Journal of Engineering Science and Technology
Vol. 12, No. 4 (2017) 1092 - 1103

AN ANALYSIS STUDY OF PROTECTION LEVELS AT A LOW LATITUDE INDIAN STATION FOR THE GAGAN

SRIDHAR M.[1,*], PADMA RAJU K.[2], SRINIVASA RAO CH.[3]

[1]KL University, Guntur, Andhra Pradesh, India
[2]University College of Engineering, JNTUK, Kakinada, Andhra Pradesh, India
[3]University College of Engineering, JNTUK, Vizianagaram, Andhra Pradesh, India
*Corresponding Author: sridhar.m@kluniversity.in

Abstract

GPS-aided Geo-augmented Navigation (GAGAN) provides an improvement in accuracy and integrity to Global Navigation Satellite System (GNSS) signals for navigation and positioning applications in India. GAGAN system expected to meet Category I Precision Approach (PA) requirements (Horizontal positional accuracy: 7.9 m (95%) and Vertical positional accuracy: 4.3 m (95%)) for aircraft landings. Ionospheric differential corrections must be estimated using GNSS satellite signals since it is rather random and less predictable in low latitude ionospheric regions. Ionospheric irregularities cause changes in amplitude and phase of GPS signal, thus, introducing range errors. The calculation of protection levels is important in the evaluation of accuracy and integrity requirements. In this paper, GNSS data collected at Koneru Lakshmaiah (KL) University, Guntur, India was considered for carrying out the analysis of protection levels for GNSS users. Horizontal and Vertical Protection Levels were calculated and compared with the values measured on quiet and disturbed days. It is evident from the results that as the range error and TEC variations were more predominant during the disturbed days, the protection limits exceeded the permissible range (Vertical protection limit = 50 m and Horizontal protection limit = 40 m). It is observed that there was a significant rise in DOP values indicating the reduction of accuracy and availability.

Keywords: GPS; GAGAN, Horizontal protection level, Vertical protection level, Dilution of precision, Total electron content.

1. Introduction

The importance of civil aviation is increasing day by day, and this purports the improvement in the features of navigation systems. Global navigation satellite

Abbreviations

DOP	Dilution of Precision
GDOP	Geometric Dilution of Precision
GPS	Global Positioning System
GNSS	Global Navigation Satellite System
GAGAN	GPS-aided Geo-augmented Navigation
GBAS	Ground-based Augmentation System
HDOP	Horizontal Dilution of Precision
HPL	Horizontal Protection Limit
ILS	Instrument Landing System
LAAS	Local Area Augmentation System
PDOP	Position Dilution of Precision
RAIM	Receiver Autonomous Integrity Monitoring
SBAS	Satellite-based Augmentation System
TDOP	Time Dilution of Precision
TEC	Total Electron Content
VDOP	Vertical Dilution of Precision
VPL	Vertical Protection Limit

system (GNSS), with a suitable augmentation, is considered for increasing its integrity, accuracy and availability with worldwide coverage [1]. Global positioning system (GPS), Global navigation satellite system (GLONASS), Galileo and BeiDou navigation satellite system are few navigation satellite systems that are in force for providing accurate autonomous geo-spatial positioning. India has developed its own regional satellite-based augmentation system (SBAS), GPS-aided geo-augmented navigation system (GAGAN) for improving the accuracy of GNSS users [2]. Indian Space Research Organisation (ISRO), in collaboration with Airports Authority of India (AAI), has implemented GAGAN, which is fast becoming an alternate for Instrument landing system (ILS) for aircraft landing applications. Local area augmentation system (LAAS) was considered for providing the navigation and landing system for different categories of precision approaches like Category (CAT) I, II, and III [3]. Accuracy, availability and integrity are the main standards of a navigation system that play a vital role in civil aviation precision approach standards. The potentiality of a system to caution the users when using the navigation system under severe position/range error conditions is referred to as integrity of the system [4]. The integrity can be improved by using differential GPS principles; however, errors like ionospheric delay, tropospheric delay, and multipath error introduce range errors. Specifying a protection level is very crucial in improving the integrity of the system and is defined as the maximum navigation system error from the actual location that can happen in a particular direction (horizontal or vertical). Receiver autonomous integrity monitoring (RAIM) algorithms calculate the horizontal protection limit (HPL) and vertical protection limit (VPL), which are continuously compared with suitable alert limits [5]. If the HPL or VPL exceeds the respective alert limit, the navigation system becomes unusable for the given application and can be considered only when the protection levels fall below the alert levels [6-8].

Several studies have been performed for investigating the impact of scintillations and total electron content (TEC) on the navigational capabilities of the GNSS receiver [9 - 13]. A real-time software receiver has been implemented with low-cost components for calculating the appropriate protection [14]. A technique was suggested to calculate the accurate composite protection limits that assume position domain error as non-zero mean multivariate normal [15]. SBAS and LAAS uses various methods to generate differential correction integrity information for providing accurate and safe aircraft guidance [16]. To eliminate the drawbacks of conventional GBAS/LAAS standards, an alternate architecture was proposed, which is backward compatible and allows user avionics to evaluate protection levels directly [17].

In this paper, ionospheric data collected at Koneru Lakshmaiah (KL) University, Guntur during the years 2013 to 2015 was considered to analyse the impact of ionospheric irregularities on the protection levels of GAGAN system. The protection limits HPL and VPL along with DOP values were calculated during a quiet day (March 12, 2013) and during a storm event (June 29, 2013).

2. Horizontal and Vertical Protection Limits

Integrity is a scale of confidence that is considered for the precision of the data furnished by the complete unit [1]. It enhances the capability of a system to provide correct and appropriate warnings to the user, called as alerts. Receiver autonomous integrity monitoring (RAIM) algorithm is one of the solutions for performing a continuous check on the measurements of the satellite. The parameters that are necessary as inputs for RAIM algorithm are the measurement geometry, standard deviation of the measurement noise, and the maximal usable probabilities for a wrong alert and a lost detection. The output parameters of this algorithm are horizontal and vertical protection levels [18].

HPL and VPL are defined as the radii of the circles, focused at the actual aircraft position that is ensured to comprise the given horizontal and vertical positions, respectively, with the known probability of faulty alert and missed detection. These are calculated as:

$$HPL = P_{MD}\sqrt{\sum_{k=1}^{M} S_{h,k}^2 \times \sigma_k^2} \tag{1}$$

$$VPL = P_{MD}\sqrt{\sum_{k=1}^{M} S_{v,k}^2 \times \sigma_k^2} \tag{2}$$

where P_{MD} is the probability of missed detection, $S_{h,k}$ and $S_{v,k}$ are the horizontal and vertical components of projection matrix of k^{th} ranging source, respectively, σ_k^2 is the variance of the error of each satellite keeping in view k^{th} ranging source [19].

If measured HPL and VPL values are below the horizontal alert limit (HAL) and vertical alert limit (VAL), respectively, integrity is said to be available for the given phase of flight. However, if the PLs exceeds the alert limits ALs, aircraft user should be warned immediately to avoid using GPS system for that phase of flight. SBAS systems like GAGAN provide the necessary integrity and differential corrections for each satellite under consideration [20].

Dilution of Precision (DOP) parameters was considered to represent the GPS satellite geometrical factors. Higher the DOP values, more is the probability of occurrence of positional error that dilutes the precision of the position determination [21]. Geometric Dilution of Precision (GDOP), Position Dilution of Precision (PDOP), Horizontal Dilution of Precision (HDOP), Vertical Dilution of Precision (VDOP) and Time Dilution of Precision (TDOP) parameters are used for analysing the amount of errors introduced and are computed as:

$$PDOP = \frac{\sqrt{\sigma_e^2 + \sigma_n^2 + \sigma_u^2}}{\sigma} \quad (3)$$

$$HDOP = \frac{\sqrt{\sigma_e^2 + \sigma_n^2}}{\sigma} \quad (4)$$

$$VDOP = \frac{\sigma_u}{\sigma} \quad (5)$$

$$TDOP = \frac{\sigma_t}{\sigma} \quad (6)$$

$$GDOP = \sqrt{(PDOP)^2 + (TDOP)^2} \quad (7)$$

where σ_e^2, σ_n^2, and σ_u^2 are the variances of east, north, and up components of the receiver position estimate, respectively, and σ_t^2 indicates the variance of the receiver clock offset estimate. σ is the standard deviation of pseudo range error [22].

3. Results and Discussion

The architecture of GAGAN is similar to that of WAAS and the network contains 8 GPS receivers operating at L1 and L2 frequencies. The services of GAGAN will improve the accuracy of GNSS receivers as it provides the required differential corrections leading to improved confidence levels in the approach. Also, it assists in improving the integrity and availability of GPS receivers, thereby guiding the aircraft with the vertical guidance of a GNSS system. The data collected by GPS receivers are used to estimate the ephemeris corrections and model the propagation effects of the ionosphere. The vertical and horizontal alert limits of approach with vertical guidance (APV) level 1/1.5 service are 50 m and 40 m, respectively.

The ionospheric data obtained during the years 2013 to 2015 at KL University, Guntur, India were considered to carry out the investigations on TEC and the irregularities during the geomagnetic quiet and disturbed conditions. Table 1 indicates the geographical details of the location along with the specifications of the experimental setup.

During the geomagnetic storms, the ionosphere is unstable and induces sudden variations and strong spatial gradients, giving rise to plasma bubbles [23, 24]. The impact of the storms on the ionosphere depends on the intensity and phase of the storm, time of occurrence, geographical latitude and longitude, and season. The intensity of geomagnetic storms can be explained using the metrics like Kp index, Ap index, Dst index and SYM – H index.

Disturbance storm time (Dst) index is a measure of the ring current during the storm, with a 1-hour time resolution and measured in nanotesla (nT). Symmetrical disturbance index in the horizontal direction (SYM-H) is another metric used to measure the intensity of the storm with 1-minute resolution and hence, considered in place of Dst index. The details of the various geomagnetic storms during the years 2013 – 2015 have been included in Table 2 with the indices indicating the strength of the storms. Figure 1 indicates the variation of TEC and the rate of TEC for PRN 2 on March 12, 2013. TEC values were depleted and small changes in the rate of TEC could be observed, indicating the presence of small-scale irregularities in the ionosphere.

Table 1. Particulars of the experimental setup.

	Specifications
Station	KL University, Guntur, India
GPS Receiver	GPStation 6, Novatel, Canada
Frequency of operation	L1 -- 1.57542 GHz (C/A) L2 -- 1.2276 GHz (P (Y))
Geographical Latitude & Longitude	16.31° North & 80.37° East
Geomagnetic Latitude & Longitude	7.44° North & 153.75° East

Table 2. Dst and SYM-H indices for the geomagnetic storms during the Years 2013 – 2015.

	Dst index	SYM – H index
March 17, 2013	-132 nT	-131 nT
June 1, 2013	-119 nT	-137 nT
June 29, 2013	-98 nT	-111 nT
February 19, 2014	-112 nT	-125 nT
March 17, 2015	-220 nT	-232 nT
June 23, 2015	-195 nT	-208 nT

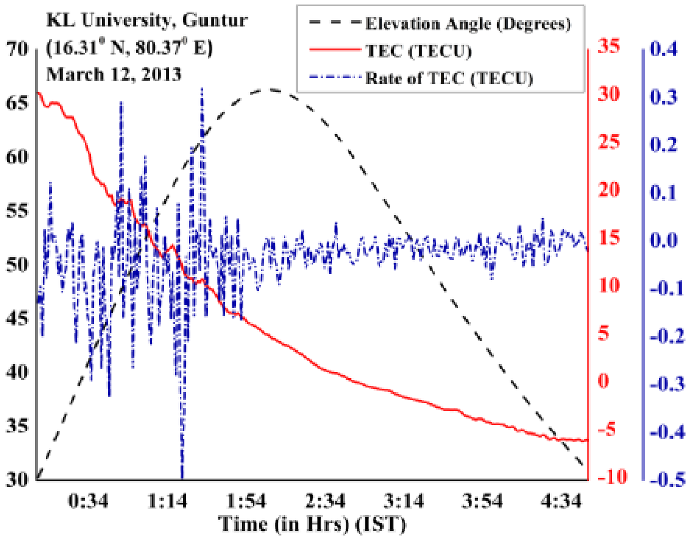

Fig. 1. Variation of ionospheric parameters on March 12, 2013 at KL University, Guntur.

During the magnetically disturbed conditions on June 29, 2013, PRN 15 was affected severely and the results indicate the rapid variation of ionospheric parameters. It is evident from the figure that the TEC variations are more dominant because of the rapid movement of irregularities during the storm. During the post-sunset hours, a sudden decrease in TEC was observed due to equatorial ionisation anomaly (EIA). TEC depletions will take place when the plasma bubbles move slowly in the LOS path between the receiver under consideration and the satellite. Several TEC depletion instances were observed, indicating the presence of gradients in the ionosphere. TEC enhancement of about 25 units was found between 22:50 Hrs (LT) and 23: 05 Hrs (LT), as shown in Fig. 2.

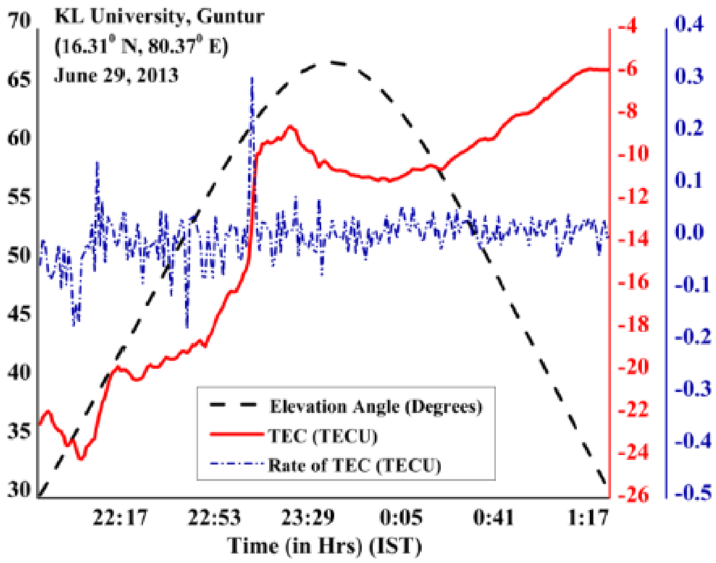

Fig. 2. Variation of ionospheric parameters on June 29, 2013 at KL University, Guntur.

Figure 3 indicates the ionospheric time delay observed on March 12, 2013 during which TEC variations were small in magnitude. It is evident that though the maximum error observed was 9 m, fewer variations were observed post-sunset as it was a quiet day. However, rapid changes were observed in the ionospheric delay during the storm on June 29, 2013.

Figure 4 shows the variation of ionospheric delay with time on June 29, 2013 where the peak value of error observed was 7 m. Rapid fluctuations were observed in the delay, indicating changes in TEC and the rate of TEC values. These changes will cause an increase in the horizontal and vertical protection levels (HPL and VPL) and consequently, degrade the efficiency of GNSS receiver.

Figure 5 shows the variation of HPL values with local time on March 12, 2013. As the TEC variations are less dominant, HPL values are below the alert limits, indicating proper communication between the satellite and receiver. The maximum HPL value obtained was 3.40 m at 09.45 Hrs (LT) and at 18:15 Hrs (LT), with the recorded peak value being 3.35 m.

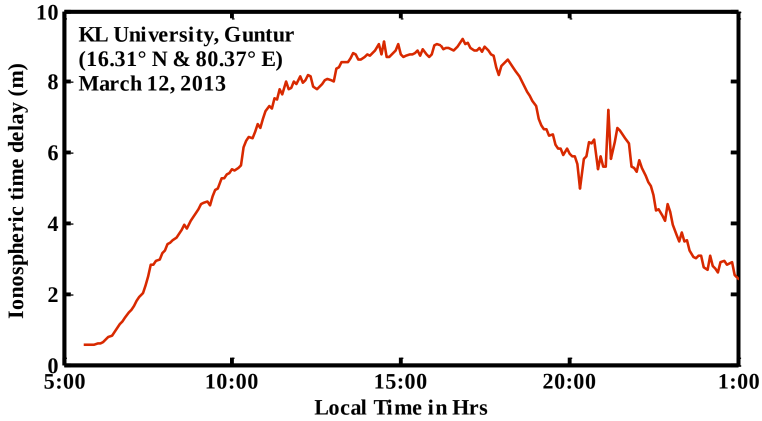

Fig. 3. Ionospheric Time Delay observed on March 12, 2013 at KL University, Guntur.

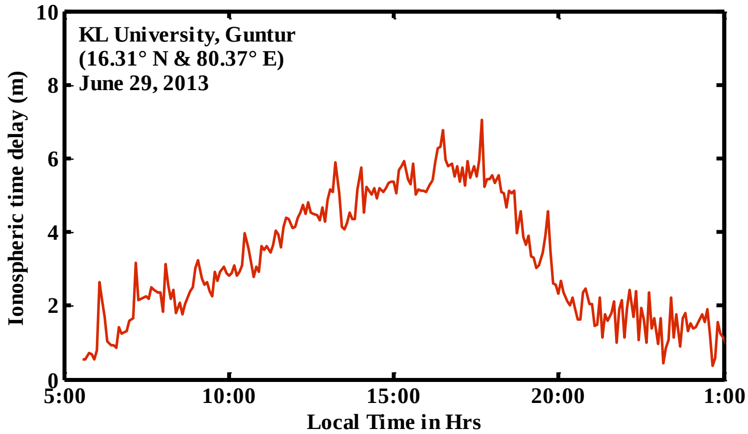

Fig. 4. Ionospheric Time Delay observed on June 29, 2013 at KL University, Guntur.

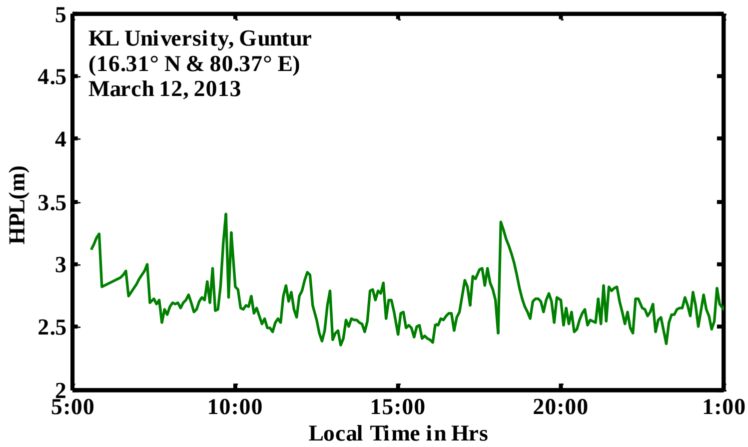

Fig. 5. Variation in HPL on March 12, 2013 at KL University, Guntur.

Since these values are in the acceptable range, no range error was introduced and hence, the precision of accuracy was better. Similarly, the HPL values were calculated on June 29, 2013, as indicated in Fig. 6; the fluctuations indicate the impact of ionosphere on the GPS signal. The maximum value of HPL observed was 4.1 m at 16:42 Hrs (LT). Also, fast changes were observed during the post-sunset period. Since the HPL variations are predominant, range errors will be introduced in estimating the exact location of the user.

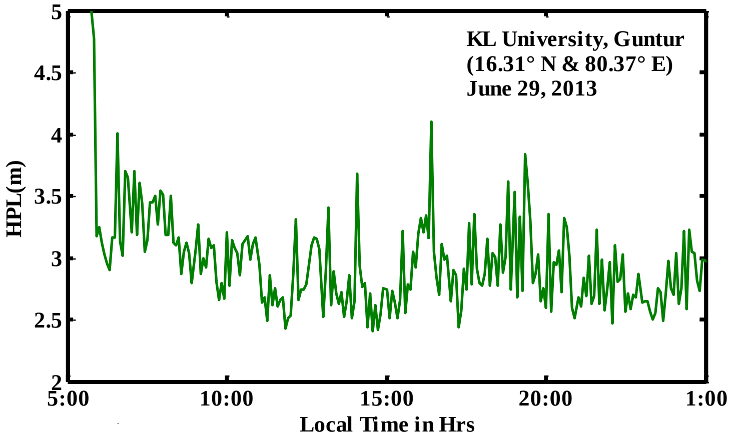

Fig. 6. Variations in HPL on June 29, 2013 at KL University, Guntur.

The VPL values were calculated on March 12 and June 29, 2013 and the results are summarized in Figs. 7 and 8. There was a rise in the VPL on June 29, pronouncing the effect of the storm on the GNSS signals. VPL values have been exceeded the permissible alert limits (VAL = 50 m for APV1/1.5) and the observed peak value was 80 m during the day time indicating the magnetic disturbances on June 29. 52 m was the peak VPL value obtained on March 12, which was within the required limits (Figs. 7 and 8).

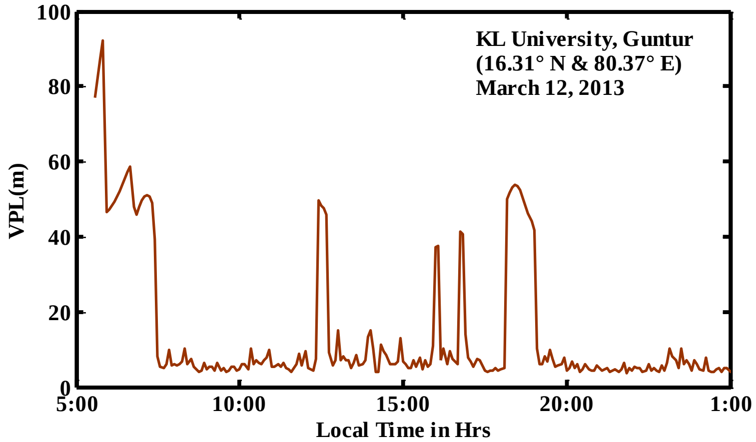

Fig. 7. Variations in VPL on March 12, 2013 at KL University, Guntur.

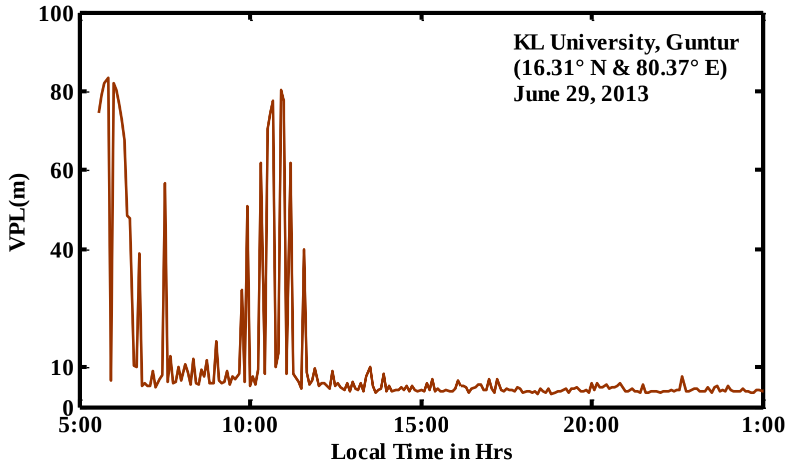

Fig. 8. Variations in VPL on June 29, 2013 at KL University, Guntur.

DOP parameters play an important role in estimating the range errors. Figure 9 indicates the DOP parameters calculated on March 12 and June 29, 2013. It is evident from the results that there is a significant increase in DOP values during the stormy day, compromising the positional accuracy.

The spikes in the DOP parameters indicate the reduction in the number of visible satellites, which may be due to random electron density irregularities. During March 12, the obtained DOP values were relatively lower than the DOP values on June 29, indicating the visibility of more satellites on that day.

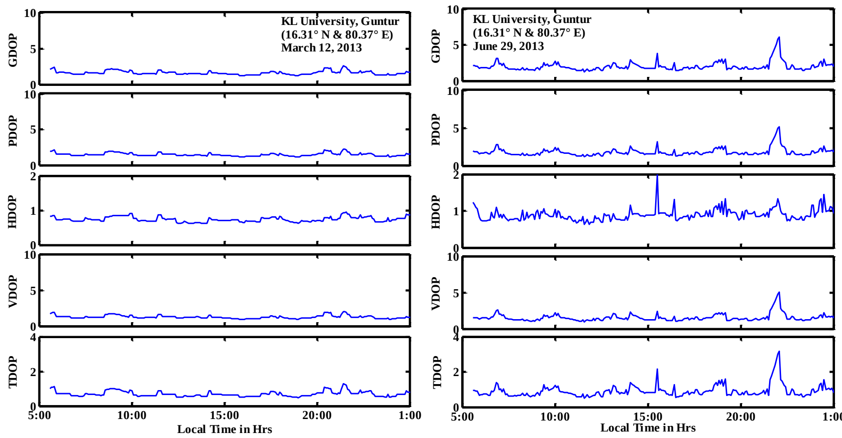

Fig. 9. Dilution of Precision (DOP) parameters on March 12 and June 29, 2013 at KL University, Guntur.

In general, a PDOP value of 5 or less is accepted and recommended for ensuring high-precision GPS positioning. On June 29, the maximum value of

PDOP attained was 5.17 at 22.08 Hrs (LT), indicating the impact of geomagnetic disturbance on the performance of the GAGAN system (Fig. 9).

Table 3 shows the variations in the protection limits and ionospheric time delay during the geomagnetic storm conditions that occurred between 2013 to 2015. The variation is predominant on these days, which depends on the intensity of the geomagnetic disturbance. During the geomagnetic storm event on June 1, 2013, the VPL value observed was 80.73 m, which is more than the permissible alert limit (50 m). Also, there was a significant rise of 4.18 m in the HPL value. Though these protection limits are above the respective alert values, the observed ionospheric time delay is less than the time delay of the quiet day considered in the analysis. The maximum ionospheric time delay of 11.15 m was observed during the storm on March 17, 2013. However, the protection levels measured were close to the alert limits on that day. The maximum HPL value of 4.2 m was observed on the February 19, 2014 storm event along with significant changes in VPL and ionospheric delay. During the severe magnetic storm (SYM-H value of -208 nT) on June 23, 2015, the parameters under consideration were lower than the permissible alert limits. Among the storm events considered for the analysis, the intensity of the storm was very high on March 17, 2015 (SYM-H = -232 nT) and the observed VPL and HPL values were 64.99 m and 4.02 m, respectively.

Table 3. Details of the protection limits and ionospheric time delay during the storm events of 2013 – 2015.

	Vertical Protection Limit (VPL) (m)	Horizontal Protection Limit (HPL) (m)	Ionospheric time delay (m)
March 17, 2013	53.89	3.32	11.15
June 1, 2013	80.73	4.18	8.68
June 29, 2013	80.28	4.1	7.05
February 19, 2014	71.77	4.20	11.12
March 17, 2015	64.99	4.02	10.58
June 23, 2015	40.2	3.08	6.776

4. Conclusions

In this paper, the effect of TEC was studied on GPS signals during geomagnetic storm conditions on June 29, 2013. The horizontal and vertical protection limits were computed on March 12 and June 29 and compared with the permissible alert limits. It was observed that the protection limits had exceeded the acceptable limits, decreasing the accuracy and availability of the GAGAN system.

The observed HPL and VPL values were 4.1 m and 80 m respectively, on June 29, 2013. Also, the DOP parameters were calculated during these two days and from the results it is evident that the increase in DOP values during the storm degrades the navigational capacity of the GNSS receivers. The analysis was also extended to the other storm events from 2013 to 2015. The results obtained are useful in understanding the morphology of ionospheric gradients and can be considered in analysing the effect of TEC on navigational capabilities of GNSS receivers.

Acknowledgements

The above work has been carried out under the project entitled “Development of Ionospheric Forecasting models for Satellite-based Navigation Systems over low latitude stations” sponsored by the Department of Science and Technology, New - Delhi, India, vide sanction letter No: SR/FTP/ETA- 0029/2012, dated: 08.05.12 and SR/FST/ESI-130/2013(C) FIST program. The authors are thankful to Dr. D. Venkata Ratnam, Professor in ECE, KL University for his valuable suggestions and cooperation.

References

1. Teunissen, P.J.G.; and De Bakker, P.F. (2013). Single-receiver single-channel multi-frequency GNSS integrity: outliers, slips, and ionospheric disturbances. *Journal of Geodesy*, 87(2), 161-177.
2. Rao, K.S. (2007). GAGAN-The Indian satellite based augmentation system. *Indian Journal of Radio and Space Physics*, 36(4), 293-302.
3. Lee, J. (2004). LAAS position domain monitor analysis and test results for CAT II/III operations. In *Proceedings of the Institute of Navigation GNSS 2004*.
4. Stankov, S.M.; and Jakowski, N. (2007). Ionospheric effects on GNSS reference network integrity. *Journal of Atmospheric and Solar-Terrestrial Physics*, 69(4), 485-499.
5. Hewitson, S.; and Wang, J. (2006). GNSS receiver autonomous integrity monitoring (RAIM) performance analysis. *GPS Solutions*, 10(3), 155-170.
6. Kintner, P.M.; and Ledvina, B.M. (2005). The ionosphere, radio navigation, and global navigation satellite systems. *Advances in Space Research*, 35(5), 788-811.
7. Ratnam, D.V.; and Sarma, A.D. (2006). Modelling of Indian Ionosphere using MMSE Estimator for GAGAN Applications. *Journal of Indian Geophysical Union*, 10(4), 303-312.
8. Juan, J.M.; Hernández-Pajares, M.; Sanz, J.; Ramos-Bosch, P.; Orus, R.; Ochieng, W.; Feng, S.; Jofre, M.; Coutinha, P.; Samson, J.; and Tossaint, M. (2012). Enhanced precise point positioning for GNSS users. *Geoscience and Remote Sensing, IEEE Transactions on*, 50(10), 4213-4222.
9. Seo, J.; Walter, T.; and Enge, P. (2011). Availability impact on GPS aviation due to strong ionospheric scintillation. *IEEE Transactions on Aerospace and Electronic Systems*, , 47(3), 1963-1973.
10. Shanmugam, S.; Jones, J.; MacAulay, A.; and Van Dierendonck, A.J. (2012, April). Evolution to modernized GNSS ionospheric scintillation and TEC monitoring. In *Position Location and Navigation Symposium (PLANS), 2012 IEEE/ION*, 265-273.
11. Jakowski, N.; Wilken, V.; Schlueter, S.; Stankov, S.M.; and Heise, S. (2005). Ionospheric space weather effects monitored by simultaneous ground and space based GNSS signals. *Journal of atmospheric and solar-terrestrial physics*, 67(12), 1074-1084.
12. Kumar, P.N.; Sarma, A.D.; and Reddy, A.S. (2014). Modelling of ionospheric time delay of Global Positioning System (GPS) signals using

Taylor series expansion for GPS Aided Geo Augmented Navigation applications. *IET Radar, Sonar & Navigation*, 8(9), 1081-1090.

13. Kumar, P.N.; Rasool, N.; Krishna, K.M.; Sarma, A.D.; Mridula, N.; Pant, T. K.; Sreelatha, P.; Rosmi, J.; Santosh, K; Praveen Kumar; and Sharma, R. (2013). Ionospheric variability of low and equatorial latitude regions over India–A study using RaBIT on-board YOUTHSAT. *Indian Journal of Radio & Space Physics*, 42, 136-142.
14. Chen, Y.H.; Lo, S.; Akos, D.M.; Choi, M.; Blanch, J.; Walter, T.; and Enge, P. (2014, January). Development of a Real-time GNSS Software Receiver for Evaluating RAIM in Multi-constellation. In *Proceedings of the ION Institute of Navigation International Technical Meeting, San Diego, CA, USA*, 2729, 525-533.
15. Bruckner, D.; van Graas, F.; and Skidmore, T. (2011). Statistical characterization of composite protection levels for GPS. *GPS solutions*, 15(3), 263-273.
16. Takeyasu, S.; Keisuke, M.; Takayuki, Y.; and Susumu, S. (2009). Air Navigation with Global Navigation Satellite Systems and the Ionospheric Effects. *Journal of the National Institute of Information and Communications Technology*, 56(1-4), 231-242.
17. Rife, J.; Pullen, S.; and Enge, P. (2007, April). Evaluating fault-mode protection levels at the aircraft in Category III LAAS. In *Institute of Navigation: Proceedings of the ION Annual Meeting, Cambridge, Massachusetts*,356-371.
18. Lijun, P.; Kai, J.; Xiaojun, D.; Yan, Z.; and Wenqiang, Y. (2012, January). Receiver autonomous integrity monitoring parameter design and analysis for multi-constellation navigation. In *China Satellite Navigation Conference (CSNC) 2012 Proceedings*, 15-27.
19. Srinivas, V.S.; Sarma, A.D.; Reddy, A.S.; and Reddy, D.K. (2014). Investigation of the Effect of Ionospheric Gradients on GPS Signals in the Context of LAAS. *Progress In Electromagnetics Research B*, 57, 191-205.
20. Ratnam, D.V.; Sujatha, C.; Sarma, A.D.; and Ravindran, S. (2009, December). Modelling of GAGAN TEC data using Spherical Harmonic Functions. In *Computers and Devices for Communication, 2009. CODEC 2009. 4th International Conference on* ,1-4.
21. Massatt, P.; and Rudnick, K. (1990). Geometric formulas for dilution of precision calculations. *Navigation*, 37(4), 379-391.
22. Huihui, W.; Xingqun, Z.; and Yanhua, Z. (2008). Geometric dilution of precision for GPS single-point positioning based on four satellites. *Journal of Systems Engineering and Electronics*, 19(5), 1058-1063.
23. Uma, G.; Brahmanandam, P.S.; Kakinami, Y.; and Dmitriev, A. (2012). Ionospheric responses to two large geomagnetic storms over Japanese and Indian longitude sectors. *Journal of Atmospheric and Solar-Terrestrial Physics*, 74, 94-110.
24. Rama Rao, P.V.S.; Gopi Krishna, S.; Vara Prasad, J.; Prasad, S.N.V.S.; Prasad, D.S.V.V.D.; and Niranjan, K. (2009). Geomagnetic storm effects on GPS based navigation. *Annales Geophysicae*, 27(5), 2101-2110.