2.4	1.6	0.4	0.6	0.2	YES
Gannoruwa	16th , 09:14	1.7	0.6	0.8	0.2	0.9	0.4	NO
Kegalle	16th , 14:34	6.9	4.9	0.8	0.3	1.4	0.9	NO
Homagama	17th , 11:33	4.0	2.8	1.1	0.6	0.9	0.6	YES
Ambalangoda	20th , 10:12	3.4	1.8	1.0	0.6	0.3	0.2	YES
Mathara	20th , 16:26	2.1	0.9	1.4	1.1	0.9	0.4	YES

SD = Standard Deviation (m)
A3D = Average 3D Positional Error (m)

Table 2. Accuracy assessment of line features.

Feature	No of Observed points		Total Distance (m)		Distance difference (m)
	GAGAN Receiver	Total Station	GAGAN Receiver	Total Station	
Road center line	29	29	560.04	560.00	0.04
Edge of a road	15	15	299.43	300.00	0.57
Line on a playground	3	3	64.42	64.23	0.19

In order to test the accuracy of area feature collection, a playground with an undisturbed boundary and open sky view is selected. The area is calculated by observing 11 points along the boundary with a GAGAN active L1 receiver and to validate its accuracy the same polygon is surveyed with total station with the same number of points. Table 3 shows the quantitative results of this accuracy validation. Accordingly, the area measurement difference is calculated as 43m^2 or 1.68 perches. This accuracy is sufficient for many GIS applications with medium or small scale mapping. However, the accurate area measurements are very important for cadastral surveying which mainly deals with the extent of land plots. According to Sri Lanka Survey Department regulations, the acceptable difference for cadastral surveying is calculated based on Eq. (1). Based on which, the acceptable difference for the tested polygon is 7.79m^2 or 0.31 perches. However, the observed area difference for the tested polygon is 43 m^2 or 1.68 P as listed in Table 3. Therefore, the accuracy of GAGAN based DGPS is not recommended for cadastral surveying in Sri Lanka.

$$\Delta€= +\text{-}0.04\ [P \sin (360/N)]^{1/2} \tag{1}$$

Δ€- Acceptable difference in Perches, P - Area computed in perches, N - Number of Observed points

Table 3. Accuracy assessment of area feature.

	GAGAN Receiver	Total Station
No of Observed points	11	11
Areas (A. R. P)	0 A 2 R 29.86 P	0 A 2R 31.54 P
Areas (Ha)	0.2779	0.2821

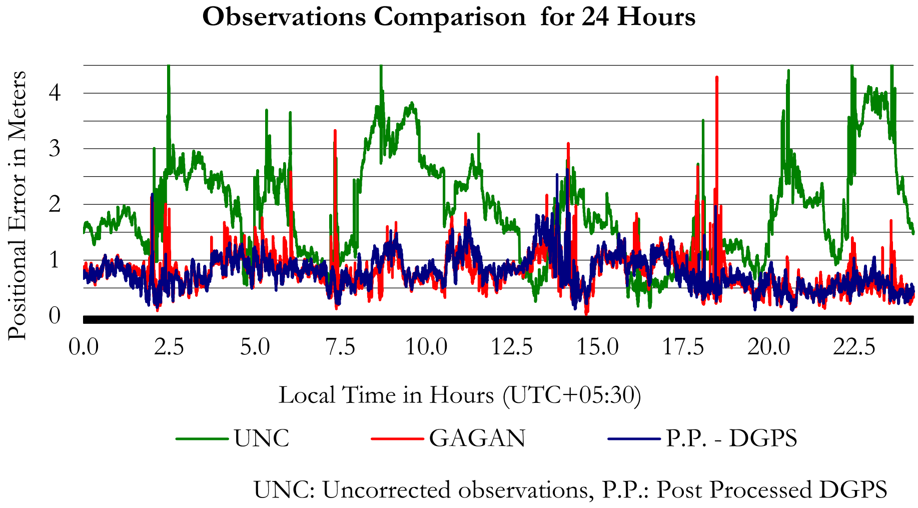

Fig. 4. 3D positional accuracy for a continuous observation of 24 hours for L1 GPS receiver.

Further analyses were carried out to test the 3D positional accuracy of GAGAN based continuous observations for over 24 hours. The observations were carried out from 27th to 28th September 2016 at Belihuloya, Sri Lanka. The accuracy is compared with uncorrected and local DGPS corrected coordinates obtained from L1 GPS receiver as illustrated in Fig. 4. Accordingly, the 3D positional error of GAGAN observations are deviated from post-processed DGPS results at various time slots of 24 hours of observations. However, there are several significant variations, some times more than 1m, and they could be due to the local variations of the ionospheric effect. This indicates that the GAGAN ionospheric model has limitations on local ionospheric corrections and that confirmed by the DGPS results at the same period since it can successfully eliminate this effect. Hence, a continuous and reliable accuracy of single-frequency users with real-time GAGAN corrections could be achieved by introducing a supplementary local ionospheric model, especially for the GAGAN users.

For the same 24 hours of observations, the percentage of 3D positional accuracy is calculated according to less than 0.5m, 1.0m and greater than 1.0m as presented in Table 4. This indicates that almost 79% of observations have an accuracy of less than 1m and that is acceptable for many spatial data collection applications. Further, it is clear that the local DGPS correction has higher reliability than GAGAN corrections and that has shown of almost 85% of observations with less than 1m error. However, this freely available and real-time GAGAN based corrections would make significant accuracy enhancement while maintaining higher reliability on positioning and navigation applications of Sri Lanka.

Table 4. Percentage of 3D positional accuracy for 24 hours of observations.

Observation Mode	**Percentage of observations**		
	< 0.5m	**< 1.0m**	**>1.0m**
UNC	0.00%	7.50%	92.50%
GAGAN	18.90%	78.90%	21.10%
P.P. -DGPS	23.50%	85.00%	15.00%

4. Conclusion and Recommendations

According to the system architecture of GAGAN, only two satellites PRN 127 and 128 are currently available for GAGAN users. However, throughout the observations done in different areas of Sri Lanka only the signals from PRN 128 (GSAT-10) were received. For this initial study, GPS observations were done only at 7 locations in 6 districts, at each point the GAGAN satellite signal was tracked without any delay or difficulty. Most importantly, the results confirmed that, less than 1-meter accuracy could be achieved in real-time with the use of GAGAN corrections for a single frequency GAGAN active receiver.

It has been confirmed that the GAGAN corrections are accurate and reliable enough, over standalone L1 observations, for point, line and area feature collection of many GIS applications. However, the accuracy is not according to the standard requirements of cadastral surveying applications. The 24 hours observations confirmed that the achievable accuracy and reliability of GAGAN service and it has higher potential to use in various applications from LBS to spatial data collections in Sri Lanka. However, further investigations are expected to be carried out to identify the deviations of local ionosphere and GAGAN ionospheric model as reflected in the 24 hours observations. Further, to enhance the continuous and reliable accuracy of single-frequency users with GAGAN could be achieved by addressing its limitation on local ionospheric corrections by the establishment of a supplementary local ionospheric model. In addition, it is recommended to test the availability and the effectiveness of GAGAN corrections during high and low solar activity periods as well.

Acknowledgements

This paper is based on the presentation made at the 37th Asian Conference on Remote Sensing, Colombo, Sri Lanka, 17-21 October 2016.

References

[1] P. Misra and P. K. Enge, *Global Positioning System Signals, Measurements, and Performance*. Lincoln, Massachusetts, UK: Ganga-Jamuna Press, 2004.

[2] C. Rizos, “Principles and practice of GPS surveying,” School of Surveying and Spatial Information Systems (formerly School of Geomatic Engineering), The University of New South Wales, Sydney, Australia, 1997.

[3] C. Rizos and C. Satirapod, “Contribution of GNSS CORS infrastructure to the mission of modern geodesy and status of GNSS CORS in Thailand,” *Engineering Journal*, vol. 15, no. 1, pp. 25-42, 2011.

[4] B. W. Parkinson and J. J. Spilker, *Global Positioning System: Theory and Applications*, vol. I. Washington, DC, USA: American Institute of Aeronautics and Astronautics, 1996

[5] T. Tsujii, T. Fujiwara, T. Kubota, C. Satirapod, P. Supnithi, T. Tsugawa, and H. Lee, “Measurement and simulation of equatorial ionospheric plasma bubbles to assess their impact on GNSS performance,” *Journal of the Korean Society of Surveying, Geodesy, Photogrammetry and Cartography*, vol. 30, no. 6, pp. 607-613, 2012.

[6] C. Kitpracha, D. Promchot, P. Srestasathiern, and C. Satirapod, “Precise tropospheric delay map of Thailand using GNSS precise point positioning technique,” *International Journal of Geoinformatics*, vol. 13, no. 2, pp. 17-21, 2017.

[7] B. W. Parkinson and P. K. Enge, “Differential GPS,” in *Global Positioning System: Theory and Applications*, vol. 2, B. W. Parkinson and J. J. Spilker, Eds. Washington, DC: American Institute of Aeronautics and Astronautics, Inc., 1996, pp. 3-50.

[8] K. K. Fan and X. L. Ding, “Estimation of GPS carrier phase multipath signals based on site environment,” *Journal of Global Positioning Systems*, vol. 5, no. 1-2, pp. 22-28, 2006.

[9] T. L. Dammalage, P. Srinuandee, L. Samarakoon, J. Susaki and T. Srisahakit, “Potential accuracy and practical benefits of NTRIP protocol over conventional RTK and DGPS observation methods,” in *Proceedings of MapAsia*, Bangkok, Thailand, 29 August-1 September, 2006.

[10] T. L. Dammalage, C. Satirapod, S. Kibe, and C. Ogaja, “Wavelet transform application to C/A code multipath mitigation at GPS reference stations for improved differential GPS corrections,” *Survey Review*, vol. 42, no. 317, pp. 240-255, 2010.

[11] T. Charoenkalunyuta, C. Satirapod, H. K. Lee, and Y. S. Choi, “Performance of network-based RTK GPS in low-latitude region: A case study in Thailand,” *Engineering Journal*, vol. 16, no. 5, pp. 95-103, 2012.

[12] T. Charoenkalunyuta and C. Satirapod, “Effect of Thai ionospheric maps (THIM) model on the performance of network based RTK GPS in Thailand,” *Survey Review*, vol. 46, no. 334, pp. 1-6, 2014.

[13] C. Kee, “Wide area differential GPS,” in *Global Positioning System: Theory and Applications*, vol. 2, B. W. Parkinson and J. J. Spilker, Eds. Washington, DC: American Institute of Aeronautics and Astronautics, Inc., 1996, pp. 81-115.

[14] V. Ashkenazi, C. J. Hill, W. Y. Ochieng, and J. Nagle, "Wide areas differential GPS: A performance study," *NAVIGATION: Journal of The Institute of Navigation*, vol. 40, no. 3, pp. 297-319, 1993.
[15] M Abousalem, "Development and analysis of wide area differential GPS algorithms," Ph.D. dissertation, Department of Geomatics Engineering, the University of Calgary, Calgary, Alberta, Canada, 20083, 1996.
[16] A. Leick, *GPS Satellite Surveying*, 3rd ed. New Jersey, USA: John Wiley & Sons, Inc., 2004.
[17] Federal Aviation Administration (FAA), "Wide Area Augmentation System (WAAS) specifications," Department of Transportation, FAA-E-2892B, March 10, 1997.
[18] N. Pringvanich and C. Satirapod, "Performance of SBAS algorithm through the implementation of the Asia-Pacific GNSS test bed: Initial study in Thailand," *Journal of Navigation*, vol. 60, no. 3, pp. 363-371, 2007.
[19] N. Pringvanich and C. Satirapod, "Flight test results and analysis of SBAS-like algorithm from the implementation of the Asia-Pacific GNSS test bed," *Aeronautical Journal*, vol. 113, no. 1139, pp. 35-40, 2009.
[20] A. S. Ganeshan, S. V. Satish, A. Kartik, S. Nirmala, G. Ramesh, "India's satellite based augmentation system," *InsideGNSS*, pp. 42-48, Jan.-Feb. 2016.
[21] B. Murugan, "The land based positional accuracy of GPS and GPS augmented by GAGAN over the Indian geographical region," *International Journal of Scientific and Technology Research*, vol. 3, no. 4, 2014.
[22] K. N. Suryanarayana, "GAGAN—The indian satellite based augmentation system," *Indian Journal of Radio & Space Physics*, vol. 36, pp. 293-302, 2007.
[23] ISRO. (2017). *Satellite Navigation Programme*. [Online]. Available: http://www.isro.gov.in/applications/satellite-navigation-programme-0